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MATHEMATICAL MODELLING OF THERMAL STRATIFICATION PHENOMENA IN STEEL LADLES

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Abstract

This paper presents a three-dimensional numerical model simulating fluid flow and heat transfer in 105 t steel ladles before and during the casting process. The model was developed by combined implementation of a numerical simulation package, TEMPSIM, and a computational fluid dynamics (CFD), simulation package, ADINA (Automatic Dynamic Incremental Nonlinear Analisys). In this study, TEMPSIM was used to calculate the heat transfer in ladle linings and predict the heat losses from the steel melt to the linings. These data were used as input into ADINA for 3-D CFD modeling of fluid flow and heat transfer.

Key Words:

Model, numerical simulation, CFD, steel ladle, fluid flow, heat transfer, stratification.

1. INTRODUCTION

The melt stratification phenomenon, which results from the natural convection in ladles holding molten steel, is of fundamental importance for the temperature control in continuous casting process. The progressively increasing stress on the quality of continuously cast products necessitates much tighter tundish temperature control, which in turn will require a more precise definition of the extent of melt temperature stratification in ladle.

According to the data to be found in the reference literature, the hydrodynamics of the fluid alloy in the casting ladle during the casting process has been studied by means of 2-D, symmetric - axial simulations of a ladle with the central tapping [3] and by means of 3-D symmetric - axial simulations of an eccentric tapping ladle [4]. The results of such simulations have been compared to those obtained by means of physical models using water [7], or by temperature measurements [1, 2, 3, 5].

The objective of the present study is to establish, under more precisely defined conditions, a 3-D CFD model for simulating stratification and fluid flow in steel ladles during both the holding period and the casting period. The transient and ladle configuration dependent heat losses from steel ladle linings were more accurately predicted by using a numerical simulation package, TEMPSIM. These data were used as boundary conditions for further simulation on the fluid flow and heat transfer, by using a commercial CFD simulation package, ADINA.

2. SIMULATIONS CONDITIONS

Considering these aspects, we simulated the hydrodynamics of the fluid alloy in the 105-t ladle used by S.C. Mittal Steel S.A. Hunedoara, before and during the casting process by means of CFD-3D model. This is also due to the fact that the ladle, whose configuration and geometrical dimensions are given in figure 1, has an eccentric tapping.

At first, a geometrical sketch of the ladle was made (fig.2), starting from the configuration and geometrical dimensions of the industrial casting ladle (fig.1). As it can be noticed, in order to simplify the modeling, we neglected the fact that the ladle has a conical shape, it being considered cylindrical.

In order to achieve a closest simulation of the hydrodynamics and temperature of the fluid alloy in the ladle during taping, we considered it necessary to take into consideration the fact that the metal bath in the ladle is thermally stratified at the moment of tapping. The consideration given above is mandatory, as in the secondary refining station (LF), the metal bath is homogeneous from the thermal point of view, but during the ladle transportation from the LF station to the tundish a thermal stratification of the metal bath takes place because of natural convection.

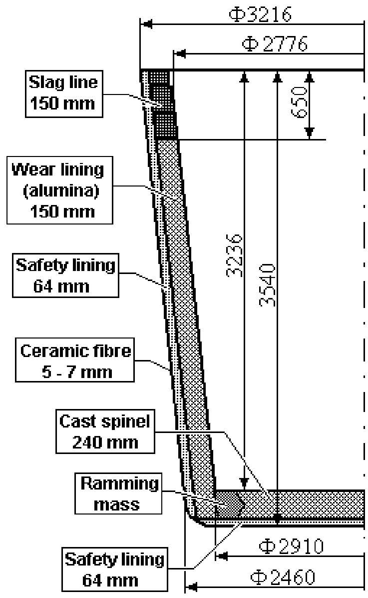

Fig.1. Geometric dimensions and configuration of the refractory masonry of the ladle under study

Considering this, the simulation will be done in two stages: the first will simulate the 10 minute-station of the ladle, when the metal bath will be thermally stratified, and the second will simulate the ladle emptying during the casting process.

The emptying stage also involves two periods:

- the first period, which lasts about 3 minutes, represents the filling of the 15-t tundish;
- the second period, which lasts about 40 minutes, corresponds to the normal casting rate.

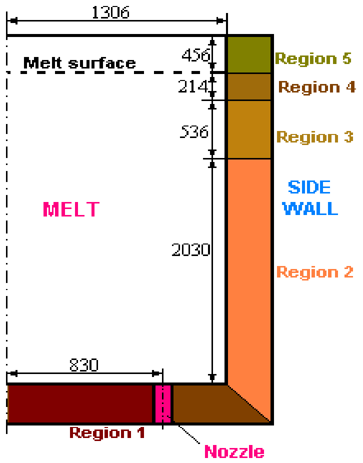

Fig.2. The geometry of the ladle used in the CFD-3D simulation

According to the reference information and also considering the practice of continuous casting (TC) at S.C. Mittal Steel S.A. Hunedoara, in the simulations we considered constant casting flow rates of 77,8 kg/s for the first period of emptying, respectively 36,1 kg/s for the second period.

Using two custom softwares, we simulated the hydrodynamics and the temperature of the fluid alloy in the ladle during the period of its emptying.

3. RESULTS OF NUMERICAL SIMULATIONS

After having simulated the thermal stratification of the metal bath, for a 10-minute period of stationing, we obtained the rate field (fig.3) and the distribution of temperature (fig.4). These data shall be further used as initial conditions in the stage of ladle emptying. In order to better emphasize the temperature differences arising in the thermally stratified metal bath, because of the phenomenon of thermal convection, we gave the distribution of temperature field for different planes of the field of analysis (fig.5). Further on, we gave the results of the simulations after 10, 25, and 39 minutes from the opening of the tap.

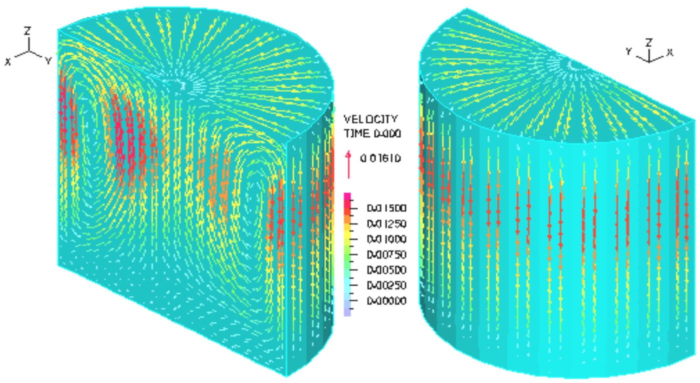

Fig.3. The rate field after 10 minutes of thermal stratification simulation

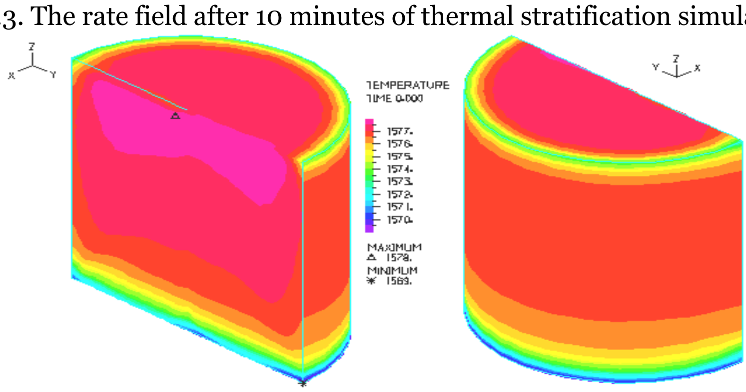

Fig.4. The rate field after 10 minutes of thermal stratification simulation

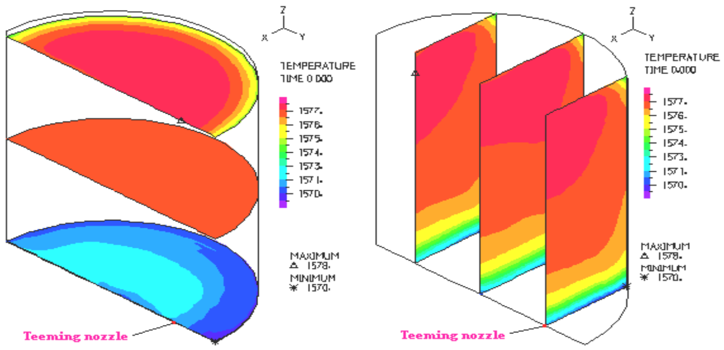

Fig.5. The temperature of the metal bath in different horizontal and vertical planes, after 10 minutes of thermal stratification

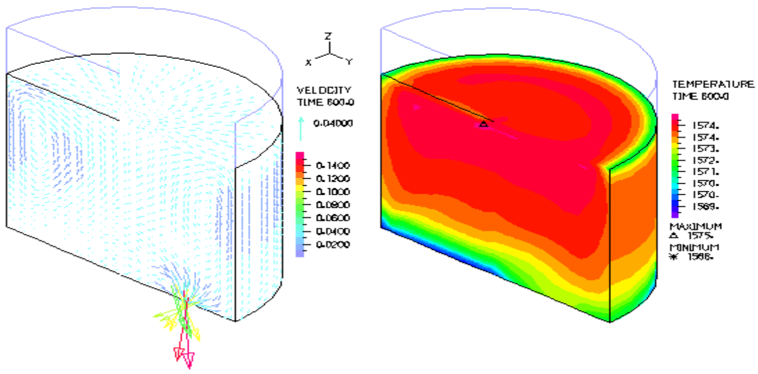

Fig.6. The field of rates and temperatures of the metal bath after 10 minutes from the opening of the tap.

4. ANALYSIS OF THE SIMULATION RESULTS

Figure 6 gives the field of rates and the distribution of temperature in the metal bath after 10 minutes from the opening of the tap. One can notice that the movement of the alloy in the ladle is further due to the phenomenon of natural convection, the rate field having the same profile as in the initial stage (fig.3).

Continuing the analysis of the rate field evolution, one can notice that it starts being influenced increasingly by the fact that a movement of the alloy arises from its flowing out through the tap. After about 25 minutes from the opening of the tap (fig.7), this movement starts to prevail over the one due to natural convection.

This tendency is also revealed by the evolution of the temperature field inside the metal bath. Thus, at the beginning of tapping, the phenomenon of thermal stratification is still present because the metal bath keeps losing heat to the environment and natural convection is still present. In the latter half of the tapping period (after about 25 minutes from the opening of the tap), because of the low level of the metal bath in the ladle, the heat lost to the exterior is diminished and the phenomenon of thermal stratification comes to an end. At the same time, the movement of the fluid alloy through the tap determines the mixing of the metal bath, which leads to diminishing the thermal stratification already existent.

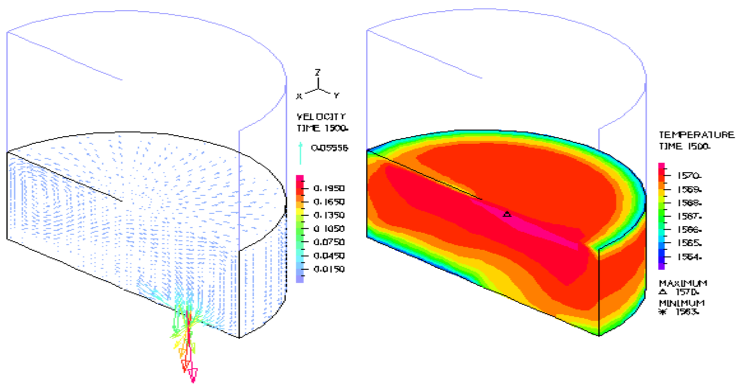

Fig.7. The field of rates and temperatures of the metal bath after 25 minutes from the opening of the tap

One very important result to be noticed when simulating the hydrodynamics and temperature of the fluid alloy from the ladle during its emptying is the fact that we know the temperature of the fluid alloy at the knots of the domain of analysis, corresponding to the entrance of the ladle tap. Taking into consideration the fact that, on leaving the tap, the alloy flows through a protection ceramic tube, up to the tundish of the continuous casting machine, and the loss of heat to the walls of this ceramic tube is very low (corresponding to a decrease of under 0,1 °C of the temperature of the fluid alloy [6]), we can consider that this is the temperature at which the fluid alloy enters the tundish and we shall further call it *the temperature of the alloy flow*.

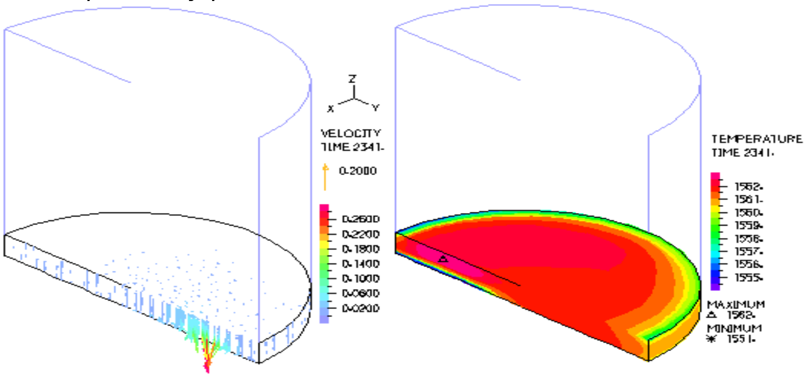

Fig.8. The field of rates and temperatures of the metal bath after 39 minutes from the opening of the tap.

5. CONCLUSIONS

The results obtained by modelling and simulating the hydrodynamics and temperature of the fluid alloy in the ladle during its emptying stage can lead to the following conclusions:

- the three-dimensional model developed in order to simulate the phenomena occurring in the ladle before and during its emptying stage is valid if one considers the results obtained. This model has been developed starting from the one-dimensional model of thermal conduction (1-D), which simulates the non-stationary heat transfer through the refractory masonry of the ladle, and also using the CFD-3D model, which simulates both the thermal stratification of the fluid alloy in the ladle during its stationary period and the hydrodynamics and heat transfer occurring in the fluid alloy during the emptying of the ladle.
- at the beginning of the emptying period, the phenomenon of thermal stratification is still present, as the metal bath keeps losing heat to the environment by natural convection. In the second period of emptying (after about 25 minutes from the opening of the tap), because of the fact the level of the metal bath in the ladle is low, the amount of heat lost to the environment diminishes, and the phenomenon of thermal stratification halts. At the same time, the movement of the fluid alloy due to its flowing out through the tap triggers a mixing process of the metal bath, which leads to the diminishing of the existent stratification.
- once we know the variation of the alloy flow temperature into the ladle, we can take technological steps in the sense of increasing, respectively decreasing the temperature inside the tundish in order to range it within the limits required by the continuous casting technology.

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