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WATER MODEL AND NUMERICAL SIMULATION OF A SINGLE STRAND SLAB CASTER TUNDISH

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Abstract. *The steel production process through continuous casting is widely used worldwide, being responsible for a large part of the world production of this metal. The tundish is an extremely important vessel in this process, being responsible, among other factors, for promoting inclusion flotation and for supplying the mold with a constant flow of steel, guaranteeing the continuity of the casting process. Due to its importance in the process, the flow inside the tundish is widely studied by several authors and was the object of this study. Since the process is characterized by high temperatures (over 1500ºC), water modeling is an important resource capable of providing information about the phenomena that occur inside the tundish and cannot be observed during operation. Due to the large size of the equipment involved in the process, scale models are generally used. Here, Froude similarity criteria was considered for the similarity between model and prototype and analyzes the fluid dynamic phenomena that occur during the ladle change, a phenomenon characterized by transience. Injections of saline and dyed solutions were performed in the laboratory, and flow rate and electrical conductivity sensors were used to monitor the flow evolution. The data acquired through the water model are used to validate a mathematical model, developed using the Ansys Fluent software. The results showed the mixing pattern that occurs in a single-strand slab caster tundish during a ladle change with a change in the chemical composition of the steel being casted. There is a window of time in which the mold is fed by a mix between different grades of steel, which can cause a downgraded ingot. The mathematical model was able to represent the main fluid dynamic phenomena involved in the studied process, being able to be used for the optimization of variables.*

Keywords: *computational fluid dynamics, continuous casting, multi-phase flow, tundish, water model*

1. INTRODUCTION

Continuous casting is the main process by which steel is produced nowadays. The metal solidification occurs in a continuous manner, which is guaranteed by the tundish. This vessel also plays a key role in the quality of final products, with the flotation of the non-metallic inclusions. Unfavorable flow may lead to several issues and even to the termination of cast. Therefore, it is largely studied by many authors, such as Resende et al. (2021), Hackl et al. (2019) and Wang et al. (2022).

As most of the metallurgical processes, the continuous casting is characterized by a severe heat exchange. The ladle steel temperature may reach 1600ºC, and a complete ladle draining may last almost an hour. As the ladle drains, the molten steel loses heat to the environment and refractories around it, and has its temperature decreased. Consequently, the tundish inlet temperature is maximum at the opening of the ladle and minimum at the end of emptying, which might be related to flow variations.

The thermal effects involved in the metallurgical process that occurs inside a tundish during ladle change may have a large influence on the steel flow pattern, as well as in the steel mixing curve and, consequently, in the chemical composition and quality of the ingot. To evaluate that process, experimental and numerical models are largely used techniques.

In this study, water model experiments are used to represent physically the tundish flow. A potassium chloride solution is applied to quantify the concentration of the fluids that come from different reservoirs (ladles) once it can be related to the mixture's electrical conductivity (measured by a sensor). Dye injection is used to track and visualize the flow, expounding its patterns and the dead zones.

On the other hand, the mathematical approach is able to computationally represent the physical experiments, aiming to visualize a similar flow behavior to the one seen in the experimental model. The validated numerical model may be used to compare different parameters in future works, such as the flow rate and the impact pot geometry, defining the optimized configuration to minimize the intermix time.

This paper aims to use the above-mentioned tools to investigate the influence of the thermal phenomenon on the mixing curve and flow pattern during ladle exchange in a single-strand slab caster tundish. The 10%-90% intermix time will be compared between the isothermal and non-isothermal water models, as well as the flow pattern and dead zones. The electrical conductivity data at the tundish outlet will be used to compare the experimental and numerical models.

2. WATER MODEL

Water modeling is a powerful tool to investigate the tundish flow. Due to the elevated temperatures of the process, together with other critical conditions, direct measurement of flow is challenging. Therefore, even with simplifications, water modeling is able to provide useful information and to assist in optimizations. The experimental study is carried out in a model that has a geometric scale of 1:3 and represents a single-strand tundish for slab casting with an impact pot.

2.1 Similarity criteria

For the experimental representation in scale, it is desirable to ensure several similarities, such as geometric, dynamic, kinematic (Mazumdar, 1999). The geometric similarity is reached by scaling all the system lengths in the same scale, called scale factor (λ). The dynamic similarity is achieved through the equivalence of dimensionless Reynolds and Froude numbers between model and prototype. Eq. (1) gives the Reynolds number (*Re*) and Eq. (2) gives the Froude number (*Fr*). The Froude number represents the ratio of the flow inertia to the external field (gravity), while the Reynolds number is the ratio of inertial forces to viscous forces.

$$Re = \frac{\rho V L}{\mu}, \tag{1}$$

$$Fr = \frac{V^2}{gL}, \tag{2}$$

where ρ is the density, V is the velocity, L is a characteristic length, μ is the viscosity, g is the gravitational acceleration and L is a characteristic length. Eq. (3) and Eq. (4) must be followed in order to guarantee a Reynolds and Froude similarity, respectively.

$$\left(\frac{\rho V L}{\mu}\right)_m = \left(\frac{\rho V L}{\mu}\right)_p, \tag{3}$$

$$\left(\frac{V^2}{gL}\right)_m = \left(\frac{V^2}{gL}\right)_p, \tag{4}$$

notice that m and p indexes represent model and prototype, respectively.

The water at room temperature and the steel at tundish temperature (around 1600ºC) present similar kinematic viscosity (within 10%), as mentioned by Sahai and Emi (1996). Therefore, Reynolds similarity gives

$$V_m \approx \left(\frac{1}{\lambda}\right) V_p, \tag{5}$$

where V_m is the model velocity, V_p is the prototype velocity and λ is the scale factor. Thus, Froude similarity gives

$$V_m = \sqrt{\lambda} * V_p, \tag{6}$$

Eq. (5) and (6) cannot be followed simultaneously unless $\lambda = 1$, what means a full-scale model. Due to the large size of the equipment involved in the process, scale models are generally used, and as discussed by Zhu et al. (2022) and Sahai and Emi (1996), the Froude similarity is likely to represent the main tundish flow phenomena accurately. Reynolds similarity is relevant when both laminar and turbulent flow are present, which is typically not the case in steelmaking.

The Froude number represents the ratio of the flow inertia to the external field (gravity), while the Reynold number is the ratio of inertial forces to viscous forces.

2.2 Experimental setup and methodology

The structure used for the experiment is composed of two water reservoirs, a heater, two pumps, a tundish, pipes and pipe connections. Reservoir 1 is filled with water, while reservoir 2 is filled with water mixed with potassium chloride with a concentration of 66.7 g/m³. Figure 1 presents a schematic of the assembly used and Figure 2 shows a picture of the experimental setup.

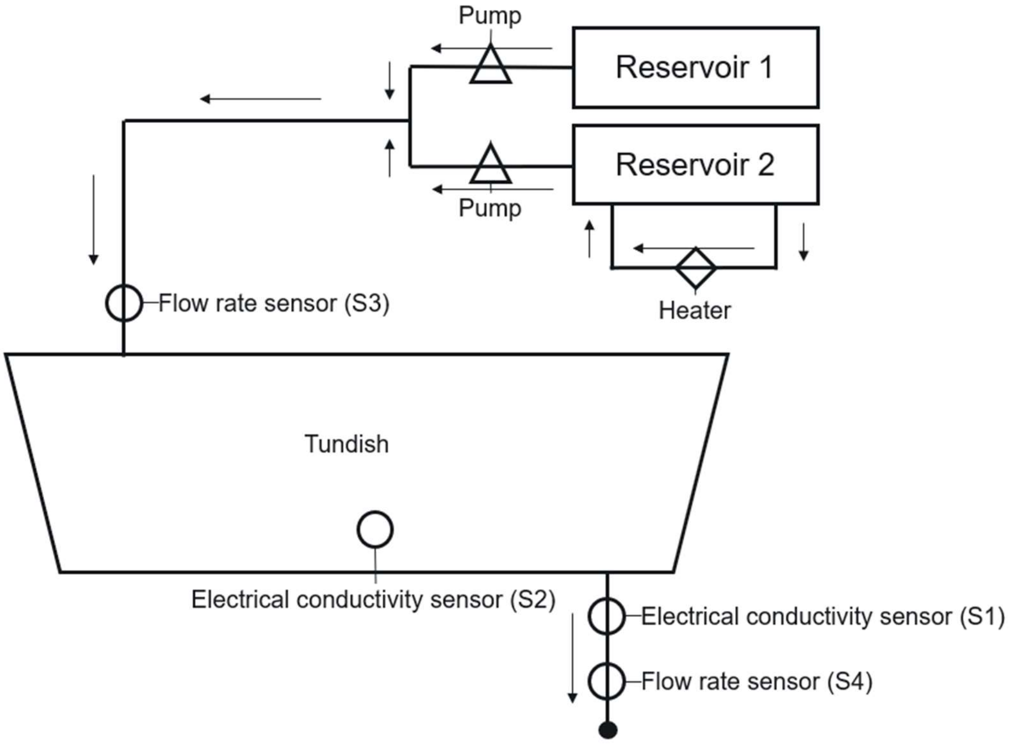

Figure 1. Schematic diagram of the experimental setup.

Figure 2. Picture of the experimental setup.

The experiment starts with a stationary tundish level of 322 mm and remains in that condition for three mean residence times (~900 s). The water is pumped from reservoir 1. The inlet of water is stopped and the bath level decreases for 52 seconds, representing the moment when the ladle is being exchanged. Afterwards begins the entry of the saline solution (water and potassium chloride) from reservoir 2, with a volume flow rate of 64 L/min for 52 seconds. After this time, the bath reaches back its working level (322 mm) and the inlet flow rate is reduced to 32 L/min. The bath level is held stable for three residence times (~900 s), while sensors data are acquired.

Four sensors are used:

- Electrical conductivity sensor at the tundish outlet (S1).
- Electrical conductivity sensor inside the tundish (S2).
- Volumetric flow sensor at the inlet (S3).
- Volumetric flow sensor at the outlet (S4).

Sensors S1 and S2 measure the electrical conductivity of the mixture, which is affected by the potassium chloride concentration. Thus, this data can be related to the concentration of water from reservoir 2 that is found in the positions where sensors S1 and S2 are located.

The above-described methodology was performed for two conditions:

- Condition 1 (isothermal):
    - Water temperature at reservoir 1: 16 ºC
    - Water temperature at reservoir 2: 16 ºC
- Condition 2 (non-isothermal):
    - Water temperature at reservoir 1: 16 ºC
    - Water temperature at reservoir 2: 31 ºC

2.3 Test conditions

Table 1 presents the test conditions used in the experiments.

Table 1. Experimental test conditions.

Properties	Model	Prototype
Fluid	Water	Molten steel
Stationary inlet flow rate, L/min	32	500
Filling up flow rate, L/min	64	1000
Draining down duration, s	52	90
Filling up duration, s	52	90

3. MATHEMATICAL MODEL

Computational fluid dynamics (CFD) is a powerful tool to investigate the tundish flow. Due to the elevated temperatures of the process, together with other critical conditions, direct measurement of flow is challenging. Even with simplifications, it is possible to provide useful information and to assist in optimizations.

A mathematical model was developed aiming to represent the main phenomena seen in the water model. The Ansys Fluent multiphase model Volume of Fluid (VoF) is used in a 3-D domain composed by two phases: water and air. The model domain is shown in Figure 3.

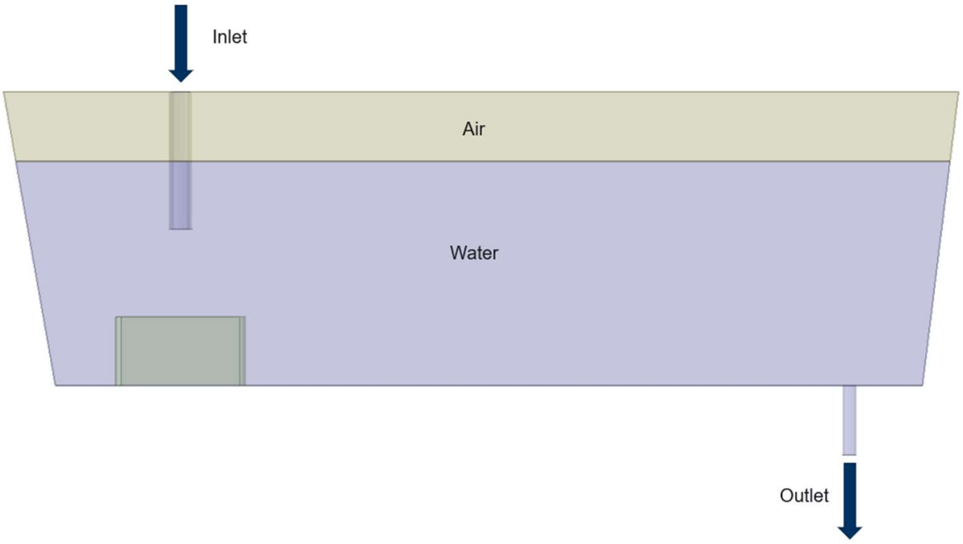

Figure 3. Domain of the mathematical model.

The mathematical model solves the continuity, momentum, and scalar quantity equations (Eq. 7, 8 and 9). The effect of turbulence is modelled through an eddy viscosity approach, Shear Stress Transport (SST) k-ω.

Continuity equation:

$$\frac{\partial}{\partial t}(\rho) + \frac{\partial}{\partial x_j}\left(\rho U_j\right) = 0, \tag{7}$$

Momentum equation:

$$\frac{\partial}{\partial t}(\rho U_i) + \frac{\partial}{\partial x_j}\left(\rho U_i U_j\right) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu_{eff}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)\right], \tag{8}$$

Scalar equation:

$$\frac{\partial}{\partial t}(\rho\emptyset) + \nabla.(\rho\emptyset\vec{u}) = -p\nabla\vec{u} + \nabla.[(\Gamma)(\nabla\emptyset)] + S_{\emptyset}, \tag{9}$$

where t is the time, x_j is the coordinate in the j-direction, U_j is the velocity in the j-direction, P is the pressure field, μ_{eff} is the effective viscosity, $\emptyset$ is the scalar quantity that is conserved (such as the temperature or concentration), $\vec{u}$ is the fluid velocity and Γ is the diffusion coefficient.

4. NUMERICAL IMPLEMENTATION

The above-mentioned equations are solved in the 3-D domain discretized by mesh, created during the pre-processing. The mesh is composed of approximately 800,000 polyhedral cells and 3,150,000 nodes and is represented in Figure 4.

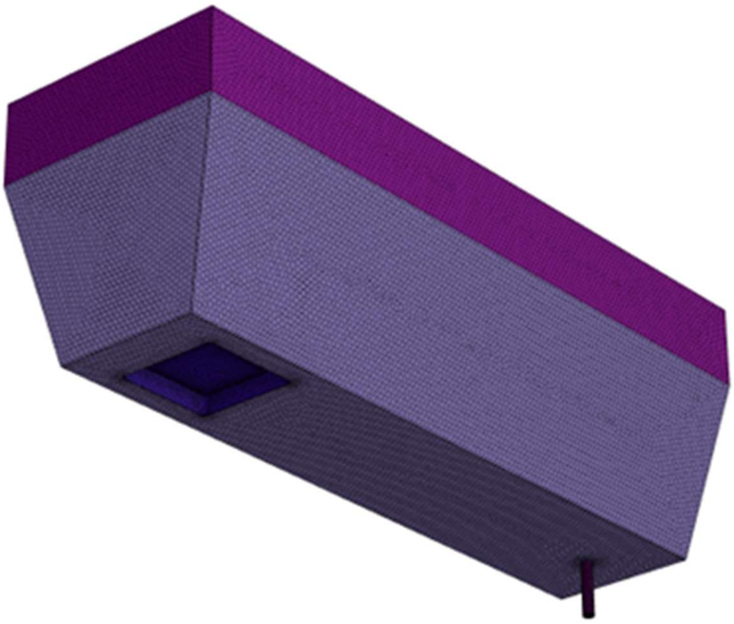

Figure 4. Mesh.

The numerical simulation is composed by 5 steps, as shown in Figure 5. It starts with a steady state solver, which result is used as initialization for the transient steps. Then, the steady bath height is simulated with the same flow rate at the inlet and outlet. Following, the drain down and fill up steps take place, representing the moment in which the ladle is being exchanged. And last a second steady bath height is simulated.

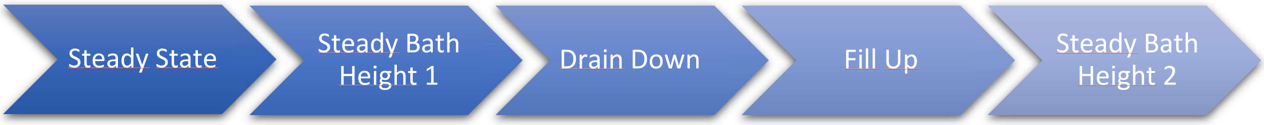

Figure 5. Numerical simulation workflow.

The inlet flow rate is defined as a boundary condition during all the steps. Its value follows the same approach as the water model, as seen in Table 1. The duration of steps 3 and 4 also follows the laboratory experiments. During all the steps, the outlet boundary condition is a gauge pressure, defined as 0 Pa. Therefore, the outlet flow rate is calculated by the model. The Ansys Fluent default convergence criteria of 1e-3 was used, and the pressure-velocity coupling method PISO was selected.

5. RESULTS

During the simulated metallurgical process, the tundish inlet temperature may vary according to the plant operation parameters. Two different thermal conditions were studied through the water model: isothermal and non-isothermal. The main difference between the analyzed configurations is the buoyancy effect.

Dye injection was used in order to visualize the flow pattern inside the tundish, as can be seen in Figure 6 for different times. The time count starts at the beginning of the fill up (step 4).

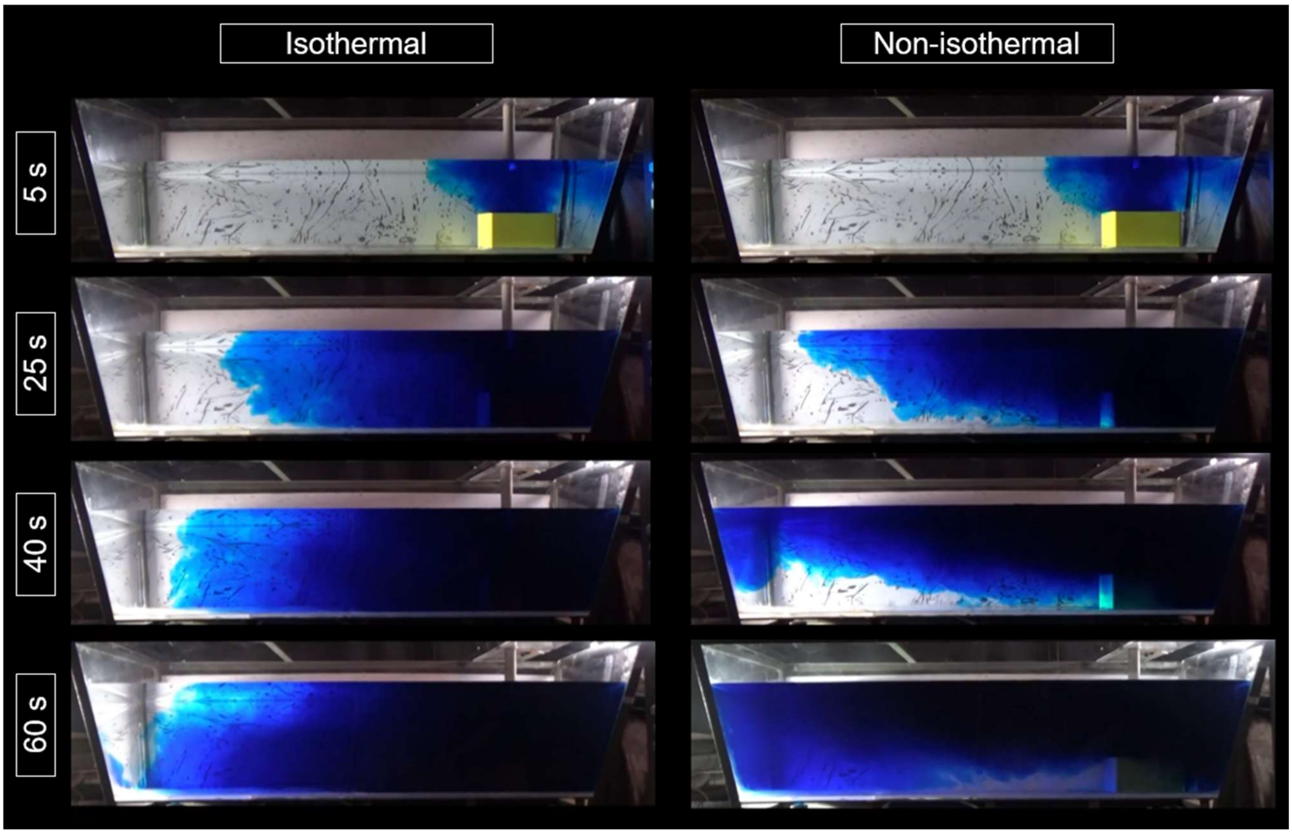

Figure 6. Water model dye injection in four different times and two different thermal conditions.

In a continuous casting, the steel that enters in the tundish right after the ladle change presents a higher temperature. It is represented in the non-isothermal configuration by injecting hot water from reservoir 2. The hot water is characterized by lower densities, and therefore tends to occupy the upper region of the vessel due to the buoyancy force. This effect is seen in Figure 6 and shows to be of great importance when analyzing the flow inside the tundish. Due to the flow pattern, a dead region is formed at the tundish bottom for the non-isothermal configuration. On the other hand, for the isothermal case, the dead region is located at the upper region, furthest from the inlet. Figure 7 highlights the dead zones.

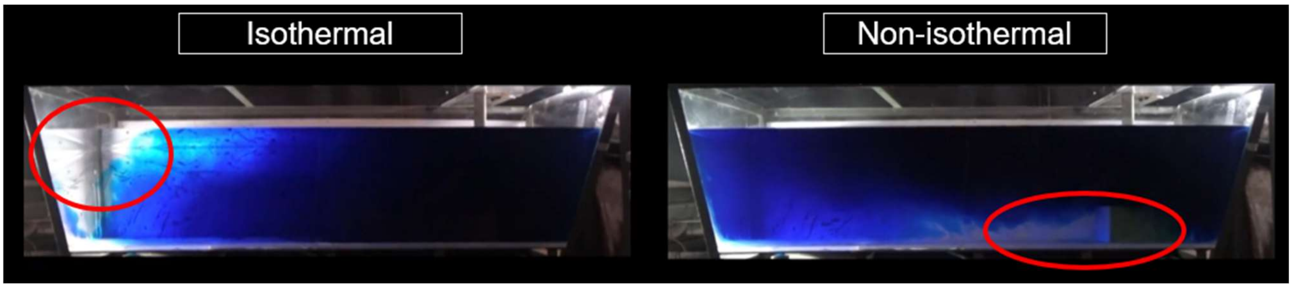

Figure 7. Dead zones.

Ladle changes can be accompanied by a change in the steel chemical composition. When it happens, different steel grades are mixed inside this vessel and an ingot downgrade might happen. This phenomenon is called intermix. In order to evaluate that, the new grade concentration data acquired at the outlet is analyzed and presented in Figure 8.

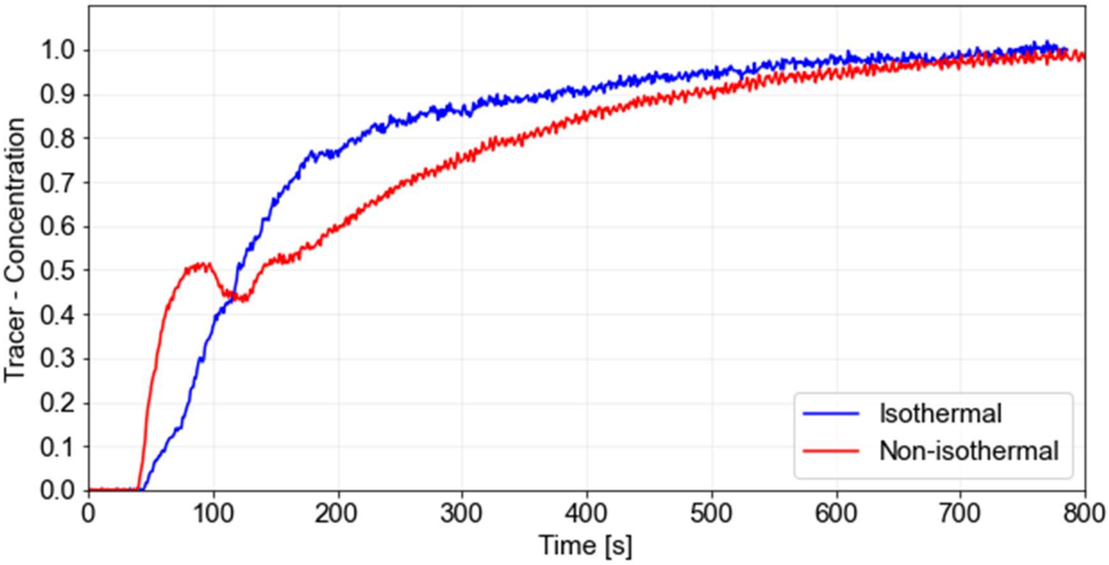

Figure 8. New steel grade concentration at the outlet – isothermal and non-isothermal conditions.

The curve begins at the start of the liquid flow from reservoir 2 (step 4). At the beginning, a higher amount of new steel grade reaches the outlet in the non-isothermal configuration. After approximately 100 seconds, its concentration decreases for a while and remains below until the end of the process, when compared with the isothermal configuration. The thermal effect is clearly affecting the system and might not be neglected.

The grade change duration can be used to estimate and minimize the amount of steel that would be downgraded due to the intermix. If the selected threshold for the volumetric fraction of each steel grade is 90%, for example, the mixture in which the new steel grade concentration is between 10% and 90% will represent a downgraded steel. Table 2 shows that comparison. The 10%-90% intermix time is also affected by the buoyancy effect. The temperature difference contributes increasing the intermix duration.

Table 2. Time between 10% and 90% concentration of new steel grade at the outlet.

New steel grade	**Isothermal**	**Non-isothermal**
10% - 90%, s	313	442

Results from water model are used to compare the thermal effects and also to validate the mathematical model. Once the steel grade concentration at the outlet is one of the most important parameters when analyzing intermix, it is defined as a parameter to be compared between experimental and numerical analyses. Figure 9 shows a steel grade comparison between numerical and water models, evaluated at the outlet, 100 seconds after the ladle opening. The isothermal condition is used for the comparison. Both curves present a similar behavior of the new steel grade concentration at the outlet, showing a good agreement between experimental and numerical models. In the next steps, the experimental uncertainties will be evaluated to improve model validation.

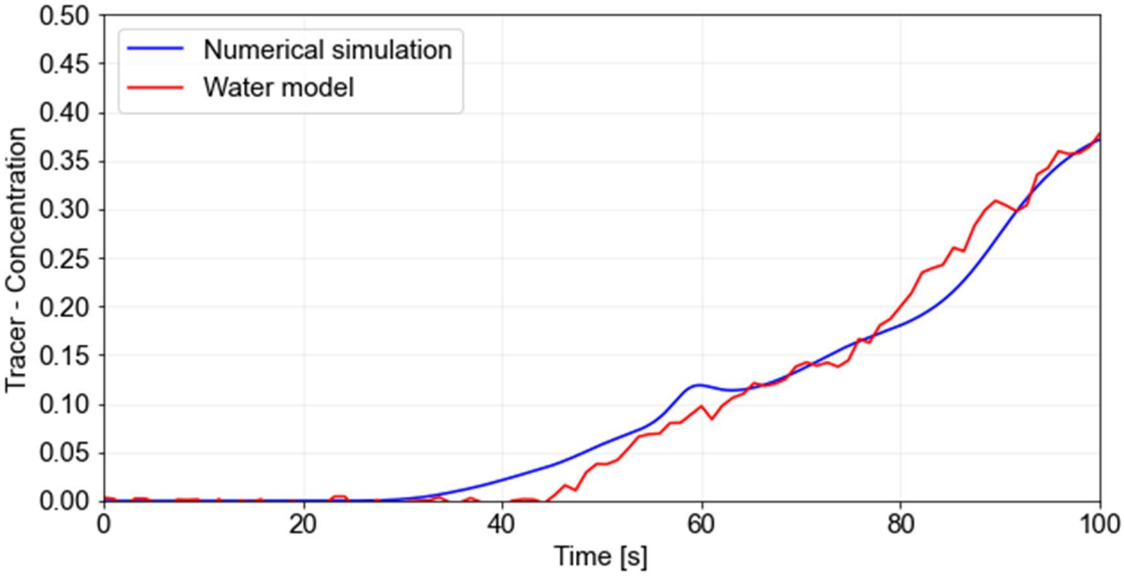

Figure 9. New steel grade concentration at the outlet – experimental and numerical models.

6. CONCLUSIONS

In the present work, water model and numerical simulations are performed in a single-strand slab caster tundish. The ladle change transient process is the focus. Some important conclusions can be delivered:

- The buoyancy effect has an important role in the tundish flow. The hotter fluid is characterized by a lower density and therefore presents an upward movement, causing as consequence a tundish bottom filling mainly with cold steel. When there is no temperature difference (isothermal), the dead zone is formed at the external top region. The steel flow pattern is considerably different and affected by thermal conditions.
- The non-isothermal configuration presents a greater 10% - 90% intermix, which is not desirable. It is related to a bigger amount of downgrade steel due to intermix.
- The mathematical model developed can be used to evaluate different parameters of tundish operation, such as impact pot geometry and superheat temperature.

7. ACKNOWLEDGEMENTS

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