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ELECTROMAGNETIC PROCESSING OF HIGH-TECH GLASSES IN A SPECIAL DEVICE - NUMERICAL INVESTIGATIONS

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ABSTRACT

The main field of this work is outlet of special glass melting system numerical investigation. These glasses needs appropriate operating conditions to achieve good thermal and chemical homogeneity. New technology is developed and investigated to improve material homogeneity and to ensure control of material processing.

Index Terms – Glass melt, induction heating, Lorentz force, laminar flow.

1. INTRODUCTION

New technologies for glass processing are developed to meet the needs for special-purpose glasses. The production of glasses requires appropriate operating conditions to achieve good thermal and chemical homogeneity in the melt. In practice the throughput of glass melting devices is limited due to nonuniform residence time distribution which corresponds to the flow pattern in the glass melt and results in high specific energy consumption.

The electromagnetic forces facilitate the improvement of reliable flow control or accurate flow prediction. Although electromagnetic (EM) impact is widely used in metallurgic and semiconducting material technologies with typical electric conductivities of 10^5-10^6 S/m, it can be also used for weak conducting material processing (σ~10-100 S/m).

The main field of this work is the numerical optimization of a magnet system positioned at the outlet of a special glass melting device.

2. INVESTIGATED EQUIPMENT

The melt is contained between two metallic cylinders in a coaxial arrangement. Interaction of the magnet flux density and the electric current in the glass melt results in electromagnetic 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.

Complex 3D flow may occur in the glass melt as it is influenced by two different EM field sources – azimuthally directed induction currents are generated by alternating currents in the coils; potential difference applied to the metallic shells results in radially directed electric currents.

The high electric conductivity of the platinum shells (~10^6 S/m) is limiting the possible operating frequency of the magnet system – skin layer depth is about 10 mm for a frequency of 1 kHz, and it should not be less than the thickness of the wall. On the other hand - low frequencies are undesirable due to Pt specific reaction with glass melt. In analyzing of such system fully coupled approach is required, while all effects are coupled due to strong temperature dependence of material properties. Nevertheless, due to high viscosity of glass melts, laminar flow is expected where Reynolds number does not exceed 1. Such flow velocity also means small magnetic Reynolds number (Re_m~10^{-9}), and melt flow influence on magnetic field can be neglected.

3. MATHEMATICAL MODEL

Maxwell equations in quasi-stationary (charge accumulation and displacement current are discarded) approximation were used to study electromagnetic processes in described equipment [1]. Well-known potential approach was used for this purpose:

$$\vec{E} = -\nabla\varphi - \frac{\partial \vec{A}}{\partial t};$$

$$\vec{B} = \nabla \times \vec{A},$$

where E – electric field intensity, φ – electric scalar potential, B – magnetic field induction, A – magnetic vector potential. This approach along with Ohm's law leads to following equation system:

$$\vec{j} = \sigma(T)\left[-\frac{\partial \vec{A}}{\partial t} - \nabla\varphi\right]; \qquad (1)$$

$$\nabla^2 \vec{A} = -\mu_0 \vec{j}; \qquad (2)$$

$$\nabla \cdot \vec{A} = 0, \qquad (3)$$

where σ – material electric conductivity, ∇ – del operator, j – electric current density.

Known EM sources (force density in melt, joule heat in conductive parts of system) are used in thermal field and fluid flow calculation. Temperature field is determined by solving heat transfer equation:

$$\rho(T)c_p(T)\left[\frac{\partial T}{\partial t}+\nabla(T\vec{v})\right]=\nabla(\lambda(T)\nabla T)+q\,, \quad (4)$$

where T is temperature, c_p – specific heat capacity, λ – heat conductivity, ρ – density, q – Joule heat density:

$$q=\frac{j^2}{2\sigma(T)}\,.$$

Incompressible fluid flow is described by Navier-Stokes equation [2]:

$$\rho(T)\frac{\partial v_i}{\partial t}+\rho(T)v_j\frac{\partial v_i}{\partial x_j}+\frac{\partial p}{\partial x_i}-\frac{\partial \tau_{ij}}{\partial x_j}=f_i\,; \quad (5)$$

$$\tau_{ij}=\eta\left(\frac{\partial v_i}{\partial x_j}+\frac{\partial v_j}{\partial x_i}\right)-\frac{2}{3}\eta\frac{\partial v_k}{\partial x_k}\delta_{ij} \quad (6)$$

$$\nabla\cdot\vec{v}=0\,, \quad (7)$$

where v is velocity, p is pressure, η - viscosity, f – force density, τ – stress tensor.

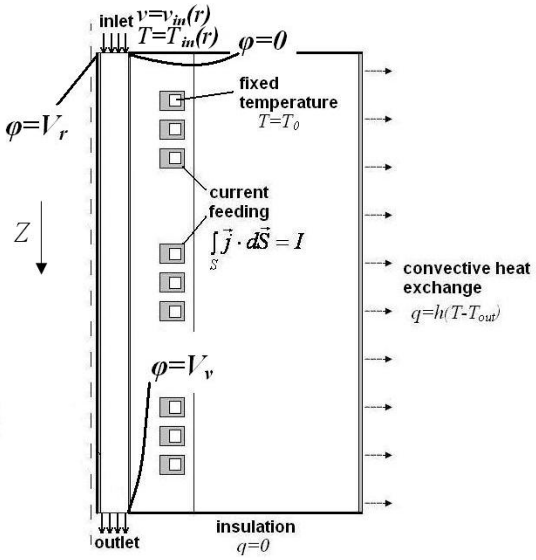

Figure 1. Boundary conditions for investigated model.

It is clear that taking material temperature dependence sets those separate equations in one equation system, and this leads to complicated nonlinear problem. Therefore fluid flow equation was “decoupled” assuming that flow influence on temperature field is small – convective heat transfer term in equation 4 is neglected. Due to low velocity in meridional plane this assumption is allowable (Peclet number is small Pe<0.1).

Right side term f in equation (5) is a sum of Lorentz force density

$$\vec{f}=\frac{1}{2}\mathrm{Re}\left[\vec{j}\times\vec{B}^*\right] \quad (8)$$

and buoyancy forces

$$\vec{f}=-\rho(T)\vec{g}\,. \quad (9)$$

Due to such force combination, complicated flow structure can appear both in the meridional plane and in the azimuthal direction, though azimuthal flow is determined only by Lorentz force, while meridional flow is determined only by buoyant forces (in case of temperature homogeneity buoyancy can also be neglected) and transit flow, which is taken into account velocity distribution $v=v_{TR}(r)$ at upper end of concentric shell tube (Figure 1).

Adiabatic thermal condition was used on inner shell while outer shell was surrounded by insulation material. Constant temperature cooling was set in coils and convection boundary type on outer surface of insulation.

EM calculations are performed in ANSYS and PROMETHEUS, while hydrodynamic and thermal calculations – in ANSYS CFX. Self-made external coupling code ensures coupling between both programs.

4. NUMERICAL RESULTS

Most of physical effects in this investigation were studied separately to ensure clarity of obtained results. All calculations done in this work uses 500Hz operating frequency for applied current and voltage.

4.1. Electromagnetic analysis

Flow of viscous melt is generally directed azimuthally and is determined by current in radial direction and axial component of magnetic field. Therefore magnetic field distribution over height may ensure different homogenization conditions.

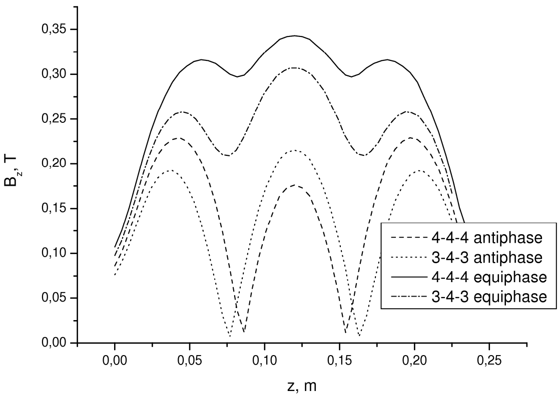

Figure 2. Magnetic flux density amplitude axial component distribution over height at different inductor geometry

Calculations with different inductor configurations showed that it is possible to change magnetic field distribution substantially by changing inductor geometry and current phase shift.

Figure 2 shows magnetic field axial component distribution over height at different inductor geometry: 3-4-3 and 4-4-4 configuration, where each number shows number of turns in one coil of the magnet system. The coils are connected equiphase (0°-0°-0°) or antiphase (0°-180°-0°). Instant direction of magnetic flux density vector in the location surrounded by a coil is determined by current phase in that coil. As a result magnetic field is also antiphase and this leads to a zero magnetic field value on line between opposite-phase coil sections (see Figure 3 where real part of solutions is shown, imaginary part is small, while generated by secondary induced currents).

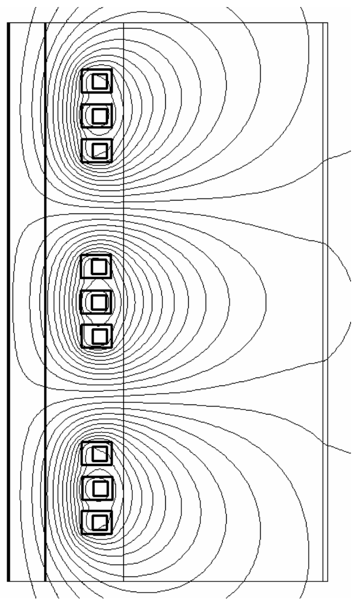

Figure 3. Magnetic field lines.

Distribution of Lorentz force absolute value along height is similar to the magnetic field intensity distribution while in case of homogenous current in radial direction (this is applicable assumption) Lorentz force can be written as

$$f_{\varphi} \sim j_R \cdot B_z(z) \, ,$$

where j_R=*const*. In case of antiphase Lorentz force density azimuthal component is directed opposite in different parts of system.

For full EM analysis (with both induction and conduction effects) assumption was made that EM fields of both sources can be superposed. This allows to calculate and analyze effects separately.

4.2. Heating condition analysis

Besides Lorentz force there is Joule heat generation in the system due to EM sources, which causes non uniform heating and it is one of limiting factors in this equipment.

Heating condition optimization is required to achieve good melt thermal homogenization, as movement in meridional plane is small and stirring effect is not relevant. When all EM sources are involved, optimization of heating conditions becomes complicated – three parameters needs to be varied: vertical potential gradient in outer electrode (voltage V_v in Figure 1), potential difference between inner and outer electrode (V_r) and current in coils (I).

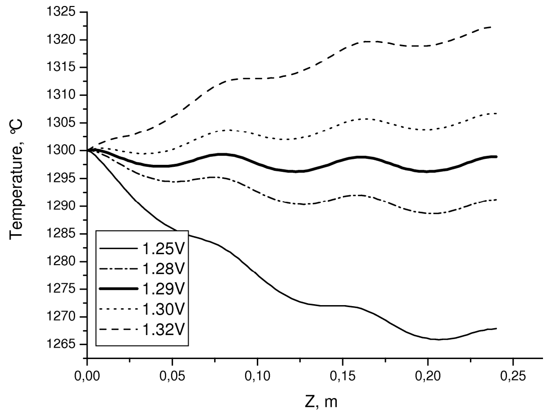

Figure 4. Temperature distribution along height (Z axis) of melt (r=20mm) at different V_v values.

Influence of V_v and V_r heating sources was analyzed. One source heating – potential difference in outer electrode V_v is easy to optimize, while one parameter changing is required. Fixed temperature cooling condition was used in coils. For each calculation corresponding heat removed by cooling was calculated – this allows to evaluate necessary water flow rate in coils. Temperature distribution along height (line *r=20mm*) is given in Figure 4 – "waves" in distribution curve are due to non uniform cooling, but average slope of each line is constant. The reason is almost constant heating along height (small irregularities appear due to conductivity dependence on temperature).

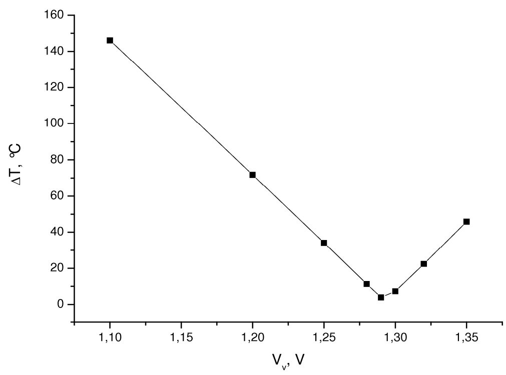

Figure 5. Temperature difference (T_{max}–T_{min}) dependence on V_v , V_r=0.

Temperature difference dependence on voltage curve ($\Delta T(V_v)$, $\Delta T=T_{max}- T_{min}$) has minimum at one certain point, but close to this point results show that slope of the curve is steep - ~ 0.4°C/mV (Figure 5). Since potential difference on both ends of outer electrode is ~1.2 V, this number is high – 4% voltage change results in 20°C larger temperature difference. In experiment this could mean that real-time adjustment of this parameter is limited, and this is a proof of numerical investigation significance for this equipment.

Optimal V_v value was the reference point for two parameter (V_v and V_r) optimization. In this case temperature distribution along height is slightly different (Figure 6). In this case heating is not uniform – potential is applied at certain point at inner electrode. As a result higher current in melt appears in upper part of system. This is visible in Figure 6, where temperature in all curves is rising at near inlet.

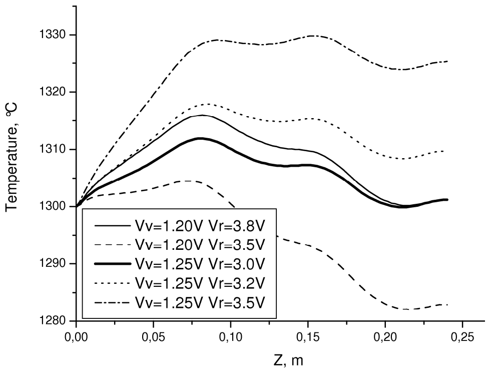

Figure 6. Temperature distribution along height (r=20mm) at different V_v and V_r values .Right end is inlet, left end – outlet.

$\Delta T(V_r)$ curve was made for several fixed V_v values. It is obvious that each curve in Figure 7 has only one minimum point. When V_r is small, there is only V_v influence on ΔT, but at higher values slope of curve becomes similar to the one obtained without V_r – obviously character of temperature difference dependence on voltage is similar in both cases.

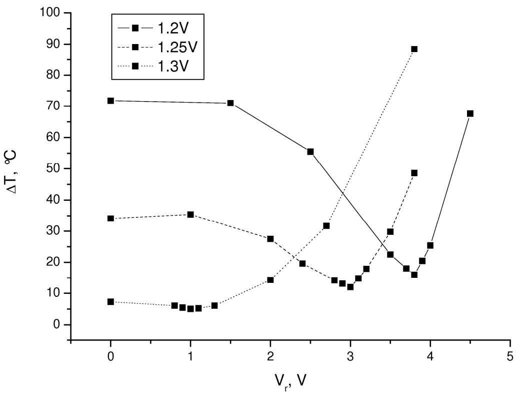

Figure 7. Temperature difference (T_{max}–T_{min}) dependence on V_r with several fixed V_v values.

4.3. Hydrodynamic analysis

In previous work [3] results for simplified system were obtained. Results show that using this approach it could be possible to achieve significant velocities in azimuthal direction, but in meridional plane calculated velocities are insufficient for good material stirring (Figure 8). Melt flow velocity dependence on EM parameters (frequency and current in coils) was obtained as well.

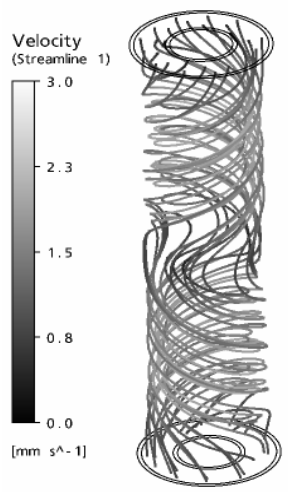

Figure 8. Example of melt flow streamlines [3]

5. CONCLUSIONS

Main task of investigated equipment is to provide temperature homogenization of melt. Unlike equipments for liquid metal operating, in this case main homogenization “tool” is heat conductivity

Numerical calculations show that it is possible to ensure temperature homogenization in melt by adjusting heating parameters (V_v, V_r).

Not all physical effects were investigated in this work – induction heating still to be introduced. This task is not simple, because at this stage both temperature homogeneity and azimuthal flow intensity will be optimization criteria.

Thermal radiation in melt also is a point of interest to ensure full process analysis, while experimental validation in future will provide certainty of obtained results.

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