DK 666.1.031.15:666.1.031.13:532.5:666.1.031.2.001.57

Using residence time distribution to obtain figures of merit for melter studies

Von ARNOLD J. GOLDBERG, Harmarville, Pa. (USA)

(Vortrag auf der 46. Glastechnischen Tagung am 5. Juli 1972 in Wiesbaden)
(Mitteilung aus der PPG Industries, Inc., Glass Research Laboratory, Harmarville, Pa. (USA))
(Eingegangen am 2. Juni 1972)

Model studies were undertaken to map the flow paths in a glass melter in order to determine the residence time distribution of molten glass traversing the region from the batch cover to the spring zone. This, together with the temperature distribution measured at the same time, was used to compute the percentage reduction in a local inhomogeneity whose residence time in the melter is least, using a standard solution to the diffusion problem.

This number is selected to gauge the extent of progress of homogenization, one of several physico-chemical rate processes taking place in the melter. As such it is one figure of merit to measure the capability of a melter design.

A figure of merit was obtained for a so-called 'standard' situation and used as a basis against which to compare the effectiveness of other melter systems in transporting homogenized material to the refiner. In the cases examined it was found that the minimum melter residence time for material melting off the bottom of the batch was of the order of 10 h and that a greater than 95% reduction in local inhomogeneity could be expected in the melter.

Utilisation de la distribution des temps de séjour en vue d'obtenir une évaluation chiffrée des fours de fusion

Des études sur modèles sont entreprises en vue de dresser une carte des parcours des courants dans un four de fusion de verre, de manière à déterminer la distribution des temps de séjour du verre fondu qui traverse la région qui s'étend de la zone d'enfournement au point chaud. Ces données, de même que la distribution de température mesurée simultanément, sont utilisées pour calculer sur ordinateur le pourcentage de réduction d'une inhomogénéité locale dont le temps de séjour dans le four est le plus bref possible. Une solution normalisée est utilisée pour le problème de diffusion.

Ce nombre est choisi, en vue d'évaluer le progrès de l'homogénéisation car celle-ci représente l'un des nombreux processus physico-chimiques qui interviennent dans le four de fusion. Comme tel, ce nombre est donc l'une des valeurs qui permettent d'évaluer l'efficacité d'un four.

Un autre critère d'évaluation est obtenu pour une situation dite «normale» et est utilisé comme point de référence en vue de comparer l'efficacité d'autres systèmes de fours en ce qui concerne le transport du verre homogénéisé vers la zone d'affinage. Dans les cas examinés, on constate que le temps de séjour minimum dans le four de matériaux fondant à partir du fond de la composition est de l'ordre de 10 h et qu'une réduction de plus de 95% des inhomogénéités locales peut être obtenue dans le four.

Benutzung der Aufenthaltszeitverteilung zur Verbesserung der Gestaltung von Glasschmelzwannen

An Hand von Modelluntersuchungen wurden die Glasströmungen in einer Schmelzwanne bestimmt, um daraus Rückschlüsse auf die Verweilzeitverteilung des geschmolzenen Glases zwischen Gemengebereich und Läuterbereich ziehen zu können. Aus dieser und der gleichzeitig gemessenen Temperaturverteilung wurde der prozentuale Abbau einer lokal auftretenden Inhomogenität innerhalb einer Mindestaufenthaltszeit in der Schmelzwanne nach einer Standardlösung bei Annahme von Diffusion berechnet.

Dieses Ergebnis wurde benutzt, um das Ausmaß des Homogenisierungsprozesses abzuschätzen, der als einer von mehreren physikalisch-chemischen Prozessen innerhalb der Schmelzwanne abläuft. Hierzu ist es auch vorteilhaft, die tatsächliche Belastbarkeit einer Wanne zu ermitteln.

Für einen sogenannten „Standardzustand" wurde eine optimale Ausbildung ermittelt und als Vergleichsbasis für die Homogenisierungsleistung anderer Wannensysteme während des Transportes der Schmelze in den Läuterbereich benutzt. In allen überprüften Fällen konnte festgestellt werden, daß die Mindestaufenthaltszeit des an der Gemengeunterseite abschmelzenden Materials in der Größenordnung von 10 h liegt und daß ein mehr als 95%iger Abbau einer lokalen Inhomogenität erwartet werden kann.

To reach a certain level of quality in a glass furnace, each element must remain at an elevated temperature for a length of time sufficient for all the rate processes of melting, chemical reaction, particle dissolution and homogenization to proceed to completion. Because these rate processes slow down quickly as temperature drops, the length of time that the glass spends in the melter portion of a furnace where the highest temperature are found is of critical importance. Not only the residence time but also the path of the glass through the melter is of interest, because the extent of homogenization in the system will depend on the amount of time spent by the glass at each temperature level, which is to say that as is generally recognized, glass quality will be a function of its particular time-temperature history.

It is therefore of interest to study the residence time distribution together with the flow and temperature patterns of a melter in order to gain insights regarding improved design for achieving better quality or higher throughput. Usually the attempt is made to achieve these goals via increases in furnace size or increases in the amount of energy imparted to the furnace. The wide variations in the results of these efforts is ample evidence that at best in few cases has the added capacity been utilized to fullest advantage. This lack of uniformity of results would be attributable to flow related phenomena which may very well be different from case to case.

Accordingly the author has been considering the conditions required for satisfactory melter operation. His concern is with large flat glass furnaces, in particular, the interval between the instant the raw materials begin to heat up until the molten glass has passed the spring zone. The main interests of the present work are the flow paths followed by elements of melting material as it passes through the system as well as the temperatures and the flow environment encountered by the fluid elements along their path.

1. Characterizing of melter effectiveness

In view of the impossibility of obtaining this information via direct measurement in existing systems and the need for making suitable projections regarding the effectiveness of new designs or modes of operation, it is desirable to evaluate or to represent melter effec-

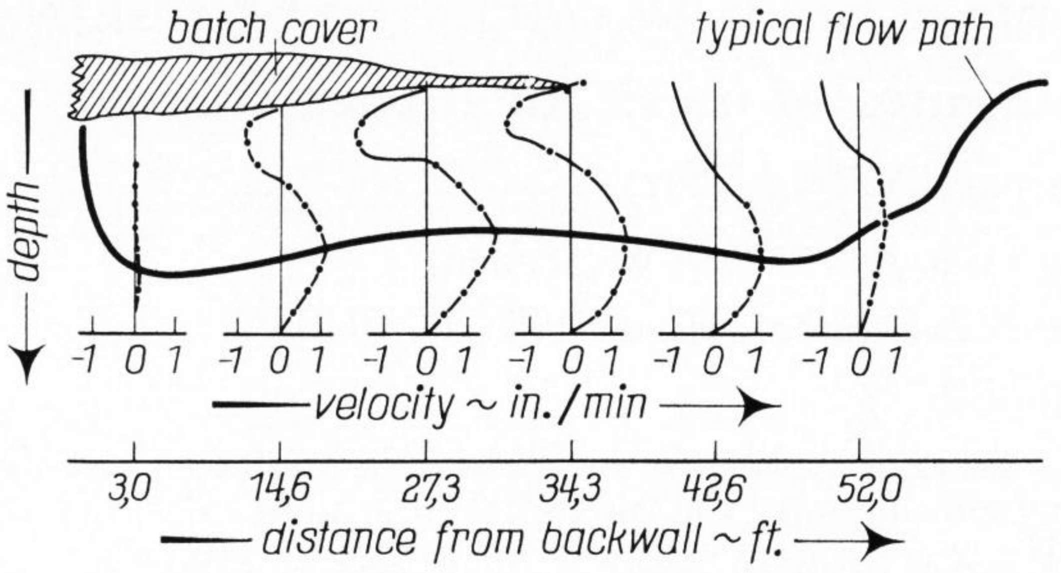

Figure 1. Melter velocity distribution.

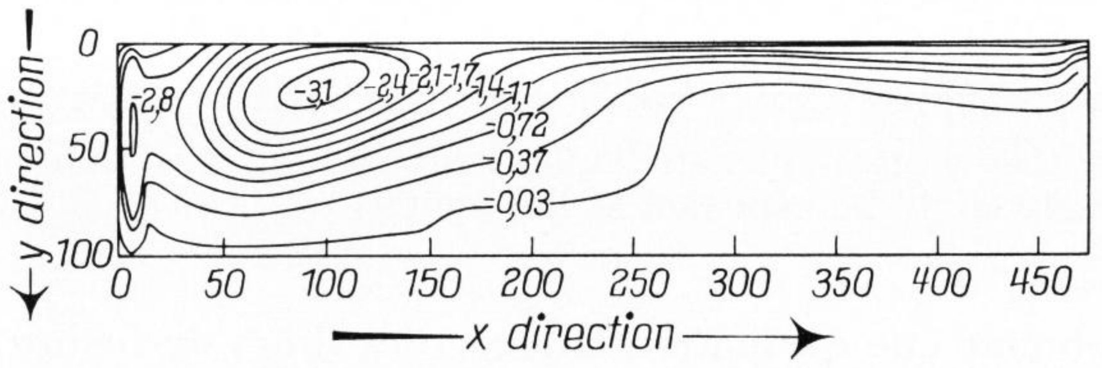

Figure 2. Computer generated streamlines in a glass furnace. Case 1: 100 tonnage units.

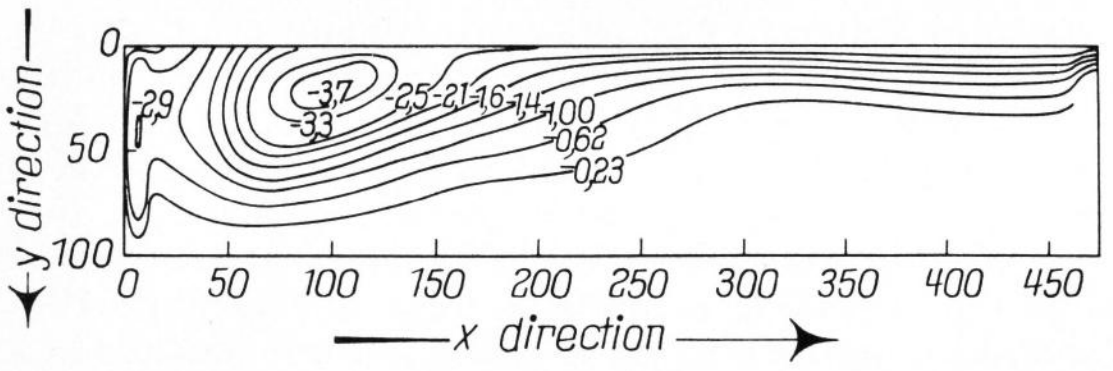

Figure 3. Computer generated streamlines in a glass furnace. Case 2: $133^1/_3$ tonnage units.

tiveness in terms of quantities which can be examined via analytical methods or via scale models. A logical approach is to simulate melter flow and temperature distributions which information can be used to define quantitative variables as candidates for characterizing melter systems.

One way to characterize a melter is to specify the melter residence time. This reflects the time available for melting to take place and is indicative of the level and rate of energy flow to the melter which is required to sustain the melting rate for a specific combination of melter size and throughput level.

Of particular importance is the minimum residence time through the melter. In order for the glass which experiences the minimum residence time to be melted and homogenized to an acceptable level, it must be subjected to temperature and shear fields of greater intensity than those encountered by the other fluid elements in the melter which progress to the same level. Accordingly it would be certain that a melter is adequately designed if it were possible to demonstrate that the glass which spends the least time in the melter experiences a time-temperature history which is adequate to bring it to an acceptable level of quality.

This requires one first to describe the time-temperature history in some detail and second to make use of this information to characterize the degree to which this has resulted in the raw materials being transformed into glass of acceptable quality.

Because it was not possible to gather the detailed information from furnaces, models were used. From the models it is possible to establish flow profiles in the melter such as those shown in figure 1. These profiles were measured at intervals along the furnace beginning from a point just a few feet downstream of the feed end. These profiles which are fairly typical show the flow convection moving upstream away from the spring zone and being retarded by the presence of the batch. The volume of flow moving forward in the system is evidenced by the bulge in the lower part of the velocity profile. As the glass flows proceed downtank, they are augmented by material being transferred from the bottom of the batch and so the profile becomes more pronounced. A typical streamline through the melter is shown by a line running through the system which intersects successive points on the velocity profiles.

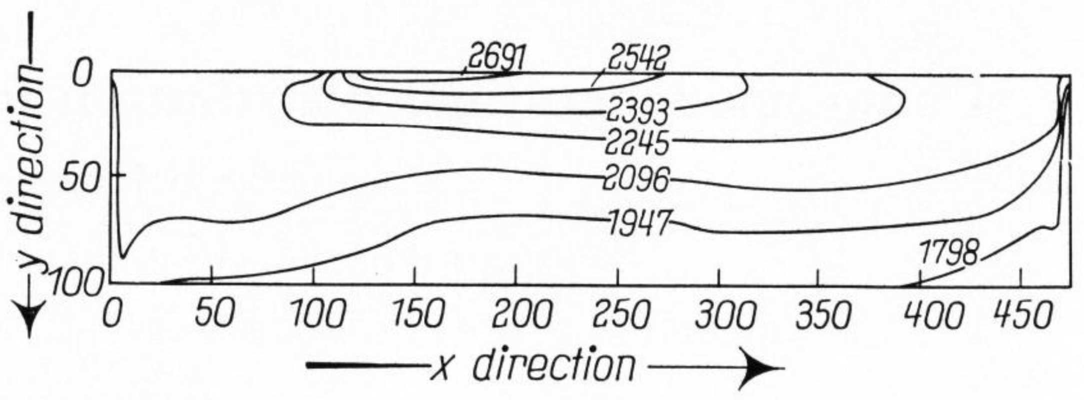

Figure 4. Computer generated isotherms. Case 1.

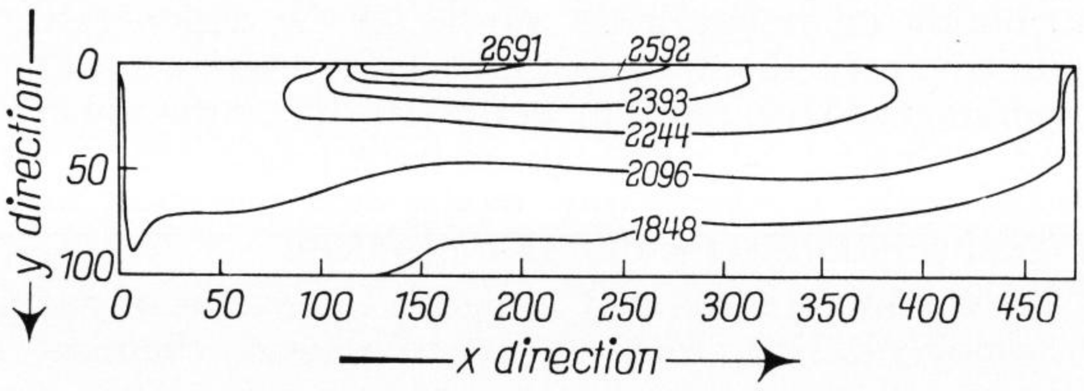

Figure 5. Computer generated isotherms. Case 2.

For the given purposes it is desired to find that streamline which represents the path followed by that fluid element whose residence time is least. To find this streamline a two-dimensional numerical solution to the flow equations was used to search for the streamline which satisfies the aforementioned requirement.

Computer generated streamlines for two of the cases that were studied are reproduced in figures 2 and 3. These are solutions to two hypothetical situations which will be used for the balance of this discussion.

The chief difference between case 1 and case 2, shown in figures 2 and 3 respectively, is the level of output which is responsible for the changes in temperature and flow patterns that will be compared. In case 1 the throughput is set at 100 units and in case 2 the throughput is one-third higher. Each tank is divided into arbitrary length and depth units as shown in the figures. The melter section extends about 40% of the distance along the x-axis.

The computer searches for the streamline corresponding to the minimum residence time path. Once this is found any variable or quantity can be computed along the streamline using the available velocities and temperature data.

Typical temperature data is presented in figures 4 and 5 for the two cases under comparison. Isotherms are shown which can be generated by the computer based on the numerical solution to the flow equations. Comparing figure 4 and figure 5 it is to be seen that in a gross sense the isotherm patterns are very similar but that there are significant differences in detail. In the former case in which the tonnage is lower, the melter temperatures are higher particularly along the bottom of the furnace than they are in the latter case. The implica-

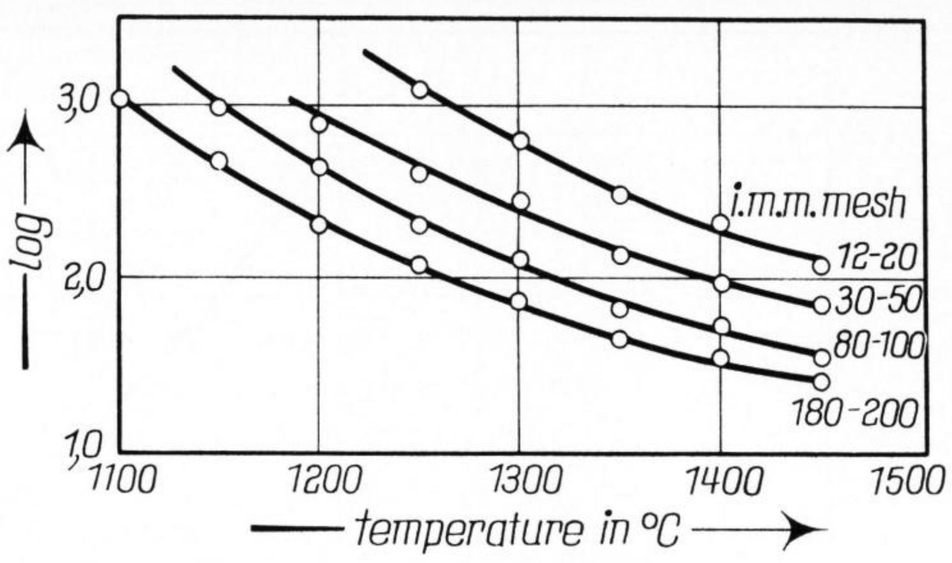

Figure 6. Relation between melting rate and temperature of the standard batch.

tion is that at the higher tonnage it will be necessary either for there to be an increase in the minimum melter residence time or a change in the shear field in order to bring the increased volume flow of glass to the desired state at the point at which it exits the melter.

2. Role of particle dissolution for interpretation of melter phenomena

A quantitative characterization of the desired state must be at hand, however, in order to make precise comparisons between these two systems or among any others that are to be examined. Now consider some of the indicators, or figures of merit, which were deemed appropriate to use as guides to the interpretation of melter phenomena. An obvious way to characterize the melter is via the minimum residence time itself. However, from the computer solutions there are sufficient data to establish certain other quantitative benchmarks for melter performance.

These benchmarks are chosen to reflect the extent to which the normal physico-chemical processes have taken place in the system under scrutiny. These processes take place in an array of sequential and parallel steps beginning with radiant heat transfer from the flame to the batch and glass surface. Subsequent steps involve convective and conductive heat transfer from the fluid in motion in the melter to the batch to support the initial melting followed by chemical reaction and particle dissolution which must take place to convert the batch to molten glass. Subsequent steps in the process involve the elimination of gaseous inclusions and the combined processes of shear and diffusion which serve to reduce the level of inhomogeneity in the system. For this discussion it is assumed that there is adequate energy transfer in a gross sense and that adequate time is available for fining. Attention must be focused on rates of particle dissolution and homogenization which are of particular interest, because they must proceed consecutively and because each may require a considerable time interval to proceed to completion. In this sense, dissolution and homogenization are a rate limiting or throughput limiting sequence of steps for a flat glass melter.

First it is considered that it is possible for partially dissolved sand particles to be caught up in the melter flow system, and so it must be inquired whether the minimum residence time in the melter is adequate for the largest sand particle introduced into the system to be completely melted when subjected to the thermal environment encountered along the flow path. It is assumed that if unmelted particles are permitted to leave the melter then quality problems are almost sure to ensue because the refiner temperatures are too low and the refiner shear field is too weak to promote effective homogenization.

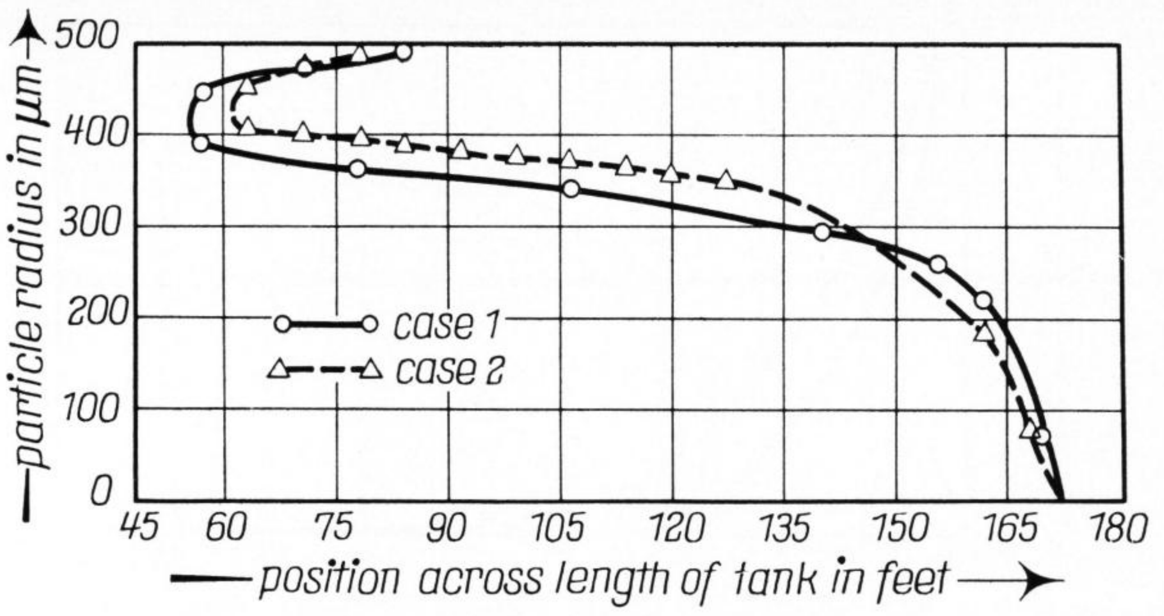

Figure 7. Change in particle radius as it progresses along melter streamline.

It is reasonable to suppose, however, that in general sand particles will be completely dissolved and that some diffusion and attenuation also takes place in the melter, perhaps to a considerable degree. Accordingly a more useful question than the one posed above is, how far along the streamline does the largest sand particle progress before it is completely melted? To answer this question it is necessary to know the rate of particle dissolution as a function of temperature in addition to the information generated by the computer flow solution. Although a considerable body of literature exists about particle melting rates, data generated specifically for each case under study would perhaps be more useful. However, for purposes of illustration it is possible to use well known data generated by PRESTON and TURNER [1] (see figure 6) which shows the relation between the initial size of a sand particle and the time necessary for particle dissolution at various temperatures. Making use of this information it is possible to project the particle size reduction of a grain of unmelted sand during each interval of time along the streamline. To simplify matters it may be assumed that particles are effectively spherical, that the melting rate is proportional to heat transfer per unit particle volume and that conduction is the principal heat transfer mode. It can then be shown that the change in particle radius is directly proportional to the time elapsed from the inception of the melting process.

3. Results

The results are shown in figure 7 where the particle radius is shown plotted for both cases of the present discussion. Because the temperature distributions in the two tanks vary, the rates of particle dissolution as a function of position differ. However, the dissolution process accelerates in both cases as the particles move into the hotter regions of the furnace which are in the vicinity of the spring zone. As a consequence it is found that the particle radii approach zero at approximately the same location. To all appearances output could probably be increased in this furnace by a significant margin before difficulties would be experienced as a result of material passing through the spring zone before having undergone complete melting. In this sense the figure of merit which has been just described is useful for comparing systems, proposed designs or modes of operation.

The position at which the particle can be said to have completely melted is but one indicator of the nature of the flows. Another measure of interest is the

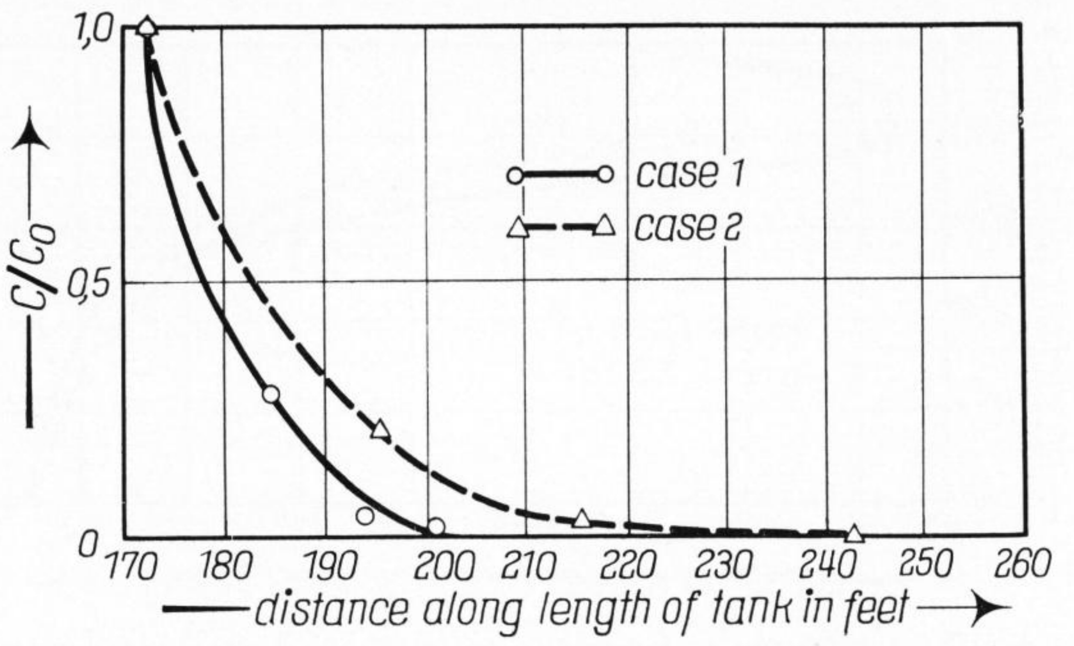

Figure 8. Reduction in excess silica concentration as inhomogeneity proceeds along streamline.

strength of the shear field to which a volume element is subjected as it moves along the streamline.

It is possible to have the computer calculate integrated values of the shear force exerted along a streamline. However, the shear field strength is not the sole determinant of the extent to which an element is homogenized. Here too temperature plays a vital role. In particular, one can use the derivation of GEFFCKEN [2] and BECKER [3] which related the degree of reduction of concentration differences in a glass melt to flow properties according to the following relation:

$$C/C_0 = \varphi\left(\frac{d/2}{\sqrt[2]{\frac{t^3}{D3}(\triangle V)^2}}\right),$$

where C_0 and C are the initial and final relative concentrations respectively, φ is the upper limit of the error integral, D the diffusion coefficient and $\triangle V$ the velocity gradient. Making use of this relation and the results of the computations, the percentage reduction of the excess silica concentration of a particle as it processes along a streamline can be computed. In figure 8 the percent reduction is plotted as a function of the position of the particle on the streamline along the length of the furnace. The effects of the smaller residence time and lower temperatures in case 2 are evident.

The local inhomogeneity is presumed to first appear at the point where the silica grain is found to have completely dissolved. For this reason the two curves in figure 8 originate at a point along the x-axis corresponding to that point in figure 7 at which the particle radii are computed to have approached zero. While it is undoubtedly true that diffusion of material away from the partially melted sand grain takes place simultaneously with the melting process, this transfer is slower at lower temperatures. Accordingly it is estimated that the size of the local inhomogeneity may in some cases be as great as the diameter of the original unmelted particle caught in the flow. The assumptions made remain consistent from case to case so that the validity of comparisons which can be made is sustained. In any case, neglecting the varied amount of diffusion which may occur before the sand particle is completely dissolved results in a slightly more cautious interpretation of the consequences of a particular melter move.

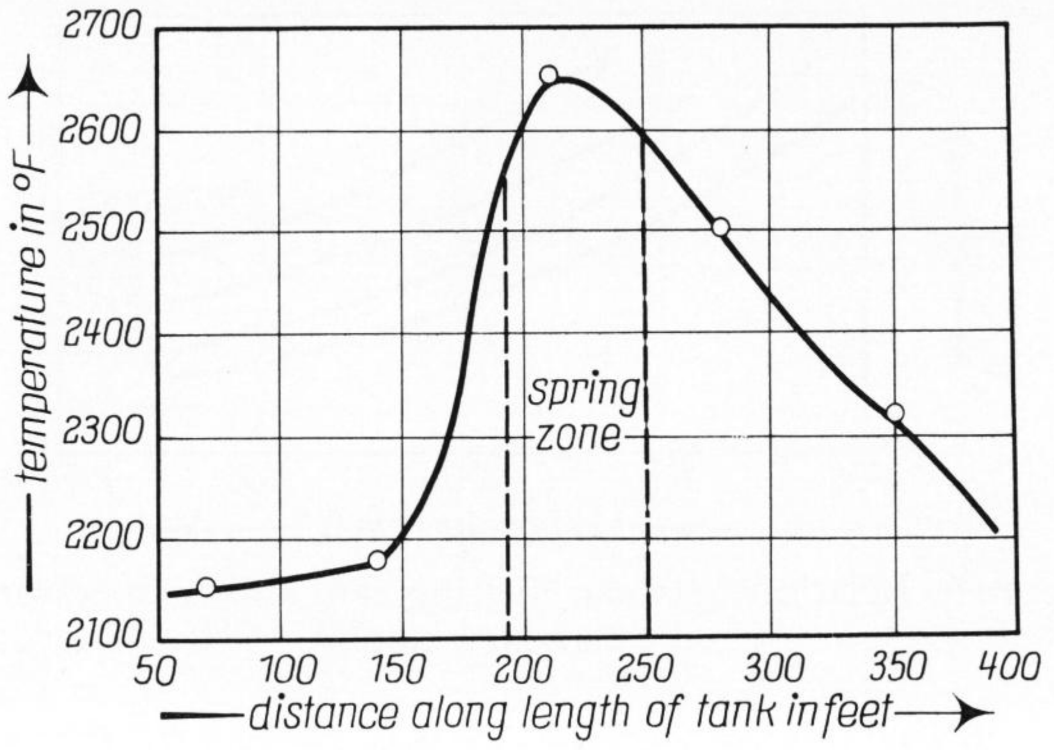

Figure 9. Temperature distribution along streamline.

For these reasons the reduction in excess silica concentration has been computed which occurs after the particle has melted for each of the two cases. The ratio C/C_0 is plotted as a function of distance along the tank in figure 8. The curves are continued to the point at which excess silica is reduced to 0,1% or less, a figure which satisfies the most stringent quality requirements. From figure 8 it is to be seen that in case 2, which corresponds to the higher tonnage level, the particle must travel significantly further along the length of the furnace before it is homogenized to the same degree as particles in the standard or low tonnage case. In case 1, the particles can be said to be effectively homogenized by the time they reach the center of the spring zone whereas in case 2, the particles have passed beyond the spring zone or thermal hot spot before reaching this state. The temperature distribution showing the approximate spring zone location is shown in figure 9.

Thus in case 2 there is no margin for error in assumption or in the computer analysis. Any particle that is forced along a slightly shorter or colder path than the one shown by the computer will find itself in the refiner in an unhomogenized state. In view of the fact that the refiner is deficient in both temperature and shear forces, such a particle is likely to pass through the refiner portion of the furnace without undergoing any significant homogenization. Therefore it may be concluded that case 2 compares unfavorably with case 1 based on this particular figure of merit and that tank flows and temperatures must be changed to bring the homogenization curve for case 2 in figure 8 more in line with that shown for case 1.

4. Conclusions

Although the assignation of a figure of merit such as the one which has been discussed represents a characterization of but one element, albeit a major one, of a multi-faceted problem, it is nevertheless illustrative of an approach which is useful in guiding melter analysis. Whereas the values generated in this way may not be entirely accurate on an absolute scale, they do provide quantitative bases of comparison which would allow particular furnace conditions to be gauged against a standard.

5. References

[1] PRESTON, E. and TURNER, W. E. S.: Fundamental studies of the glass melting process. The effect of particle size and temperature on the rate of glass formation of a pure soda-lime silica glass. J. Soc. Glass Technol. **24** (1940) p. 124 – 138. [Ref. Glastechn. Ber. **19** (1941) S. 130.]

[2] GEFFCKEN, W.: Vorgänge der Homogenisierung in der Schmelze, Ausziehen der Schlieren, Diffusion. Glastechn. Ber. **30** (1957) p. 143 – 145.

[3] BECKER, H.: Abbau von SiO_2-Schlieren in Gläsern durch Diffusion und Strömung. Glastechn. Ber. **35** (1962) p. 387 – 392.

73R0389