Mathematical and physical modeling of thermal stratification phenomena in steel ladles

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Abstract. By means of CFD numerical modeling, a systematic analysis of the similarity between steel ladles and hot-water model regarding natural convection phenomena was studied. The key similarity criteria we found to be dependent on the dimensionless numbers $Fr$ and $\beta \Delta T$. These similarity criteria suggested that hot-water models with a scale in the range between 1/5 and 1/3 and using hot water with temperature of 45 °C or higher are appropriate for simulating natural convection in steel ladles.

With this physical model, thermal stratification phenomena due to natural convection in steel ladles were investigated. By controlling the cooling intensity of water models to correspond to the heat loss rate of steel ladles, which is governed by $Fr$ and $\beta \Delta T$, the temperature profiles measured in the water bath of the model were used to deduce the extent of thermal stratification in liquid steel bath in the ladles. Comparisons between mathematically simulated temperature profiles in the prototype steel ladles and those physically simulated by scaling-up the measured temperatures profiles in the water model showed good agreement. This proved that it is feasible to use a 1/5 scale water model with 45 °C hot water to simulate natural convection in steel ladles. Therefore, besides mathematical CFD models, the physical hot-water model provided an additional means of studying fluid flow and heat transfer in steel ladles.

1. Introduction

Due to inevitable heat losses, natural convection is a common phenomenon occurring in steel ladles during the holding period prior to casting. A typical consequence of this phenomenon is thermal stratification of the liquid steel bath. The thermal stratification phenomenon in steel ladles and its potential influence on temperature control during continuous casting are important in steelmaking. This is because the temperature of liquid steel coming from a thermally stratified melt bath held in the ladles, i.e., teeming stream temperature, will have a direct impact on the temperature of steel melt held in the tundish. Therefore, investigation concerning this impact are obviously necessary, which, in turn, presupposes a good understanding of thermal stratification phenomena inside the steel ladles.

By means of CFD numerical modeling, a systematic analysis of the similarity between steel ladles and hot-water model regarding natural convection phenomena was studied, [1-3]. The key similarity criteria we found to be dependent on the dimensionless numbers $Fr$ and $\beta \Delta T$, [4].

These similarity criteria suggested that hot-water models with scale in the range between 1/5 and 1/3 and using hot water with temperature of 45 °C or higher are appropriate for simulating natural convection in steel ladles, [4].
The present study focuses on establishing a hot-water model to simulate natural convection phenomena in steel ladles during the holding period before casting for the following purposes:
- Realization of an experimental physical model;
- Further evaluation of the key similarity criteria previously obtained from non-isothermal physical modelling of fluid flow and heat transfer in steel ladles, i.e., Fr and βΔT;
- Validation of the CFD models developed for simulating natural convection in steel ladles.

2. Realization of experimental physical model

Based on the previous analysis of the similarity between natural convection phenomena in steel ladles and in hot water models [4], which suggests that the water models with size scale in the range between 1/5 and 1/3 could be appropriate for modeling steel ladles, a 1/5 scale hot-water model of mid-aged 105 t steel ladles was set up in the laboratory, [5]. Figure 1 illustrates this physical model set-up.

The model consists of two cooling chambers:
- The one is a cylindrical cooling chambers for simulating the ladle wall;
- The other is a flat cooling chambers for simulating ladle bottom.

The cooling chambers are made of 0.5 mm-thick stainless steel. Hot water is used as the liquid bath simulating liquid steel bath in ladles, while cold water with controllable temperatures is tangentially introduced into the cooling chambers in directions shown in Figure 1. KTY81-120-type temperature sensor were employed to get the temperature information from the water model. Principle of functioning of these sensors is based on the phenomenon of change electrical resistance with temperature and measuring range is between -50 ... 150 °C. Was preferred using these sensors in place of thermocouple elements as temperatures developed in the installation during the simulations are relatively low (max. 50 °C), and for this domain temperature sensors used have a measurement error small (± 1%) .

Figure 1 also schematically illustrates the sensor measurement position. 18 sensors were used for measuring the temperature profile in the water bath on a vertical plane bounded by sidewall and center axis. 4 sensors were used for measuring temperature of water inflows and outflows of the cooling chambers. All the temperature signals were recorded into a data logger for post processing.
To prevent heat loss from the top free surface of the water bath, the free surface was covered with a light porous plastic plate that can float on the surface. In order to homogenize the hot-water bath, if needed, pressurized air can be blown into the water bath via the tuyere located at the center of the bottom-cooling chamber.

1) A series of tests using this hot-water model was carried out with the following general procedure:
2) Supply cold water to cooling chambers at certain temperatures and flowrates;
3) Fill the model with hot water (around 50 °C) to a certain bath level;
4) Stir the hot-water bath by blowing pressurized air until the average temperature of the water bath decreases to about 45 °C;
5) Stop stirring the hot-water bath for a certain time lapse (i.e., the holding period for the development of thermal stratification);
6) Stir the hot-water bath again or drain the hot water out.

From the water model tests, temperature profiles in the hot-water bath were measured. The measured temperatures can be used to compare the predictions of the CFD model developed for the water model as an indirect verification of the CFD model developed for steel ladles. Furthermore, by controlling the cooling intensity to correspond to the heat loss rate of steel ladles, obeying the similarity criteria, the temperature profiles (exhibiting thermal stratification) obtained from the water model may be used directly to deduce the extent of thermal stratification in the prototype steel ladle.

![Experimental installation, [5]](image)

2. Mathematical simulation

2.1. Mathematical equations that govern the phenomena
In order to use the results obtained by physical modeling with water based models for validating the CFD model to simulate the natural convection phenomenon in steel ladles, the same CFD model can also be applied to the water model. In fact, flow phenomena due to natural convection, both in liquid steel and in water, are governed by the same set of partial differential equations of turbulent flow, Navier-Stokes type, the differences occurring being due to the different thermo-physical properties of those two fluids and different initial and contour conditions. In Cartesian coordinates, these equations have the following form:

Continuity equation:
\[ \frac{\partial p}{\partial t} + \frac{\partial (\rho v_j)}{\partial x_j} = 0 \] (1)

The moment transfer equation:

\[ \frac{\partial (\rho v_j v_i)}{\partial t} + \frac{\partial (\rho v_j v_i)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[ \rho \left( \frac{\partial v_j}{\partial x_i} + \frac{\partial v_i}{\partial x_j} \right) \right] - \rho_{\text{ref}} \beta \Delta T g \] (2)

where the approximation of Boussinesq on the ascension force was made.

Energy transfer equation:

\[ \frac{\partial (\rho cT)}{\partial t} + \frac{\partial (\rho v_j cT)}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \lambda_{\text{ref}} \frac{\partial T}{\partial x_j} \right) \] (3)

Turbulent flow equations:

To describe the effects of turbulent flow occurring in the case of natural convection phenomena in liquid steel and water, the standard k-ε model of turbulent flow was used. This is described by the following equations:

- the equation of the turbulent kinetic energy:

\[ \frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho v_j k)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \rho \left( \frac{\partial v_j}{\partial x_i} + \frac{\partial v_i}{\partial x_j} \right) \right] + \nu_t \left( \frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right) \frac{\partial v_i}{\partial x_j} - \rho \varepsilon \] (4)

- the equation of the speed of dissipation of turbulent energy:

\[ \frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho v_j \varepsilon)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \rho \left( \frac{\partial v_j}{\partial x_i} + \frac{\partial v_i}{\partial x_j} \right) \right] + C_{1v} \nu_t \varepsilon \left( \frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right) - C_{2v} \rho \varepsilon^2 \] (5)

In these equations, \( v_{\text{ef}} = v_l + v_t \) is laminar viscosity, and \( v_t \) turbulent viscosity. Similarly, effective thermal conductivity is defined as, \( \lambda_{\text{ef}} = \lambda_l + \lambda_t \), where \( \lambda_l \) is laminar thermal conductivity, and \( \lambda_t \) is turbulent thermal conductivity. Using the turbulence model described above, \( v_t \) and \( \lambda_t \) can be determined by means of relations:

\[ v_t = C_{1v} \rho \frac{k^2}{\varepsilon} \] (6)

and

\[ \lambda_t = \frac{v_t c}{Pr_t} \] (7)

Where Pr_t is the Prandtl number of turbulent flow, this value being 0.9 for fully turbulent flows [6].

According to the recommendations of the literature [7], the constants that appear in the standard k-ε model of the turbulent flow have the following values:

\[ C_{1v} = 0.09; C_1 = 1.44; C_2 = 1.92; \sigma_k = 1.0; \sigma_\varepsilon = 1.3 \]

2.2. Mathematical simulation

In order to use the water modeling results to validate the CFD model developed for simulating natural convection phenomena in steel ladles, the same CFD model should be applied to the water model as well. In fact, the natural convection flows in liquid steel and in hot water are governed by the same set of turbulent Navier-Stokes type partial differential equations, except from the differences in thermal-physical properties of the fluids and initial and boundary conditions.
For the present study, a two-dimensional CFD model were developed. The model simulate heat transfer both in liquid and in solid, so-called conjugate-heat-transfer CFD model. This CFD model was established specially for the water model which calculates fluid flow and heat transfer both in hot-water bath and in the cold water flowing in cooling chambers including heat conduction inside the inner walls of the chambers. For this, a two-dimensional cylindrical-polar computation domain was defined for the water model as shows in Figure 3.

![Figure 3. Computation domains and grids used for CFD simulations of water model](image)

The reason for developing a conjugate-heat-transfer CFD model was that it was found from water model experiments and test simulations, [8], [9], that the extend of thermal stratification in the hot-water bath is dependent not only on the average magnitude of the heat loss flux but also, more crucially, on the heat flux distribution along the side wall. Therefore, it is obvious that such knowledge cannot be directly obtained from the water model by measurements. Thus, the heat loss fluxes and their distributions have to be totally calculated by means of mathematical simulations.

Table 1 list the description of various regions in the computational domains defined in Figure 3.

| Regions | Descriptions                                           |
|---------|--------------------------------------------------------|
| ABCD    | Hot-water bath                                        |
| EFBA    | Bottom-cooling chamber                                |
| EFGH    | Bottom-cooling water                                  |
| HGBA    | Inner shell of bottom-cooling chamber                 |
| BJKC    | Side-cooling chamber                                  |
| IJL     | Side-cooling water                                    |
| BILC    | Inner shell of side-cooling chamber                   |
| FG      | Inlet of bottom-cooling chamber                       |
| EM      | Outlet of bottom-cooling chamber                      |
| IJ      | Inlet of side-cooling chamber                         |
| LK      | Outlet of side-cooling chamber                        |
| ED      | Centre axis                                           |
| MF      | Interface between cooling water and outer shell of bottom-cooling chamber |
| JK      | Interface between cooling water and outer shell of side-cooling chamber |
3. Results and discussions

3.1. Comparison between water model and mathematical model simulation results

Figure 4 shows the comparison between the measured temperatures and those predicted using the conjugate-heat transfer CFD model for a water model simulations case.

![Comparison between measured and calculated temperatures](image)

**Figure 4.** Comparison between temperatures calculated (lines) and measured (symbols) at different position in the water model.
In this simulations case, initially, after stop the gas bubbling, the hot-water bath was nearly homogeneous and had an average temperature of 45 °C. It was cooled by introducing 12 °C cold water into the side and bottom cooling chambers at flowrates of 10 liters per minute. The cooling lasted 6 minutes to allow the development of thermal stratification in the hot-water bath. It can be seen from this Figure that a generally satisfactory agreement between calculated temperatures and measurement ones was obtained, showing that the conjugate-heat-transfer CFD model developed in the present study is feasible for use. It should be noted that in the flow regions close to the top surface the calculated temperatures decrease relatively faster than the measured ones. This discrepancy could be due to the use of the standard high-Reynolds number k-ε two-equation turbulence model that may overestimate turbulent heat transfer in this flow region.

3.2. Flow and temperature fields in hot-water model

Figure 5 illustrates the flow and temperature fields in the hot-water model after 6 min. of cooling, predicted by the conjugate-heat-transfer CFD model, for the above-mentioned experimental case.

![Figure 5](image)

**Figure 5.** Predicted flow and temperature fields, after 6 min. of cooling, in a 1/5 scale hot-water model

Due to axis-symmetry, only a half of the flow field and a half of the temperature field are shown in the Figure. It is seen that the CFD model well revealed the natural convection flow pattern and thermal stratification in the hot-water bath. In addition, with help of conjugate-heat-transfer CFD model, fluid dynamics in the cooling chambers can also be examined. A well-established radial plug-flow is found in the bottom-cooling chamber with a nearly uniform velocity distribution appearing across the vertical gap inside the chamber. A nearly vertical plug-flow is found in the side-cooling chamber but with noticeable velocity gradients across the radial gap inside the chamber. It is believed that the difference in velocity distributions between bottom and side cooling chambers is caused by the buoyancy effect, which is weaker inside the bottom and side cooling chamber, but rather stronger inside the side-cooling chamber. As results, a nearly temperature distribution is revealed in the
bottom-cooling chamber, while a non-uniform temperature distribution is found in the side-cooling chamber with, of course, higher temperatures appearing close to the wall of the chamber.

4. Conclusions
From these studies can be drawn following conclusions:

- The present non-isothermal water model study has confirmed the validity of the dimensionless number Fr and β∆t as key criteria governing the similarity between natural convection phenomena in hot-water models and in prototype steel ladles.
- Establishing a non-isothermal water modeling system is useful for verification of CFD mathematical modelling results. In addition to mathematical methods, the hot-water model provides an alternative means of studying fluid flow and heat transfer phenomena in steel ladles.
- It is feasible to use a 1/5-scale hot-water model to simulate natural convection and resulting thermal stratification phenomena in steel ladles during the holding period before casting, if the heat loss fluxes and, especially, their distributions in steel ladles are accurately known.
- The water modeling results prove the fact that the in steel ladles development rate of thermal stratification is linearly proportional to the bulk-cooling rate, as has been reported by other authors.

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