Technical Note

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Mathematical Simulation for the Effects of Flow Control Devices in a Six – strand Tundish in Continuous Casting of Steel Billet

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Abstract

The method of continuous casting of steel is now often used in the metallurgical industry, due to the increasing demand for the production of high – quality steel. An important device of continuous casting machine is the tundish, in which a stabilized steel flow has a crucial effect on the quality and efficiency conditions of the continuous casting process. In this study fluid flows in a six – strand tundish for billet continuous casting were performed with mathematical simulation methods. The molten steel flow and velocity fields in the tundish with a turbulence inhibitor, without it and with turbulence inhibitor plus weir in different distance from center were numerically calculated. Simulation results showed that the tundish with turbulence inhibitor and weir in 300 mm distance from center has a significant effect on the flow fields of the tundish. Also the results showed inclusion removal increases by producing a uniform flow field with re-circulatory zone away from the nozzles. It can be seen that circulation region is produced in the all tundish models. However, in case of using tundish without turbo stop, it increased in comparison to others.

Keywords: Fluid flows; Tundish; Turbulence inhibitor; Weir; Mathematical simulation.

1. Introduction

The method of continuous casting of steel is now often used in the metallurgical industry, due to the increasing demand for the production of high – quality steel. There is therefore a need for continuous improvement of this method by proposing anew technical solution in different elements of the continuous casting machine. The obtainment of quality steel from a continuous casting machine is dependent on a large number of interlinked process parameters of the main ladle; tundish and continuous steel casting (CSC) mould [1)]. Molten steel at an appropriate temperature is poured from the main ladle to the tundish at a preset rate, then flows over this vessel and fills it up to a specified height. Next, the steel flows out through the openings in the tundish bottom to the CSC mould [1)]. An important device of continuous casting machine is the tundish, in which a stabilized steel flow has a crucial effect on the quality and efficiency of the continuous casting process. A large number of studies have been reported in the literature dealing with the physical and mathematical modeling of fluid flow conditions together with the inclusion motion behavior inside a tundish for

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different tundish geometries and flow conditions. Kumar et al. simulated fluid flow and residence time distribution in a four – strand tundish for enhancing inclusion removal. They concluded that the use of dam eliminated the short – circuiting phenomenon in the tundish [2]. Zhang et al. studied three-dimensional fluid flow in a single-strand tundish using three models, viz., and floatation to the free surface, collision and coalescence of inclusion and adhesion to the lining of solid surface. With the help of water models, it was concluded that collision of inclusion and adhesion to lining were also the major source of inclusion removal and employing flow modifiers favors the inclusion removal [3]. Morales et al. used water modeling and mathematical simulation techniques to study the effect of turbulence inhibitors in a multi-strand bloom caster tundish and concluded that turbulence inhibitors together with a pair of dams provided better performance as compared to the complex furniture employed in a tundish [4]. Kim constructed a full scale model of a delta shape four-strand tundish and observed that about 99% of inclusions above 150 μm size were separated by the flow modifiers [5]. Tripathi and Ajmani modeled a curved shaped six-strand tundish using RTD (residence time distribution) plots. They confirmed that a curve shaped tundish provided better flow characteristics comparing to a delta shaped tundish [6]. Lei and He developed a three dimensional mathematical model to predict the dynamic growth of alumina inclusions in a continuous caster. They found that large inclusions have good chance to trap other inclusions [7]. Zhang used the k-ε model of turbulence together by the use of both the stochastic and non-stochastic models to simulate fluid flow in a single strand tundish [8]. He concluded that the non-stochastic model was not accurate for predicting the inclusion motion and concluded that analyzing the residence time of the particle in molten steel was not so meaningful for studying the behavior of inclusions inside the tundish. Gang et al. showed with their RTD curves, inclusion separation, and streamline experiment, that the tundish having weirs and turbulence inhibitor, produces a large effect on the flow field and the inclusion separation [9]. Zhang et al. studied the removal efficiency of inclusion in a tundish using gas bubbles. Their result showed that for large particle, bubbling the removal did not change much but it had a strong impact on smaller particles [10]. The purpose of the present study is to determine the influence of flow control devices of tundish. The commercial CFD software "FLUENT" was used for the mathematical simulation. The flow characteristic of the molten steel was determined by the flow control devices. Moreover, the velocity fields were discussed in the numerical modeling.

2. Experimental

2. 1. Mathematical modeling

The tundish considered in the present study is shown in Fig. 1. Half of the tundish is shown because of the symmetry relative to the transverse plane passing through the inlet. The detailed constructional parameters are represented in Fig. 1. The inlet and outlet diameters of the gate are taken as 60 mm and 18.5 mm, respectively. Five types of tundish are considered in this study: 1- without turbo stopper, 2- with turbo stopper, 3- with turbo stopper and a weir with 100 mm distance from center, 4- with turbo stopper and a weir with 200 mm distance from center and, 5- turbo stopper and a weir with 300 mm distance from center. The values of the properties of liquid steel are shown in Table 1.

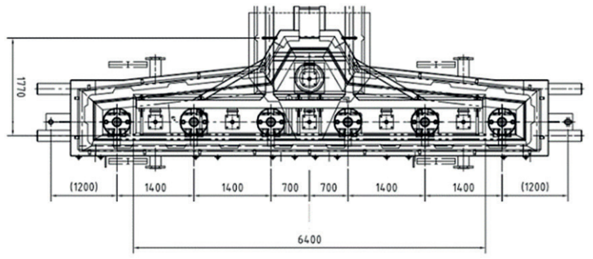


Fig. 1. Geometry of six-strand tundish considered in the present study.

Table 1. The values of the properties of liquid steel.

Specific density	7200 kg/m^3
Specific heat	821 j/kg.k
Thermal conductivity	30.5 w/m.k
Viscosity	0.007 kg/m.s

2. 2. Model formulation

The commercial CFD package "FLUENT" was used to predict the flow field prevalent in the tundish in a steady state. The following assumptions were made:

a) Cartesian coordinate system in two dimensions has been used to represent the tundish geometry.

b) Flow has been assumed to be dynamically steady and two – dimensional.

c) Flow is turbulent throughout the tundish.

The associated governing equations (continuity, momentum and turbulence equations) can be written in Cartesian coordinate system (x, y, and z) under a steady state condition.

2. 3. Equation of continuity

$$\frac{\partial}{\partial x}(pu)+\frac{\partial}{\partial y}(pv)+\frac{\partial}{\partial z}(pw)=0 \quad \text{Eq. (1)}$$

2. 4. Equations of Momentum

- X- Momentum

$$\frac{\partial}{\partial x}(puu)+\frac{\partial}{\partial y}(puv)+\frac{\partial}{\partial z}(puw)=-\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\left(\mu_{eff}\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_{eff}\frac{\partial u}{\partial y}\right)+\frac{\partial}{\partial z}\left(\mu_{eff}\frac{\partial u}{\partial z}\right)+\frac{\partial}{\partial x}\left(\mu_T\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_T\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial z}\left(\mu_T\frac{\partial w}{\partial x}\right) \quad \text{Eq. (2)}$$

- Y- Momentum

$$\frac{\partial}{\partial x}(puv)+\frac{\partial}{\partial y}(pvv)+\frac{\partial}{\partial z}(pvw)=-\frac{\partial p}{\partial y}+\frac{\partial}{\partial x}\left(\mu_{eff}\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_{eff}\frac{\partial v}{\partial y}\right)+\frac{\partial}{\partial z}\left(\mu_{eff}\frac{\partial v}{\partial z}\right)+\frac{\partial}{\partial x}\left(\mu_T\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_T\frac{\partial v}{\partial y}\right)+\frac{\partial}{\partial z}\left(\mu_T\frac{\partial w}{\partial y}\right) \quad \text{Eq. (3)}$$

- Z-Momentum

$$\frac{\partial}{\partial x}(puw)+\frac{\partial}{\partial y}(pvw)+\frac{\partial}{\partial z}(pww)=-\frac{\partial p}{\partial z}+\frac{\partial}{\partial x}\left(\mu_{eff}\frac{\partial w}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_{eff}\frac{\partial w}{\partial y}\right)+\frac{\partial}{\partial z}\left(\mu_{eff}\frac{\partial w}{\partial z}\right)+\frac{\partial}{\partial x}\left(\mu_T\frac{\partial u}{\partial z}\right)+\frac{\partial}{\partial y}\left(\mu_T\frac{\partial v}{\partial z}\right)+\frac{\partial}{\partial z}\left(\mu_T\frac{\partial w}{\partial z}\right) \quad \text{Eq. (4)}$$

Eqs. (2) to (4) are called Reynolds-averaged Navier-Stokes (RANS).

2. 5. Standard coefficient k-ε model.

The standard coefficient k-ε model is a semi empirical model based on a modeled transport equations for the isotropic turbulence kinetic energy ($k = 3/2\left(\bar{U}^2\right)$) and its dissipation rate ($\varepsilon = -dk/dt$). The turbulence kinetic energy and its rate of dissipation are obtained from the following transport equations:

- Conservation equations for the turbulence kinetic energy:

$$\frac{\partial}{\partial x}(puk)+\frac{\partial}{\partial y}(pvk)+\frac{\partial}{\partial z}(pwk)=\frac{\partial}{\partial x}\left(\frac{\mu_{eff}}{\sigma_k}+\frac{\partial k}{\partial x}\right)+$$
$$\frac{\partial}{\partial y}\left(\frac{\mu_{eff}}{\sigma_k}+\frac{\partial k}{\partial y}\right)+\frac{\partial}{\partial z}\left(\frac{\mu_{eff}}{\sigma_k}+\frac{\partial k}{\partial z}\right)+G_K-\rho \quad \text{Eq. (5)}$$

- Conservation equations for the dissipation rate of turbulence kinetic energy:

$$\frac{\partial}{\partial x}(pu\varepsilon)+\frac{\partial}{\partial y}(pv\varepsilon)+\frac{\partial}{\partial z}(pw\varepsilon)=\frac{\partial}{\partial x}\left(\frac{\mu_{eff}}{\sigma_\varepsilon}+\frac{\partial \varepsilon}{\partial x}\right)+$$
$$\frac{\partial}{\partial y}\left(\frac{\mu_{eff}}{\sigma_\varepsilon}+\frac{\partial \varepsilon}{\partial y}\right)+\frac{\partial}{\partial z}\left(\frac{\mu_{eff}}{\sigma_\varepsilon}+\frac{\partial \varepsilon}{\partial z}\right)+\frac{1}{k}\left(C_1\varepsilon G_K-C_2\rho\varepsilon^2\right) \quad \text{Eq. (6)}$$

In these equations, Gk represents the generation of turbulence kinetic energy due to the mean velocity gradients and can be expressed as:

The turbulent viscosity, μ_T is computed by combining k and ε as follows:

C_1, C_2, C_μ, σ_k and σ_ε are the five empirical constants of the k-ε model. The standard values of these constants are 1.43, 1.92, 0.09, 1 and 1.3 respectively.

2. 6. Boundary conditions

The flow was assumed steady and incompressible with no entrainments of air and gas by the incoming metal stream. The surface of the tundish was considered flat. The velocity at the inlet gate was taken 1.2 m/s with the turbulence intensity of 5%. The wall functions were employed to obtain the values of k and ε, wall shear stress, and all the velocity components parallel to the boundary at the first computational grid point adjacent to the wall. The top surface of the liquid steel was assumed free with the zero shear stress. Also, the velocity inlet and pressure outlet boundary conditions were assumed for inlet gate and all outlet strands respectively. A simple algorithm was used for the pressure – velocity coupling and quick scheme was used for the discretization of momentum, energy, turbulent kinetic energy and turbulent dissipation rate equations.

3. Results

Tundish without turbo stopper is shown in Fig. 2. As can be seen the turbulence intensity of molten steel in the center of tundish and in the tundish impact area where the steel pours is very high. Turbulence of steel is very high under this condition and on contrary, it was an ideal condition for continuous casting. It means that the laminar flow of molten steel is better than the turbulence flow from point of casting. On the other hand, the chance of inclusions entrance from tundish to the mold goes up when the molten steel flow is turbulent. These factors make the use of a tundish without flow control devices in not appropriate. A tundish with turbo stop is shown in Fig. 3. As can be seen the turbulence intensity of molten steel is better especially in the center of tundish where metal pours. Consequently, the flow condition of molten steel is better compared to the former case that had much more turbulence. Generally using turbo stop more

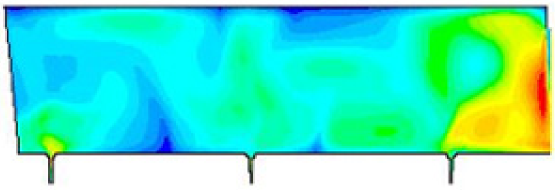


Fig. 2. Field of liquid steel flow in the tundish without any control device.

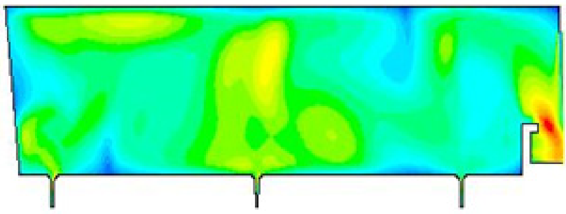


Fig. 3. Field of liquid steel flow in the tundish with turbo stop.

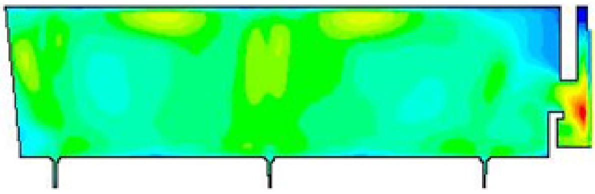


Fig. 4. Field of liquid steel flow in the tundish with turbo stop and a weir with 100 mm distance from center of tundish.

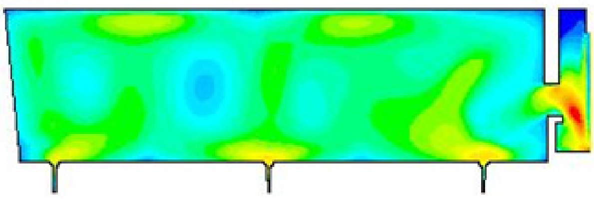


Fig. 5. Field of liquid steel flow in the tundish with turbo stop and a weir with 200 mm distance from center of tundish.

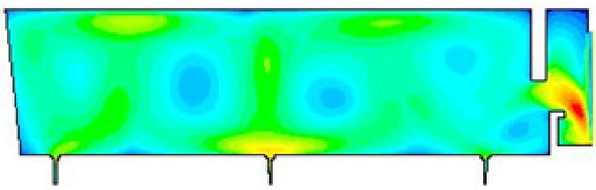
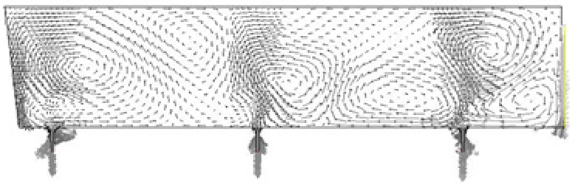
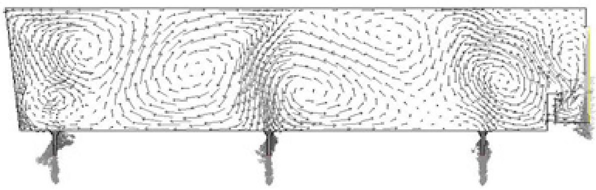


Fig. 6. Field of liquid steel flow in the tundish with turbo stop and a weir with 300 mm distance from center of tundish.

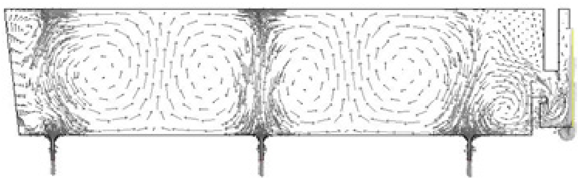
than the flow control makes a resistant area in where the molten metal pours. Figs. 4, 5 and 6 show tundish with turbo stop and weir in 3 cases of 100 mm, 200 mm and 300 mm distance from center. As can be seen, the minimum turbulence intensity is shown in Fig. 6. In real by increasing the distance of weir from 100 mm to 300 mm the turbulence intensity has been decreased and this is because of the growth of weir operation area. As can be



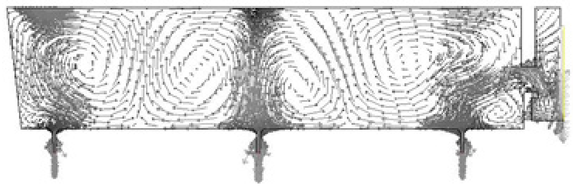
(a)



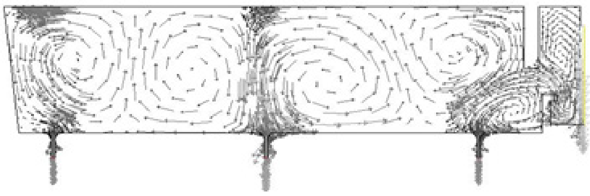
(b)



(c)



(d)



(e)

Fig. 7. Velocity vectors distribution of steel flow in the tundish: a) without control device. b) With turbo stop. c) With turbo stop and a weir with 100 mm distance from center. d) With turbo stop and a weir with 200 mm distance from center. e) With turbo stop and a weir with 300 mm distance from center.

seen in Fig. 4 the limit of weir is placed inside of the turbo stop area and in an improper position. In real if the function of weir is to control the molten steel stream so, the position of the weir should not be inside of the turbo stop area. Rather by changing the position of the weir to outside, the turbulence intensity decreases. This result is confirmed in Fig. 6.

The velocity fields are shown in Fig. 7 for five kinds of tundish. As can be seen in Fig. 7a the stream of the molten metal after coming into contact with the tundish bottom, move the tundish nozzles toward. A uniform flow field is shown in Fig. 7d. Inclusion removal increases by producing a uniform flow field with re-circulatory zone away from the nozzles 11). It can be seen produced in all tundish models. However, in case of using the tundish without turbo stop, the circulation region increased more than others did.

4. Conclusion

A mathematical modeling was used for the effects of flow control devices in a six – strand tundish in continuous casting of billet. The Following conclusions may be drawn from this study:

- The tundish without turbo stop was not appropriate for casting because the stream of molten metal was very turbulent especially close to the center.
- The tundish with turbo stop was better than without turbo stop. The turbulence stream obtained less than former.
- The use of weir had more efficiency on the turbulence stream in the tundish and by increasing the distance of weir from 100 mm to 300 mm from center, the turbulence intensity decreased in which it was due to the growth of weir operation area.

A circulation region produced in all tundish models. However, in case of using tundish without turbo stop, it increased in comparison to others.

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