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Effect of Gas Injection on Fluid Flow in Mold

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Abstract: A mathematical and physical model was adopted to compute the fluid flow distribution in case of local gas holdup in mold. The photography was used to show the fluid field. The predicted flow patterns show reasonable agreement with experiment observations using actual water model.

Key word: mold; gas holdup; fluid field

The distribution of fluid field in mold has been done by some researchers represented by B G Thomas[1~3]. Artificial damping method was used in Ref. [4] to calculate the fluid field of vertical jet in mold. A simple method was used in Ref. [5] to calculate the fluid field in slab continuous casting caster. In this paper, some experiments displaying the fluid field in water model of 1:1 are developed, the fluid flow is calculated and the change of the fluid field because of the quantitative difference of argon gas coming from the argon tube of submerged entry nozzle (SEN) is analyzed according to the continuous caster with section 1 350 mm × 230 mm in The Third Steelmaking Plant of Anshan Iron and Steel Complex (Anshan, China).

1 Mathematical Model

A three-dimensional mathematical model of fluid flow can be used to calculate the velocity in each direction V_X, V_Y, V_Z.

1.1 Assumptions

(1) Fluid is incompressible viscous fluid;
(2) The existence of solidified shell is neglected;
(3) The flowing pattern of fluid is steady and it is symmetrical about planes of *XOZ* and *YOZ*, so only one quarter of the field is modeled.

1.2 Fundamental equation

According to the laws of mass and momentum conservation, the three-dimensional turbulent motion equation of the liquid is obtained. It is same as the equation in References [1 ~ 3] and can also be found in Ref. [6] about the fluid mechanics. In order to get the coefficient of viscosity, the momentum equations in $k-\varepsilon$ turbulence model of Lauder and Spalding are used. But the density (ρ) in the equation is calculated according to the following

$$\rho = \rho_g \sigma + \rho_l (1-\sigma) \tag{1}$$

where ρ_g is the density of gas, ρ_l is the density of liquid, σ is gas void fraction.

The gas void fraction is calculated according to the following equation

$$u\frac{\partial \sigma}{\partial X} + \frac{\partial \sigma}{\partial Y} + (w + v_s)\frac{\partial \sigma}{\partial Z} = \frac{1}{\rho} \times \left[\frac{\partial}{\partial X}\left(D_e^b \frac{\partial \sigma}{\partial X}\right) + \frac{\partial}{\partial Y}\left(D_e^b \frac{\partial \sigma}{\partial Y}\right) + \frac{\partial}{\partial Z}\left(D_e^b \frac{\partial \sigma}{\partial Z}\right)\right] \tag{2}$$

where v_s is the slip velocity of gas bubble in the water model. According to experiments, the average diameter of bubbles is about 5×10^{-3} m, and in accordance with Stokes equation, v_s is about 0.24 m/s. D_e^b is equivalent coeffient of diffusion bubbles, it equals the effective coefficient of viscosity of the fluid[7]. σ is local gas viod fraction.

2 Boundary Conditions and Solution Method

2.1 Boundary conditions

(1) Inlet: the inlet velocity is obtained according to the equivalence of rate of rate flow and casting speed, k, ε are functions of the inlet velocity.
(2) Outlet and symmetry plane: for the outlet, the normal gradients ($\partial/\partial n$) of all variables, including V_X, V_Y, V_Z, k, ε and σ are set to zero; the same conditions

are used for each node on a symmetry plane.

(3) Top surface: V_Z is set to zero, the normal gradients of the other variables (V_X, V_Y, k, ε and σ) in the direction of Z are set to zero.

(4) Solid wall: the velocities are set to zero, k and ε are calculated according to wall functions.

2.2 Solution method

Owing to the rectangular geometry of the mold, the finite difference method is chosen to solute this problem. The difference equations and boundary conditions are discretized into finite difference equations, using a staggered grid and seven-point stencil of controlling volume. The domain is divided $26 \times 12 \times 64$ rectangular grids in order to obtain reasonably-converged distributions of velocity of molten steel. Due to the high degree of recirculation, the current strategy is successive ADI method, choosing an under-relaxation factor of 0.2 or 0.3, until total mass source is less than 0.001 that of first iteration, about 600 iterations are required to achieve this result.

3 Physical Water Model Experiments

According to the dimensions of mold, a water mold in proportion as 1 to 1 are made of organic glass which thickness is 20 mm. Based on the principle of equivalence of quasi-number, the physical water model experiments are developed. In order to display the states of fluid flow in mold, the particles of polyvinyl chloride (PVC) are added with water from the submerged entry nozzle (SEN). Instead of argon, different amount for air are blown into from the SEN. The water in mold is provided in cycles. The visualized experimental results are displayed in Fig. 1.

4 Calculation Results

The flow state in mold is displayed in Fig. 2(a). The fluid leaves the SEN as a strong jet and splits vertically to upper and lower recirculation regions which are very large. At the end, the fluid is brought back the SEN. In the mold of water model, the water flow in XOZ plane is dominant with the flows in the other planes such as XOY and YOZ. When gas is blown into from the SEN, the flow field is changed and the mainly effected area is the upper recirculation region. In the area with bigger gas holdup, the fluid impinges upon meniscus directly, so the center of eddy in the lower recirculation zones rises up, shown as Fig. 2(b). For convenience, only the fluid field on XOZ wide face of $Y = 0$ is discussed.

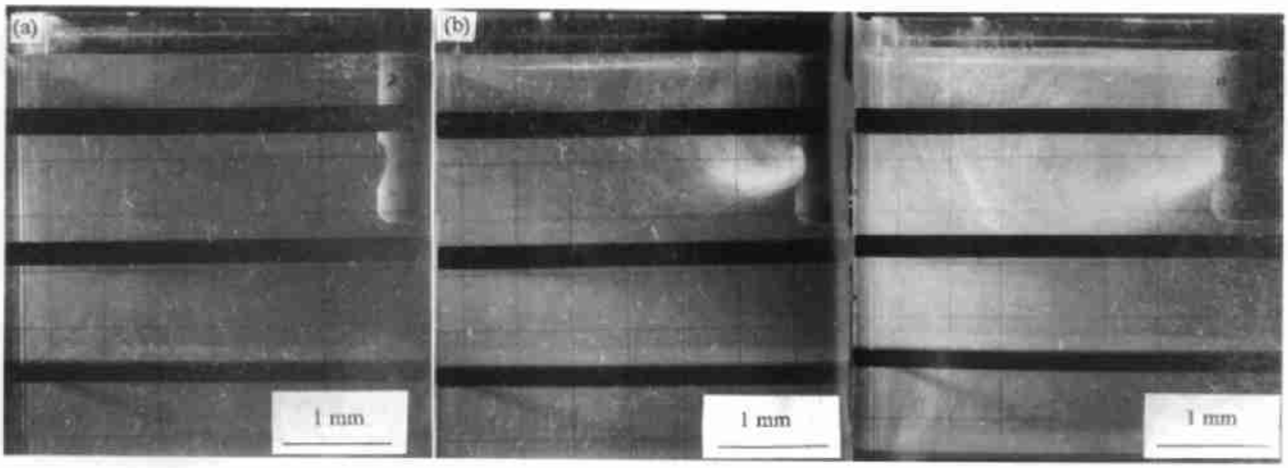

Fig. 1 Water model experiment, different gas holdup, $Y = 0$, XOZ center section fluid field

(1) The effect of the different amount of gas blown into on the fluid field of mold

Assuming the following factors as constant, it is to say, when casting speed $V_{cast} = 1.0$ m/min, the width of slab $L_X = 1.35$ m, the height of SEN under meniscus $L_h = 0.24$ m, the angel of the jet is 15° down, and with the different amounts of gas are blown from the argon tube at the upper location of SEN, the fluid fields of mold are shown as Fig. 3. With the increasing of gas holdup, the upward velocity of upper field increases and the center of eddy in lower recirculation region moves upward slightly. Although it is beneficial to prevent the blocking of SEN and decrease the unevenness of temperature at the meniscus, it is easy

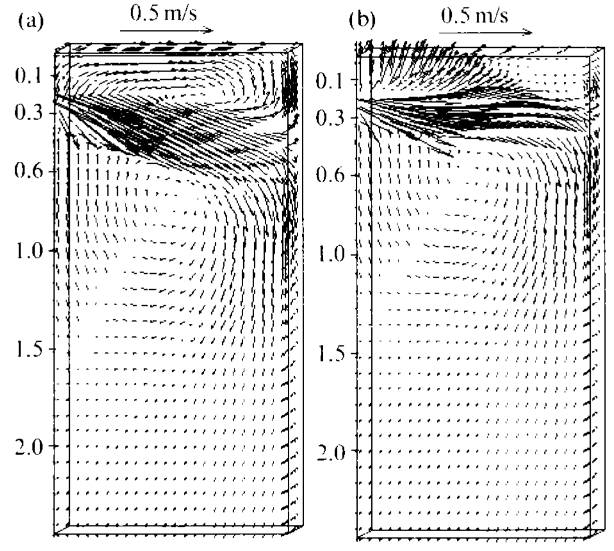

Fig. 2 3-dimension fluid field in mold, (a) $\sigma = 0$, (b) $\sigma = 0.05$

to cause jetting phenomena because of the increasing of disturbance of meniscus. There are local recirculation zones in upper region when the amount gas is small (σ = 0.03). Fig. 3(a, b, d) are similar to the result of experimental water mold in proportion as 1 to 1 (shown in Fig. 1).

(2) The effect of the different amount of gas blown into on the gas holdup of center wide face of mold

When some factors are constant (the same as above-mentioned) and different amounts of gas are blown into, the distribution of gas holdup of $Y = 0$, XOZ center faces are shown as Fig. 4. It shows that the gas coming from the mold SEN begins to move to the upper location of SEN before it reaches the narrow face and distributes as fan-shape in the 2/3 zone along X direction on the cross section near SEN. With the increasing of gas holdup, the gas holdup of water in

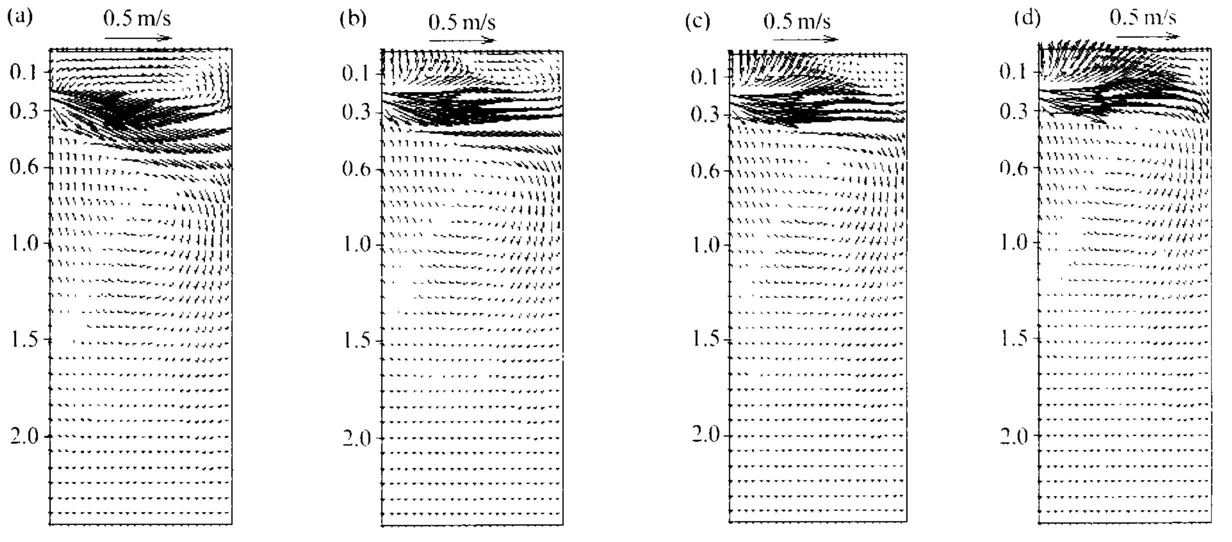

Fig. 3 Fluid field of various gas holdup on $Y = 0$, XOZ center sections, (a) $\sigma = 0$, (b) $\sigma = 0.03$, (c) $\sigma = 0.05$, (d) $\sigma = 0.08$

mold also increases, the gas also moves closer and closer to the narrow face, just similar to the result of water model experiments (shown in Fig. 1).

(3) Gas holdup distribution on different sections of mold

It is assumed that some factors are constant (the same as above-mentioned), Fig. 4(a) and Fig. (5) reveal gas holdup distribution on different sections in mold when the same amounts of gas blown into from the upper region of SEN. The gas holdup distribution on $Y = 0$, XOZ center section shown in Fig. 4(a) and Fig. 5(b) is the biggest, it is very small on other faces, especially on the $Z = 0.4$ m, XOY face (shown in Fig. 5(d)), it distributes only in a small region of the center, the biggest gas holdup is 0.01% of that of inlet. So gas holdup mainly distributes in a certain region near the outlet of SEN.

5 Conclusions

(1) Based on finite difference method, the distribution of the three-dimensional fluid field and gas holdup in mold with SEN with a whole in each side are calculated. A reasonable agreement between the mathematical model and water model is obtained.

(2) When the flow state being considered, and inert gas being blown into from the argon tube at the upper location of SEN, it concentrates in certain zone near the SEN. It is beneficial in decreasing stagnant areas near the meniscus, preventing low temperature in

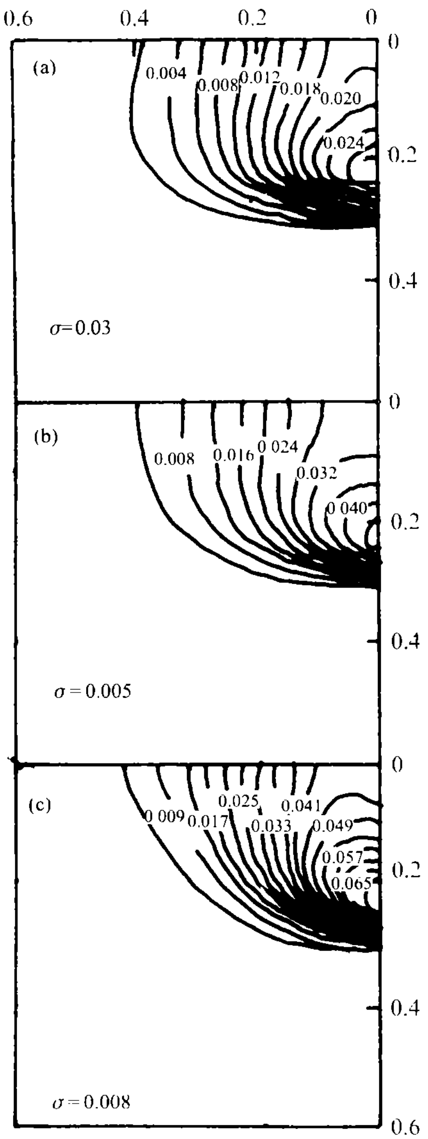

Fig.4 $Y = 0$, XOZ **center faces gas holdup distribution**

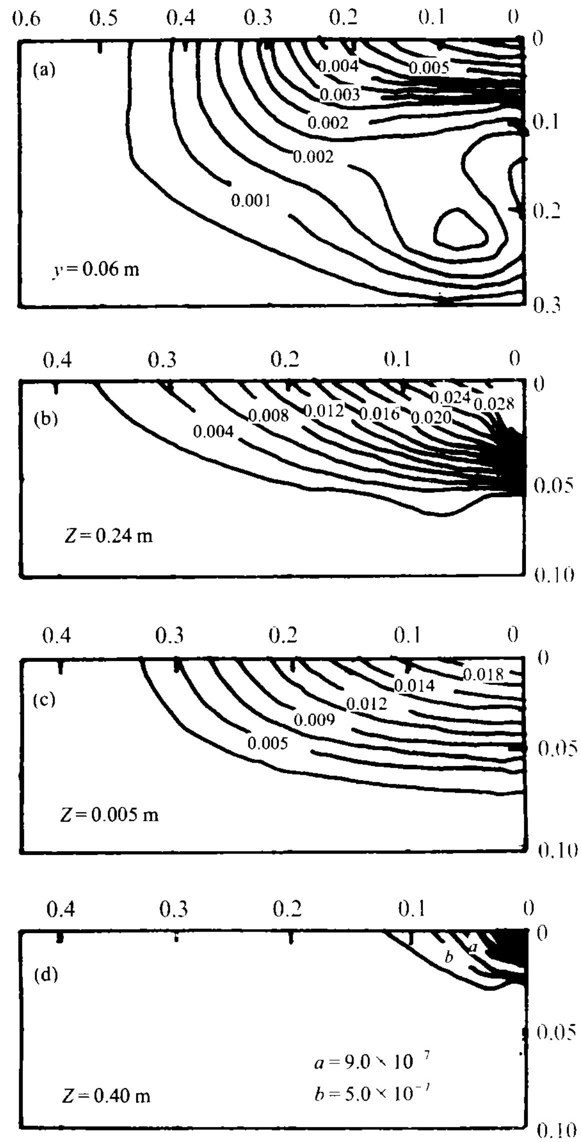

Fig.5 Gas holdup distribute in various sections (a) XOZ **face, (b), (c), (d)** XOY **faces**

these areas, and preventing the bubbles from being brought the lower region of mold, which can cause gas hole and affect the quality of slab bad. Excessive amount of gas may cause excessive velocity upward in upper region of mold, and disturbance of meniscus and jet.

(3) For the slab continuous caster with section of 1 350 mm × 230 mm in The Third Steelmaking Plant of Anshan Iron and Steel Complex (Anshan, China), when the jet angle is 15 ~ 25° down, SEN depth under meniscus is 0.24 ~ 0.30 m, casting speed is 1.0 ~ 1.2 m/min, the optimum amount of gas blown into for water model in proportion as 1 to 1 is 0.55 ~ 0.75 m^3/h. When the expansion of argon bubble being considered, the optimum amount of argon is 0.10 ~ 0.13 m^3/h.

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