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Influence of Material Properties on the Electromagnetic Homogenization of Glass Melt in the Special Melter

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Abstract

The aim of this paper is the numerical investigation of the outlet of a special glass melter, which enhances homogenization of output material by means of electromagnetic mixing. The main purpose of this equipment is to achieve good thermal and chemical homogeneity of output material. Series of experiments with soda lime glass showed that it is possible to ensure significant mixing. Commercially interesting application of investigated equipment should be found – broad variety of glasses with different material properties are known, but due to physical restrictions this approach can be used only for certain class of glasses.

Introduction

The production of glasses requires appropriate operating conditions to achieve good thermal and chemical homogeneity in the melt. At JSJ Jodeit GmbH there is currently working equipment for special glass processing which is being expanded and developed to obtain better quality of output material. Although electrical conductivity of glass is low ($\sigma \approx 10$ S/m), electromagnetic (EM) impact is used to generate movement of melt and ensure homogenization in this equipment. On the other hand natural convection, which is main movement source in glass melting furnaces is negligible in this equipment due to small radial dimensions of melt container – gap between inner and outer electrode is 15 mm.

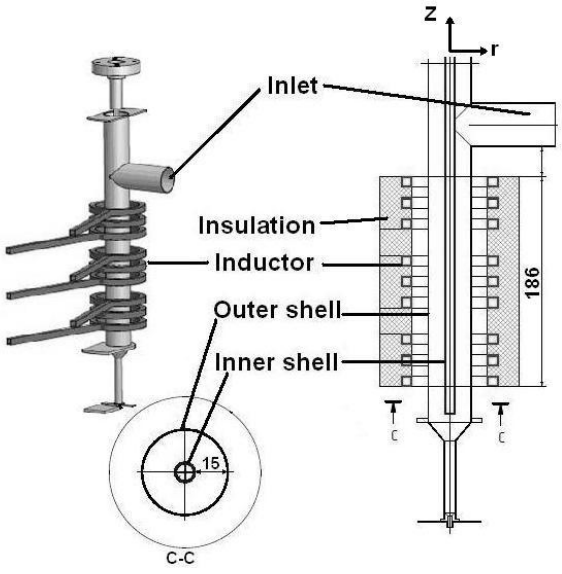

Fig. 1. Scheme of investigated equipment

In previous papers [1], [2] numerical models for EM, thermal and fluid dynamic calculations were experimentally verified. Besides transit flow (< 0.4 mm/s), azimuthal flow is generated with up to ~1 mm/s velocity. Since there is no significant movement in radial direction, this movement could be insufficient for good chemical homogeneity, because all fluid tracer stays at the initial radius and no direct radial mixing is present. Nevertheless, mixing also takes place due to velocity gradient in radial direction – stretching of liquid elements enlarges its area, which leads to enhanced diffusion.

It is very hard to obtain homogeneous temperature distribution in axial direction, and this could lead to significant temperature differences in output material (glass droplets). Reason for this is non-uniform inductive heating of outer electrode. However, due to high thermal conductivity of glass (~100 W/(m·K) at 1300°C), temperature differences in radial direction are very small (≈2°C), therefore thermal gradients in glass droplets are insignificant.

1. Investigated Equipment

1. 1. Experimental Device

The melt is contained between two cylindrical shells made of platinum in coaxial arrangement (r_{in}=5 mm, r_{out}=20 mm) (see Fig. **1**). Inductor system generates AC magnetic field and ensures non-uniform inductive heating of shells ($\sigma=2\cdot10^6$ S/m), but induced Joule heat in the glass melt is insignificant. Additional direct heating by AC current of outer shell is present due to potential difference V_V, as well as electric potential difference between inner and outer shell V_R – it ensures radially directed AC current in the melt. Interaction of the magnet flux density and the electric current in the glass melt results in EM stirring effects which are strongly dependent on the material properties (electric conductivity, viscosity of melt, material density), the heat transfer and the electric power feed to the magnet system. Besides this, electric current sources V_V and V_R have different frequency, frequencies of V_R and magnetic field are matching (otherwise alternating Lorentz force will act on melt in azimuthal direction). Azimuthal component of Lorentz force is dominating, other are negligible due to insignificant induction effect in glass. Frequency of V_R is variable (500-2000 Hz) and much higher than frequency of V_V (fixed 50 Hz).

Glass melt pull rate is approximately 20 g/min, which means transit flow velocity of 0.15 mm/s. To study mixing intensity, additional colored glass cube with mass ≈4 g was added on top surface. Since there is almost no movement in this part, additional 60 g of glass powder were added on top to push tracer in the flow. Obtained glass droplets and flakes (some droplets were pressed) were cut in slices and color distribution in each slice was observed to evaluate mixing intensity (figures 2 and 4). Several experimental tests were done with rotation of inner electrode, with typical rotation velocity 1 rpm. The idea is to change boundary conditions for laminar flow, therefore changes velocity profile in azimuthal direction, and increase velocity gradient, which ensures better stretching of fluid element.

1. 2. Characteristics of the System

Frequency range for this system is chosen as 500-2000 Hz, because higher frequencies causes screening of magnetic field in outer shell, but small frequencies are undesirable due to the increased corrosive reactions of Pt with the glass melt. Other restriction to current in inductors is induced power in outer electrode, exceeding certain limit may cause damage of platinum shells. Current in melt is also significant restriction – exceeding 1 A/cm^2 causes overheating of melt and many gas bubbles are observed in output material.

Tab. 1. Dimensionless parameters for investigations with soda lime glass

Parameter	Label	Value
Reynolds number in melt	Re	$8\cdot10^{-4}$
Peclet number for heat transfer in axial direction	Pe_T	0.06
Peclet number for mass transfer in axial direction	Pe_M	223
Hartmann number	Ha	$9\cdot10^{-4}$

In analysis of such systems a coupled approach is required – all effects are coupled due to strong temperature dependence of material properties (e.g. σ(T), η(T)). Nevertheless, due to

high viscosity of glass melts ($\eta \approx 50$ Pa·s), laminar flow is expected without inertial effects, where Reynolds number is strongly below 1 (Table 1). Such flow velocity also means small magnetic Reynolds number ($Re_m \approx 10^{-9}$) - melt movement influence on magnetic field can be neglected. Due to high viscosity, velocity profile in the tube is determined by viscous forces and not by EM force – Hartmann number is small.

Convective heat transfer term in heat transfer equation is neglected because melt movement in meridional plane is insignificant and heat transfer Peclet number is small – $Pe_T<0.1$, which says that heat conduction is highly dominating over heat transport by melt movement.

For diffusion coefficients which are typical for glasses of 10^{-8}-10^{-10} m^2/s ($logD \approx -10$ for Co, which is used in experiment), convective mass transfer plays major role (mass transfer Peclet number is 223 for $D=10^{-10}$ m^2/s). This is clear for glass movement in axial direction (transit flow). But for mass transfer in radial direction diffusion is more important [3], because radial component of melt motion velocity is very small and present only in the region where inner electrode ends. Therefore radial mass transfer Peclet number is very close to zero and radial mixing is determined only by diffusion.

1. 3. Dependence on Material Properties

It is important to find a glass which is profitable to use in such kind of equipment. But high viscosity and low electrical conductivity are limiting factors for use of many well known glasses. Furthermore, soda lime glass, which was used for experimental tests, has high thermal conductivity, but some other glasses may have lower values. Therefore, mixing quality and operation conditions dependence on material properties have to be investigated.

To estimate quality of mixing dependence on electrical conductivity, calculations with varied soda lime data were done ($\sigma_{SL}(T)$ multiplied by certain coefficient). Same was done with viscosity. Results of these calculations show main tendencies in dependence on material properties.

1. 4. Approach for Calculations

2D axisymmetric approach is used for calculation of EM processes – although current density vector has all three components, all variables are dependent only on two variables – r and z. But this method contains several assumptions. At first - conduction currents do not cause induction effects (DC approximation). This assumption is realistic, because conductive current in radial direction can have observable magnetic flux density values only at the ends of system. Conductive current in axial direction (direct heating of outer electrode) can produce significant magnetic flux density only in α direction and only outside of the electrode ($r>r_{out}$). Another assumption is about symmetry of system – although it is not axisymmetric at the inlet zone, deviation is not playing major role, furthermore, it allows to reduce calculation time significantly.

Thermal calculations were done with EM heat sources and proper boundary conditions, and obtained temperature field used to set correct spatial viscosity field for HD problem. Thermal model was solved in 2D axial symmetry, full 3D tube was modeled for HD to allow introducing of non-axisymmetric conditions.

For calculation of mixing transport equation for scalar concentration C is solved. Small area of C=1 is set on top surface, C=0 set on rest inlet surfaces. Distribution of relative concentration $C / \overline{C}$ is observed at outlet to estimate mixing effect. For quantitative estimation of mixing, according to [3], coefficient of variation can be used:

$$CoV = \frac{s}{\bar{C}} = \frac{\sqrt{\frac{1}{A}\int_A \left(C - \bar{C}\right)^2 dA}}{\bar{C}},$$

where are s – standard deviation and $\bar{C}$ - mean concentration.

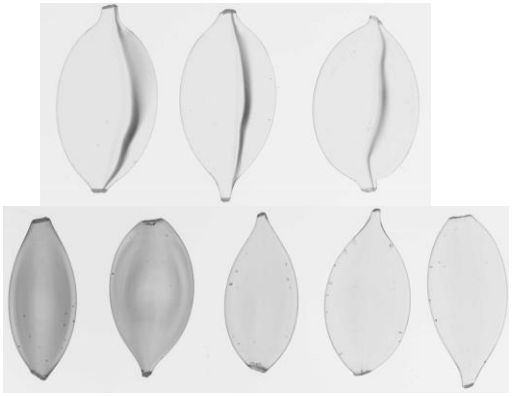

Fig. 2. Glass flakes obtained in experiment. Above – no EM mixing, flakes obtained with 10 min difference, below – with EM mixing

2. Results

2. 1. Experiments and Calculations with Soda Lime Glass

Observation of flakes obtained in experiment with ($u_z \approx 0.15$ mm/s, $u_\alpha \approx 0.5$ mm/s) and without EM mixing, it is visible that there is significant difference, and mixing effect is present. Calculations also shows this tendency – single striae of admixture at the outlet appears. In flakes obtained with EM mixing (Figure 2, below), maximal concentration is between centre and edge of flake.

This distribution of admixture in case with EM mixing is connected to location of admixture on the top – it mostly stays at the initial radius, and homogenization is most efficient in tangential direction (figures 3 and 4).

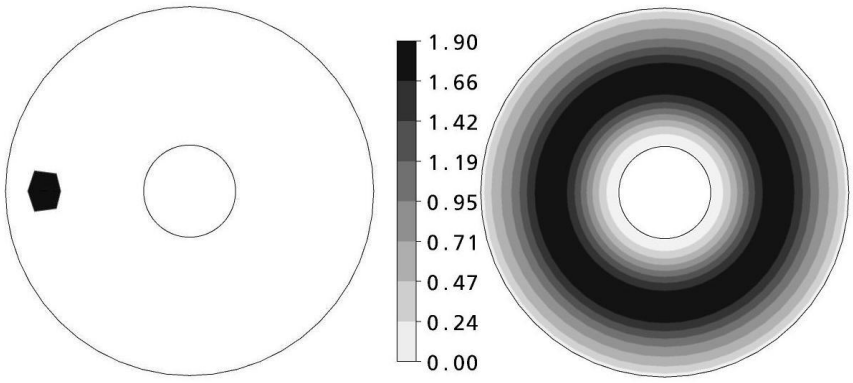

Fig. 3. Admixture concentration obtained in calculation at inlet (left) and outlet (right). Relative concentration is shown on right. Absolute concentration (C_{max}=1) on the left.

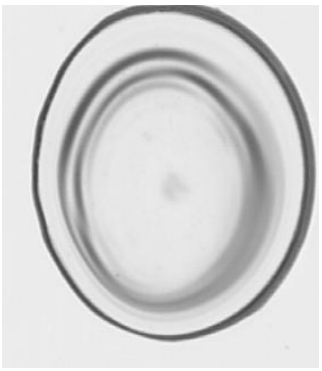

Fig. 4. Colour glass droplet cross section obtained in experiment

2. 2. Rotation of Inner Electrode

Taylor-Couette velocity profile is obtained in case of inner electrode rotation, furthermore velocity fields from rotation and EM impact can be superposed due to very low Reynolds numbers (Figure 6). EM impact in combination with rotation of inner electrode causes higher velocity gradients, which leads to better mixing effect.

Two cases can be distinguished – rotation in same direction as Lorentz force (left – L, negative angular velocity), and rotation in opposite direction to EM impact (right – R, positive angular velocity). Higher velocity gradient appear in case R.

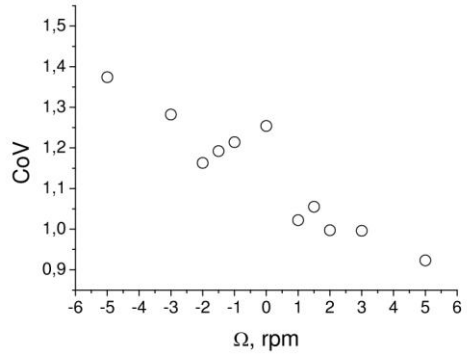

Fig. 5. Coefficient CoV of variation at different inner electrode rotation velocities

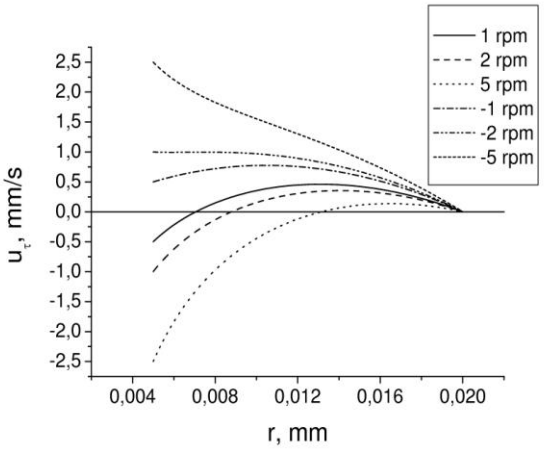

Fig. 6. Tangential velocity profile at different inner electrode rotation velocities

Figure 5 shows values of CoV at different inner electrode rotation velocities. A tendency is visible, that in cases with rotation in same direction as influence of EM mixing, better result (CoV → 0) is obtained. It is possibly due to larger velocity gradients in L rotation case because in case with R rotation gradients are significant only at inner electrode, but nearly zero at outer. Irregular dependence on rotation velocity is connected with different velocity gradients along radius, thus different stretching of admixture fluid element.

2. 3. Influence of Material Properties

Lorentz force depends on glass electrical conductivity linearly – skin effect in glass is negligible for conductivity values that are proper to glasses and for frequency range that is used in this equipment. Transit flow dependence on viscosity is also linear due to low Reynolds number and negligible convective terms in Navier-Stokes equation. However these conclusion does not point to mixing quality dependence on material properties. Another influencing factor is operating condition dependence on thermal conductivity, which may lead to different temperature field and cause different electrical conductivity and viscosity distributions.

Comparing calculations with different electrical conductivity, it was shown that this dependence is not linear, but more like exponential (figure 7). For electrical conductivity of soda lime, coefficient of variation is *CoV=1.42*, and decrease of conductivity leads to significant decrease of mixing quality (*CoV=2.86* with $0.2\sigma_{SL}$). This is because melt tracers in soda lime glass makes full ≈8 loops, which are sufficient to make uniform distribution along azimuth. Smaller conductivity leads to smaller number of loops. Increase of conductivity leads to better mixing, due to stretching of admixture fluid volume and larger area for diffusion. But enhancement of mixing is limited, because after admixture is uniformly distributed along azimuth, mixing in radial direction is needed.

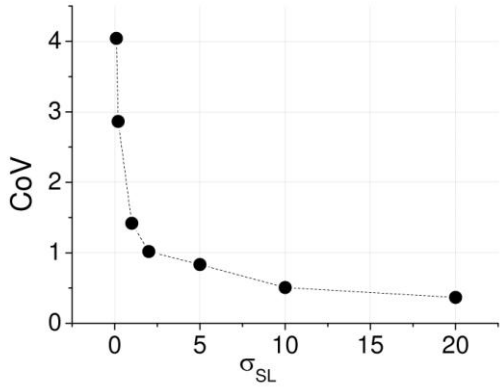

Fig. 7. Mixing index CoV obtained with different electrical conductivities

EM force dependence on conductivity is linear, as well as dependence on viscosity, therefore *CoV* changes with viscosity in same manner – 5 times decreased viscosity leads to same result as 5 times increased conductivity, what was proven in calculations.

To explain dependence on material properties two bounding cases can be distinguished. If no Lorentz force acts on melt, concentration distribution at outlet is similar as one at inlet (figure 3, left). If Lorentz force is significant, intensive azimuthal mixing appears and concentration is distributed at the outlet as in figure 3, right. Further increase of Lorentz force would not lead to better mixing quality, because does not influence mixing in radial direction.

In practice higher viscosity means lower velocity, but it also means lower glass pull rate, because in this equipment pull is ensured by height of glass melt in riser tube, and longer residence time leads to better mixing.

Conclusions

Results show that there is qualitative agreement between experimentally obtained glass flakes and droplets with admixture and numerical simulations, therefore used models are suitable for investigation of mixing.

Glass with higher electrical conductivity will affect mixing positively, but, since glass is well mixed in tangential direction already, it will not give significant improvement in homogenization quality, a technique for radial mixing is necessary.

Lower viscosity would lead to same effect as increased electrical conductivity, if glass pull rate is kept at the same level. But in reality it leads to higher pull rate (if glass level in riser is similar), and it does not affect mixing quality well – small residence time is undesirable, however large residence time leads to enhanced diffusion.

References

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