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2D Modelling of EM Glass Convection by Temperature Dependent Material Properties

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Abstract

An application of external magnetic field induced Lorentz force in the stirring process of oxide melts is a well-known industrial method. In this case not only the thermal convection caused by direct (thermal) and indirect (Joule) heating is present but also a contribution of Lorentz force $\vec{F} = \frac{1}{2} Re\left[\vec{j} \times \vec{B}^{*}\right]$, which is used to intensify the stirring process.

A prediction of experimentally reasonable working conditions - temperature range etc. could face various difficulties if a material with non-linear physical properties is used. In our present publication we discuss the results we have gained in ANSYS CFX simulations of an opaque glass melt in 2D approximation. We compare our results with experiments described in [1].

Introduction

In [1] experimentally measured axial temperature profiles are used to characterise the impact of an external magnetic force on temperature homogenisation process in the melt. In addition to these experiments we are interested in developing a model, which shows character of the flow in a complete volume. Keeping in mind that this process is 3D, two simplified 2D models have been developed.

We carried out various simulations with the aim of finding the working conditions, which would allow us to investigate the motion of the melt in the temperature range observed in the experiment [1]. The main goal of modelling was to observe the impact of a thermal convection and a magnetic force on the distribution of temperature, which is one of the main pre-requisites for high quality of glass.

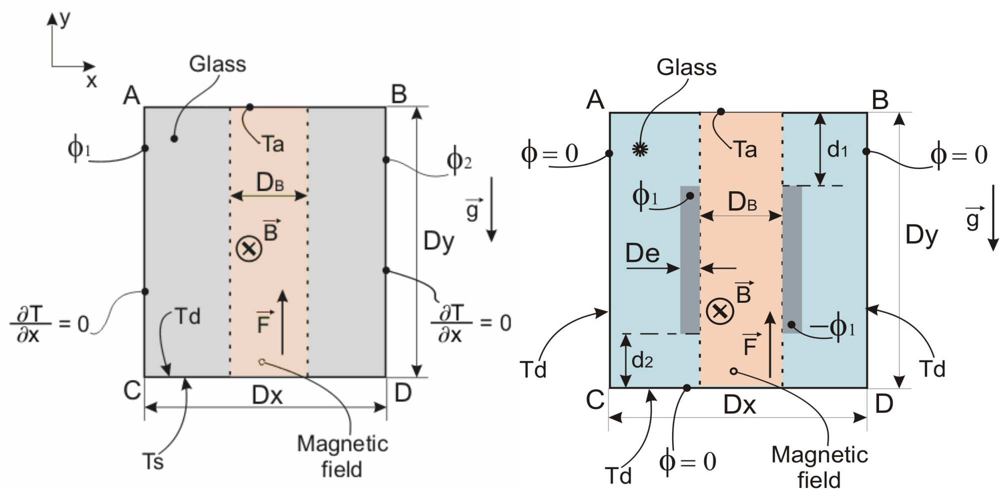
1. Experiment

Experimental set-up described in [1] consists of axi-symmetric platinum crucible $10\ cm$ in height and $8\ cm$ in diameter inserted in an isolated furnace, which has been located in the air gap between electromagnet poles; two $8 \times 6\ cm$ platinum plate electrodes are used to induce Joule heat in the volume of the melt. The distance between electrodes is $2\ cm$. An alternating magnetic field with the effective induction $B = 0.044T$ was applied in the region between the electrodes parallel to its planes.

This was done in order to investigate the distribution of temperature in the melt. Field of temperature has been characterised using the temperature profile along the axis of symmetry of the crucible. Experimental proof has been obtained that external magnetic field plays an important role in homogenisation of temperature field as well as in the chemical homogeneity of the melt. In the case of $\vec{B}=0$ a $30^0 K$ temperature difference has been observed between its highest value 1570 K located ≈ 3 cm below the free surface and the value on the crucible bottom, while in the case when an external magnetic field with $\varphi = 0^0$ was applied the difference decreased to $15^0 K$ approximately.

2. Mathematical model

Two 2D models have been developed to simulate an electromagnetic stirring of glass melt. We implemented our models for different crucible temperatures and two opposite directions of external magnetic field. We take into account a magnetic force, which is caused by different phase shifts between AC $I = Re\left[I^{i\omega t}\right]$, which amplitude changes in time with frequency ω and the external alternating magnetic field, which induction $B = Re\left[B^{i(\omega t+\varphi)}\right]$ alternates with the same frequency. ANSYS CFX 10.0 software has been used in this study, equations for the potential, temperature and incompressible flow have been solved. We were looking for the stationary solution of the problem, which physical model is shown in Fig. 1.



(a) (b)

Fig. 1. 2D models for a stirring process of glass: a) without, b) with immersed electrodes.

Tab. 1. Parameters of the models (where A_i, B_i, C_i are approximation constants)

$\vec{B}=0.044[T]$	$\rho(T) = A_\rho \cdot T + B_\rho$
$D_x = D_y = 0.08[m]$	$\sigma(T) = A_\sigma \cdot \exp\left[-\frac{1}{T}\right]$
$D_B = d_1 = d_2 = 0.02[m]$	$\lambda(T) = A_\lambda \cdot T^2 + B_\lambda \cdot T + C_\lambda$
$D_e = 0.002[m]$	$\eta(T) = A_\eta \cdot \exp\left[-\frac{1}{T^2 + B_\eta \cdot T + C_\eta}\right]$
$\phi_1 = 17.5[V], \phi_2 = -17.5[V]$	$c_p = const$

Tab. 2. Boundary conditions for potential in models (a) and (b)

	Boundary conditions of the model	
Surface	(a)	(b)
AC	ϕ_2	$\phi = 0$
BD	ϕ_1	$\phi = 0$
CD	$\frac{\partial \phi}{\partial y} = 0$	$\phi = 0$
Electrodes	-	ϕ_1, ϕ_2
AB	$\frac{\partial \phi}{\partial y} = 0$	$\frac{\partial \phi}{\partial y} = 0$

In both models magnetic field with the effective value of induction $\vec{B}$ is present in zone D_B and the fixed value of temperature is applied on surfaces AC, CD, DB. Radiation heat flux is leaving the surface AB, the reference temperature of the infinite environment $T_{reff} = 350\,K$ has been chosen. Laplace equation $\Delta\phi = 0$ has been solved in both cases. One of the main difference between the models is in distribution of electric current density, which is caused by an applied potential. Applied boundary conditions for the potential are shown in Tab. 2. Another important difference is that the flow is allowed to leave the region between the electrodes in the model (b). We would like to mention that model (b) simulates the situation when electrical conductivity of a crucible is much higher than that of the melt. A typical conductivity field is illustrated in Fig. 2. In model (b) unlike model (a) the electrodes, which are assumed to be heat conducting with temperature dependent thermal conductivity [2], are included. Joule heat $s = \frac{\vec{j}^{\,2}}{2\sigma}$ induced by the current has been taken into account in both models. Triangular mesh has been used with approximately $2 \cdot 10^4$ -10^5 elements.

3. Results

The 2D study of the problem (formulated as shown in Fig. 1. and Tab. 1,2.) shows that the applied magnetic field plays an important role in determining the character of the temperature field. In [1] the axial temperature profiles are used to characterise the melting process. The results of our model predict that an external magnetic force impacts not only the the temperature range present in the melt but also the location of the hottest regions. Fig. 6a shows that in case of upwards-oriented external Lorentz force the axial profile measurements would indicate that much higher temperature regions are present outside the central part of the crucible. On the contrary, in

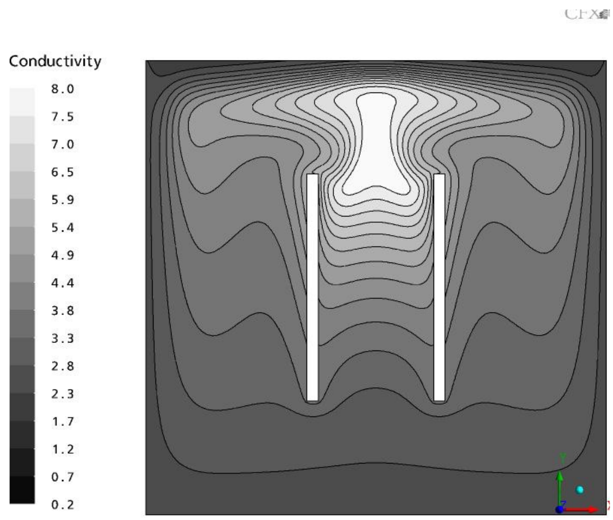


Fig. 2. Example of an electrical conductivity $[S/m]$ distribution in the melt: $T_d = 1410\,K$

case of downwards-oriented external Lorentz force an axial temperature profile gives the full information about the highest temperature in the melt.

As already mentioned before, a coupling of electrical, thermal and hydrodynamic processes together with the temperature dependent material properties according to the experiments of the authors of [1] are included in both models. During the simulations we faced the issue - a considerable convergence dependence on the average temperature in the melt, especially in the case of $\varphi = 180^0$. The temperature dependant behaviour of the system is illustrated in Fig. 5. It shows that in the temperature range of our interest the small changes in T_d gives a sharp increase of an average temperature. With an increase of an average temperature in the melt the finer mesh and a smaller step were required.

Data points in Fig. 3 and Fig. 4 refer to cases of different applied temperatures T_d on a crucible surface.

To keep an experimentally reasonable temperature range our model predicts the characteristic velocities of $\approx 3 mm/s$ in case of $\varphi = 0^0$, which is approximately threefold the case of $\vec{B} = 0$.

We keep in mind that we have implemented a lot of assumptions and simplifications in our analysis of the stirring process – an internal magnetic force, which occur due to currents flowing in the region and 3D flow characteristics has been excluded. Fig. 7. shows that unlike a strong impact of the external magnetic force on the velocity field in the central region of the crucible (Fig. 7. II) our simulations until now are not able to give evidence of a considerable decrease in axial temperature gradient (temperature homogenisation effect) when upwards-oriented external Lorentz force is applied (Fig. 7. I).

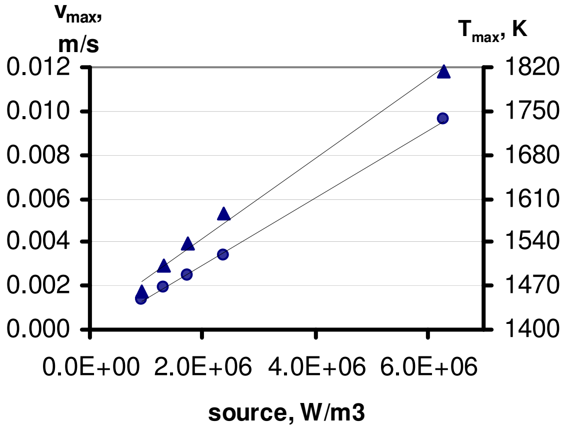


Fig. 3. Correlation of a Joule heat produced and the maximal velocity (*circles*) and temperature (*triangles*): $\varphi = 0^0$, $1370\,K < T_d < 1430\,K$

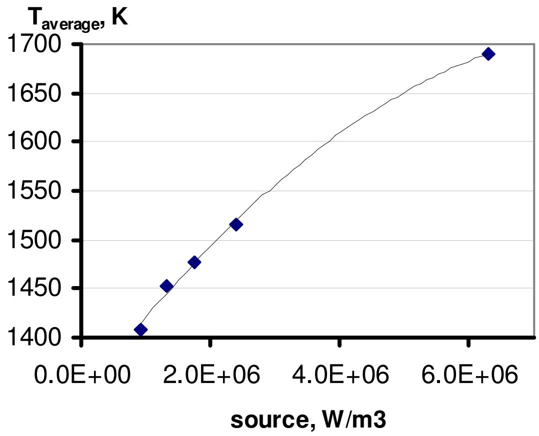


Fig. 4. Correlation of a Joule heat produced and the average temperature in the melt: $\varphi = 0^0$, $1370\,K < T_d < 1430\,K$

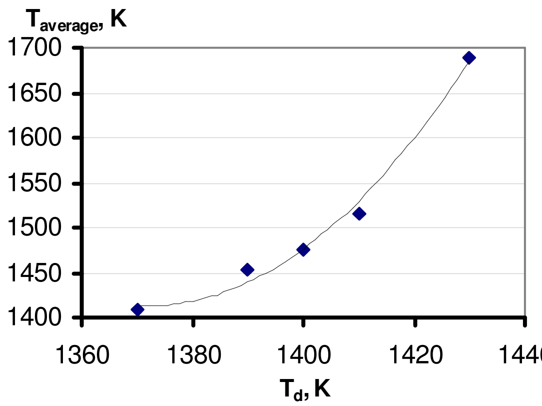
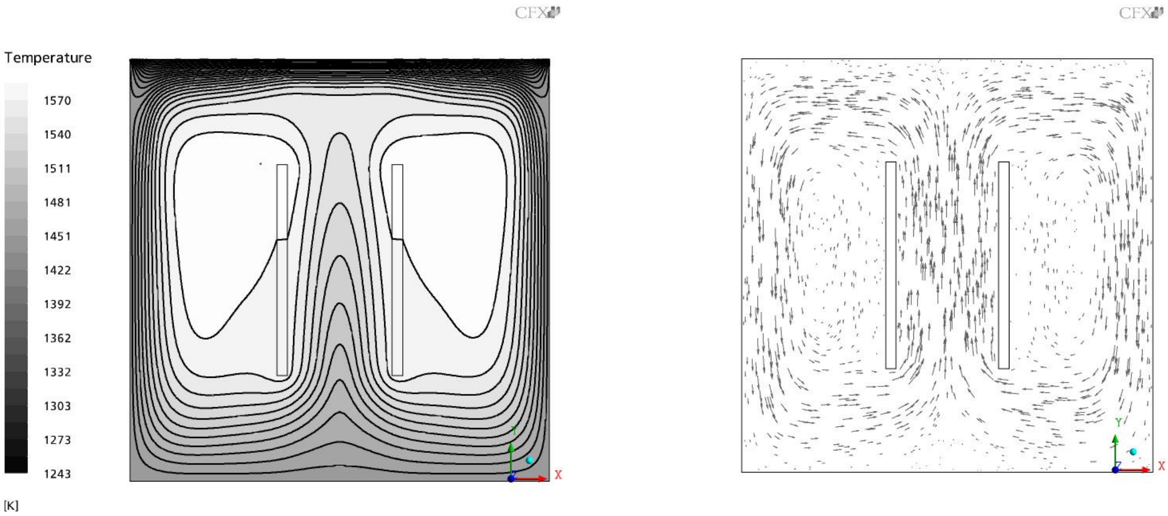
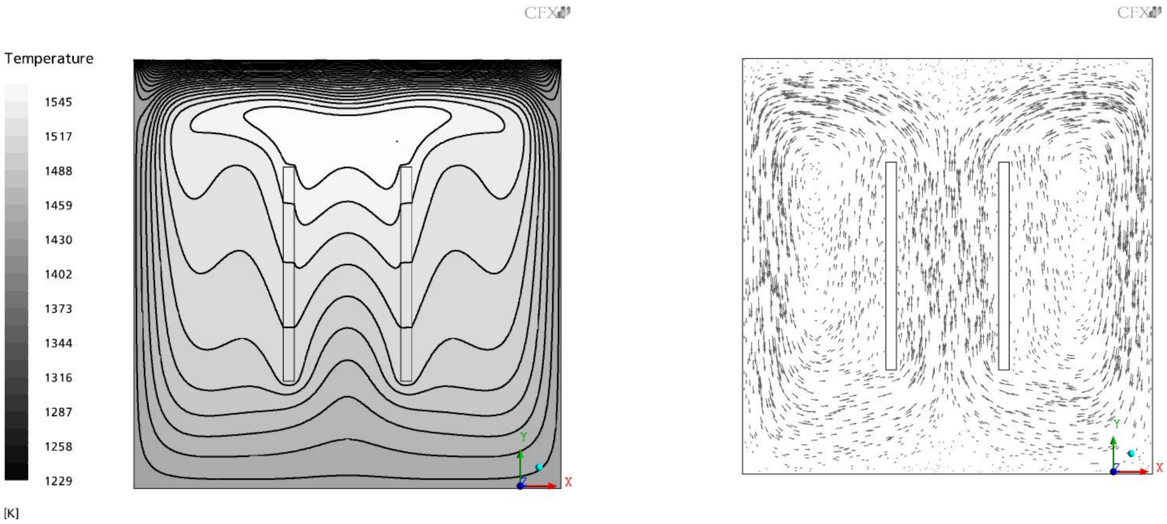


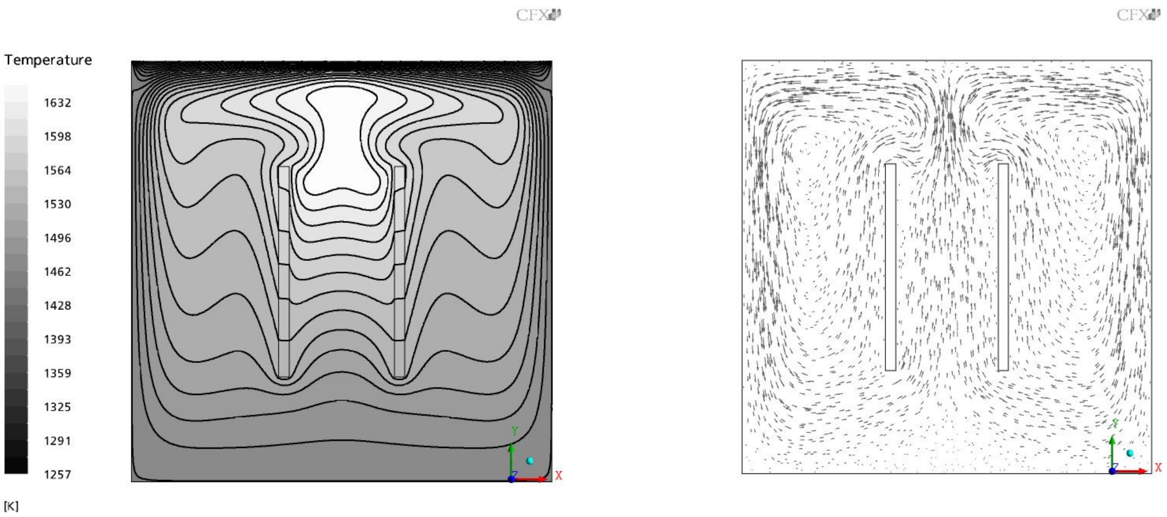
Fig. 5. Correlation between T_d and the average temperature in the melt: $\varphi = 0^0$



a) $\varphi = 0$

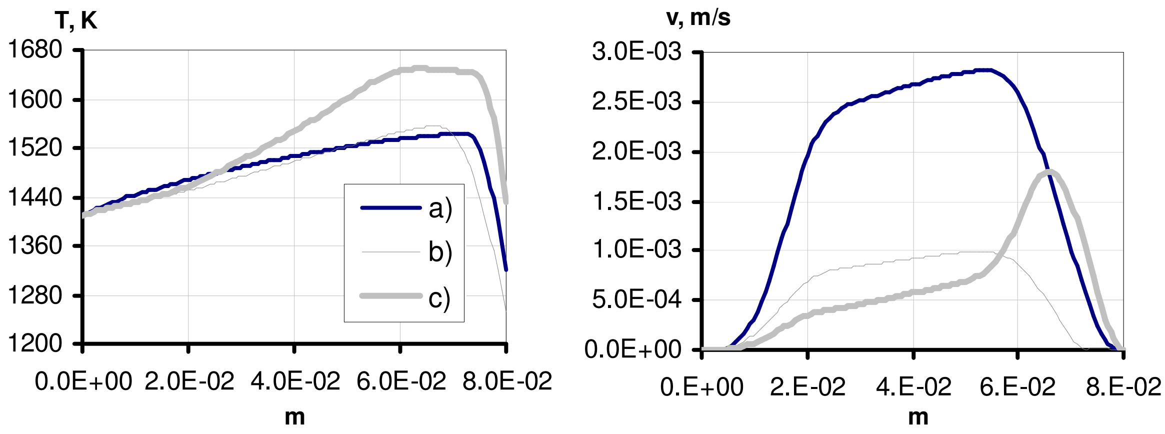


b) $\vec{B} = 0$



c) $\varphi = 180^0$

Fig. 6. Distributions of temperature and velocity in the glass melt: $T_d = 1410\,K$



(I) (II)

Fig. 7. Axial temperature (I) and velocity (II) profiles: a)with upwards-oriented ($\varphi=0^0$), b) without an external magnetic force, c) with downwards-oriented ($\varphi=180^0$) external magnetic force: $T_d=1410\,K$

Conclusions

Our results show that an external magnetic field strongly impacts the character of the flow and is able to increase and decrease the magnitude of axial velocity when compared with a case of $\vec{B}=0$. Our simulations until now are not able to give evidence of considerable decrease in axial temperature gradient (temperature homogenisation effect) when upwards oriented external Lorentz force is applied.

Bearing in mind that the solution of complete 3D simulation including also an internal magnetic force would be important, our up to date experience of considerably sensitive convergence lead to the decision that the investigations should be continued in the direction of fitting the boundary conditions closer to those present in the experiment. An opportunity to compare the results with the experimental measurements gained in rectangular 3D crucible with immersed electrodes would be useful as well.

References

[1] Dagmar Hulsenberg, Bernd Halbedel, Gerhard Conrad, Andre Thess, Yuri Kolesnikov, Ulrich Ludtke, Electromagnetic stirring of glass melts using Lorentz forces - Experimental results. Glass Sci. Technol. 77, 2004, No. 4, pp. 186 - 193.

[2] *Handbook of chemistry and physics*, 84 th edition, 2003 - 2004, CRC Press.

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