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PHYSICAL MODELING OF OSCILLATION EFFECT ON FLUID FLOW IN MOLD

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This paper focuses on physical modeling of oscillation effect. Two new similarity criterions, $\pi_1 = fl / v$ and $\pi_2 = A / l$, characterizing the effect of frequency and amplitude respectively on fluid flow, are obtained by dimension analysis method. Based on the similarity principle and the boundary layer theory, a full-scale water model experiment was carried out. Oscillation affected more on fluctuation than surface velocity. Frequency, especially high-frequency, has a greater impact on fluctuation than amplitude does. Compared with non-oscillation, the wave heights have a 300 % increase at 160 r/min frequency and 10 mm amplitude, while the surface velocity has a 15 % rise.

Key words: continuous casting, modeling, mold oscillation, similarity criterion, fluctuation, surface velocity

INTRODUCTION

In the conventional continuous casting, mold oscillation improves lubrication and helps steel shell heal cracks, playing a vital role in obtaining good facial quality of slabs. In the aspect of numerical simulation, much research has been made: B. G. Thomas [1,2] quantitatively depicted the change of fluid flow, transfer of heat, formation of oscillation marks and facial quality of slabs in different periods of an oscillation cycle; M. Y. ZHU [3] analyzed the effect of oscillation on slab surface cracks. However, research on physical model mainly focuses on the effect of casting parameters such as casting speed and submerged entry nozzle (SEN) structure on flow field [4-6] and mold entrapment [7-9], but almost neglects an influential factor — oscillation. As an initial step in quantitative understanding of its effect, similarity criterions characterizing the effect of oscillation should be derived to simulate the behavior of fluid flow. This work provides a theoretical foundation for future study on mold oscillation in physical modeling.

Mold powder affects several important phenomena, including protecting molten steel from oxidation and absorbing inclusions from molten steel. The pumping effect created by oscillation and the drag by moving steel shell could infiltrate the powder into the gap between shell and mold. Because of the great temperature gradient from cold mold wall to inner field, the slag solidifies against the mold wall. Of great importance is the effect of the solid slag rim on the meniscus behavior and the oscillation mark formation [1].

This paper, based on the similarity principle, gave some similarity criterions to depict the effect of mold oscillation on fluid flow and then discussed the experiment results from physical modeling established by the theoretical analysis.

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ESTABLISHMENT OF OSCILLATION MODEL

The flow of liquid steel in mold can be regarded as the unsteady and isothermal flow of incompressible and viscous fluid. The physical model was established as shown in Figure 1.

The oscillating effect can be divided into two parts: one is the friction force between mold wall and molten steel; the other is the periodic beating of slag rim on molten steel.

Effect of slag rim

Under oscillating condition, the slag rim periodically beats the liquid level up and down, contributing to the

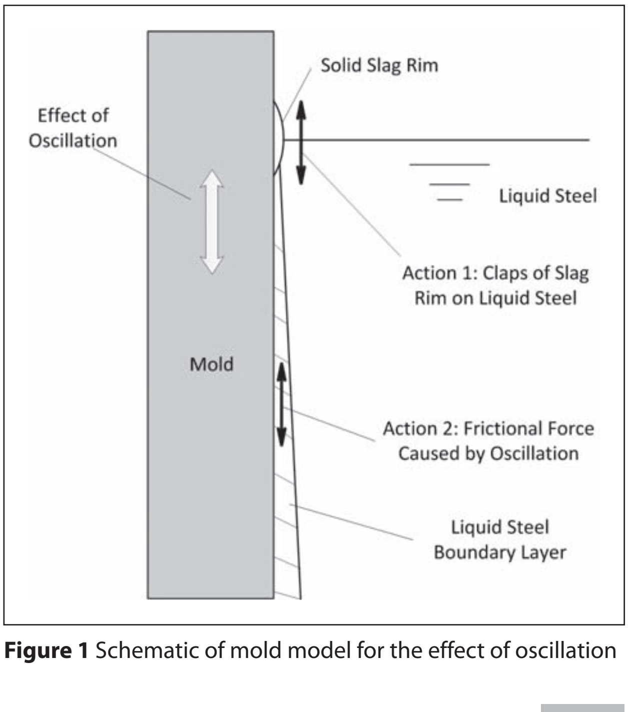

Figure 1 Schematic of mold model for the effect of oscillation

turbulence near the meniscus and the formation of oscillation marks in slabs. Furthermore, vibration waves resulting from the beat may even have a resonance with the wave of the flow itself.

Effect of friction force

The friction force between mold wall and molten steel is caused by the effect of fluid viscosity. According to the non-slip condition of boundary layer theory, the viscosity effect mainly acts on the boundary layer. Previous work indicates that the thickness of boundary layer is at a millimeter level [10], which is so thin that could be neglected in comparison with the whole flow field. Hence the friction force is disregarded in this paper. The effect of mold oscillation is suggested to be simplified as the pumping effect of slag rim.

IDENTIFICATION OF SIMILARITY CRITERIONS

Derivation of criterion on oscillating effect

This paper adopts the dimension analytic method to obtain the similarity criterion and takes sinusoidal oscillation as an example. The specific steps are summed up as follows.

With oscillation taken into account, the flow state in mold tends to be relevant with the following 9 factors: velocity of molten steel (v), density of molten steel (ρ), viscosity of molten steel (μ), feature size of the mold (l), oscillation frequency (f), oscillation amplitude (A), interfacial tension between molten steel and slag (σ), gravity acceleration (g) and time (t). The general equation depicting the relation among them is given below:

$$f\left(v,\rho,\mu,\mathrm{l},\mathrm{f},\mathrm{A},\sigma,\mathrm{g},\mathrm{t}\right)=0 \tag{1}$$

Three physical quantities (l, v, ρ) which are independent in dimension are chosen as the basic quantities to obtain a series of dimensionless criterions π.

$$\pi_1=\frac{fl}{v} \tag{2}$$

$$\pi_2=\frac{A}{l} \tag{3}$$

$$\pi_3=\frac{\mu}{vl\rho}=Re \tag{4}$$

$$\pi_4=\frac{\sigma}{v^2 l\rho}=We \tag{5}$$

$$\pi_5=\frac{gl}{v^2}=Fr \tag{6}$$

$$\pi_6=\frac{vt}{l}=Ho \tag{7}$$

where Re is the Reynolds number, We is the Weber number, Fr is the Froude number and Ho is the time-average number.

The π_1 number is the ratio of the residence time in a system to the oscillation period, characterizing the influence of frequency to the fluid flow. The π_2 number is the ratio of the oscillation stroke to the mold's feature size, giving an index to the effect of amplitude on the fluid flow.

Determination of similarity condition

For dynamic similarity, the Re number of both the prototype and the model should be guaranteed in the same self-modeling domain and the Fr number should be equal [11]. In a physical model concerning oscillation effect, the two new criterions, π_1 and π_2, should be considered. Following this, we get:

$$\frac{v_m}{v_p}=\left(\frac{l_m}{l_p}\right)^{\frac{1}{2}}=\lambda^{\frac{1}{2}} \tag{8}$$

$$\frac{f_m}{f_p}=\frac{v_m l_p}{v_p l_m}=\frac{v_m}{v_p}\cdot\lambda^{-1}=\lambda^{-\frac{1}{2}} \tag{9}$$

$$\frac{A_m}{A_p}=\lambda \tag{10}$$

where the subscripts, m and p, identify the model and prototype, respectively; λ is the scaling factor of geometric similarity.

EXPERIMENT AND DISCUSSION

Experimental methods

To satisfy Equation (8), (9) and (10), a full scale model was selected. Figure 2 shows a schematic diagram of the experimental apparatus. The vessel made of transparent acrylic resin has a cross-section of 1 300 mm × 230 mm. The slag rim has a length of 1 200 mm, a width of 200 mm, and a depth of 3,5 mm, as shown in Figure 3. The oscillation is driven by eccentric shaft us-

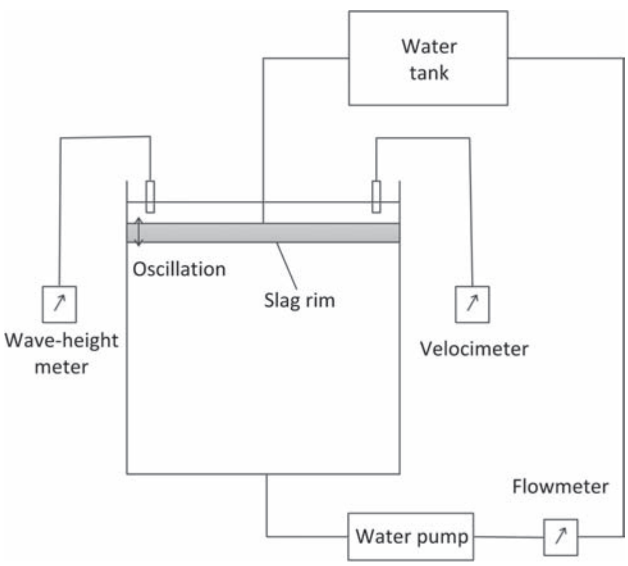

Figure 2 Schematic diagram of water model experiment for oscillation

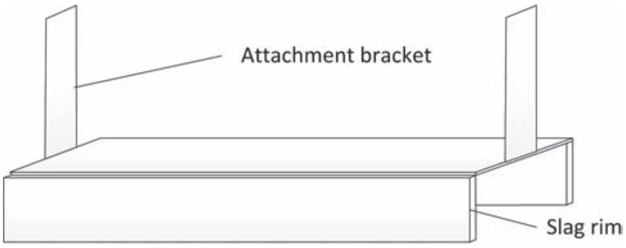

Figure 3 Schematic diagram of the slag rim

ing leaf spring in sinusoidal mode. The amplitude is controlled by eccentric degree, and the frequency is adjusted using current frequency convertor. Referring to the continuous thin slab casting mold of a steel plant in China, the casting speed is fixed at 1,2 m/min, and the SEN is immersed 120 mm deep with no gas blown. The fluctuation is inspected by the multi-functional hydraulic detection system, DJ800, and the surface velocity by the helical rotor velocimeter.

Effect of oscillation on fluctuation

The level fluctuations were measured at three points, including 20 mm away from the narrow face, 1/4 the wide face, and near the SEN. Mean wave heights were obtained by averaging the measuring values. Figure 4 shows the influence of frequency and amplitude on wave heights.

Wave heights at different amplitudes vary with frequency in the same tendency. The average wave heights under the frequency of 121 r/min are somewhat lower than those in non-oscillation. When the frequency rises from 121 r/min to 150 r/min, the heights increase slightly. With the frequency rising over 150 r/min, the fluctuation increases sharply — about a 20 % rise in wave heights at each 1 % increase of frequency.

During the oscillating period, the claps of slag rim on the fluid in the vessel create a sort of stationary waves, which cancel out parts of stationary waves generated from the strike of the upper recirculating flow near the narrow face of mold. That is the reason why the fluctuation degree is relieved at the 121 r/min frequency. The amount of cancellation waves grows smaller with the rise

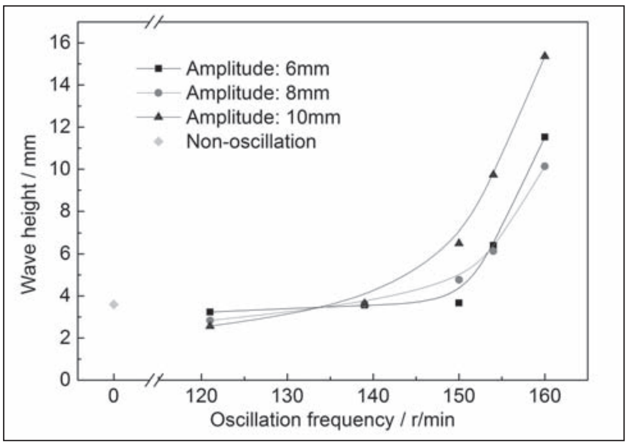

Figure 4 Influence of frequency and amplitude on level fluctuation

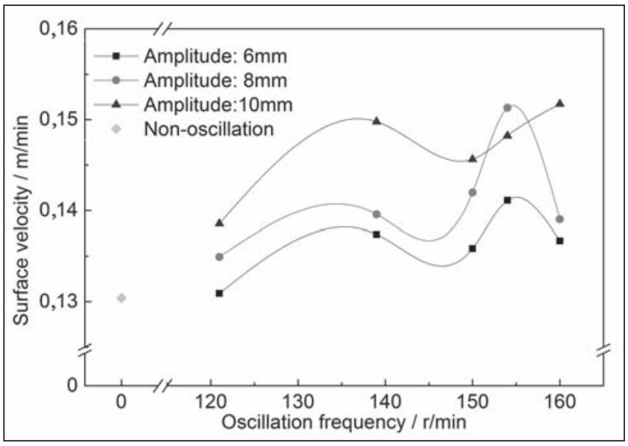

Figure 5 Influence of oscillating frequency and amplitude on surface velocity

of oscillation frequency. When the frequency goes up to more than 150 r/min, the two stationary waves are in resonance, strengthening the fluctuation.

The increasing amplitude does not affect the fluctuation in a clear way, but a rising tendency.

At 160 r/min frequency and 10 mm amplitude, the fluctuation increases in a 300 % margin in comparison with non-oscillation. It indicates that a strong oscillation has a significant effect on fluctuation.

Effect of oscillation on surface velocity

The surface velocities were measured 300 mm away from the narrow face. Figure 5 shows the influences of frequency and amplitude on surface velocities, which are higher on the whole after oscillation. Based on the law of energy conservation, a part of energy generated from claps of slag rim against water levels is converted to kinetic energy, supporting the surface flow in mold.

With the frequency increasing from 120 r/min to 139 r/min, the surface velocities are on the rise — a 3 % rise at every 10 r/min increase of frequency. When the frequency goes up to more than 140 r/min, the surface velocities do not have a steady and clear change tendency. The surface velocity has an increasing tendency with the rise of amplitude. At 160 r/min frequency and 10 mm amplitude, the surface velocity has a 15 % rise.

CONCLUSIONS

In a physical model with oscillation taken into account, two similarity criterions, $\pi_1 = fl / v$ and $\pi_2 = A / l$, can be adopted to simulate the effect of oscillation on the flow field in mold. The effect of oscillation is mainly manifested in the claps of slag rim on the liquid steel near the meniscus.

Wave heights at the 121 r/min frequency are a bit lower than those in non-oscillation condition. With the frequency rising, the fluctuation increases slowly at first, but goes up sharply with the frequency rising over 150 r/min. In comparison, the amplitude does not affect the fluctuation in a clear way.

With the rise of frequency or amplitude, surface velocities are in an increasing tendency, but fluctuate in detail.

A strong oscillation has a great impact on the fluid flow. At 160 r/min frequency and 10 mm amplitude, the fluctuation has a 300 % increase and the surface velocity a 15 % rise, compared with non-oscillation. Therefore, the slag rim should be cleared up timely in production process. Much future work is needed to investigate the effect of oscillation on fluid flow.

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