GLASS – A Sustainable Building and Packaging material

Technical Articles

An AIGMF Publication

www.aigmf.com

Prof. (Dr.) A. K. Bandyopadhyay

$$\frac{dn}{dk} = -\frac{g\rho}{2\eta}k^{-2} + \frac{\gamma}{2\eta} = 0$$

$$\sigma_{Th} = \sqrt{\frac{\frac{E\gamma}{a}}{(\frac{\pi\delta}{\lambda} + \frac{2\pi^2\delta^2}{\lambda^2})}}$$

$$\int_0^{\lambda/2} \sigma_{Th} \sin(\frac{2\pi X}{\lambda}) dX = \sigma_{Th}(\frac{\lambda}{\pi})$$

AIGMF

About The All India Glass Manufacturers' Federation

The All India Glass Manufacturers' Federation was founded in 1944. The Federation is made up of five Regional Associations viz.

Eastern India Glass Manufacturers' Association (EIGMA)-Kolkata

Northern India Glass Manufacturers' Association (NIGMA)-Haryana

South India Glass Manufacturers' Association (SIGMA)-Hyderabad

Uttar Pradesh Glass Manufacturers' Syndicate (UPGMS)-Firozabad and

Western India Glass Manufacturers' Association (WIGMA)-Mumbai

The Federation was incorporated under the Companies Act, 1956 (No. 1 of 1956) as a Limited Company on 15-6-1970. The main aims & objectives of the Federation are:-

- To encourage, promote and develop the manufacture of glass articles of all kinds and to safeguard and protect the interests of glass industry and glassware business in India.
- To form a common link amongst Glass Manufacturers' in India and thus develop a spirit of mutual help and co-operation with one another.
- To promote the study and research in Glass Technology.
- To consider all matters relating to the manufacture and marketing of glass articles in India and the question of export and import thereof.
- To devise ways and means for securing necessary supply of raw materials required for the manufacture of glass articles at comparatively lower prices and thus to decrease the cost of production and increase the national wealth.
- To collect necessary information and data and propagate it for the benefit of Glass Industry and trade in India.
- To make representations whenever necessary to the Union Government or any unit of the Union of India for the removal of difficulties that might hamper the trade of glass articles or for grant of special facilities for the Glass Industry.
- To draw Government or public attention to the difficulties in the way of Glass Industry and to solve other problems confronting it and to solicit their help and support through concerted action.
- To organise a united front on behalf of all glass manufacturers and thus strive to gain all those advantages which may not be possible through individual effort.

All those engaged in the manufacture of glass and glass articles are enrolled as **Ordinary Members** of the AIGMF and those associated with the Glass Industry are enrolled as **Affiliate Members** of the Federation.

Almost all glass manufacturers including many in the small scale sector are 'Ordinary' members of the Federation.

Articles of Association of the AIGMF were amended in September 1992 to enroll foreign companies as Affiliate Members of the Federation ■

GLASS – A Sustainable Building and Packaging Material

Compilation of Technical Articles published in KANCH (*Quarterly Journal of The All India Glass Manufacturers' Federation)*

By

Prof. (Dr.) A. K. Bandyopadhyay

Member Editorial Board,
Kanch (quarterly journal of the AIGMF)
Technology Consultant & Ex–Principal,
Govt. College of Engg. & Ceramic Technology
West Bengal University of Technology, Kolkata

Reference of KANCH has appeared in all articles.

Online issues of KANCH are available at http://www.aigmf.com/kanch.php

To order print copies, please send mail to info@aigmf.com

Price: ₹500 (within India) + ₹ 50 for postage
Overseas: US$ 60 (including postage and bank charges)

Front Cover Photographs *(from top to bottom)*:

a) 302 KVA rooftop installation on top of 80000 sq. ft. warehouse of Borosil Group Company © Borosil
b) Lotus shaped glass facade building of Motisons Jewellers at Jaipur- © AIGMF
c) Glass Bottles specially manufactured by HNG & Inds Ltd., in tune with Swachh Bharat Abhiyan- Clean India Campaign © AIGMF

Published & printed by Vinit Kapur on behalf of The All India Glass Manufacturers' Federation from 812, New Delhi House, 27 Barakhamba Road, New Delhi – 110001, INDIA
T: +91 11 2331 6507 F: +91 11 2335 0357 E: info@aigmf.com
Printed at: New United Process, A-26, Ph-II, Naraina Indl. Area, New Delhi-110028

Foreword

Ever since announcement made by the Government of India on Swachh Bharat Abhiyan (Clean India Campaign) and Smart Cities, Glass Industry has made sincere efforts to showcase glass as an excellent building material for smart and solar cities. Similarly, Glass being a sustainable packaging material supplements Swachh Bharat Abhiyan.

The All India Glass Manufacturers' Federation (AIGMF) organized special programmes in Delhi / Jaipur / Mumbai and other parts of India, where emphasis was given on use of more glass application as it directly aides both these pilot projects of Govt. of India. On September 12, 2015, an Interactive Session on Green Buildings was organised at Paharpur Business Centre, LEED Platinum/BEE 5 star Building in New Delhi with an idea to introduce Green Buildings concept to its members and to debate on use of glass in buildings as eco-friendly measure. As Corporate Social Responsibility, 100 glass water bottles were gifted to Paharpur Business Centre to further strengthen green building concept.

On December 19, 2015, an interactive session with Honb'le Minister of Industry for Rajasthan, Mr. Gajendra Singh was organized at Jaipur, which provided an opportunity to debate on use of glass containers as responsible and safe packaging for clean India campaign and use of glass as eco-friendly building material for Smart Cities.

Mr. Singh emphasized use of more solar and flat glass for building Smart Cities. He appreciated Glass Industry's commitment towards 'Swachh Bharat Abhiyaan' & 'Smart Cities' and offered support to the Industry with regard to investments in State of Rajasthan.

Mr. C K Somany, Former AIGMF President / Former CAPEXIL Chairman and Chairman of HNG Group gifted 500 glass water bottles (specially manufactured by Hindustan National Glass and Industries Ltd.) to the Honb'le Minister for use in 'Secretariat' which carried a logo of Swachh Bharat Abhiyaan enabling people demand responsible and safe packaging.

While in Jaipur, AIGMF members visited select glass façade buildings to showcase its commitment for the uninterrupted supply of glass as a vital building material for Smart Cities.

As Corporate Social Responsibility, AIGMF gifted 200 glass water bottles to Jaipur Marriot Hotel and 50 bottles to lotus shaped glass façade building of Motisons Jewellers.

As a Supporting Association, AIGMF participated in IGBC's Green Building Congress 2015 at Gandhinagar, Gujarat from Nov 19-21, 2015 wherein Mr. Sourabh Kankar, Member, Architectural Glass Panel (AGP) / AIGMF and Manager - Architectural, Gujarat Guardian Ltd., gave a presentation on Principles of Glass Selection for Facades at the Indian Green Building Council's (IGBC) Conference.

With regard to solar cities, one of our prominent members, Gujarat Borosil Limited (GBL) is the only manufacturer of High Transmission Low Iron Textured Solar Glass in India. This finds wide application in Solar Photovoltaic modules, Solar thermal heaters and Green houses. The highly rated testing laboratory SPF of Switzerland has rated this glass as having an efficiency of 95.2% thus making it the world's highest performing solar glass for application in photovoltaic panels.

Further, at 80 PPM, this glass has been acknowledged by Fraunhofer Institute, Wurzburg, Germany to have the lowest iron content in the world. When tested by PICON, Berlin, Germany, for Potential Induced Degradation (PID) in solar modules, alongwith glass from four other leading manufacturers of the world including in Europe, their glass has been found to be the highest performing amongst all. In a technological breakthrough, GBL has become the world's first manufacturer to produce solar glass without Antimony, a highly toxic element.

Consultations have been carried with The Ministry of New and Renewable Energy (MNRE), Bureau of Energy Efficiency (BEE), Ministry of Commerce and Ministry of Finance to provide special subsidy to promote solar glass as a sustainable building material for Smart cities in order to achieve Prime Minister's vision for Clean India.

I am pleased to inform that Dr. AK Bandyopadhyay, Member Editorial Board of KANCH (quarterly journal of The All India Glass Manufacturers Federation) has been writing regularly on glass sector including glass usage in smart cities and container glass packaging solutions for Swachh Bharat Abhiyan. For the benefit of readers, AIGMF decided to compile select Articles contributed by Dr. Bandyopadhyay in KANCH (http://www.aigmf.com/kanch.php) which is presented in this book.

I would like to thank Dr. AK Bandyopadhyay for his excellent contributions and hope this book would prove to be a useful resource for building solar and smart cities and will also supplement Swachh Bharat Abhiyan as Glass Industry's initiative.

Sanjay Ganjoo
President AIGMF
And COO, Asahi India Glass Ltd., Taloja (Maharashtra)

About the Author

Prof. (Dr.) Asis Kumar Bandyopadhyay is a truly materials scientist with specialization in glass technology with about 38 years of experience in Industry, Academia and Research in diverse fields of materials science and engineering. After obtaining his B.Tech. in Ceramic Technology from Calcutta University in 1971 with a Gold Medal, he went to the Indian Institute of Technology (Kanpur) in the materials science department for doing his M.Tech. in 1974, and his research project was then sponsored by Pilkington Bros. (UK) on 'semiconducting switching oxide glasses containing bismuth and selenium nano granules'. He then proceeded to UK to do his Ph.D. in glass technology in the most prestigious institute at Sheffield University with a fellowship from SRC (UK) and completed his work in a record time of 2 years and 8 months in January, 1977, on "electrical conduction and spectroscopic behaviour of oxide glasses containing transition metal oxides'. The latter work was also useful for colouration in container glasses.

After a brief stint at Sussex University near London as a post-doctoral fellow on 'solid state battery systems on Suzuki crystals' useful for batteries in the automobile sector, Dr. Bandyopadhyay proceeded to work in one of the most famous Glass Laboratories in Europe at Montpellier (France) in January, 1978, under Prof. J. Zarzycki (ex-Director, St. Gobain Research in Paris) on nano materials and glass-ceramics, where he did a lot of collaborative work with industries in Europe including St. Gobain at Aubervilliers. He was on a special UN project in Mexico City for 4 months in 1982.

After returning to India in 1983, he spent about 4 years in teaching and research at College of Ceramic Technology (Kolkata) he worked in several industries such as Grindwell Norton Ltd at Bangalore (now St. Gobain) and KHSL at Kolkata in very senior positions and later worked for Indian Rayon Ltd. (Aditya Birla Group) as Vice-President (Marketing). After 1987, he spent about 2 years as a consultant in Ent. Gagneraud (Paris). After about 12 years in industry, he decided to come back to academia again as a Professor in glass technology in 2000 at Govt. College of Engineering & Ceramic Technology (Kolkata), where he became Principal in 2007 to take care of a large project funded by World Bank. He retired in 2010 after successfully completing the project, apart from teaching and research in collaboration with various US and European Universities.

Thereafter, he devoted his time for research on materials science in collaboration with several Universities in the USA as well as some consultancy work with a strong inclination towards mergers & acquisitions (M & A).

Since 2012, Dr. Bandyopadhyay has been actively associated with AIGMF in the Editorial Board of "KANCH" and other relevant activities. His recent interest is on 'solar energy for smart cities', which involve a tremendous level of activities in both Govt. and Private sectors. He is a first class strategist and as a regular writer in KANCH (http://www.aigmf.com/kanch.php) on various issues on glass science and technology, he has been making a serious effort in promoting the usage of glass in India thereby helping the ever-growing glass industry.

Dr. Bandyopadhyay can be reached at asisbanerjee1000@gmail.com

Contents

Glass, Smart City and Solar Installations

ABSTRACT

Apart from safety and security of buildings in India that consume a large tonnage of float glass and other glass items, the energy efficiency or rather optimum energy consumption in each of these buildings assume special significance, particularly in the light of several **'Smart Cities'** coming up. People often understand 'Smart Cities' by cleanliness and safety requirements, wherein glass has a role to play. The construction of 'Smart Cities' also require more energy, i.e. clean and smart energy. This brings us to the solar energy that is also renewable and is environment friendly. All these activities have a direct relation to the glass industry with the volume of sales of float glass increasing tremendously. To appreciate the level of such endeavours, some of these activities in other countries are highlighted in this article so that collaboration can be achieved between float glass manufacturers and solar energy producers in an effective manner.

INTRODUCTION

Smart City as a brief pathfinder has been explored in a previous article in KANCH [1], with the importance of the use of float glass in this sector. For many decades in India, for the 'building construction industry', glass has been increasingly used: first the flat products and then the more transparent float glass. This is not only of primary concern to the glass manufacturers, but also to the industry association like AIGMF. On this issue during the last few years, some articles have also been written in KANCH, as in Ref. [2] to [6]. With the start of more foreign direct investment (FDI), the investment in both public and private sectors will pick up after necessary restructuring of the banking sector for adequately capitalizing them. With this surge of new investment scenario and many collaborative arrangements with foreign companies or countries will further push FDI both in the field of 'Smart City' and 'Solar Energy'. Both these activities are inter-related as well as have a strong relation with the total volume of sales of float glass (i.e. doors and window panels for buildings, and solar panels made of float glass sheets). This should obviously boost our glass industry, as it will also augment the usage of more and more of different types of 'contain glasses' (bottles, bowls, drinking glasses, laminated coloured glass plates for interiors, decorative pieces, etc.). Therefore, the activity of 'Smart City' has a special meaning for all of us in AIGMF. Since 2014, the Govt. of India has also been seriously talking and implementing such projects involving 'Smart Cities'.

In the previous article [1] on "Smart City', the scenario of solar power sector in the USA was described vis-à-vis the Indian situation. As it is not possible to explore this scenario in details in each of the important countries in terms of all solar energy installations, a brief view is given in this article mainly on such installations of the top ten producing countries of solar power. While it is important for the glass industry to know and assess the total quantity of glass to be needed for both buildings and solar panels, it is equally important to know the total area to be covered by solar panels. The glass industry could then do the necessary impact analysis of the respective areas of building construction (in terms of total millions of square feet of construction) vis-à-vis the number of solar panels in a given area to assess the need for float glass (in terms of either total square feet of glass or total tonnage). This will be separately discussed for project evaluation in a future article in KANCH. Let us give some data on solar power in different countries.

TOP 10 COUNTRIES USING SOLAR POWER

The latest data available till the end of 2014 for solar power for the Top ten countries are shown below along with those of 2010 (shown within the bracket) to be able to compare the tremendous amount of growth during this period. It is designed to show the current pulse of the global leaders in solar power and it also shows just how quickly the world is switching to affordable and clean solar energy. In order to gauge the mood of the solar power industry around the world for giving an insight to the producers of solar energy in India as well as construction giants for 'Smart City', the energy unit has been up-scaled from MW to GW to be able to accommodate this rapid growth. The data given below indicate the "installed capacity" of photovoltaic (PV) solar energy plants. The order of countries also gives a fascinating insight on how fast things are happening in the world [7].

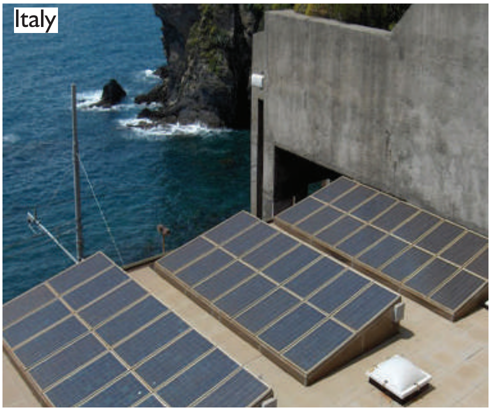
1. Germany: 35.5 GW
(2010: 9.8 GW—1st place)

Germany is clearly the world leader, as also in 2010, and has only continued the trend. Germany installed 3.8 GW of PV solar capacity in 2009 alone, and further added new solar capacity of at least 3.3 GW/year, and about 6 GW/year between 2010 and 2012. It has also introduced feed-in-tariff (FIT) scheme that is combined with a) good financing opportunities, b) a large availability of skilled PV companies, and c) a good public awareness of the PV technology, which mainly contributed to this success. By their approach and achievement, they got recognition from "European Photovoltaic Industry Association" (EPIA) [7].

Despite a slowdown in 2013, Germany is expected to remain at the top of solar market in Europe for the coming years, and still boasts a quarter of the world's installed PV capacity of 26%, compared to the 13% held by each of the next two countries on the Top 10 list, i.e. China and Italy.

2. China: 18.3 GW (2010: 305 MW — 8th Place)

China has an industrial culture of doing anything in a big way, and the solar energy is no exception. As China is the most populous nation in the world, and that also with the biggest carbon footprint, it is great news that China has made such a massive commitment to solar power. China has grown its solar capacity by an amazing 6,000% since 2009-10 — from less than 1/3rd of one GW of capacity to 18.3 GW today. China is also one of the largest manufacturers of solar panels that had helped a lot in augmenting their solar power capacity. A repeated upward revision of the "targets" on solar power had to be done by the Chinese Govt. to motivate both the producers and the users — from a plan of 20 GW by 2020 to 20-30 GW by 2020 to the current target of an incredibly high as 70 GW of solar power by 2017. This is astounding indeed. Due



to severe climate change issue, the Govt. planners had to commit to cut its coal use drastically that also makes the world's biggest carbon polluter soon to be the country powered with the maximum 'green energy'. This is a laudable achievement coupled with a large vision for solar energy.

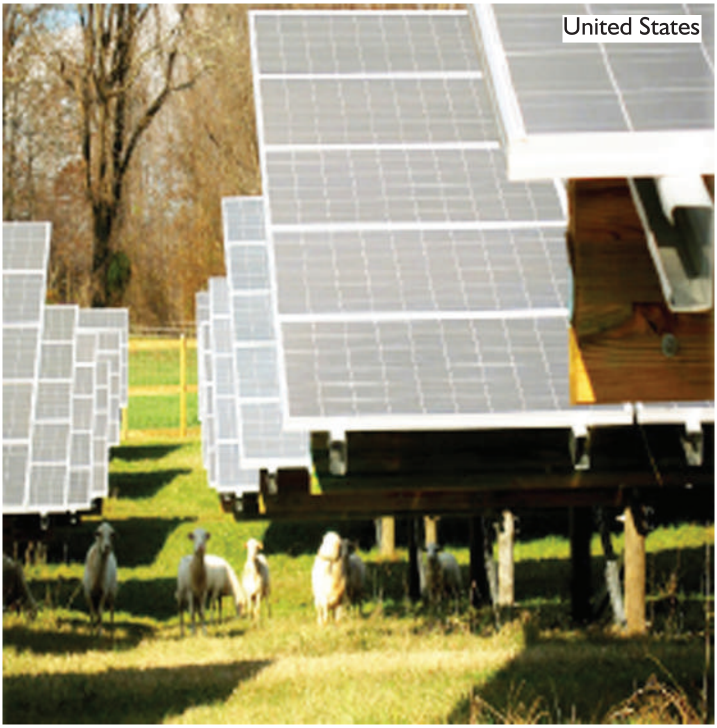
3. Italy: 17.6 GW
(2010: 1.2 GW — 5th Place)

Not far behind China is Italy with a plenty of sun shine in the country, and it continued its leadership in solar power — rising from 5th place in 2010 to 3rd place at the end of 2013. Actually, it generates more of its energy from solar than any other nation, with 7.8% of its energy coming from solar, compared to 6.2% for Germany. Mixing net-metering and a well-segmented FIT, Italy has become a world leader in solar energy. Restructuring of the administrative procedures are needed that will drive the future growth prospect, which will be ultimately aided by an expected price decrease.

4. Japan: 13.6 GW
(2010: 2.6 GW — 3rd Place)

A reverse situation arises in case of Japan, wherein it dropped from the 3rd place in 2010 to 4th place in 2014, but it still remains an exemplary country, as during the past four years, Japan was able to grow its solar capacity by more than 500%. The reasons are: a) Govt. residential PV programs, b) adoption of net-metering system, c) high national solar energy target to reach 28 GW by 2020 and 53 GW by 2030, and d) the support of local authorities and the private sector. These efforts eventually made Japan a world leader in this field. In the wake of the Fukushima Daiichi nuclear disaster, the country has renewed its dedication to solar power, particularly with the recent innovative announcement of the first of many "floating solar farms" off the coasts of this island nation.

5. United States: 12.0 GW
(2010: 1.6 GW — 4th Place)



USA is an example that just goes to show how quickly the field is changing, although it grew its solar capacity by 750% in four years, it could still have lost the ranking in the global solar boom. However, the USA have benefited as much as any other nation from: a) the steadily dropping price of solar energy, b) aided by smart financing, and c) some supportive state-level policies -- to grow its domestic solar industry. With many large ground-mounted solar projects in the pipeline (as shown in above picture), the US is expected to grow its installed capacity significantly in the next few years. Moreover, if the 'national legislation' for the promotion of solar energy comes through, the USA could significantly move forward. Further growth was promoted in this industry, as the cap on the federal "solar tax credit" was lifted in 2009.

6. Spain: 5.6 GW
(2010: 3.4 GW — 2nd Place)

In the newly installed PV solar capacity (2,605 MW) in 2008, Spain was the world leader due to the Govt.'s focus on creating a national solar energy industry, but since then it has dropped significantly — between 2010 and 2013. Despite planning, Spain

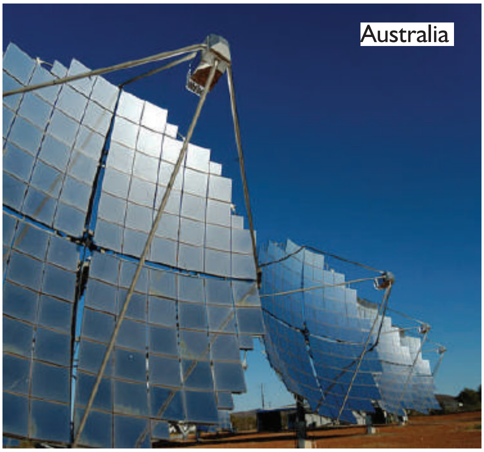
could not even double its capacity mainly due to financial problem, while Germany nearly quadrupled its solar capacity. The reasons for this drop are also attributed to: a) complexity and delays related to a new government subsidy program and b) a decrease in energy demand due to the economic crisis. With expectations that both of these will improve in 2010, and considering its excellent sun irradiation and PV potential, Spain is expected to bump up its solar energy capacity again this year.

7. France: 4.6 GW
(2010: 272 MW — 9th Place)

France has benefited from a well-designed FIT for building-integrated photovoltaic (BIPV), and has continued to reap this benefit. However, due to a lack of political support for solar incentives, the solar growth in France has been slow. The EIPA in its 2014 report also attributed this slower growth to the adverse effects from the industries involving the nuclear and fossil fuels [7].

8. Australia: 3.3 GW
(2010: 125 MW)

In the list of the Top 10 countries using solar power, Australia enters as a newcomer, as during the past 5 years, it has made the most of its sun-drenched status, although many raise question about its continued growth. This large continent-like country in 2009 only claimed 125 MW of solar capacity. However, it subsequently adopted the following smart policies: a) a FIT system, b) rebates, and c) a federal mandatory renewable energy “target”, which all led to a growth of 2600% by the end of 2013, reaching 3.3 GW. It is known that Australia boasts some of the greatest solar potential in the world. This fact coupled with steadily



dropping solar prices give rise to the 'solar power costs' less than half what grid electricity costs. As the Govt. is considering to reduce the federal 'renewable energy target', this might slow if not stop the country's upward movement in the 'top ten list' [7].

9. Belgium: 3.0 GW
(2010: 363 MW — 7th Place)

The image above shows Belgian solar flowers. Belgium has been a surprising solar contender even since 2009. Belgium's success was from a well-designed "Green Certificates" scheme that actually works as: a) adoption of a FIT system, b) combining additional tax rebates, and c) electricity self-consumption. These policies, coupled with the steady drop in solar panel prices, have kept Belgium growing its solar market year-over-year since 2009 [7].

10. United Kingdom: 2.9 GW
(2010: 27 MW)

For the global solar boom, another feather in the cap is the UK that was nearly a non-entity in 2009-10, as it did not make up in the Top 10 list -- with just 27 MW of solar capacity. However, it has made quite fast recouping all the necessary resources since that period, and as EPIA reports in 2013, the UK nearly doubled its solar capacity [7], installing more than even Italy, which is in the 5th place in ranking.

CONCLUSIONS

Looking at the above list of Top ten countries and also the pictures of different installations in these countries, one surely gets an impression that the roof-mounted to wall-hanging to ground-mounted systems of glass-panel arrays are all possible

eventually to augment the capacity. The demand for float-glass panels in India will also go up tremendously with more such installations not just across the country, but also in the coming 'Smart Cities'. This is a typical situation of co-existence of 'Smart Cities' and 'glass-panels' for clean, environment-friendly and renewable solar energy in India.

REFERENCES

1. A. K. Bandyopadhyay, "Solar Energy for the Smart City – A Brief Pathfinder", KANCH, Vol. 3 [2], (2015), 5-8.
2. A. K. Bandyopadhyay, "Transparency in Float Glass and some Applications", KANCH, Vol. 2 [3], (2014), 37-40.
3. Shashi Kant, "Glass – Indispensable Building Material", KANCH, Vol. 5 [4], (2012), 21-25.
4. A. K. Bandyopadhyay, "Technology of Float Glass Process", KANCH, Vol. 5 [3], (2012), 33-36.
5. A. K. Bandyopadhyay, "E-glass as an Important Component in Building Construction", KANCH, Vol. 2 [4], (2015), 32-36.
6. A. K. Bandyopadhyay, "Glass Safety for Building Construction and Environmental Protection", KANCH, Vol. 2 [5], (2015), 21-25.
7. Various IEA reports and EPIA documents as well as several websites: www.alexandredang.com & http://en.wikipedia.org

Smart City and Glass Science for Flat-Screen Products

ABSTRACT

From the glass technologist viewpoint, with the advent of the new concept of designing and creating **'Smart Cities'** in India, there is a huge demand coming up for float glass for windows and doors and also there is a new surge of activity to equip these cities with various types of gadgets – mainly electronics type that needs glass flat-screen products. These gadgets and various other types of devices that are necessary to make the smooth running of the general administration of different public utilities successful also need huge amount of displays of flat-screen variety made of glass. To make these 'Smart Cities' energy efficient, there is also a great need of creating 'green energy' installations, as already pointed out in several articles of KANCH. In this article, the glass science behind making such flat-screen products is briefly elaborated. In a future article, different types of products in this segment along with various technologies involved in making such products will be described.

INTRODUCTION

The electronics industry involving new generations of wide-screen TV, Tablets and various sizes of Smartphone, etc. consist of a large part of our business world. For the glass industry, to get an idea of the market size for 'glass covers' worldwide, the shipments for these three items alone are expected to rise from 1.5 billion in 2013 to more than 2 billion pieces in 2015 and will touch about 2.5 billion in 2017. To get an idea on the Indian pace of development in Smartphone segment along: its growth has been phenomenal from 20 million in 2012 to about 45-50 million pieces in 2013 with a compounded annual growth rate of about 57% in the next five years, i.e. it will cross the 100 million marks very soon.

The business in such electronics products is worth not just billions, but much more than one trillion of dollars around the world with participation of many large players in the USA, China, Japan, South Korea, Taiwan and lately in the Indian manufacturing sector. The size and the level of activity of such modern plants in some of the above countries are gigantic and mindboggling too. With the new "**Skill India**" movement, a cohesive strategy can be developed to correlate this activity to "**Smart City**" projects in India, as these new entities will be the largest consumer of such products not only by ordinary citizens, but also for running various organizations.

To note that in order to run these 'Smart Cities' effectively and also efficiently, we need more and more of such smart gadgets, particularly the products involving 'flat screen' with touch-screen facility in public utility or locations for letting people know different type of necessary information. So, there is no point of assessing the 'actual demand' of such products at this moment, as it will be continuously evolving, along with many other types of glasses, such as float glasses for windows, doors for shops and offices, E-glass for smart windows, and also a large segment of container glasses that are needed by domestic as well as commercial users. However, the important point to be mentioned here is that it is overall good for the glass industry, and it is definitely of great concern to AIGMF. This has been mentioned in several recent articles of KANCH [1,2].

In our cricket or football season, we immediately understand that it is flat screen season, when the sales of flat-screen TV's soar to a high point and the marketers give also all sorts of incentives to keep the market hot. It augurs well for the glass industry serving this sector and other related industry, as just prior to such seasons, the glass producers in this segment also become very active. However, such glasses used for flat screen TV should not be considered as just a seasonal product, as we have many festivals round the year and TV sales also has certain buoyancy almost during the entire year in India. Moreover, the electronics industry is environment-friendly causing no carbon footprint and thereby attracts no adverse attention of the 'climate change' proponents.

It is thus appearing to be important to consider the science behind the LCD glass substrates of our flat screen TV to insist on the point that good science done well is essential to commercial success. Here, we need to emphasize that to design new oxide glasses for the next generation of Widescreens, Tablets and Smartphone, there is a clear need of tuning various properties simultaneously, such as viscosity, coefficient of thermal expansion, elastic moduli, chemical durability, etc. However, some of the most important properties to consider are "liquidus temperature" and "melt viscosity". This means that we strike a balance between thermodynamics and kinetics of the concerned system of glass.

LIQUIDUS TEMPERATURE

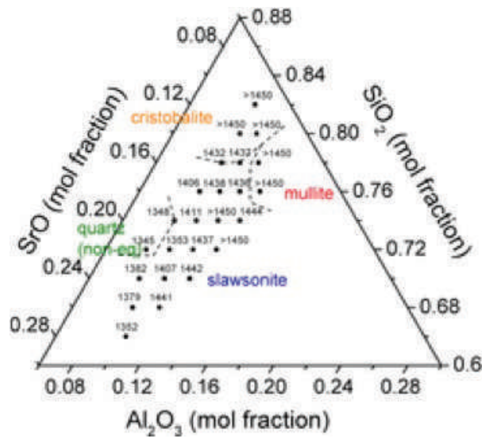
It is known that 'liquidus temperature' does matter a lot for commercial glass production. This needs some elaboration as the energy is of primary concern for the glass manufacturers, and hence we need to do "compositional engineering" to drive down the temperature of melting to save cost on furnace operation, although it is not always possible and/or advisable to do so. If by compositional engineering, one could lower the glass melting temperature, it will obviously need less energy. However, it cannot be done at all by compromising on glass quality.

Glass is an amorphous material and it can only be formed by avoiding crystallization. So, the molten glass coming out of the glass tank furnace must be at a temperature above the liquidus temperature to prevent crystallization, i.e. the liquid has failed to become a homogeneous glass, and it also leads to significant problems in any glass manufacturing process. It should be noted that along with giving due importance to liquidus temperature, it needs to be considered that the "liquidus viscosity" is also more important. By 'liquidus viscosity' it is meant that the glass-forming liquid is at its 'liquidus temperature'.

It has also to be understood why it is so. As the glass is more fluid, i.e. less viscous, the constituent atoms are more mobile within the melt and then the glass can crystallize more easily. On the other hand, a high-viscosity melt presents a large kinetic barrier to crystallization, i.e. more congenial for glass formation. Hence a compositional engineering must consider this fact, i.e. how to strike a balance between liquidus temperature and liquidus viscosity. This was discussed in details in several articles in KANCH (see for example Ref. [3]).

It has to be noted that by increasing the alumina content in a given glass composition, the melt temperature increases, although the glass could be mechanically stronger. So, for making mechanical shock-resistant glass, we must strike a balance with total alumina content in a silicate glass. Lime gives a high chemical resistance, but increasing its content in a silicate glass could pose problem with the viscosity, e.g. a proper viscosity of the melt is suitable for not only glass formation, but also for moulding it to different shapes and sizes, i.e. glass fabrication. However, replacing calcium by strontium oxide in an alumino-silicate glass gives rise to certain properties that are good for flat screen products.

This brings us to a new system of SrO-Al_2O_3-SiO_2 glass-forming composition, which has been recently reported by Corning Glass (USA) that now finds a place in the list of "Phase Equilibria Diagrams Database" of American Ceramics Society-National Institute of Science and Technology (ACS-NIST). This is a very important ternary system for the commercial manufacture of glass for LCD substrate, as SrO is a constituent in all LCD glass. The researchers at Corning focused their attention on commercially relevant areas of this ternary phase diagram and determined liquidus temperatures and primary devitrification phases for 24 compositions with SiO_2 contents of 65–80 mol% and alumina contents of 10–15 mol%. This diagram is shown here for an understanding of such an interesting ternary system [4].



It was found that the liquidus temperature decreases as the SrO/Al_2O_3 ratio increases. A Similar trend has been observed in the MgO–Al_2O_3–SiO_2 system for increasing MgO/Al_2O_3 and in the CaO–Al_2O_3–SiO_2 systems for increasing the ratio of CaO/Al_2O_3. The above ternary phase diagram provides information about the thermodynamic possibilities. Obviously, now the question comes as to whether the kinetics, or rather its barrier is also favourable. For glass manufacturers, the most important parameter is viscosity at the 'liquidus temperature'. It is of particularly interest to establish a correlation of viscosity with temperature and composition. Accurate prediction of the melt viscosity is important for processing but also challenging because it ranges over 12 orders of magnitude between melting and forming temperature regimes.

The multi-component oxide glasses can be modelled by "first principles" computation with a lot of difficulty, but with molecular dynamics simulation technique, some progress has been made by various workers to compute certain physical properties (see for example Ref. [5]). However, modelling by topological constraint theory (TCT) can also be applied to establish a 'phenomenological model' for viscosity based on just two parameters — glass transition temperature and liquid fragility, as done by Corning researchers [6].

In this theory, the model is based on 'temperature-dependent constraint theory', where the composition is treated in terms of a network of bond constraints. This effort could be considered very significant as the Corning database was extensive indeed, e.g. the model was tested against 7,141 actual viscosity measurements for 760 silicate glass compositions with 3 to 11 oxide components. A plot of actual isokom (constant viscosity) temperature against predicted isokom temperature revealed a root mean square error of only 6.55K, effectively validating the topological model [6].

LIQUIDUS VISCOSITY

The viscosity is a measure of the resistance of a liquid (glass) to a shear deformation. In SI units, it is expressed as dynes-second/sq cm or Poise (P), taken as logarithmic numbers, as the values are very high up to 12 orders of magnitude. In the realm of non-Newtonian fluid, i.e. non-linear stress-strain behaviour, a plot of shear stress vs. shear rate shows different interesting aspects [7].

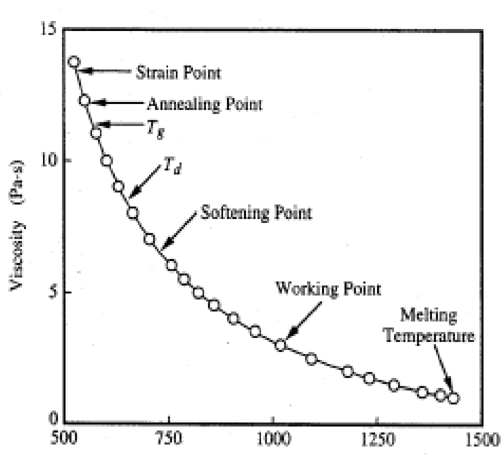
This involves Bingham Plastic (paints, slurries, etc.), Dilatent Flow (ceramic slips, corn starch, etc.), Thixotropic behaviour and finally Pseudo-plastic Flow exhibited by glass melts at very high shear rate. The latter has processing consequences, such as fibre-drawing, controlling "gob" behaviour, etc. There are a number of "reference points" in the viscosity-temperature curve (shown in the diagram).

The important features for log viscosity are as follows [7]:

1. At a typical (practical) Melting Temperature: (log viscosity is less than 1 Pa-sec). Here, the melt is fluid enough for fining/homogenization to occur in a ‹practical›, i.e. more reasonable amount of time. This is not the temperature of the melt associated with a crystal→liquid phase transition.

2. Working Point: (log viscosity= 3 Pa-sec). At this point, the temperature at which the molten glass can be formed/manipulated, i.e. the viscous gob deformed into final shape. The viscosity is low enough for some shear processing (pressing, blowing, etc.) but high enough to retain some shape after shear is removed.

Name of reference temperature	*Viscosity (Pa-s)*
Practical melting temperature	≈1-10
Working point	10^3
Littleton softening point	$10^{6.6}$
Dilatometric softening temperature	10^8-10^9
Glass transformation temperature	≈$10^{11.3}$
Annealing point	10^{12} or $10^{12.4}$
Strain point	$10^{13.5}$



3. Softening Point: (log viscosity = 6.6 Pa-sec), i.e. the temperature at which glass will deform under its own weight. The ‘Littleton Softening Point’ is a standard fiber elongation test (1mm/min).

Here, some notes are given on processing:

a) Working Range: Temperature, where log viscosity is between 3 and 6.6 Pa-sec

b) Wide Working Range (large difference in T): Long Glasses

c) Narrow Working Range (small difference in T): Short Glasses

d) Working Range at a higher temperature than SLS glass: Hard Glass

e) Working Range at a lower temperature than SLS glass: Soft Glass

4. Annealing Point: (log viscosity = 12-12.4 Pa-sec), i.e. the temperature at which ‹stress is substantially relieved› in a few minutes. It is measured by a standard fiber elongation test.

5. Strain Point: (log viscosity = 13.5 Pa-sec), i.e. the temperature at which ‹stress is substantially relieved› in several hours. At this point, the glass is essentially an elastic solid at temperature less than ‘strain point’ temperature. Also there are no significant structural rearrangements or no permanent flow.

The above is in every glassmaker’s handbook, but it is reminder of the fact that the test should be rigorous for a better control of fabrication and eventual quality of the glasses that are very much needed in flat-screen glass products [3].

There are also other useful viscosity reference points. From a dilatometer measurement in terms of the curve of expansion vs. temperature, the following details are obtained: a) Glass Transformation Temperature (Tg) -- 11-12 Pa-sec. In many cases, these data are not precise depending on the type of dilatometer and heating rate, etc. b) Dilatometric Softening Point (Td) -- 8-9 Pa-sec.

CONCLUSIONS

The significance of a ‘Smart City’ has already been described. The involvement of glass industry in terms of a specific, but significant, demand of flat-screen glass products for the purpose of display as well as for consumer items is also described. In the present article, the glass science behind making such flat-screen glasses is elucidated to highlight on the importance of liquidus temperature and liquidus viscosity. This has been discussed for relevant temperature range, where both glass formation and glass fabrication are considered important.

REFERENCES

1. A. K. Bandyopadhyay, "Solar Energy for the Smart City – A Brief Pathfinder", KANCH, Vol. 3 [2], (2015), 5-8.

2. A.K. Bandyopadhyay, "Transparency in Float Glass and some Applications", KANCH, Vol. 2 [3], (2014), 37-40.

3. A. K. Bandyopadhyay, "Glass Manufacturing – Part III: Fluid Flow in Glass Fabrication", KANCH, Vol. 2[1], (2014), 39-42.

4. J. C. Mauro et al., "Liquidus Temperature of SrO-Al_2O_3-SiO_2 Glass-Forming Compositions", Intl. J. Appl. Glass Sci., Vol. 4[3], (2013), 225-230.

5. S. Das et al., J. App. Phys., to be published in 2016.

6. J. C. Mauro et al., Intl. J. Appl. Glass Sci., Vol. 4, (2013), 408-413.

7. J. E. Shelby, "Introduction to Glass Science & Technology", Royal Society of Chemistry, London, (1997).

Solar Energy for the Smart City: A Brief Pathfinder

ABSTRACT

In the recent past, there has been a surge in the activity of building construction, particularly in the conclave or block mode and some even giving shape to a sort of mini-city with almost all types of amenities and certain facilities that are needed in modern day living. However, with voluminous activities in this field, there is now a 'specific demand' for '**Smart Cities**' with a considerable portion of business activities that further requires more energy than that need for modern housing alone. Ultimately, the core issue is "energy", more particularly "clean" or "renewable" energy. This is the subject matter of this article, where a brief review is given on solar power industry that must be considered for building 'Smart Cities'.

INTRODUCTION

As a primary concern to AIGMF and other relevant organizations or people, glass is a very important material for the 'building construction industry' for many decades in India. Some articles have also been written in KANCH, as in Ref. [1,2], during the last few years on this issue. Many years ago, say 25 to 30 years ago, people used to do construction of residential or commercial buildings – mostly in isolation in discrete plots of land in and around large or medium sized cities in India. Although, there were few who constructed a bunch of buildings together (called 'building complex'), depending on the availability of a suitable size of land. However, in those years, mostly this type of activity was badly organized or very much unregulated with scant regard to environmental issues. Also, there was a shortage of suitable type of 'construction materials' or components. This was also compounded by the lack of business interest by the well-known group of industries, who did not even venture into this field. Since that period of time, there has been a sea-change in the mindset of various industrial groups, obviously with a lot of 'investment' into this sphere of activity. Only, in 2013-14, the Govt. of India has been seriously talking about large parcels of land in a new area to be able to construct 'Smart Cities'.

In the language of the modern day information technology (IT), 'Smart Cities immediately mean a lot of clean industry providing jobs and residential complexes that conform to the basic norms of IT in terms of automation of various systems or functions of a city. For example: (a) transport system (like in Singapore or similar cities), (b) waste disposal system (like in Taiwan), (c) sewage system (like in S. Korea), (d) safety and security system with smart cameras and sensors, (e) use of normal 'float' glass as doors and windows [3] as well as photo-reflective glasses as in E-Glass [4] and different types of "facades" consistent with the quality and safety norms for modern buildings [5], (f) distribution system of residential apartments or commercial offices, (g) employment generation and recruitment system, etc.; the last one being very important as the number and quality of employment will primarily drive the "performance" of a 'Smart City'. For example, it is observed in many new office/housing complexes, the employees from IT and related fields openly eating in shanty shops/eateries where no consideration is given to basic hygiene and sanitation. While these issues are taken into consideration, the "energy" remains the main focus area, as described recently in several articles in KANCH and elsewhere [6-8].

In the present article, mainly solar power will be discussed as a 'pathfinder' for making a significant impression or rather contribution towards creating smaller modern cities with a possibility of enlarging them to a larger dimension – not only with all the modern amenities and special facilities – but also a supply of plenty of energy. If such amount of energy is produced through the solar route, then the impact on the environment will be minimal – as the so-called environmentalists go against the use of glasses in the building construction industry. In this respect, a good 'collaboration' between AIGMF and Confederation of Construction Products and Services (CCPS) would be an essential component in giving a constant guidance as well as new ideas to the government for achieving the success in making 'Smart Cities'.

SCENARIO IN THE USA

Before embarking on the issue of use of solar power, the relevant details on the scenario in the international arena need to be described here in brief to insist on the point that "solar power is making a splash in very recent periods". This renewable power is growing at such a rate that it had its hottest year for growth in the history of solar power, and the future still looks bright. For example, last year in the context of USA, solar activity is beating the 'tech company average' as an industry – according to a Forbes Magazine study on the top 25 growing business: Google, Amazon, Facebook and Apple grew by 30, 32, 38 and 39% respectively – whereas the growth of solar power was even higher than "Apple" at 40% (only, LinkedIn grew faster than solar power). So, the solar power is the 'state champion'.

It is also useful to compare the strategic position of solar energy within the 'energy producing community' that will gauge the incremental effect and its 'growth impact' further. Already in the lead as the fastest-growing clean and renewable energy source in America, solar power is growing to account for 29% of new American electricity, trailing just behind natural gas at 46%. Surely, this should give enough motivation to our domestic companies to aggressively pursue the route to solar energy. This assumes more importance as the government is seriously trying to make 'Smart Cities'.

Solar Power is spreading its way across every corner of America, but for now California is still in the lead for new installations. More than half of last year's solar power growth was from California alone, generating 2,621 MW. Not far behind California were Arizona at 421 MW, and North Carolina at 335 MW. Together, these states, with Massachusetts and New Jersey in the north-east made 81% of the 2013 installations (see for example, SEIA and GTM Research studies). Markets for each state still have plenty of room to grow.

It is said that while 2017 will be a critical year, as the "tax credit" in the USA is dropping from 30% to 10% for solar power, unless the Federal Government does something special during the coming years. Moreover, this disincentive even would not put a stop to the growth of solar installations. Now, there are already enough solar panel installations to power more than 20 lakh homes, and solar power is just starting to really ramp up. If things keep going this way, solar power might affect energy companies the way the internet impacted the newspaper industry.

The Cost Factor and Growth

The cost of solar power installation is also important, as there is a massive effort to reduce the overall cost in every country pointing at Sunny days for solar power. For example, the changes in solar panel technology are making solar power installations easier, quicker, and cheaper. That's why we see how solar power has grown and changed in recent years. In 2006, a solar panel installation was occurring every 80 minutes. Now, a solar power system is being set up every 4 minutes. By 2016 it will be every 80 seconds. With the reduction in time of installation, the cost should be reduced correspondingly. With the cost of solar power installations falling, and already down almost 10% from last year, it can be safely said that the industry is growing rapidly. In the last year, solar power observed a massive 41% increase in installations. In the previous 18 months, the growth of solar power outweighed its progress in the last 30 years. That's commendable and definitely worth a mention in this context.

Concurrent activity in the field of reducing cost by developing 'innovative methods and technologies', more and more plants are coming up. As a result, two-thirds of all the solar projects worldwide, i.e. 66%, were built in the past two and a half years — the same proportion holds true in the USA. Surprisingly, in 2011, after 40 years of solar power, the total installations still stood at only 50 GW. By 2012, they had doubled to more than 100 GW. By 2015, the size of global solar power should exceed 200 GW, considering the completion of many on-going projects. The US had 930 MW of solar power installations in the third quarter of 2013 alone. Now, it has more than 12 GW of solar power and is one of top 5 countries in the world to pass that mark. While much of solar power still relies on the state subsidies, 51% of California's residential PV systems were installed without assistance from California's Solar Initiative.

For the above speed of activity, in order to top it up, the marketing efforts are also accelerated to a great extent. GTM research forecasts that more than $1 billion will be spent by the solar power industry to acquire customers. This will account for about 10% of the total cost of installations. In order to stay competitive, top solar panel companies are working hard to have the best sales and marketing processes. There are still lots of room for innovation in this space.

INDIAN SCENARIO

There is a market-buzz that India is said to be making a target of 1000 MW solar capacity addition for 2015. Among many regions, Delhi Capital Region (DCR) badly needs solar power and it will be interesting to know the capacity of DCR to be added in the new target. India seems to have just increased the amount of solar power plant licenses it plans to award next year by 30% — a move that adds one additional GW of capacity to the government's 2015 target.

The push is part of India's "J. N. National Solar Mission (JNNSM)". The goal is to install 10 GW of solar by 2017 and 20 GW by 2022. India's current solar capacity now stands at 2.18 GW — part of 27 GW of overall renewable capacity that includes wind and hydropower — after it added one GW of solar installations over the course of 2013. This appears to be rather slower, but efforts are being made to augment it to a greater extent. This would also allow India to gain slightly on the 'carbon credit' front, in terms of international recognition for showing lesser reliance on the fossil fuel (mainly coal) to generate our energy needs.

However, the Indian government also down-scaled its target for 'solar-thermal' plants in the same decision, reducing its 2015 target to 100 MW of capacity from 1,080 MW originally. Rather than producing electricity from solar photovoltaic cells, solar-thermal plants use mirrors to concentrate massive amounts of sunlight on a single point, thus heating water to steam that drives electricity-generating turbines. Only one of the eight solar-thermal projects India had scheduled for completion last year is finished, while the other seven have faced delays and cost overruns.

India's push for solar has not come without a few other bumps. The JNNSM raised the ire of American officials by requiring that half of the solar components purchased to meet the target come from domestic Indian suppliers. More recently, Phase II of the JNNSM expanded that requirement to the purchase of thin film solar panels, which the USA often exports to India. USA representatives say that the requirement violates trade agreements between the two countries under World Trade Organization (WTO) rules. India and the USA have little time left to reach an agreement, before the WTO could move into this matter to resolve the dispute.

With the "**Make in India**" mission in place by the present government, it is clear that India has to create domestic manufacturing capacities. India must create more capacities, by considering our future needs, like China has done so to keep their business mission intact a long time ago. This is a serious policy matter, where there seems to be not much option left. Otherwise, we will end up importing for the rest of our lives that will have contradiction with the above slogan for the domestic industry.

It is known that 66% of India's electricity comes from burning coal at present, and the country's coal imports actually hit a record high in the last fiscal year. With the introduction of rationalization of auction process for 'coal blocks', the situation might improve a little bit on the 'balance of payments' front. However, as a result, India's smog problem comes closer to that of the rival China's, and the use of combined fossil fuel of the two countries has made Asia the biggest territorial emitter of carbon dioxide in the world. On top of that, acquiring coal supplies is becoming both a more costly endeavour for India and a less reliable one. This caution on the environment has been duly mentioned several times in the articles in KANCH during the last few years, while writing about solar energy and energy efficient buildings with E-glass.

Climate change driven by humanity's carbon emissions is also a serious issue for India: the latest Climate Change Vulnerability Index (CCVI) determined the country is facing "extreme risk" from the droughts, floods, sea level rise, and the extreme storms that global warming will bring. As there is a massive effort in terms of international conferences and meetings all over the world, India has to do something tangible to reduce carbon emission with due regards to climate change issues.

The New Concept

The fact that energy systems must go non-conventional is quite apparent. But to do it in a manner that would be cost-effective and actually bear returns on investment would be the challenge. Sometimes, we may not think of a 'return on investment' as we normally do for other businesses. However, the cost-effectiveness is definitely an important issue. A new concept, such as "Pay as you Save" is a concept that has found its place in promoting solar energy in the city, and is generating quite a bit of enthusiasm. This concept in terms of a simple payment mechanism, as practiced by some

investors and entrepreneurs, is becoming quite popular. It is also devised as a clever strategy for future business growth.

The company has to chip in with a portion of capital amount of the total budget after deducting the subsidy quotient. The remaining capital amount would be paid as a fixed monthly amount equivalent to price per kWh for a period of 5 to 10 years. This scheme, called "Pay as you Save", seems to be a very good deal and a company called Aspiration Energy has ventured into this arena, where others are also trying for a meaningful entry. Industries have been keen on taking this up, in order to achieve substantial savings in energy expenditure.

This has worked very well in the 630 KW heating plant installed in Wheels India plant at Padi. Every year, an amount of about Rs. 49 lacs was saved on furnace oil. No wonder the concerned industry is convinced that the system was way ahead of conventional heating technology that uses furnace oil.

The above type of new concept in getting customers interested in such "win-win" ventures becomes effective. This is due to the fact that by harnessing solar energy for industrial purposes is yet to gain currency mainly due to the involvement of huge capital costs and it also suffers from poor efficiency. This is where the 'rooftop solar thermal power system', which has been installed in Padi, can be employed for heating operations, and also this type of system obviously comes in handy. The rooftop solar thermal power system is a technology used for high degree heating in several industries including milk, automobile, electroplating and chemical. *Each of these industries is also a great consumer of container and other glasses, and hence it is of concern to AIGMF*. A picture of "Rooftop Solar Thermal Power System" is shown above, which is not only more efficient but also achieve considerable savings.

By comparing the positive aspects of the 'solar thermal power system' to the PV cells both cost- and efficiency-wise, it can be pointed out that the cost works out to only Rs. 3/kWh and gives 100% heating efficiency, whereas the efficiency level of PV cells is around 15%; although there are all-out efforts in increasing the efficiency of the PV cells by some innovative methods.

CONCLUSIONS

After depicting the importance of solar energy in creating 'Smart Cities', first the actual scenario is shown in case of the USA in some details that could be considered as benchmark for India, e.g. California Solar Initiative (CSI), and it could also give us a great motivation for our development in this nascent field. By describing briefly the cost aspect and concurrent growth with its vast potential, the solar energy scenario in India is discussed with some newer development for solar heating installations for different industries. It is quite clear that there is a strong need to change our pace of development to augment the capacity of solar power plants further for the betterment of our projects on 'Smart Cities' in general, glass industry in particular.

REFERENCES

1. A. K. Bandyopadhyay, "Transparency in Float Glass and some Applications", KANCH, Vol. 2 [3], (2014), 37-40.
2. Shashi Kant, "Glass -- Indispensable Building Material", KANCH, Vol. 5 [4], (2012), 21-25.
3. A. K. Bandyopadhyay, "Technology of Float Glass Process", KANCH, Vol. 5 [3], (2012), 33-36.
4. A. K. Bandyopadhyay, "E-glass as an Important Component in Building Construction", KANCH, Vol. 2 [4], (2015), 32-36.
5. A. K. Bandyopadhyay, "Glass Safety for Building Construction and Environmental Protection", KANCH, Vol. 2 [5], (2015), 21-25.
6. E. Lorenzo et al., "Solar Electricity: Engineering of Photovoltaic Systems", 1994, (Progensa: Seville, Spain), 340.
7. S. Das and A. K. Bandyopadhyay, "A Perspective on Renewable Energy and Solar Photovoltaic Power Plants", KANCH, Vol. 2 [4], (2015), 21-25.
8. A. K. Bandyopadhyay, "Photovoltaic Effect and Solar Energy: A Brief Perspective – Part I", KANCH, Vol. 2 [5], (2015), 27-31.

Technology of Float Glass Process

ABSTRACT

Among all the plate or sheet glasses, the "float glass" made by floating a sheet of glass over molten tin bath is the most popular and also technologically involved subject of concern to the building construction industry in general, and glass industry in particular. The novelty of this process is that the accuracy of the glass thickness free of any surface aberrations or irregularities is exceptional, which is inherent in the process technology itself. The process technology of float glass is presented here in terms of mathematical models for smoothening of the surface.

INTRODUCTION

Like many other processes of making glass, here also the chemical ingredients are mixed and then fed automatically in a controlled manner into a glass tank furnace for melting and refining. However, the float process has a peculiarity after this stage, i.e. after drawing a sheet of glass from the working end of the tank furnace. After melting the glass in a tank furnace, the next step is to shape it into a desired form. The size is also of great importance in the building construction industry. The fabrication process of float glass is highly mechanized and it is evolve continuously, even to the extent of newer products, such as coated glass with high emissivity for keeping the building cooler inside. For the flow in fabrication processes, it is convenient to deal with some aspects of the recently developed 'float process' for the manufacture of flat glass. Here a brief account is given on the process technology along with some data on float glass plants in India and abroad. Both chemical and physical aspects are also discussed.

THE FLOAT PROCESS

The 'float process' can be described as follows:

a) The glass flows from the furnace down a refractory 'spout', and onto a solid refractory piece, where a roller type 'tweel' holds the glass flat.

b) Then, it flows as a flat ribbon or sheet on a shallow bath of molten tin, which is kept under a non-oxidising atmosphere to avoid oxidation of tin and subsequent deposition on the surface of the glass ribbon/sheet.

c) As it passes through the ‘chamber’ containing the molten tin, the glass is gradually solidified until it is sufficiently viscous not to deform, when it is lifted from the tin bath and is fed (supported by a series of rolls) to the annealing furnace

d) Due to floating on the molten tin, the bottom surface of the ribbon/sheet is very smooth. The smoothness in the top surface is maintained by six rollers onto the ribbon/sheet on each side of the molten tin bath. This makes the surface of the float glass superior to any other sheet or plate glass made by other processes.

In this new process, the viscosity of the glass is sufficiently low as it is fed onto the tin bath for the natural forces of gravity and surface tension in order to be able to remove any surface irregularities. On leaving the tin bath, the glass ribbon is so flat and free from surface irregularities that the grinding/ polishing operations are not required, as done in the past. The elimination of the mechanical finishing processes results in a considerable saving of factory space and a reduction in the total power requirement.

So, there are two forces at play → gravitational and surface tension forces, which are ultimately responsible for the removal of surface irregularities, but they are very low → only a few Newtons/m^2. Thus, the viscosity must be correspondingly low if the ‘forces’ have to generate the required effect in a reasonably short period of time. According to Charnock1, the surface irregularities can be removed in 1 min if the viscosity is about 103 Ns/ m^2. For the glass composition normally used, this corresponds to a temperature of about 1050°C. As there is close relation between viscosity and chemical composition of any given glass, it is important to deal with chemistry before going to the physical aspects. Next, let us discuss about some chemical aspects of float glass.

CHEMICAL ASPECTS

It is a typical soda-lime-silica glass like container glass, but with some modifications. The typical chemical composition of float glass is given as percentage:

SiO_2 = 73.0, Na_2O = 13.6, CaO = 9.6, $A1_2O_3$ = 0.97, MgO = 0, BaO = 0, SO_3 = 0, K_2O = 0.6, Fe_2O_3 = 0.10, TiO_2 = 0.02.

Here, the % BaO is zero, but many companies use 0.5-1 % BaO to bring shining aspect to the glass, since the refractive index of BaO is very high due to the heaviness of Ba atoms. Similar atoms such as lead (Pb) is also very heavy atom, but its use has been discarded by almost all due to pollution problem and health hazards. The combined alkali expressed as sodium and potassium oxides is 14.2%, which is quite sufficient for maintaining the required temperature and consequently the ‘viscosity’ in the melt. It helps in the consequent refining process in terms of bubble or chord removal.

The percentage of silica sand (73%) is normal for soda-lime-silica glass. A higher amount of silica can be attempted for higher strength and other reasons, but an imbalance will be created in the composition. The viscosity has also to be managed very cautiously. So the idea of increasing silica content in the float glass can be safely dropped. The percentage of lime (i.e. about 10%) is all right for imparting chemical durability to the float glass and make it resistant to any chemical attack or weathering. The latter point about "weathering" is quite important. The percentage of MgO is shown zero here, but some companies use about 1% or little more in order to control the viscosity for the smooth flow of the glass ribbon/sheet to the molten tin bath and consequent smoothening of the surface. About 1% of alumina is necessary for the formation of alumino-silicates, which are generally good for giving enough strength to the float glass.

The iron oxide (0.10%) is considered high for the sake of coloration, which is highly detrimental for the quality of float glass. For better quality control, the silica sands are acid-washed to reduce the iron impurities. Another method is to create a sufficiently oxidising atmosphere in the glass tank furnace so that all the ferrous iron can get converted to ferric iron, and hence the Fe ions will mostly stay as 'ferric' ions giving neutral colour to the soda-lime-silica glass matrix, thereby reducing the unacceptable effect of coloration of the float glass. The redox reaction of any glass composition with even 0.1% of iron oxide is very important for fixing the strategy of controlling the atmosphere in the glass tank furnace.

The above explanations more or less sum up the chemical aspect of the float glass. Now, a description is necessary for different physical aspects of the process technology, which is given below:

PHYSICAL ASPECTS

First of all, the process can be briefly summed up as:

Raw Materials (Mix + 25% Cullets) → Glass Tank Furnace → Tweel Rolls (For Flat Ribbon) → Controlled Atmosphere → Liquid Tin Bath (With 6 Rolls on each side → for Smooth Surfaces) → Annealing Lehr (For Stress Removal) → Packaging → Automatic Warehouse → Automatic Stacking → Order Supply → Control Points. It is important to know about the details of the process parameters of the float glass manufacturing technology, which would enlighten us on certain physical aspects. The details are shown below:

ANALYSIS OF THE PROCESS

During the process, through our naked eyes, we cannot observe that the surface aberrations are actually wave-like or wavy in nature. This needs to be removed, as first illustrated by Pilkington [2]. The damping of this oscillation on the surface of the float glass is a subject of intensive study [3].

S. No.	Item	Foreign Co.	Typical Indian Co.
1.	Furnace Type	Side Port Regenerative	Same Type
2.	Furnace Capacity	1600 TPD	650 TPD
3.	Fuel of the Furnace	Fat. Gas/Fur. Oil	Furnace Oil
4.	Electrical Boosting	Yes	Yes
5.	Melting Temp	1593°C	1580°C
6.	Exit Temp to Tin Bath	1093 °C	1050°C
7.	Furnace Area	53.1 x 9.1 $mt.^2$	33.6 x 8.5 $mt.^2$
8.	Glass Level	1.22 mt.	1.05 mt.
9.	Tin Bath Entrance	1038°C	1005°C
10.	Tin Bath Exit	688°C	650°C
11.	Tin Bath Length	48 mt.	58 mt.
12.	Width (Front/Back)	6.1/4.3 mt.	6.0/4.2 mt.
13.	Volume of Tin	150 $mt.^3$	165 $mt.^3$
14.	Depth of Tin	5.1-7.6 cm.	5.5-7.5 cm.
15.	Bath Atmosphere	94%N_2 + 6%H_2	Same
16.	No. of Rolls	6 on each side	7 on each
17.	Roll-to-Roll	1.5 mt.	1.5 mt.
18.	Lehr Entrance	607°C	610° C
19.	Lehr Exit	282 °C	285°C
20.	Lehr Length	116 mt.	110 mt.

In 1959, Mullins[4] developed the first theory of surface smoothness by surface tension forces → which involves smoothening of irregularities of small wavelengths, as in the case of sintering of metals. A more general theory [5] was developed by Woe in 1969. When the glass thickness is large relative to the wavelength of the irregularities, the problem is relatively easy to solve. It may be shown that the amplitude of a sinusoidal surface distortion of wavelength (λ) decays exponentially with a 'decay constant' (n), which is given by:

$$n = \frac{g\rho + \gamma k^2}{2\eta k} \quad ...(1)$$

where, k = wave vector = 2π/ λ, γ the surface tension, g the gravitation constant, ρ the density of the glass and η is the viscosity at a given temperature of glass fabrication. The decay constant has to be minimized. The value of n is a minimum, when :

$$\frac{dn}{dk} = -\frac{g\rho}{2\eta}k^{-2} + \frac{\gamma}{2\eta} = 0$$

...(2)

or,

$$k^2 = \frac{g\rho}{\gamma}$$

...(3)

or,

$$\lambda = \frac{4\pi^2\gamma}{g\rho}$$

...(4)

Thus, the irregularities of the above wavelength are the slowest to disappear. By using appropriate values of γ and ρ, this wavelength is found to be 22 mm. If the glass has a viscosity of 10^3 Ns/ m^2, then the minimum value of n will be 0.99/s, and the amplitude of irregularities will fall to less than 1% of the initial value in less than 60 seconds. This value is in agreement with the experiments of Charnock.[1]

The glass thickness produced by the 'float process' can be controlled either by restricting the "lateral spread" of the 'ribbon' on the tin bath, or by applying stretching forces along the direction of the movement. It is interesting to note that if the glass is allowed to establish its own thickness without any interference, the balance of surface tension and gravitational forces produce a ribbon with a thickness of 7 mm, which happens to satisfy about 50% of the demand for float glass. This is perhaps the only known example of 'providence' being on the side of the glass technology.

The factor determining the equilibrium thickness of one liquid floating on another, when the floating liquid does not spread, are clear from Langmuir's analysis [3] of the "geometry of oil lenses" on water. Assuming that the lens is sufficiently extensive so that the curvature of the oil - water - air boundary may be neglected, the thickness of the 'oil layer' well away from the boundary may be obtained by considering a 'balance' of "hydrostatic and surface tension" forces, acting horizontally. The following equation is obtained for the equilibrium thickness (t_∞) as :

$$t_\infty^{\ 2} = \frac{2F_s\rho_1}{g\rho_2(\rho_1 - \rho_2)}$$

...(5)

where, ρ_1 = density of water (in this case, molten tin), ρ_2 = density of oil (or molten glass), F_s = spreading coefficient, which is calculated as :

$F_s = \gamma_1 - \gamma_2 - \gamma_{12}$ ...(6)

The interfacial tension (γ_{12}) is not known for the glass-tin system. The observed fact that the equilibrium thickness (t_{∞}) for this system is 7 mm indicates that γ_{12} is about 0.5 N/m, which is about the same as the surface tension for the tin-atmosphere interface (i.e. γ_2).

The above description then sums up various types of possibilities in the realm of theoretical analysis to enlighten us on this very important aspect of glass surface smoothness and optimum thickness of the float glass.

CONCLUSIONS

The float glass process technology has been explained in terms of basic principles on how the process works and then a flow diagram has been shown to identify the most important stages of production. The chemical aspects have also been discussed in terms of engineering a good composition. The physical aspect has been described in terms of different important process parameters for two float glass plants in India and abroad. A closer look at these parameters show immense possibility of 'quality control' in this process technology. Finally, an analysis has been shown where it is clearly demonstrated how to achieve optimum thickness for the float glass and how to smoothen the surface irregularities for a superior quality float glass for the booming building construction industry and shopping malls.

ACKNOWLEDGEMENTS

The author would like to thank Mr. Kamal Choudhary of Department of Materials Science at the University of Florida at Ganesville (USA) and Mr. Arnab Sengupta at Perm State University (USA) for helpful discussions.

REFERENCES

1. H. Charnock, Physics Bulletin, 21 (1970), 153.
2. L. A. B. Pilkington, Proc. Royal Society, A314 (1969), 1.
3. A. K. Bandyopadhyay, Unpublished Work (University of Sheffield, UK).
4. W. W. Muffins, J. Appl. Phys., 30 (1959), 77.
5. W. Woe, J. Appl. Phys., 40 (1969), 3140.

Transparency in Float Glass and Some Applications

ABSTRACT

The glasses are generally known to possess a high degree of transparency and it is also commonly taken as one of the main characteristics of glass. Flat or sheet glasses are commonly referred to as the indicator of transparency. Among this category of glasses, the 'float' glasses made by floating a sheet of glass ribbon over molten tin bath is the most popular and also technologically a very involved subject of concern to the building construction industry in general, and glass industry in particular. A very high accuracy of the glass thickness free of any surface aberrations or irregularities is exceptional, which is inherent in the process technology itself.

INTRODUCTION

Like many other processes of making glass, for 'float' glass where transparency matters a lot, the chemical ingredients are mixed and then fed automatically in a controlled manner into a glass tank furnace for melting and refining. However, the float process has a peculiarity after this stage, i.e. after drawing a sheet of glass from the working end of the tank furnace, the glass ribbon is made to float on a molten tin bath to achieve an excellent surface finish and also smoothening of the surface aberrations, which are both essential for increasing the transparency. After melting the glass in a tank furnace, the next step is to shape it into a desired form. As it is used in the building construction industry for both residential and commercial purposes, the size is also of great importance.

The fabrication process of float glass is highly mechanized and it is evolving continuously, even to the extent of newer products. The process requires a specific knowledge of both chemistry and physics, and it also requires continually improving the process of manufacturing that is a core competency in many glass companies around the world. Here, it has to be emphasized that 'float' glass has a variety of applications in a wide range of sizes and thicknesses: (a) High light transmission, (b) Optical clarity, and (c) it can be further fabricated into reflective, low-E, laminated, security, insulating, heat-treated and ceramic decorated glass articles.

At this point, it can be said that a variety of 'float' glass producers make a very wide range of products. Some of these items can be described briefly in terms of some more applications:

Clear Glass: Ideal where high visibility and clarity are required and the thicknesses range from 2 to 12 mm for a variety of applications, such as Windows, Solariums, Shelves, Tabletops, Skylights, Greenhouses, Display cases, Picture frame, Doors, Mirrors, Handrails, Appliances, Atriums, Safety glazing, and a host of Furniture applications.

Green Glass: Suitable when high light transmission and reduced solar heat gain are required with a standard thicknesses from 2 to 8 mm for Windows, Solariums, Tabletops, Skylights, Handrails, Atriums, Safety glazing and also a host of items in the furniture industry.

Bronze and Gray: Suitable when reduced light transmission and reduced solar heat gain are required, and also when colour is desired to enhance the aesthetics and increase design flexibility with a standard thicknesses of 3 to 6 mm.

The details of the 'float' process are dealt with in another issue of KANCH [1]. The heat and mass transfer problems in glasses, particularly in sheet glasses, are also discussed [2,3]. The concept of improving the furnace yield that is relevant for glass tank furnaces melting sheet or float glass has also been described in KANCH [4]. In this brief article, transparency will be described for glasses in general, with a particular reference to sheet or float glasses. Next, let us deal with the property of transmission as a general case in oxide glasses.

PROPERTY OF TRANSMISSION

When the rays of light or light waves pass through a piece of glass, two things could happen as: 1) Some part of light are transmitted through the glass piece, and (2) Some part (may be a smaller part) may be absorbed by the glass depending on the presence of transition metal ions (such as Fe, Mn, Cr, etc.) or impurities inside the glass. If the glass is hazy or opaque, then a major part of the light waves are absorbed by the glass, and if the impurities are bare minimum, then almost the entire light is transmitted through the glass. So it is basically a relative matter. It is now clear that the transmission of light will depend on the internal condition of the glass itself (all other conditions remaining the same). Hence, the process of manufacture to make a good quality and highly transparent glass is of utmost importance. A very small part can also be reflected from the surface of a transparent glass. The common use of oxide glasses is linked to their good 'transmission' in the optical spectra, i.e. in the combined band of the Ultraviolet (< 400 nm wavelength) + Visible spectrum (400 -700 nm)+Infra-red (IR) band (>700 nm). This optical window that corresponds to spectral sensitivity of human eyes is due to an 'electronic transition' between the lower energy valence band to the higher energy conduction band, which is near to the UV cut-off edge, whereas the vibration of the atoms or ions in the glass network (i.e. silicon-oxygen vibrations in the silicate glasses) produces their effect on the IR band. What human eyes can see is the visible band (400-700 nm) which is the superposition of the tails of (electronic) UV and (vibrational) IR bands. To this superposed part, one has to add the effect of impurities, e.g. the concentration of transition metal ions (i.e. Fe, Mn, Cr, etc.) that gives undesirable coloration to the glasses. The thermodynamic behavior oxidation-reduction of different transition metals at various temperatures of melting is also of importance that guides the ultimate coloration of the glasses due to the presence or absence of certain ions in the final melt.

To start talking about transparency, what immediately comes to our mind is the oxide glass. However, for the concept about transparency, it is equally important to talk about non-oxide glasses, such as 'chalcogenide' glasses containing various combinations of sulphur, selenium, arsenic, tellurium, etc. as these compounds are transparent in the infra-red (IR) part of the optical band. The chalcogenide glasses have many important applications, such as "IR-Optical Window" in defense equipment for night warfare and also as "IR Cameras" in the photography of behavior of different animals in the forests at night. However, mainly for human applications in the most fundamental need of human life, i.e. residential units, we mean oxide glasses in the form of plate/sheet glass and float glass, and also as optical glasses whose importance is known to all.

In order to understand the transmission property of light, what is needed is a good understanding of the refractive index of glasses. A transparent glass should not only have a proper and well defined refractive index, but it also needs to be constant over a certain range of wavelength so that no distortion or constancy of transmission occurs while in use under varied conditions of light. Next, let us talk about the refraction.

In Netherlands, in the year 1580-1626, the refractive index (or index of refraction) was first noticed by Willebrord Snell van Royen aka Snellius. This is a measure of how much the speed of light waves (or other waves, such as sound waves) is reduced inside the medium. For example, typical soda-lime glass has a refractive index close to 1.50, which means that in a glass, the light travels at 1/1.5 = 2/3 of the 'speed of light' in vacuum. In other words, if the refractive index of glass could be increased to, say, 2.0, then the light would travel much faster within this glass at half the 'speed of light'. Therefore, for certain special applications, through compositional engineering and/or by other technologies, the refractive index needs to be increased so that light travels relatively faster within the material giving rise to higher transmission. As “sound waves” were also mentioned above, it is the same logic that has to be followed or, applied for making nearly sound-proof rooms or buildings so that “sound waves” travel slower.

Two common properties of glass and other transparent materials are directly related to their refractive index. First, light rays change direction when they cross the interface from air to the material (say, window glass) that is an effect used in the lenses. Secondly, light reflects partially from surfaces that have a refractive index different from that of their surroundings. Therefore, knowledge about refractive index and how it changes with different parameters should be taken into consideration while designing a particular building for a given purpose.

For a better transmission of light through a glass, the thickness throughout the ‘glass piece needs to be constant. Compared to normal sheet or plate glass, the light transmission property of ‘float’ glass is much more enhanced that is already inherent or rather included within the process of fabrication itself in terms of achieving a more or less constant thickness. This normally takes care of various forces that operate within the system that also includes the stretching force of the glass ribbon over the molten tin bath when rollers are applied over the surface and also during its movement towards the annealing lehr. This is further reinforced by various means available to the glass technologist as control parameters. Still, there are thickness aberrations which are discussed in the next section.

A typical view of the Burj Khalifa building in UAE is shown, wherein many of the calculations, as briefly mentioned above, have been performed. This is obviously true for many such buildings around the world.

CONTROL OF THICKNESS

The importance of thickness control is of primary importance in the overall ‘quality control’ aspects of a ‘float’ glass, and thereby smoothening of the two flat surfaces with minimum errors is definitely needed. We cannot observe that the surface aberrations are actually wave-like or wavy in nature during the process of making a 'float' glass through our naked eyes. This needs to be removed to a large extent. It is like an oscillation type of situation. The damping of this oscillation on the surface of the 'float' glass is a subject of intensive study.

Whenever we talk about a 'surface', the forces acting on a given surface, i.e. the surface tension, has to be taken into account. The first theory of surface smoothness by surface tension forces involves smoothening of irregularities of small wavelengths. This is the same concept that is used in the case of sintering of metals. However, we need a more general theory. When the glass thickness is large relative to the wavelength of such irregularities, the problem is relatively easy to solve. It may be shown that the amplitude of a sinusoidal surface distortion of wavelength (l) decays exponentially with a 'decay constant' (K), which is given by:

$$K = \frac{g\rho + \gamma k^2}{2\eta k}$$

where, k = wave vector = $\frac{2\pi}{\lambda}$, γ is the surface tension, g the gravitation constant, ρ the density of the glass and η is the viscosity at a given temperature of glass fabrication. The decay constant has to be minimized so that the surface aberrations are at an optimum level. The value of K is a minimum, when the 'differential' of K with respect to that of the wave vector is equal to zero (i.e. dK/dk=0) by the simple rule of calculus when the viscosity will get cancelled, and we get:

$$\lambda = \frac{4\pi^2\gamma}{g\rho}$$

Thus, the irregularities of the above wavelength are the slowest to disappear. By using appropriate values of γ and ρ, this wavelength is found to be 22 mm. If the glass has a viscosity of 10^3 Ns/m^2, then the minimum value of K will be 0.99/s, and the amplitude of irregularities will fall to less than 1% of the initial value in less than 1 minute. This value has been found to be in agreement with several experiments.

The glass thickness produced by the 'float process' can be controlled either by restricting the "lateral spread" of the glass 'ribbon' on the tin bath, or by applying stretching forces along the direction of the movement towards the annealing zone. Moreover, this is true when six sets of rollers apply the requisite forces on the (almost) freshly prepared viscous glass after it enters the molten tin bath. Obviously, here the viscosity plays a very important role. As the entrance temperature to the tin bath is about 1005 to 1038^{0}C in several plants in various locations, the viscosity can be found out from the curve of "log of viscosity against temperature". This would also be a good controlling parameter for the speed of the 'rollers'.

It is interesting to note that if the glass is allowed to establish its own thickness without any interference, the balance of surface tension and gravitational forces produces a ribbon with a thickness of about 7 mm, which happens to satisfy about 50% of the present demand for float glass. In order to meet the balance 50% demand, we need to fix a lot of 'controlling parameters' to develop smooth glass surface for better optical transmission property.

The factor determining the equilibrium thickness of one liquid floating on another, when the floating liquid does not spread, are clear from Langmuir's analysis of the "geometry of oil lenses" on water. By considering a 'balance' of "hydrostatic and surface tension" forces acting horizontally, an optimum thickness can be obtained. This could be done by involving its inverse relationship with the density of molten tin and density of molten glass along with various surface tension forces (i.e. the spreading coefficient). This is supposed to be one method of calculation, but more modelling could be done in future.

CONCLUSIONS

In the float glass process, the technology can be improved by a proper understanding of refractive index of glasses and how it affects the overall transmission property. It also shows that there are immense possibilities of 'quality control' in the process technology in terms of smoothness of the two flat surfaces for further enhancing the transmission property. The possibility of gaining knowledge on the optimum thickness is also briefly discussed. This analysis with an eye on certain newer applications, as mentioned above, should help to obtain a superior quality float glass for the booming building construction industry and shopping malls.

ACKNOWLEDGEMENTS

The author would like to thank Dr. S. Das at the University of North Texas at Denton (USA) and Dr. K. Choudhary of Dept. of Materials Science at the University of Florida at Gainesville (USA) for many helpful discussions.

REFERENCES

1. A. K. Bandyopadhyay, KANCH, Vol. 5 [3], (2012), 33-36.

2. A. K. Bandyopadhyay, KANCH, Vol. 1 [4], (2014), 37-40.

3. A. K. Bandyopadhyay, KANCH, Vol. 1 [4], (2014), 49-53.

4. A. K. Bandyopadhyay and A. Charit, KANCH, Vol. 2 [2], (2014), 29-32.

Photovoltaic Effect and Solar Energy: A Brief Perspective – Part I

ABSTRACT

It is known that coal, gas, oil, etc., are not abundantly available in the planet, i.e. non-renewable, but exhaustible fuels for thermal power plants, nor they are very cheap from the financial point of view. However, the sunlight carrying a lot of energy is abundantly and freely available with some geographical variations and/or some seasonal variations within a given geographical region. Therefore, in the entire world, there is a huge surge of activity in the field of solar energy that comes from a renewable source. Some perspectives of renewable energy as well as some aspects of solar power plants have already been discussed in brief in KANCH (Ref. [1]). In this article in the Part - I, the science behind the solar energy production would be described in some details.

INTRODUCTION

There is a 'strong' need for 'energy' in our day-to-day human life. So, there is always some activity not only to maintain and eventually sustain the on-going process of production of different forms of energy arising out of different 'sources of energy' in our planet, but also there is a surge of activity for newer technologies in the respective fields. For the utilization of different sources of energy, such as coal, gas, oil, nuclear, etc, there is a growing impatience and consequently protests against such usage from the "environment-friendly lobby" around the world. Out of all the sources of energy, both wind and solar powers have received a great but positive attention of the technologists as well as the 'environment lobby'. Some perspectives of the renewable energy and also some aspects of the solar power plants have been discussed in brief in KANCH (Ref. [1]), particularly the debate on "Wind Vs. Solar" was raised with some useful data in this paper. As glass technologists have an important role in the production of 'solar power' in terms of utilization of 'float glasses' for the construction of 'solar panels', this topic will be taken up in some articles in the future. In the Part - I of this article, the science behind the solar energy production would be described in some details so that an understanding of the process is developed ultimately with the aim of showing 'environmental' concern from the glass technologist as well as from the AIGMF.

To get an idea on solar energy, first of all it is necessary to have an understanding of the *photovoltaic effect* in the creation of “voltage” or “electric current” in a material upon exposure to solar light. For this purpose, we need to also understand the nature of “bandgap” in different materials. In the scale of energy, a ‘bandgap’ is the difference between the ‘valence band’ where electrons are arranged/bonded and the ‘conduction band’ where the electrons flow to give rise to the conductivity of a material. If this ‘gap’ is very large, we call the material as “insulators”, i.e. glass, ceramic, wood, etc. If the ‘gap’ is almost zero, then we call the materials as “metals”, i.e. copper, aluminium, iron, etc., which are known as good conductors of electricity. However, if the value of the ‘bandgap’ is somewhere intermediate between the above two types, then the material is called “semiconductors”, i.e. silicon, germanium, gallium arsenide, etc. which brings us to the ‘photovoltaic effect’ and ‘solar cells’ for energy production.

There is a difference in the processes between the standard and obvious photovoltaic effect. When any light (i.e. the sunlight in this case) is incident upon a material surface, the electrons present in the ‘valence band’ absorb energy and, being excited, jump to the conduction band and become free. These highly excited, non-thermal electrons diffuse, and some reach a junction, e.g. p-n junction in a semiconductor in a solar cell, where they are accelerated into a different material by a built-in potential that is known as ‘Galvanic’ potential. This generates an ‘electromotive force’, and thus some of the “light” or “photons” energy is converted into “electric energy”. As the photons in the sun-light provoke this ‘electromotive force’ or rather ‘electric energy’, the process is called “photovoltaic effect” that was first observed by French physicist A. E. Becquerel in 1839, which is the fundamental basis for the solar energy. It should be mentioned that the ‘photovoltaic effect’ could also occur when two photons are absorbed simultaneously in a process called ‘two-photon photovoltaic effect’. This will not be discussed here.

In the standard ‘photoelectric effect’, the electrons are ejected from a material›s surface into vacuum, upon exposure to light. This also generates some electric energy, as the ejected electron is eventually captured on another electrode, although there is typically a high photon energy threshold. The ‘photovoltaic effect’ that is discussed here differs in that the excited electrons pass directly from one material to another, avoiding the difficult step of passing through the vacuum in between.

The ‘photovoltaic effect’ could also arise simply due to the heating caused by absorption of the light, apart from the ‘direct excitation’ of free electrons. The heating leads to an increase in temperature, which is accompanied by temperature gradients. These thermal gradients in turn may generate a voltage through the Seebeck effect. It should be clear that whether ‘direct excitation’ or ‘thermal effects’ dominate in the system, the ‘photovoltaic effect’ will depend on many material parameters.

In most photovoltaic applications, the radiation is sunlight, and the devices are called solar cells. In the case of a p-n junction solar cell, illuminating the material creates an electric current as excited electrons and the remaining holes are swept in different directions by the built-in electric field of the depletion region [2].

THEORY OF SOLAR CELLS

In the theory of solar cells, we need to explain the physical processes by which 'photons' of sun-light are converted into electrical current, when striking a suitable semiconductor device. The theoretical studies are of practical use because they predict the fundamental limits of solar cell, and give guidance on the phenomena that contribute to the losses and the solar cell efficiency.

A Simple Description

1. The 'photons' of sunlight hit the solar panel and they are absorbed by the semiconducting materials, such as silicon wafers.
2. The negatively charged 'electrons' are knocked loose from the silicon atoms, allowing them to flow through the material to produce electricity. It is due to the special composition of 'solar cells', the electrons are only allowed to move in a single direction.
3. An array of solar cells converts solar energy into a usable amount of direct current (DC) electricity, which is then converted to AC electricity, as per the requirement.

The Photogeneration

In the photogeneration of charge carriers, when a 'photon' hits a piece of silicon wafer, one of the three things can happen:

1. The photon can pass straight through the silicon wafer — this generally happens for lower energy photons.
2. The photon can reflect off the surface.
3. The photon can be absorbed by the silicon if the photon energy is higher than the silicon band gap value. This generates an electron-hole pair and sometimes heat that depends on the band structure.

When a photon is absorbed, its energy is given to an electron in the crystal lattice. Usually this electron is in the valence band and is 'tightly bound' in covalent bonds with neighboring atoms, and therefore unable to move far. The energy given to the electron by the photon «excites» it from the valence band into the conduction band, where it is free to move around within the semiconductor (i.e. silicon wafer). After the electron participating in the covalent bond formation is excited to higher energy, the valence band has one electron missing, i.e. one fewer electron, which is known as a “hole”. The presence of a missing covalent bond allows the bonded electrons of neighboring atoms to move into the «hole,» leaving another new “hole” behind, thus propagating holes throughout the crystal lattice of the ‘silicon wafers’. Thus, it can be said that photons absorbed in the silicon semiconductor create mobile electron-hole pairs throughout the system.

A photon need only have greater energy than that of the ‘band gap’ in order to excite an electron from the (lower energy) valence band into the (higher energy) conduction band. However, the “solar frequency spectrum” approximates a black body spectrum at about 5,800 K, and as such, much of the solar radiation reaching the Earth is composed of photons with energies greater than the ‘band gap’ of silicon [2]. These higher energy photons will be absorbed by the solar cell, but the difference in energy between these photons and the silicon ‘band gap’ is converted into heat (via lattice vibrations — called phonons) rather than into usable electrical energy. Thus, we are unable to effectively utilize the total quantum of photons falling on the solar panels. As mentioned above, the photovoltaic effect can also occur when two photons are absorbed simultaneously in a process called ‘two-photon photovoltaic effect’. However, high optical intensities are required for this nonlinear process.

The Separation of Charge Carriers

Mainly, there are two modes for separation of charge carriers in a solar cell:

1. The “drift” of carriers, driven by an electric field established across the device.
2. The “diffusion” of carriers due to their random thermal motion, until they are captured by the electrical fields existing at the edges of the ‘active region’.

There are both thick and thin solar cells. In the case of thick solar cells, there is no electric field in the ‘active region’, so the dominant mode for separation of charge carriers is ‘diffusion’ that is controlled by the diffusion-length, i.e. the “length” that photo-generated carriers can travel before they recombine. In this type of thick cells, the ‘diffusion length’ of minority carriers must be large compared to the cell thickness. In the case of thin film cells, such as amorphous silicon, the diffusion length of minority carriers is usually very short due to the existence of defects, and the dominant charge separation is therefore ‘drift’ that is driven by the electrostatic field of the junction, which extends to the whole thickness of the cell [2].

Once the minority carrier enters the drift region, it is ‹swept› across the junction and does not return. This sweeping is an irreversible process since the carrier typically relaxes to a lower energy state before it has a chance to be elastically scattered back to its starting point.

The p-n Junction

The most commonly known solar cell is configured as a large-area p-n junction made from silicon. As a matter of simplification, we could imagine bringing a layer of n-type silicon into direct contact with a layer of p-type silicon. In actual practice, the p-n junctions of silicon solar cells are not made in this way, but rather by diffusing an n-type dopant into one side of a p-type wafer or vice versa.

If a piece of p-type silicon is placed in close contact with a piece of n-type silicon, then a diffusion of electrons occurs from the region of high electron concentration, i.e. the n-type side of the junction → into the region of low electron concentration, which is the p-type side of the junction. In the process of diffusion of the electrons across the p-n junction, they recombine with the holes on the p-type side. However, this diffusion of carriers does not happen indefinitely, as the build-up of charges on either side of the junction that creates an electric field. This electric field then creates a diode that promotes charge flow, known as drift current that opposes and eventually balances out the diffusion of electrons and holes. This region where electrons and holes have diffused across the junction is called the depletion region because it no longer contains any mobile charge carriers. It is also known as the *space charge region*.

EFFECT OF EXTERNAL LOAD

In order to apply an external load into a given system, such as solar panels, we need to make metallic contacts that must have suitable ohmic resistance. This type of Ohmic metal-semiconductor contacts are made to both the n-type and p-type sides of the solar cell, and the electrodes are then connected to an external load. Electrons that are created on the n-type side, i.e. the electrons that are «collected» by the junction and swept onto the n-type side, may travel through the wire, power the load, and then continue through the wire until they reach the p-type 'semiconductor-metal contact'. Here, they recombine with a hole that was either created as an electron-hole pair on the p-type side of the solar cell, or a hole that was swept across the junction from the n-type side after being created there.

The Fermi level of energy is generally situated in the middle of the valence and conduction bands that have a significant effect on the 'population density' of the charge carriers, i.e. electrons and holes, which has an important consequence on the current density in the system of study. For the above description, the voltage measured must then be equal to the difference in the quasi Fermi levels of the minority carriers, i.e. electrons in the p-type portion and holes in the n-type portion of the system. Any system with a voltage-current characteristic can be always represented or modelled by a combination of different necessary (or concerned) 'circuit elements' – that is normally described by a circuit diagram. Thus, at this point, we need to elaborate little bit on the equivalent circuit of a 'solar cell'.

The Equivalent Circuit

The necessity of representing the voltage-current system, as described above, can be modelled by an "equivalent circuit" and also the 'schematic symbol' of a solar cell is shown in Figures 1 and 2:

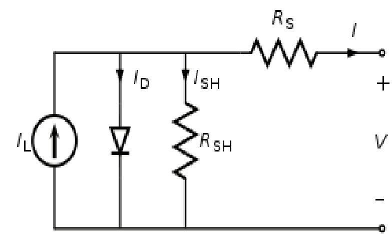


Figure 1: Equivalent Circuit

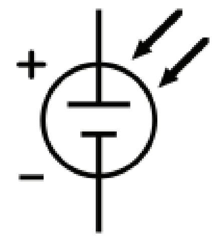


Figure 2: Schematic Symbol

As noted above, to understand the electronic behaviour of a solar cell, it is useful to create a model which is electrically equivalent that is based on discrete 'electrical components' (called circuit element) whose behaviour is well known. In an ideal solar cell, a "diode" can be put in parallel to the 'current source', and the solar cell may be modelled accordingly. However, in actual practice, no solar cell is ideal, thereby adding a 'shunt resistance' and a 'series resistance' component to the model. The resulting 'equivalent circuit' of a solar cell (as shown in Figure 1) and also the 'schematic representation' (as shown in Figure 2) can be used in the circuit diagrams [3]. To note that without a proper circuit diagram, no modelling can be done.

The Characteristic Equation

After showing the necessary circuit diagrams, it is quite relevant to develop certain equations that are necessary for calculating the values of current. This is done by the design engineers to be able to compare them with actual situation for a given system. From the 'equivalent circuit', it is evident that the current produced by the solar cell is equal to that produced by the current source, minus that which flows through the diode, minus that which flows through the shunt resistor as follows [4,5]:

$$I = I_L - I_D -- I_{SH}$$

Where,

- I = Output Current (Ampere)
- I_L = Photo-generated Current (Ampere)
- I_D = Diode Current (Ampere)
- I_{SH} = Shunt Current (Ampere)

The current through these 'circuit elements' is governed by the voltage across them**:**

$V = V_j + IR_S$

Where,

- V_j = Voltage across both Diode and Resistor R_{SH} (Volt)
- V = Voltage across the Output Terminals (Volt)
- I = Output Current (Ampere)
- R_S = Series Resistance (Ohm)

Shockley developed an equation for diversion of the current through the "diode", as shown below [6]:

$I_D = I_0 \{exp[qV_j/nkT] – 1\}$

Where,

- I_0 = reverse saturation current (ampere)
- n = diode ideality factor (1 for an ideal diode)
- q = elementary charge
- k = Boltzmann›s constant
- T = absolute temperature

At 25°C, kT/q = 0.0259 Volt

By Ohm›s law, the current diverted through the 'shunt resistor' is**:**

$I_{SH} = V_j /R_{SH}$

Substituting these into the first equation produces the characteristic equation of a solar cell, which relates solar cell parameters to the output current and voltage:

$I = I_L – I_0\{exp\{q(V + IR_S)/nkT\} – 1\} – (V + IR_S)/R_{SH}$

An alternative derivation of the above equation is possible that gives rise to a similar equation, except the voltage (*V*) on the left-hand side. These two alternative equations are identical, and on computational work, they give rise to the same results.

In principle, given a particular 'operating voltage' (*V*) the equation may be solved to determine the operating current (*I*) at that voltage. However, since the equation contains the current (*I*) on both sides in a transcendental function, the equation has no general analytical solution. It should be mentioned that even without a solution, it is physically instructive. Moreover, it is easily solved using numerical methods, which is a matter of technicality.

As different parameters (such as I_0, n, R_S, and R_{SH}) cannot be measured directly, the most common application of the above characteristic equation is "nonlinear regression" to extract the values of these parameters on the basis of their combined effect on the behaviour of the 'solar cell'. Computer models for representing circuit diagrams have also been developed that help us to derive the values of basic parameters or circuit elements that represent the 'solar cells'. Further, computer simulation is also performed on the size of the solar panels that will be discussed in the future issues of KANCH. In this respect, the size of the glass panels is quite important that is of business significance to the manufacture of glass sheets that would be increasingly used for solar energy.

CONCLUSIONS

A general perspective of solar power plants with important statistics was given earlier in KANCH. In this article, the science behind the production of solar power has been given in some details. An understanding of the scientific process behind solar energy formation is necessary not only to design better and effective solar cells, but also to have a correct perspective for the 'float glass' that has to be used in the overall system. More such usage obviously augurs well for the power sector in general and the glass industry in particular.

REFERENCES

1. S. Das and A. K. Bandyopadhyay, "A Perspective on Renewable Energy and Solar Photovoltaic Power Plants", KANCH, Vol. 2 [4], (2015), 21-25.
2. D. Carlson and C. Wronski, "Topics in Applied Physics: Amorphous Semiconductors: Amorphous Silicon Solar Cells", (Springer, Berlin), 1985.
3. E. Lorenzo, "Solar Electricity: Engineering of Photovoltaic Systems", Progensa, 1994.
4. A. Luque and S. Hegedus, "Handbook of Photovoltaic Science and Engineering", (John Wiley & Sons, New York), 2003.
5. A. G. Aberle, S. R. Wenham, and M. A. Green, «A New Method for Accurate Measurements of the Lumped Series Resistance of Solar Cells», Proc. "23rd IEEE Photovoltaic Specialists Conference", (1993), 113-139.
6. L. D. Nielsen, "Distributed Series Resistance Effects in Solar Cells», IEEE Trans. on Electron Devices, Vol. 29 [5], (1982), 821-882.

Photovoltaic Effect and Solar Energy: A Brief Perspective – Part II

ABSTRACT

It is known that sunlight transports a lot of energy, which is abundantly and freely available with some variations from one geographical region to the other. Moreover, there is some seasonal variation from summer to winter months within a given geography. Hence, there is a huge surge of activity in the field of solar energy in the entire planet, and this source of energy is renewable. Some perspectives of renewable energy as well as some aspects of solar power plants were discussed in brief in KANCH (Ref. [1]). Then, some details were given in terms of a brief perspective in the Part – I of an article on 'photovoltaic effect and solar energy" in KANCH (Ref. [2]). Some more aspects on the science behind the solar energy production would be described in some details in the Part – II in this article.

INTRODUCTION

An understanding of the *photovoltaic effect* in the creation of "voltage" or "electric current" in a material upon exposure to light is essential to get a good grasp on solar energy [1]. In different materials, it is also essential to understand the nature of bandgap, which signifies the difference between the 'valence band' where electrons are arranged and the 'conduction band' where the electrons flow to give rise to the conductivity of a material. If this gap is very large, the material is known as insulator, i.e. glass, ceramic, wood, etc. If the gap is almost zero, then the material is considered as metal, i.e. copper, aluminium, iron, etc., which are known as good conductors of electricity. However, if the bandgap is somewhere intermediate between the above two types, then the material is called semiconductor, i.e. silicon, germanium, gallium arsenide, etc., that helps us to understand the photovoltaic effect and consequently the mechanism of solar energy production [2].

There is a difference in processes between the standard and obvious photovoltaic effect. When the sunlight is incident upon a material surface, the electrons present in the valence band absorb energy and, being excited, jump to the conduction band and become free. These highly excited, non-thermal electrons diffuse, and some reach a junction, e.g. p-n junction in a semiconductor in a solar cell, where they are accelerated into a different material by a built-in potential that is known as Galvanic potential. This generates an 'electromotive force', and thus some of the light or "photons" energy is converted into "electric energy". As the photons in the sun-light provoke this 'electromotive force' or rather 'electric energy', the process is called "photovoltaic effect". The 'photovoltaic effect' (whether created by direct excitation or thermal effects), it will depend on many material parameters.

In most photovoltaic applications, the radiation is sunlight, and the devices are called solar cells. In the case of a p-n junction solar cell, illuminating the material creates an electric current as excited electrons and the remaining holes are swept in different directions by the built-in electric field of the depletion region [3].

In Part-II of this article, some more aspects will be discussed to get a better view of solar cells or rather on their application in the production of solar energy in terms of a characteristic equation.

EQUATION FOR SOLAR CURRENT

Before going into the details, a brief recapitulation is necessary on the theory of solar cells, wherein the physical processes by which 'photons' of sun-light are converted into electrical current need to be explained when striking a suitable semiconductor device. The theoretical studies are of practical use because they predict the fundamental limits of solar cell, and give guidance on the phenomena that contribute to losses and solar cell efficiency. Let us give a simple description as: (a) The 'photons' of sunlight hit the solar panel and they are absorbed by the semiconducting materials, such as silicon wafers, (b) The negatively charged 'electrons' are knocked loose from the silicon atoms, allowing them to flow through the material to produce electricity. It is due to the special composition of 'solar cells', the electrons are only allowed to move in a single direction, (c) An array of solar cells converts solar energy into a usable amount of direct current (DC) electricity, which is then converted to AC electricity, as per the requirement.

It is noted that to understand the electronic behaviour of a solar cell, it is useful to create a model which is electrically equivalent that is based on discrete 'electrical components' that are known as 'circuit elements', whose behaviour is well known. In an ideal solar cell, a "diode" can be put in parallel to the 'current source', and the solar cell may be modelled accordingly. However, in actual practice, no solar cell is ideal, thereby adding a 'shunt resistance' and a 'series resistance' component to the model [4]. The resulting 'equivalent circuit' of a solar cell as well as the 'schematic representation', as shown in Ref. [2], can be used in the circuit diagrams.

The characteristic equation of a solar cell, which relates solar cell parameters to the output current and voltage, is described as follows:

$$I = I_L - I_0\{exp[q(V + IR_S)/nkT] - 1\} - (V + IR_S)/R_{SH}$$

Where, I = output current in Ampere, I_L = photo-generated current in Ampere, I_0 = reverse saturation current in Ampere, V = voltage across the output terminals in Volt, R_S = series resistance in Ohms, n = diode ideality factor (1 for an ideal diode), q = elementary charge, k = Boltzmann›s constant, T = absolute temperature, and R_{SH} = shunt resistance in Ohms.

In principle, given a particular operating voltage V the equation may be solved to determine the operating current I at that voltage. However, because the equation involves I on both sides in a transcendental function the equation has no general analytical solution. However, even without a solution, it is physically instructive. Furthermore, it could easily be solved using numerical methods. Since the parameters I_0, n, R_S, and R_{SH} cannot be measured directly, the most common application of the characteristic equation is nonlinear regression to extract the values of these parameters on the basis of their combined effect on solar cell behaviour.

OPEN-CIRCUIT VOLTAGE

When the cell is operated at open circuit, $I = 0$ and the voltage across an output terminals is defined as the *open-circuit voltage*. Assuming that the shunt resistance is high enough to neglect the final term of the characteristic equation, the open-circuit voltage V_{OC} is expressed as:

$$V_{OC} \approx \{(nkT)/q\}ln(I_L/I_0 + 1)$$

Where, the terms have their usual meaning, as explained above.

Similarly, there is another situation in which the cell is operated at short circuit, $V = 0$ and the current I through the terminals is defined as the *short-circuit current*. It can be shown that for a high-quality solar cell (low R_S and I_0, and high R_{SH}), the short circuit current I_{SC} is written as:

$$I_{SC} \approx I_L$$

It is not possible to extract any power from the device when operating at either open circuit or short circuit conditions.

Effect of Physical Size

The values of I_0, R_S, and R_{SH} are dependent upon the physical size of the solar cell. In comparing otherwise identical cells, a cell with twice the surface area of another will, in principle, have double the I_0 because it has twice the junction area across which current can leak. It will also have half the R_S and R_{SH} because it has twice the cross-sectional area through which current can flow. For this reason, the characteristic equation is frequently written in terms of current density (***J***), or current produced per unit cell area as:

$$J = J_L - J_0\{exp[q(V + JR_S)/nkT] - 1\} - (V + JR_S)/R_{SH}$$

Where, J = current density, J_L = photogenerated current density and J_0 = reverse saturation current density in ampere/sq. cm; R_S = specific series resistance and R_{SH} = specific shunt resistance in Ohms-sq. cm.

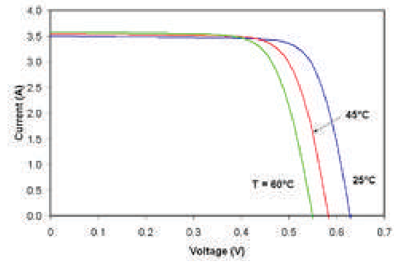
This formulation has several advantages. One is that since cell characteristics are referenced to a common cross-sectional area they may be compared for cells of different physical dimensions. While this is of limited benefit in a manufacturing setting, where all cells tend to be the same size, it is useful in research and in comparing cells between manufacturers. Another advantage is that the above current density equation naturally scales the parameter values to similar orders of magnitude, which can make numerical extraction of them simpler and relatively more accurate even with naive solution methods.

There are practical limitations of this formulation. For instance, certain parasitic effects grow in importance as cell sizes shrink and can affect the extracted parameter values. Recombination and contamination of the junction tend to be greatest at the perimeter of the cell, so very small cells may exhibit higher values of J_0 or lower values of R_{SH} than larger cells that are otherwise identical. In such cases, comparisons between cells must be made cautiously and with these effects in mind.

This approach should only be used for comparing solar cells with comparable layout. For instance, a comparison between primarily quadratical solar cells like typical crystalline silicon solar cells and narrow but long solar cells like typical thin film solar cells can lead to wrong assumptions caused by the different kinds of current paths and therefore the influence of for instance a distributed series resistance R_S. Macro-architecture of the solar cells could result in different surface areas being placed in any fixed volume - particularly for thin film solar cells and flexible solar cells which may allow for highly convoluted folded structures. If volume is the binding constraint, then the 'efficiency density' based on surface area may be of less relevance [5,6].

The Cell Temperature

The effect of temperature on the current-voltage characteristics of a solar cell is shown on next page. The temperature affects the characteristic equation in two ways: (a) directly, via T in the exponential term, and (b) indirectly, via its effect on I_0. Strictly



speaking, the temperature affects all of the terms, but these two far more significantly than the others. While increasing T reduces the magnitude of the exponent in the characteristic equation, the value of I_0 increases exponentially with T. The net effect is to reduce the open-circuit voltage (V_{OC}) linearly with increasing temperature. The magnitude of this reduction is inversely proportional to V_{OC}; that is, cells with higher values of V_{OC} suffer smaller reductions in voltage with increasing temperature. For most crystalline silicon solar cells, the change in V_{OC} with temperature is about -0.50% /°C, though the rate for the highest-efficiency crystalline silicon cells is around -0.35% /°C. By way of comparison, the rate for amorphous silicon solar cells is -0.20% /°C to -0.30% /°C, depending on how the cell is made.

It has to be noted that the amount of photo-generated current I_L increases slightly with increasing temperature because of an increase in the number of thermally generated carriers in the cell. However, this effect is modest: about 0.065% /°C for crystalline silicon cells and 0.09% for amorphous silicon cells.

The overall effect of temperature on 'cell efficiency' can be computed using these factors in combination with the characteristic equation. However, since the change in voltage is much stronger than the change in current, the overall effect on efficiency tends to be similar to that on voltage. Most crystalline silicon solar cells decline in efficiency by 0.50% /°C and most amorphous cells decline by 0.15-0.25% /°C. The figure above shows I-V curves that might typically be seen for a crystalline silicon solar cell at various temperatures.

The Series Resistance

As series resistance increases, the voltage drop between the junction voltage and the terminal voltage becomes greater for the same current. The result is that the current-controlled portion of the I-V curve begins to sag toward the origin, producing a significant decrease in the terminal voltage (V) and a slight reduction in I_{SC}, the short-circuit current. Very high values of R_S will also produce a significant reduction in I_{SC}; in these regimes, series resistance dominates and the behavior of the solar cell resembles that of a resistor. Losses caused by series resistance are in a first approximation given by $P_{loss}=V_{Rs}I=I^2R_S$ and increase quadratically with photo-current. The losses arising out of the series resistance are therefore most important at high illumination intensities.

The Shunt Resistance

As shunt resistance decreases, the current diverted through the shunt resistor increases for a given level of junction voltage. The result is that the voltage-controlled portion of the I-V curve begins to sag far from the origin, producing a significant decrease in the terminal current $\boldsymbol{I}$ and a slight reduction in V_{OC}. Very low values of R_{SH} will produce a significant reduction in V_{OC}. Much as in the case of a high series resistance, a badly shunted solar cell will take on operating characteristics similar to those of a resistor.

The Reverse Saturation Current

If one assumes infinite shunt resistance, the characteristic equation can be solved for V_{OC} as:

$$V_{OC} \approx \{(kT)/q\} \ln(I_{SC}/I_0 + 1)$$

Thus, an increase in I_0 produces a reduction in V_{OC} proportional to the inverse of the logarithm of the increase. This explains mathematically the reason for the reduction in V_{OC} that accompanies increases in temperature described above. Physically, the 'reverse saturation current' is a measure of the «leakage» of carriers across the p-n junction in reverse bias. This leakage is a result of carrier recombination in the neutral regions on either side of the junction.

The Ideality Factor

The ideality factor (also called the emissivity factor) is a fitting parameter that describes how closely the diode›s behavior matches that predicted by theory, which assumes the p-n junction of the diode is an infinite plane and no recombination occurs within the space-charge region. A perfect match to theory is indicated when $n = 1$. When recombination in the space-charge region dominate other recombination, however, $n = 2$.

It can be stated that most solar cells, which are quite large compared to conventional diodes, well approximate an infinite plane and will usually exhibit near-ideal behavior under Standard Test Condition ($n \approx 1$). However, under certain operating conditions, the device operation may be dominated by recombination in the space-charge region. This is characterized by a significant increase in I_0 as well as an increase in ideality factor to $n \approx 2$. The latter tends to increase solar cell output voltage while the former acts to erode it. Therefore, the net effect is a combination of the increase in voltage for increasing $\boldsymbol{n}$. Typically, I_0 is the more significant factor and the result is a reduction in voltage.

CONCLUSIONS

In order to understand photo-generation of electric current, the photo-voltaic effect and its influence on the solar energy production in typical silicon wafers placed on the flat glass surfaces are described in terms of various parameters, such as physical size, cell temperature, series and shunt resistances, reverse saturation current and finally the ideality factor. To get a better output from a given cell configuration, these parameters could be varied in a controlled manner for better efficiency of solar energy production. The use of flat glass will also increase with more and more solar plants.

REFERENCES

1. S. Das and A. K. Bandyopadhyay, "A Perspective on Renewable Energy and Solar Photovoltaic Power Plants", KANCH, Vol. 2 [4], (2015), 21-25.

2. A. K. Bandyopadhyay, "Photovoltaic Effect and Solar Energy: A Brief Perspective – Part I", KANCH, Vol. 2 [5], (2015), 1-5.

3. D. Carlson and C. Wronski, "Topics in Applied Physics: Amorphous Semiconductors: Amorphous Silicon Solar Cells", (Springer, Berlin), 1985.

4. E. Lorenzo, "Solar Electricity: Engineering of Photovoltaic Systems", Progensa, 1994.

5. A. G. Aberle, S. R. Wenham, and M. A. Green, «A New Method for Accurate Measurements of the Lumped Series Resistance of Solar Cells», Proc. "23rd IEEE Photovoltaic Specialists Conference", (1993), 113-139.

6. L. D. Nielsen, "Distributed Series Resistance Effects in Solar Cells», IEEE Trans. on Electron Devices, Vol. 29 [5], (1982), 821 – 882.

A Perspective on Renewable Energy and Solar Photovoltaic Power Plants

ABSTRACT

Among all the plate or sheet glasses, the “float glass” made by floating a sheet of glass over molten tin bath is the most popular and also technologically involved subject of concern to the building construction industry in general, and glass industry in particular. These sheet glasses are very useful in making solar panels for generating sizeable proportion of electrical energy from the sun light via photovoltaic (PV) cells that are adequate for lighting and other purposes for both residential and commercial buildings. A perspective of solar energy is discussed in this article to highlight the importance of this form of renewable energy that is highly congenial for the protection of our environment.

INTRODUCTION

In the totality of the industrial activity, the building construction plays a very important role in any national economy, sometimes comprising of about 25% of GDP, e.g. in Singapore, where this industry is quite pervasive and visible almost everywhere in this city-nation. In a 10 ft by 10 ft room (i.e. 100 square ft area) with a height of about 10 ft, if one facade of this room is fully made by “glass” sheet, then the requirement of glass is 100 square ft (7-8 mm thick) for a 100 square ft room, i.e. the ratio is just 1. This ratio varies with the design of the building and our desire to see light. However, depending on such design, as the building construction activity increases in the evolving economy, the requirement of the glass also increases. This is good news for the glass industry, if they could convince the user industry to consume more and more of glass facade in the design of their buildings. This is also guided by the ‘transparency’ of glasses, as described for float glasses in various issues of KANCH, particularly in Ref. [1] and [2].

In this context, we cannot forget about Charles-Edouard Jeanneret-Gris (born in 1887), popularly known as Le Corbusier, who was a Swiss-French architect, designer, painter, urban planner, writer, and one of the pioneers of what is now called “modern architecture". Le Corbusier once said that "Light is Necessary so that the 'Matter' can Manifest itself and be Visible". This concept has been extensively used in the design of the buildings in the modern era. Another important industry is "electrical energy" that is used by the consumers who inhabit such buildings. This electrical energy is mainly produced via thermal route by burning coal, although there are other important sources for electric power generation, such as nuclear, hydro, wind, solar, etc.

However, due to burning of coal, there is an emission of carbon dioxide which creates an environmental problem for all of us. In all the "multi-lateral environment" conferences, there is a tremendous effort for each country to reduce the level of emission of such toxic gases, and they even go to the extent of giving "carbon credit" to those countries who comply with the acceptable norms. This takes us to non-conventional but renewable energy like solar, wind, etc. For example, Germany produces 6% of its total power generation via solar energy route thereby making it the most laudable contender for carbon credit. Here, before talking about solar energy, let us talk briefly about some data on power.

It is important to understand the gigantic nature of the top ten major power plants in the world, although none of them are 'thermal power' plants. Seven out of the top ten are actually renewable, i.e. hydro-electric and three are nuclear.

Even among the top 20 major power plants, 11 are hydro-based and 6 are nuclear plants. Only 1 each is based on coal, natural gas and fuel oil respectively, but none of these plants is in India indicating that we are still far apart from polluting the earth's atmosphere, although this complacency is not desirable under any circumstances. The above is a list of the top ten power plants in the world. While there are 3 such large plants in China and 2 in Brazil, there is 1 plant each in USA, Canada, South Korea, Japan and Venezuela respectively. The total installed capacity for ten plants alone is more than 100,000 MW, and the combined power generation is over 500,000 billion units serving well the need of these countries. India's position in this respect is quite dismal, although there is too much talk about power generation.

The debate on different modes of power generation will continue in the world, but there is no denying the fact that despite having more than a billion tons of reserves of 'good coal' in India, we should desist from exploring the prospect of "solar energy". We as glass technologist have a strong interest in developing a solar energy market so that the demand for sheet glass will go up by the day with the increase in the value-added building construction segment. Although there is a temporary set-back in terms of financing large building projects, this industry will prosper with 100% FDI in the sector, and eventually through the infusion of 'private equity' capital from USA and other countries, who are flush with funds.

Name of the Plant	Country	Type	Capacity (MW)	Annual Power Generation (Billion Units)
Three Gorges	China	Hydro	22,500	92,200
Itaipu	Brazil	Hydro	14,000	98,630
Xiluodu	China	Hydro	13,860	57,100
Guri	Venezuela	Hydro	10,235	47,000
Tucurui	Brazil	Hydro	8,370	21,400
Kashiwazi	Japan	Nuclear	8,200	60,300
Bruce NGS	Canada	Nuclear	6,810	45,000
Grand C. Dam	USA	Hydro	6,800	21,000
Longtan Dam	China	Hydro	6,400	18,700
Hanul	S. Korea	Nuclear	6,175	48,160
		TOTAL	**103,340**	**509,490**

Hence, the glass industry in India could try to develop a strategy of attracting the prominent private equity investors, as many of them have already invested heavily in the real estate market of USA as well as in the Euro zone, particularly in Spain. Moreover, it is a very plausible strategy for our future that is also viable, as the sunlight is free as a raw-material for power generation compared to that of coal or fuel oil, which is becoming costly day by day, thereby increasing the power bill of general consumers as well as having higher expenditure on the glass production cost. Next, to understand the impact of solar energy generation, let us have a comparison with another renewable source of energy, i.e. wind energy.

WIND v/s SOLAR ENERGY

First of all, a distinction has to be made between these two forms of energy. Both are renewable and both are naturally available without paying any cost on raw materials, like coal or fuel oil. However, the weather department goes through a very complicated process of computer modelling and calculations to predict the wind directions and speed that determine the efficiency of wind power system. In order to sustain the required power generation level, i.e. efficiency, the weather prediction has to be correct. The weather report for the availability of 'sun shine' is more or less predictable. In other words, except in some specific locations, solar power can be generated almost everywhere and with the advent of technology of "tracking system", the orientation of solar panels could be changed to get the optimum output. In case of wind power, this cannot be said and certain specific locations are intentionally chosen, where the wind speed is certain to be quite adequate for the purpose of making the wind turbine work effectively. This excludes the other merits and demerits of these systems of generation of electrical energy with the relevant details on the cost of investment.

Here, of course, no comparison is made between the respective technology, as both are quite extensive and driven by strong R & D work. So, there is always an angle of "investment" for the future. From the general statistics, it is known that "wind power" expanded by almost 20% in 2012 around the world to reach a new peak of 282 gigawatts (GW) of total installed capacity, while solar power reached more than 100GW, having more than doubled in two years, up from 71GW in 2011 and just 40GW in 2010. More than 45GW of new wind turbines arrived in 2012, with China and the USA leading the way with 13GW each, while Germany, India and the UK were next with a capacity in each of about 2GW.

Due to some financial problems, China paused for some time, while both the US and European markets had exceptionally strong years, as per the report of Global Wind Energy Council (GWEC). Moreover, the report added that Asia still led the global markets, but with North America a close second, and Europe not far behind. In the world for installed wind power, the UK now ranks sixth with 8.5GW, while in Europe, only Germany (31GW) and Spain (23GW) rank higher. However, undisputedly, China leads the world with 77GW of installed capacity and the US is second with 60GW.

Due to technological development, the UK is by far the world leader in "offshore" wind deployment, installing 0.85MW in 2012 to bring the total so far to 3,000MW. Denmark in this respect ranks second with a total of 900MW installed, and Belgium is ranked third with 400MW. This part of the success story in these countries speaks of the sustained efforts by their department of energy as well as by the climate change advocacy. For the future low energy carbon, the technology is driven forward with 6MW "offshore turbine" currently under installation in the North Sea.

As per the report of GWEC on the market consolidation that is pinpointed as the reason of a relative slowdown in China, while "a lapse in policy" caused a similar slowdown in India, but it is expected that the Asian dominance of 'global wind markets' will continue. The record year for installation in the USA was driven by a rush to beat an anticipated end to tax credits: 8GW of the total 13GW were installed in the last quarter of 2012. However, the tax credit has since been extended by the Federal Govt., which means that a dramatic slowdown in the USA is less likely in the future. The report further added that the outlook for 2013 in Europe was uncertain due to the Euro-zone debt crisis, but that the EU's legal commitments and 2020 targets for renewable energy ensured "a degree of stability".

There is very little wind power installed in Africa, but sub-Saharan Africa's first large commercial wind farm came on line in 2012, i.e. a 52MW project in Ethiopia. This seems to be just the beginning of the African market. With construction started on over 500MW in South Africa, it is expected that Africa will be a substantial new market, where clean, competitive, energy generated with the indigenous sources is a priority for economic development.

As said earlier, solar power reached 100GW installed capacity in 2012 for the first time, according to data from the European Photovoltaic Industry Association (EPIA), up from 71GW in 2011 and just 40GW in 2010. The largest market by far is Europe, with Germany (32GW total) and Italy (16GW) being the leaders. However, while solar panel connections in Europe fell by 5GW in 2012 compared to that in the previous year, the installations rose by 5GW in the rest of the world, notable China, the USA, Japan and India. This actually made up the shortcoming and kept the pace ahead. As per the report of EPIA, even in tough economic times and despite growing regulatory uncertainty, the performance of the year 2011 has been maintained in 2012. However, a continued oversupply of solar panels would most likely make coming years difficult for photovoltaic companies. Accordingly, there is a fall of investment in all renewable energy of over 10%, which has been due to large Govt. support in the USA, Spain, and Italy. However, it continues to rise in Asia that auger well for India.

Recently, the International Energy Agency (IEA) noted that low-carbon energy was growing quickly, driven largely by state subsidies. However, the IEA highlighted that fossil fuels received six times more subsidy, i.e. 523 billion US dollars in 2011 that is up 30% from 2010 level than low-carbon energy. There is still some scope of development of renewable energy in general and solar energy in particular in India as long as the subsidies are focussed with a correct strategy. Without going into the details of technology that will be dealt with in another issue of KANCH, next let us talk about the photovoltaics (PV).

PHOTOVOLTAICS

Photovoltaics (PV) is a method of converting solar energy into direct current electricity using semiconducting materials that exhibit the photovoltaic effect. Semiconductors are intermediate between the (a) metals, where electrons flow freely without any bandgap, and (b) dielectrics or insulators, where there is a larger bandgap so that electrons cannot flow showing very little or no conduction of electricity. With the improvement of semiconductor technology, a lot of solar energy is being produced by harnessing their potential. It has to be also added that the light (i.e. solar light) is like waves. In the context of duality, these waves when quantized gives rise to the concept of quantized particles like 'photons'. So, the photons of Sun light have a great role in converting solar energy or radiation into electrical energy via the electrons in the semiconductor with a reasonable band gap. The photons from the solar light excite the electrons from the lower valence band to higher conduction band within different type of "solar cells", i.e. semiconducting materials (like silicon), imprinted on the sheet of glass that generates the electric current.

PHOTOVOLTAIC SOLAR PLANTS

A photovoltaic system employs "solar panels" (made of sheet glass) that is composed of a number of "solar cells" imprinted on them to produce usable solar power. Power generation from solar PV has long been seen as a clean and sustainable energy technology [3], which draw upon the planets' most plentiful and widely distributed renewable energy source, i.e. the Sun. The direct conversion of sunlight to electricity occurs without any moving parts or environmental emissions during the operation. It is well proven, as photovoltaic systems have now been used for fifty years in specialized applications, and grid-connected PV systems have been in use for over twenty years [4].

Driven by the advances in technology and increases in manufacturing scale and sophistication, the cost of photovoltaics has declined steadily since the first solar cells were manufactured [4,5], and the levelised cost of electricity (LCOE) from PV is competitive with the conventional electricity sources in an expanding list of geographic regions [6]. Net metering and financial incentives, such as preferential feed-in tariffs for solar-generated electricity, have supported solar PV installations in many countries [7]. With current technology, photovoltaics recoup the energy needed to manufacture them in 1.5 (in Southern Europe) to 2.5 years (in Northern Europe), as per the data compiled by various sources [8].

Solar PV is now, after hydro and wind power, the third most important renewable energy source in terms of globally installed capacity. More than 100 countries use solar PV. Installations may be ground-mounted or, built into the roof or walls of a building; this could be building-integrated photovoltaics to reduce overall cost or simply on the rooftop. The ground-mounted installations, mostly done in the country-side where the land space is available, could also be integrated with "farming and grazing" that should definitely be very popular in the Northern Hilly areas in India to harness the real potential of PV technology. It also opens up the possibility of making the electricity reach to the distant locations in the Himalayan or similar regions, where there is a plenty of sunlight almost everywhere.

In 2013, the fast-growing capacity of worldwide installed solar PV increased by 39% to 139GW. This is sufficient to generate at least 160,000 billion Kwh or units, i.e. about 0.85% of the electricity demand on the planet. China, followed by Japan and the USA, is now the fastest growing market, while Germany remains the world's largest producer, contributing almost 6% to its national electricity demands, as said earlier. Looking at the immense possibility of using solar panels and consequent increase of

Name of the Plant	Country	Capacity (MW)	Annual Power Generation (Million Units)	Remarks
Topaz Solar Farm	USA	550	1096	550 MW reached in November, 2013
Desert Sunlight Solar Farm	USA	550	1050	Final stage reached in January, 2015
Longyangxia Dam Solar Plant	China	320	640	Full load reached in December, 2013
California Valley Solar Ranch	USA	292	399	First 130MW reached in February, 2013
Agua Caliente Solar Project	USA	290	626	Thin-film Cell with no Tracking System
Antelope Valley Solar Ranch	USA	266	525	With Govt Loan Guarantee
Mount Signal Solar	USA	266	520	Full load reached in May, 2014
Charanka Solar Park	India	224	408	Collection of 17 co-located plants
Mesquite	USA	207	413	8 lacs Panels (Sempra Energy)
Huanghe Hydro. Goldmud	China	200	317	Pure PV Plant (Yingli Solar)
Gonghe Industrial Park (Phase-1)	China	200	300	Full load reached in December, 2013
Imperial Valley Solar Project	USA	200	300	Full load reached in August, 2013
	TOTAL	**3,015**	**5,498**	

demand of float glass in India, it is quite tempting to record some of the great producers in the world in order to attract the attention of all concerned in the energy sector in India. Next, let us give some details on the largest solar energy plants in terms of top twelve producers in 2014.

Apart from the above dozen of the largest plants, there are some other solar PV power plants, notably the "Catalina Solar" with an 'annual power generation' capacity of 204 million Kwh or units (MU) in a 143MW plant in California (USA), which offsets 74,000 tons of gas emission (i.e. tough standard), "Silver State" in Nevada (USA) with 122 MU (98MW plant), which involves thin-film solar farm, one in Ontario (Canada) named "Sarnia PV" with a capacity of 120 MU (97MW plant) that involves 13 lacs panels with cadmium-telluride thin-film technology. There are also three more plants in China: namely "Xitieshan PV" in Qinghai with a capacity of 164 MU (100MW plant) that was No. 1 in 2011 developed by CGN and "Ningxia Qingyang" in Ningxia with a capacity of 150 MU (100MW plant) that was developed by GCL Poly (Hong Kong), and "Gansu Jiayuguan Solar Park" also with a capacity of 150 MU (100MW plant). This is not an exhaustive list, but it is given here to show the order of magnitude of the solar PV power generation plants ultimately to have an idea on the size of the projects. This should encourage the local investors to tie up their capital that is usually required for such projects [7-9].

Several solar photovoltaic power plants around 150MW capacity or below have been built, mainly in Europe. As of July 2012, some other large photovoltaic (PV) power plants in the world are the Solarpark Meuro (Germany, 166MW), Neuhardenberg Solar Power (Germany, 145MW), Templin Solar Park (Germany, 128.5 MW), Toul-Rosieres Solar Park (France, 115MW), Perovo Solar Park (Ukraine, 106MW) developed by Active Solar (Austria), Brandenburg-Briest Solarpark (Germany, 91MW), Solarpark Finow Tower (Germany, 84.7MW), Montalto di Castro PV Power Station (Italy, 84.2 MW), Eggebek Solar Park (Germany, 83.6 MW), Senftenberg Solarpark (Germany, 82 MW), Finsterwalde Solar Park (Germany, 80.7MW), Okhotnykovo Solar Park (Ukraine, 80MW), Lopburi Solar Farm (Thailand, 73.16MW), Rovigo PV Power Plant (Italy, 72MW), and the Lieberose PV Park (Germany, 71.8MW) [9].

There are also many larger plants under construction, notably the Blythe Solar Power Project, which is a 500 MW photovoltaic station under construction in Riverside County, California (USA), and McCoy Solar Energy Project with a capacity of 750MW. There are so many others in the USA and Europe. Many of these plants are integrated with agriculture and some use innovative tracking systems that follow the Sun's daily path across the sky that is fitted with high quality sensors to generate more electricity than conventional fixed-mounted systems. There are no fuel costs or emissions during operation of the power stations, i.e. environment-friendly.

Therefore, Indian Glass Manufacturers under the aegis of AIGMF could start negotiations with the present "Central Govt" as well as "Private Equity" investors from Europe and USA to have an "integrated strategy" to finance such larger solar PV power plants. This power is not only meant for commercial and residential purposes in large metro cities, but also to produce a "very high-value vegetable items" in large "covered area" to be grown in colder climate in the Himalayan mountains or similar locations, which is of great interest to the concerned Govt. organizations. So, it is a viable strategy to ponder over and make implementation.

CONCLUSIONS

A very general perspective on the application of 'float glass' is given in terms of solar photovoltaics power plants. First, a short view has been given with data on installed capacity in MW and annual power generation in million units in a dozen of top plants; then for some other larger plants in the USA and Europe as well as in

China where a majority of activities are taking place. It is found that the application of solar PV plants for growing certain high-value items in the field of 'agriculture' in Himalayan and other similar locations could be considered important. A viable strategy for AIGMF members has been devised for a proper implementation

REFERENCES

1. A. K. Bandyopadhyay, "Technology of Float Glass Process", KANCH, 5 [3] (2012), 33-36.
2. A. K. Bandyopadhyay, "Transparency in Float Glass and some Applications", KANCH, 2 [3] (2014), 23-26.
3. J. Pearce, "Photovoltaics – A Path to Sustainable Futures", 34 [7] (2002), 663–674.
4. M. Bazilian et al., "Re-considering the Economics of Photovoltaic Power". Renewable Energy (2013), 53.
5. R. M. Swanson et al., "Photovoltaics Power Up", Science 324 [5929] (2009), 891–2.
6. K. Branker et al., (2011). "A Review of Solar Photovoltaic Levelized Cost of Electricity", Renewable and Sustainable Energy Reviews, 15 [9] (2011), 4470.
7. "Renewable Energy Policy Network for the 21st century (REN21)", Renewables 2010 Global Status Report, Paris, (2010), 1–80.
8. "Photovoltaics Report", Fraunhofer Institute for Solar Energy Systems ISE. November 7, (2013).
9. "Global Market Outlook for Photovoltaics 2014-2018", European Photovoltaic Industry Association, June 12, (2014).

E-Glass as an Important Component of Building Construction

ABSTRACT

The "float" or sheet glasses with no surface aberrations give rise to a good transparency, but they have a very high emissivity or low reflectance so that undesirable light rays with wavelength in the infrared region of the solar spectrum are not filtered through the windows. A lower emissivity can be imparted in double or triple layers of window glasses with special coatings that considerably reduce the heat losses keeping the buildings cooler in the summer months, but warmer in the winter months. While this has a strong implication in the saving of energy, it also indicates much lower carbon dioxide emission, as desired by the environmental authorities. A description of the Low-E glass is given here that is under constant research and development in this field.

INTRODUCTION

It can be easily said that our "home", like a Bird's Nest, is a fundamental necessity of human beings, and everyone wants a 'sweet home' according to his capability for his dwelling in all hues and colours. Hence, the construction of buildings and houses will continue with the progress of time, as we shall always need them. It is also known that the float or sheet glass with no surface aberrations gives rise to a good transparency, and it is one of the most important components of construction for both interior and exterior of a given residential or commercial building, particularly during the last 15-20 years [1,2]. Here, we are mainly concerned with the windows or facades that make us see the light of the day, i.e. the visibility. However, recently, there has been a surge of activity for energy saving thereby enhancing the need to keep our houses and buildings cooler in the hot summer months and warmer in the winter months. This brings us to the subject of E-glass or rather Low-E glass, i.e. the float or sheet glass coated with special materials that have specific thermal property. Glass is one of the most popular and versatile building materials used today due to the reason of its constantly improving solar and thermal performance. This is achieved through the use of passive and solar control "Low-E" coatings. Here, "E" stands for emissivity.

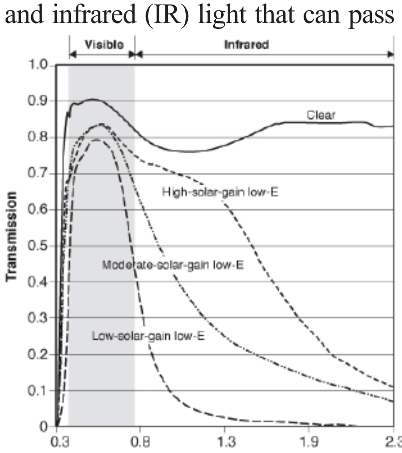
In order to have a good grasp on coatings, it's important to understand the solar energy spectrum or energy from the Sun, which are divided into three parts: (a) Ultraviolet (UV) light, (b) Visible light and (c) Infrared (IR) light. They all occupy different parts of the solar spectrum – the differences between the three are determined by their wavelengths [2]. The UV wavelength of interest is from 300 to about 400 nanometers (nm), the visible segment of the spectrum spreads between 400 to about 700 nm, and the IR wavelength starts from about 700 nm going upto about 800 nm and beyond. Solar infrared is commonly referred to as short-wave infrared energy, while heat radiating off of warm objects has higher wavelengths than the Sun, and it is referred to as long-wave infrared.

The components of solar radiation are: (a) 53% of IR component (i.e. thermal), (b) 44% of visible light (i.e. optical -- for our visibility), and (c) 3% of the UV light (energetic waves, but not visible). The latter is quite undesirable, as this has a bad effect on our skin and it also fades the colour of our dresses as well as other fabrics inside the building, such as curtains, table tops, etc. Any material (e.g. coated glass) can absorb, reflect or emit low levels of radiant (thermal) energy.

If any material absorbs the solar radiant energy in totality, then we call it a black-body. Emissivity is the value given to materials based on the ratio of heat emitted compared to a blackbody, on a scale from zero to one. A blackbody would have an emissivity of 1 and a perfect reflector would have a value of 0. Before we talk about "Low-E" glass, let us look at the transmission curve below at different wavelengths for a standard "clear" glass and those with different low-emissivity coatings are also shown to understand the spectral behaviour of Low-E glass (*Courtesy: Lawrence Berkeley National Lab, California, USA*).

WHAT IS LOW-E GLASS?

Low-E coatings have been developed to minimize the amount of ultraviolet (UV) and infrared (IR) light that can pass through glass without compromising the amount of visible light that is transmitted. It is clearly seen from the figure that the transmission curve of a high solar-gain E-glass has some similarity with that of a standard clear glass. Beyond visible band, the transmission starts falling quite sharply.



When heat or light energy is absorbed by glass, it is either made to get away via convection by moving air or re-radiated by the glass surface. The ability of a material to radiate energy is called its emissivity. All materials, including windows, emit (or radiate) heat in the form of long-wave (far-IR) energy depending on their temperature. This emission of radiant heat is one of the important components of heat transfer for a window. Hence, if we reduce the window's emittance or emissivity, it could greatly improve the insulating properties that drive the new surge in the manufacture and usage of E-glass in the booming building construction industry. This not only enhances our visibility but also consumes lesser energy thereby ensuring lesser carbon dioxide emission. This is good for our environment.

This is where low emissivity or Low-E coatings come into play. Low-E glass has a microscopically thin, transparent, coating that reflects long-wave infrared energy (or heat). Some Low-E's also reflect significant amounts of short-wave solar infrared energy. When the interior heat energy tries to escape to the colder outside during the winter, the low-E coating reflects the heat back to the inside thereby reducing the radiant heat loss through the glass. The reverse happens during the summer time. One simple analogy can be drawn in that low-E glass works the same way a 'thermal flask' does. A thermal flask has a silver lining, which reflects the temperature of the drink (hot tea or cold drink) back in. Thus, the temperature is maintained because of the constant reflection that occurs as well as the 'insulating benefits' that the air space provides between the inner and outer shells of the thermal flask, i.e. similar to an insulating glass unit or E-glass. Here, the same theory could be applied, since Low-E glass consists of extremely thin layers of silver or similar materials, i.e. the Low-E coating reflects the interior temperatures back inside, keeping the room warm or cold.

Low emissivity (Low-E or Low-(thermal) Emissivity) refers to a surface condition that emits low levels of radiant thermal (heat) energy. Reflectivity is inversely related to emissivity and when added together, their total should be equal to 1. Therefore, for a very well-known "reflector" material like aluminium, if it has a thermal emissivity value of 0.03, its thermal reflectance value would be 0.97. This means that it absorbs and emits only 3% of radiant thermal energy and reflects 97%. Conversely, a High-E material reflects lesser amount of solar radiation and emits relatively more of the radiation energy, i.e. a standard "float" glass.

Standard clear glass has an emittance of 0.84 over the long-wave portion of the 'solar energy' spectrum, meaning that it emits 84% of the energy possible for an object at its temperature. It also means that 84% of the long-wave radiation striking the surface of the glass is absorbed and only 16% is reflected. By comparison, Low-E glass coatings can have an emittance as low as 0.04. Such glazing would emit only 4% of the energy possible at its temperature, and thus reflects 96% of the incident long-wave (IR) radiation. The manufacturers of low E-glass windows give product information that does not list "emittance ratings". The effect of the Low-E coating is rather incorporated into the U-factor for the unit or glazing assembly.

The 'solar reflectance' of Low-E coatings can be manipulated to include specific parts of the visible and infrared spectrum. If the visible part is permitted, we get good (or enough) visibility, and if certain portion of IR band is also allowed, then such a combination becomes the genesis of the term 'spectrally selective coatings'. This ensures the desirable wavelengths of energy that has to be transmitted and others specifically reflected. A glazing material can then be designed to optimize 'energy flows' for solar heating, day-lighting and cooling [3]. This could be also considered as an 'energy issue' combining the power of solar energy as well as the novelty of "float" glass to drive the technology of E-glass.

So, an uncoated smooth glass, e.g. window glass, has a very high emissivity value of 0.84 meaning thereby only 16% is reflected; incidentally, silver that is a good coating material has an emissivity value of 0.02. This brings us to the subject of coating 'glass surface' that has substantially lower emissivity so that we could achieve a proper thermal property, which is very much a necessity for a proper building design. Apart from window glass manufactured with metal-oxide coatings, the components of 'low-emissivity building' include other materials as well, such as house-wrap materials, reflective thermal insulations and other forms of radiant thermal barriers. All materials absorb, reflect and emit radiant energy, but here, the primary concern is a special wavelength interval of radiant energy, namely thermal radiation of materials with temperature in the range of 40 to 60^0C. Next, let us briefly look at different methods of coating, before we embark on the performance of E-glass.

DIFFERENT METHODS FOR E-GLASS

As said above, 'window glass' is by nature highly thermally emissive. So, to reduce its emissivity eventually to improve the thermal efficiency (i.e. insulation properties), thin film coatings are applied to the raw soda-lime-silica glass or "float" glass. There are two primary methods in use [4, 5]:

1) Pyrolytic Chemical Vapour Deposition (CVD), and
2) Magnetic Sputtering

Specially designed coatings are applied to one or more surfaces of insulated glass. These coatings reflect radiant infrared (IR) energy, thus tending to keep radiant heat on the side of the glass where it originated, while letting the visible light pass through the window glass to the interior of the building. This results in more efficient windows, because radiant heat originating from indoors is reflected back inside -- making the building warmer in the winter, while infrared heat radiation from the Sun is reflected away -- keeping it cooler inside during the summer months. The latter is more useful in the context of Indian situation.

A) Pyrolytic Coatings

Actually, among two different types of Low-E coatings, i.e. "passive" Low-E coatings and "solar control" Low-E coatings, the former is manufactured using the pyrolytic process. The coating is applied to the glass ribbon while it is being produced on the 'float line'. The coating then "fuses" onto the hot glass surface, creating a strong bond, or a "hard-coat" that is very durable during fabrication. For very cold climates, particularly in the winter months, the passive Low-E coatings are good → as they allow some of the Sun's short-wave IR energy to pass through, which helps in heating the building during the winter, but they still reflect the interior long-wave heat energy back inside.

The pyrolytic method involves deposition of fluorinated tin oxide (SnO2: F) at high temperatures. A typical pyrolytic coating is a metallic oxide (most commonly tin oxide with some additives), which is bonded to the glass while it is in a semi-molten state. The process by which the coating is applied to the glass surface is called "chemical vapour deposition" or CVD, which is extensively used in the field of 'coating technology'. This technique gives rise to a "baked-on surface layer" that is quite hard and thus very durable. This is the reason why pyrolytic Low-E coating is sometimes referred to as "hard-coat Low-E". A pyrolytic coating can be ten to twenty times thicker than a sputtered coating, but it is still extremely thin. These coatings can be exposed to air and cleaned with traditional glass cleaning products and techniques without damaging the coating.

Due to their inherent chemical and mechanical durability, pyrolytic coatings may be used in monolithic applications, subject to manufacturers' approval. They are also used in multi-layer window systems, where there is air flow between the two glazed surfaces as well as with non-sealed glazed units. It can be generally said that pyrolytic Low-E coating is most commonly used in sealed insulating glass units with the Low-E surface that is facing the sealed 'air space'.

B) Sputtered Coating

The 'solar control' Low-E coatings are manufactured using this process – the coating is applied off-line to pre-cut glass in a vacuum chamber at room temperature. The method involves deposition of thin silver layers with anti-reflection layers. Sputtered coatings are multilayered (5 to 10 layers) coatings that typically consists of metals, metal oxides, and metal nitrides. These materials are deposited onto the glass or plastic film in a vacuum chamber with multiple deposition chambers in a process called "physical vapour deposition". Although these coatings range from five to possibly more than ten layers, the total thickness of a sputtered coating is significantly less than the thickness of a human hair. Sputtered coatings often use more than one layer of silver to achieve their 'heat reflecting' properties. As silver is an inherently soft material that is susceptible to corrosion, the silver layer(s) must be covered by other materials that act as 'barrier layers' to minimize the effects of humidity and physical contact. In other words, silver-based films are environmentally unstable and must be enclosed in insulated glazing or an insulated glass unit (IG) to maintain their properties over time, i.e. stable.

Considering the coating quality, the sputtered coatings are described as "soft-coat Low-E", as they offered little resistance to chemical or mechanical attack. Over the past 25-30 years or so, while advances in material science and engineering have significantly improved the chemical and mechanical durability of some sputtered coatings, the glass industry continues to generically refer to sputter coated products as "soft-coat Low-E". The best performing 'solar control' coatings are ideal for mild to hot climates that are more dominated by the use of 'air-conditioning' in commercial buildings, particularly in warmer countries like India.

Most sputtered coatings are not sufficiently durable to be used in monolithic applications. However, when the coated surface is positioned facing the air space of a sealed insulating glass (IG) unit, the coating should last as long as the sealed glass unit. Sputtered coatings have emittance as low as 0.02, which are substantially lower than those for pyrolytic coatings. Therefore, this type of coating is relatively more effective in the design consideration of the buildings. Next, let us talk about certain useful 'performance parameters' for judging the quality of E-glass for buildings and some related but important aspects.

C) The Performance Parameters

After having explained the salient points about the two important methods of making E-glasses, it is quite pertinent to mention briefly about the performance parameters for E-glass. First let us start with different potential surfaces of interest. Low-E coatings are applied to the various surfaces of insulating glass (IG) units. In a standard double panel IG, there are four potential coating surfaces to which they can be applied: (a) the first surface faces outdoors, (b) the second and (c) the third surfaces face each other inside the insulating glass unit and are separated by an air-space and an insulating spacer, and finally (d) the fourth surface faces directly indoors, i.e. interior of the building.

Low-E: 1.25 cm air & 0.63 cm clear	**U-Value**	**VLT**	**SHGC**	**LSG**
Pyrolitic	0.35	64%	0.55	1.17
Sputtering (Double Silver)*	0.29	61%	0.34	1.87

**Triple-silver coating will have a better performance than double-silver coating.*

Whether a Low-E coating is considered ‘passive’ or ‘solar control’, they offer improvements in performance numbers in terms of four main parameters. To measure the effectiveness of glass with Low-E coatings, the following terms are used:

1) **U-Value** is the measure of how much ‘heat loss’ is allowed for a given window design.
2) **Visible Light Transmittance (VLT)** is a rating of how much ‘light could pass’ through a window.
3) **Solar Heat Gain Coefficient (SHGC)** is the fraction of incident solar radiation permitted through a window, i.e. both directly transmitted and that is absorbed and re-radiated inward. The lower a window’s SHGC, the less solar heat it transmits.
4) **Light to Solar Gain (LSG)** is the ratio between the window’s SHGC and its VLT rating.

The following table shows how the coatings made by different methods measure up by minimizing the amount of UV and IR light that can pass through a glass window without compromising the amount of ‘visible light’ that is transmitted:

On retro-fitting, it should be noted that Low-solar-gain “Low-E coatings” on plastic films can also be applied to existing glass as a retrofit measure, thus reducing the SHGC of an existing clear glass considerably while maintaining a high visible transmittance and lower U-factor. Many buildings at present use different “tints”, but these conventional tinted and reflective films will also reduce the SHGC but at the cost of lower visible transmittance. Reflective mirror-like metallic films that are often used in some new buildings could also decrease the U-factor, since the surface facing the room (i.e. interior) has a lower emittance than uncoated glass.

For a significant amount of solar radiation to pass through the window, conventional clear glazing is the ‘choice’, and in this case, heat from objects within the ‘interior space’ is re-radiated back into the glass → then from the glass to the outside of the window. For maximizing energy efficiency during under-heated periods, a glazing design would ideally allow the entire solar spectrum to pass through, but it would block the re-radiation of heat from the interior space. The first low-E coatings, intended mainly for residential applications, were designed to have a high SHGC and a high VLT to allow the maximum amount of Sun-light into the interior space, while reducing the U-factor significantly. A glazing designed to minimize summer heat gains, but allow for some day-lighting, would allow most visible light through, i.e. relatively higher VLT, but this design would make all other portions of the solar spectrum blocked, including UV and near-IR, as well as long-wave heat radiated from outside objects, such as pavements and adjacent buildings. These second-generation Low-E coatings still maintain a low U-factor, but are designed to reflect the solar near-IR, thus reducing the total SHGC while providing high levels of daylight transmission (i.e. higher VLT).

The beneficial solar gain is reduced by the 'Low-solar-gain' coatings that could be used to offset 'heating loads', but in most commercial buildings this is significantly outweighed by the 'solar control' benefits. It is common to apply Low-E coatings to both tinted and clear glass in many commercial buildings, Actually, the 'tint' lowers the VLT somewhat, but it contributes to 'solar heat gain' reduction and 'glare control'. Low-E coatings can be formulated to have a broad range of 'solar control' characteristics while maintaining a low U-factor.

D) Some Related Aspects

It is interesting to note that glass can be made with differing thermal emissivity, but this is not used for windows. Certain properties such as the iron content may be controlled, which changes the thermal emissivity properties of glass. This "naturally" low thermal emissivity is found in some formulations of Borosilicate or Pyrex. Naturally Low-E glass does not have the property of reflecting near-IR (NIR) /thermal radiation; instead, this type of glass has higher NIR transmission, leading to undesirable heat loss (or gain) in a building window.

Having explained different aspects of E-glass, it must be added that there is also a certain degree of criticism on the usage of E-glass. Since energy-efficient windows reflect much more Sun-light than standard glass windows, when these windows are somewhat concave they can focus Sun-light and cause damage. The damage to the sidings of homes and to automobiles has been reported in 'news stories' [6,7]. Low E-glass windows may also block radio frequency signals. Then, the buildings without distributed antenna systems may suffer degraded cell phone reception [8]. As 'smart' mobile phones are very much in use in both residential and commercial buildings that are increasing by the day in numbers, the need for further development cannot be denied.

Here, it is useful to mention about the "Reflective Thermal Insulation" (RTI). It is typically fabricated from 'aluminium foil' with a variety of core materials such as low-density polyethylene foam, polyethylene bubbles, fiber-glass, or similar materials. However, each 'core material' shows its own set of benefits and drawbacks based on its ability to provide a "thermal break", "deaden sound", "absorb moisture", and finally "resist combustion" during a fire break-out. When we use 'aluminium foil' as the 'front material', the RTI can stop 97% of radiant heat transfer. Recently, some RTI manufacturers have switched to a "metalized polyethylene" as 'front material'. The long-term efficiency and durability of such facings are still not properly understood, and hence, there is a need for further development.

Further, the RTI can be installed in a variety of applications and locations including residential, agricultural, commercial, and industrial structures. Some common installations include house wraps, duct wraps, pipe wraps, under radiant floors, inside wall cavities, roof systems, attic systems and crawl spaces. Also, the RTI can be used as a stand-alone product in many other applications, but it can be used in 'combination systems' with mass insulation as well, where higher value of the reflectance is required.

CONCLUSIONS

As the building industry expands in terms of both volume and quality, there is an urge for energy saving as well as for smart buildings with the use of E-glass windows that are capable of reflecting undesirable wavelengths of the solar spectrum, while making the visible solar spectrum to enter into the interior space of the building. This gives us enough visibility and also more saving of electrical energy, which is good for the environment. It is needed in both residential and commercial segments, where its usage surely makes the value-addition meaningful. The definition of E-glass has been given in details. The methods of preparation have been briefly described with their benefits and drawbacks as well as in terms of performance parameters that should guide the user industry to select the right type of E-glass for the building industry. Some other related issues have also been discussed. There is a scope of not only expanding the market for the glass industry, but also there are immense possibilities of tailor-making thereby improving the market further.

REFERENCES

1. A. K. Bandyopadhyay, "Technology of Float Glass Process", KANCH, 5 [3] (2012), 33-36.

2. A. K. Bandyopadhyay, "Transparency in Float Glass and some Applications", KANCH, 2 [3] (2014), 23-26.

3. ASHRAE Handbook: Fundamentals – 'American Society of Heating, Refrigerating and Air-Conditioning Engineers', (IP Edition, Atlanta), 2009.

4. R. Hill, "Coated Glass Applications and Markets", Fairfield, CA: BOC Coating Technology, (1999), 1–4.

5. J. Carmody et al., "Residential Windows: A Guide to New Technologies and Energy Performance", 1st Ed., (Norton, New York) 1996.

6. S. Wornick, WCVB, 6 July, 2012.

7. R. Paige, CBS, Los Angeles, 25 January, 2012.

8. T. Ford, RCR Wireless News, 23 June, 2011.

Glass Safety and Environmental Protection for Building Construction and: Proceedings of AIGMF and CCPS Joint Conference

ABSTRACT

Safety in the field of construction industry in terms of glass usage, particularly for the application in the glass windows and facades, is increasingly becoming very important. In the absence of a comprehensive law or regulation, the compliance is simply ruled out giving rise to several accidents in different parts of the country. A thought process or planning has started in some places, which is a good sign. Moreover, the glass industry as it is wrongly blamed for some sort of ineffectiveness in the overall coordination process also wake up to the reality and start effective communications with different groups of concerned people that finally gave rise to an unique two-day 'interactive conference' organized by AIGMF in Mumbai in March 2015. This gave us a lot of insights into the subject of safety of building in general, and of glass in particular. A short description is given here in the Part-I of this article.

INTRODUCTION

Environment is a nice but very common word now-a-days, and its protection assumes more significance that is also quite fashionable in several discussions at present, particularly when people are discussing about environment in terms of various disastrous incidents, which also brings us to the subject of safety. Generally, when we talk about environment, we normally tend to use certain terminology, such as general pollution, carbon emission, etc., which are threatening the existence of our planet. It is too simplistic that glass industry is often put on the block, whereas the basic tenets are concerned with the emission of carbonaceous gases that cause harm to the earth's atmosphere. A new word called 'climate change' has been recently coined within the realm of this subject and a lot of activities have already started. Moreover, the strong defence in favour of glass industry is that glasses are increasingly used as 'solar panels' for renewable energy [1] that cuts down on emission problem (i.e. environmental protection) as well as the application of glass sheets or float glass, as windows or facades with special coatings, involves low emissivity glasses (i.e. E-glass) [2] that also cuts down on the use of energy in a residential or commercial building thereby reducing the overall carbon emission.

On the above counts, the float glass can be considered not only as the important material for building construction industry, but also can be viewed as energy-friendly or rather environment-friendly. In this regard, technological efforts have been made to a great extent to make this noble objective successful. There is a strong debate that despite the significantly positive contribution of float glass towards the environment, its application, mainly for windows, facades etc., is still a matter of concern to all the stakeholders, such as Building Sanctioning or Municipal Authorities including Fire Brigade, a host of Architects and Civil/Structural Engineers, Construction Companies and finally the Residents/Users of these buildings. This brings us to the actual context of "glass safety" or shall we say that the contextual meaning encompasses (a) various dangers posed by broken glass, (b) the space constraint for evacuation of people when the buildings catch fire, (c) sufficient space for movement within the building even during normal condition, etc.

Therefore, the above fits into the right description of "glass safety". As the experts say that the "building is beautiful" with nice but colourful pieces of glass windows and facades, but it cannot be a necessary or, only condition in this respect. It has to be ensured that the people living or using it for official duty in such new high-rise buildings are safe. So, here we are mainly concerned with "People Safety", apart from "Building Safety". In other words, from the concept to actual design stage itself, the predominant thoughts in our mind should be directed towards "safety", and then we should look for the beautification aspect without compromising on "safety' of a given building. In this scenario, it would not be difficult to get the necessary 'sanction' from the concerned authorities. As there is a financial aspect to this effort in terms of optimizing the "floor to space ratio" (FSR), some adjustments and re-adjustments are definitely possible in the realm of confederation of the interested parties, or rather when we take everyone on board. However, caution should be exercised in that the architects must not go overboard on such issues of safety nor it is expected that the builders will always think of optimizing FSR. This will obviously make the 'conflict resolution' more difficult. So, there is a need for fresh and fair discussion after presentation of the facts and figures.

In this regard, after a long 'thought process', AIGMF decided to sincerely collaborate with the Confederation of Construction Products and Services (CCPS) to organize a two-day seminar in Mumbai in connection with the bi-annual event of

Glasspex-India-2015 in March. This was done in Mumbai to be able to attract many interested companies and people due to the large number of construction projects in and around this great metropolis, apart from attracting many National and International visitors to Glasspex-India's gala exhibition, which is normally very well attended by a larger audience. As a representative of the glass industry, AIGMF rightly showed its great concern to this problem of safety and even wanted to continue such seminars in the near future in other large cities in India, where there is also growing activity of construction projects.

ROLE OF DIFFERENT BODIES

For the construction industry, glass is a very important material. Therefore, AIGMF on behalf of the manufacturers of sheet or float glass wanted to organize such a conference on "glass safety' to be able to interact with various people or groups connected with the construction industry, such as (a) Statutory Authorities: Central Govt. Experts from CPWD, Construction/Structural Engineers in Municipal Bodies, Fire Brigade for discussing fire safety norms that also involves an 'awareness programme', etc. and (b) Architects for design considerations, Safety Equipment Suppliers connected with the construction industry, etc. Secondly, another objective was to create a "collaborative environment" for the betterment of the industry. Obviously, there is a clear-cut goal of selling a higher volume of float glass which is produced more or less optimally in the country. If in a bad patch of economic scenario (as prevalent during the last so many years), the glass sales are already down, then it is our ardent duty to see that it does not get further bogged down by so many safety regulations and norms that are not really necessary. Hence, AIGMF must listen to all concerned. It is a kind of 'rectification' efforts on our part to be able to serve our customers better in the future without compromising on the 'glass safety'.

For the above goals, AIGMF could not find a better partner or collaborator than "Confederation of Construction Products & Services" (CCPS) to jointly sponsor such an 'interactive conference'. Moreover, for a long time, CCPS has been engaged in creating a basis for formulating regulations and norms for the ultimate safety of our buildings in consultation with not only Govt. Officials at Delhi and/or local bodies like Municipalities, but also with a large number of Architects, Suppliers and Builders **[3]**. CCPS made all the necessary efforts to bring this larger audience into one platform and finally helped AIGMF to organize such a conference with the aim that "we must talk". Obviously, this effort is also a sincere attempt to remove all the inhibitions and technical prejudices that create a sort of "wall" between glass producers and all the concerned people and their organizations.

THE CONFERENCE

The title of the conference was divided into two parts with the first part on "Cost Effective Technology in Container Glass for Tomorrow", where important lectures were delivered by mainly International Experts (almost 8 of them) who were present in Mumbai for Glasspex-India [4]. Although there were heavy doses of technological aspects involved in these presentations, some of the sub-topics could definitely be considered important for the float glass, as they were concerned with either furnace operations and/or batch handling. This was a pre-lunch session on 13th March (Friday). There was a very short question-answer session after all the presentations that were duly moderated by the present author as well as by Prof. Devendra Kumar of Dept. of Ceramic Engineering from IIT, Varanasi.

After lunch, the main focus of this two-day conference was directed towards the special session on the "Use of Glass in Building--Facades of the Future" as well as on the "Need for Regulations relating to Human Impact, Fire Safety and Energy". Both were clubbed together for obvious reasons. For the Welcome Address, on behalf of AIGMF, (a) the President (Mr. Sanjay Ganjoo) stood up to welcome the guests and participants, and also gave a very interesting lecture to create the basis for the whole conference, where he clearly mentioned about the role of float glass and our expectations from the concerned people in various segments of the construction industry. Then, there was a very good presentation from (b) Asahi India (Mr. Somasundaram Senthil Kumar) on "Modern Trends in Glass Facades to achieve Sustainability". This sustainability aspect is very important as we design a new building with the changed concepts with an eye on 'fire safety'. Moreover, we should also look for any other 'quality norm' that has to be sustainable in the long run, or rather there should be some sort of continuity, as the whole process is evolutionary in nature. This presentation did precisely meet this objective.

The next presentation was by: (c) Gold Plus (Mr. Vivek Dubey) on "Glass Selection Factors". This was important as we clearly know them as the most relevant factors, since it is easier to create 'inputs' for better design. Then, a very general lecture was given by: (d) Gujarat Guardian Ltd. (Mr. Sanjiv Srivastav) on the "Use of Glass in

Buildings" in which various aspects of the use of different types of glasses in building construction was presented from a 'glass producer' perspectives. After the Tea-break, there was a good presentation from (e) Dow Corning India (Mr. S. Ravishankar) on the "Role of Sealants in Structural Glazing and Fire Seals". This was very much interesting indeed as we seem to forget the role of sealants and often consider them trivial in the overall process of fitting and fixing glass windows and facades in a given building. After a brief introduction of Dow Corning in USA (a giant multinational organization) that is deeply involved in a massive R & D effort, the presenter showed how special sealants could help us in fixing certain dimensions of the glass piece, as those 'sealants' were very stable and durable in the long run.

The next item for presentation gave a 'mechanical twist' to the whole subject of fittings and fixtures for windows and facades. This was presented by a relatively newer company in Indian construction scenario: (f) LGF Sysmac India Pvt. Ltd. (Mr. Deepak Chug), who showed not only different mechanical design, but also the modality of fixing the system with 'float glass' pieces of various sizes that additionally mentioned about various advantages so far the safety is concerned. At this point, a very interesting but academically stimulating presentation was made by: (g) Prof. Devendra Kumar (I.I.T., Banaras Hindu University, Varanasi) on "Industry-Academia Interactions for Glasses: National Perspective". This was a very elaborate presentation by a learned Professor in the field, although it had to be cut short due to the lack of time. Such presentations might invoke fresh thoughts for collaboration in the future not only for glass production but also in the field of environmental security and safety.

Then, there was a "panel discussion", chaired by myself, on the entire 'afternoon proceedings' being summarized on behalf of AIGMF, and many people seriously participated to give a new dimension to this discussion almost at the end of the day **[4]**. The conclusion was obvious that the safety of a building is of utmost concern to all. This created a good basis for the presentation of the next day.

On the next day on 14^{th} March, the inaugural morning session started with Session-1 on "Façade: Future, Emerging Directions & Challenges". This was done with a welcome address by the President of AIGMF to the audience that was slightly but relatively more tilted towards the participation of Govt. authorities and Fire Brigade personnel. This was done in the presence of the Chief Guest of the session: Mr. Sunil H. Nesarikar (Chief Fire Officer, Mumbai Fire Brigade) and the Guest of Honour, Mr. Kamal Preet Singh (Special Director General, CPWD). To keep up with the tone of the conference, the first inaugural talk was given by: (a) Mr. Nesarikar, who gave a brilliant lecture on 'Fire Safety' and different actions taken up by his department in removing the 'bottlenecks' for not only combating fire menace in the existing buildings but also suggested many ways by which we could avoid such accidents in both the existing and new buildings.

From this point onwards, the Architects dominated the conference scenario that was started by a powerful environment activist: (b) Archinova Environ (Ms Poonam V. Mescarenhas). This topic was on "Facades of the Future", which was forcefully presented to prove how we should be combating a battle against the environmental degradation without any regards to the beautification plan, as normally practiced by the standard Architects for the use of float glass. She even showed a futuristic type of small building design with trees on the balcony of each flat on every floor. As claimed, such flats in Goa are all sold out showing the concern of certain individuals as well as the popularity of the environment protection issue. No mention was, however, made on the use of E-glass that is known to be environment-friendly due to the lower consumption of energy.

The above was followed by another forceful presentation by: (c) Façade India Testing Inc. (Mr. V. S. Ravi) on "Quality Assurance and Testing of Facades". In the evolution of human endeavours from making automobile cars (using glass to cover our head in the olden days and the front shields) toward float-glass-clad buildings, this brilliant presentation was actually meant for more practical solutions to our main problems of 'quality assurance'. This was accomplished with a special mention about his long experience in the middle-east that has witnessed a massive construction boom. Some alternative designs were also proposed, but there was no attempt to underestimate the importance of the application of 'float glass' in the buildings in the future. This was definitely praise-worthy for the manufacturers of different types of glasses.

After this great morning session charged with new ideas on "façades" that was also very much a part of this conference theme, there was a lively 'panel discussion' chaired by a very pro-active Architect in the field: Mr. Deepak Gahlowt in which a number of people was involved including the present author. Here, I had a chance to again highlight the importance of glass, as already done by Mr. Sanjay Ganjoo, President of AIGMF. It was also invoked that all concerned should come forward to bring a fruitful solution to the problem of 'safety' in our buildings instead of merely blaming the use of 'float glass' for the 'facades'.

In the Afternoon after Lunch, the Session-2 of the conference was devoted to the most 'important' and 'relevant' to glass as well construction industry on "Modern Facades: Regulations and Standards". It is called "important", as without any proper regulation and standard, the construction industry cannot progress and as there are a lot of accidents, the blame-game would be easier that is normally tilted towards the glass industry. Moreover, it is called "relevant", as there is more number of building projects coming up in India, and it is high time we take cognizance of the existing rules and norms as well as develop ideas for future direction. This was amply indicated in the theme of the topic of discussion for this last session.

After a brief introduction to this effect by the President of AIGMF, the first presentation was made by: (d) Façade Concept Design Group (Mr. Hasan Baig) on "LEEDs Requirements & Sustainability Management for Building Facades". This was quite informative and innovative in the sense that a lot of new designs were shown with a particular emphasis on the LEEDs requirements. This was quite new to many present in the audience. The next one was made by: (e) Meinhardt Façade Technology (I) Pvt. Ltd. (Mr. A. P. Mahesh) on "Regulations relating to Building Façade – International Perspective". This presentation was very relevant in the sense that the audience should know more about various nitty-gritty of evolving 'safety regulations' in the western countries to put the 'safety matters' straight in a proper context for our national scenario. Many pertinent examples were obviously given in this regard.

At the end of the morning session, a very important and most relevant topic was discussed on behalf of CCPS by a renowned Architect: (f) Mr. Deepak Gahlowt and later by another famous Architect from Indore: Mr. Conrad Gomes on "Glass Façade with reference to Human & Fire Safety". While Mr. Gahlowt did an in-depth analysis with a lot facts and figures to bring 'safety' into the main focus, Mr. Gomes described a tragic incident of one of his family members due to the non-compliance of norms for using and fixing glass doors in the balcony and also suggested various useful means of avoiding such incidents in the future for the benefit of all.

After the Tea-break, the Session-2 continued with a brilliant lecture by someone who has a long experience in the Govt. construction sector: (g) Central Public Works Dept. (CPWD -- Dr. K. M. Soni) with others on "CPWD Scenario of Glass Use in Mumbai". Dr Soni mainly showed the design activity of different large buildings completed or under construction by his team in CPWD in the Mumbai region, by saliently mentioning different points on 'safety measures' taken up by them in the execution of such large but impressive building projects. However, he did not mention anything against the use of 'float glass in such projects. This kind of positive approach without compromising on 'safety' was really appreciated by many people in the audience.

The exclusive details on the maintenance of 'safety' were quite noticeable in the next presentation by (h) a Scientist of Bureau of Energy Efficiency (BEE) on "Green Rating Parameters and Case Studies". There were so many details on technicality but this was quite informative when summarized. At the end of this session, there was an informative presentation by the most concerned organization on the 'safety' measures: (i) Mumbai Fire Brigade (Mr A. V. Kale) on "Ground Realities of Fire-fighting and

Adequacy of Current Codes /Standards", the title by itself was self-explanatory and coming from the Fire Brigade in the largest city of India (i.e. Mumbai), it made a lot of sense, particularly on the question of 'adequacy of the present standards and norms'.

As already done previously after each sub-session, a very lively 'panel discussion' took place by involving Mr. Hasan Baig, Dr. K. M. Soni, Mr. A. V. Kale including the present author on the (a) overall issue of 'safety', (b) various measures to be taken up for the proper implementation of the standard rules and norms, (c) glass manufacturers responsibility, and (d) dissemination of useful information though CCPS, AIGMF, etc. as well as (e) a constant interaction in the style of this present conference or even better by taking up issue by issue and discuss them thoroughly in the future in another city of importance to building construction industry. In this regards, Mr Gomes strongly suggested to both CCPS and AIGMF to organize such a two-day conference in Indore, where a booming construction activity is taking place, to be able to discuss about 'glass safety' and various important safety measures taken up by the Architects as well as the Building Construction Industry.

CONCLUSIONS

The above conference was meticulously handled by both AIGMF and its partner (CCPS) in not only formulating various topics of interest on the subject of 'building safety', but also in selecting important speakers, albeit internal resources of AIGMF could be better used for this noble purpose of dissemination of knowledge and information to all concerned. This gives us future directions on the 'safety' norms to be followed as well as on the use of 'float glass' in terms of fitting and fixing procedures to be adhered to -- by the glass experts and AIGMF together in consultation with CCPS. This has to be seriously taken up with the most well-known strategy of 'win-win' situation for the overall improvement on 'glass safety'.

REFERENCES

1. S. Das and A. K. Bandyopadhyay, "A Perspective on Renewable Energy and Solar Photovoltaic Power Plants", KANCH, Vol. 2 [4], (2015), 21-25.
2. A. K. Bandyopadhyay, "E-Glass as an Important Component in Building Construction", KANCH, Vol. 2 [4], (2015), 11-16.
3. CCPS Documents on "Human & Fire Safety requirements for Glass Wall and Façade in Building – Regulations/Norms", 2015.
4. Lectures and Panel Discussions at the 2–day Conference on "Glass-Safety" during Glasspex-India-2015 in March at Mumbai www.aigmf.com/past-events.php#27

Key to Enhance Glass Yield in a Tank Furnace

ABSTRACT

The subject of 'glass yield' in a tank furnace has been well studied for the last 30-40 years. It is still being studied to improve the quality as well as the productivity in a glass plant with particular reference to a glass tank furnace. Although, an exhaustive treatment cannot be given here, a short description is presented in this article on different aspects of a tank furnace along with a brief discussion on the management's perception on this important subject as well as the dimensionality of different parts of the tank furnace that has some effect on the glass yield.

INTRODUCTION

In the last several issues of KANCH, different production processes for special glasses as well as float and container glasses have been discussed [1-4]. The issues related to the heat-transfer and mass-transfer within a tank furnace was also discussed in terms of their interaction, and also the specific role of viscosity elaborated [5-7]. Before we talk about glass yield in a tank furnace, there are various aspects of design and operation that is important to realize. Many people believe that melting different batches and refining the molten glass are enough to understand the production process or operation in a glass plant. It is not possible here to give a detailed lay-out of a tank furnace and then describe the required design considerations and every little operational part that occur within it. Some of the important features can be described or, with little elaboration, an attention can be drawn of the concerned people who are involved in the furnace operation process. Normally, yield of commercial glass production varies a lot. The target of management always remains to enhance and stabilize the yield. To have a proper appreciation of this point, it is important to understand the role of different people who are concerned with the glass yield and its improvement in a tank furnace.

It is generally said that a properly designed Glass Tank Furnace can give rise to good yield. Now, the design of a tank furnace is not a job of the people who are involved in the operation, it is done by expert designers backed by some consultants, who are also good in operation management on many instances. Even for 'problem solving processes' during operation, it is always better to rely on such consultants, as the operation personnel are too busy in day-to-day matters concerning the overall production process. However, it cannot be denied that the shop-floor personnel are equally important to keep it at the right place.

The key to success in this aspect is to make the history of total mass of molten glass same. The management has to ensure that every part of a glass product (sheet, container, etc.) should pass through similar processes. In such case, the entire parts of the glass will have similar properties. Thus, the loss due to non-homogeneity will be minimized. The glass forming/shaping will also become much easier so that in a continuous operation, the speed of production can be maintained. Here is a case in point where some audit of the system is necessary for better implementation of the operational process.

MANAGEMENT VIEWS AND SOME SOLUTIONS

The views of the management personnel running a glass plant in terms of quality and productivity are both very important. When the market demand for a given glass product is very high, there is a tremendous pressure on the management to meet up the demand. In particular, if the tank furnace is very new at this point of time, the situation can sometimes go out of hand, as the furnace is not fully stabilized. Nevertheless, along with certain problems, some solutions are given together to draw attention of all concerned about the need of a consultant. In this respect, the following points to ponder:

~ The molten glass flowing at spout/discharge end must be kept (more or less) constant. In many glass production units, the molten glass production varies a lot in consecutive days, or sometimes within the same day in different ‘shifts’ due to some exigency. This kind of fluctuation is not normally desirable, but tolerated by some operational people as the available options are limited. As a matter of fact, a daily variation of more than 9-10% can create a lot of problems. Obviously, the management has to cope up with varying market demand. However, the molten glass consumption (by forming machines) must not vary on a daily basis.

~ Job changes in a ‘forming machine’ and preventive maintenances must be properly planned, that is normally practiced in most of the ISO or similarly-certified glass plants. This information should be conveyed to the glass furnace personnel beforehand so that they can take actions to keep molten glass flow almost at a constant level that is desirable, as mentioned above.

~ Sometimes unnoticed changes occur in the ‘fore-hearth’ temperature settings. This results in the change of ‘gob weight’ that would affect the dimension of the glass product, e.g. thickness of a glass bottle. Thus, the glass flow rate also changes. This has got to do with the temperature-viscosity relation that was described in previous issues of KANCH [5,6]. If the temperature decreases, the viscosity increases due to the decreasing exponential relation of 'logarithm of viscosity' with temperature. Then, the fluidity of the (input) molten glass to the 'forming machine' will be lower making it difficult to be formed. Consequently, it raises the rejection rate and also the quality of the container glass product will be lower.

~ For glass yield, the correct measurement of the 'level' of molten glass is very important in order to have a smooth input batch flow through 'feeder channels' that is automatically controlled by PID controllers. Control of molten 'glass level' by means of 'electrode system' is thus significant factor. When molten glass level at the melting zone fluctuates so much that it can be visually detected, and in such case, it will add some melting problems. The glass level indicator system has a direct connection with the batch feeder system or 'chargers'. As the level goes down, more of batchers are required in the pre-melting zone and vice-verse. This is a kind of 'balanced situation' that must be respected.

~ The Batch House plays a big role to make the required glass quality. The activities of the Batch House should be taken care with professional supervision. Thus, many problems can be solved; or rather the batch system is stabilized so that the amount of batch input going into the tank furnace is considered to be optimum.

~ There are two types of refractory in a tank furnace. One type is in constant touch with the molten glass, albeit at various temperature levels depending on different zones of the tank furnace, the others such as the 'roof' and certain portion of the walls are not in touch with the molten glass. In the former type of refractory, as the furnace life is prolonged, it is possible some parts are being eroded or corroded. One has to be careful about the worn-out refractory, as this will cause glass defects. It has to be seriously taken care of.

~ Finally, it is quite important to say that a glass tank furnace must be backed-up with laboratory to do an elaborate study of the whole system. As a majority of the good glass plants do such a study, it is only a small reminder that 'glass pathology' always helps to take timely decisions.

Apart from the above points, the management should make tailor-made designs by qualified and experienced Glass Consultants to get a breakthrough in this field. It is also important for any management to decide on the thin-line between the specific roles of a glass consultant with a direct operation man. This will pave the way and shape our future glass industry in terms of productivity and also quality.

SPECIFIC YIELD AS A PRODUCTION INDEX OF A TANK FURNACE

The question of a method for calculating the 'specific yield' of a glass as a production index of a tank furnace is worth considering. The 'specific yield' of a glass characterizes the working intensity of the tank furnace. According to this factor, the planned output is established, and also together with a 'utilization coefficient' as the processing of 'prepared glass' before the machine. The value of specific yield serves as a basis for comparing the following:

a) Schedules of Construction,

b) Actual Construction of a Working Furnace,

c) Select useful Constructional Changes, and also

d) Determination of the Furnace Dimension (depending on required output).

Being a synthetic factor, for determining the furnace efficiency as a whole, this parameter to a greater degree should express the "dynamics" of the processes that take place in different zones of the furnace. Otherwise, evaluating the performance of the furnace is determined by its construction, where many mistakes are made and many errors occur in terms of deviation from the design parameters and dimensionality. Such errors are sometimes unavoidable. For example, as at present, if we typify the output and efficiency of a tank furnace, say for a plate glass, by specific yield from the total area of the tank furnace. This is what we mostly do, but this might not be a correct step, as shown later. This parameter is erroneous as it does not reflect either technological or heating behaviour of a glass tank furnace [8].

On the question of dimensionality of the tank furnace, first of all, let us talk about the 'Dog House'. Its width in a flat glass plant should be 65-75% of the width of the melting end. The corresponding 'Active Charger Front' is determined by the total width of all the 'chargers' as 45-65% of the melting tank. The specific yield of the glass is measured by the daily output of the furnace with the furnace area as a whole or in certain specific furnace parts, where certain processes are taking place, for example, pre-melting, melting, refining, cooling, etc. Investigations show that melting of the batch, initial fining of the freshly melted glass, and its homogenization takes places mainly in the 'melter' part of the furnace in the limits of 'loading chamber' to the "quell point", i.e. the maximum temperature of the glass. For clarity, it is necessary to define the 'melter' as understood to be a part of the tank furnace, wherein the surface is covered by the batch and the foam (arising out of different raw materials).

In the maximum temperature region, the glass flows in two opposite directions to the overflowing side and to the conditioning side simultaneously fining, i.e. getting rid of the gaseous inclusions from the melt. This process proceeds in a considerable part of the "mirror area" on both sides of the 'quell point' area constituting the 'fining zone' of the furnace.

Beyond the 'quell point' starts the 'cooling zone', since at this point of the furnace with the completion of the refining process, the cooling process occurs and the glass is becoming ready for the working process. Here again, the knowledge on the viscosity temperature relation is important. Whenever we talk about cooling, i.e. temperature decreasing, we have to understand that the fluidity is also decreasing so that fully 'low viscosity molten glass' now transforms itself to a more workable 'viscous mass' that is ready to be introduced into, say, the IS machine for container glasses or other shape-building machines. In a plate-glass plant, the cooling of the glass takes place in the 'unheated portion' of the equipment, i.e. collars and channels of the conditioner.

The dimension of each of the above zones and consequently the magnitude of the 'glass yield' from these parts will depend on various factors that occur simultaneously. Thus, the extent of the melting zone is determined by the following:

a) Tank's Output,

b) Temperature of the Flame Region over the Batch and Foam, and

c) Temperature of the Glass under them.

There are also other factors. Apart from the composition of the batch, i.e. the amount of soda ash, sulphate, reducing agent and the melting accelerators, having an effect on it, the other important points can be described as follows:

a) Ratio of the Batch to Cullet,

b) Composition and Pressure of the Glass in the Tank Furnace, and

c) Capacity of the Overflow Cycle of the Convection Current.

For somebody with bookish knowledge about glass technology, the "batch:cullet" ratio is more or less considered to be 3:1. However, on a sudden visit to a glass plant, it will be sometimes evident that this important ratio that determines the quality of the glass product as well as furnace operation is actually much less – going down to 2:1 or even less. The opposite is true, when there is an acute shortage of cullet, as it consists of both 'internal generation' and 'external sourcing' (keeping the effort of maintaining the 'required composition' almost intact). Obviously, the total production on such a day takes a heavy beating, as 'good glass products' have to be broken to increase the 'internal generation' of cullet. This is a standard practice on a dull day in a given glass plant.

At this stage, it is important to define the 'fining zone'. This part depends on the batch and glass compositions, and to a large degree, it also depends on the temperature of the 'flame region' and of the glass in the 'melting zone'. The greater it is, the lower is the indicated temperature. Moreover, due to a change in the suppliers of raw-materials or their origin of provenance, the melt behaviour could obviously change -- sometimes in a little bit erratic way. In such a case, the length of the fining zone may either shorten or elongate. These are considerations that are either specified by the supplier/designer of the furnace system (or, even suppliers of temperature controllers) or by trial and error system of managing glass production that is mostly backed by a consultant. As said earlier, the people in the operation cannot be pushed too much as their activities are quite intensive, and it is thus preferable to take the help of a consultant. After going through the rigorous process of running the furnace for a few years, this knowledge of doing micro-adjustment (i.e. micro-management to a general degree) becomes also a 'normal habit' or rather a part of the 'daily life' in a typical glass plant.

Moreover, the dimension of the 'fining zone' depends on the capacity of gas-saturation, and also on the temperature and velocity of surface currents of the glass that is moving towards the conditioning side of the furnace. The velocity of the conditioning cycle of the currents is quite important. In its turn, the velocity is determined by the obstacles of the glass, and by the rate of cooling, i.e. by the nature of the cooling temperature of the structure of the upper tank in the portion of the hot point to the end of the heated part of the tank furnace. It should be noted that apart from the composition of the gaseous atmosphere, its pressure at the 'mirror point' level also affects the extent of the 'fining zone'. It has to be remembered that the 'negative pressure' in the 'wedge' level gives rise to the 'inflow' of air into the furnace and thereby cooling the upper layer of the glass. This could change the composition of the gas over the 'mirror point' level.

For a discussion on the 'cooling zone', it has to be noted that near or far from the loading end of the furnace, all melting processes are completed in the heated part of the melting zone of the tank furnace. Theoretically, the cooling should occur in the cooler zone. The required area of this zone is mainly determined by the capacity of the conditioning cycle that mainly depends on the design of the 'cooling tank' and the 'obstacle' in the way of currents (convection). The smaller is this area, the less is the cross-section of the cooler, i.e. the lesser is the width of the neck to a greater degree to a lesser depth.

In the way of convection currents, there are glass 'obstacles' that normally intensify the 'rate of cooling'. It is done by separating the conditioning cycle of the convection currents. This process leads to the mixing of the glass to the direct current, which passes through them at the slower rate with 'cold returning glass' often rising to the surface beyond the obstacle. Moreover, in this case, the fall in temperature directly depends on the depth of the immersion of the 'boundary floats' or rather the height of the baffle. An investigation of the behaviour of the cooling part of the tank furnaces showed that in the 'direct-feeding' machine channels, the glass is cooled twice as rapidly as in the throat, e.g. the drop in temperature in the channel is 14-17C per meter length instead of

5-7C in the throat. The cross-sectional dimensions of the channels exert a much larger effect on the 'rate of cooling' than the degree of insulation of their structure.

Finally, the issue of heat-transfer in a tank furnace can be briefly discussed, as detailed in the previous articles in KANCH [5,6]. Using different data on the heat transfer rate and the results of the studies of heat-flow through the tank wall, it is possible to calculate what amount of the total heat-input to the tank furnace comprises of the total loss with the cooling of the walls.

For this purpose, two courses of fireclay or other blocks should be considered and heat-input is taken as 100,000 kcal/m^2, the glass temperature to be 1300C (basis=specific water cooling or evaporation) with the wall thickness to be 25 to 400 mm. Even with a thin wall thickness of 25-35 mm, when the temperature of the internal surface is so low that a type of 'erosion' ceases to occur, the heat losses during cooling of the walls do not exceed 5-15% for the majority of the furnaces. For very small furnaces – the loss consists of 25-35% of the value of the 'heat-input'.

An increase of the heat-input of the tank furnace by 10-15%, necessary for the compensation of the heat loss with tank cooling and to maintain the required furnace output, is possible by increasing the "luminosity" of the flame or by somewhat increase in the flame's temperature – bearing in mind, at present, the structure of the upper part of the tank furnace limits the service period less than the tank. It should be considered that with the water cooling, the 'campaign period' sharply increases and hence increases the annual output of the furnace.

This does not analyze the 'effect of cooling' the blocks on the 'intensity' of the 'convection currents' near the walls on which to some extent the 'erosion' process depends. Therefore, the "trials" are necessary to prove the "viability" of intensifying the cooling of the blocks. These should be carried out with the use of "evaporative" cooling of the walls, and based on the results of such trials, a proper equipment should be designed.

CONCLUSIONS

A glimpse of 'glass yield' is given here with special reference to management's perception on productivity and quality. Different aspects and important issues are discussed in terms of various possible solutions. For 'specific yield' of a glass tank furnace, different aspects of furnace design are considered in terms of construction matters and how they could affect the yield. The dimensionality of different parts of the tank furnace and their limitations are elaborated in terms of different processes involved in pre-melting, melting, refining and cooling zones within a tank furnace.

ACKNOWLEDGEMENTS

I would like to thank Dr. Santanu Das, Dept. of Materials Science & Engineering at the University of North Texas, Denton (USA), for many valuable comments.

REFERENCES

1. A. K. Bandyopadhyay, "Technology of Float Glass Process", KANCH, Vol. 5 [3] (2012), 33.
2. J. Zarzycki, "Les Verres et l'Etat Vitreux", Mason, Paris, (1982).
3. A. K. Bandyopadhyay, "Nano Materials", Tunbridge Wells, UK (2010).
4. A. K. Bandyopadhyay, KANCH, Vol. 6 [1], (2012), 31.
5. A. K. Bandyopadhyay, KANCH, Vol. 1 [4], (2014), 31.
6. A. K. Bandyopadhyay, KANCH, Vol. 1 [4], (2014), 49.
7. A. K. Bandyopadhyay, KANCH, Vol. 2 [1], (2014), 39.
8. K. K. Vilnis, V. V. Pollyak and V. S. Pavlov, Stkl. Ceramica, Vol. 17 [3], (1967), 9.

Glass Manufacturing - Part I: Heat Transfer Process in Glass Tank Furnace

ABSTRACT

In the glass manufacturing process there are various features that are also dependent on the type of glass and the manufacturing method. This is already known to all concerned in the glass industry. Many people make glasses without going deeper into the subject. However, some important aspects in the manufacture of glasses are very important and they mainly pertain to theoretical understanding of different processes involved in making the glass. These aspects are heat-transfer and fluid flow, particularly the interaction between them is very important to study. In this article, only the heat transfer process in the glass tank furnace is taken up in terms of different issues involved and the second part will deal with heat transfer in the glass fabrication, while fluid flow is also very interesting subject that will be dealt with in the future publications.

INTRODUCTION

First of all, it should be emphasized that there is a significant difference between ceramics and glass products manufacturing. The oxide and non-oxide ceramics in powder form (mixed with little or no water to make dry/moist solid or liquid) are fabricated by various manufacturing techniques for a variety of shapes and sizes, and then dried to remove the water (if any) and fired to impart strength so that they can be handled for other supplementary manufacturing process/es. Eventually, apart from customer appeal, they must be mechanically stronger for handling during their usage. However, for glass manufacturing, mainly oxides, carbonates, nitrates, etc., are homogeneously mixed and then directly fired or rather melted in a typical tank furnace at very high temperature depending on the glass composition, viscosity, etc. In any manufacturing process, two types of system are possible. Either it is a batch type, e.g. optical glasses melted in a pot (about 1 to 1.5 ton capacity) to maintain high level of homogeneity, and also special types of glasses [1,2] - or, it is a continuous process of manufacture [3,4], e.g. float glass, container glass, glass fibre etc. For continuous operation, right from the mixing stage of different raw materials, feeding, melting, refining and then fabrication of various types of glasses - different processes are operative, e.g. heat transfer inside the glass tank furnace, heat-transfer in the glass fabrication and fluid flow, etc.

Recently, there has been a massive development in the field of "materials science" or "materials technology" for developing newer class of materials and newer types of techniques that involves the study of this technology more extensively. This has a possibility of overlooking the existence of such large materials manufacturing industries, i.e. glasses, that have been developed over so many years and they involve (a) large capital investment, (b) employment of a large number of people, (c) millions of tons of materials, etc. A proper understanding of the 'physical principles' of different processes used in the glass manufacturing industry is clearly needed. Needless to say, the mechanization of the glass manufacturing processes in the late nineteenth and early twentieth century was solely achieved by trial and error method. If there were any standard booklet available for fixing the conditions in a tank furnace or in the forming machines, and about their proper synchronization, then starting a given 'glass plant' would have been much easier and less time-consuming thus reducing the total cost of the project.

As an example, about 3-5 years ago, in a given glass plant of a large industrial group, 50-55 senior engineers and technical managers were brought into India from their US and Brazilian plants to stabilize the tank furnace conditions, and even so they took about 2.5 to 3 months to do the needful. Then, more time was spent on stabilizing the fabrication conditions. The total cost must have been more than a few million US$ just for this purpose, as this plant with a larger capacity than the existing one needed about 7-8 months to be ready for production after all the installations were completed. Although such type of scenarios involve a massive management and logistics approach, but the depth of the technology knowledge and its application on the shop-floor for this type of purpose cannot be ruled out. Overall, there is a strong need of correcting many aberrations in our approach towards technology and we still need to do a lot more in careful planning and implementation. If this approach is coupled with many technological insights that are the result of intensive R & D work in different facets of glass technology. In this article, only heat-transfer problem in a glass tank furnace will be discussed in the context of glass manufacturing process.

RADIATIVE TRANSFER OF HEAT

During the last 50-60 years, there has been a series of newer interesting developments in field of glass technology, counting the small but incremental developments. One of them is a more or less adequate knowledge or clarifications on the 'role, of radiation' as a mechanism of heat-transfer process in glass. This can occur at high temperatures

(1250 - 1600C) as well at relatively lower temperatures (620 - 1100C) encountered in the different fabrication processes. Heat is transferred from one body or system to another by three different means – viz. conduction, convection and radiation. The latter is very important in relation to the other two mechanisms that depend on certain factors.

IR Absorption Study

First of all, we have to indicate the ability of glass to absorb and emit the radiation, which ultimately depends on the absorption spectrum of the concerned glass related to its chemical compositions, more particularly from infra-red (IR) absorption curves. In the IR spectra of glasses, the absorption coefficient, $\alpha(\lambda)$, considerably varies with the wavelength (λ) in µm and also with temperature of the glass inside the tank furnace. For the latter, as we cannot do the IR absorption measurement inside a glass tank furnace, different set-ups were devised to do such experiments with the glass melt in a small refractory or platinum crucibles at different temperatures. Some features need to be mentioned here. The following are the main features of the IR spectra:

a) At about 1.11 µm, there is an absorption peak that increases with decreasing temperature; this peak at 1.11 µm is ascribed to the absorption of Fe^{2+} (ferrous) ion. This means that if the furnace atmosphere is highly reducing, more of Fe^{2+} ions will be frozen in the glass that will show up in the observation of this peak. This is prevalent in window glass, which is also the case for other ‘commercial’ but colorless glasses. This peak depends on the percentage of iron oxide present as impurity in different raw materials and also upon whether the furnace atmosphere is oxidizing or reducing. For example, for very low iron content, if the furnace is operating under oxidizing condition, then almost all the iron ions will be in the Fe^{3+} (ferric) state, and it will impart a tinge of color to the melt or glass. So, for a given iron content, ultimately the concentration of Fe^{2+} ions matters to make an effective colorless glass.
b) From about 2.92 µm to 3.54 µm, there is quite a steep rise in absorption coefficient that is ascribed to the presence of OH ions. This means that however efficient one’s dryer system is in operation for drying of different raw materials, there has to be a very minute proportion of water molecules that are manifested as OH ions in the glass melt, which can be tested by IR absorption method and characterized by peaks in this range of wavelength. So, this characterization is very important in glass technology.
c) At about 4 µm, there is again a rapid rise that is due to stretching vibration of -Si-O-Si- bonds present in the glass network formation. This strong absorption indicates the strength of network formation and hence good structure with mechanical strength. It should be pointed out that some glasses are coloured with a small addition of

transition metal oxides. This is intentionally done for having colored window glasses, and these colouring additions have a significant effect on the radiative heat transfer in the hot glass. This also depends on how the IR absorption spectra are affected by such additions. However, the effect of temperature on IR spectra is not known with great details.

Mathematical Relations

For a given glass, the spectral volume 'emissive power', J(λ) is known to be directly proportional to the absorption coefficient (α(λ)). The relation between these two parameters is expressed as:

$$J(\lambda) = \alpha(\lambda)n(\lambda)^2B(\lambda)_T \qquad ...(1)$$

Where, n(λ) is the refractive index of glass, $B(\lambda)_T$ is the intensity of black radiation of wavelength λ at temperature T [5]. After specifying the concerned properties of the material, the complicated task of solving various technological problems of interest remains at hand, i.e. for different elements with a given material, the mathematical equation that describes the 'energy balance'. This requires some equations involving some terms describing the emission and absorption of radiation for a typical material element, and others describing the changes in heat content due to conduction and possibly also to another method of heat-transfer, i.e. convection. Inside the glass tank furnace, the "glass-air interface" is also very important in that the effects of reflection and refraction of radiation incident in each direction on the interface are taken into consideration.

In many fields of physics, a tremendous amount of work has been done towards solving problems of heat-transfer by radiation in an absorbing medium. However, in the field of glass technology, the problem of radiative heat-transfer is much more complicated. This assumes more significance, as other heat-transfer mechanisms are included in the process as well as the reflection and refraction effects of boundaries that influences the technological interest. In many situations, analytical solutions are not possible due to several factors at play at the same time (i.e. during the melting process) and it is safer to take recourse to well-known numerical simulation techniques that are aided by a variety of new software. Moreover, many glass companies are now having a band of software engineers who could also do the job. There are various good reviews that could be of some help [6,7].

We have to decide now about the problem to be solved? It is the steady-state heat-transfer by radiation in large thicknesses of glass, such as that found in the actual glass tank furnaces for melting. This thickness is about 1 to 1.2 meters depending on the furnace capacity. About 50-55 years ago, the comprehension on this issue of radiation heat through the thickness of the melt was not adequate. For transferring any significant amount of thermal flux down from the ‘burner flame’ and the ‘furnace crown’ through the glass, the understanding was that the radiation alone could not be held responsible. This is due to that fact that simpler calculations indicated that the penetration of most of the radiation from the crown was not significant, and that the absorption could only occur within a few centimeters of the glass surface. If we take an example on the temperature of a typical crown as 1620C, then we find that the concerned wavelength distribution of black body radiation has a maximum intensity at 1 μm. For window glass, at this wavelength, the absorption coefficient is about 0.02 mm^{-1} at typically 1320C. Therefore, the intensity of the radiation entering the volume of glass from the crown is reduced in 100 mm to a fraction of 13% of its initial intensity. It has to be noted that the fraction reaching the bottom of the glass in the furnace is very much negligible.

At this point, by efficient use of the thermocouples in different locations along the thickness of the glass melt and the bottom refractory body, a close inspection has to be done on the vertical temperature gradients. There is another mechanism in addition to the thermal conduction of heat through the glass. If we consider a steady-state condition, the downward heat flux is the same in the refractory base as it is in the glass melt. Incidentally, the thermal conductivity of glass is very similar to that of refractory. But it is not manifested in the curve wherein we plot the ‘thermal gradient’ (temperature) vs. ‘vertical distance from glass surface’. Actually, the temperature gradient is quite sharp in case of bottom refractory blocks compared to that in the glass melt, say, after 1 meter thickness. Therefore, it is quite evident that a relatively smaller fraction of thermal flux inside the glass can be accounted for by thermal conduction.

It is apparent that a contradictory situation has arisen. A clear qualitative explanation is thus needed. It is known that the surface layers absorb the radiation entering the glass melt from the furnace crown. These surface layers are always at a higher temperature and hence they emit radiation. There are successive steps of radiation and absorption for passing thermal energy deeper into the glass melt. This requires a good qualitative understanding of mathematical development [8].

There is a simplified approach in the analysis of radiation heat-transfer that is regarded the radiation as being propagated only in the direction of the normal to the glass surface, which is the direction of the heat flow. The second simplification consists of considering the glass as a grey absorber, i.e. with an absorption coefficient (α) which is independent of wavelength. The above two simplifications permit an expression to be derived for the ‘emissive power’ per unit area of a slice of thickness (x) at a temperature (T degree Kelvin). This equation is shown as:

$$J(T) = 2n^2 \alpha\sigma T^4 x \qquad ...(2)$$

At this point, for the balance of radiation energy for such a slice of thickness of glass, another equation has to be derived. This equation is shown below relating the "net radiation heat flux density" (Q_R) that is flowing down through the glass thickness in the direction of increasing "x", i.e. towards the refining and working ends of the glass tank furnace, and "vertical temperature gradient (dT/dx):

$$Q_R = -(\alpha^{-1})d/dx(2n^2\sigma T^4)$$
$$= -(\alpha^{-1})[8n^2\sigma T^3]dT/dx \quad ...(3)$$

On the right hand side, the factor in the third bracket is very important, which is equation as the radiation conductivity (K_R). This is shown as:

$$K_R = 8n^2\sigma T^3 \quad ...(4)$$

The equation (2) also suggests that the total heat flux density may be calculated by multiplying the temperature gradient (dT/dx) by a total conductivity, which is the sum of the radiation conductivity and the true thermal conductivity of the glass. More work has been done on this subject and considering the diffuse nature of radiation, the modified equation for the radiation conductivity is written as:

$$K_R = (16n^2\sigma T^3)/3\alpha \quad ...(5)$$

The above equations were based on the absorption coefficient (α) being independent of the wavelength (λ). However, there is a method of calculating the 'Radiation heat flux', when the absorption coefficient varies with wavelength by deriving its normalized value. This consists of an integral of $dB(\lambda)_T/dT$ with respect to dλ between zero and infinity containing $\alpha(\lambda)^{-1}$ and divided by the same integral without any α(λ) term. This is the usual way to take the mean value of a given parameter [6].

For a commercial glass that is colourless, the radiation conductivity obtained by this formula is typically within the range: 70 - 80 $Wm^{-1}C^{-1}$ at 1320C. This value appears to be at least 30-40 times greater than the true thermal conductivity. Therefore, it is possible to get a satisfactory quantitative account on the heat flux density and temperature distribution in the glass melt in a tank furnace.

For a large thickness of glass melt (say, 1 to 1.20 meters), if we consider the heat flow, the concept of radiation heat conductivity appears to have some meaning, but a more careful look will tell us that its general usefulness is rather limited. The proximity of the boundaries and the nature of boundary conditions in the mathematical formulation seem to quite remarkably affect the relative amounts of the total heat flux carried by radiation, the relationship between heat fluxes and temperature gradients, and conduction [9].

Let us take a sheet of glass sandwiched between two blackbody slabs 1060 and 960C respectively, as a matter of a simple example, the temperature distribution is not linear. It could be linear if the glass had a constant 'total thermal conductivity' throughout its thickness. For a given sheet of glass, the calculations indicate that the heat flux carried by radiation varies through the sheet and it is found that this is minimum at the two surfaces than inside the bulk. The heat flux through the sheet of glass calculated from the radiation conductivity of the glass is about 82 KW/m^2, whereas it is found to be considerably lower in experiment at about 45 KW/m^2. This information gathered on the radiative heat transfer inside a glass tank furnace is quite useful while dealing with heat transfer in general for the fabrication of glasswares, e.g. container glasses. It was also noted that the boundary conditions are much more important while dealing with very thin glassware of about a few millimeters thickness, although in many instances, the contribution of radiation heat flux could be considered as negligible.

CONCLUSIONS

For glass technology both heat transfer and fluid flow are important considerations for developing our required theoretical understanding on the manufacturing processes. In this first part of the article, only heat transfer process is discussed with a particular reference to the radiation heat transfer process in a glass tank furnace and the mathematical relations that are important to calculate the relevant parameters to get an overall view of the process are elaborated to some extent. In the second part, the heat transfer process will be discussed in relation to the glass fabrication technique. The question of fluid flow will be taken up in a future publication in KANCH.

REFERENCES

1. A. K. Bandyopadhyay, KANCH, Vol. 6 [I], (2012), 31.
2. A. K. Bandyopadhyay, "Nano Materials", Tunbridge Wells, UK (2010).
3. A. K. Bandyopadhyay, "Technology of Float Glass Process", KANCH, Vol. 5 [3] (2012), 33.
4. J. Zarzycki, "Les Verres et I'Etat Vitreux", Mason, Paris, (1982)
5. R. Garden, J. Am. Ceram. Soc., Vol. 39, (1956), 278.
6. E. U. Cordon, J. Quant. Spectrosc. Radiat Transfer, Vol. 8, (1968), 369.
7. R. Garden, "8th International Congress on Glass", London (UK), (1969), 85.
8. J. Kellet, J. Opt. Soc. Am. Vol. 43, (1953), 1231.
9. G. K. Chu and R. Garden, J. Am Ceram Soc., Vol. 52, (1969), 548.

Glass Manufacturing - Part II: Heat Transfer Process in Glass Fabrication

ABSTRACT

There are various features in the process of manufacturing of glasses. This normally depends on the type of glass and the manufacturing method. Some important aspects in the manufacture of glasses are very important and these aspects mainly hint at theoretical understanding of different processes involved in making the glass. These aspects are heat-transfer and fluid flow, particularly a study of the interaction between them is very interesting indeed. The heat transfer process in the glass tank furnace has already been discussed in the first part. In this article, the second part will deal with heat transfer in the glass fabrication, while the fluid flow is also a very interesting subject that will be dealt with in the future publications.

INTRODUCTION

During the past several decades, there have been a lot of newer interesting developments in field of glass technology, counting all the small but incremental developments. One of them is a more or less adequate knowledge or clarifications on the 'role of radiation' as a mechanism of heat-transfer process in glass. This can occur at high temperatures (1250 -1600C) inside the 'glass tank furnace' for melting as well as at relatively lower temperatures (620 - 1100C) encountered in the different fabrication processes. Heat is transferred from one body or system to another by three different means - viz. conduction, convection and radiation. The latter is very important in relation to the other two mechanisms that depend on certain factors. The process of radiative transfer of heat flux at higher temperature that occurs in the glass tank furnace has already been discussed. However, the process of heat transfer at lower temperature that occurs during the fabrication of different glass products assumes special importance.

Compared to ceramics manufacture, where shapes are made first and then the firing is done, for glass manufacturing, the raw materials are first homogeneously mixed and then melted and refined at high temperature. The refined melt is then used to shape different products, including special type of glasses [1,2]. This is true for batch type of operation, i.e. for optical glasses, as well as for continuous operation of float glass, container glass, etc. [3,4]. Depending on whether the glass melting is batch type or continuous type, the fabrication technique could be continuous, and hence heat-transfer in the glass fabrication process also assumes importance.

HEAT TRANSFER IN GLASS FABRICATION

The field of engineering related to glass fabrication encompasses a whole gamut of applications, such as mechanical, electrical, electronics, robotics, etc. After melting and refining at high temperature, where radiative heat transfer is significant in the glass tank furnace, the glass products are fabricated at lower temperature (620-1100C) to attain the required higher viscosity so that the fabrication of the right size or shape can be performed. At this lower temperature range, the heat transfer process is also important.

Container and Other Classes

A large variety of fabrication processes are used in different glass plants for different range of products. For container glass manufacture, the products are made by pressing in contact with metal moulds. As the glass first comes in contact with the mould, its temperature is around 1000-1100C, while the surface of the mould is at much lower temperature, i.e. at 400-500C. For the metal moulds, the surface temperature is of utmost importance, as it determines not only the smooth heat-transfer process, but also fixes the quality of the glass products.

For example, if the temperature is too high, the viscosity of the glass will be such that it will stick to the mould increasing the rejection losses. However, if it is too low, the glasses will have poor surface finish that will be less appealing to the customers of the particular product items. This is a serious "quality control" problem, but it should be also viewed by the knowledge of the "glass technologists" regarding viscosity - temperature relation that is fundamental to glass making. The curve of viscosity falls exponentially with temperature, i.e. viscosity increases sharply with decreasing temperature. A higher temperature at the mould surface will prevent the heat-transfer between the glass and the mould, thereby increasing the glass temperature, or rather the temperature does not fall enough to give rise to the required viscosity. This in turn will decrease the viscosity so that the fluidity of the hot glass is enough to give rise to "sticking" problem during the fabrication of container glasses. On the other hand, a lower surface temperature will enable a faster heat transfer, but in that case the "glass surface" will be affected.

Ultimately, the temperature difference in the "glass-mould" interface is of interest to glass fabrication. If the initial temperature difference at the interface is large, then there will be correspondingly larger heat flux across this interface, which is of primary importance. The magnitude of such heat flux depends upon the thermal resistance of the interface, which finally depends on the "intimacy" of contact between the mould and the glass. So, for container glasses, the nature of heat-transfer is conductive. In other processes, such as the manufacture of glass tube (i.e. for lighting) and glass fibres (i.e. for insulation purpose), the moulds are not used. In such cases, the glass looses heat by radiation and convection to the surrounding atmosphere. However, in such processes, the "heat flux density" of the surface is much less than that of 'container glasses' involving the physical contact with metal moulds.

As the temperature is reduced, its viscosity increases, i.e. the fluidity decreases that tend to be more like a solid. Hence, the distribution of temperature in a glass at any moment of time obviously determines the viscosity distribution, i.e. it decides on the way the glass will flow in relation to the force applied to the glass. Therefore, one has to understand the factors controlling heat transfer during the fabrication process, which is a very important component for a thorough knowledge of the process.

Non-Steady State Heat Transfer

For the radiative heat-transfer, the steady-state problem was discussed in the first part of the paper. In the glass fabrication process, the non-steady state heat transfer problem is encountered, wherein the heat transfer is by both radiation and conduction. In the shaping process, the behavior of coloured glass is expected to be different from that of colourless glass, if it is proven that the part of the total heat flux through radiation is large enough and it has an important effect in determining the temperature distribution inside the glass. This is quite obvious for glassblowers who find difficulty in blowing coloured glass, as the cooling rate is different in differently coloured glasses in free cooling crucibles. Therefore, it is again proven that the radiation is relatively more important. Thus, the "glass colour effect" significantly varies from one set of conditions to another. The physics of the whole situation had to be properly understood so as to appreciate why coloured glasses behave differently in relation to the colourless glasses.

In order to start the discussion, it is convenient to mention about the "emission" of radiation from a sheet of glass, which is initially in isothermal condition at a temperature T °K. This isothermal sheet of glass is assumed to be suddenly exposed to cold surroundings. Therefore, it is possible to neglect the 'radiation' that has to be received by the glass sheet from the surroundings. Let us calculate the total radiation emitted by the sheet and then in the initial rate of cooling at different positions of the sheet. The theory for this purpose was developed by Gardon [5,6]. Let us take a sheet of thickness X made from a grey absorber of absorption coefficient (α), and the expression for initial radiant emission is:

$$M_{\varepsilon} = \varepsilon\sigma T^4 W/m^2 \quad ...(1)$$

Where the emissivity (ε) being the function of the dimensionless "optical thickness" (αX) of the sheet. However, when α is a function of wavelength (λ), the emissivity can be deduced by calculating the 'optical thickness' using a mean value of the absorption coefficient. This 'mean value' is normally deduced by an integral (within the limits of 0 and ∞) of the 'intensity of black radiation' multiplied by the absorption coefficient.

There is a shift of the radiation energy distribution in relation with increasing temperature toward the shorter wavelength. At this shifted wavelength, most commercial glasses have lower $\alpha(\lambda)$ values, and consequently the emissivity decreases with increasing temperature. This point is quite important in the glass fabrication process. Therefore, at room temperature, a 10 mm thick 'window glass' sheet has an emissivity of 0.93. This value decreases to 0.56 at a very high temperature of 1200C. Here, the treatment is done on a sheet of glass that is initially free from any temperature gradients, and the initial cooling rates at different positions in the sheet are determined only by the radiation terms in the energy balance equation

GARDON'S TREATMENT

Garden treatment [5] is very well-known in the field of heat-transfer during fabrication process, where the rate of cooling is considered at the centre of a glass sheet. At very low value of the absorption coefficient ($\alpha(\lambda)$), the rate of emission of radiation from the glass is low, i.e. the "rate of cooling" is low. When $\alpha(\lambda)$ is high, the emitted radiation is very quickly re-adsorbed within a short distance from the centre of the sheet. Therefore, as a consequence, the "net rate of loss of energy" from the central layer is again small. Garden's analysis of this problem shows the rate of cooling at the centre of the glass sheet is a maximum, as the optical thickness (αX) is 1.5.

This is a piece of interesting information that is to be understood in terms of certain features of heat transfer during glass fabrication process. In order to develop a presentable model, the situation or rather simulation of the problem at hand, i.e. "pressing operation" for the container glasses, an assembly can be considered with a 10 mm thick sheet of glass with similar absorption properties as that of window glass, which is also initially considered to be at a uniform temperature of 1000C. The model is further expanded with this glass sheet suddenly sandwiched between two metal plates at a lower temperature of 400C, and the plates are in contact with the glass. However, in this model, the main concern is that the transparent glassy material is considered and the initial rate of cooling will be zero at the centre of the glass sheet, and also it would remain very small for some time after the glass comes into contact with the metal plates.

It has been found that a large amount of cooling would take place for values of dimensionless parameter less than about 2 and this value is described by: $X/4(at)^{1/2}$, where "X" is thickness of the glass sheet and "α" the thermal diffusivity of the glass. The corresponding time is 2 seconds for a 10 mm thick glass sheet. For pressing operation in the container glass production, this is about the time at which the plunger in an IS machine comes into contact with glass "gob". Therefore, there will be very small cooling at the centre without any radiation. It is worth noting that due to the radiation effects, the initial rate of cooling is quite large. As per the analysis of Gardon, it can be easily shown that the initial rate of cooling there is around 7 °C/s. It has also to be noted that for a heavily coloured glass, it is usual to neglect the radiation effect. In such a case, the problem is simplified in that the heat transfer takes place mainly by conduction, whose solution is already known.

In a sheet of glass, the rate of cooling at its centre is much less important than at the surface. During the shaping process in the fabrication of various glass articles, both the temperature and the corresponding viscosity at the surface, as discussed in the Section-2.1, have a much greater effect on the overall behavior of the glass. As it will be evident later, normally the radiation has a minor effect in determining the distribution of temperature and heat flux close to the glass-mould interface. When the contact between the mould and the glass is considered to be perfect, the surface temperature of both glass and the mould change immediately after coming into contact at a temperature that can be taken as the "critical temperature (T_c), which ultimately remains constant for some time. The value of T is given by

$$T_c = T_{Mi} + (T_{Gi} - T_{Mi})E_G/(E_G + E_M) \quad ...(2)$$

Where, T_{Gi} and T_{Mi} are the initial uniform temperatures of the glass and the metal mould respectively [7]. The parameters (E) are denoted as "thermal contact coefficients" [8] that are related to the "thermal conductivity" (K) "thermal diffusivity" *(α)* as:

$$E = K/\sqrt{\alpha} \quad ...(3)$$

Actually, the thermal contact between glass and metal mould is hardly perfect. There are various reasons for this imperfectness that is due to thermal resistance of the interface temperature of glass and mould tends towards the T_c value given by the equation (2) at a finite rate. The heat flux across the interface at any instant is proportional to the difference between the surface temperatures of the glass and metal mould, which is expressed as:

$Q(t) = h(T_{Gs}-T_{Ms})$ ...(4)

Where *h* is the "interface heat transfer coefficient". The single most important factor is perhaps the value of h for determining the rate at which heat is "extracted" during glass forming processes that involve metal moulds. Generally speaking, it is practically impossible to determine the value of *h* by experiments under the "conditions" that are relevant to the fabrication of glasses. The reason for this experimental difficulty lies in the fact that the "values" are greatly affected by the "pressure" applied across the mould-glass interface. Moreover, from computer analysis, it has been found by McGraw [9] that the value of h considerably decreases during the "time period" of contact between glass and mould. Normally, for ordinary glasses, these values are in the range: 1 - 10 KW/m^2.

If we assume an initial difference of surface temperature between glass and mould of 500C, the initial heat flux across the interface will be in the range: 0.5 - 5 MW/m^2. This is definitely more remarkable than that expected from a contribution of radiation. Hence, at a much higher temperature of 1000C, the value σT^4 is only 0. 1 5 MW/m^2. A detailed computer simulation work by McGraw [9] and Jones and Basnett [10] support the above conclusions. The idea is that while the glass is in contact with the mould, the variation of the 'absorption coefficient' of the glass has no practical significance on the distribution of temperature near the interface and the heat flux from the glass to the metal mould. Therefore, in this kind of shaping or forming process, glasses differently coloured would behave in a similar manner.

It is well known to glass technologists dealing with container glass that when the glass article is removed from the mould, the surface temperature of the glass starts to increase. This is due to the combined effect of the large reduction in the "rate of heat extraction" from the surface of the glass. This is also due to a very steep temperature gradient that occurs when the glass was still under the contact with the metal mould. This is a typical "reheat" effect, which is an important feature of glass manufacturing process.

On the question of container glasses, they are made of two moulds. The first one called a "parison" mould that is used for forming the "neck" of the particular container and a 'preform' of the body. The final product is made by blowing out 'preform' or 'parison' in the second mould. When the glass 'parison' is released from the 'parison' mould, its surface needs to allow an increase of temperature or "reheat" before the final shape can be blown. Moreover, when the finished product, e.g. a container bottle, is released from the "blow mould", some 'reheating' takes place at the surface of the glass, and on release from the 'blow mould', when the rise in surface temperature is too large, the glass piece could collapse under its own weight.

Here, there is a role played by surface viscosity. As the surface temperature rises due to this 'reheating', the viscosity decreases (i.e. increased fluidity) and consequently the glass bottle could deform or collapse (where its weight also plays a role), thereby increasing the 'rejection losses'. Moreover, in this reheat part of the manufacturing process, the radiation heat transfer within the glass as well as from the glass surface might have a significant role.

The above describes the situation for container glasses (i.e. bottles, drinking glass, bowls, etc.). Another example can be described for 'glass tubes'. In this case, the glass does not come into contact with metal moulds, and so the radiation is the dominant mechanism of heat transfer in the process of tube manufacture. Here, the heat is lost from the outer surface of the glass tube by natural convection and also by radiation. For natural convection, the coefficients of heat transfer are of the order 10W/m^2 giving a value of I 10kW/m^2 for the 'surface heat flux' from the glass surface at about 1000C to air at ambient temperatures.

In my Department of Glass Technology at the University of Sheffield (UK), our great Professor Turner did an extensive work on coloured glasses [11]. Therefore, an example should be given on coloured glasses vis-a-vis. For a 10 mm thickness of a commercial coloured glass, the 'radiation heat loss' is much larger, i.e. about 80 kW/m^2. Therefore, in this type of process for making coloured glasses, there is a marked effect of "colour" on the rate of cooling and hence on the working behavior of the glass during the shaping process [12].

CONCLUSIONS

In the first part, a description on the heat transfer process in the glass tank furnace was given in details. In this article, in the second part, the heat transfers that take place during fabrication or forming processes are described. In particular, the heat transfer is discussed in terms of container glass manufacture and then the non-steady state heat flow during the glass fabrication process is briefly discussed. Finally, Garden's treatment is elaborated with some real data that could help the glass technologists to undertake some small steps of calculations of various heat flux data with a particular reference to container glass manufacture, but some data are also shown on glass tubes for lighting as well as for coloured glasses, which behave differently than that of commercial colourless glasses.

REFERENCES

1. A. K. Bandyopadhyay, KANCH, Vol. 6 [I], (2012), 31.

2. A. K. Bandyopadhyay, "Nano Materials", Tunbridge Wells, UK (2010).

3. A. K. Bandyopadhyay, “Technology of Float Glass Process”, KANCH, Vol. 5 [3] (2012), 33.

4. J. Zarzycki, “Les Verres et I’Etat Vitreux”, Mason, Paris, (1982).

5. R. Gardon, J. Am. Ceram. Soc. 39, 278 (1956).

6. R. Gardon, J. Am. Ceram. Soc. 44, 305 (1956).

7. H. S. Carlshaw and J. C. Jaeger, “Conduction of Heat in Solids”, 2nd Ed. (1959), Oxford: Clarendon Press, Oxford (UK).

8. K. J. K. Buettner, Applied Optics 8, 212 (1969).

9. D. A. Mcgraw, J. Am. Ceram. Soc. 44, 353 (1961).

10. S. P Jones and P Basnett, “Symposia on the Hot Glass in Contact with the Metal, (1964) 439-56.

11. A. K. Bandyopadhyay, unpublished Work, University of Sheffield (UK), 1977.

12. J. Boow and W. E. S. Yurner, Glass Technology 27, 207 (1944).

Glass Manufacturing Part III: Fluid Flow in Glass Fabrication

ABSTRACT

In the process of glass manufacturing, there exist various features. Normally, it is dependent on the type of glass and the manufacturing method. Practical knowledge comes out of a good understanding of the theoretical aspects. It is very important to have a full theoretical understanding of the glass-fabrication through different processes. These aspects are heat-transfer and fluid flow, particularly a study of the interaction between them is very interesting indeed. The heat transfer process in the glass tank furnace and the heat transfer in the glass fabrication have already been discussed in the previous issues of KANCH. In this article, the third part will deal with the fluid flow that is also a very interesting subject in a glass tank furnace with an important influence on the glass fabrication.

INTRODUCTION

There are various branches of core engineering fields, such as mechanical, electrical, electronics, robotics, etc., related to glass fabrication that encompasses a whole gamut of applications. The glasses are made by first melting and refining at high temperature involving radiative heat transfer within a glass tank furnace. Then, the glass products are fabricated at lower temperature to attain the required higher viscosity or lower fluidity so that the fabrication of the right size or shape can be performed. It is the fluidity at the fabrication temperature that is really important in the glass technology. For example, if the fabrication temperature is lowered, then the viscosity will increase or fluidity will decrease making the process quite difficult. Therefore, at this lower temperature range, the heat transfer process is also important. As discussed below, this has also been described earlier [1,2].

A large variety of fabrication processes are used in different glass plants for different range of products. For container glass manufacture, the products are made by pressing in contact with metal moulds. As the glass first comes in contact with the mould, its temperature is around 1000-1100C (i.e. lower viscosity), while the surface of the mould is at much lower temperature, i.e. at 400-500C (i.e. higher viscosity). For the metal moulds, the surface temperature is of utmost importance, as it determines not only the smooth heat-transfer process, but also fixes the quality of the glass products.

For example, if the temperature is too high, the viscosity of the glass will be such that it will stick to the mould increasing the rejection losses. However, if it is too low, the glasses will have poor surface finish that will be less appealing to the customers of the particular product items. This is a serious “quality control” problem, but it should be also viewed by the knowledge of the “glass technologists” regarding viscosity-temperature relation that is fundamental to glass making. The curve of viscosity falls exponentially with temperature, i.e. viscosity increases sharply with decreasing temperature, i.e. an inverse relationship between temperature and viscosity. A higher temperature at the mould surface will prevent the heat-transfer between the glass and the mould, thereby increasing the glass temperature, or rather the temperature does not fall enough to give rise to the required viscosity for fabrication. This in turn actually decreases the viscosity so that the fluidity of the hot glass is enough to give rise to “sticking” problem during the fabrication of container glasses. On the other hand, a lower surface temperature (i.e. higher viscosity) will enable a faster heat transfer, but in that case the “glass surface” will be affected.

Ultimately, the temperature difference in the “glass-mould” interface is of interest to glass fabrication. If the initial temperature difference at the interface is large, then there will be correspondingly larger heat flux across this interface, which is of primary importance. The magnitude of such heat flux depends upon the thermal resistance of the interface, which finally depends on the “intimacy” of contact between the mould and the glass. So, for container glasses, the nature of heat-transfer is conductive. In other processes, such as the manufacture of glass tube (i.e. for lighting) and glass fibres (i.e. for insulation purpose), the moulds are not used. In such cases, the glass looses heat by radiation and convection to the surrounding atmosphere. However, in such processes, the “heat flux density” of the surface is much less than that of ‘container glasses’ involving the physical contact with metal moulds.

As the temperature is reduced, its viscosity increases, i.e. the fluidity decreases that tend to be more like a solid. Hence, the distribution of temperature in a glass at any moment of time obviously determines the viscosity distribution, i.e. it decides on the way the glass will flow in relation to the force applied to the glass. Therefore, one has to understand the factors controlling heat transfer during the fabrication process, which is a very important component for a thorough knowledge of the process.

During the past several decades, there have been a lot of newer interesting developments in field of glass technology, counting all the small but incremental developments. One of them is a more or less adequate knowledge or clarifications on the 'role of radiation' as a mechanism of heat-transfer process in glass. This can occur at high temperatures (1250 – 1600C) inside the 'glass tank furnace' for melting as well as at relatively lower temperatures (620 – 1100C) encountered in the different fabrication processes. Heat is transferred from one body or system to another by three different means – viz. conduction, convection and radiation. The latter is very important in relation to the other two mechanisms that depend on certain factors. The process of radiative transfer of heat flux at higher temperature that occurs in the glass tank furnace has already been discussed. However, the process of heat transfer at lower temperature that occurs during the fabrication of different glass products assumes special importance.

Compared to ceramics manufacture, where shapes are made first and then the firing is done, for glass manufacturing, the raw materials are first homogeneously mixed and then melted and refined at high temperature. The refined melt is then used to shape different products, including special type of glasses [3,4]. This is true for batch type of operation, i.e. for optical glasses, as well as for continuous operation of float glass, container glass, etc. [5,6]. Depending on whether the glass melting is batch type or continuous type, the fabrication technique could be continuous, and hence heat-transfer in the glass fabrication process also assumes importance. As viscosity or fluidity is intimately connected with the fluid flow or fluid mechanics in glassy materials, the interaction between fluid mechanics and heat-transfer is an important study that is being attempted in this article.

FLUID FLOW IN THE GLASS FABRICATION

For modelling of fluid flow in a given system, the simple geometry has to be considered in order to easily calculate temperature distribution in the glass for many steady-state as well as time-independent problems. Despite the calculation of such a distribution involves certain simple assumptions, there is a good correspondence between experimental and calculated values, whenever comparisons are possible to be made in the field of glass technology. In any given glass plant, there should be a set of values for various physical parameters so that the glass technologist could do a series of calculations or computation on a range of data. In this manner, one could get valuable ideas about the "main factors" controlling heat transfer as well as temperature distribution for a given glass system.

As described above, the temperature distribution is important only due to the fact that it determines the viscosity-distribution in the glass. In turn, the viscosity determines the way in which the glass will flow in response to the forces applied to it.

It is a matter of convenience first to consider the problems of glass-flow calculation in a tank furnace. As the geometry is simple and the boundaries of tank furnace are stationary, it is quite easier to deal with this issue. It also emphasizes that the treatment of boundaries is easily tackled. The flow of glass during the fabrication process, say, for a container glass, is obviously much more difficult as in case of 'metal moulds', as there is moving free boundaries to deal with.

Glass-Flow in a Tank Furnace

In a tank furnace, we are concerned with melting different components and refining the glass, but the flow pattern is also of considerable practical importance. A mixture of powdered raw materials when melted gives rise to rather viscous melt. This happens due to the chemical reactions between different raw materials gives rise to the formation of several complex silicate phases with different melting points. As such the melt is quite inhomogeneous and contains several bubbles with varying sizes, when the last part of solid material has gone into the melt. This inhomogeneous glass needs to be refined to get rid of such bubbles, or even some unmelted portion of the solid mixture. However, it can be sufficiently homogeneous only by some type mixing action, which is provided by the "pattern of flow" in the tank. Here, there is a play between heat diffusivity and fluid velocity showing important relation between heat transfer and fluid mechanics.

There are mainly two factors that determine the flow: (a) Throughput Flow – this has to be understood by the drag force of drawing glass for the machine and the feeding rate of raw materials mixture. As this 'feeding rate' has to cope with the 'drawing rate' to maintain the level of glass inside the tank furnace, say, about 1 meter depth, the glass flows at a particular rate; and (b) there is the "complex pattern of re-circulating" natural convection flows that are driven considerably by the temperature gradients, which exists in the horizontal direction in the glass melt. At the bottom of the tank furnace, the temperature is always lower than that in the surface, where the fluid flow is more apparent. It is the reason why ultimately the whole ensemble of glass melt comes to some kind of equilibrium that is driven by glass temperature and consequently by glass viscosity with the help of "flow" as the molten glass tends towards 'refining zone' and then towards the 'working end'.

Here, a little bit mention could be made on the relation between drawing and feeding rates and their near-equalization. In our common knowledge, we know that as the drawing rate is faster than the feeder rate when some 'urgent demand' of a particular glass for a day or two has to be satisfied, then the level of glass inside the furnace "goes down" from its usual level of 1 to 1.2 meters. However, if the drawing rate (i.e. rate of production at any given moment) is slower than the feeder rate, then the glass level will "go up" from its usual level to about 1.4 meters or higher thereby creating distortion in the fluid flow. It is a debatable point that in order to maintain the quality level, whether the glass technologist in a given plant will encourage such a scenario, or rather maintain it within a closed range, as the glass level going higher or lower (than stipulated) might disturb the heat distribution along the depth of glass and consequently the 'flow patterns'. In the case of ISO certification, it is not known whether the 'glass level' with a strict small range is clearly specified, or simply a larger range is noted as per the particular furnace design. Nevertheless, its importance in the day-to-day running of the furnace and maintaining the quality of glass cannot be seen as a trivial matter.

The 'flow patterns' within the tank furnace is quite complex due to a variety of reasons. Trier [7] has studied this complex pattern within a glass tank furnace, which mainly shows the radial flow starting from a centre towards the wall of a tank. The mixture of raw materials is actually fed onto the surface of the molten or semi-molten glass through the feeder chamber. The refined/finished glass is fed to the machine through three or more channels (depending on the design) that radiate from the semi-circular compartment, i.e. working end of the tank furnace. Due to highly viscous nature of the glass and also due to the relatively lower applied forces, the velocities of the glass flow are also quite low, i.e. typically around a few meters/hour. The velocity gradients that are created are responsible for proper mixing. This occurs due to 'shear' and modification in the adjacent regions which are initially of different compositions. In particular, the distortion due to 'shear' has relatively more effect by the increasing concentration gradients. This accelerates the homogenization process by chemical diffusion that is again dependent on temperature of the melt. One has an impression that the entire glass melt is of uniform composition from the very start (from the feeder chamber). But it is the fluid flow that ultimately brings this 'uniformity' or rather homogenization of the glass that has a strong bearing on the ultimate quality of the glass. Therefore, to understand defect-free glass, one has to study 'fluid flow' very carefully in terms of chemical diffusion, as also emphasized by several workers, such as Geffcken [8] and Cooper [9,10].

In a tank furnace, as the glass is very hot and also inaccessible, it is not generally possible to do any direct measurement of fluid flow by any suitable technique. One could do experiment with liquids at room temperature by taking care of certain useful parameters by somehow upscaling or downscaling them, as needed or found convenient for calculation. Transparent plastics or polymeric materials (having different viscosity characteristics) have been used for this purpose to simulate the melting conditions, based on certain mathematical equations. While this kind of modelling has certain drawbacks and draws criticism, it is also sensitive to the design parameters of the tank furnace. However, it is still useful to do some kind of simulation experiment to have some ideas about 'flow patterns' inside a glass tank furnace, as the acquisition of knowledge is not always worthless.

In the distant past, a tremendous amount of work has been done into this field by various workers, particularly on the investigation of 'flow patterns' by computer simulation of differential equations of fluid flow and heat-transfer. Some of these works were published, notably by Wright & Rawson [11] as well as by Austin & Bourne [12]. Recently, however, a lot of work has been done in the general field of "computation fluid dynamics (CFD)", notably by Roach [13]. There are many methods available for solving problems, such as 'flow patterns' in a tank furnace, involving viscous incompressible fluid and natural convection of heat. For this purpose, simultaneously several equations have to be solved and satisfied throughout the whole ensemble of glass melt in the tank furnace. These equations are: the famous Navier-Stokes vector equation, the continuity equation and the energy equation respectively. These equations indicate that there is an interaction between heat transfer and fluid flow by showing a strong temperature dependent relation between thermal diffusivity and vertical component of the fluid velocity. With the proper boundary conditions in different equations, one could compute the flow pattern by a numerical approach, as developed by Noble et al [14]. These computer simulation results were compared with those of the room temperature experiments with plastics, as mentioned above, and fairly good correspondence was obtained.

CONCLUSIONS

In the previous two articles, heat transfer processes in both during melting and during fabrication of glass products have been discussed. Heat-transfer process has a strong influence on the viscosity of the glass melt and hence on the flow patterns. In this article, the importance of heat transfer and its interaction with the flow patterns has been elaborated. Various other related issues, such as the glass level in terms of glass drawing rate and the feeding rate of raw materials mixture as well as homogenization of the melt through chemical diffusion, are also mentioned as relevant topics of interest for the ultimate quality of glass products. A comprehensive view on the fluid flow has to be taken into the consideration by the glass technologists based on the relation between the heat diffusivity and vertical component of velocity of molten glass following Navier-Stokes equation and other related equations. Some computer simulation methods through improved software development have to be adopted by different plants to suit different designs of glass tank furnaces. These fluid flow models involving computer simulation techniques have to be refined to ultimately predict and maintain a consistent quality of a given glass product.

REFERENCES

1. A. K. Bandyopadhyay, KANCH, Vol. 1 [4], (2014), 31.
2. A. K. Bandyopadhyay, KANCH, Vol. 1 [4], (2014), 49.
3. A. K. Bandyopadhyay, KANCH, Vol. 6 [1], (2012), 31.
4. A. K. Bandyopadhyay, "Nano Materials", Tunbridge Wells, UK (2010).
5. A. K. Bandyopadhyay, "Technology of Float Glass Process", KANCH, Vol. 5 [3] (2012), 33.
6. J. Zarzycki, "Les Verres et l'Etat Vitreux", Mason, Paris, (1982).
7. W. Trier, Glasstechnische Ber., Vol. 37, (1960), 401.
8. W. Geffcken, Glasstechnische Ber., Vol. 30, (1957), 143.
9. A. R. Cooper, Chem. Engg. Sci., Vol. 21, (1966), 1095.
10. A. R. Cooper, Glass Technology, Vol. 7, (1966), 2.
11. S. Wright and H. Rawson, Glass Technology, Vol. 14, (1973), 42.
12. M. J. Austin and D. E. Bourne, Glass Technology, Vol. 14, (1973), 78.
13. P. J. Roach, "Computational Fluid Mechanics", Hermosa Publishers, Albuquerque, USA (1972).
14. J. J. Noble, L. A. Clomberg, A. F. Sarofin, H. C. Hottel, J. Heart Transfer, Vol. 94, (1972), 149.

Flaws and Fracture of Container Glasses

ABSTRACT

The mechanical properties of glasses are very important considerations for glass quality. By using Griffith formulation of theoretical strength of glassy materials, a modification of the equation for theoretical strength could be achieved by changing the limit of integration within the zone where fracture occurs in brittle glasses, based on a sinusoidal approximation. Here, the question of measuring fracture in glasses is discussed on commercial container glasses with some data and the relevant equations, which are used to quantify flaws and fracture in glasses.

Keywords: Griffith equation, theoretical strength, Hook's law, Fused silica.

INTRODUCTION

Glasses are brittle materials and hence they easily break. For practical applications of container glasses for the packaging industry, however, the mechanical strength is very important. It is also important for their marketability. It appears from a vast amount literature data that there is a considerable amount of work done on fracture, the effect of micro-flaws on fracture, the effect of fracture strength on the overall mechanical behaviour of glasses, etc. The sheer number of papers on this subject justifies its importance. Thus, the study of fracture on glasses assumes special significance for the mechanical properties [1-4].

In an article on "Theoretical Strength of Glasses" in KANCH [5], the problem of theoretical strength in glassy materials was discussed in the context of Griffith formalism by taking fluctuation in spatial elongation near the maximum value of applied stress. In this manner, the theoretical strength could be predicted by a multiplication factor, when micro-flaws are present in glasses. The mechanical properties in terms of fracture of such glasses are also of great importance, since these glasses are mostly used in the building industry and facade decoration purposes, wherein fracture in any form can cause damage to the installation that will result in a loss to the investment made. Although the present article deals with the problem of fracture in brittle materials, such as commercial glasses, the importance has to be also given to the float glasses, as these glasses have aesthetic appeal with the highest quality requirements so far the glass industry is concerned [6].

There has been a tremendous amount of work done in the field of fracture mechanics in brittle materials and glasses, particularly on their theoretical strength for a long time [1,2]. This is mainly done on Griffith equation based on the formation of an elliptical crack and its main plank is the utilization of material parameters or constants, which are measurable, in designing suitable materials for various important applications [1]. An insight should be obtained on the nature of theoretical strength based on a sinusoidal approximation in the stress vs. spatial elongation curve. In the context of this approximation, our focus was on the “fluctuation” of the spatial elongation value at or near fracture so that a modified equation could be developed to better predict the theoretical strength of glasses.

Although the subject of much research over the past decades, the fracture of brittle glassy materials remains in many ways not understood. Of particular interest is the mechanism by which energy in the system is dissipated. Experimental measurements of the flow of energy into the tip of a running crack have indicated that the fracture energy (i.e., the energy needed to create a unit extension of a crack) is a strong function of the crack’s velocity and that the majority of the energy stored in the system prior to the onset of fracture ends up as heat. An example of the fracture of soda-lime-silica glass has been taken into consideration. Residual stress profiles were introduced in sodium alumino-silicate glass disks using an ion-exchange process, i.e. after chemical strengthening. They were fractured in two loading conditions: indentation and biaxial flexure. The fractal dimension of the macroscopic crack branching pattern called the crack branching coefficient (CBC), as well as the number of fragments (NOF) were used to quantify the crack patterns. The fracture surfaces were analyzed to determine the stresses responsible for the crack branching patterns. The total strain energy in the body was calculated. The CBC was a good measure of the NOF. They are directly related to the tensile strain energy due to the residual stress profile for fractures due to indentation loading. However, in general for materials with residual stresses, CBC (or NOF) is not related to the strength or the stress at fracture, or even to the total stored tensile strain energy. A study was done to determine the geometric characteristics associated with the critical crack caused by cyclic loading in baria-sillicate glass [3]. Such studies have also been undertaken in many other systems of glasses including many commercial glasses.

The objective of such a study on fracture is to understand how flaws in a material affect fracture and appreciate the basic features of a brittle fracture surface. One should be able to calculate the average flaw size present in a sample or its fracture stress and then understand why the fracture stress of a brittle material varies from sample to sample.

DESCRIPTIONS OF THE EXPERIMENT

Most materials, when subjected to a tensile stress, break without any apparent plastic flow, and these are known as brittle materials. Even though there is no plastic flow, they still break at a stress well below the theoretical value calculated from the strength of the atomic bonds. One should look at an experiment in which glass rods break under an applied load. Examination of the fracture surface allows us to determine how they failed, i.e. the failure analysis. The analysis of the fracture stresses enables some conclusions to be drawn about the link between this failure stress and the surface treatment of the rods.

In this experiment, a cylindrical soda-lime silica glass rod with diameter (d) is fixed as a cantilever. A constant load (W) is applied to the free end and the free length (L) of the cantilever rod which is gradually increased until the rod fractures. For each specimen the free length at which the rod fractures is measured. The highest tensile stress in the rod is at a point closest to the fixed end. The maximum tensile stress under these loading conditions is calculated using the expression:

$$\sigma_{max} = 32WL/\pi d^3$$

To examine the effect of surface treatment, we compared the results from testing as-received rod with those obtained where (a) Surface of the rod was abraded using silicon carbide abrasive paper with a grit size of about 60 microns and (b) Flame polishing was done by heating the lengths of rod in a blue Bunsen flame by moving the flame up and down the length of the rod. This is a method to heal the flaws.

The examination of the fracture surfaces showed that the fracture originated from a flaw on the top surface of the glass rod. Three distinct regions could be seen on the fracture surface:

a) A smooth region surrounding the fracture origin called the mirror zone

b) A small band of rougher surface surrounding the mirror region, which is known as the mist zone

c) An area beyond this is known as the hackle zone, which is composed of large irregularly oriented facets fracture surfaces

The fracture process involves a tensile crack initiating from a flaw on the top surface, which travels quickly through the rod until it reaches the mid-point (neutral axis). Here the crack continues to propagate, although the stresses in the rod become compressive. This assumes that the stresses are unaffected by the propagating crack, which is a reasonable assumption as the crack is growing much more rapidly than the rod can deflect.

RESULTS AND DISCUSSION

The results of the above experiment are given below:

Sample	Mean Fracture Stress (MPa) [Std. Deviation]
As-received	118 [22]
Abraded	70 [11]
Flame Polished	132 [16]

The above results show that the flame polished samples break at a higher mean fracture stress (by as much as 12%) than that of the as-received samples, while abrading the surface lowers the fracture stress by a significant value, i.e. by 41% compared to that of the as received sample. It is interesting to note that the standard deviation for all the experiments is quite large, but as a percentage of mean fracture stress, it is 19%, 16% and 12% for the three samples respectively. The scanning electron micrographs (SEM) on the surfaces of the glass rods showed that abrading has introduced some larger flaws in the surface of the glass, thereby reducing the strength by about 41% from 118 MPa to 70 MPa. The surface of the flame polished rod shows much lesser number of flaws than were present in the as received glass, thereby increasing the strength by 12% from 118 MPa to 132 MPa.

The importance of flaw sizes was discussed in Ref. [5]. On many occasions, a visual check under a powerful microscope on the "flaw sizes" will reveal the difference in strength of two pieces of glasses, if they are to be compared on their different mechanical behaviour. From the relationship derived by Griffith, it is now possible to calculate the "flaw sizes" present in the glass rods. The average flaw size is related to the mean fracture stress by:

$$C \propto \frac{1}{\sigma_f^{2}}$$

So, we can write the following relation as:

$$\sigma_f = \frac{K_c}{\sqrt{\pi C}}$$

Where, σ_f is the fracture stress, K_c is the fracture toughness and C is the flaw size. To estimate the fracture toughness, K_c, we need to know the flaw size present on one of the rods. If we assume that the flaw size of the abraded sample is the same as the grit on the abrasive paper, i.e. 60π microns, then for a flaw size of 60 microns and a fracture stress of 70 MPa, (after dropping) the fracture toughness K_c is found as:

$K_c = 70x10^6$ Pa x $(60x10^{-6})^{1/2}$ $m^{1/2}$ = 0.54 $MPa.m^{1/2}$

The flaw sizes for the as-received sample, abraded and flame polished rods can now be calculated from their respective mean fracture stresses. In comparison with the as-received sample, the abraded samples have a larger average flaw size, whereas the flame polishing reduces the average flaw size. The important conclusion is that the introduction of larger flaws into the surface of a brittle glassy material will lower the stress at which it fractures. This means that the samples with larger flaw sizes will always break easier and faster.

As also indicated in Ref. [5], the glasses contain microflaws at the smaller length scales. The initiation of the cracks start at this point through nucleation of smaller cracks, which then propagate as the applied stress increases on the glass rod. After the critical limit, these cracks ultimately give rise to the fracture of the glasses. It means that the fracture is a two-step process. So, the history of the glass subjected under certain stress is very important to know the fracture behaviour and hence to predict the mechanical behaviour of glasses. This must be supplemented by the observation of flaw sizes, their number and also the orientation. A classic example is that a piece of glass with uniform distribution of smaller size flaws might not crack so easily compared to another glass having less uniform distribution with the same number or even lesser number of flaws.

Therefore, the flaw sizes within the glass matrix and/or on the surface will clearly determine the suitability of a particular glass composition in a given environment. For example, for windows or large glass doors in a dusty environment (say, near a Thermal Power Plant with abrasive "fly ash" flying around), the resistance of the float glass or normal window glass has to be mechanically much stronger, or rather they have to contain lesser number of flaws with smaller size. Under each value of flaw size for the above three samples, the 'mean fracture stress' in MPa is given in third bracket in the table that is shown below:

Sample	**Flaw Size (micron) [Mean Fracture Stress (MPa)]**
As-received	21 [118]
Abraded	58 [70]
Flame Polished	17 [132]

As far as the statistical treatment is concerned, it is seen that the standard deviation calculated for each of the experiments is fairly large. It is the largest for the as-received rods and this reflects some statistical variation, possibly due to fluctuation of composition at smaller length scales, i.e. inherent inhomogeneity. The introduction of flaws of a certain dimension or the removal of the majority of the flaws from the surface (for example, by flame-polishing) causes a reduction in the standard deviation. Under given conditions, microflaws in different pieces of material will vary in size, number and orientation. From this observation, it becomes evident that there will be some statistical variation in the fracture stress of each sample. This could happen even if several samples are made from the same large piece of material.

CONCLUSIONS

From this investigation, it is now understood how flaws affect the stress at which a material will fracture. All materials contain defects, and in brittle materials such as glasses, these defects act as tiny pre-existing cracks, which could propagate through the material to cause fracture. The propagation of these cracks is dependent on an energy balance, which leads to a critical crack length. The stress at which a glass fractures depends on the size of the largest flaws present, i.e. the larger the flaw, the lower the fracture stress. For commercial soda-lime-silicate glass, the behaviour is dominated by the surface defects, and the condition of the surface of the glass controls its strength. If steps are taken to remove or avoid the presence of defects, then the glass can be very strong. However, without special precautions, the strength of the glass is rather low and can show substantial statistical variations.

REFERENCES

1. A. K. Varshneya, Strength of Glass in “ Chemistry of Glasses”, Ed. A. Paul, Chapman & Hall, London (1982), 140.
2. J. J. Mecholsky, S. W. Freiman and R. W. Rice, “Effect of Surface Finish on Strength of Fracture of Glass”, Proc. Xlth Intl. Congr. on Glas, Pragu, July (1977).
3. K. Supputtamongkol, K. A. Anusavice and J. J. Mecholsky, “Fracture mechanics analysis of crack shapes by cyclic loading in Ba-silicate glass” J. Mater. Res. (2007).
4. A. K. Bandyopadhyay, “Nano Materials (Chap 5)”, New Age Sci., (Turnbridge Wells, Kent, UK, 2010).
5. A. K. Bandyopadhyay, “Theoretical Strength for Brittle Glassy Materials”, KANCH, Vol. 5 [4] (2012), 13.
6. A. K. Bandyopadhyay, “Technology of Float Glass Process”, KANCH, Vol. 5 [3] (2012), 33.

Theoretical Strength for Brittle Glassy Materials

ABSTRACT

By changing the limit of integration within the zone where fracture occurs in brittle glassy materials, based on a sinusoidal approximation as used in the Griffith formulation of theoretical strength of such solids, a modification of the equation for theoretical strength can be achieved. This modified equation for theoretical strength has been developed using the linear Hook's law near to the maximum of applied stress by taking a small variation in the spatial elongation. This equation gives rise to a multiplication factor, which has to be used to predict the theoretical strength when micro-flaws are present in the glassy materials. This theoretical result is discussed in terms of the available data on fused silica and other materials that are used in the glass industry.

Keywords: Griffth equation, theoretical strength, Hook's law, Fused silica.

INTRODUCTION

In an article on float glass technology in KANCH [I], apart from various chemical aspects, the problem of thickness variations was discussed. However, the mechanical properties in terms of fracture of such glasses are also of great importance, since these glasses are mostly used in the building industry and facade decoration purposes, wherein fracture in any form can cause damage to the installation that will result in a loss to the investment made. Although the present article deals with the problem of fracture in brittle materials, such as glasses, the importance has to be given for float glasses, as these glasses have aesthetic appeal with the highest quality requirements so far the glass industry is concerned.

There has been a tremendous amount of work done in the field of fracture mechanics in brittle materials and glasses, particularly on their theoretical strength for a long time [2-8]. This is mainly done on Griffith equation based on the formation of an elliptical crack and its main plank is the utilization of material parameters or constants, which are measurable, in designing suitable materials for various important applications [2]. An insight should be obtained on the nature of theoretical strength based on a sinusoidal approximation in the stress vs. spatial elongation curve (see Fig. 1). In the context of this approximation, in the present article, our main focus is on the "fluctuation" of the spatial elongation value at or near fracture so that a modified equation can be developed to better predict the theoretical strength of glasses.

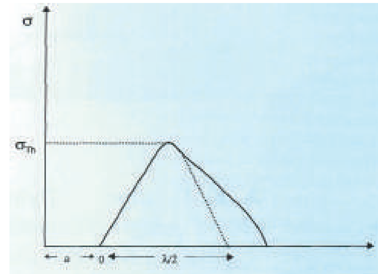


Fig. 1: Stress vs. elongation curve with sinusoidal behavior

Although the subject of much research over the past decades, the fracture of brittle glassy materials remains in many ways not understood. Of particular interest is the mechanism by which energy in the system is dissipated. Experimental measurements of the flow of energy into the tip of a running crack have indicated that the fracture energy (i.e., the energy needed to create a unit extension of a crack) is a strong function of the crack's velocity and that the majority of the energy stored in the system prior to the onset of fracture ends up as heat. An example of the fracture of soda-lime-silica glass has been taken into consideration. Residual stress profiles were introduced in sodium aluminosilicate glass disks using an ion-exchange process, i.e. after chemical strengthening. They were fractured in two loading conditions: indentation and biaxial flexure. The fractal dimension of the macroscopic crack branching pattern called the crack branching coefficient (CBC), as well as the number of fragments (NOF) were used to quantify the crack patterns. The fracture surfaces were analyzed to determine the stresses responsible for the crack branching patterns. The total strain energy in the body was calculated. The CBC was a good measure of the NOF. They are directly related to the tensile strain energy due to the residual stress profile for fractures due to indentation loading. However, in general for materials with residual stresses, CBC (or NOF) is not related to the strength or the stress at fracture, or even to the total stored tensile strain energy. A study was done to determine the geometric characteristics associated with the critical crack caused by cyclic loading in baria silicate glass [9] (see the references therein for other useful references). Next, we show the theoretical side of the story.

THEORETICAL DEVELOPMENT

The theoretical strength (σ_{Th}) of a 'body' is the stress required to separate it into "two parts", with the separation taking place simultaneously across the cross-section. To estimate σ_{Th}, let us consider 'pulling' on a cylindrical bar of unit cross section. The "force of cohesion" between the two planes of atoms varies with their separation, after the inter-atomic spacing (a):

$$\sigma = \sigma_{Th} \sin\left(\frac{2\pi X}{\lambda}\right) \qquad ...(1)$$

A part of the curve is approximated by the sinusoidal relation [3], as shown in Fig.1. This equation represents the so-called governing equation of stress (σ) against the spatial elongation (X). The work per unit area to separate the two planes of atoms is then calculated by the integral of the curve between X = 0 and X = λ/2:

$$\int_0^{\lambda/2} \sigma_{Th} \sin(\frac{2\pi X}{\lambda}) dX = \sigma_{Th}(\frac{\lambda}{\pi}) \quad ...(2)$$

This work or energy is then equated with the surface energy (2γ) of the two newly created surfaces that give rise to $\sigma_{Th} = (\frac{2\pi\gamma}{\lambda})$ for the initial part of the curve near the equilibrium spacing (a), as in Fig. 1.

As we know, from the Hook's law that $\sigma = E(\frac{X}{a})$, where, E = Young's modulus. At this small part of X of this curve, from Equation (1), the following relation has been deduced:

$$\int_0^{\lambda/2} \sigma_{Th} \sin(\frac{2\pi X}{\lambda}) dX = \sigma_{Th}(\frac{\lambda}{\pi}) \quad ...(3)$$

This is done at X = 0. Equating this with the Hook's law i.e. $\sigma_{Th} = (\frac{2\pi\gamma}{\lambda})$ we get the following:

$$\sigma_{Th} = (\frac{E\gamma}{a})^{1/2} \quad ...(4)$$

Typical values of E = 3 x 10^{11} dynes/cm^2, y= 10^3 ergs/cm^2 and E = 3 x 10^{-8} cm, and σ_{Th}= 10^{11} dynes/cm^2 as per equation (4). If λ≈a, then we can show σ_{Th} varies from E/5 to E/10. For window glass, the strength is 10^4 psi, σ_{Th} = E/1000, and for alumina ceramics, the strength is 5 x 10^4 psi, σ_{Th} = E/1000. It has to be noted here that alumina is an important component in the window glass composition, as suitable mechanical strength is desired by the consumers.

Therefore, between the theoretical predictions and the actual experimental values, there is a discrepancy, which needs to be solved. It should be mentioned that involving material's constants (E and γ) and half of the elliptical crack length (c), Griffith's criterion of the maximum strength at which the material fails on cracking is based on the above equation. Hence, this equation certainly merits careful attention. Moreover, in line with Griffith's concept of micro-flaw formation, the reduction of theoretical strength also merits further attention. Flaws in this kind of brittle glassy materials may not have the nature of classical Griffith micro cracks, but may rather take the form of embryonic defects with intensely concentrated residual stress fields [9,10].

In the above mathematical formulation, the limits of integration have been taken between 0 and λ/2, i. e. the work or energy is calculated upto a limiting point (i.e. λ/2) before which the material has already cracked, whereas linear Hook's law has been applied to the other end, i.e. at X = 0, when σ = 0. It should be clearly mentioned that the value of σ is maximum, which is the value of σ_{Th}, at X = λ/4.

In this theoretical development, we are inclined to take a 'small variation' around this value of X around λ/4. Let us assume that this variation is δ, i.e. the maximum strength can be assumed to be arrived at (λ/4). A brittle material cracks at or just after σTh, we can do the integration of equation (1) upto a limit of (λ/4 +δ) for the energy formulation in order to be able to be equated with the surface energy (2γ), instead of extending it upto λ/2, when the material or glass has already cracked or fractured. However, for linear Hook's law, it can be easily applied at (λ/4 -δ), when it is perfectly possible to differentiate σ at X = (λ/4 -δ), which was done at X = 0 as in equation (3). Therefore, the basic tenets of these two approaches are clear from the above. Under the above assumption, we find the total work done and equate with the surface energy of the newly created surfaces due to fracture. After some differentiation and mathematical workouts, we arrive at the modified Griffith equation as:

$$\sigma_{Th} = \sqrt{\frac{\frac{E\gamma}{a}}{\left(\frac{\pi\delta}{\lambda} + \frac{2\pi^2\delta^2}{\lambda^2}\right)}} \qquad ...(5)$$

Therefore, it is clearly seen that our above equation will put an incremental effect on the theoretical estimate of maximum strength with respect to a simple Griffith criterion $(E\gamma/a)^{1/2}$ involving the material parameters, with "a" replaced by half of the elliptical crack length. It is known for a long time that Griffith criterion of predicting and eventually designing the right materials, only through measurable material properties like surface energy (γ) and elastic modulus (E), has been very popular, since the equilibrium interatomic distance (a) is approximately known for glasses.

RESULTS AND DISCUSSION

It should be pointed out that if we put δ/λ to be much less than 1/4, then it would be possible for us to predict the correct theoretical strength of brittle glassy materials. Therefore, this equation (5) can be used to precisely do this prediction by adjusting the value of δ/λ. For example, for three different values of δ/λ = 0.1, 0.01, 0.001, we have to multiply Griffith value (under the square root sign) with 1.40, 5.47 and 17.10 respectively. In the literature, very often, there is a factor of √2 in the Griffith's value. In the first case, our assumption of taking the value $\delta/A = 0.1$ gives rise to a multiplication factor of 1.40 (close to $1.414 = \sqrt{2}$).

The above treatment will help us analyze a variety of materials with different values of the ratio of δ/λ (non-dimensional value) to fit the experimental value with that of the theoretical estimate. Since both the values of δ and λ are not measurable, it is always better to take a ratio to estimate the strength as per equation (5).

Let us take the example of a common glass, where the value of σ_{Th} is 14 GPa as per equation (4), but as the experimental values are always lower, Griffith [2] put forward a new equation of $\sigma = (2E\gamma/\pi L)^{1/2}$, where L = length of the micro flaws, which were considered to reduce the strength, as in many other brittle materials. As per this revised equation, Griffith [2] postulated that even micron (10^{-6} m) sized flaw could reduce the observed strength of the glass by a factor of 100. Thus, the ratio δ/λ is to be still lower, and the multiplication factor is higher. Actually, this ratio clearly dictates the presence of micro-flaws.

Finally, an example of fused silica is given here, as we normally try to understand its behavior with that of float or other glasses. The parameters are: $\gamma = 1.75$ J/m^2 and E = 72 GPa and taking a = 1.6 x 10^{-10} m, we find a theoretical value of strength as per equation (4) as 28.1 GPa, whereas the experimental value is 24.1 GPa. The close similarity of these values clearly indicates that it does not take the 'micro-flaws' into account. The theoretical value should be much higher. By multiplying the Griffith value with 1.40 (i.e. $\delta/\lambda = 0.1$), we estimate the strength value as per equation (5) as 39.34 GPa. This discrepancy (or even more discrepancy) will actually justify the presence of the 'micro-flaws' in fused silica, which is a known fact [7,10]. However, an analysis can be based on the estimated value of strength as 28.1 GPa.

As per the revised equation of Griffith involving micro-flaws, if we take the size (L) of the flaws at the quantum level, i.e. the value of "a" in equation (4), the theoretical strength goes down to 22.39 Gpa. As the size of the flaw increases to a level normally considered in the micron level, the value goes down by a factor of 100, i.e. it becomes 0.2239, as also mentioned above. This necessitates the inclusion of the ratio δ/λ in the calculation of theoretical strength, which should also be in consonance with the data on fused silica on the probable flaw size.

The concept of micro flaws needs to be introduced, which is calculated from our equation (5) taking smaller values of δ/λ ratio. It is seen that as the level of micro flaws goes to a "usual" granular level, the value of δ/λ ratio becomes still smaller, and the need for a higher multiplication factor. It is pertinent to mention that although the data for fused silica are fitted here, the information given above can be obtained on a variety of other ceramic brittle materials in order to be able to explain the discrepancy between theoretical and experimental values of strength for effective design.

Here, we have calculated theoretical strength of different materials at the flaw size of 1.6xl0^{-10} meter using the equation (4) and are trying to show that how theoretical strength of materials (σ_{Th}) changes with fluctuation ($\frac{\delta}{\lambda}$) as per Equation (5). It is always true to the fact that different materials have different theoretical strength (σ_{Th}). It is clear from the Eqn. (5) that with an increase in the $\frac{\delta}{\lambda}$ ratio, there is always decrease in the theoretical strength of the material. Thus, the characteristics of different materials are shown in Fig. 2. Except NaCl, all the materials in Fig. 2 are used in the glass industry and their comparison with the data of fused silica makes sense in understanding the overall mechanical behavior of commercial glasses. It is clear that the different materials of the same $\frac{\delta}{\lambda}$ ratio have different value of theoretical strength. The theoretical strength of magnesia (MgO) is at the highest level and its value is 64.23 GPa. The next material is alumina ($A1_2O_3$), then glass, fused silica and sodium chloride (NaCl) respectively. The material having the lowest theoretical strength is sodium chloride (NaCl) whose theoretical strength value is 18.36 GPa.

CONCLUSIONS

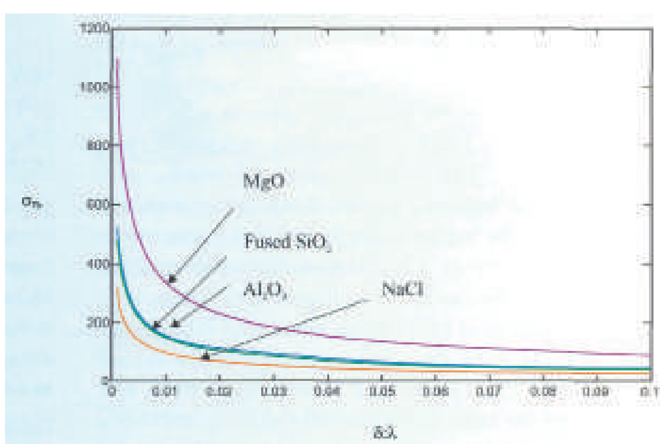


Fig. 2 Theoretical Strength vs. fluctuation for different materials

The modification of the basic equation on theoretical strength has been achieved, within the context of a sinusoidal approximation in the applied stress vs. spatial elongation curve [3], by assuming a small spatial variation and by changing the limit of integration in the energy formulation for crack formation. This modification yields a ratio of this variation giving rise to a multiplication factor, which can correctly predict the theoretical strength of brittle ceramic materials. The available data on fused silica has been fitted with this new model and found to be effective in explaining a lower observed strength due to the presence of micro-flaws. Many such data on other brittle ceramic materials can be fitted in future to give it a comprehensive shape.

ACKNOWLEDGEMENTS

The author would like to thank Prof. Loc Vu-Quoc of Department of Mechanical Engineering at University of Florida (USA) for many stimulating discussions during the preparation of this manuscript.

REFERENCES

1. A. K. Bandyopadhyay, "Technology of Float Glass Process", KANCH, Vol. 5 (3) (2012), 33.
2. E. Orowan, Inst. of Engg. & Shipbuilders in Scotland, 42 (1945-6), 165.
3. A. A. Griffith, Phil. Trans, of Royal Society, Series A, 221 (1920), 163.
4. W. D. Kingery, H. K. Bowen and D. R. Uhlmann, Introduction to Ceramics, John Wiley & Sons, New York (1976), 783.
5. S. M. Wiederhorn, J. Am. Ceram. Soc., 50 (1967), 407.
6. G. R. Irwin, Encyclopedia of Physics, Vol. IV, Springer-Verlag, Berlin (1958), 551.
7. W. B. Hillig and R. J. Charles, High Strength Materials, Ed. V. F. Zackay, John Wiley, New York (1965), 682.
8. A. K. Varshneya, Strength of Glass in "Chemistry of Glasses", Ed. A. Paul, Chapman & Hall, London (1982), 140
9. K. Supputtamongkol, K. A. Anusavice and J. J. Mecholsky, "Fracture mechanics analysis of crack shapes by cyclic loading in Ba-silicate glass" J. Mater. Res. (2007)
10. A. K. Bandyopadhyay, "Nano Materials (Chap 5)", New Age Sci., (Tunbridge Wells, Kent, UK, 2010).

Special Glasses for Electro-Chemical Applications

ABSTRACT

Technology is driven by the development of basic science, whose principles are eventually used in the design of various technologies, and glass technology is no exception in this respect. While appreciating the evolution of glass technology over many hundred years, comparatively speaking, development in the field of newer types of glasses and moreover on the newer types of applications is relatively recent. Some details on special types of glasses are presented for "electrochemical applications" for sensors in order to appreciate how the development takes place by the need of the society.

INTRODUCTION

Glasses have been used for various purposes for thousands of years. However, until recently, silicate glasses were the major type of material that was commonly used by the households, different industries, building and other construction purposes, decorative applications, etc. The advent of float glasses has also evoked a number of new applications [1]. During the past decades, so many new types of glasses have been discovered for satisfying different technical and other needs of human society. The method of fabrication of such type of so-called technical glasses with a wider composition range outside the realm of silicates comes into existence. The refinements of the process technology are continuously evolving for satisfying the needs of the hour, and thereby cutting cost and easy availability. In that sense, there is a similarity with those evolution processes of commercial silicate glasses. A comparison is beyond the scope of this present article.

These special or technical glasses are available in the form of both bulk and thin-films. From the business point of view, it makes sense for value addition and it gives a very good measure of "tonnage to investment" ratio. This might be one of the main reasons for their rapid development and also the expansion of the field of work, and thereby extending the range of their usage, e.g. in electro-chemical, electronic, magnetic and optical applications. Some of these applications could be considered predominant in the hi-tech domain.

Glassy materials have several advantages over their crystalline counterparts as far as applications are concerned. Generally speaking, glassy materials are relatively much easier to fabricate: large areas [2], homogenous thin-films [3], complicated shapes [4] could be prepared. For example, Si:H for solar cell or thin-film transistors, while bulk glasses could readily be prepared from the melt of different volumes by relatively slower quenching procedure or by sol-gel route. Moreover, quite importantly, the material of fabrication could remain workable near the glass transition temperature. This means that the viscosity remains relatively low for the glass to be workable over the range of temperature so that it could be fashioned into various shapes and sizes, or drawn into fibres, as desired. It should be further noted that particularly bulk glasses are often structurally homogeneous and isotropic on macroscopic length scale (i.e. uniform property in any direction). As a result, the concerned physical properties are also isotropic and homogeneous unlike crystalline materials for which the intrinsic behaviour of even single crystals may be anisotropic (i.e. different values of a given property in different directions), and also the presence of 'grain boundaries' in polycrystalline samples could dominate the overall behaviour.

Therefore, the large-scale optical transparency is readily achievable, e.g. in silicate glasses for optical components including optical windows and fibre-optic cables for optical communication systems. The absence of structural defects, such as grain boundaries or dislocations as an area of concern in crystalline materials, also has a tremendous impact on the 'mechanical behaviour' and on the use of glassy materials in mechanical engineering applications. Due to this mechanical advantage, the glasses could often reach the 'ideal' value of mechanical strength and consequently the fibres of silica glass or ribbons of metallic glasses could be used as fibre-reinforcement elements in composite materials. It has to be noted that some of these composites could be very expensive in the aviation industry.

Moreover, glassy materials have another important advantage over their crystalline counterparts in getting a homogeneous structure even in the multi-component systems in a wide range of compositions. The physical properties are sometimes "additive" in nature, and they can be varied continuously by changing the percentage of one or more components within a particular base-glass composition. In this way, in the ornamental or decorative silicate glass matrix, the intensity of the colour can be controlled by varying the concentration of transition metal ions, i.e. colouring agents.

In this paper, one of the important technological applications of glassy materials is explored. In particular, here electro-chemical applications are considered in terms of electro-chemical sensors in Part-I. In the Part-II for the same application, solid-state batteries based on glassy materials will be described, i.e. it is focussed on two most popular applications in the field.

ELECTRO-CHEMICAL APPLICATIONS

Preamble

The diffusion of different alkali ions, such as Na^+, K^+ or Li^+ and alkali metal ions, e.g. Ag^+ inside the glass matrix is important to understand different chemical behaviours of glasses. This diffusion is a thermally-activated process and hence to stop diffusion of such ions at higher temperature of exposure of a given glass could be somewhat difficult. Likewise, the same is true for the chemical corrosion of a glass at elevated temperature. This behaviour can be also due to a chemical gradient and an electric field gradient.

The ability of such ions to diffuse readily in oxide or chalcogenide (i.e. sulphur, selenium, and tellurium) based glasses in the present of a concentration gradient or an electric field opens up a range of options in the field of electro-chemical applications. For example, in energy storage (batteries), displays or chemical sensors, glassy materials can be good candidates by offering certain advantages in such applications over their crystalline or liquid counterparts. Glassy electrolytes that could be often made in the form of thin-film have more isotropic diffusion compared to many well known crystalline electrolytes.

For commercial glass production, the difficult matter of electrochemical behaviour of glass melts and solid glasses that lays the foundations for a sound understanding of physico-chemical redox and ion transfer processes is of fundamental importance. Also, the interpretation of experimental results as well as the control of production processes, including refining, interface reactions and thermodynamic equilibria of glass melts with refractories and the surrounding atmosphere, could be better understood with the knowledge of this behaviour.

The Definitions

Electrochemistry is a branch of chemistry that studies chemical reactions which take place in a solution at the interface of an electron conductor (the electrode: a metal or semiconductor) and an ionic conductor (the electrolyte), and which involve electron transfer between the electrode and the electrolyte or species in solution.

If a chemical reaction is driven by an external applied voltage, as in electrolysis, or if a voltage is created by a chemical reaction as in a battery, it is an electrochemical reaction. In contrast, chemical reactions where electrons are transferred between the molecules are called oxidation/reduction (redox) reactions. In general, electrochemistry deals with situations where oxidation and reduction reactions are separated in space or time, connected by an external electric circuit. Oxidation and reduction always occur in a paired fashion such that one species is oxidized when another is reduced. This paired electron transfer is called a “redox” reaction.

An electrochemical cell is a device that produces an electric current from energy released by a spontaneous redox reaction. This kind of cell includes the Galvanic cell or Voltaic cell, named after Luigi Galvani and Alessandro Volta. Both scientists conducted several experiments on chemical reactions and electric current during the late 18th century. Electrochemical cells have two conductive electrodes (the anode and the cathode). The anode is defined as the electrode where oxidation occurs and the cathode is the electrode where the reduction takes place. Electrodes can be made from any sufficiently conductive materials, such as metals, semiconductors, graphite, and even conducting polymers. In between these electrodes is the electrolyte, which contains ions that can freely move.

To provide a complete electric circuit, there must also be an ionic conduction path between the anode and cathode electrolytes in addition to the electron conduction path. The simplest ionic conduction path is to provide a liquid junction. To avoid mixing between the two electrolytes, the liquid junction can be provided through a porous plug that allows ion flow while reducing electrolyte mixing. To further minimize mixing of the electrolytes, a salt bridge could be used which consists of an electrolyte saturated gel in an inverted U-tube. As the negatively charged electrons flow in one direction around this circuit, the positively charged metal ions flow in the opposite direction in the electrolyte. A voltmeter is capable of measuring the change of electric potential between the anode and the cathode. Electrochemical cell voltage is also referred to as electromotive force or simply e.m.f.

Electro-Chemical Sensors

At the interfaces between the cathode or anode and an electrolyte (i.e. a glass), there are certain electro-chemical processes taking place. This can be used to measure the concentration or activity of the electrochemically active ionic species in the electrolyte. This is done by simply monitoring the e.m.f. of the cell thus formed. Hence, if glassy materials have to be used as ion-selective electro-chemical sensors, they should satisfy the requirements for their use in the energy-storage or battery applications.

The so-called ‘glass electrode’ that is commonly employed to monitor proton activity or pH level of a given chemical solution is the breeding ground for the widespread use of glassy materials as an electrochemical sensor [5,6]. In this type of sensor, a cell is constructed from the glass membrane in the form of a sealed tube containing an internal ‘buffer solution’ and reference electrode, i.e. the glass electrode, together with another reference electrode and both are in contact with the solution being measured. For the glass electrode, the glass that is used for the active membrane could be a simple alkali-silicate glass, if hydrogen ion concentration or pH has to be measured. Otherwise, various alkali-alumino-silicates or boro-silicate glasses could be employed, if the "alkali-ion selectivity" (pM, where M = alkali metal ion) is desired. Normally, one could use any glass as long as the type of alkali ion that is used as a "network modifier" in the glass electrode should be different from that which is desired to monitor the solution.

The mechanism underlying the operation of the glass electrode can be appreciated as follows [6]: Let us consider a simple alkali-silicate glass. The surface of the glass electrode contains - Si - O - M' groups, where M' is the modifier ion in the glass, and it is in contact with an aqueous solution containing M^+ ions. The single "dash" on the left hand side of Si atom actually consists of three bond directions. Here, as said above, M' and M^+ are different alkali metal ions. These groups will totally dissociate, as there are no M' ions in the solution. In this condition, there will be a complete equilibrium that can be attained by the resulting surface 'siloxy' groups (– Si – O^-) with the protons in the solution forming "silanol" groups as:

$$SiOH + H_2O\ SiO^- + H_3O^+$$

For this reaction, the e.m.f. of the cell reaction can be written as **[6]:**

$$E = - (RT/F)\ 1n\ K_d + (RT/F)\ ln\ [(a_{H30} \cdot a_{sio-})/a_{siOH}]$$

Where R is the gas constant, F is the Faraday's constant, K_d is the dissociation equilibrium constant for the silanol group reaction, and a_x is the activity of the respective species involved in the reaction process. Therefore, the above equation shows that the e.m.f. of the glass electrode should be linearly proportional to pH. This behaviour can be experimentally observed over a pH range of 10-11 units. The metal ion (pM) response of the glass electrode can be regarded as arising from an association equilibrium between siloxy group at the surface and metal ions in the solution as:

$$\text{-- Si - O - } M^+ \text{ (solution)} <=> \text{--Si - } O^- \text{....} M^+.$$

In this case, an expression similar to that of the above e.m.f. equation can be derived, whereby K_d is replaced by the 'association constant' (K_a) for the above equilibrium reaction. Here, a_{H30+} is replaced by a_{M+} and hence the e.m.f. is linearly proportional to pM.

As oxide glasses are used to normally fabricate ion-selective membranes, it was demonstrated that chalcogenide glasses (e.g. As_2Se_3) doped with an appropriate metal can be used as the basis for electro-chemical sensors for Cu^{2+} or Pb^{2+} ions, and Hg^{2+}

or Cd^{2+} ions, respectively [7]. These sensors appear to be attractive, as the glasses are predominantly electronically conducting, rather than ionically-conducting. Hence, the problem with the reversibility at the interface between the membranes and the back contact are relatively minimized. Barium-boro-vanadates are glassy semiconductors that could also be used for this purpose [8].

Newer Developments

A majority of newer developments have taken place around nano materials or glasses containing different nano varieties. Electrochemical devices have the potential to pose powerful solutions in addressing rising energy demands and counteracting environmental problems. However, currently, these devices suffer from meager performance due to poor efficiency and durability of the catalysts. These suboptimal characteristics have hampered widespread commercialization. It was reported that $Pt_{575}Cu_{147}Ni_{53}P_{225}$ bulk metallic glass (Pt-BMG) nanowires had novel architecture and outstanding durability that could circumvent the performance problems of electro-chemical devices [9]. Pt-BMG nanowires were fabricated using a facile and scalable nano-imprinting approach to create de-alloyed high surface area nanowire catalysts with high conductivity and activity for methanol and ethanol oxidation. After 1000 cycles, these nanowires maintained 96% of their performance, i.e. 2.4 times as much as conventional P1/C catalysts. Their properties make them ideal candidates for widespread commercial use such as for energy conversion/ storage and sensors [9].

A new approach was used to investigate a well-known chemical process, the propagation of electro-chemical signals through a thin glass membrane. This process, which has been extensively studied over the last century, is the basis of the response of a potentio-metric glass pH sensor, as no ampero-metric glass sensors have yet been reported because of its high ohmic resistance. Voltammetry at nano-electrodes has revealed that water molecules could diffuse through nanometer-thick layers of dry glass and undergo oxidation/ reduction at the buried platinum surface. After soaking for a few hours in an aqueous solution, voltammetric waves of other redox couples, such as $Ru(NH_3)_6$ could also be obtained at the glass-covered platinum nano-electrodes. This behaviour suggests that the nanometer-thick insulating glass sheath surrounding the platinum core could be largely converted to hydrated gel, and electrochemical processes occurred at the platinum/ hydrogel interface. Potential applications range from use in solid-state pH probes in the nanometer scale and determination of the water content in organic solvents to glass-modified voltammetric sensors and electro-catalysts.

CONCLUSIONS

In the Part-I of this article, the electro-chemical behaviour has been shown to be important for technical applications as sensors as well as in understanding the behaviour of both liquid and solid commercial glasses in terms of production processes. After a general introduction and basic definition of the process, the behaviour of glass sensors has been shown with required theoretical explanations. Some newer developments have been covered very briefly. Considering the widespread use of such sensors, it is argued that such materials should be produced in bulk volume with continuous research and development efforts, as the return on investment is quite high.

REFERENCES

1. A. K. Bandyopadhyay, "Technology of Float Glass Process", KANCH, Vol. 5 [3] (2012), 33.
2. J. Zarzycki, "Les Verres et 1'Etat Vitreux", Mason, Paris, (1982).
3. A. K. Bandyopadhyay, "Nano Materials", Tunbridge Wells, UK (2010).
4. A. K. Bandyopadhyay, KANCH, Vol. 6 [1], (2012), 31.
5. F. G. K. Bauck, "Glass: Current Issues", A. F. Wright and J. Dupuy (eds.), Martinus Nijhoff (1985), 481.
6. G. Eisenman (ed.), "Glass Electrodes for Hydrogen and Other Cations: Principle and Practice", Dekker, (1967).
7. A. E. Owen, J. Non-Crystalline Solids, Vol. 35, (1980), 999.
8. A. K. Bandyopadhyay, J. O. Isard and *S.* Parke, J. Phys. D: Applied Physics, Vol. 11, (1978), 2559.
9. M. Carmo et al., ACS Nano, Vol. 5 [4], (2011), 2979.
10. J. Velmurugan, D. Zhang and M. V. Mirikin, Nature Chem., Vol. 2, (2010), 498.

Shaping Special Glass Components and the Uses of Carbon

ABSTRACT

The importance of carbon in the form graphite is described in the glass industry for fabrication of special glass components. Various techniques have been described in terms of process technology as well as their advantages. This opens a new area of producing special items with high value addition that is considered a good business strategy.

INTRODUCTION

Carbon is a very important material both in various industries as well as in various scientific investigations. In particular, in glass industry, the importance of its use cannot be denied. There are various forms of carbon. In the form of "graphite", carbon is used by the 'glass blower' for making tool material for shaping various products of scientific uses. However, this graphite form of carbon has several drawbacks, such as strength and durability that are lower than those of cast iron, which is normally used for glass moulds. However, it does have the desirable property that it will not stick to any fluid (hot or cold) glass, even though it might reach the temperature of the glass at the formation point.

This indicates that graphite can be used to shape glass to metallic seals and similar glass compositions that are made in a tank furnace, which requires that a non-oxidizing atmosphere prevails in the furnace in order to prevent its attack. The electrical conductivity of graphite allows it to be heated by radio frequency (RF) induction, and therefore, it could form both oven and glass mould if required.

For the manufacture of 'glass tubing' into unconventional shapes, graphite formers and mandrels are used. For example, a rectangular section graphite mandrel drawn through a heated cylindrical glass tube of suitable size will make a 'rectangular' section glass tube. In a similar manner, commercial tubing of variable internal diameter could be given a semi-precision bore. In this short article, some refinements to these techniques are presented so that the readers get a quick grasp on the utility of graphite in the glass industry.

VARIOUS TECHNIQUES

There are various techniques available for the use of graphite in shaping special glass components. In this section, mainly three specific techniques will be described, such as: 1) Use of Mouldable Graphite, 2) To Form Glass Envelopes by Flowing Conical Glass over Carbon Patterns, and 3) To Form Glass Shapes in Carbon Moulds by the Use of Centrifugal Force.

Use of Mouldable Graphite

Solid graphite is commercially available in the carbon industry, particularly those manufacturing graphite electrodes for melting various metals and also oxides as fusion products. The solid graphite can be usually utilized for machining graphite moulds. For the well-known application, such as 'glass to metal seals' fabrication, this is evidently the easiest method of manufacture.

However, as a 'by-product' of other works, a method has been developed in UK quite some time ago to prepare solid graphite from a suitably loaded graphite powder by pressing it with a heated moulding tool. In this process, any required pattern included into the 'moulding tool' can be formed in the graphite. A broad outline is given as follows:

A) Industrial graphite powder is mixed with phenol/formaldehyde type of resin and a special type of hardener. The mix is then pressed in the warm moulding tool that is heated at 150°C. The pressure varies according to the final surface requirements and it ranges between 100 and 1500 psi. The graphite shape is then removed from the mould and heated at 840-850°C in a hydro-carbon bearing atmosphere for a few hours to fill the pores with dense carbon. Due to the closure of pores, the shrinkage occurs, but this could be controlled so as to make it negligible.

B) Evidently, any pattern without re-entrants that can itself withstand the moulding pressure and temperature could be reproduced, and the process is mainly used to make carbon 'spark eroding' tools. Glass working applications are increasing and some examples are listed below, which are both useful and decorative:

1) Glass Reproduction of Plaques and Medallons - These are made by centrifugally coating glass into moulded carbon,
2) Mould Blown Glass Tube - These bulbs are conventionally blown in carbon moulds, which again withstand the treatment remarkably well, and

3) These are conventionally pressed by using carbon moulds formed from an original pattern, instead of using cast iron moulds. The carbon moulds and the dies last quite long enough to give sufficient faceplates for pre-production work.

To Form Glass Envelopes by Flowing Conical Glass over Carbon Patterns

Cathode-ray tubes are used in various scientific instruments and they can be made in various shapes. For a glass envelope, typically a cathode-ray tube, if a non-standard shape is required, it is usually necessary to make a pressing or blowing mould from cast iron to the new form. This could be a time-consuming operation, and due to subsequent modifications to the moulds are difficult, it is not practical to experiment with the 'envelope shape' to any great extent.

At least for pre-production quantities, the mould making process can be bypassed by taking a block of graphite and sculpting it to the required internal bulb shape. A standard envelope or "cone" of adequate wall thickness and reasonably close dimension to the new form is then heated and pushed over the graphite until it conforms to this shape. Normally, the graphite former is held on one chunk of a 'glass lathe' that could be worked with the bed either vertically, horizontally or at any intermediate position. While the flame heating is done, the glass bulb is held in the other chunk and the two are brought together.

At this stage, the bulb gets deformed and it is gradually paddled and work around the graphite. At the end of this operation, vacuum could be applied to bring any glass not coming into full contact with the former. Then, the glass is removed and annealed, and finally trimmed to size. It is now obvious that a special operational skill is required to keep the glass flowing in the preferred direction. It is important to maintain adequate wall thickness and the outside dimension must be kept within reasonable limits, although the latter is difficult to control.

There is an advantage of using this technique, i.e. the 'speed' with which a new form is developed. In a matter of few hours of work that is necessary to carve the graphite block provided the shape is not difficult, and with a few more hours of work, it is possible to provide the sample bulb. As the removal of graphite is important, the modification is easier to make and it has been found to be quite convenient to build blocks up from segments that are bolted together. Obviously, there is some graphite erosion during glass shaping, but it is within the acceptable limits, as the erosion-resistance of graphite is known to be quite high.

Although there are various other techniques available for using graphite in shaping special glass components, only one more technique will be mentioned that could be quite useful.

To Form Glass Shapes in Carbon Moulds by the Use of Centrifugal Force

It has been already stated that glass-to-metal seals are often formed in carbon moulds by passing the mould pre-loaded with glass and metal through a heated belt furnace. There is some kind of variation to this technique, i.e. to substitute for the belt furnace, a closed metal annular trough typically about 62 cm total diameter that could be horizontally rotated at a speed of 300-700 rpm about its own axis. As this rotation takes place within a heated furnace, any glass inside the drum will soften and will be thrown outwards by a 'centrifugal force'. This effect can be utilized to force glass into any carbon mould that is positioned outside it.

Generally, the carbon moulds are arranged vertically against the inside of the outer wall of the 'trough' with the glass and metal wires horizontal and they are projecting radially inwards. The rotation of the 'trough' and heating of the furnace make the pieces of glass to soften and it is forced outwards into their appropriate carbon mould cavities. In contrast to the 'static gravity feed', the advantages of this technique are as follows:

The glass could be in the form of a rod or tube rather than powder or sintered pre-forms. It does not have to fill the mould before spinning.

The plunger of the top mould is not required to force the glass into the mould detail.

Many small components, which are difficult or perhaps impossible to be formed in any other manner, become comparatively easy to form.

Nitrogen is generally used as an inert gas. The gas passes up through the central spindle and into the 'trough'. In addition to the usual type of compression soda glass seal and matched boro-silicate glass seal, it has been found that the seals using 'lead-glass' can also be made quite successfully, provided care is taken, although lead is a banned item for most of the special glasses.

Apart from the above advantages, there is also a disadvantage that is production related. Although a large number of moulds could be spun at one loading, the process is essentially a batch technique in contrast to the continuous operation of the belt furnace.

CONCLUSIONS

In this article, it is shown that carbon is very important material in the glass industry. In the form of "graphite", carbon is used by the 'glass blower' for making tool material for shaping various products of scientific uses. However, this graphite form of carbon has several drawbacks, such as strength and durability of cast iron that is normally used for glass moulds. However, it does have the desirable property that it will not stick to any hot or cold fluid glass, even though it might reach the forming temperature of the glass. Apart from various techniques available for processes for different difficult shapes and sizes, only a few techniques have been discussed here with their advantages for making a variety of special glass components. As these glass components make a high value addition in a given glass company, it could be thought of using these technique as a matter of strategy for better product-portfolio.

REFERENCES

1. F. V. Tooley, "Handbook of Glass Manufacture" (Vol. 2), Ashlee Pub. Co., New York (1984).
2. J. Zarzycki, "Less Verres et Letat Vitreaux", Mason, Paris (1982).
3. G. W. Morey, "The Properties of Glass", Reinhard, New York (1954).

Vitreous Silica and its Various Properties

ABSTRACT

Vitreous silica is a very important material in terms of its various properties and different uses in scientific laboratories and industries. Its structural property can be used as a benchmark for developing our knowledge on other more complicated commercial silicate glasses. Here, a brief review is given on vitreous silica and some interesting properties, notably its thermodynamic properties.

INTRODUCTION

In modern technology, silicate glass has been extensively used. There is a multitude of the specialized applications in communications, electronics and composites, wherein traditional uses for containers, windows, lamps, and optical components are being supplemented. Fibre optic waveguides, laser optics for initiating fusion reactions and container for radioactive wastes are some of the recent developments that demonstrate the importance, versatility, and promise of glass for additional uses.

Data on silicate properties of glasses are abundantly available in different textbooks, journals and corporate datasheets on glasses. Considering the utility of such glasses, risk can be taken even on repetition of certain known facts for the ready-made knowledge of the concerned readers. The objective of this article is thus to broaden our knowledge-base on a particularly important glass product, i.e. vitreous silica, to technologists and scientists, albeit these glasses are produced in a smaller scale of operation.

Compositionally speaking, it is the simplest silicate glass and has a lot of commercial importance. It is already known that many properties of silica normally guide our basic understanding of properties of multi-component silicate glasses, as the silicon-oxygen network is the fundamental structural component of all silicate glasses. It also determines many properties that depend on the distribution of such SiO_4 tetrahedral network.

For commercial silicate glasses, the compositions are generally expressed as representative and not always exact, because in commercial practice, especially for large tonnage glasses such as soda-lime-silica, wide variations in composition is tolerated for various applications. These variations are frustrating for controlled studies of properties and for some applications but must be recognized with a proper perspective. Most of property values for commercial glasses should be taken from the datasheets of various manufacturers [1].

VITREOUS SILICA

Vitreous silica (SiO_2) is the simplest silicate glass and for some properties such as strength and optical properties can be used as a starting point for the understanding of other commercial silicates glasses. Other properties such as viscosity, thermal expansion and electrical conductivity are strongly dependent on glass composition. Even for these properties, there are similarities in the behavior of vitreous silica and multi-component silicate glasses.

Vitreous silica is also called silica glass, fused glass, fused quart, or simply quart. The terms vitreous silica and silica glass are preferred because different methods of manufacture and starting materials give the same final structure, but quartz is not *a* suitable term because of the confusion of the crystalline quartz. Various Properties are discussed here.

Types of Compositions

As silica is the simplest form of raw material for any industrial glasses, it could be thought that it is very easy to choose silica as a raw material. In practice, it is not so, since there are not only different forms of silica existing in nature, but also there are a variety of locations with a range of different impurities that are present in silica. Hence, the choice of raw material in case of vitreous silica also needs special attention and consideration. Mainly, there are various types of silica. Some types are based on natural quartz crystals — either chunks or sand, as raw materials. So the impurity content is variable, but it can be reduced by pretreatment, especially of sand. There are other types that are purer, but they are quite expensive due to the nature of processing techniques and their cost.

Types of Uses

Vitreous silica is one of the purest materials commercially available. It is used for crucibles and furnaces for high-temperature processing, especially of semiconductors, for lamp envelopes, for electrical transducers and insulators, and for optical components such as fibre optics telescope mirror, lenses, and prisms. These uses become possible due to different properties of high purity, high-temperature stability, low thermal shock, low electrical conductivity and dielectric loss, high chemical durability and a wide range of high optical transparency. Even wider use of vitreous silica is limited by it’s high cost, that results from the high temperature which is needed to melt silica (nearly 2000°C) and the expense of the container and power used.

Two newly developing applications of vitreous silica are of special importance and interest: Optical Waveguide of vitreous silica of very high transparency, replacing metallic cables in many communications systems. The high optical transparency, resistance to radiation damage and easy formability of vitreous silica made it ideal for this application. The oxidation of silicon to form a thin layer of vitreous silica on its surface in "electronic devices" provides a stable, high-resistance insulator. The silica formed in this way has the same properties of bulk vitreous silica of high purity.

Method of Manufacture

Vitreous silica crucibles are often made by arc melting of quartz sand that acts as a self-container. This method gives many bubbles. Ingots of vitreous silica are made by heating quartz sand or chunks in crucibles of graphite, molybdenum, or tungsten in vacuum or in an inert or reducing atmosphere. The temperature is usually 1800 to 2000°C. It must be greater than the melting temperature of cristobalite of 1740°C. The ingot is then cut up or drawn to other shapes as tubing or rod.

Very pure vitreous silica is made from vapour-phase oxidation or hydrolysis of silicon tetrachloride ($SiCl_4$. In one method the $SiCl_4$ is mixed with oxygen and natural gas, fed through a burner, and deposited on a substrate of preheated sand or, on a rotating air-cooled mandrel of aluminum. The plasma can also be used. Fibres of silica can be pulled from a pre-formed vitreous silica rod or other convenient shape.

The most interesting method of fabrication of vitreous silica crucibles and other items for laboratory and technical uses is that due to Corning Glass Works (USA). It is called Vycor 7900 glass. This is made by etching a phase-separated boro-silicate glass to give finely porous structure - so called "thirsty glass" and then heating the porous material at ~1000°C to form a dense and clear glass. It contains about 96% SiO_2, 4%B_2O_3, and 0.03%Na_2O, K_2O and $A1_2O_3$. Due to the presence of boric oxide, the temperature and consequently the viscosity can be controlled for the purpose of easier fabrication of different shapes, as desired. The porosity in such compositions arises due to the presence of phase-separated globules all over the glass matrix and these globules get etched out by a treatment with acidic solutions leaving behind a fine distribution of pores that is finally removed by the heat-treatment.

The Structure

The basic structural unit of vitreous silica is obviously silicon-oxygen tetrahedron, as in all silicate glasses or crystalline silicates. There are two methods of determining the tetrahedral nature as the fundamental building block of silicate glass, such as small angle X-ray diffraction and neutron diffraction through Fourier analysis of the diffraction data. The method is to calculate the radial distribution function (RDF) from the diffraction diagrams through Fourier Transform technique and then plot it against distance [2]. The first peak due to Si-O bond is integrated by computer to determine the co-ordination number of silicon as “4”. In vitreous silica, these tetrahedra are linked to other tetrahedra at their corners in a 3-D network. The structure has order on a “short range” of a few Armstrong – one or two co-ordination of sphere of tetrahedra around a central atom (i.e. silicon), but no “long range” order beyond a few tetrahedra. This structure is best described by random network theory, as developed by Mozzi and Warren in 1969 [3]. Many other research workers have also proposed micro-crystallite models.

THERMODYNAMIC PROPERTIES

Among all the properties studied on glasses, thermodynamic property is the most important one. It not only determines the possibility of formation of glasses within a given zone of composition, but also it allows us to calculate thermal property, such as heat capacity or specific heat, to be able to estimate the requirement of total energy even for commercial glasses that are melted in a tank furnace. Some authors [4] have given details of calculation of thermodynamic properties of silica at high temperature and experimental results for many different reactions involving silicon and oxygen. The author used heat capacity values (in kilojoule per mole per degree Kelvin) of silica calculated from the following equation:

$$C_p=55.98+(15.40x10^{-3})T-(14.4x10^5/T^2) \quad ...(1)$$

where, T is the absolute temperature in degree Kelvin. This equation follows closely the data chosen by Sosman, as given in Ref. [4]. The data are questionable above about 1100°C. So, more reliable values should be used above 1100°C for better accuracy. Below the melting temperature of silicon (1412°C) the formation equation is

$$Si\ (solid) + O_2\ (gas) = SiO_2\ (vitreous) \quad ...(2)$$

The heat of formation ΔH_f at temperatures different from 25°C can be calculated from the reaction where ΔC_p is the difference in heat capacities at constant pressure for reaction (2):

$$\Delta C_p= C_p(SiO_2)-C_p(O_2)-C_p(Si) \quad ...(3)$$

The entropy of formation ΔS_f can be calculated from the relation and finally the free energy of formation as a function of temperature can be expressed as:

$$\Delta G_f = \Delta H_f-T\Delta S_f \quad ...(4)$$

MELTING TEMPERATURE

The measurement of the melting temperature of cristobalite is probably 1734°C, although lower values near 1725°C are often quoted. Quartz melts at 1410°C and is the stable phase below 870°C. Small amounts of impurities stabilize tridymite from

870 to 1470°C, with a melting temperature of 1680°C. Each of these three phases have α and β modifications which represent small structural variants. The $\alpha \rightarrow \beta$ transformation occurs at the following temperatures: a) quartz, 573°C, b) tridymite, 163°C, c) cristobalite ~270°C.

HEAT CAPACITY

The heat capacity at constant pressure (C_p) for type-1 (water-free) vitreous silica is quite interesting. The values from -200 to 1100°C can be taken from different compilations in the earlier years [5]. They agree well with those published recently [4] from 30 to 200°C, but above 200°C some other data are progressively lower at 428°C. For example, at 400°C, it was found to be 62.8 $Jmole^{-1}K^{-1}$.

Up to 1100°C the heat capacities of vitreous silica and crystalline cristobalite are nearly the same, except near the α–β transformation of cristobalite. Above about 1100°C, the values chosen by Sosman for vitreous silica show an anomalous increase above those of cristobalite. He apparently derived these anomalous values from the result of Wietzel [5], whereas at least one other set of data showed no anomalous increase up to 1400°C. Above 1100°C vitreous silica crystallizes, and it is possible that the higher values were influenced by crystallization. In any even' it seems to be better to use the heat capacities of cristobalite for vitreous silica above 1100°C. There have been a number of recent measurements of heat capacities that are higher than expected from the Debye model.

VAPOUR PRESSURE

Above about 1350°C vitreous silica begins to vaporize by the following reaction:

$$SiO_2=SiO+1/2O_2 \quad ...(5)$$

The SiO only exist in vapor. It forms on depositing on the solid surface. In flame working vitreous silica, one can observe a band of haze just outside the intensely heated region, which results from re-deposited SiO_2 granules. The haze can be removed by gentle reheating in the flame. The vaporization reaction is much enhanced in vacuum or in a reducing atmosphere. An equation for the pressure of SiO in atm over vitreous silica under neutral conditions above 2000 K is

$$\ln p(SiO)=18.41[1-(3160/T)] \quad ...(6)$$

with T in degree Kelvin. The total pressure is just 1.5p(SiO). Below 2000 K the equation is expressed as:

$$\ln p(SiO)=19.72[1-(3075/T)] \quad ...(7)$$

In air of pressure p_t the SiO pressure over vitreous silica is:

$$P_{SiO}(P_t+P_{sio})^{1/2}=\exp[28.0(1-3110/T)] \quad ...(8)$$

Rate of Crystallization

The rate of crystallization of vitreous silica rises from zero at the melting point of cristobalite (about 1740°C) to a maximum of about $2x10^7$ cms^{-1} at about 1675°C decreases to lower rates at lower temperatures. Nevertheless, surface crystallization or "devitrification" can be significant in practical uses of vitreous silica to temperatures as low as 1000°C, especially if the surface is in contact with some foreign substances that can act as a nucleation agent. The crystalline phase that forms is β-cristobalite, which has almost the same den and refractive index as vitreous silica, so it may not notice at higher temperatures. At about 270°C or bel the α-cristobalite transforms to more dense α-cristoba with a large volume change that causes crackin aroi the crystals, thereby reducing the strength and opti clarity of the silica.

Surface Energy

The theoretically calculated surface energy vitreous silica at 25°C is about 5.2 J m^{-2}. The calculated value of 3.5 J m^{-2} for soda-lime glass agrees with the lowest fracture energies of this glass found experimentally, as expected. The 5 values are much higher than the surface tension c a molten silica surface of about 0.3 J m^{-2} at 1800°C, because the later is rapidly covered with silanol group (SiOH) after its formation.

CONCLUSIONS

In conclusion, it can be said that vitreous silica, although manufactured in a relatively smaller scale, commands a lot of importance so far the industrial silicate glasses are concerned. As the structure is simpler due to the use of the simplest raw material, i.e. silica, this glass can be used as a benchmark for studying the structure of more complicated multi-component silicate glasses. Moreover, its properties can also serve as a knowledge-base for studying other commercial silicate glasses. Only thermodynamic properties have been briefly discussed here. In the second part other properties will be elaborated with some details.

REFERENCES

1. J. E. Stanworth, "Physical Properties of Glass", Clarendon Press, Oxford (1950).
2. A. K. Bandyopadhyay, "Nano Materials", New Age Sci., Tunbridge Wells, UK (2010).
3. H. Rawson, "Inorganic Glass-Forming Systems", Academic Press, New York (1967).
4. J. Zarzycki, "Les Verres et L'etat Vitreaux", Mason, Paris (1982).
5. G. W. Morey, "The Properties of Glass", Reinhard, New York (1954.

Special Glasses for Solid State Battery Applications

ABSTRACT

The development of basic science drives Technology. The principles of basic science are always used in the design of various technologies, and glass technology is no exception in this respect. Comparatively speaking, the development in the field of newer types of glasses and moreover on the newer types of applications is relatively recent. This has to be appreciated in the context of glass technology over many hundred years. Some details on special types of glasses are presented for "electrochemical applications" for solid state batteries in order to appreciate how the development takes place by the need of the society.

INTRODUCTION

Very recently, silicate glasses were the major type of materials that were commonly used by the households, different industries, building and other construction purposes, decorative applications, etc., although glasses have been used for various purposes for thousands of years. The advent of float glasses has also evoked a number of new applications [1]. During the past decades, so many new types of glasses have been discovered for satisfying different technical and other needs of human society. The method of fabrication of such type of so-called technical glasses with a wider composition range outside the realm of silicates has come into existence. The refinements of the process technology are continuously evolving for satisfying the needs of the hour, and thereby cutting cost and easy availability. In that sense, there is a similarity with those evolution processes of commercial silicate glasses. A comparison is not made here, as it is beyond the scope of the present article.

These special or technical glasses are available in the form of both bulk and thin-films. From the business point of view, it makes sense for value addition and it gives a very good measure of "tonnage to investment" ratio. This might be one of the main reasons for their rapid development and also the expansion of the field of work, and thereby extending the range of their usage, e.g. in electro-chemical, electronic, magnetic and optical applications. Some of these applications could be considered as hi-tech in terms of applications.

Glassy materials have several advantages over their crystalline counterparts as far as applications are concerned. Generally speaking, glassy materials are relatively much easier to fabricate: large areas [2], homogenous thin-films [3], complicated shapes [4] can be prepared. For example, Si:H for solar cell or thin-film transistors, while for bulk glasses can readily be prepared from the melt of different volumes by relatively slower quenching procedure or by sol-gel route. Moreover, quite importantly, the material of fabrication could remain workable near the glass transition temperature. This means that the viscosity remains relative low for the glass to be workable over the range of temperature so that it could be fashioned into various shapes and sizes, or drawn into fibres, as desired. It should be further noted that particularly bulk glasses are often structurally homogeneous and isotropic on macroscopic length scale (i.e. uniform property in any direction). As a result, the concerned physical properties are also isotropic and homogeneous unlike crystalline materials for which the intrinsic behaviour of even single crystals may be anisotropic (i.e. different values of a given property in different directions), and also the presence of 'grain boundaries' in polycrystalline samples could dominate the overall behaviour.

Therefore, the large-scale optical transparency is readily achievable, e.g. in silicate glasses for optical components including optical windows and fibre-optic cables for optical communication systems. The absence of structural defects, such as grain boundaries or dislocations as an area of concern in crystalline materials, also has a tremendous impact on the 'mechanical behaviour' and on the use of glassy materials in mechanical engineering applications. Due to this mechanical advantage, the glasses can often reach the 'ideal' value of mechanical strength and consequently the fibres of silica glass or ribbons of metallic glasses could be used as fibre-reinforcement elements in composite materials. It has to be noted that some of these composites could be very expensive in the aviation industry.

Moreover, glassy materials have another important advantage over their crystalline counterparts in getting a homogeneous structure even in the multi-component systems in a wide range of compositions. The physical properties are sometimes "additive" in nature, and they can be varied continuously by changing the percentage of one or more components within a particular base-glass composition. In this way, in the ornamental or decorative silicate glass matrix, the intensity of the colour can be controlled by varying the concentration of transition metal ions, i.e. colouring agents.

In this paper, one of the important technological applications of glassy materials are explored. In particular, here electro-chemical applications are considered in terms of electro-chemical sensors in Part-I. In the Part-II for the same application, solid-state batteries based on glassy materials will be described, i.e. it is focussed on two most popular applications in the field.

ELECTRO-CHEMICAL APPLICATIONS

The diffusion of different alkali ions, such as Na^+, K^+ or Li^+ and alkali metal ions, e.g. Ag^+ inside the glass matrix is important to understand different chemical behaviours of glasses. This diffusion is a thermally-activated process and hence to stop diffusion of such ions at higher temperature of exposure of a given glass could be somewhat difficult. Likewise, the same is true for the chemical corrosion of a glass at elevated temperature. This behaviour can be also due to a chemical gradient and an electric field gradient.

The ability of such ions to diffuse readily in oxide or chalcogenide (i.e. sulphur, selenium, and tellurium) based glasses in the present of a concentration gradient or an electric field opens up a range of options in the field of electro-chemical applications. For example, in energy storage (batteries), displays or chemical sensors, glassy materials can be good candidates by offering certain advantages in such applications over their crystalline or liquid counterparts. Glassy electrolytes that could be often made in the form of thin-film have more isotropic diffusion compared to many well known crystalline electrolytes.

Solid-State Batteries

At present, due to increasing usage of many home appliances, all-solid-state battery is the norm of the day and increasingly becoming popular in day-to-day use. This is achievable by using a solid electrolyte at high temperature, in the application in micro-electronic devices, and to avoid leakage and packaging problems that are inherent in liquid battery cells involving conventional liquid electrolytes. If ionically conducting solids have to be used as electrolytes in batteries, several specific requirements have to be satisfied. These requirements can be summarized as follows:

1) There are certain constraints on the conductivity, i.e. the ionic conductivity should be high compared to that of liquid electrolytes, whose conductivity value at room temperature is 10^{-2}/ Ohm.cm. It means that the solid glass should be superioic so that the internal resistivity of the components of battery-cell is not significantly high. On the contrary, the electrolyte material should have a negligible 'electronic' conductivity such that the battery-cell is not internally short-circuited that could shorten the life-cycle of the battery.
2) Certain chemical constraints have to be considered, such as the stability of the glassy material that should be high, particularly with respect to the electrode reactions at the interface with the anode and the cathode.
3) Some mechanical considerations have to be given on the sufficient flexibility of the so-called ideal electrolytes for internal mechanical contact. Therefore, the electrical

contact has to be maintained throughout the discharge process of primary cell when the material is removed from the anode area, and throughout the charging and discharging cycles of a secondary cell, when a change of volume may take place. This becomes important when intercalation-type materials are used in the system.

From a survey of the existing literature on the subject, it is found that ionically conducting glasses fulfill most of these requirements, if not all. Consequently, such solid electrolytes are getting used in certain battery applications. These electrolytes have an extra advantage over conventional 'liquid electrolytes' in that only one type of ion is generally 'mobile' and the other being part of the structural framework of the glass is immobile [5].

In this context, lithium-based batteries are gaining popularity in energy-storage systems, where a high specific energy capability that is expressed as Wh/Kg. A typical cell which has been designed consists of Li-metal anode, a crystalline TiS_2 intercalation-type cathode and as electrolytes, a LiI-doped Li_2S-P_2S_5 glass. This glass has a room temperature Li^+-ion of conductivity of $2x10^{-3}$ Ohm.cm [6]. This type of battery has a high specific energy characteristic of 150 Wh/Kg compared to that of 40 Wh/Kg for a lead-acid accumulator cell and there is an output voltage of around 2V. This is obtained with a rather high current density that ranges from 0.11 to 1.01 mA/cm^2 for room temperature and 100^oC respectively [6,7].

Glassy electrolytes are also employed for other applications, e.g. in the sodium sulphur battery that is operated at high enough temperature (300 C), at which both sodium and sulphur ions are in the liquid state. This is to enable Na_2S to be dissolved well in the sulphur. In this case, the electrolyte is sodium-borosilicate glass in the form of hollow fibre, which then serves to separate molten electrode materials. This cell also has a high specific energy characteristic at 120 Wh/Kg, and a voltage of 2V, and it can provide current densities up to 4 mA/cm^2 [7].

There has been a certain amount of research activity on the development of glassy electrolytes that are suitable for better applications, but lesser amount of work has been done in the study of glassy cathode materials making the 'monolithic battery' elusive. One such possibility for making cathode material is to explore the prospect of constructing the 'rechargeable, i.e. secondary, all-solid-state batteries. This method consists of insertion of crystalline layered compounds, such as TiS_2 in which the cell ions, i.e. Li ions, can be intercalated. It is noteworthy that the metal intercalation is accompanied by the charge transfer to the host metal d-band in the form: $Ti^{4+} + e^- \rightarrow Ti^{3+}$. Although these types of cathode materials have the disadvantage of appreciable change of volume during de-intercalation process, it leads to the problem of 'contact', as described in point number (3) above, the cathode electrolyte interface that results in the loss of reversibility in the charging or discharging cycle.

This problem could be solved by using glassy cathode materials within which Li ions may be reversibly introduced. This may be considered as ‘mixed conductors’, they show an intrinsic electronic conductivity. This allows a cathode made from such a material to be in good electrical contact with the external circuit as well as extrinsic ionic conductivity when containing inserted ions. To give an example, such possible glassy cathode materials are glasses containing transition metals, e.g. $V_2O_5 – P_2O_5$ [8] or $BaO-B_2O_3–V_2O_5$ [9] mixtures and glassy molybdenum sulphides, i.e. MoS_2 , MoS_3. In such situations, the electronic conductivity arises from hopping of electron+oxygen charge cloud (collectively called ‘small polaron’) from lower valence state to higher valence state (say, from V^{4+} to V^{5+} in vanadate glasses). These materials are attractive, as the changes in volume occurring upon insertion can be relatively smaller than that characteristic of crystalline compounds, say, in Ca-stabilized zirconia, which is a good ionic conductor.

CONCLUSIONS

After having described solid-state battery systems, it has to be said that another goal is to find a glass-forming material that could be sulphide-based chalcogenide type of glass. This could be used as the basis of superionic-glassy solid electrolyte, and also to form an electronically conducting cathode material. This is called “monolithic battery cell”, as described above. Here, mobile ions would not sense the interface between the electrolyte and cathode, and consequently over-potentials that are associated with such interfaces would be relatively reduced to some extent.

REFERENCES

1. A. K. Bandyopadhyay, “Technology of Float Glass Process”, KANCH, Vol. 5 [3] (2012), 33.
2. J. Zarzycki, “Les Verres et l’Etat Vitreux”, Mason, Paris, (1982).
3. A. K. Bandyopadhyay, “Nano Materials”, Tunbridge Wells, UK (2010).
4. A. K. Bandyopadhyay, KANCH, Vol. 6 [1], (2012), 31.
5. J. P. Gabano, Glass: Current Issue, A. F. Wright and J. Dupuy (eds.), Martinus Nijhoff (1985).
6. J. R. Akridge and H. Vourlis, Solid State Ionics, Vol. 18, (1986), 1082.
7. J. L. Souquet, Sol. State ionics, Vol. 28, (1988), 693.
8. A. Mansigh and M. Sayer, J. Non-Crystalline Solids, Vol. 7, (1972), 12.
9. A. K. Bandyopadhyay, J. O. Isard and S. Parke, J. Phys. D: Applied Physics, Vol. 11, (1978), 2559.
10. A. E. Owen, J. Non-Cryst. Solids, Vol. 35, (1980), 999.

Abbe Number and Transparency for Optical Glasses

ABSTRACT

Many glasses including flat or sheet glasses are commonly taken as the indicator of transparency. Technologically, many factors are taken into account to make these glasses transparent including the composition with low-iron content. Here, a very high accuracy of the glass thickness free of any surface aberrations or irregularities is exceptional, which is inherent by itself in the process technology of float glasses. For all such glasses, the refractive index and its dispersion are very important, particularly for optical glasses. A brief summary is given here to give an idea of Abbe number involving the dispersion of refractive index with wavelength that characterizes the optical glasses thereby giving us insights on the need of overall transparency in glassy materials.

INTRODUCTION

It is generally known that glasses posses a property of high transparency, particularly the optical glasses, whose properties create a sort of benchmark that drives our knowledge on this subject. Transparency is also commonly taken as one of the main features of glasses.

Almost all industrial glasses are made by mixing various chemical ingredients and then feeding the mixture automatically in a controlled manner, to avoid de-mixing, into a glass tank furnace for melting and refining. To achieve an excellent surface finish and also smoothening of the surface aberrations, which are both essential for increasing the transparency, a lot of care is taken by controlling different parameters of the process control. The fabrication process of float glass is highly mechanized and it is evolving continuously, even to the extent of newer products, such as coated glass with high emissivity (known as E-Glass) for keeping the building cooler inside. After melting the glass in a tank furnace, the next step is to shape it into a desired form. As it is used in the building construction industry for both residential and commercial purposes, the size is also of great importance. The details of the 'float' process were dealt in one of the issues of KANCH [1]. The heat and mass transfer problems in sheet glasses as well as the concept of improving the furnace yield were also discussed in KANCH [2-4]. In this brief article, transparency will be described for glasses in general, and optical glasses in particular, with special reference to Abbe number through which these glasses are coded for commercial market. Next, let us deal with the property of transmission as a general case in oxide glasses.

OPTICAL TRANSMISSION

The common use of oxide glasses is linked to their good 'transmission' in the optical spectra, i.e. in the combined band of the Ultraviolet (< 400 nm wavelength)+Visible spectrum (400 -700 nm)+Infra-red (IR) band (>700 nm). This optical window that corresponds spectral sensitivity of human eyes is due to an electronic transition between the lower energy valence band to the higher energy conduction band, which nears the edge of the UV cut, whereas the vibration of the atoms or ions in the glass network (i.e. silicon-oxygen vibrations in the silicate glasses) produces their effect on the IR band. What human eyes can see is the visible band (400-700 nm) which is the superposition of the tails of (electronic) UV and (vibrational) IR bands. To this superposed part, one has to add the effect of impurities, e.g. the concentration of transition metal ions (i.e. Fe, Mn, Cr, etc.) that gives undesirable coloration to the glasses [5-7]. The thermodynamic behavior oxidation-reduction of different transition metals at various temperatures of melting is also of importance that guides the ultimate coloration of the glasses due to the presence or absence of certain ions in the final melt [8].

To start talking about transparency, what immediately comes to our mind is oxide glasses. However, for the concept of transparency it is equally important to talk about non-oxide glasses, such as 'chalcogenide' glasses containing various combinations of elements, such as sulphur, selenium, arsenic, tellurium, etc., as these compounds are transparent in the infra-red (IR) part of the optical band. These chalcogenide glasses have many important applications, such as "IR-Optical Window" in defense equipment for night warfare and also as "IR Cameras" in the photography of behavior of different animals in the forests at night. However, mainly for human applications in the most fundamental need of human life, i.e. residential units, we mean oxide glasses in the form of plate or sheet glass and float glass, and obviously as optical glasses whose importance is known to all.

As we melt our glasses at very high temperatures, we tend to think that there is no water or OH ions present in the glass. In fact, from some of the ingredients containing water molecules, the complete non-evaporation of water during melting and refining processes makes some of these OH ions in traces being trapped inside the silicate glass network that are sometimes invisible to the naked eyes. For certain applications, particularly those in the infra-red region, the presence of such trace OH ions could be little bit disturbing as impurity that affects the optical properties [9].

In many glass laboratories, the IR spectroscopic studies on glasses containing water as a function of partial pressure show the presence of hydroxyl ions (OH-). Their presence is normally detected in the near IR range of wavelength at about 3570 cm^{-1}. In a silicate glass containing silica 'tetrahedra' as the fundamental building blocks or units, some oxygen ions may not be bonded to two nearby tetrahedron thereby creating non-bridging or non-bonding oxygen. In case some hydroxyl ions can interact with non-bridging oxygen ions, the additional bands could also be observed at higher wavelengths, i.e. near 4462 cm^{-1} and 5737 cm^{-1} respectively. This type of experiment of different bands could help the glass technologists to dope some glasses with requisite amount of hydroxyl ions for special applications.

It is worth mentioning that for the fabrication of glass-fiber for the purpose of fiber-optics application in the communication industry, the bands due to such hydroxyl ions play a very important role. A combination of the above bands could provoke the presence of a particular band at around 1205 cm^{-1}. It is known that tuned 'laser light' carrying 'information' is transmitted through fiber-optical cable that is very effective in the communication of voice and data transmission. To understand the transmission properties of sheet or float glass, it is equally important to take note of the above knowledge gained through various experiments, i.e. via IR spectral study that is also carried out for these commercial glasses to find ways of improving the transmission property as well as for heat-resistant glasses. In other words, more in-depth knowledge on optical glasses gives us more insights on the optical quality of transparent sheet or float glasses that bring us to the subject of Abbe number in terms of classification of optical glasses.

CLASSIFICATION OF OPTICAL GLASSES

As pointed out earlier, the optical glasses form the core of the transmission of 'images' through fiber-optical cable in the diverse field of communication. For such applications, these materials must possess a very high level of homogeneity and a constant as well as well-defined refractive index. The variation in the index must not cross the following limits: (a) 10^{-4} for ordinary applications, (b) 10^{-5} for common optical usage, and (c) 10^{-6} for those to be used in certain scientific and astronomical applications. These data are cited here, as this effort distinguishes such high-purity and high-quality glasses from those of the commercial glass, where a larger difference in the index is generally tolerated.

At this point, the method of manufacturing optical glasses should be described in brief so that the question of achieving high-purity and consequently the homogeneity can be well understood. All the constituent oxides are very thoroughly mixed for longer hours and then slowly charged (to avoid any de-mixing) to a tall but well sintered crucible that is heated from outside by a gas burner. In order to avoid any contamination or refractory inclusions, some glass-makers even use a thin platinum sheet lined-crucible. The top of the crucible is covered with a refractory plate to contain the heat during refining process. With a small hole on this refractory plate, the molten glass is continuously stirred with a platinum stirrer for better homogenization.

Here, the cooling of such a melt is very important compared to those of commercial glasses to avoid the thermal stresses. Incidentally, in case of commercial glasses, these stresses are removed by a proper design of an annealing furnace and/or by extending the annealing zone and thus ensures a proper cooling. For optical glasses melted at 1250 and 1300C, the cooling speed has to be very slow at the rate of 400 - 500C/hour (or even lower) for cooling to room temperature. After the cooling operation is over, the crucible is broken and good pieces are collected for optical polishing, particularly those pieces from the middle portion of the crucible for higher homogeneity. It is noted that in the past, small size tank furnaces lined with thin platinum sheets was used, but the homogeneity level could not be ensured in many cases.

After the above brief description of fabrication process of optical glasses, it has to be pointed out that it is not enough to have a constant refractive index, but it must also be known with a high level of precision. It is also known that the refractive index of many well-known glasses show dispersion with the wavelength. As refractive index of a glass is normally measured at a particular wavelength, its application at another wavelength will be in jeopardy, if there is a relatively stronger dispersion. In other words, depending on this dispersion, the refractive index must be more or less constant over the concerned range of wavelength. Next, let us look at how Abbe number is calculated for commonly known optical glasses.

ABBE NUMBER

First of all, it is important to know about the dispersion behavior of refractive index of different glasses in the wavelength range of interest: 300 to 1100 nm. For 'heavy flint' glass, the refractive index decreases from 1.70 at 300 nm to about 1.61 at 1100 nm. For 'light flint' glass, it decreases from 1.66 to about 1.55 within the above range of wavelength and that for a 'borosilicate' glass it decreases slightly less, i.e. from 1.55 to about 1.50. This dispersion in refractive index is quite noteworthy for various applications within the chosen range of wavelength. Around 500-650 nm, three wavelengths are chosen as: (1) 486.1 nm (the blue ray of the spectrum) denoted as ‘F’, (2) 589.6 nm (the yellow ray of sodium) denoted as ‘D’, and (3) 656.3 nm (the red band of hydrogen) denoted as ‘C’. How do we identify an ‘optical glass’? It is done by the value of $n_D$of the average refractive index, and the average dispersion is characterized by the Abbe number (ν) that is also called by the term ‘constringence’ as:

$$\nu = (n_D - 1)/(n_F - n_C)$$

where, n_F and n_C represent the indices for the reference bands. It has to be noted that the bands other than F and C are also used as per the German specification: DIN 58 925. A better representation consists of plotting n against Abbe number that creates several distinct zones for different types of glasses. For example, at higher Abbe number with lower refractive indices, there are ‘fluoride’ glasses that are well known in the field of optics, whereas the oxide glasses have relatively lower Abbe number with slightly higher refractive indices.

In fact, a large number of optical glasses exist, and a series of such glasses are found with each one having a different value of Abbe number with varied dispersion behavior. Now, it is interesting to see the importance of the values of Abbe number. For example, the glasses with smaller values of $v > 35$ are termed as “crown”, and those with higher values, but with $v < 50$ are termed as “flint”. There are a large number of other glasses with intermediate values, which find their applications in the “chromatic correction” of the object and other parts of optical equipment.

It is noted that the catalogues of the manufacturers of such glasses, there is a “numerical code”, wherein the type of the glass is denoted by the first “three decimal” places in their values of (n_D – 1) that is followed by the first ‘three numbers’ (rounded) of Abbe numbers. For example, for ‘barium crown 5’ glass, the values of (n_D – 1) = 1.556710 -- the first three decimal places are then 557. The value of v = 58.65 -- the first three numbers are 586. Therefore, it is easy to know why the code this ‘barium crown 5’ glass is known as: 557 586. Similarly, all other glasses are coded in this way. It is pertinent to mention that the industrial glasses are almost all of the “Crown” type, except the type “Pyrex” tends towards “Borosilicate Crown” and the “Crystal” glasses tend towards the “Flint” type. Therefore, the above description not only gives us knowledge on the Abbe number, but it also gives us a ‘clue’ on how a particular glass is numerically coded that is almost universally accepted. For float glasses with an eye on optical quality or property, such ‘coding’ is important in the commercial market place to be more precise in describing their quality for the benefit of the consumers in the building construction and related industries.

CONCLUSIONS

After describing the importance of transparency and the property of transmission of light through a piece of glass, the meaning of index of refraction and its role in the dispersion behavior of glasses is highlighted, particularly for optical glasses whose significance in our daily life cannot be underestimated. After dealing briefly on their method of fabrication that is highly delicate, the dispersion behavior of optical glasses is explained through the Abbe number. The numerical coding of optical glasses is done via Abbe number and its importance is highlighted in this brief article.

REFERENCES

1. A. K. Bandyopadhyay, KANCH, Vol. 5 [3], (2012), 33-36.
2. A. K. Bandyopadhyay, KANCH, Vol. 1 [4], (2014), 37-40.
3. A. K. Bandyopadhyay, KANCH, Vol. 1 [4], (2014), 49-53.
4. A. K. Bandyopadhyay and A. Charit, KANCH, Vol. 2 [2], (2014), 29-32.
5. A. K. Bandyopadhyay, "A Study of Interaction between Copper & Manganese in a Soda –Borate Glass by ESR", J. Materials Science, Vol. 15, (1980), 1605–1608.
6. A. K. Bandyopadhyay, "Optical & E. S. R. Investigation of Borate Glasses Containing Single & Mixed Transition Metal Oxides", J. Materials Science, Vol. 16, (1981), 189-203.
7. A. K. Bandyopadhyay, "Thermodynamics of Oxidation-Reduction of Vanadium in Borate Glasses", J. Materials Science, Vol.15, (1980), 1478–1482.
8. A. K. Bandyopadhyay, M. Ribes, F. Pernot and J. Zarzycki, "Mössbauer & E.S.R. Studies on Mixed Transition Metal Oxide Glasses", Physics & Chemistry of Glasses, Vol. 23 [1], (1982), 31–35.
9. A. K. Bandyopadhyay, R. Jabra and J. Phalippou, "Association of OH Groups with Boron and Silicon Atoms in SiO2 – B2O3 Glasses by IR Spectroscopy", J. Materials Science, Vol. 8, (1989), 1464–1467.

Nyquist Diagram and Stability Aspects of Control Systems in Glass Industry

ABSTRACT

We speak of glass technology more in terms of mechanical and electronics engineering than the glass itself. The glass industry constitutes a highly automated process and the importance of control system cannot be denied at any stage of production. While control system involves the use of different mathematical techniques that cannot be avoided at times, the use of computational method assumes special significance [1-3]. In any control system, one of the most important aspects is the stability. It is known for a long time that Nyquist criterion is better used for the purpose of stability analysis of a given closed-loop control system that is used in the automation process in the glass and related industries. Here, a glimpse on this issue is highlighted to make the concerned engineers aware of its usefulness as an analytical tool in the entire automation process.

INTRODUCTION

It can be stated that from the food and beverages industry to the ever expanding building sector, down to the automotive industry - the global demand for glass products is substantial. However, the processing of raw materials into end products made of glass entails enormous expenditures in terms of energy and work. At the same time, the requirements placed upon profitability, energy and resource efficiency as well as environmental compatibility are on the increase in the glass production sector. Increasing international competition and substitution products such as PET and combipacks result in reinforced price pressure on glass products. Rising energy costs, resource scarcity and an increasing demand for energy-saving end products represent highly topical subjects in the glass industry. All these issues take our focus point towards automation and automatic control systems, whose necessity cannot be denied under any circumstances.

First of all, certain terminologies are clarified. Automation, automatic control, control engineering, control system and even process engineering are all parts of the same game, i.e. “automatic control”. This is one of the most significant areas of science and technology. This can be attributed to the fact that automation is linked to the development of almost every form of technology. No wonder that it finds its use to a considerable extent even in the glass technology. By its very nature, automatic control is a multi-disciplinary subject. It constitutes a core course in many engineering departments, such as Electrical, Electronics, Mechanical, Chemical, Aeronautical, and finally in Information Technology due to the use of both software and hardware as the integral part of the control system. Automatic control requires both a rather strong mathematical foundation and implementation skill [1,2] to work with various controllers that are needed in various parts of a glass plant for the manufacture of any type of glass.

As the glass tank furnace constitutes almost the main and crucial part of a plant independent of its product, more controls are slowly being implemented in this sector. This is particularly noticeable in the container and float glass industries. In the context of Indian Glass Industry, it may be pertinent to mention that a majority of local glass manufacturers did not involve heavy component of “automation system” in their respective plants, when initial investments were made. However, with the progress of time and with the newer invention coming to our knowledge on design aspects of various controllers, new investments started pouring into the glass industry and/or they were being slowly pumped into the operation process. It has to be further noted that about 20 years ago, when an International Company invested more than Rs. 75 million in the control systems in a specific glass production, it was considered too high in those days and the shareholders kept the share prices bearish for quite some time, before the company started showing profits. This example is quite noteworthy in the Indian context.

Automatic control has rapidly developed over the last 60 years or so. An impressive boost to this development was provided by the technologies that grew out of space exploration and World War II. In the last 20 years, automatic control has undergone a significant and faster development mainly due to Digital Computers. Indeed, recent development in digital computers - particularly their increasingly lower cost has facilitated their use in controlling “complex systems and processes”. Automatic control is a vast technological area whose central aim is to develop control strategies that improve performance when they are applied to a system or a process. The results reported so far on control design techniques are quite significant from both theoretical and practical perspectives [1].

From the theoretical standpoint, these results are generally discussed in great depth covering a wide variety of modern control problems, such as (1) Optimal and

Stochastic Control, (2) Adaptive and Robust Control, (3) Kalman Filtering, and (4) System Identification. From the practical point of view, these results have been successfully implemented in numerous practical systems and processes, such as (a) Controlling Temperature, Pressure and Fluid Level (useful for glass industry), (b) Electrical Energy Plants, (c) Industrial Plants, (d) Nuclear and Chemical Reactors, (e) All types of Transportation Systems, and finally (f) Robotics, Space Applications, Farming, Biotechnology and Medicine. The list is ever increasing on the newer applications.

The main advantages of the control system can be elaborated as follows:

a) Consistency over all levels for optimized processes and reduced total cost of ownership
b) Openness, modularity and scalability for flexible responding to current market requirements and for investment protection
c) Very high plant availability
d) Increased system performance
e) Optimized further processing and ancillary processes due to integration.

It is quite tempting to write a little on the history of control system, as briefly elaborated in the next section.

HISTORY

In the ancient world, the field of control systems essentially started. Mainly the Greeks and the Arabs in the early days of civilizations were heavily preoccupied with the accurate measurement of time, the result of which were several “water clocks” that were designed and implemented.

However, actual progress was made in the field of engineering until the beginning of the renaissance in Europe. Leonhard Euler (for whom Euler’s Formula is named) discovered a powerful integral transform, but Pierre-Simo n Laplace used the transform (later called the Laplace Transform) to solve complex problems in probability theory. Joseph Fourier was a court mathematician in France under Napoleon I. He created a special function decomposition called the Fourier Series, that was later generalized into an integral transform, and named in his honor (the Fourier Transform) [2].

The “golden age” of control engineering occurred between 1910-1945, where mass communication methods were being created and two world wars were being fought. During this period, in the classical domain, some of the most famous names in control engineering were doing their work: Nyquist and Bode.

Hendrik Wade Bode and Harry Nyquist, especially in the 1930’s while working with Bell Laboratories (USA), created the bulk of what we now call "Classical Control Methods". These methods were based on the results of the Laplace and Fourier Transforms, which had been previously known, but were made popular by Oliver Heaviside in UK around the turn of the century. Previous to Heaviside, the transforms were not widely used, nor respected mathematical tools.

Bode is credited with the "discovery" of the open-loop feedback system, and the logarithmic plotting technique that still bears his name (bode plots). Harry Nyquist did extensive research in the field of system stability and information theory. He created a powerful stability criterion that has been named after him (The Nyquist Criterion).

Modern control methods were introduced in the early 1950's, as a way to bypass some of the shortcomings of the classical methods. Rudolf Kalman is famous for his work in modern control theory, and an adaptive controller called the Kalman Filter was named in his honor. Modern control methods became increasingly popular after 1957 with the invention of the computer, and the start of the space program. Computers created the need for digital control methodologies, and the space program required the creation of some "advanced" control techniques, such as "optimal control", "robust control", and "nonlinear control".

These last subjects, and several more, are still active areas of study among research engineers. This makes us define different areas of control engineering.

BRANCHES OF CONTROL ENGINEERING

Here we are going to give a brief listing of the various methodologies within the sphere of control engineering. It has to be noted that often, the lines between these methodologies are blurred, or even erased completely.

Classical Controls

Control methodologies where the Ordinary Differential Equations (ODEs) that describe a system are transformed using the Laplace, Fourier, or Z Transforms, and then they are manipulated in the transform domain [1,2].

Modern Controls

Methods where high-order differential equations are broken into a system of first-order equations that are relatively easier to handle to solve a particular control problem. The input, output, and internal states of the system are described by vectors called "state variables". This is an important point to be noted.

Robust Control

Control methodologies where arbitrary outside noise/disturbances are accounted for, as well as internal inaccuracies caused by the heat of the system itself, and the environment.

Optimal Control

In a given system, performance metrics are identified, and arranged into a “cost function”. The cost function is minimized to create an operational system with the lowest cost. This is very important for investment decision, e.g. in glass industry.

Adaptive Control

In adaptive control, the control changes its response characteristics over time to better control the system. This can be repetitive, but is adaptive to the system necessity.

Nonlinear Control

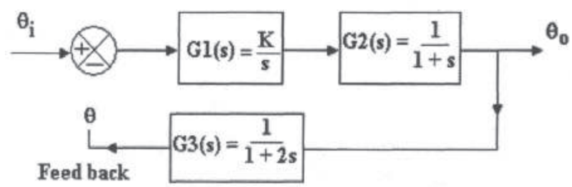
This is the youngest branch of control engineering involving nonlinear functions which are sometimes difficult to handle. Nonlinear control encompasses systems that cannot be described by linear equations or ODEs, and for which there is often very little supporting theory available. Sometimes, linearization is done with certain assumptions [2].

Game Theory

Control theory finds its close relative in the Game Theory, and especially robust control and optimal control theories. In game theory, the external disturbances are not considered to be random noise processes, but instead are considered to be “opponents”. Each player has a cost function that they attempt to minimize, and that their opponents attempt to maximize. This is how the optimization of the system progresses.

STABILITY AND NYQUIST CRITERIA

Having discussed the history and different branches of control engineering, without going into too much mathematics, let us deal with the stability criteria. For the classical control techniques, it has to be noted that using Proportional-Integral-Derivative (PID) controllers that have existed since 1942 predominate in the overall practice of control engineering today. Despite impressive progress since the 1940s, the practical applications of modern control techniques (such as Pole Placement, State Observer, and Optimal Controller Design Techniques) are limited. This is considered a serious gap between theory and practice. To reduce this gap, the techniques of modern control engineering should be designed with an eye to its applicability in the industrial scenario to facilitate their use in practice. To achieve this objective, modern control techniques must be presented in a simple and user-friendly manner to the practicing ‘instrumentation engineers’ in the glass industry so that these techniques find immediate and widespread applications. In turn, control engineering could serve human needs better and provide the same breadth of technological



applications found in other related areas, such as communications and computer science. Next, let us deal with Nyquist diagram for stability of control systems.

Why Nyquist Diagram

In control systems there are open-loop and closed-loop operations. The Nyquist plot allows us to predict the "stability and performance of a closed-loop system" by observing its open-loop behaviour. While the Bode plots or Bode design methods assume that the system is "stable" in open-loop, the Nyquist criterion can be used for design purposes regardless of the open-loop stability. Therefore, we use this criterion to determine closed-loop stability when Bode plots display confusing information.

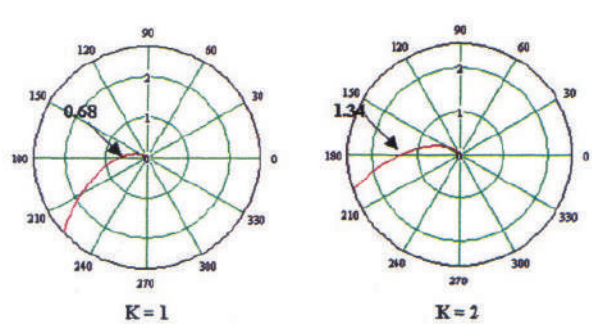
Application

The Nyquist diagram is the "locus of the open-loop transfer function" plotted on the complex plane. If the system is inherently unstable, the Nyquist diagram will enclose the point -1, the point where the phase angle is 180 degree and unity again. Let us consider the following system:

The transfer function θ1 and θ is G(s)G1 x G2 x G3 = K/[s(s+l)(l+2s)] in the Laplace domain. By converting it in the complex domain (s = jω), where gives rise to the frequency response of the system, we find the following relation:

$$G(j\omega) = K(-3\omega^2)/[9\omega^4 + (\omega - 2\omega^3)] - j\,K(\omega - 2\omega^3)/[9\omega^4 + (\omega - 2\omega^3)]$$

Such type of functions can be easily handled by simple computer program in MATLAB [3], which could generate various plots of interest for analysis that gives rise to a proper outlook for the overall management of control systems in the



glass Industry. The usual polar diagrams (Nyquist) are shown above for different values of K. We can see that at the 180 degree position, the radius is less than 1 when K = 1, so the system will be "stable". However, when K = 2, the radius is greater than 1 so that the system is "unstable". Now, we can conclude that tuning up the "gain" makes the system unstable.

The plot will cross the real axis, when $\omega = 2\omega^3$ or $\omega = 0.707$, and this is true for all the frequencies. The plot will enclose the -1 point if $K(-3\omega^2)/ [9\omega4 + (\omega - 2\omega^3)] \leq -1$, so the limit is when $- 3K\omega^2 = 9\omega^4 + (\omega - 2\omega^3)$. Now, putting cd = 0.707, the limiting value of K is 1.5.

CONCLUSIONS

The importance of control system has been elaborated for industrial scenario, particularly for the glass industry, where more and more of control systems are being introduced with the stepped-up investment that can be easily justified in today's market condition in India and abroad. The importance of Nyquist stability criterion in this respect for a given control system is briefly shown. By rigorous mathematical analysis and computational tool such as MATLAB, very useful research work can be done for the purpose of development of glass industry.

REFERENCES

1. J. Nagrath and M. Gopal, "Control System Engineering", New Age International, (New Delhi, 2003).
2. A. K. Bandyopadhyay et al, "Mathematical Physics for Engineers", New Age Sci., (Tunbridge Wells, Kent, UK, 2009).
3. "Springer Handbook of Automation", Ed. Shimon Y. Nof (Springer Verlag, 2009).

Competition Law and Trade Associations

ABSTRACT

In June, 2013, AIGMF organized a one-day seminar on competition law for trade associations in India as well as on marketing excellence and systems. The latter was presented in the form of an article on strategic management in glass industry in the April-June issue of KANCH. As AIGMF is a trade body comprising of corporate entities and business executives, it is important for all concerned to know what is the status of this law, or rather what is the reach of this regulation in the context of trade associations in India so that the members get awareness on this important issue and take corrective measures, if any, to avoid any future inconveniences in their operations. A very general outline is given here.

INTRODUCTION

First of all, it is important to know: Why a Competition Law? Then, it is possible to understand the role of different trade associations in raising awareness among their members so that unfair competition does not occur in a system. In a given economic system, we have certain productive processes. These processes are necessary for smooth running of the organization for the ultimate financial and other goals as well as to see that it does not in anyway take part in any unfair means for achieving this goal. One such avenue is to raise the level of 'competition' so that the quality and eventually the productivity increase in a given set of industry. To achieve this objective, it is necessary to enact laws with many provisos for all the companies to follow so there is even ground for fair-play for all. As the famous dictum goes: it is not enough to be fair, one has to be seen to be fair so far any law is concerned, in particular those involving various segments of the industry. In India, all these laws are mostly enacted by the 'Ministry of Company Affairs' that almost always remains under the 'Ministry of Finance' portfolio of the Central Govt. Obviously, such laws cannot be passed by simply making an 'executive order' by the cabinet, but by bringing the full bill to be passed by the parliament going through the entire rigmarole and/or a gamut of procedures with necessary amendments from time to time. The first 'competition' law in the true sense was passed in 2002.

Both in Europe and USA, there are massive activities in the field of mergers and acquisitions (M & A), i.e. companies are constantly buying other companies or trying to merge one company with another (or even attempting to buy other companies). Although it is not as popular in India, M & A definitely make sense to get rid of unnecessary fat, by cutting costs through common or shared personnel/departments and shared facilities, to serve customers better (as discussed in Ref [1]), and also to remain competitive in the world markets. In USA, this activity is really rampant making consultants, lawyers, accounting firms, investment bankers very rich by the fat 'commission' amount they receive in a given M & A deal.

Incidentally, in the year 2002 or before, when the new 'competition' laws were enacted by our parliament, one could hardly remember many cases of M & A in Indian industry, e.g. to name a very few in those days, buying of TOMCO and famous Lakme brand by Hindustan Lever Ltd. (HLL) from Tata Group, or even Govt. selling 'Modern Bread' to HLL and some others. However, attempts to buy DCM and Escorts by a very well-known NRI businessman that was thwarted both by the owners and the Govt. by certain proviso of MRTP act were noteworthy. Many people wondered about the finest lawyers involved in this long and protracted battle who may not have rightly advised their NRI client what was construed as the 'long arm' of MRTP act. It was almost a case of 'awareness' about the existing provisions of law in those days.

Ultimately, this resulted in huge losses of money by the NRI businessman and loss of our reputation abroad. This was the era when the Indian companies were heavily restricted to import good technology and materials, let alone be taken over by a company of foreign origin. MRTP act even did not allow the participation of more than 40% equity in a given venture. Even so, it was extremely tough to get all the necessary clearances from various Govt. departments. It was mentioned in Ref. [1] that from 1991 onwards with the onset of economic liberalization, things started getting easier and Indian companies even started buying companies (including glass and ceramic companies) abroad with the help of consortium of foreign banks. This included some companies who even formed so-called Bombay Club after 1991 to protect Indian industry from foreign competition that was thought to be unnecessary by some critics even in that period of time. It was mainly due to some over-restrictive practices by the concerned Govt. departments and the consequent mindset of our industry that was previously created by the Govt.

Having given some clarity on some of the issues in the 'competition' scenario in India, it is better to address the main issue of this article, i.e. the role of different 'trade associations' in terms of competition laws in the country. If the 'trade associations' correctly start raising various issues of importance to their respective members, then the correct awareness of the industry will slowly grow and the enacted laws with possible ‘amendments’ from time to time will have the right impact for our economy. In fact, it is through greater awareness on the ‘specific issues’, the industry could raise good points to the attention of the concerned ministry for undertaking an effort for so called ‘amendments’.

COMPETITION LAW AND COMPLIANCE

It is good to remember that before the first competition law was passed by the parliament in 2002, there was a draconian law existing for the purpose that was ruthlessly applied to many industries in the old days. This used to be called “Monopolies and Restrictive Trade Practices” (MRTP Act). The ‘competition’ laws existed and were always there in the advanced industrial nations, like USA, UK, etc. Although minor modifications have been made, but no fresh bill has ever been brought to British or European Parliament or US Senate. In USA, it is mainly called ‘anti-trust laws’ to curb large multinational companies trying to avoid ‘competition’ in the marketplace, and their marketplace is enlarged and considered to be the whole world. In Europe, the European anti-trust body takes care of the implementation of such laws in the Euro zone. Sometimes, the battle is very severe – even to the extent of bitterness between the two countries.

First of all, it should be made clear that in either closed or open economy, there is always a need of ‘trade associations’, who apart from various technical activities do also lobby to the Govt. for various optional analysis and consequent change of certain laws in part or full for the benefit of a given industry for the ultimate success of our economy. Lobbying is a very specialized activity in USA and other countries, where top-notch executives or retired government officials are permanently deputed near to the Senate where they could properly lobby with the lawmakers. These special groups comprise in large part of M & A activities to be able to avoid anti-trust cases in the first place and then the effort is to dilute the financial obligations on the part of the bidder in a given deal. So, the existence of the trade associations are of paramount importance, particularly if they are armed with multiple ‘lobbying’ teams with clearly defined objectives.

It should be mentioned that in an open economy, when laws are enacted for better industrial climate, a ‘regulatory’ mechanism should be in place for better implementation of such laws among various corporate citizens. So, a “Competition Commission of India” (CCI) was also set up in this respect: 6 years after the law was passed, i.e. in 2009. The idea was to develop ‘competition compliance programme’ (CCP) to oversee the applicability of ‘competition law’ to the various ‘trade associations’, apart from different other activities to make sure that the competition in a given industry is not curbed. Hence, the role of ‘trade associations’ cannot be denied at any point of time.

A brief background of the present law can be given here. In 1999, “Raghavan Committee” was set up to examine the so-called bad parts of the then existing law (MRTP Act), and eventually submit recommendations for a revised or new law to the ‘Ministry of Company Affairs’, who prepared the draft bill and made it go through various statutory bodies (such as ‘select committee’) in the parliament. Then, the bill was ultimately passed by the parliament in 2002. It should be noted that in the newspapers of that year, this new ‘competition law’ was judged by the eminent people as most revolutionary for the betterment of Indian industry and economic success. When any law is passed, there is a possibility of litigations in the court, as it happened in this case as well. So, the required Notification came into effect in 2003 to make the ‘Competition Law’ enforce in our country. This law was subsequently amended in 2007, as some objections were still raised between 2003 and 2006. For better implementation, a regulatory authority (CCI) was also set up in 2009. As mentioned earlier, in USA, there are not so many amendments in the anti-trust laws, as in India. Here, it was again amended in 2010. The long period of seven years is also considered too long. However, for the sake of better economy and a better law, all these lapses should be excused and hence tolerated.

The provisions of this law mainly prohibit “Anti - competitive agreements” between two industry entities and “Abuse of dominant positions” for a company within a given industry to dictate, e.g. prices in the market or any other relevant issues under the provisions. It also regulates “Combinations” and even mandates “Competition Advocacy”. The latter is very important to create healthy competition in different industry segments. About 15 years ago, people talked about ‘price understanding’ in the ‘auto tyre’ industry, i.e. ‘price rigging’ or ‘curtail’ among various players, but such an attempt among the ‘refractory’ manufacturers was made to fail in totality, for a large consumption of such products in the steel industry tenders. Obviously, no one perhaps heard of glass industry doing such thing, although the consumption of glass products was not huge in Govt. sectors.

Certain provisions under this new law are worth mentioning that are also relevant for ‘trade associations’: No Person/Enterprise/Associations of Enterprises (e.g. AIGMF, which is a type of association for glass manufacturers or companies dealing with glass products, as deemed to be permitted under the statute of AIGMF) or Associations of persons shall enter into “agreements” that cause or likely to cause AAEC under the section (S.3(1)). Under the section (S.3(2)), any ‘contravening agreement’ shall be void. The next section, i.e. S.3(3), not only prohibits any such ‘agreement’, but also practices and/or decisions that pertain to: (a) Fix prices, (b) Limit output, (c) Share the markets, and (d) Enter into bid-rigging (i.e. cartel). The definition has been broadened to the extent that it takes care of any 'understanding' or 'relation' or 'action in concert' (specifically meant for 'cartel', etc.) – formal or informal and written or verbal.

On the question of 'cartels' as there are many examples in the Indian context (as mentioned above), there is a policy of 'carrot and stick' adopted under this law. For example, the carrot side is to show leniency to certain cases, whereas the stick side is two-fold: (a) Appropriate 'fines' for both corporate and individuals, and (b) some type of 'compensation' to the victim and/or affected party of a given situation arising out the actions/decisions of those making cartels or similar things.

ROLE OF TRADE ASSOCIATIONS

In the closed economic scenario, the trade/business organizations have played a historical role, as also mentioned above in terms of their importance both in the USA and India. In the context of an open market scene in India prevailing for the last 20 years or so, these entities could play even bigger and sometimes more pro-active roles, as in the USA. For example, as at present, the US Senators are deliberating on the issue of 'tax avoidance' by some US companies (mainly a large Pharmaceutical company) trying to take over another company abroad and register there, say, in Ireland where 'tax rate' is lower than the USA and where many such cases already exist. This is called an "Inversion' and heavily debated, as there are also implications for anti-trust or competition laws.

Also, for companies like 'Dollar General' (a multi-location 'discount store' for food and other household items), if their take-over bid for a smaller rival fails due to failure in the 'anti-trust objection' related cases, the relevant amount of compensation to be given by the said acquirer is in question, and this issue is hotly debated in the business press and other forum. There are so many other examples in the USA and Europe, where such take-over attempts have been 'construed' to be creating a base for 'cartels' and/or avoidance of 'local tax'. As glass is heavily consumed both by the food and pharma companies, the glass industry will be affected by these take-overs in the concerned market region. This is primarily due to a general tendency of ruthlessly cutting costs by the acquirer. There are other special examples, such as a pharma company (Allergen) recently withdrew their take-over bid abroad due to vehement 'reactions' mounted by the loyal customers in the press to boycott the company. In future, some of these issues could be relevant for India, as this type of situation will also attract amendments.

As said earlier, the 'trade associations' could also serve as a 'platform' for restricting competition. As mentioned above for the US companies, a large number of 'cartel' cases have been brought by the concerned 'trade associations' in a given country directly or indirectly -- to the notice of the regulatory bodies, such as CCI in our case. More importantly, these cases have (sometimes) been vigorously pursued by them. Instead of encouraging 'cartel' by individual companies and/or large trading agents, one important role can be 'price-fixing' by the 'trade association', subject to criticism or objections raised by the concerned member company. However, depending on the correct and transparent assessment of the economic situation, e.g. the prices of different 'controlling inputs' including the main cost (i.e. 'energy'), a "price fixing" mechanism could be devised in terms of the (a) actual unit price of a given product that is charged by the members of the association, and (b) fixing a 'benchmark' or 'minimum' price [2]. In the large tenders of the Govt. sectors, many times such an option is allowed to be exercised – particularly for continual increase (or in rare cases – a decrease) of 'energy' prices and also when 'energy' is an important component in the total 'price structure' [3]. However, caution has to be always exercised to clearly see to it that such a mechanism does not hurt anyone.

In continuation of the role and conduct of the responsible 'trade associations', it can be stated that the matter of 'terms and condition' of sales should also be elaborated. This involves devising another set of 'standard/common formulation' for 'terms and conditions' of sales as applied by the members in their trading relationships. It should be clearly remembered by the 'marketing personnel' that on certain 'terms and conditions' (called standard or not), no compromise will/could be made, and hence a type of 'sanctity' shall be maintained in their dealings. For example, the building industry is going through a terrible pain with about 7 lacs housing units and a large number of commercial buildings remaining "unsold" at this moment. Moreover, the building companies who are one of largest consumers of flat glass and other ceramic products also remain heavily indebted to the tune of about Rs. 30,000 crore at present. Many glass companies may be tempted to grant some sort of 'concessions' towards this sector in terms of payment terms that affects the 'receivables' situation [3].

If the companies have cheaper access to the working capital, then it is tolerable to bend the 'norm'. As it is almost purely "cyclical" and it also lacks some clarity on the concerned Govt. Policies, such a temptation for 'concessions' can be checked to a great extent. In this context, the 'trade association' could obviously play a pivotal, but crucial role. It has to be noted that while some price reduction to the extent of about 40% in NCR region (varying in different cities) in commercial units has been offered, no such reduction has been visibly offered in the housing side of the business. Hence the marketers of flat glass products must also factor this point into account in their respective dealings, where again the role of 'trade associations' could be considered to be important.

Further, it should be stated that although fixing 'marketing territories' may not be acceptable by certain members, the 'trade associations' could again devise suitable sets of systems for creating 'exclusive territory' or certain 'marketing arrangements' on behalf of their members subject to the condition that it is a "win-win" situation for all concerned. Moreover, they should also discourage 'collusive tendering' or 'bid-rigging' that is very common in the marketplace, as the competition is very severe at times.

Finally, The trade association must also adhere to certain 'principles' or norms, such as (a) Not insisting on strict 'rules of membership', (b) Free or Paid Exchange of relevant but sensitive 'commercial information', (c) Setting of closed/ exclusive 'industry standards', (d) Not imposing 'marketing restrictions', and (e) Not adopting pricing and other trading practices that could limit the freedom of the members to freely compete in a given market. These are fair enough and sufficient conditions for a very healthy competition in the industry, e.g. in the glass and ceramics industry [4].

CONCLUSIONS

Understanding the concept of competition is very important in any industry and in any economy, particularly in an open market scenario where the competition raises both quality and productivity. At the same time, such competition also allows us to cut cost so that the prices are reasonable to a set of customers. A glimpse of the 'competition law' is presented in this short article where some details are accommodated to elaborate the 'rules of the game' with a particular reference to the 'trade associations'. Certain important roles of such associations are also elaborated with a reference to the glass industry. With the progress of the building industry and newer usages of glass products in the hospitality industry, the volume of glass sales might cross a threshold limit of US$15-20 billion, when the urge for quality will evolve to a greater extent with a stronger bias on the productivity. This augurs well for all of us concerned in the glass and ceramics industry that should evolve faster.

REFERENCES

1. A. K. Bandyopadhyay, KANCH, Vol. 2 [1], (2014), 15.
2. One-day Seminar of AIGMF on "Competition Law in India", June, (2013).
3. A. K. Bandyopadhyay, "Marketing Excellence & Systems", New Age Publishers, New Delhi, India, (2006).
4. A. K. Bandyopadhyay and S. Maitra, "Strategic Management in Ceramics Industry", Indoceram, Vol. 39, (2002), 19.

Strategic Management in Glass Industries

ABSTRACT

In June, 2013, AIGMF organized a very good one-day Seminar on "Competition Laws in India" and obviously its impact on different industries, particularly on glass industry, was also deliberated. AIGMF is an organization consisting of corporate entities, and also technical or commercial executives and scientists are the members. They regularly read the official journal of AIGMF, i.e. KANCH. Hence, it is quite natural to reflect on different issues of such seminars that are useful to the industry as well as to technical/commercial personnel. In this article, the topic of "strategic management" that was also presented in the same seminar as: "Marketing Excellence & Systems" in terms of its role in competition. Here, it will be discussed and in subsequent issues, the other relevant topics will be dealt with including the main topic on competition.

INTRODUCTION

In any business, the "strategy" is very important to make progress, even for the day-to-day operation or planning. The business in "Glass Industry" cannot be an exception. Among many other important things, here comes the strategic management in order. A viable model for strategic management has been developed for various businesses, which is obviously suitable for glass industry. This model is described in comparison to Mckinsey's **7S** model to better understand the customer angle with 'customer equity'. An in-built 'marketing audit recipe' is presented to monitor the general progress of the implementation of such a model in any glass industry.

The economic liberalization era started in India in the early 1991, wherein the pace of economic activity and hence the economic progress were quite slow compared to that in China, despite having some patches of good growth over 8% before 2008. Due to various policies in India, except for a few plants in some sectors, many plants are not on "economy of scale" and also there is not much "automation" exclusively for the purpose of improving the "productivity" level in a given industry. Without going to any debate, it could be safely said that India is not only investment-starved, but also its productivity (with some exception) is quite low in many sectors.

It seems difficult to emulate the 'Chinese strategic vision', unless there is a semblance or even parity of the economic activity levels in various industries, or in various sectors of the economy. Nevertheless, compared to previous periods (prior to 1991), we have come a long way in liberalizing our economy in various sectors giving us prosperity and some kind of progress in many fronts of Indian economy, except for the last 3-4 years. The basic tenets of this 'progress' is that we have opened the 'floodgate' of imports of hundreds or even thousands of products leaving the markets wide open to competition, thereby giving various options on quality, price and delivery to the customers. In this process, the Indian industry has also revived in terms of many desired parameters to make themselves ready for foreign competition. Some companies perish, but some companies do prosper to have adopted a viable strategy in time. That's the buzzword for this success. This article is precisely to deal with this issue. The customer's choice is the name of the game today. No one could deny it and no one could by-pass this matter in India today.

A brief outline on Indian economy and industry are given above just to emphasize the point that where we stand. What about the glass industry? It is not good. As there is no real-time data on the inventory, it is often noticed that there is a massive inventory piling up in certain sectors, where despite good marketing efforts, things are not going the way as desired. There is some kind of invasion by foreign products by imports. No one needs to be scared of competition, if one adopts and follows the path of 'strategic management'. A clear focus is given here for the corporate world in general, and glass industry in particular, about the need and importance of strategic management [1] and this issue is coupled to the technology development as well that has been discussed in a number of technical articles in KANCH [2-6]. One similar article was written on the health of refractory industry with a 'strategic management' angle for the technical implementation [7], as refractories are also important components in the glass and ceramic industry.

After describing McKinsey's 7S model of strategic management, let us describe our pragmatic **5C** model. We could adhere to this model or any other that is strategically fit. A strategy is something that one could drown oneself so that its implementation could be smooth. Also, there is no alternative to a situation that encourages 'continuous improvement' in evolving new strategy for better output. This effort very well serves the purpose of the organization and of course of all the concerned stakeholders – i.e. shareholders, employees, suppliers, and finally the customers. This aspect of "customer focus" is perfectly understandable in any business context [1,8]. A company with an ISO certification normally has a better understanding of all these factors, as a 'culture of quality', and a 'culture of customer care' has already been generated or absorbed within the system.

For certain glass plants, the cost-benefit analysis of a large process control system implementation was discussed a long time ago [9,10], when it was almost inconceivable for any glass company to be able to invest a large sum of money for such a robust control process. Now, both for the sake of 'quality' and higher 'productivity', it is considered a viable strategy for many operations. In the present article, we will talk about the need and importance of a model in 'strategic management' in the particular context of glass industry.

STRATEGIC MANAGEMENT MODEL

First of all, let us talk about good old model of Mckinsey that is called **7S** model, which is described with **S** as the first letter as:

Structure – which a company must have anyway,

Strategy – which a company must adopt,

Systems – which a company must evolve to run a business,

Skill – which is summation of employees' skill that a company possess,

Style – which a company must possess that usually evolves with time,

Staff – which a company do have to take care of the above – all these attributes having in possession or developed lead to the last item:

Shared values – that's a 'must' anyway.

The above descriptions sum up the entire **7S** model of Mckinsey. The peculiar thing to note in our comments on the right hand side – which all sound too obvious. Then, what is our problem? Everywhere, we write that "which a company must have" – which means that a 'company' do have some kind of 'structure', may be a stereo-typed 'strategy', some 'systems' in place, a degree of 'skill', a particular 'style' of management, and finally a company must have some 'shared values', whether the company runs on a so-called paternalistic pattern or in a professional manner. Somehow, the above model misses on something that we do not have or we do not do. A simple 'management audit' would reveal: who does what and what is the efficiency? Whatever the companies do, in the face of fierce competition in the marketplace (both internal and external), the results are not too good for all to see and judge. So, that brings us to our universal **5C** model, which has been seen to be used around the world in many companies. Here, an attempt is made in simply articulating the workable ideas on this **5C** model as follows:

Culture → **Communication with Clarity** → **Create with a Purpose** → **Consolidate the Gains** → **Customer Satisfaction**

Various components in the 5C model needs explanations as follows:

1) **Culture:** It is of utmost importance, since the culture could be visible (e.g. the behaviour or attitude), or invisible (e.g. customer care). The CEOs must try to imbibe a good culture in the company which the other employees would emulate – so we need a strategy. However, would any glass company care to appoint a person to calculate how much money the company loses due to the "lack of culture" of the people involved in a particular job or operation, i.e. marketing, HRD, etc.

2) **Communication:** How many glass companies could boast of a good two-way communication between the employees for better quality, better marketing and even better receivables collection that matters a lot for the company for cash flow position. So, this needs to be encouraged with one condition – clarity, again from the top – so we need a strategy. Would any glass company care to meticulously calculate the cost involving the 'lack of communication' either to the suppliers or to the customers (two most important stakeholders). This could be the world of "information". This bit of information will already generate a lot of "cash" for the company by reducing the deleterious effects and helping the "dispute resolution" mechanism among various sections of the employees.

3) **Create:** Many people in some glass companies are creative., but how much of this creative activity is with a 'purpose' that has been fruitfully utilized, e.g. Indian glass companies still do not live upto the standards on colours in industrial and consumer glass articles sectors. Here is one field among many others, where the creativity could really work wonders – so we need to have a strategy on how to unleash the "creative energy" of a company. However, would any glass company care to calculate the loss incurred for not listening to good creative ideas ready for implementation due to a last-minute somewhat illogical or hasty (or, both) decisions.

4) **Consolidation:** There are myriads of examples, where glass companies like many others must have experienced that they could not hold out to the "gains" in the absence of any viable 'consolidation strategy' – so in this case, we also need to adopt a strategy for consolidation of our strategy – e.g. market gains, market penetration, market segmentation, HR training, HR output or productivity, prudent financial analysis, useful financial investment in incremental manners, etc. The list could go on and on. Then, how many glass companies would care to do a serious "audit" and eventual in-depth analysis of the "missed opportunities" due to the lack of 'consolidation' efforts, particularly in marketing.

5) **Customer satisfaction:** The positive side of all of the above will get washed away, if we finally do not pay a massive respect to our customers, listen to their problems, separate the problems and then tackle each one of them in a cohesive

Thought *Process* → **Strategic *Development*** → **Strategic *Review*** → **Strategic *Refinement*** → **Strategic *Implementation***

manner – eventually to serve them well with utmost care and concern. So, we need a viable strategy for 'customers in order to increase the 'customer equity'. The 'customer equity' will never increase unless the customers are really satisfied. We could dwell on the complex issues of 'customer equity' in a separate article in future issue of KANCH. But then why not initiate a series of serious efforts on the customer satisfaction by means of an 'audit' that is based on some well-known methodology. This effort should include an in-built refining approach for better efficiency of the audit system.

MODEL FOR IMPLEMENTATION

Finally, a model of implementation is presented above, which is a modified version of 'management audit system' or 'strategic management system' that could be used with common sense, but with extreme care and care for refinement. So, it is basically a 'refining approach', which is described as follows:

1) Without the 'thought process', nothing can be started – as the famous dictum goes as – 'the action follows feelings'. Unless we feel for something, we cannot act on any issue or topic of interest within the company. So, CEOs would generally ask what we are thinking about an issue and then ask what we have done or what we are planning to do. This is the right approach. Hence, a glass company must encourage the "thought process". However, during a 'hasty' professional life, many such decisions appear to be unnecessary or people just do not have enough time to think on a day-to-day basis. Thus, it is suggested that CEOs start a weekly 'creative session' in a carefully designed 'creative room' so that some ideas crop up on a weekly basis – and then judge the possibility of implementation.

2) Based on the written down information list/idea list, choose the best possible opinions by the "option weighing mechanism" with some degree of consensus (not too much though).

3) Here, the real work starts – i.e. start questioning every bit of 'information' list and suggest remedial measures – i.e. the 'pros' and 'cons analysis of the list.

4) The above helps to refine the approach and prepare a modified 'action plan' with clear guidelines with some minimal options, if needed, and the personal responsibility is clearly spelt out or pinned down on certain individuals.

5) The famous dictum goes like – "All is well, if that ends well". The idea is to simply follow the 'action plan' as rigorously as possible. There is no scope of dithering on any issue anyway, since some weighted options are already provided with

implementation list or the original 'idea list'. Finally, if the implementation fails, we should review and then start at the beginning of the process of 'idea generation'. That's the price we must pay for the 'faulty' implementations – and the employees must learn. However, this 'learning curve' must be as short as possible, since no one has 'enough' time. In this manner, the life remains simple and we do not have to do too much 'fire-fighting'. The "Implementation Culture" should be taught, if not already learnt.

Does the above looks tedious or time-consuming? The answer is a big NO!! Once we see the ball rolling, and once the CEOs start the above process sincerely, the culture becomes 'ingrained' in the body and spirit of the employees. This is the reason why we first talked about "Culture" at the beginning of this article on our above 'strategic management model' that should be pervasive all over the concerned company. Someone has to bell the cat and somehow, somewhere, someone has to start it for the betterment of glass industry – which might be eventually helpful for the entire industry.

In the proverbial tone, we could say "nothing succeeds better than success". So, once the above model is successfully implemented – that success leads to do more and achieve a greater height. If that's not splendid – "What is Splendid in Business Management"?

Finally, it should be clearly pointed out that our model is applicable in any business situation and in any operation of any scale. From a complex delivery or shipment problem to a technical problem to fix a 'specification' or for offering a set of goods and services, just try this model – it will definitely work for the better.

CONCLUSIONS

The main problem in the **7S** model of Mckinsey is that there is no customer angle in the explicit form. Moreover, many aspects look too obvious, and the companies follow them in one way or the other. Our model on "Strategic management" looks simple and pragmatic in the sense that when successfully implemented, it directly and explicitly makes a contribution towards "customer satisfaction", which finally counts at the end of the day. This will definitely augment the 'customer equity', which will increase the 'profitability' of those glass companies, who clearly want to stay ahead in the fiercely competitive marketplace. The 'implementation angle' with a "refining approach" is a 'double dose' that is really necessary in today's business environment, which is intentionally highlighted as some kind of pessimism does not settle in the minds of the concerned people. More such practical models will be presented through KANCH in the future editions with the hope that they will be somewhat useful to the glass industry.

REFERENCES

1. A. K. Bandyopadhyay, “Marketing Excellence and Systems”, New Age Publishers (New Delhi, 2006).

2. A. K. Bandyopadhyay, Mousumi Das, Papiya Biswas, Sahin Ali, A. Goswami, I. Bhattacharya, B. Show, G. Chand and G. Saha, “Technology of Float Glass”, I. I. C. Bulletin, Vol. 14 [1] (2005), 10.

3. A. K. Bandyopadhyay, KANCH, Vol. 1 [4], (2014), 31.

4. A. K. Bandyopadhyay, KANCH, Vol. 1 [4], (2014), 49.

5. A. K. Bandyopadhyay, KANCH, Vol. 6 [1], (2012), 31.

6). A. K. Bandyopadhyay, “Technology of Float Glass Process”, KANCH, Vol. 5 [3] (2012), 33.

7. A. K. Bandyopadhyay, “Refractory Industry – Any Problem?”, Iron & Steel Review, Vol. 8 (1994), 24.

8. Phillip Cottler, “Business Management” (The Millennium Edition), Prentice Hall of India (New Delhi, 1999).

9. A. K. Bandyopadhyay and S.Maitra, “Strategic Management in Ceramics Industry”, Indoceram, Vol. 39 (2002), 19.

10. S. Maitra, A. K. Bandyopadhyay, A. K. Samanta and S. G. Mukherjee, “Importance of causality function on the transfer function of process control operations in ceramics industry”, Indoceram, Vol. 39 (2002), 23.

AIGMF

THE ALL INDIA GLASS MANUFACTURERS' FEDERATION
www.aigmf.com
Founded 1944

UMBRELLA ORGANISATION FOR GLASS INDUSTRY IN INDIA

Glass Containers, Flat Glass including Solar,
Tableware including Opal and Crystal,
Glass Décor Products, Bangles & Many More ...

AIGMF *- Catering to the needs of Glass Industry*

glass WORLDWIDE
Preferred International Journal of AIGMF in association with KANCH

Kanch
The Quarterly Journal of the All India Glass Manufacturers' Federation

The All India Glass Manufacturers' Federation
812, New Delhi House, 27 Barakhamba Road, New Delhi - 110001, India
Telephone : +91 11 23316507 *Fax :* + 91 11 23350357 *E-Mail :* info@aigmf.com *Website :* www.aigmf.com