Study of Fluid Flow, Heat Transfer and Surface Wave Vibration Behaviour for Steel in Continuous Casting Process Using Mathematical Modelling and Physical Modelling

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Abstract: - In this paper, fluid flow, heat transfer and surface wave fluctuation behavior of steel in mold region during continuous casting process is studied via physical and numerical modelling techniques. The melt free surface fluctuation studied quantitively using a digital wave measurement device installed on the water-based physical model. On this basis, a three-dimensional mathematical model combining fluid flow, heat transfer and solidification is established in OpenFOAM to study the influence of various strand diameters, casting speed and nozzle shapes on the casting process of the steel. Based on above research, the optimal combination of casting condition is determined for reduced free surface vibration and uniform flow and heat transfer in mold region, which is beneficial for reducing slag entrainment and improving the quality of strand solidification structure.

Key-Words: - Steel, Continuous Casting, Water Model, Computational Fluid Dynamics (CFD), Heat Transfer, Solidification

1 Introduction

During the continuous casting process of steel in industry, the molten steel with certain superheat would be poured into tundish from ladle[1–5]. Then, the molten steel would flow into mold region from submerged entry nozzle (SEN). As is indicated by many researchers[6–13], the flow pattern and heat transfer phenomenon in mold is important for controlling the initial solidification of casting strand as well as reducing the entrapment of non-metallic inclusions, which are all key quality issues in steel industry. Research on this aspect has arouse broad attention since the development of steel continuous casting. Industrial experts, engineers, as well as researchers from casting and solidification has utilized various kinds of method to study the flow and solidification of molten steel in mold ranging from industrial trials, physical-based modelling and numerical modelling of the process, regardless of the steel grades or mold shape/dimensions. In this work, based on actual working condition of continuous casting mold for round billet from a special steel plant from China. The molten steel transport behaviour in mold region is studied based on physical modelling and numerical modelling, respectively. First, the molten steel flow behaviour is simulated and visualized by water model experiment and the free surface fluctuations under various SEN depths below molten steel free surface, casting speed and billet diameters are measured and analysed accordingly with wave measurement device. Then, a three-dimensional CFD model is established in the open source software OpenFOAM to study the fluid flow, heat transfer and solidification of molten steel under different casting condition. The overall research gives a detailed view of the transport phenomenon of steel during continuous casting process.

2 Physical Modelling

According to actual production process and real dimension of the casting mold, a water simulation model (scale ratio 1:1) is established, as indicated in **Figure 1**. Main parts consist of tundish, mold and circulation water channel, flowrate control device is used to control water flowrate to simulate the effect of casting speed in actual production. Moreover, a wave measurement device is inserted below free surface of molten steel, a data acquisition device tracks the free surface wave data and transmits them into PC for further analysis. The water model experiment is based on similarity theory, the water flowrate in the model system is adjusted properly by satisfying the requirements of Froude number and Reynolds number.

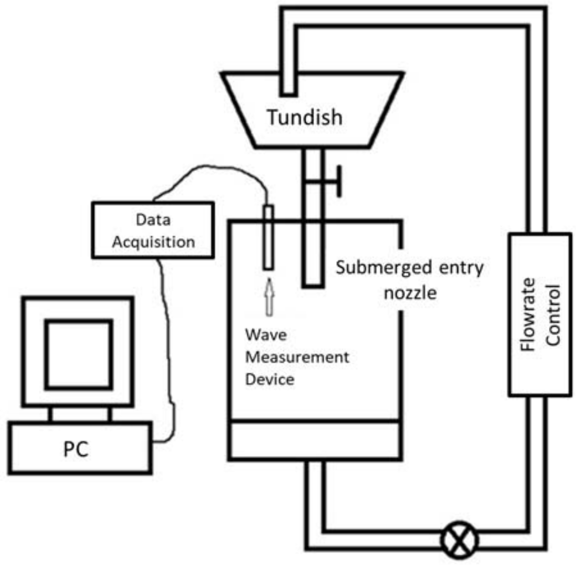


Figure 1 Setup of water model

3 Numerical Modelling

A three-dimensional model is established with CAD software, considering the flow symmetry and to save computational time, only ¼ of the entire mold is modelled. Then, meshing is performed in OpenFOAM using blockMesh and snappyHexMesh utilities, as is shown in **Figure 2**. To further study the influence of SEN shape on molten steel flow pattern, two types of SEN are used, which can be seen in **Figure 3**. The materials properties and necessary process parameters used in this work are listed in **Table 1**. The equations for mass, momentum and heat transfer is solved numerically with finite difference method.

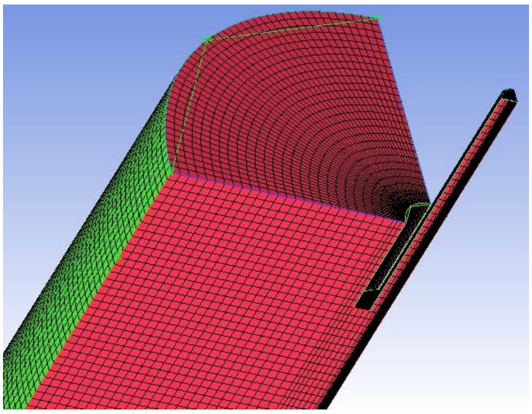


Figure 2 Mesh and geometry for the model (1/4 symmetry)

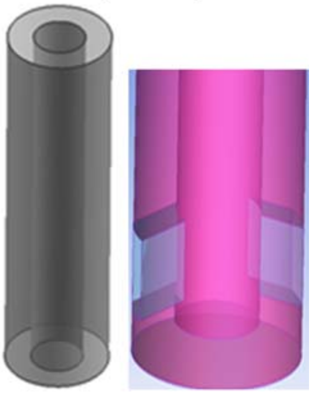


Figure 3 Three types of SEN, left: straight; right: twin ports

Table 1 Parameters used for modelling

Steel Grade	20CrMnTiH
Liquidus, K	1783
Solidus, K	1743
Superheat, K	27
Specific Heat, J/(kg·K)	850
Latent Heat, J/Kg	272000
Mold Water Flowrate, L/min	2000
Water Temperature Difference, K	7
Water Flowrate for 1st segment, L/min	68.1
Water Flowrate for 2nd segment, L/min	110.9

Continuous Equation

$$\nabla \cdot \vec{v} = 0 \qquad (1)$$

Momentum Equation

$$\frac{\partial(\rho\vec{v})}{\partial t} + \nabla \cdot (\rho\vec{v} \cdot v_i) = \nabla \cdot (\mu\, \nabla\vec{v}) - \nabla p \qquad (2)$$

To describe the turbulence of melt during casting process, $k-\varepsilon$ turbulence model is used.

$$\frac{\partial(\rho k)}{\partial t}+\nabla\cdot(\rho\vec{\boldsymbol{v}}k)=\nabla\cdot\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\nabla k\right]+G_k-\rho\varepsilon \quad (3)$$

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\nabla\cdot(\rho\vec{\boldsymbol{v}}\varepsilon)=\nabla\cdot\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\nabla\varepsilon\right]+\frac{\varepsilon}{k}\left(C_{1\varepsilon}G_k-C_{2\varepsilon}\frac{\varepsilon^2}{k}\right) \quad (4)$$

Energy Equation:

$$\frac{\partial(\rho c_p T)}{\partial t}+\nabla\cdot(\rho\vec{\boldsymbol{u}}T)=\nabla\cdot(k\,\nabla T)+S_T \quad (5)$$

The solidification source term S_T of the melt is described using enthalpy method as follows:

$$\mathrm{H(T)}=\int_0^T C_P(T)dT+L(1-f_s) \quad (6)$$

In above equations, $\boldsymbol{v}$ is velocity, ρ is time, P is pressure, μ is melt viscosity, k and ε are turbulence parameters, T is temperature, c_p is specific heat, L is latent heat during solidification, H is enthalpy. PISO algorithm is used to solve pressure and velocity.

4 Results and Discussions

4.1 Free surface fluctuation at mold region

The influence of inserting depth of SEN and casting speed on fluid free surface fluctuation is researched by water modelling experiment and the surface wave fluctuation is measured and summarized as **Figure 4**. It could be seen that the surface wave height decreases as nozzle depth increases. In the meantime, increased casting speed would cause severe free surface fluctuation. Hence, it would be necessary to properly control the combination of casting speed and nozzle depth, especially for high casting speed continuous casting process for thin steel strand.

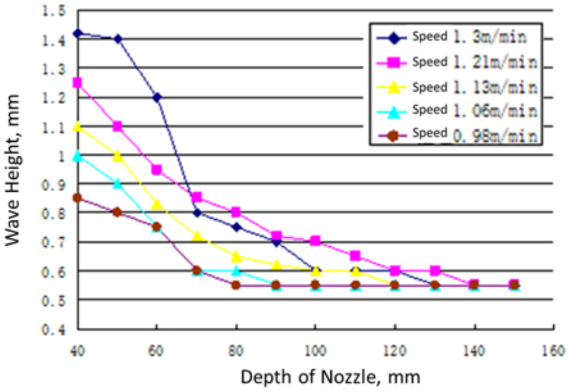


Figure 4 Free surface fluctuation for billet of Φ280mm, straight SEN

4.2 Visualization of flow field in mold

During the water model experiment, some color particles are put into the tundish and flow into mold region with the molten steel, which can be utilized to visualize the flow field. **Figure 5** shows the flow field for water model experiment. It could be seen obviously that for twin ports SEN, the two flow jets would impact on the strand side walls and particles would become dispersed and float to free surface. This is especially useful for the removal of non-metallic inclusions formed prior to continuous casting. **Figure 6** shows the free surface fluctuations for twin ports SEN increases with larger casting speed. In comparison with **Figure 4**, it could be noticed that more severe fluctuation happens at the free surface with twin ports SEN. For inserting depth of 80mm in both cases, the wave height is in the range of 7~10 mm while it is in the range of 0.5~0.9 mm when straight SEN. Hence, to separate the inclusions in mold region, twin ports SEN and proper casting condition could be further utilized for this purpose.

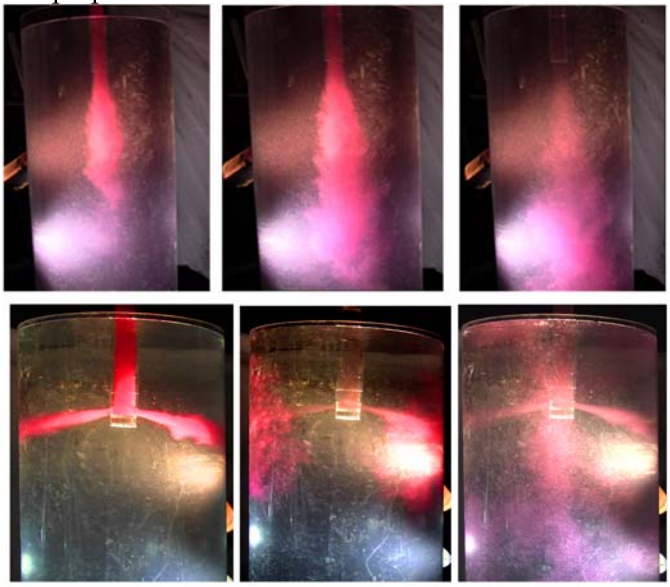


Figure 5 Visualization of flow field in water model, first row: straight SEN; second row: twin ports SEN

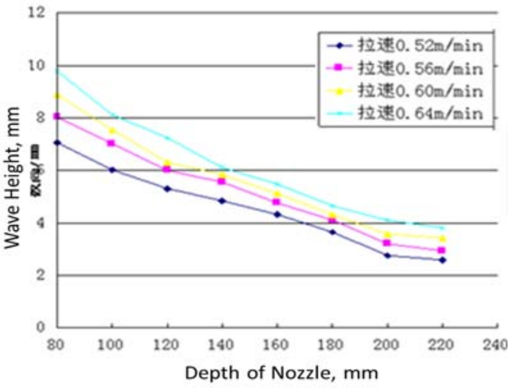


Figure 6 Free surface fluctuation for billet of Φ280mm, twin ports SEN

4.3 Flow field from numerical modelling

The molten steel flow, heat transfer and solidification are modelled numerically. **Figure 7** shows the influence of casting speed on molten steel velocity at centerline of mold region, it could be seen that with the distance from meniscus increasing, a vigorous flow region first appears and then fluid velocity decreases. Increased casting speed tend to trigger more violent flow field in mold region.

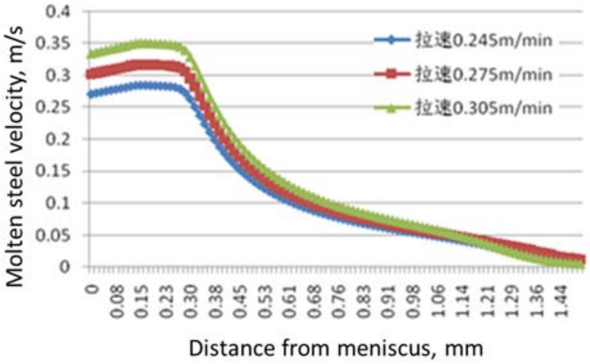
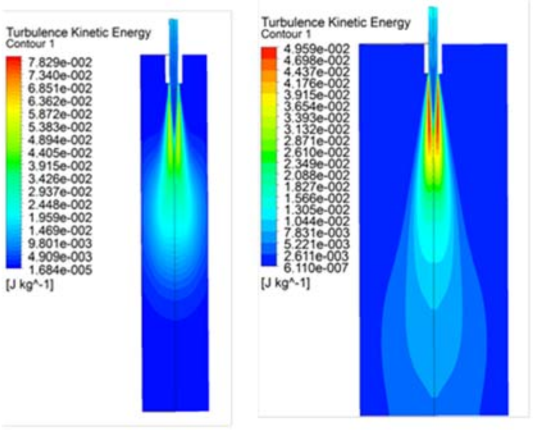


Figure 7 Influence of casting speed on centerline fluid velocity, straight SEN

Figure 8 displays the turbulence kinetic energy evolution with two strand dimensions. Apparently the larger mold would undergo more turbulence in molten steel pouring process, which would cause non-inclusion particles to move more randomly in strand.



a) ϕ280mm b) ϕ600 mm

Figure 8 Influence of strand dimension on turbulence flow in mold, straight SEN

Figure 9 is an enlarged view of backflow region in the upper part of the mold, it could be seen that vortex flow exists in this region, which could bring flow onto free surface causing surface fluctuations and inclusion floatation. Considering the twin ports SEN, it could be known that similar but more complex flow happens in the mold, as indicated by **Figure 10**.

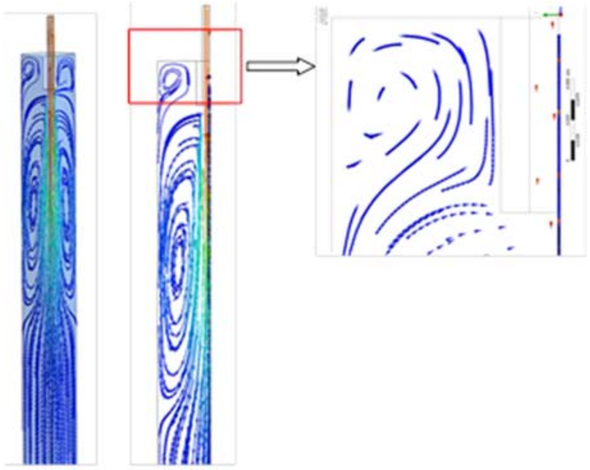


Figure 9 Magnification of backflow region in mold with straight SEN

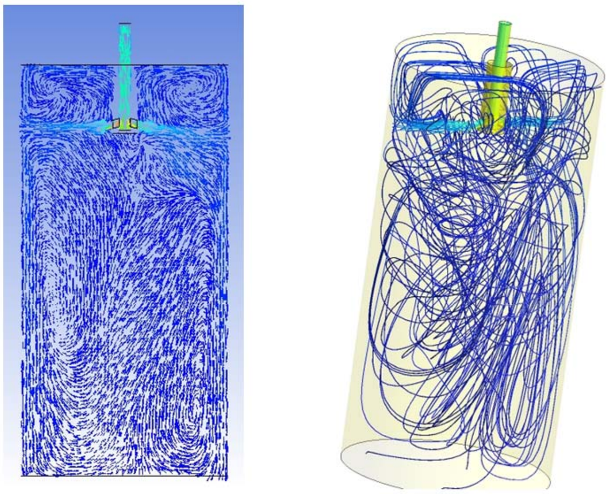


Figure 10 Flow field in mold with twin ports SEN, left: velocity vector, right: flow line

Figure 11 shows the heat transfer and solidification behavior in mold region. It could be noticed that the temperature distribution either inside the mold or on the surface of the strand is non-uniform, which would lead to non-uniform microstructures and a chance of hot cracking. The solidified shell would gradually become thicker along the casting direction. If the casting speed, SEN depth and molten steel superheat is not combined properly, the solidified shell thickness would become too thin to cause strand breakout, which is dangerous for actual production. So, it is essential to formulate the casting process condition properly according to steel type and casting dimension.

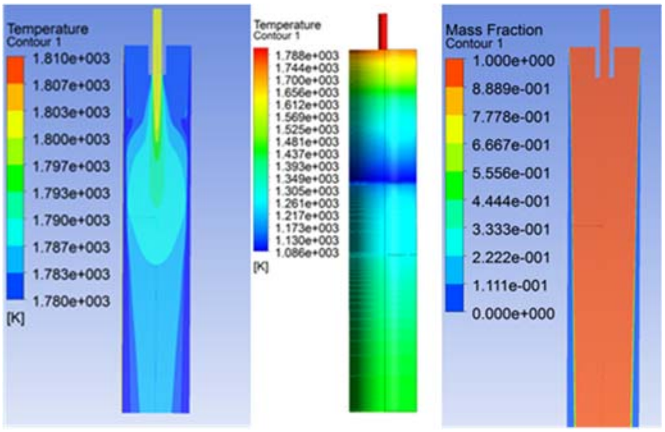


Figure 11 Solidification of molten in mold region, left: cross section temperature; middle: surface temperature; right: liquid fraction

5 Conclusion

In this paper, the fluid flow, heat transfer and surface wave vibration behavior for steel in continuous casting process is studied using mathematical modelling and physical modelling. Various factors are considered such as nozzle shape, casting speed and strand dimension. The transport phenomenon of mass, momentum and heat is studied and analyzed. This work would provide some guidance for steel continuous casting process and directions for non-metallic inclusion removal and steel cleanliness control.

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