SELECTING THE CHARACTER OF GLASS MELT FLOW IN TANK MELTING ZONES

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Requirements for the properties of the melting zones of glass furnaces were formulated on the basis of ideal conditions for the actual melting process, refining and homogenization, as well as on that of the effect of the shape of flow on power consumption. Having compared these requirements with the properties of an ideal mixer and piston flow, the authors proposed a combination of both extreme types and called it pseudopiston flow. They also defined the means of influencing the macroscopic shape of flow in the melting zone, which, in the form of theoretical models, could be used in seeking and designing new furnace types.

1. INTRODUCTION

Theoretical models and experimental results of research of the glass melting process allow the significance, mutual relations and possibility of mutual interactions of the melting processes to be defined. On the other hand, it has so far been difficult, and not much attempted, to determine a priori any significantly favourable types of glass flow through the melting zones. The results of a study of energy demands of the melting process [1] indicate the significance of glass flow in terms of the technological characteristics of glass. It would no doubt be correct to base the study on knowledge of the basic processes involved, and not on findings and experience acquired with actual melting furnaces, and to attempt to define a priori the posible favourable types of flow and/or their laws, and to verify the viability of their practical implementation by means of mathematical models. It seems obvious that this might represent a suitable way towards finding less traditional or new melting methods, as such approaches would be free of any burden of tradition. This type of study may thus be divided into the following two stages:

1. Determination of favourable types of flow and conditions for their implementation.
2. Utilization of theoretical models in seeking and verifying the suggested types of flow and the conditions for their implementation.

The present study had the objective of accomplishing the programme of point 1, on the basis of existing knowledge of the basic melting processes.

2. DETERMINING THE IDEAL CONDITIONS OF THE COURSE OF MELTING PROCESSES IN THE MELTING ZONES

In order to establish the optimum character of glass melt flow and the conditions for its realization, it is first necessary to define the optimum conditions for the basic melting processes. For this purpose, it is advantageous to divide the actual melting process into its basic components, i.e. the melting proper (involving chemical reactions and dissolution), refining and homogenization.

With all these stages, minimizing the time for their accomplishment will be of decisive value, as the time factor is a very significant melting characteristic [1]. It is always assumed that the processes are not controlled by energy transport or the behaviour of froth.

I. The actual batch melting

The respective processes include above all the dissolution of solid particles in the melt, and are effected by chemical reactions and diffusion. Their rate can be raised by high temperature and extensive convection. Under ideal conditions of blending, the time of accomplishment of the melting proper can be reduced to that required for the chemical reactions τ_{chem} at the given temperature, and the maximum particle size. If the temperatures exceed the melting points of the dissolving particles, the time is zero. The ideal conditions can therefore be defined as follows: temperatures above the melting point of the dissolving particles, ideal mixing, technologically and economically viable reduction of the maximum particle sizes.

II. Refining

The so-called seed-free time, that is the time for achieving a buble-free melt, is of basic importance. As the mechanism of bubble elimination by dissolving is only exceptional and even theoretically cannot become the main process of seed removal [2], attention should be focused on the mechanism of bubble rising to the melt surface. A significant part is played here by the diffusion growth of bubbles, the diffusion rate being controlled by temperature (equilibrium of refining agents in the melt, the values od diffusion coefficients), convection of the melt, as well as by the speed of bubble movement with respect to that of the melt. The behaviour of the bubbles, once they have risen to the melt surface, is not yet considered. The state of the system is significantly affected by temperature, as well as by pressure. The rising of bubbles is a so-called macroprocess, whose rate is also determined by geometrical conditions (e.g. the glass melt thickness). Forces promoting the coalescing of bubbles (ultrasound, centrifugal force) as well as surface forces resulting from the difference in surface stress or equilibrium of ions producing diffusive gases (electric potential) may also be significant. Under ideal conditions, the time of refining can be reduced to the time required for the bubbles to rise to the melt surface: in that case the bubble growth is controlled solely by the viscosity forces of the melt, or large coalesced bubbles are removed. For this case, the ideal conditions may be defined as follows: temperatures ensuring oversaturation of the melt by gaseous components (or utilization of the respective electric potentials), use of substances liberating gases or vapours under suitable conditions, a low pressure, conditions for rapid coalescence (these cannot be defined in a simple way), suitable geometry (a short bubble ascent path). While at first neglecting the more complex conditions such as the effects of electric potential, surface tension forces, centrifugal forces and ultrasound, we shall define the optimum just by high temperature (oversaturation by diffusing components), low pressure (technically attainable), optimum additions of refining agents, ideal blending and a short bubble ascent path.

III. Homogenization

The respective processes include equalization of concentration gradients of reacting, melting and dissolving batch components. This equalization takes place on both macro- and microscales, being in both cases strongly affected by temperature, but particularly so by mixing. Under conditions of ideal mixing, the time of homogenization is zero. The ideal conditions for homogenization can then be defined as follows: high temperatures, and above all ideal mixing.

The conditions mentioned above define the state necessary for attaining the maximum rates of the melting processes: in the case of the actual melting zones, one has also to include conditions associated directly with the melt flow dynamics. On doing this and summarizing all the conditions, one obtains the following requirements for glass melting furnace zones:

a) Maximum rate of the courses of melting processes – extreme temperatures (above the melting points of the particles being dissolved, or ensuring oversaturation of the melt with refining components), ideal mixing ability, low pressure, optimum application of refining agents, a short bubble ascent path.

b) Zero proportion of dead areas in the melting zone [1].

c) The same formation history of all glass melt elements, attainable either by a history identical as to all the conditions necessary (time, temperature, etc.) or by a history including compensation.

The term history is understood to mean the behaviour of a glass melt element from the moment it entered the melting zone to that of its exit. The term "history including compensation" covers such cases when an unfavourable factor of the history of a glass element (such as temperature) has been completely or partially compensated by another factor of the history (e.g. the time of residence in the melting zone).

3. SELECTION OF THE OPTIMUM CHARACTER OF MELT FLOW THROUGH THE MELTING ZONE

It is important to notice how the demands on optimum melting zones are met by actual or designed furnaces. The requirements may be divided into several groups:

a) Real (classical) melting furnaces.

The maximum rate of the melting processes has not been ensured, or at the best only in a part of the furnace. The temperatures do not attain the melting points of the particles being dissolved, and on the other hand sometimes and somewhere exceed those adequate for rapid refining. The mixing capability is either very poor or satisfactory in a small part of the zone only, low pressures are not applied (with the exception of discontinuous furnaces), the bubble ascent paths are usually long. The furnaces contain large or small dead areas, the glass element histories show great differences, compensation is only partial and rather accidental.

b) Melting zones operating under extreme temperature conditions.

The requirement for extreme temperature is not met in the entire melting zone, the temperature does not attain the melting point of the particles being dissolved. The desired conditions are approached by some types of electric furnaces. The future might bring very small (but efficient) melting zones operated at about the melting points of the particles being dissolved, with zero dead areas and a virtually piston-type of flow. The practical obstacles include a shortage of suitable refractories, their corrosion and excessive volatilization of glass components.

c) Melting zones (ensuring a rapid course of only some of the melting processes) are operated at extreme mixing conditions. This group includes the proposed melting in turbulence furnaces [3], particularly the use of special mixing burners (supplying both the heating medium and the batch), combined with melting in a flowing layer [4] and the use of submerged burners [5]. In such furnaces, there would be no dead

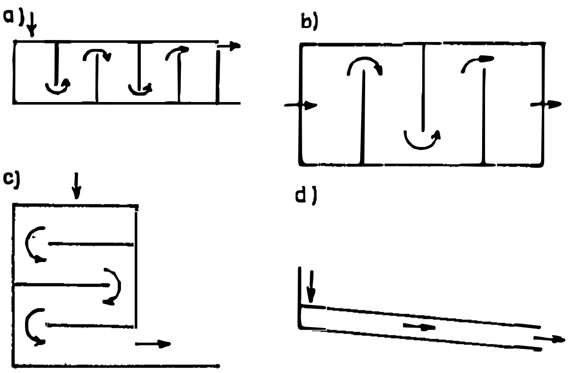

Fig. 1. Schematic representation of various possibilities of simulating the piston flow in melting zones. a – transverse partitions elongating the working stream vertically; b – transverse partitions elongating the working stream horizontally; c – horizontal partitions; d – an inclined plane.

areas, and the element histories would be quite identical (with the exception of the case of submerged burners). However, such melting zones would have the disadvantages of extensive corrosion and erosion of the walls, and extensive volatilization from the melt. The furnaces would be technologically very demanding.

Melting refinig zones:

A subgroup of these types of melting zones is represented by areas or conditions ensuring solely refining, that is seed elimination. The use of ultrasound has so far been hindered by both material and technolgical obstacles [6], and application of underpressure by inadequate knowledge of suitable conditions, volatilization and technological problems (feeding). The centrifugal method would also have to overcome serious technological problems associated with glass melt rotation [7]. Refining under reduced pressure at medium temperatures in separate furnace compartments appears to be feasible [8]. For the latter case, the existence of dead areas is of no great significance, and identical glass element history is not ensured.

d) Melting zones free from circulation flow (using piston flow only). With this type of furnace, one dimension usually greatly exceeds the other two, so that no conditions for circulation arise. A similar effect can be achieved by dividing the melting zone by partition walls, as shown on the examples in Fig. 1 a–c, or by creating several melting zones in succession, or by using inclined planes (Fig. 1.d). These concepts have the common feature of no dead areas (this need not be the case with the partitioned zones), the element histories can differ, but in some case may become mutually compensated. The conditions for very rapid courses of the processes are not met owing to relatively low temperatures and unsatisfactory mixing conditions. Both types have the drawback of a considerable complexity and a high loss rate (with furnaces with a strongly prevailing single dimension).

There is the question whether there are at all some other possible ways of producing glass melt and meeting the requirements for ideal conditions at least to some degree. The potential melting methods mentioned above have drawbacks especially when using very high temperatures (a high theoretical heat consumption) and would have problems associated with corrosion, erosion and volatilization, and structural design. Some results presented in [1] indicate the possibility of arranging the melting proper so as to proceed at lower or medium temperatures while using controlled convection (low losses and low theoretical heat consumption), and a separate zone for refining. From the standpoint of energy savings, the refining should also be performed at reasonably low temperatures.

To be able to determine a suitable type of controlled flow, one should assess the two basic types of flow from the standpoint of determining the optimum conditions.

I. Piston flow

One of the basic conditions of the maximum rate of course of the melting processes, the mixing ability, is not met, being the lowest in the case of piston flow. However, the conditions ad b) and c) in part 2 are conformed to. The compliance with ideal conditions is shown schematically in Fig. 2 on the plot of the time of residence in the form of the probability

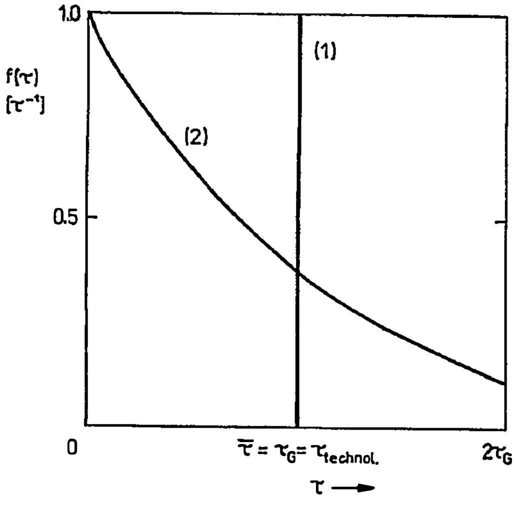

Fig. 2. Probability density of the time of residence of glass melt elements. 1 – for the case of piston flow; 2 – for that of ideal mixer in the melting zone, $\tau_G = 1$. τ_G is the geometrical time of residence; $\tau_G = V/\dot{V}$, where V is the zone capacity and $\dot{V}$ is the flow rate by volume; $\bar{\tau}$ is the mean residence time.

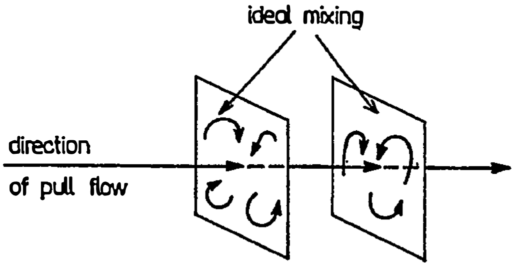

Fig. 3. Representation of the formation of currents in pseudopiston flow.

density function f (τ). The $\tau_{\rm technol}$ represents the time required for accomplishing the slowest process. A possible shift of $\tau_{\rm technol}$ to the left (dissolution of solid particles) can only be effected by raising temperature (under the given mixing conditions), a shift to zero is possible only for temperatures exceeding the melting points of the particles being dissolved. The time of homogenization will always have a non-zero value, and the same applies to refining.

II. The ideal mixer

The basic condition of the requirement for maximum rate of melting processes, an ideal mixing capability, is met, as is the condition of identical quality of paths of glass melt elements. However, the reduced time of dissolution of solid particles down to $\tau_{\rm chem}$ and the time of homogenization to zero, are compensated by an extremely disadvantageous distribution of the time of residence, as follows from curve 2 in Fig. 2. The condition of equal quality ad c) in part 2 is thus met only partially. The elimination of bubbles proceeds in a way comparable to that of the piston flow.

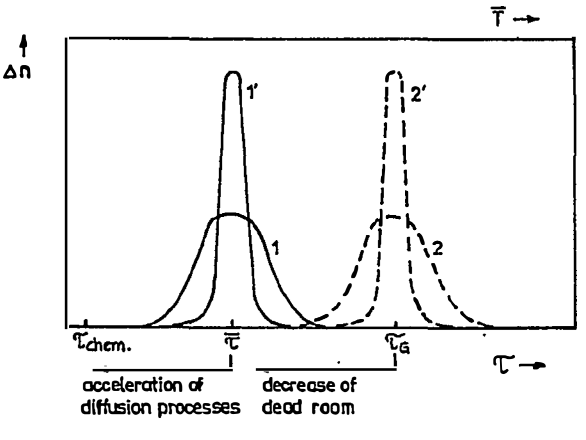

Fig. 4. Distribution of the time of residence of glass melt elements in the melting zone, possibly distribution of mean temperatures along the individual paths.

It is therefore clear that the ideal conditions being seeked should include the distribution of the residence time and the equivalence of the individual paths, characteristic of the piston flow, and the same quality of the paths and a maximum speeding up of the melting processes, characteristic of the ideal mixer. At the same time, the conditions should ensure a zero dead area, which is common to both extreme cases. One of the possibilities of approaching such ideal conditions is to adjust such a type of flow at which the melt is mixed in an ideal way only in the direction perpendicular to the local direction of flow between the inlet and the outlet (working flow). The result could be called "pseudopiston flow". Its principle is shown schematically in Fig. 3. The resulting flow would best secure the conditions a–c in part 2. Under ideal conditions of such a pseudopiston flow, the time of melt homogenization would be zero, the time of dissolution of solid particles would comprise only the time required for the chemical reactions to take place, and the seed-free time would essentially not differ from that of piston flow. The latter process would probably represent a limiting factor of the entire melting stage, and this fact speaks for the separate refining space with suitable conditions for refining (such as reduced pressure). The indicated way towards seeking the conditions of pseudopiston flow can be approached by means of residence time distribution (Fig.4).

An usual case of the distribution of particle residence time in current tank furnaces is represented by curves 1 and 1′. Both curves share the existence of dead areas, and therefore $\bar{\tau} < \tau_G$. Curve 1′ represents a somewhat more favourable case when the dispersion between the residence time is smaller (requirement c in part 2). A similar distribution can be exhibited by the quantity characterizing the melting conditions along the path, which in the case of diffusion processes can be substituted by the mean temperature $\bar{T}$ along the path. By applying a favourable type of flow (approaching the pseudopiston flow), both curves, 1 and 1′ can be shifted to the right (while somewhat changing their shape) until $\bar{\tau} = \tau_G$, as indicated by curves 2 and 2′; in that case all dead areas are eliminated and a melting reserve is formed. Curve 2′ is again more advantageous with respect to requirement ad c) in part 2. The reserve obtained can be used to increase the melting zone throughput (by reducing τ_G) until the reserve is spent. Very approximately, by reducing the dead area from the original m_1 to m_2 (corresponding to the simulated pseudopiston flow), the throughput of the melting zone could be increased $1 - m_2/1 - m_1$ times, and the melting loss reduced by the same factor. At the extensive mixing effect of the flow involved, the absolute time required for the chemical processes to take place is shortened (theoretically down to τ_{chem}), which further decreases the τ_G to a value close to that of τ_{chem}, and again increases the output and reduces losses by the $\tau_G/\tau_{\mathrm{chem}}$ ratio (at a narrow distribution).

The Figure allows the so-called compensation to be explained. If the distribution of both the time of residence and the mean temperatures is expressed by a steep distribution (e.g. by curve 1′), the state is almost ideal, similar to that expressed by meeting condition c) in part 2. If the distributions of both the time of residence and the mean temperatures are expressed by flat curves (e.g. 1), the overall path qualities may become compensated if the shortest residence times correspond to the highest mean temperatures and vice versa. However, distinct critical paths may arise if the short paths correspond to the low temperatures, and vice versa. If the time distribution is expressed by a steep curve and that of temperatures by a flat one, critical paths arise at those of the lowest temperatures. With the opposite configuration, the critical paths will occur at those with the shortest time of residence. The compensation factor may generally play a significant part in the application of the semipiston flow even when the requirement ad c) in part 2 is far from being met.

Another possibility can thus be added to the types of melting zones a–d mentioned in Chapter 3.

e) Melting zones with pseudopiston flow.

4. THE MEASURES AFFECTING FLOW IN MELTING ZONES

In order to implement the type of flow being seeked, one has to define the measures and means allowing the flow to be effectively influenced on a macroscale. The measures can be divided as follows:

1. Effects of an external force field (primarily gravitational – free convection).
2. Geometrical conditions in the melting zone.

On utilizing free convection, the aim is to find a suitable type of temperature field in the glassmelt either by attaining a certain temperature distribution on the surface (heating by burners) or by arranging the heating electrodes. The shape of the resultant temperature field is also affected by thermal insulation of the walls, and possibly also by the hydrodynamic effects of gases in the combustion space. Gravity can also be made use of by letting the glass melt flow down an inclined surface or other planes, possibly provided with openings. The most frequent application of another force field is the feeding of batch and withdrawal of glass for working, which are responsible for working flow, use of all types of agitators, and bubbling with both flammable and non-flammable gases. The use of pressure or an electromagnetic field might also be promising.

The geometrical conditions include not only the basic shape and size of the melting zone, but also all floaters, skewbacks, curtain walls extending down into the glass, the number and types of working outlets, and the numbers and types and arrangement of individual cells in the case of composite melting chambers.

To make use of all these elements in the seeking of suitable types of flow, suitable models should be available. Nowadays, the mathematical models are generally preferred because of their considerable flexibility. Of particular value are models of both simple and complex melting zones, those including heating electrodes and gas bubbling. Some models of this type are already in use.

5. CONCLUSION

It is advantageous when the seeking of more effective or quite new methods of glass melting is based on ideal conditions for effecting the main melting processes, namely the melting proper, refining and homogenization. Knowledge of these conditions allows the basic demands on the melting zones to be defined, including those associated with glass flow. On the basis of these conditions, the existing and the potential future melting methods can be divided into several categories and their advantages and drawbacks assessed. This classification as well as evaluation of ideal piston flow and an ideal mixer has allowed another alternative to be theoretically studied and proposed. It is a combination of piston flow with an ideal mixer, and may be called semipiston flow. The way towards its implementation has been indicated by defining the means available for accomplishing the task. Mathematical modelling provides the necessary tools for verifying the theoretical assumptions, and namely the respective conditions. The first step to be taken in this direction will be a study of the effects of the temperature field on glass flow in a simple melting zone, and of the possibilities of establishing the pseudopiston flow.

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VÝBĚR CHARAKTERU PROUDĚNÍ VE SKLÁŘSKÝCH TAVICÍCH PROSTORECH

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Při hledání optimálních podmínek tavení a vlastností tavicího prostoru je jedním z důležitých faktorů charakter proudění skloviny. Ukazuje se, že při tomto hledání je výhodnější vycházet ze znalostí o základních tavicích pochodech a hledat a priori výhodné typy proudění pro jejich uskutečnění, než využívat především zkušeností a poznatků o reálných tavicích agregátech. Článek definuje ideální podmínky pro uskutečnění vlastního tavení, čeření a homogenizace a definuje základní požadavky na sklářské tavicí prostory z hlediska průběhu těchto dějů. Na základě vlastností pístového toku, jakož i ideálního mísiče a s přihlédnutím k požadavkům na sklářské tavicí prostory, je navržen výhodný typ proudění v tavicím prostoru, který napodobuje pístový tok s ideálním mícháním ve směru kolmém na směr pístového toku. Tento typ proudění nejlépe splňuje požadavky na maximální rychlost průběhu tavicích pochodů, co nejmenší mrtvý prostor a srovnatelnou tavicí kvalitu jednotlivých drah skloviny tavicím prostorem. Navržený typ proudění není prozatím napodobován nebo navrhován v současných tavicích agregátech. Na příkladu distribuce dob zdržení myšleného tavicího prostoru je demonstrováno působení navrženého typu proudění na snížení energetické spotřeby a zvýšení výkonu tavicího prostoru. Jako prostředky ovlivňující proudění jsou uvedeny různé typy silových polí a geometrických podmínek. Ověření navržených typů proudění se jeví nejvýhodnějším pomocí matematických modelů, které jsou velmi flexibilní a jsou schopny zahrnout tavicí děje.

Obr. 1. Schématické znázornění různých možností napodobení pístového toku v tavicích prostorech. a – příčné přepážky s vertikálním prodloužením pracovního proudění; b – příčné přepážky s horizontálním prodloužením pracovního proudění; c – horizontální přepážky d – šikmá rovina.

Obr. 2. Funkce hustoty pravděpodobnosti dob zdržení elementů skloviny pro případ pístového toku (1) a ideálního mísiče (2) v tavicím prostoru, $\tau_G = 1$. τ_G *– geometrická doba zdržení;* $\tau_G = V/\dot{V}$*, kde V je objem zařízení a* $\dot{V}$ *objemový průtok;* $\bar{\tau}$ *– střední doba zdržení.*

Obr. 3. Znázornění vzniku proudění při pseudopístovém toku.

Obr. 4. Distribuce dob zdržení elementů skloviny v tavicím prostoru, případně distribuce středních teplot podél jednotlivých drah.