APPLICATION OF COMPUTATIONAL FLUID DYNAMICS TO STEEL REFINING AND CASTING PROCESSES

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ABSTRACT

The transport of fluid, heat ,and particles (bubbles and solid inclusions) in flowing molten steel is investigated in steel refining ladles, the continuous casting tundish, continuous casting mold and strand, and steel ingot casting processes. The two-equation k-ε model is used to simulate the turbulence. Multiphase fluid flow is numerically simulated with a Lagrangian-Eulerian approach, an Eularian-Eulerian approach and the Volume Of Fluid (VOF) method. The simulation can predict inclusion trajectories, inclusion removal fraction, free surface waves and other phenomena, which can be used to optimize these important metallurgical operations.

KEYWORDS

Computational Fluid Dynamics, Fluid Flow, Heat Transfer, Turbulence Models, Ladle, Tundish, Mold, Continuous Casting, Ingot Casting, Inclusions

INTRODUCTION

Fluid flow during steelmaking, steel refining and steel casting process is very important to steel quality because it affects other important phenomena during these mixing, refining and solidification processes. These phenomena include turbulent flow in the molten steel, the transport of bubbles and inclusions, multi-phase flow phenomena, chemical and transport interactions between the steel and the slag, the effect of heat transfer, the transport of solute elements and segregation. With the high cost of empirical investigation and the increasing power of computer hardware and software, Computational Fluid Dynamics (CFD) is becoming an important tool to understand these fluid flow-related phenomena during steelmaking and casting processes. This paper firstly summarizes the fundamentals of CFD in these metallurgical processes, such as turbulence models, particle motion, multiphase flow, heat transfer related phenomena, and application of the electromagnetic forces. Then, some recent research of the current authors is reported, including the fluid flow, heat transfer, inclusion motion, and free surface phenomena in an argon-bubbling steel ladle, a standing ladle, a continuous casting tundish, a continuous casting mold, and an ingot bottom-teeming process.

MATHEMATICAL FORMULATIONS AND BOUNDARY CONDITIONS

Fluid Flow and Turbulence Models

A typical three dimensional fluid flow model solves the continuity equation and Navier Stokes equations for incompressible Newtonian fluids, which are based on conserving mass (one equation) and momentum (three equations) at every point in a computational domain.[1, 2] The solution of these equations, given elsewhere [3], yields the pressure and velocity components at every point in the domain. At the high flow rates involved in this process, these models must incorporate turbulent fluid flow. Many different turbulence models have been employed by different researchers for fluid flow in the molten steel system, such as one equation turbulence models (turbulent energy k plus a given length-scale) [4], two-equation turbulence models such as the k-ε Model [3, 5], LES (Large Eddy Simulation)[6-10], possibly with a SGS (sub-grid scale) model [11, 12], and DNS (Direction Numerical Simulation).[3] Among these models, direct numerical simulation is the simplest yet most computationally-demanding method. DNS uses a fine enough grid (mesh), to capture all of the turbulent eddies and their motion with time. To achieve more computationally-efficient results, turbulence is usually modeled on a courser grid using a time-averaged approximation, such as the popular k-ε model, [5], which averages out the effect of turbulence using an increased effective viscosity field, μ_{eff}. This approach requires solving two additional partial differential equations for the transport of turbulent kinetic energy and its dissipation rate [3]. The standard high-Reynolds-number k-ε model generally uses assumed "wall functions" to capture the steep gradients at wall boundaries, in order to achieve reasonable accuracy on a course grid. [5, 13, 14] Alternatively, the low-Reynolds-number turbulence model treats the boundary layer in a more general way, but requires a finer mesh at the walls. Large eddy simulation is an intermediate method between direct numerical simulation and k-ε turbulence models, which uses a turbulence model only at the sub-grid scale.[6-10]

Transport of the Second Phase Particles

Two main approaches have been applied to model the behavior of these second phase particles in the molten steel:

the simple convective-diffusion approach and full trajectory calculations. In the convection-diffusion approach [15-18], particle (inclusion or bubble) motion due to turbulent transport and diffusion is modeled by solving a solute transport equation, with the addition of a particle terminal rising velocity to the vertical direction, as shown in Eq.(1).

$$\frac{\partial \sigma_P}{\partial t} + u_{ip}\frac{\partial \sigma_P}{\partial x_i} = \frac{\partial}{\partial x_i}\left(D_{eff}\frac{\partial \sigma_P}{\partial x_i}\right) \qquad (1)$$

where σ_p is the particle (inclusion or bubble) volume fraction; u_i is the liquid velocity; D_{eff} is the effective diffusion coefficient; u_{ip} is the particle velocity, which equals the liquid velocity, except in the vertical direction, where the terminal rising velocity, V_T, should be added, namely, $u_{ip}=u_i+V_T$.

In the full trajectory approach [19-24], each particle trajectory is calculated by integrating its local velocity, defined by considering the different forces which act on it, such as drag and gravity, as given in Eq.(2).

$$\frac{dv_{Pi}}{dt} = -\frac{3}{4}\frac{C_D v_{Pi}\rho}{d_P\rho_P}|v_{Pi}-u_i| + \frac{(\rho_P-\rho)g}{\rho_P}$$
$$+ C_A\left(\frac{du_i}{dt}-\frac{dv_{Pi}}{dt}\right) \qquad (2)$$

where ρ_p and ρ are the particle and liquid densities, v_{pi} is the particle velocity, C_D is the drag coefficient as a function of particle Reynolds number, C_A is a constant, g is gravity acceleration. The first term on the right of this equation is the drag force, which is always opposite to the motion direction. The second term is the buoyancy force due to gravity, and the third term is the "added mass force" [25]. The effects of turbulent fluctuations can be modeled crudely by adding a random velocity fluctuation ($\xi\sqrt{2k/3}$)

to the mean fluid phase velocity at each step, where ξ is a random number (chosen between 0 and 1 at each increment) and k is the local turbulent kinetic energy.

Multiphase Fluid Flow Models

The multiphase phenomena in steelmaking include argon injection during steel refining and continuous casting , the entrainment and emulsification of slag at the top of the molten steel, and air/slag/steel interactions during ingot teeming. There are several models to simulate multiphase fluid flow. The Algebraic Slip Model (ASM) [16, 19, 26-30] approximates the dispersed two-phase system as a single-phase mixture of liquid and gas. Flow of the liquid-gas mixture is calculated by solving only one continuity equation, one set of momentum equations, and one set of turbulence equations. The gas fraction is calculated from one additional transport equation for the gas phase: Eq.(1). The slip velocity of the argon bubbles depends on their size and shape. Usually, their terminal velocity is used.[18] The buoyancy effect of the gas bubbles on the fluid flow is taken into account by adding an extra force term to the vertical momentum equation: $S_{gz} = -\sigma_g g\rho$, where σ_g is the gas volume fraction. In the Langrangian Multi-Phase Model [31], only one velocity field is solved, (ie the Eularian liquid velocity), but the liquid volume fraction is included in every term. The liquid volume fraction is calculated from the gas volume fraction, which is solved using the particle trajectory Eq. (2). This

model has been used to calculate two-phase fluid flow in a continuous casting mold. [32] In the Eularian-Eularian two-phase model approach, velocity fields of each phase are solved, the total volume fraction of all phases is unit. [20, 25, 33-35] Bubble-induced turbulence may be added to the K and ε equations through source terms. [25, 36] In the VOF Method [37], the movement of a free surface is tracked through the computational grid by simultaneously solving for the volume of fluid per unit volume (f_i). This requires satisfaction of an additional conservation equation, such as:

$$\frac{\partial f_i}{\partial t} + \left[\frac{\partial}{\partial x_i}(f_i u_i)\right] = 0 \qquad (3)$$

This method is popular in the simulation of free surface phenomena.[23, 24, 38]

Heat-Transfer-Related Phenomena

Fluid flow models can be extended to predict the variations and evolution of the fluid temperature by solving an additional equation for the transport and dissipation of superheat in the liquid metal. Superheat is the energy contained in the liquid metal above its equilibrium solidification temperature, or "liquidus" temperature. The conversation equation of the thermal energy has been coupled to the flow equations, incorporating Boussinesque's term ($\rho g\beta\Delta T$) into the vertical direction momentum balance equation, where ρ is the density of the molten steel, g is the gravitational acceleration, β is the thermal expansion coefficient, and ΔT is the temperature difference.

Simulation of Electromagnetic Forces on the Fluid Flow in Metallurgical Systems

The application of MagnetoHydroDynamics (MHD) to control the flow of molten steel started with electromagnetic stirring (EMS) of the strand pool with a traveling (alternating) magnetic field. It has now advanced to electromagnetic stirring in the mold and to an in-mold direct-current magnetic field, which induces a braking force to slow the flow (EMBr) in the continuous caster. Owing to the difficulty of conducting measurements, development of EMS and EMBr must rely heavily on computational modeling. The flow pattern and mixing under the application of electromagnetic forces can be modeled by solving the Maxwell, Ohm, and charge conservation equations for electromagnetic forces simultaneously with the flow model equations.[39]

Boundary Conditions

For the simulation of fluid flow, a fixed velocity condition is imposed at the domain inlet, and a "pressure outlet condition" is used at the outlets. Special "wall functions" are used as boundary conditions at the walls are used in order to achieve reasonable accuracy on a coarse grid. [5] The particles are assumed to escape at the top surface and the outlet, and be reflected at other walls. Recently, an accurate entrapment criterion of inclusions/small bubbles into the solidified shell was developed. [40, 41] It is based on performing a sophisticated force balance on each particle and time increment in the fluid boundary layer ahead of a solidifying dendritic interface, as reported elsewhere. [40, 41]

RECENT APPLICATION OF CFD RESEARCH TO STEEL REFINING AND CASTING PROCESSES

The current authors have applied CFD to steel refining and casting system for many years, including single phase and multiphase fluid flow, heat transfer, and inclusion motion in ladles during steel refining process , in Argon gas - stirred processes such as RH treatment, and in continuous casting tundishes, mold regions, and strands. Recently fluid flow, inclusion motion and free surface phenomena during ingot bottom teeming process have also been investigated. Detailed research in this field by the current authors in the recent 5 years is listed in Table 1. The next sections of the current paper introduce some example simulation results of the fluid flow, heat transfer, free surface phenomena and inclusion motion in steel refining and casting processes by the current authors.

Table 1 Application of CFD to steel refining and casting process by current authors during 2000-2005

|	Description	A	B	C
Standing ladle [42]	Transient fluid flow and heat transfer	①	❶	●
Ladle argon bubbling process [25, 43-46]	Steady and transient fluid flow, mixing and inclusion growth and motion	②③	❶	○
Continuous casting tundish[43, 47-50]	Steady and transient fluid flow, mixing and inclusion motion	①	❶	◉
Continuous casting SEN[51-56][57]	Steady fluid flow and inclusion attachment	①③	❶	◉
Continuous casting mold [40, 41, 56, 58-68]	Steady and transient fluid flow and inclusion motion	①②	❶ ❷ ❸	◉
Ingot bottom teeming process[69-71]	Steady and transient fluid flow, inclusion motion, and free surface shape simulation	①④	❶	◉

A: Multiphase models (①: Single phase; ②: Lagrangian-Lagrangian two phase model; ③: Eulerian-Eulerian model; ④: VOF model)   B: Turbulent models (❶: k-ε two-equation model, ❷: Large Eddy Simulation (LES), ❸: Direction numerical simulation (DNS)) C: considering heat transfer or not (●: yes, ○: no, ◉: sometimes yes and sometimes no.)

### Fluid flow, Heat Transfer and Particle Motion in Steel Ladles

A Lagrangian-Lagrangian method has been developed using FLUENT [72] and applied to simulate two-phase fluid flow in an argon-stirred 300 tonne steel ladle with 4.5 height, 0.5Nl/min gas injection, and 30mm bubble size [43]. The classic recirculating fluid-flow pattern is generated by argon injection from the center of the ladle bottom. Similar results were obtained in a simulation with an off-center bottom injection point [45]. The recirculating path length of inclusions in the ladle is more than 10 times that of the ladle height before they touch the top surface. The path length of the argon bubbles, however, is nearly the same as the ladle height, as shown in Figure 1. Taking into account the initial freezing and later remelting of a solid steel shell around the alloy particles, a simulation of alloy mixing the ladle successfully matched measurements of alloy concentration with time .[45] Inclusions will be more easily removed if

attached on the bubble surface. A fundamental modeling study was performed to quantify the frequency of nonwetting particle attachment to bubbles in steel as a function of particle size and bubble size. [46]

The effect of natural convection on fluid flow in the same ladle during a standing period has been simulated. The results show that even in the standing ladle, there is vigorous turbulence, especially in the first 500 s after gas stirring. After 3600s, the temperature stratification is well established, and the molten steel flows downward near the side wall and upwards at the axis, as shown in Figure 2.
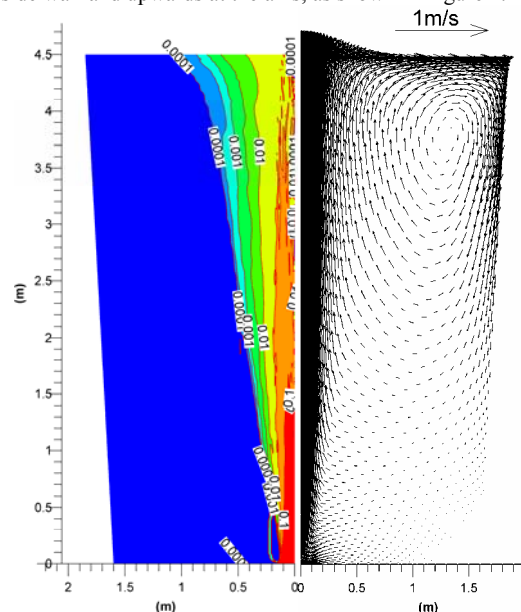
(a) gas volume fraction and velocity vector
Calculated gas column shape (0.001 isoline of the gas volume fraction)
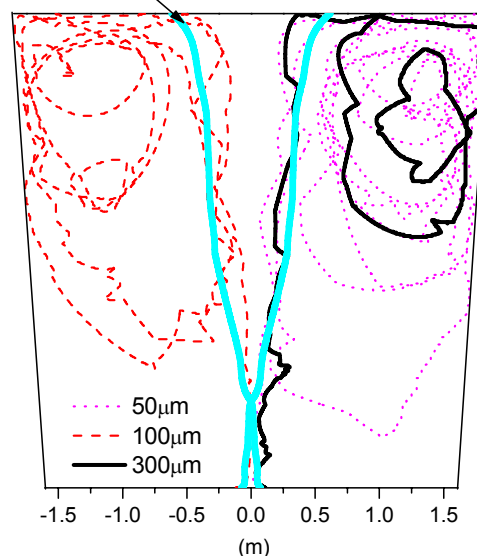
(b) trajectories of inclusions and bubbles
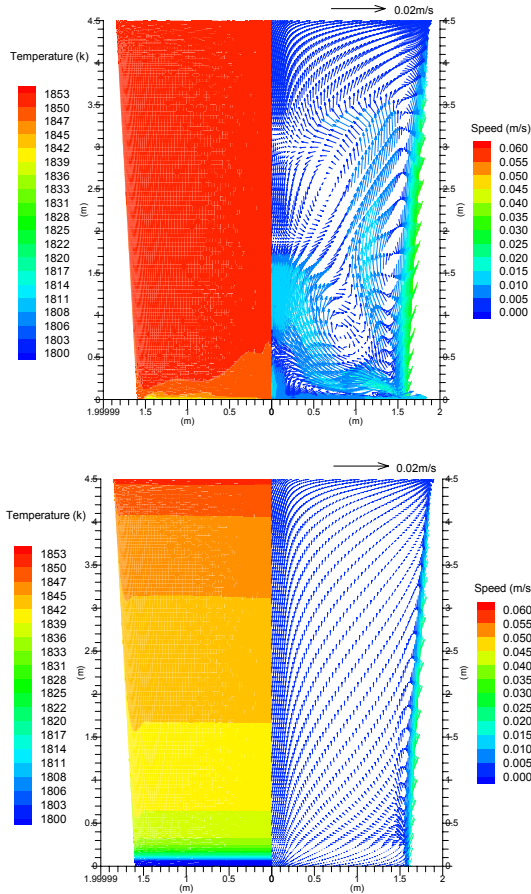Fig.1 Fluid flow and particle trajectories in an argon-stirred ladle

Fig.2 Temperature and velocity in a standing steel ladle
(upper: at 400s, lower: at 3600s)

Fluid Flow and Inclusion Motion in the Continuous Casting Tundish

Fluid flow, heat transfer, and inclusion motion in a 25 tonne 4-strand tundish has been calculated by the current author Zhang and researchers at Shougang Steel China, including the effect of thermal buoyancy. [47] The fluid flow pattern near the weir in the outlet zone and temperature on the walls are shown in Figure 3. There is a 220mm space above the weir, which has 11 holes. Most of the molten steel enters the outlet zone by flowing over the weir, inducing serious surface level fluctuation and slag entrainment. The lowest temperature is located at the first outlet near the weir. The fluid flow pattern simulated by the non-isothermal model is very different from that by the isothermal model which ignores the buoyancy force (Figure 4). The thermal buoyancy generates an overall upwards flow, so can remove more inclusions, as shown in Figure 5. More large inclusions are removed than small inclusions. The simulation also indicates that the residence time of different size inclusions is quite different from the residence time of the molten steel. Thus, using solute transport like dye injection in a water model or Cu addition in a real steel tundish cannot accurately study the motion of inclusions. Figure 6 shows typical inclusion trajectories, and the positions of 10,000 inclusions 230s after entering the tundish.
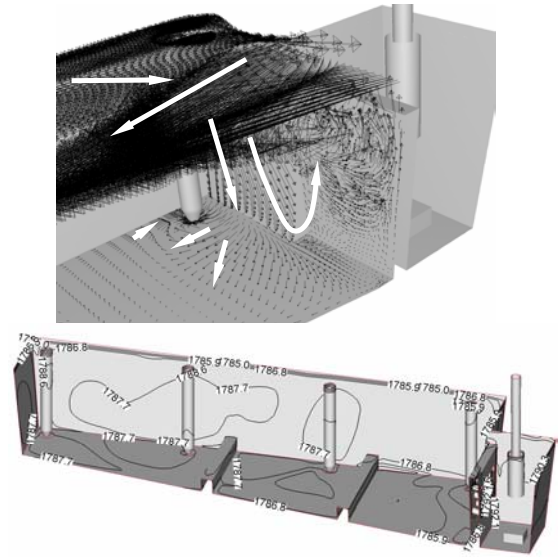

Fig.3   3-D non-isothermal Flow pattern (upper) and wall temperature distribution (lower) in a 4-strand tundish [47]
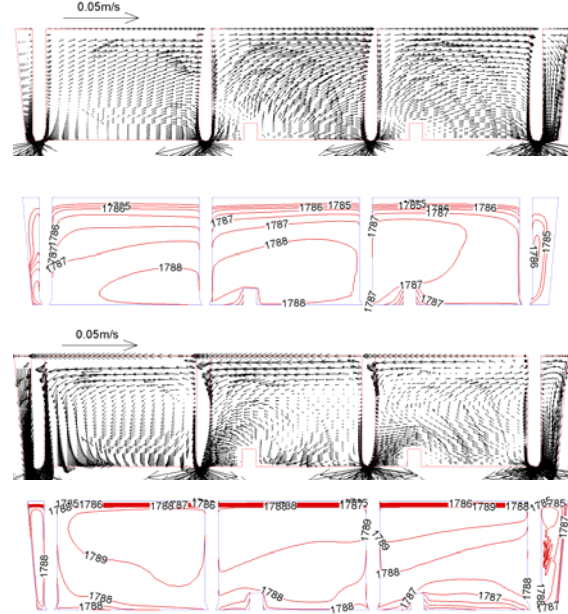

Fig.4   Effect of thermal buoyancy on the distribution of velocity and temperature in the section through all four outlets (upper two: isothermal, lower two: non-isothermal)
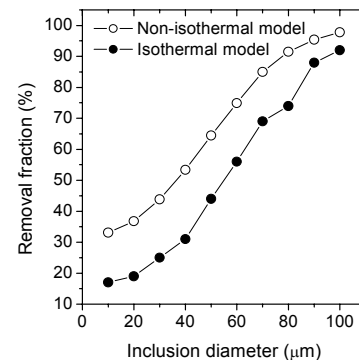

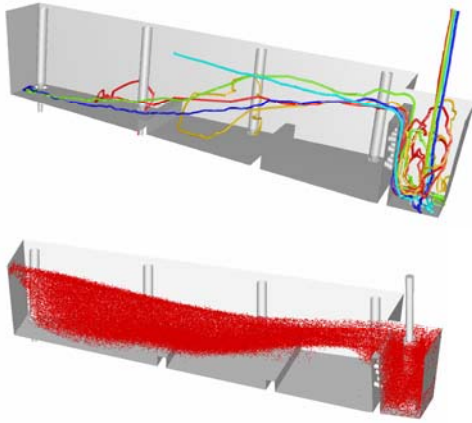Fig.5. Inclusion removal fraction in the 4-strand tundish

Fig.6 Trajectories and positions of 50μm inclusions, 130s after injection through the inlet nozzle [47]

Fluid Flow and Inclusion Motion in the SEN and the Continuous Casting Mold

Fluid flow and inclusion motion in the Submerged Entry Nozzle (SEN) and the 2.55m mold region of a continuous slab caster have been calculated using FLUENT. [31, 43] With a straight-walled nozzle tube, the uneven flow passing the slide gate generates a swirl at the bottom of the nozzle outports. This swirl is diminished if the SEN has annular steps, which also decrease the penetration depth in the mold. The fluid flow pattern in the mold without gas injection is double roll (Fig.7). The average volume turbulent energy is 1.65×10^{-3} m²/s² and its dissipation rate is 4.22×10^{-3} m²/s³. The Step SEN has 7% removal of 50μm inclusions to the top surface of the mold, compared with 3% removal by the SEN without steps. The computed locations of inclusions touching the SEN walls and entrapped into wide faces of the slab are also shown in Fig. 7. In the slab, inclusions accumulate at 12-14mm below the wide faces. The majority of simulated inclusions entering the mold (60%) are captured within 30mm of the surface of the slab, which corresponds to the top 2.55m of the caster. Because the fractions of inclusions safely removed to top surface of the mold are less than 7%, it is more important to choose nozzle designs that produce optimal conditions at the meniscus to avoid slag entrainment, level fluctuations, and other problems. Small bubbles may penetrate too deep to the curved section of the strand, such as 0.2mm bubbles as shown in Fig7, and may be entrapped in the solidifying shell and become defects such as slivers or pencil pipe due to attaching many inclusions. The concentration of alumina inclusions at 200s in the mold region is also shown in Fig.7 (right figure). Inclusions concentrate much more in the upper roll than the lower roll.
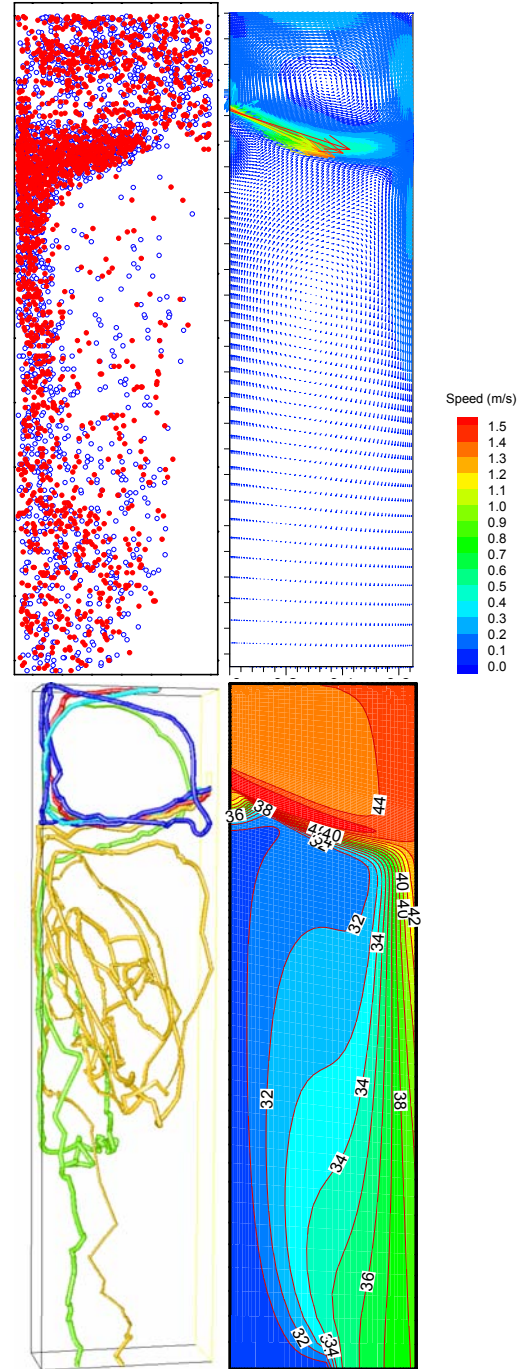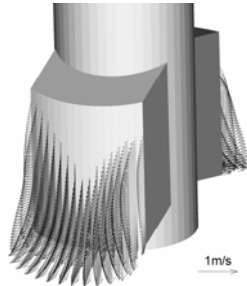

Fig.7 Flow pattern at SEN outport, 50 μm inclusion entrapment position at wide faces, fluid flow pattern in the mold, typical trajectories of 0.2mm bubbles in the mold, and 100 μm Alumina inclusions mass concentration in ppm in the mold at 200s

Figure 8 shows the fluid flow pattern in the mold region of a thin slab caster with SEN angle down 12°, submergence depth 200mm, and casting speed 4.0m/min with and without EMBr control. [63] With B=0.20T, the velocity of the jet is remarkably decreased, especially where the jet impinges the narrow face, and near the top surface. The fluid flow entering the strand is just like a plug flow. The

flow pattern with EMBr significantly lowers level fluctuations, so decreases the entrainment of mold slag.

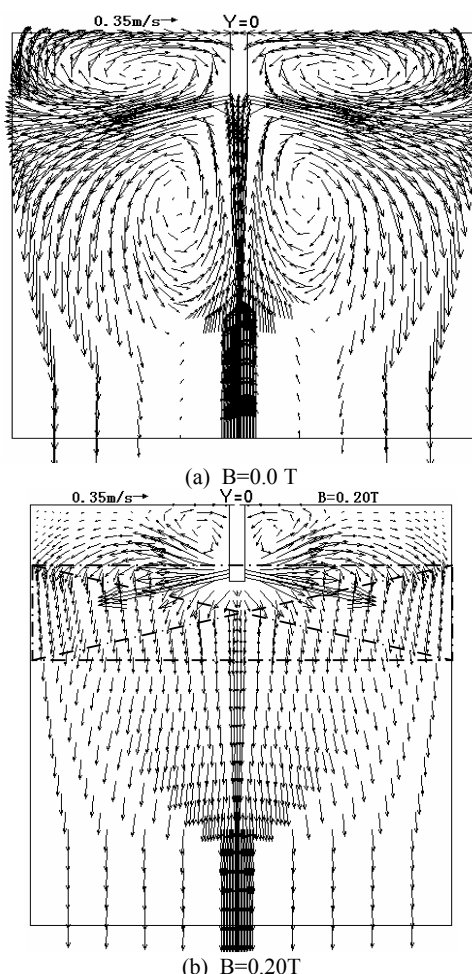(a) B=0.0 T

(b) B=0.20T

Fig. 8   Fluid flow pattern in the mold region of a thin slab caster with and without EMBr [63]

Free Surface Phenomena in Steel Refining and Casting Process

The free surface in the 300 tonne ladle during argon bubbling is investigated with an Eularian-Eularian two-phase model in FLUENT [72], as shown in Figure 9. The spout height depends greatly on the gas flow rate. Too strong gas injection may generate an excessive spout to open a bare spot in the top slag, which induces air absorption and slag entrainment. This kind of free surface fluctuation is clearly seen in the transient simulation of fluid flow in an ingot mold during bottom teeming using VOF with Fluent [72] as shown in Fig.9a. During mold filling, the jet entering the mold first spouts up to a maximum height, then falls down, then flows upwards along the walls, and then falls back. During steel uprising, air is entrained into the bulk, especially around the edge between the bottom of the spout and the surrounding air, (Fig. 9b). Many bubbles are entrained into the molten steel. To avoid air absorption, the teeming rate should be smaller than a critical value at the start period to let the molten steel rise flatly, and then after some time, the teeming rate can increases gradually.
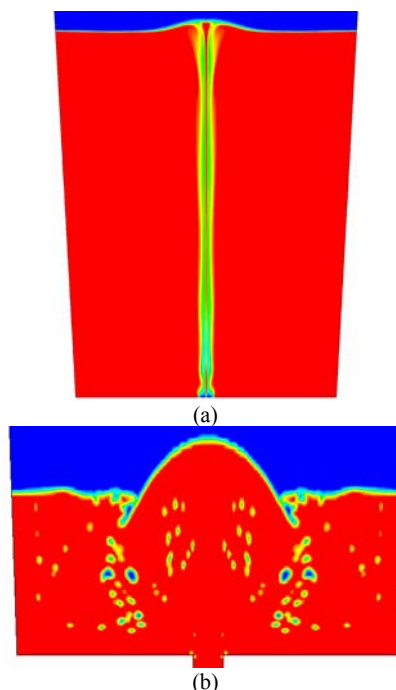

(a)

(b)

Fig.9   The top surface shape in a ladle during argon-bubbling process (a), and top surface fluctuation and gas entrainment in an ingot during bottom teeming process (b)

SUMMARY

This paper firstly summarizes the fundamentals of CFD in steel metallurgical systems, such as turbulent models, particle motion, multiphase flow, heat transfer related phenomena, free-surface motion, and the application of electromagnetic forces. Then, recent research of the current authors to simulate these phenomena in an argon bubbling steel ladle, in a standing ladle, in continuous casting tundish and mold, and during an ingot bottom teeming process is reported. Further research on the application of CFD to steel refining and casting process by the current authors include the following:

- New multiphase flow models considering particle size distributions, which evolve according to collision and agglomeration phenomena;
- Transient fluid flow in ladle, tundish, and mold at ladle change period;
- Top slag surface shape prediction during steel reining, continuous casting and ingot teeming process;
- Detailed investigation of asymmetrical fluid flow in the continuous casting mold [56, 59];
- Particle entrapment to the slag and the solidified shell;
- Inclusion nucleation and growth in the molten steel coupled with the fluid flow simulation;
- Using these models to the steel production practice to improve the steel quality by providing information on how to avoid defects from inclusions and bubbles.

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