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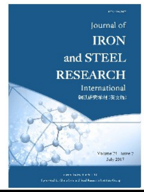

Two-phase sink vortex suction mechanism and penetration dynamic characteristics in ladle teeming process

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ABSTRACT

At the late stage of continuous casting (CC) ladle teeming, sink vortex can suck the liquid slag into tundish, and cause negative influences on the cleanliness of molten steel. To address this issue, a two-phase fluid mechanical modeling method for ladle teeming was proposed. Firstly, a dynamic model for vortex suction process was built, and the profiles of vortex flow field were acquired. Then, based on the level set method (LSM), a two-phase 3D interface coupling model for slag entrapment was built. Finally, in combination with high-order essentially non-oscillatory (ENO) and total variation diminishing (TVD) methods, a LSM-based numerical solution method was proposed to obtain the 3D coupling evolution regularities in vortex suction process. Numerical results show that the vortex with higher kinetic energy can form an expanded sandglass-shape region with larger slag fraction and lower rotating velocity; there is a pressure oscillation phenomenon at the vortex penetration state, which is caused by the energy shock of two-phase vortex penetration coupling.

1. Introduction

Continuous casting (CC), also called strand casting, is the process whereby molten metal is solidified into a semifinished billet, bloom, or slab for subsequent rolling[1,2]. The oxides and impurities in molten steel can form liquid slag that has smaller density and floats on the molten steel[3]. Apparently, slag and molten steel construct a liquid-liquid two-phase flow. When molten steel flows into a tundish, it will create a sink vortex by inertial force, gravity and Coriolis force[4,5]. The vortex can break out the surface of the two-phase flow, and then the slag goes through the vortex center by vortex suction, which is the so-called slag entrapment phenomenon. It not only causes negative influences on the cleanliness of molten steel, but also can make CC production halt in special conditions[6,7].

To solve this problem, many researches have been performed. In the late 1900s, Ye et al. [8,9] carried out water model experiments and concluded that restraining the sink vortex was an effective method to prevent slag entrapment. In 2004, Mazzaferro et al. [10] simulated and analyzed the conditions of vortex formation, and investigated the influence of geometrical and flow parameters on the amount of wasted steel. In 2006, researches[11,12] indicated that the angular velocities were responsible for the formation and development of sink vortex. In 2010, Lin et al. [13] researched the main factors influencing the sink vortex by water-model method and confirmed that the initial flow field conditions could determine the geometrical scale of sink vortex. In 2012, Wang et al. [14] established a ladle teeming physical model and concluded that the increment of the outlet flux would promote the vortex critical altitude. In 2013, Morales et al. [15] performed water modeling and mathematical simulations to reveal the mechanisms of vortex drain and sink drain flows. Tan et al. [16] developed an automatic water-model platform and proposed an improved simulated annealing artificial neural network (SA-ANN) algorithm to recognize the vibration signal of vortex shock process. In 2016, Li et al. [17] found that the Coriolis force had little effect on vortex formation, and the initial tangential disturbance was the main factor.

The physical parameters of ladle flow field contain two-phase fraction, pressure, velocity, trajec-

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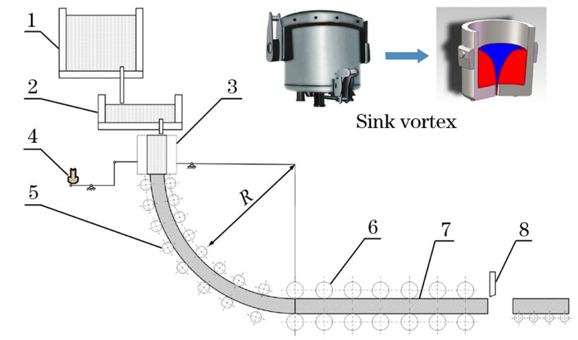
tory and turbulence intensity. It is well known that the flow field characteristics of molten steel in ladle are invisible. Therefore, it is hard to measure these parameters directly, and the profiles of ladle flow field can only be obtained by indirect methods[18,19]. Generally, physical simulation and numerical modeling are used to analyze the flow field. The former one is intuitive and credible, but has a high cost. The latter one is with low cost as well as easy to calculate, and can simulate some special conditions. To guarantee the effectiveness of numerical simulation, it should be revised and optimized according to the characteristics of actual objects[20-22].

Thus, it can be inferred that current studies on sink vortex in ladle teeming mainly focus on the physical simulation, numerical modeling and vortex formation factors. There are no research reports about the two-phase vortex suction mechanism and nonlinear coupling regularities for ladle teeming. Therefore, it is necessary to research the vortex suction phenomenon, and acquire the coupling evolution regularities of two-phase (slag-molten steel) flow. Apparently, the two-phase vortex suction process is a complex fluid mechanical issue with highly nonlinear features, and the modeling-solving requires large computation load. In this paper, the level set method (LSM) was introduced into numerical analysis of ladle teeming, and a two-phase fluid mechanical modeling method was proposed.

2. Study Objective

Taking the arc CC machine as an instance, as shown in Fig. 1, the study objective is the incompressible fluid flow phenomenon in different finite physical spaces, i. e. the steel stream in ladle flows into a tundish through shroud pipe, as shown in Fig. 2.



1—Ladle; 2—Tundish; 3—Mould; 4—Vibration exciter; 5—Cooling apparatus; 6—Roll leveler; 7—Slab; 8—Cutter.

Fig. 1. Production flow of arc CC machine.

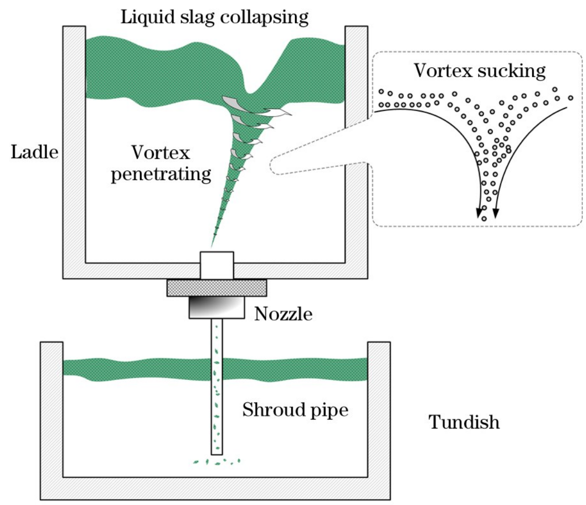


Fig. 2. Schematic of sink vortex suction in ladle teeming.

There are apparent physical property differences between molten steel and slag, and the related parameters are shown in Table 1[23,24]. In order to make the model have similar flow phenomena or dynamic characteristics with the prototype, the hydrodynamic similarity principles should be satisfied, which include geometric similarity, kinematic similarity and dynamic similarity[25-27]. Based on the similarity principles, the initial velocity components and boundary conditions for numerical simulation can be determined.

Table 1
Physical parameters of molten steel and liquid slag

Phase	Density/($kg \cdot m^{-3}$)	Absolute viscosity/($Pa \cdot s$)	Kinematic viscosity/($m^2 \cdot s^{-1}$)	Surface tension/($N \cdot m^{-1}$)
Molten steel	7.10×10^3	2.25×10^{-3}	0.32×10^{-6}	1.25
Liquid slag	$(2.80-3.20)\times10^3$	0.05－0.40	$(1.79-12.50)\times10^{-5}$	0.3－0.6

In the process of ladle teeming, the fluid flow is affected by the inertial force, gravity, viscous force and surface tension. These forces form some similarity criterion numbers for fluid flow, such as Reynolds number, Froude number, Weber number and Strouhal number[28,29]. Since the main factors of vortex formation are inertial force and gravity, the model should keep the same Froude number as the prototype. In this paper, a ladle of the Steelmaking Plant No. 2 of Wuhan Iron and Steel Group was chosen as the research objective, and the geometric parameters are listed in Table 2.

3. Fluid Mechanical Models

3.1. Control equations

Steel stream is a typical incompressible viscous fluid