

Přednáška

THE CHALLENGE TO IMPROVE LARGE SCALE GLASS MELTING*)

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INTRODUCTION

During the past twenty years or so competition between different materials has meant that few traditional markets can any longer be assumed to belong to one particular industry, ceramic, glass, or metal, and polymers have made significant inroads into many markets. Despite this glasses remain pre-eminent in several fields; many types of chemical and laboratory ware, windows and other architectural applications and lighting. During the same period several novel techniques for preparing glasses have been developed; chemical vapour deposition and sol—gel methods are now being widely investigated and have already proved invaluable in the manufacture of several important high technology products. The whole range of these methods has recently been reviewed expertly by Scherer and Schultz [1]. Among these methods the sol—gel process is often rightly claimed to reduce energy consumption in the last stage of firing to form the final glass, because lower temperatures can be used than for glass melting, but it is usually entirely erroneous to claim overall energy savings for this technique: the energy used in preparing the special starting materials will usually greatly exceed that used in normal melting and will always have to be paid for. These exciting techniques seem very likely to be restricted to thin walled tubing, fibres and thin films or special applications where cost is not a primary concern. Traditional melting techniques must therefore be assumed to have an assured future for some bulk production although improved efficiency must, of course, be avidly sought.

Glasses have been melted and traded for several thousand years. During that time techniques have generally evolved slowly but steadily with few abrupt changes. Although written records go back to Assur-banipal in Assyria (668—626 B.C.), accurate understanding of the techniques used is not possible until the second half of the 18th century when two notable contributions were published. These were the Diderot and D'Alembert Encyclopaedia articles on glass melting [2], which give very detailed painstaking descriptions of furnace construction, pot making, melting and fabrication, and the collected works of Bosc D'Antic [3], Director at Saint Gobain 1756—1758, which show, for the first time, a keen scientifically trained mind trying to understand the chemical and physical phenomena involved. Of course the primitive state of chemistry and misapprehensions about the nature and action of heat then made

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a sound scientific understanding difficult to achieve. The complexity of the phenomena is such that there are many aspects that we still do not understand. As a result there are still considerable possibilities for further progress.

A notable review by Garstang [4] showed how steady progress had been made between 1920 and 1970 in the melting of container glasses and attributed these achievements, see figure 1, largely to improvements in furnaces and refractories

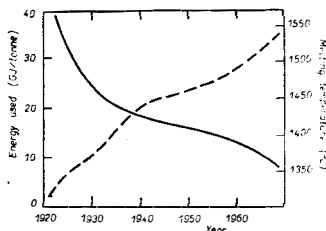


Fig. 1. Average fuel consumption (—) and melting end temperatures (— —) of container glass tanks from 1920 to 1970. After Garstang [4].

rather than deeper understanding of glass melting. It is particularly notable that increased thermal efficiency accompanied increases in melting temperatures when logical arguments based on theoretical heat requirement suggest the opposite (see, for example, Pugh [5]). This is, of course, because glass making is governed by kinetics not by simple equilibrium considerations. Barton [6] has more recently added to these data, especially for flat glass furnaces. Further improvements may become progressively more difficult to achieve but must be striven for as the most efficient glassmakers will always have an advantage. Figure 1 gives no indication of having already achieved asymptotic limits.

ECONOMIC FACTORS

Many products are no longer made from the materials traditionally used. Polymers now compete very successfully with metals for many applications and plastic containers also provide serious competition for glass. The large increases in the cost of energy during the past decade have made glass manufacturers even more conscious of melting costs and overall efficiency than they used to be. However, it would be wrong to assume that the glassmakers of the past did not have worries of this kind about costs; Bontemps [7] discusses costs at length in his well known book (1868) and the author of the Diderot and D'Alembert article on bottles makes clear how they used everything that they could, including scrapings from the floor of the furnace, to produce as much as possible at minimum cost. Different sections of the industry feel the pressures to different extents. The small quantities of glass needed for many high technology applications, such as optical fibres and electronic devices, mean that the cost of the glass is not so critical as for containers and flat glass where the glass itself is the only or major component; container manufacturer generally face the greatest challenges at present.

Despite their relative cheapness raw materials contribute considerably more to melting costs than does fuel and all manufacturers are keen to minimize these costs. Thorough understanding of all aspects of melting chemistry as well as property-

composition relations would make it much easier to achieve optimum conditions. Since we do not understand all of these things as well as we should, no review can supersede the interesting papers given at a conference like this but it may stimulate links between different areas and degrees of understanding.

CHOICE OF GLASS COMPOSITION

The users of glass products are accustomed to setting standards for properties like thermal expansion, electrical resistivity, refractive index, colour and chemical durability. Many users do not need to think about viscosity-temperature curves, heat transfer, liquidus temperature and devitrification properties but the glass manufacturer must add these to the list of criteria to be considered. It is logically impossible to match n criteria unless one has $n + 1$ components so it is easy to understand why so many commercial glasses contain at least Na_2O , K_2O , CaO , MgO , Al_2O_3 and SiO_2 ; indeed it is surprising how many different products can be made when only a few more oxides (such as Li_2O , B_2O_3 , PbO , ZnO , ZrO_2) are added to this list. Although it is true that room temperature properties are almost uniquely defined by composition (thermal history having, in general, trivial effects) it is now realized that control of oxidation and dissolved gases are sometimes very important.

Glass technologists have long been accustomed to calculating properties from composition but not to the converse approach of specifying all the important properties and then computing the most appropriate glass composition. Such an approach is now possible. Property-composition relations are not as well established as one would like but useful approximations are often available; development of better, less empirical, composition-property relations would be very helpful. One of the most obvious challenges is to produce mathematical models giving reliable estimates of liquidus temperature. Westerlund, Hatakka and Karlsson [8] have recently produced very promising models for optimizing glass composition in terms of properties and also batch cost, which show that slight relaxation of property requirements can sometimes lead to significant savings in batch cost. Of course, such computer predictions must be treated as attractive possibilities not proven conclusions. Apart from approximations in property-composition relations, they ignore differences in melting characteristics and the cheapest batch will not always lead to the minimum overall cost. Better understanding of melting, refining, homogenizing, volatilization and refractory corrosion would assist such computer modelling.

Steady development in some sections of the industry, such as container manufacture, may make it sensible to reappraise required glass properties and hence compositions. There is some chance that better compositions significantly different from current ones could occasionally be developed.

CHOICE OF BATCH MATERIALS

Selection of batch materials, even when producing nominally the same glass, can have an influence on properties through degree of oxidation and dissolved gases; it can obviously affect melting rate, refining and homogeneity. Both physical and chemical characteristics of batch materials are well known to influence melting, beginning with batch mixing, and it is not proposed to go into the familiar aspects of size distribution and impurity levels despite their importance. However, some of the possible pitfalls arising from too simple an approach should be indicated. Large particles of materials that do not melt or are not very reactive (quartz is the

most obvious) must generally take longer to be incorporated into the glass than smaller particles; hence particle size specifications limit the proportion of large grains allowed. On the other hand too much fines is also undesirable. In addition to problems of dusting in handling, fines can retard melting, probably from batch segregation, and impair refining by producing too many fine seed, so a minimum size fraction specification is needed. If dealing with a natural raw material like a typical sand it must be remembered that it will not be of uniform composition: the finest fractions will often be rich in surface contaminants and clay particles, the coarsest fractions may be unexpectedly rich in feldspar or other minerals. Taking what appears to be a suitable material except for its size distribution and then, for example, removing the coarsest 20% may appreciably change its chemical composition as well as its particle size. In such a case the expected improvement in melting characteristics may not appear because of increased fines, increased impurities, or change in overall composition.

Finding the batch that gives the lowest overall costs for the appropriate quality of product is a very important task for the glass technologist and one that must, unfortunately, be done almost entirely by intuition, trial and consequent occasional error. The two ever conflicting major factors are that silica sand, usually the largest component of the batch, is the cheapest material but the most difficult to react and dissolve whilst the soda, which most easily reacts with the silica, is by far the most expensive of the common raw materials and also impairs chemical durability. Seeking other more complex raw materials that contain significant proportions of both alkali and silica can have more than one advantage; the most obvious is to reduce the amount of soda ash needed and hence the cost of supplying it. The author also wishes to suggest that the quartz content of the batch, rather than the silica content of the glass, is likely to control batch-free time or melting rate. This is not immediately obviously from investigations of batch-free time versus composition, such as those by Conroy and Robertson [9] but some supporting evidence was found by Afghan [10] in a study of petalite as a glassmaking raw material. Some reduction in the quartz content of the batch will nearly always benefit melting even when the soda ash is also decreased but it may be possible to go too far along this path.

The most obvious additional raw material is factory cullet which is universally used to the greatest possible extent but efficiently run factories produce less than might be best. Foreign cullet has well known dangers; it is difficult to achieve a sufficiently rigorous separation of the different types and colours of glass as well as paper labels and metal bottle caps. Control of glass composition, colour, refining and homogeneity can become very frustrating in such circumstances. The most cullet-like raw material available to well controlled specifications is blended beneficiated blast furnace slag such as Calumite, the advantages of which are well known, see for example Simpson [11]. As shown in Simpson's paper there are some circumstances in which Calumite can have definite advantages over cullet and it is not to be thought just a substitute when insufficient cullet is available. The reasons for the superiority of Calumite over cullet are not entirely clear but may well relate to differences in melting behaviour. Soda ash will sometimes react more easily with cullet than with quartz so that use of cullet can retard $\text{Na}_2\text{CO}_3\text{—SiO}_2$ reactions. This is one reason for not suggesting that cullet be finely crushed. Perhaps Calumite is less objectionable in this respect, it would be useful to know. Successful use of Calumite depends on more careful control of the oxidation of the melt than used to be exercised; Simpson and Meyers [12] have shown how this can be done successfully.

The other materials that deserve to be considered for more extensive use are

minerals like feldspars and nepheline syenite but increased use of these minerals would mean the use of glass compositions richer in alumina than is generally considered appropriate; however, current assumptions may not always be valid.

THE EVOLUTION OF GLASS CONTAINER COMPOSITIONS

There is a natural tendency to assume that further progress can only be achieved by small steps beginning from established practice. When small excursions are made into unknown territory there is a strong stimulus to retire again at the first sign of any adverse result. Looking at the evolution of compositions of glasses used to make containers might make us a little bolder in experimentation but also warn us of some of the pitfalls.

Examination of expert sources from about 100 years ago, such as Appert and Henrivaux [13] shows that they list compositions for bottles which modern glass technologists find incredible: alkali contents are often less than 10% ($\text{Na}_2\text{O} + \text{K}_2\text{O}$), lime in the range 18–25% CaO and silica only about 60%. It is tempting to assume that the analyses cannot be correct but this is an undeserved insult to the pioneers of quantitative silicate analysis. The author and his colleagues have recently analysed a number of English container glasses 350–400 years old, some of which have been hardly attacked by being buried in the ground for that length of time. These include glasses from Hutton and Rosedale in Yorkshire (probably made 1580–1600 A. D.) and Kimmeridge in Dorset (1617–1623). These glasses clearly have compositions belonging to the same family at those quoted by authors such as Appert and Henrivaux [13], see Table I. These glasses are obviously not colourless but by no means as dark as people worrying about the decolorizing of 0.04% Fe_2O_3 would assume.

Table 1
Ranges of weight percent compositions of some old container glasses

Oxide	Before 1625 AD (4 glass works)	19th century (5 glass works)
Na_2O	0.6— 4.9	3.2— 6.2
K_2O	4.2— 7.4	0— 1.1
CaO	17.9—21.6	17.9—23.5
MgO	2.5— 4.7	4.5— 7.0
Al_2O_3	1.6— 3.2	3.5— 7.1
SiO_2	59.0—62.6	57.3—62.5
Fe_2O_3	0.8— 1.6	1.3— 2.7
MnO	0.9— 0.70	0 — 0.4
P_2O_5	1.9— 3.0	0 (traces?)
SO_3	0.20— 0.35	0.09— 1.1

Glasses of this type should have lower batch costs than modern container (or flat glass) compositions: when and why was the change made? The change obviously accompanied the early attempts to make containers by machine when it was found that these glasses devitrified too easily both because of high liquidus temperatures and rapid crystal growth. The liquidus temperatures of these glasses have proved to lie in the range 1140–1265 °C. This means that they cannot possibly have been melted in furnaces unable to exceed 1200 °C as is generally believed. It also means that

they could not be held at the viscosity required for gob formation without devitrifying. Having discovered this glassmakers naturally turned to long established window glass compositions for their trials with container machines.

A series of glasses of this type based on (molar %) 6.00 Na₂O, 2.00 K₂O, 22.25 CaO, 5.50 MgO, 4.25 Al₂O₃, 60.00 SiO₂ has been investigated. All had wollastonite as the primary crystalline phase and their liquidus temperatures were well represented by the empirical relation

$$T_{\text{liq}} = 1295 - 230 [\text{Na}] + 158 [\text{K}] + 200 [\text{Ca}] - 390 [\text{Mg}] - 374 [\text{Al}] \quad (1)$$

where [X] means moles of oxide (e.g. X₂O) per mole SiO₂. It can be seen that the largest beneficial effects on liquidus temperature would be obtained from increased MgO and Al₂O₃. The viscosity-temperature curve of one such glass was investigated by Shamim [14], see figure 2; although it has a higher annealing temperature than

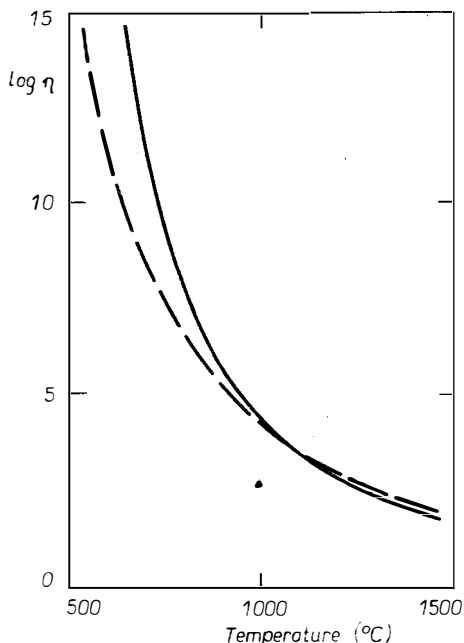


Fig. 2. Viscosity—temperature relations for a typical modern container glass (— — —) and a representative old high lime low alkali bottle glass (——).

modern glasses, there seems no reason why it could not be worked at current machine speeds if the liquidus temperature could be lowered somewhat. Whether this could be achieved by the use of dolomite and felspar remains to be seen. Use of minerals is the only relatively cheap way of introducing lithia or potash into glasses. Perhaps further evolution of container or some other glass compositions is possible: it seems attractive to see how much felspar or nepheline syenite might possibly be used in various types of glass. Interesting glass compositions of the type envisaged (with high alumina but low lime) were made thirty years ago in Czechoslovakia, as reported by Kotsmid [15]. His glass had 11.6% Al₂O₃ and only 10.4% Na₂O. Relaxation of

standards for some properties, such as colour, would increase the range of possibilities. It might, for example, be possible to develop opaque glass ceramics to replace fluoride opals.

CHEMISTRY AND PHYSICS OF MELTING

It seems one of the simplest things in the world to throw together a mixture the various materials, put them into a furnace and melt them. However, we all know that production of well refined and homogeneous glass is a very subtle art influenced by many factors. Simply getting the heat into the batch so that reactions can begin is no trivial task and has led to different preferred methods in different types of furnace.

The melting reactions are very complex both chemically and physically. Several of the processes that occur can have both positive and negative aspects. Thus vigorous evolution of gases can accelerate reactions and mixing of the melt but can also carry undissolved sand grains to the surface of the melt and help the formation of silica scum. Normal melting reactions inevitably lead to a range of liquids of varying densities, viscosities and reactivities which inevitably cause cord and ream in the melt. The processes that determine these things also largely govern refining.

As a result of empirical investigations of melting (batch-free time etc.) and use of the available laboratory tools such as thermogravimetric analysis, differential thermal analysis and hot stage microscopy, we have a sketchy outline knowledge of glass making chemistry but it is far from complete. Lack of such knowledge may inhibit improvements in glass making practices, it certainly retards the further development of computer modelling of flows in furnaces. Such work has been developed very successfully for flows in forehearths and the working ends of furnaces, see Carling [16, 17], but its extension into melting ends is inhibited by lack of data about the properties and behaviour of partly molten batch. There is an urgent need for other methods of study that will provide better insight into the details of the processes occurring during melting. The author and Martlew have made a modest attempt in this direction by studying the dissolution of vitreous silica rods in pure Na_2CO_3 , $\text{Na}_2\text{CO}_3 + \text{Na}_2\text{SO}_4$ or $\text{Na}_2\text{CO}_3 + \text{CaCO}_3$ mixtures, and Na_2CO_3 containing a few percent of silica already reacted and dissolved. The long term value of such an approach remains unclear but some unexpected findings have emerged. In one recent paper, Cable and Martlew [18] showed that corrosion of silica by Na_2CO_3 can be faster at about 900 °C than at any higher temperature up to about 1100 °C, this unexpected behaviour being due to the formation and crystallization of Na_2SiO_3 below about 1020 °C. In another paper [19] data for the corrosion of silica in melts with compositions in the range Na_2CO_3 to Na_2SiO_3 have been interpreted by the standard free convection technique, such as used by Truhlarova and Veprek [20]. Despite the very large increase in viscosity within the range Na_2CO_3 to Na_2SiO_3 , the effective diffusivity for dissolution of silica was found to be about the same for both Na_2CO_3 and Na_2SiO_3 and also showed a distinct minimum at 20 % SiO_2 .

The first of these findings, the **increasing** rate of corrosion of silica as the temperature fell from 1020 to 900 °C, turns one's thoughts to fritting. This was standard practice by bottle makers for several hundred years up to about 1880. It is widely believed that fritting can improve melting, refining and homogenizing but surprisingly little quantitative information about its effects is available. Some of the literature from about a century ago suggests that it was particularly desirable in batches containing significant amounts of sodium chloride. It is also undoubtedly useful in

laboratory melting, in those cases where ordinary procedures lead to serious melting segregation. Using the heat from waste gases to preheat batch is an obvious directly effective means of heat recovery, as was shown by the technique adopted for the Brichard [21] furnace. Unfortunately partly reacted batch has very poor flow properties and it is very difficult to design automatic equipment that will handle it and meter its supply to the furnace at temperatures between 800 and 1100 °C. The cost of the necessary engineering work could easily exceed the savings achieved by more efficient melting. The same seems to be true with briquetting. Distinct advantages can be demonstrated in many cases but are often of marginal overall financial benefit. However the benefits can be worth the costs in some particular cases, such as lead glasses where dust and volatilization can produce environmental problems, as shown by Lakatos [22]. For these reasons it is unrealistic to expect definite answers to the question whether batch preheating or briquetting are desirable without careful examination of particular cases. A broader base of soundly planned and carefully executed trials would, of course, help future investigators.

REFINING

The first extensive quantitative investigation of refining, by measuring numbers of bubbles remaining, were published by Gehlhoff, Kalsing and Thomas [23], the first calculations to cast doubt on the role of rise to the surface by Jepsen—Marwedel [24] in 1936 and the first analyses of the gases inside seed by Appen and Polyakova [25] in 1938. Despite these pioneering contributions the first detailed analysis of the role of rise to the surface was, apparently, that by Cable [26]. Since that time there has been a notable growth in the study of refining: one of the talented workers has been Nemeč [27, 28, 29]. There is now widespread agreement that mass transfer must

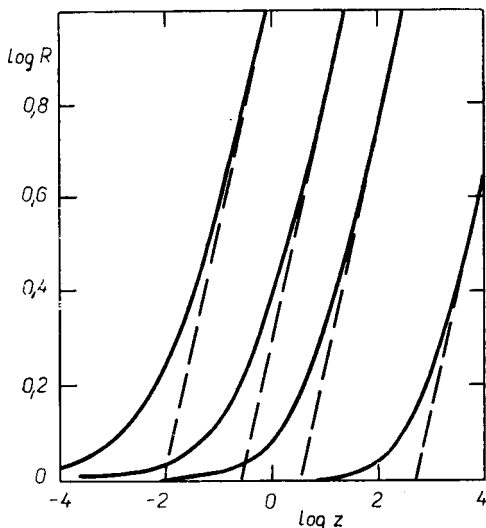


Fig. 3. The rapid convergence of analytical solutions for growth of spheres from zero size (— — —) and numerical solutions for growth from finite size (—) in diffusion controlled conditions. The four results are for solubility parameters (α), from left to right, 0.95, 0.5, 0.1 and 10^{-3} . R is dimensionless radius and Z dimensionless time (Dt/a^2).

occur between individual bubbles and the melt surrounding them. It is also clear that either growth or dissolution is possible in different circumstances (see Nemeč [27–29] and Greene and co-workers [30, 31]). Unfortunately the behaviour of multi-component bubbles is very complex, even if controlled by straightforward diffusion of dissolved gases in melt, and it is not possible to claim that we understand refining well in principle leaving only a few trivial untidy details to be cleared up in practice. Further advances have been held back both by the difficulty of obtaining the crucial experimental results and by an inadequate theoretical background. Fortunately significant advance in the latter can now be reported.

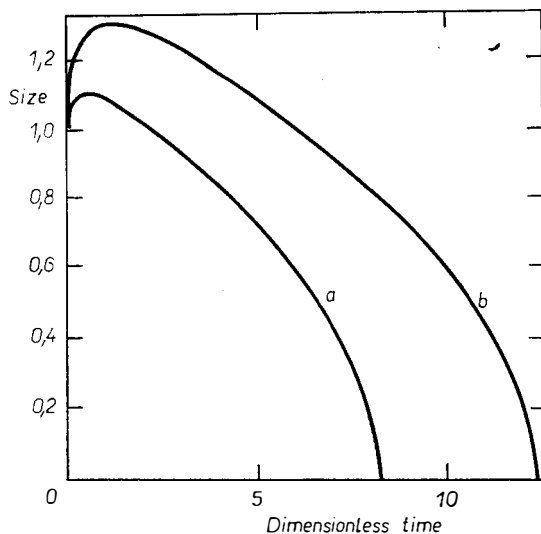


Fig. 4. Two examples of bubbles which initially grow but eventually dissolve in a two component system. (a) A bubble of pure gas 2 introduced into a liquid free from that gas but in equilibrium with 0.8 atm of gas 1 which has ten times higher solubility but the same diffusivity as 2. (b) A bubble initially containing equal proportions of gases 1 and 2 in the same conditions. In both cases the composition of the bubble rapidly approaches a composition of about 88% gas 1.

Frade [32] has completed a detailed examination of the theory of growth and dissolution of both one and multi-component stationary gas bubbles by numerical and also, where possible, analytical methods. His work has shown very close agreement between numerical and analytical solutions where both are possible but shown that the relatively simple approximations often used are all of very limited validity. Frade has shown that one component bubbles growing from finite initial size begin to grow rather more slowly than might have been expected and nearly always become indistinguishable from bubbles growing from zero initial size before they have grown to five times their initial diameter, see figure 3. It is also clear that the composition of growing multi-component bubbles always approaches an asymptotic limit, usually in a straightforward manner but change in size can be more complex: it is quite possible for a bubble to begin by growing but eventually dissolve, see figure 4. As often happens, measuring only the integrated quantity, change in size, leads to the greatest difficulties in untangling the details of what is happening.

The situation is worse for dissolving bubbles than for growing ones, because their behaviour is always in a transient regime: only in special cases does the composition of the gas in them tend to an asymptotic limit.

Figure 5 shows what is considered to be the classic change in the gas inside seed, $\text{CO}_2 \rightarrow \text{O}_2 \rightarrow \text{N}_2$, taken from work by Apak [33] on the effects of small changes in composition (not only refining agents) on the refining of a soda—lime—silica glass. Figure 6 shows another set of these data in which the bubbles never became rich in oxygen. Frade was unable to match either of these with predicted changes in the composition of growing bubbles for any plausible combination of solubilities, diffusivities and dissolved concentrations of these gases for growing bubbles. Of course we really need the theory for a freely rising bubble not a stationary one. However,

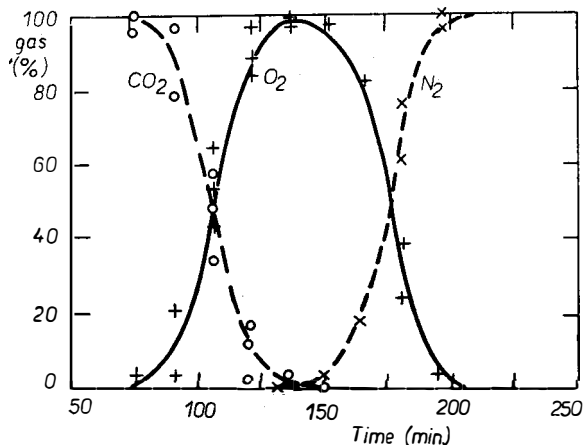


Fig. 5. The classic CO_2 — O_2 — N_2 change in the composition of seed during refining of 20 kg melts of a soda—lime—silica glass refined with arsenic and sulphate.

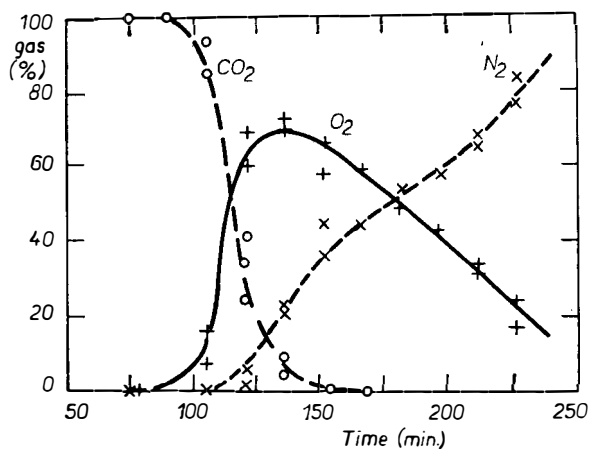


Fig. 6. Analyses of seed taken from a melt similar to that shown in Figure 5 but having slightly different additions of refining agents.

it is likely that this difference in conditions would lead to a quantitative difference in time scale but no qualitative difference in behaviour. The most glaring defect in our knowledge is lack of reliable values for diffusivities and solubilities of gases in glass melts.

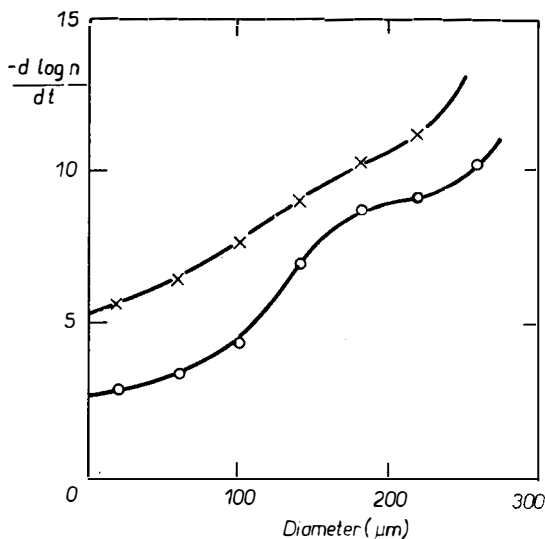


Fig. 7. Rates of disappearance ($-\frac{d \log n}{dt}$) of seed of given diameter in small melts containing no refining agent (O) and the most efficient combination tried (0.50% As_2O_3) (X). After Cable⁴⁴.

Another point rarely emphasized in the past is that there seems to be no important qualitative difference in the refining of melts with and without refining agent, see figure 7. Our understanding of the true function of refining agents is still incomplete. This is very unfortunate when arsenic, sulphur dioxide and halide vapours are all very undesirable on environmental grounds.

HOMOGENIZING

Although homogeneity is rarely measured most products have specific requirements which are not always easy to meet. Small scale laboratory melts are notoriously difficult to homogenize unless carefully stirred and the main differences in design and construction of container and flat glass furnaces are determined by standards for homogeneity. The complex flow patterns inside tank furnaces and electric furnaces are required largely to attain sufficient homogenizing action. As mentioned above much progress has now been made in the mathematical modelling of flows in furnaces but it is not yet general practice to estimate the homogenizing action of various flow paths through the furnace. It is possible that consideration of this might produce further improvements in furnace output and hence efficiency. This is suggested by figure 8 which shows the considerably different homogeneity of the glass supplied by five forehearth on a fairly large container tank, taken from work by Aylward [34]. The upper part of the diagram shows the nominal variance of refractive index of the glass evaluated by Shelyubskii's method for 12 samples taken

from each forehearth at the same times over a period of 27h. The lower part shows how the furnace load was distributed between the forehearths. The centre forehearth (No. 3) has the lowest pull and the worst homogeneity, the outside forehearths (1 and 5) have both the highest pull and the best homogeneity. This pattern may not be typical of all furnaces but tracer experiment results of Lokay [35] suggest that it may be fairly common. Decreasing the differences between forehearths by better furnace design and operation might bring useful improvements in efficiency.

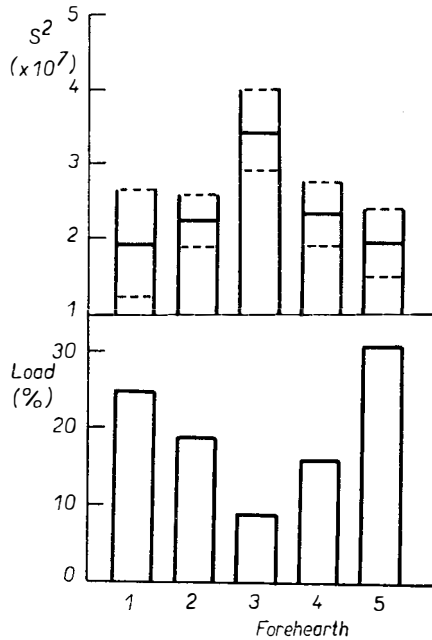


Fig. 8. Mean and range of variance of refractive index (S^2) evaluated by Shelyubskii's method for glass taken from all five forehearths of a container furnace together with the distribution of furnace load between the forehearths. After Aylward [34].

The principles of homogenizing by attenuation and alignment of inhomogeneities accompanied by diffusion are well known, see Cooper [36] and McKelvey [37]. All cases for which theoretical solutions are available were discussed in detail by Cable [38]. By considering elliptical or ellipsoidal inclusions it is possible to deal with infinitely deformable inclusions (ones with no interfacial tension) in a simple way using a solution devised for the author by Eshelby [39] which is valid for any ratio of the viscosities of the inclusion and the matrix. It is also possible to examine some aspects of the deformation of gas bubbles or other inclusions the deformation of which is limited by surface tension, using an analysis by Cox [40]. Two quite different classes of behaviour are revealed.

Infinitely deformable inclusions usually become attenuated and eventually aligned parallel to the velocity vector but viscosity can have important effects, especially for inclusions of compact (near circular) shape. Inclusions of low viscosity deform more easily than more viscous ones and increasing inclusion viscosity rapidly has

very adverse effects. This has important implications for the behaviour of certain kinds of knots and other viscous inclusions. For all of these the final shape depends on the total integrated history of the flow of the region around the inclusion. Where interfacial tension acts, the inclusion rotates and deforms to only a limited extent and comes to equilibrium quite rapidly; the shape in the finished glass then shows the stress field that existed as the melt solidified and past history has little effect. This is why the vast majority of bubbles and blisters are spherical. Although the theoretical studies could be extended further (and have been by Bilby and his colleagues [41]) enough is known to make it more profitable to apply what is already known, perhaps by using the data in mathematical modelling of furnace flows.

On a more practical level, so far as laboratory glass makers are concerned, model work by Jambor—Sadeghi [42] and Wang [43] has shown that stirrers much more efficient than the traditional ones used for homogenizing small glass melts can be devised.

CONCLUSION

This paper contains some of the author's views about the present scientific understanding of the art of glass making by normal melting techniques. There are many ways in which improvements may be possible and where background knowledge appears inadequate. Revolutionary developments seem rather unlikely in glass melting although we are in a period of rapid change in many branches of the industry. Some markets may be lost to competing materials but others seem to have an assured future. Improvement in any aspect of glass melting must help to safeguard the industry's future.

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BINDER K.: APPLICATIONS OF THE MONTE CARLO METHOD IN STATISTICAL PHYSICS (Aplikace metody Monte Carlo ve statistické fyzice), Springer-Verlag, Berlin—Heidelberg—New York—Tokyo, 1984, 311 str., 90 obr., cena 82,50 DM.

Výpočetní simulace Monte Carlo jsou nové nástroje nacházející využití v řadě vědeckých oblastí, jako je fyzika kondenzovaných soustav včetně fyziky povrchu a problémy aplikované fyziky. Jsou také využívány ve fyzikální chemii a v teorii polí. Na druhé straně simulační metody se nepoužívají pouze ve výzkumu, ale hrají stále důležitější roli i ve výuce studentů (přednášky a semináře na univerzitách), neboť se dají použít i k simulaci ekonomických a společenských situací.

Kniha svojí náplní vhodně doplňuje předešlé tituly s touto problematikou. Na začátku je uveden jednoduchý úvod, který pomáhá především začátečníkům ke zdárnému pochopení problémů. Jsou v něm vysvětleny základní pojmy, především v oblasti náhodných čísel.

Po této úvodní kapitole následují další, které jsou děleny tak, že v každé z nich je ukázáno použití simulační metody Monte Carlo v některé z oblastí statistické fyziky. Nejobsáhlejší je ihned druhá kapitola zabývající se nově vyvinutými simulačními metodami v oblasti klasických tekutin. Jde především o jednoatomové tekutiny, molekulární kapaliny, roztoky a jevy na povrchu tekutin (liquid — vapor interface). Další kapitola je věnována využití metody Monte Carlo u kritických a multikritických jevů. Následující dvě, opět rozsáhlé, kapitoly věnované jednak simulačním modelům polymerů a jednak tavení ve dvou dimenzích. Závěr tvoří dvě kapitoly věnované studiím Monte Carlo v náhodných systémech a Monte Carlo výpočtům v teorii měření prostorových mřízek krystalů.

Jednotlivé kapitoly jsou pojaty jako přehledné referáty a z toho důvodu obsahují velké množství informací a také jsou doplněny rozsáhlými seznamy literatury. Proto je kniha vhodná pro široký okruh zájemců, kteří si chtějí rozšířit znalosti v oblasti metody Monte Carlo a jejího použití.

Kasa