International Scientific Colloquium
Modelling for Material Processing
Riga, September 16-17, 2010

Numerical Simulation of Lorentz Force Enhanced Flow Patterns within Glass Melts

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Abstract

A common way to produce glass is to use melting tanks that work continually, using several megawatts per hour and producing glass with several hundred tons per day. The process of efficiently melting, refining (removing bubbles), and homogenizing the melted glass is strongly dependent on the melt flow within the tank. In order to improve the quality of glass products and the efficiency of the melting process, it is necessary to be able to predict and control the melt flow within the melting tank. In an effort to increase the amount of convective vortices, additional barriers are used, or the melt is electrically heated via electrodes (boosting), or gas is injected into the melt (bubbling). Using Lorentz force to create additional flow components based on flow density distribution and externally generated magnetic fields is an excellent method of targeted and controlled influence of the glass melt flow.°

Introduction

Fig. 1 shows a schematic diagram of a conventional fossil-fuel fired melting tank with a typical arrangement of barrier boost electrodes at the hot spot. To minimize the complexity of the simulation, the analyses were done only in the cutout section. The flow patterns for three different cases were simulated and analyzed using a block-shaped piece of the glass melt with two electrodes and a preset flow-rate. First, the flow rate of the glass melt is calculated without an electrical current in the boost electrodes. In the second case, an electrical current is sent through the electrodes. The electrode current generates so-called natural Lorentz forces around the electrodes, which influence the flow patterns of the glass melt in the electrode proximity (see Fig. 2). For the third case, the Lorentz force between the electrodes is augmented by an external magnetic field and the effect of this external field is made clearly visible in Fig. 3. The additional magnet system offers a new and innovative approach toward minimizing the bottom glass flow through the electrodes. By using additional, so-called artificial Lorentz forces between the electrodes a controllable, material-free wall is created. Thermal effects are currently neglected in our investigations.

1. Simulation Model

It is necessary to couple the numerical calculations for the electromagnetic field and the flow field in order to simulate the problem. The electromagnetic field is calculated using the commercial program MAXWELL and yields the density distribution of the Lorentz force. This then is inserted into the calculations for the flow field, for which we use FLUENT. Since the magnetic Reynolds number is low, we may assume that there is no effect of the melt flow

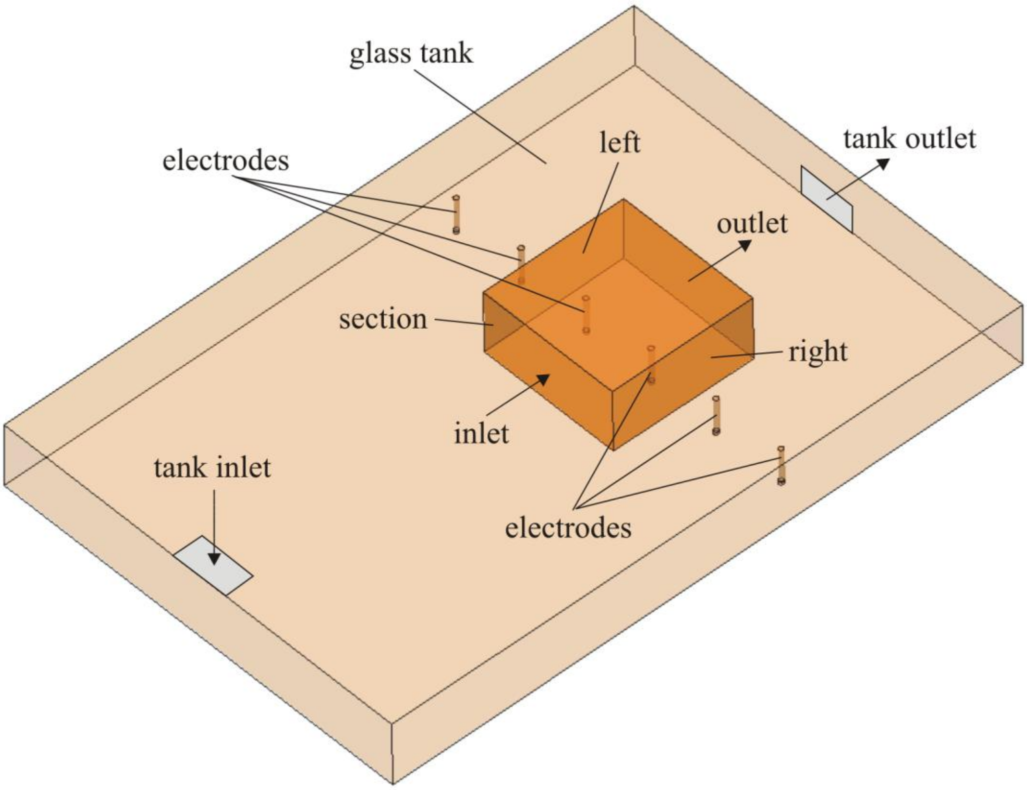

Fig. 1. Sketch of a fossil-fuel fired glass tank with typical barrier booster electrode arrangement and the section of interest for the numerical simulation (boundary conditions of the section: inlet: given velocity; outlet: const. pressure; left, right, top: shear stress zero; bottom: no slip)

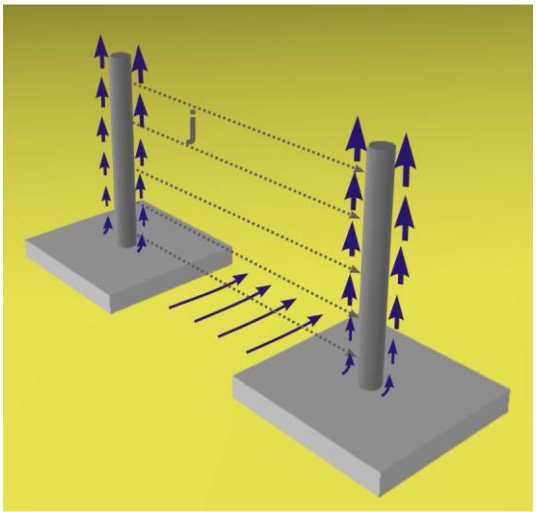

Fig. 2. Flow diagram (blue arrows) with active boosting electrodes without magnet system

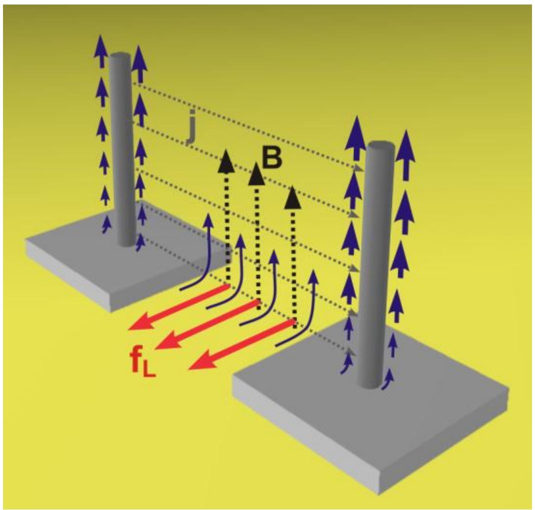

Fig. 3. Flow diagram (blue arrows) with active boosting electrodes with magnet system

(*j* - current density, *B* magnetic flux density, f_L – additional Lorentz force density) on the magnetic field. The neglect of the effect of temperature allows us to calculate the magnetic field only once. However, this simplification must be regarded very critically since the viscosity and the electrical conductivity of the glass melt are strongly dependent on the temperature. Furthermore, thermal buoyancy cannot be considered. We have decided to exclude the temperature in the three basic cases stated above because this would greatly increase the complexity of our calculations.

The data exchange between MAXWELL and FLUENT is based on ASCII files and is controlled manually by the user. MAXWELL and FLUENT use different meshes which are not necessarily compatible. The MAXWELL mesh is generally larger because the coil is located outside of the glass melt. Therefore a large area of air must be included in the mesh (see Fig. 4. First, FLUENT must be started in order to save the coordinates of the flow-cells for MAXWELL using user-defined-functions designed especially for this purpose. Then MAXWELL will calculate the electromagnetic field according to the given parameters for a sinusoidal electrical current through the electrodes and through the coil. Afterwards, the MAXWELL Field Calculator is used to assess the time averaged part of the Lorentz force density, which is then saved in a special file coordinating with the flow-cells for FLUENT. Then, the Lorentz forces can be imported with the user-defined-functions from FLUENT to start the flow calculation. A stationary flow simulation was performed because of the low Reynolds number and the expected laminar flow.

2. Results

Fig. 5 shows a nearly undisturbed streamline flow in the observed cutout of the glass tank without electrode current. The velocity with which the glass melt flows through a conventional fossil-fuel fired melting tank was calculated to be approximately $v = 0.1286$ mm/s. The electrical conductivity of the glass melt was fixed at 31.25 S/m and the viscosity was fixed at 18.2 Pas. Fig. 6 shows the streamline progression when the electrode current through the boost electrodes is at 1700 A. The effect of the natural Lorentz forces close to the electrodes and vertically to top can be clearly seen. Fig.7 shows the streamline progression with electrically active boost electrodes augmented by the external magnet system. The vertical streamlines have considerably increased, as the comparison with Fig. 6 shows. Although

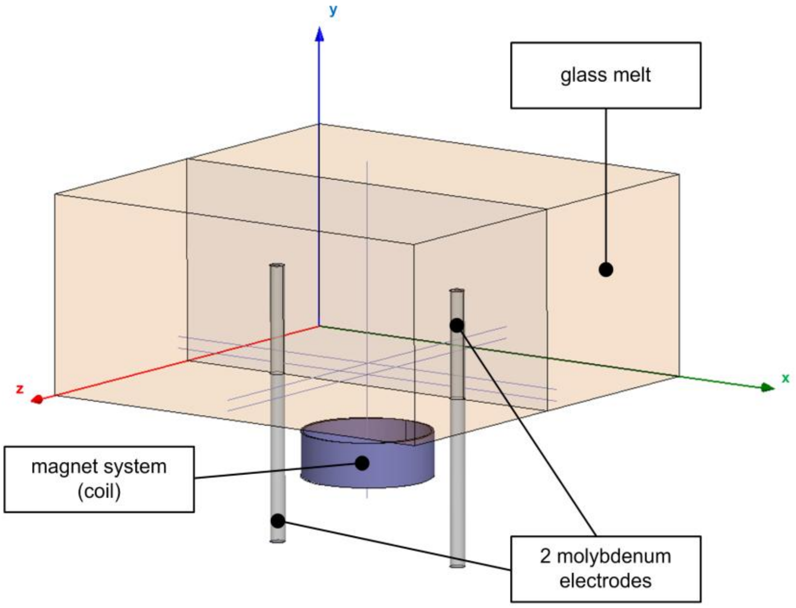

Fig. 4. The FLUENT solution area (glass melt) with two boost electrodes and the magnet system

the external magnetic field is only moderate (approx. 7.5 mT at the bottom of the glass tank in the center between the electrodes), the effect of the additional (artificial) Lorentz forces on the slowly flowing glass melt is very strong, so that the glass flow changes the direction in the area between the electrodes and in the near to the outlet of the section we observe a backflow.

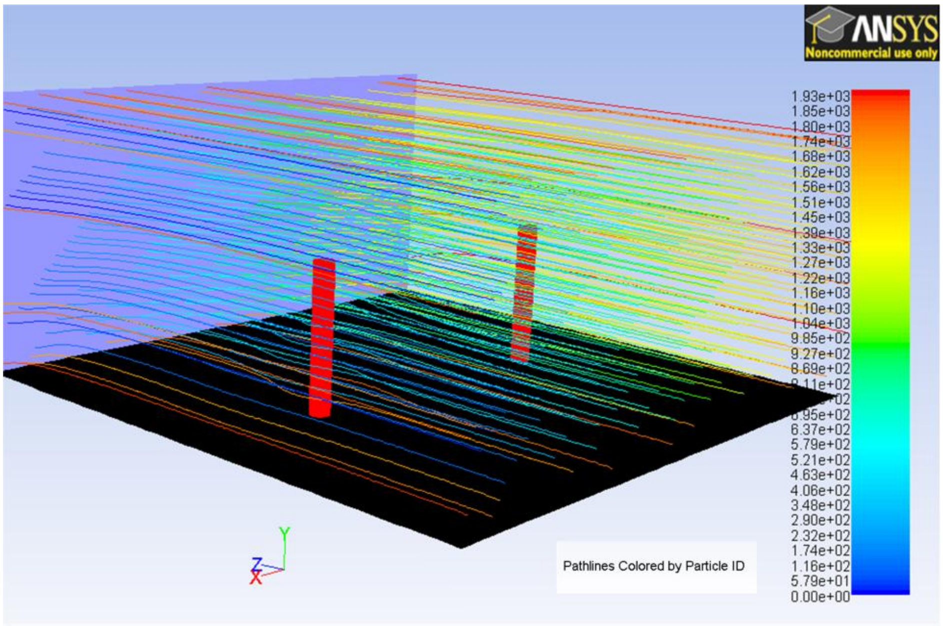

Fig. 5. Streamline progression without electrode current, inlet flow: v = 0.1286 mm/s

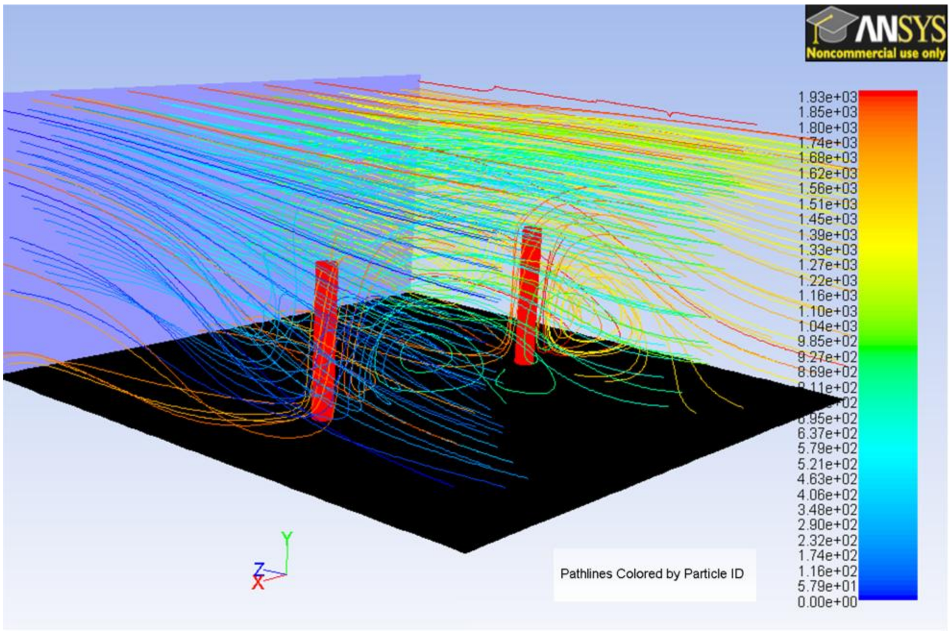

Fig. 6. Streamline progression with electrode current, inlet flow: v = 0.1286 mm/s

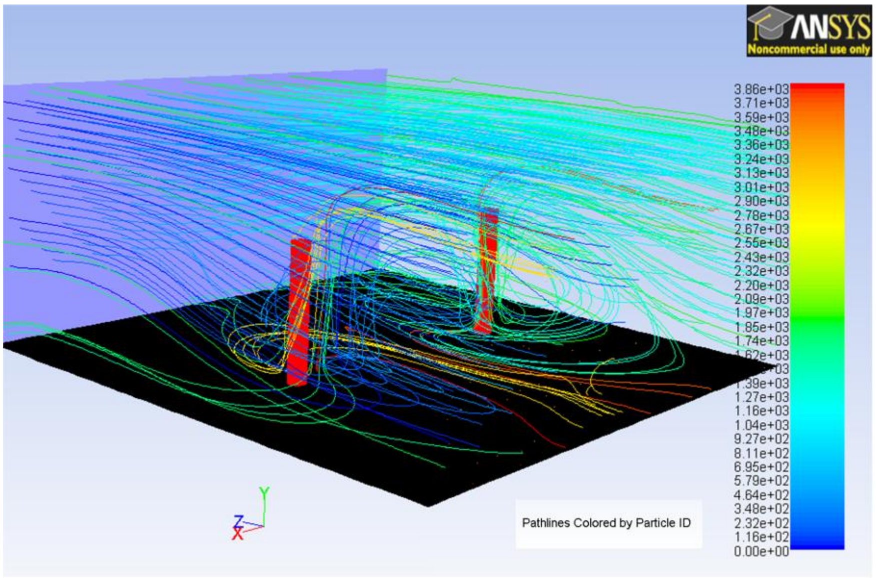

Fig. 7. Streamlines with electrode current and magnet system, inlet flow: v = 0.1286 mm/s

Conclusions

The numerical investigations show that even fairly small external magnetic fields generated additionally with simple magnet systems on the bottom of the glass tank can significantly influence the slowly flowing glass melt. The numerical simulations are an important instrument in predicting the flow pattern of the glass melt, the optimized position and design of such magnet systems. It is nearly impossible to directly measure the flow of molten glass, making a number of experiments in a real melting tank unfeasible. Thus, only numerical simulations allow us to optimize the magnet systems with the aim to reduce the width of the residence time distribution (RTD) within the melting tank, ultimately resulting in a better quality of glass and in significantly reduced energy consumption. The next step is to include the heat transport in our calculations. This would improve the precision of the simulation tool by taking buoyancy and the temperature dependency of the material properties into consideration. To validate the simulation tool, we will build a physical model of a real glass tank considering hydrodynamic similarity laws. Then, the velocity distribution of the model liquid within the tank will be measured using LDA and PIV. A last possible step is to actually simulate the melt flow in a real glass tank with a barrier boost electrode and external magnet system arrangement.

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