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Formulation of Mold Level Control Model by Molten Steel Flow Analysis Method

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Abstract

This paper describes activities relating to mold level control in continuous casting process as case examples of our process control solution business, in which we clarify and evaluate the process phenomena and design the control system. Initially, a mold level control model has been formulated by fluid flow analysis technique that evaluates molten steel flow in the mold quantitatively. The model calculates the fluid flow and free surface in the mold by molten steel flow analysis method, while control system analysis is performed simultaneously. It enables realistic simulation of the mold level control system considering the fluid flow turbulence. As a consequence, mold level control in high-speed casting can be predicted and evaluated with high accuracy.

1. Introduction

Mold level control is a function of the process control of continuous casting to maintain the level of molten steel surface in a mold (hereinafter referred to as the mold steel level) constant. This has a significant influence over the quality and yield of the final product. There is a close correlation between the fluctuation of the mold steel level and the occurrence of surface defects of final products: it is considered that, when the mold steel level fluctuates significantly, casting powder and other impurities floating on the surface of molten steel are entrapped in steel and they appear in the form of surface defects of steel sheet products during rolling. To prevent this, mold level control is designed so as to minimize the fluctuation of the mold steel level.

The dynamics of the mold steel level is, roughly speaking, a simple integral system and for this reason, the effect of mold level control has conventionally been calculated in its development stage on an assumption of an integral system. In practice, however, disturbances in molten steel flow tend to show in the form of surface ripples as the casting speed increases. As a result, with a conventional crude model, it was difficult to obtain a reliable simulation result and it was impossible to accurately predict and evaluate the control performance of a mold level control system under a condition of a high casting speed.

In view of the situation, the author has formulated a mold level control model applying molten steel flow analysis. **Fig. 1** shows a block diagram of the developed model. This model is characterized by describing the molten steel flow in a mold and the dynamics of a molten steel surface from the viewpoint of fluid flow analysis and combining them with control system analysis. As a result, a mold

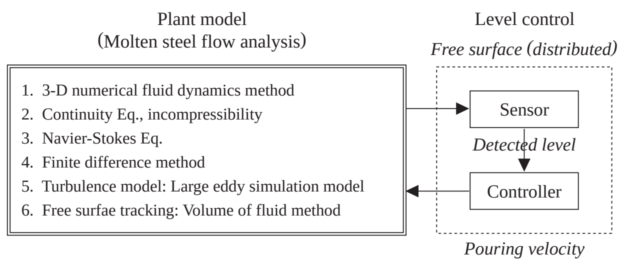

Fig. 1 Mold level control model based on molten steel flow analysis

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level control simulation in consideration of the turbulence of molten steel flow was made viable, and it became possible to accurately predict and evaluate the performance of mold level control at a high casting speed.

2. Continuous Casting Process

Before discussing the mold level control model, continuous casting equipment and mold level control, which constitute the background of the model, are briefly explained.

2.1 Continuous casting equipment

Continuous casting equipment are steel production facilities for efficiently producing slabs (or blooms or billets) for the subsequent rolling process by continuously solidifying molten steel after its refining in a steelmaking furnace such as a converter. Molten steel discharged from a ladle is temporarily stored in a tundish and then poured through an immersion entry nozzle into a mold the inside walls of which are lined with water-cooled copper plates. The solidification of the cast steel begins at its interface with the mold and progresses to attain complete solidification in the secondary cooling zone, and then the cast steel is cut to a prescribed length by a cutter. A continuous caster is schematically illustrated in **Fig. 2**.

2.2 Mold level control

As seen in Fig. 2, the mold steel level is continuously monitored with a sensor and its deviation from a prescribed target level is fed back to a controller, which outputs a signal to an actuating cylinder to adjust the opening of a sliding nozzle. The amount of molten steel flow into the mold is thus controlled and the mold steel level is controlled to the target level.

The fluctuation of the mold steel level is caused by disturbances originating from the filling and withdrawal systems of a caster. The disturbance originating from the filling system means, more specifically, the change of molten steel flow characteristics resulting from clogging of an entry nozzle with non-metallic inclusions, and that originating from the withdrawal system means periodical mold steel level fluctuation resulting from bulging (thermal deformation of cast steel) occurring in the water cooling zone of a caster.

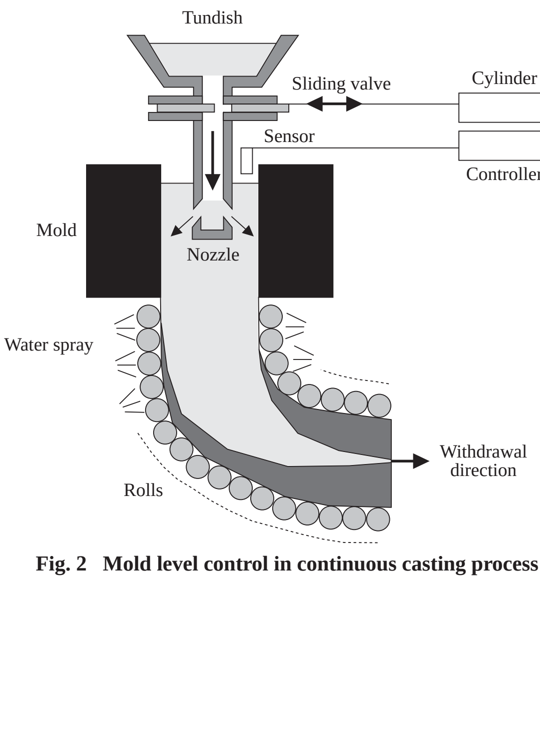

Fig. 2 Mold level control in continuous casting process

3. Mold Level Control Model

The developed mold level control model is explained here. The block diagram of the model was shown earlier in Fig. 1, and the explanations hereafter are focused on the component equations of the physical models to express the dynamics of the process in question. The developed model based on molten flow analysis is also compared with a conventional integral system model, and the difference between the two is clarified.

3.1 Integral system model

An integral system model takes into consideration only the static volumetric balance between the influx and outflux of molten steel, and assumes that the dynamic characteristic of the mold steel level can be expressed in terms of a simple integral system. In this case, the governing equation of the mold steel level is given in the form of the following linear ordinary differential equation:

$$h = \frac{1}{A}\int \left(V_{in} - V_{out}\right)dt \tag{1}$$

where h is the height of the mold steel level (m), A is the sectional area of a mold (m^2), V_{in} is the volumetric influx rate of molten steel (m^3/s), V_{out} is the volumetric outflux rate of molten steel (m^3/s), and t is time (s). Equation (1) means that the mold steel level changes in proportion to the volume of molten steel, and it gives a good approximation as far as the turbulence of molten steel flow little shows on the surface. However, in high-speed casting, in which the turbulence of molten steel flow shows itself as surface ripples, this kind of model is not effective any longer. In such a case, a model based on molten steel flow analysis as explained below is required.

3.2 Molten steel flow analysis model

A molten steel flow analysis model is based on a technique of fluid dynamics and is capable of accurately expressing the dynamic characteristics of mold steel level in consideration of turbulence of molten steel flow. When there is turbulence of molten steel flow, the molten steel flow in a mold is regarded as a 3-dimensional turbulent flow of a non-compressible fluid having a free surface, and its governing equations are given in the form of the following non-linear partial differential equations:

$$0 = \nabla \cdot u \tag{2}$$

$$\frac{\partial u}{\partial t} + u \cdot \nabla u = -\frac{1}{\rho}\nabla P + \nu_e \nabla^2 u + g + F \tag{3}$$

Equation (2) is that of continuity and equation (3) that of conservation of momentum, where u is the flow rate of molten steel (m/s), ρ is the density of molten steel (kg/m^3), P is pressure (N/m^2), ν_e is effective kinematic viscosity (m^2/s), g is gravitational acceleration (m/s^2), and F is a term of an external force (m/s^2). A large eddy simulation (LES) model is used as a turbulence model in order to express the disturbance, or the time difference, of a turbulent flow. The position of the boundary of a free surface is defined by the volume of fluid (VOF) method.

The time differences of molten steel flow rate and the free surface are calculated by discretizing these equations using the calculus of finite difference and numerically solving them using the iterative analysis method. **Fig. 3** shows the boundary conditions of a molten steel flow analysis model.

A physical model to accurately express the molten steel flow in a mold and the dynamic characteristics of a whole molten steel surface is thus constructed. This model is capable of accurately expressing the dynamic characteristics of molten steel surface at high-speed casting.

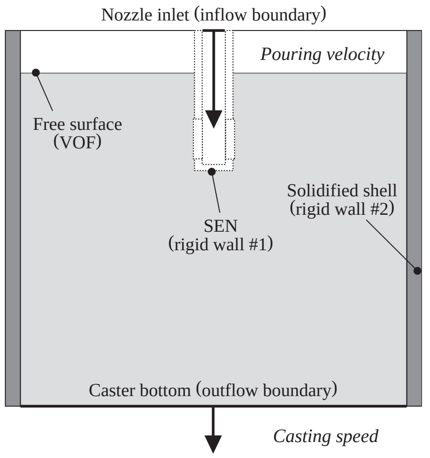

Fig. 3 Boundary conditions of molten steel flow analysis model

4. Mold Level Control Simulation

Usefulness of the mold level control model based on molten steel flow analysis in actual application is explained below based on simulation results. The results obtained using an integral system model are also explained for comparison purposes. The conditions for the analysis are shown in **Table 1**. The simulation results were analyzed under a condition of high-speed casting for the purpose of predicting the influence of turbulence of molten steel flow over the mold level control. Assuming the occurrence of bulging as an external force, a mold steel level fluctuation having a cycle time of 10 s (= a frequency of 0.10 Hz) was imposed, the molten steel level was monitored with a sensor, and the amount of molten steel influx was controlled applying PI control.

4.1 Integral system model

Fig. 4 shows the time fluctuation of detected molten steel level calculated by the simulation using an integral system model, and **Fig. 5** its power spectrum. It is clear from the figures that the integral system model detected only a molten steel level fluctuation having a frequency of 0.10 Hz caused by the imposed external force.

4.2 Molten steel flow analysis model

Fig. 6 shows the time fluctuation of detected molten steel level calculated by the simulation using the molten steel flow analysis model, and **Fig. 7** its power spectrum. It is clear from the figures that the molten steel flow analysis model detected not only the level fluctuation of 0.10 Hz but also a high-frequency level fluctuation having a frequency of approximately 0.70 Hz. The 0.70-Hz level fluctuation is presumed to represent a stationary wave in a mold. Here, the frequency of the stationary wave is calculated using the following theoretical equation:

$$f = \frac{1}{2\pi}\sqrt{\frac{N\pi g}{L}} \qquad (4)$$

where f is frequency (Hz), N is an integer (–), g is gravitational acceleration (m/s^2), and L is the width of a mold (m). When N = 1 and L = 1,500, then f = 0.71 Hz is obtained from equation (4), which value agrees well with the frequency of the rippling obtained by the molten steel flow analysis model.

The fact that such high frequency rippling is observed in actual caster operation serves as evidence of the capability of the molten steel flow analysis model to accurately reproduce the dynamic characteristics of molten steel level. **Fig. 8** is an example mold steel level chart of a commercially operated caster, wherein rippling having a frequency of roughly 1.00 Hz is detected.

With the molten steel flow analysis model, it is possible to evaluate not only a detected mold level but also a whole molten steel surface in a mold. **Figs. 9 and 10** show the distributions of the average and standard deviation, respectively, of mold steel level in mm,

Table 1 Analysis conditions of mold level control simulation

Mold width	Mold thikness	Casting speed	Reference level	Control method
1,500 mm	240 mm	2.1 mpm	–5 mm	PI

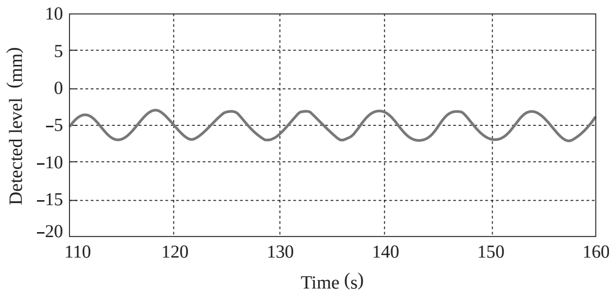

Fig. 4 Detected molten steel level calculated by integral system model

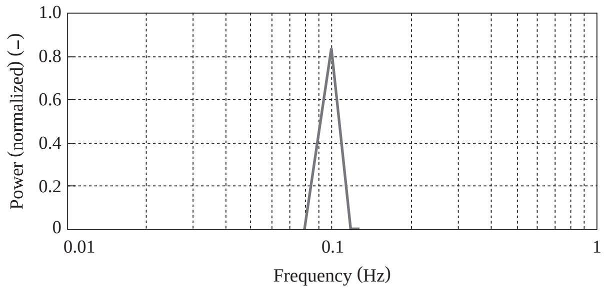

Fig. 5 Frequency characteristic of detected molten steel level fluctuation calculated by integral system model

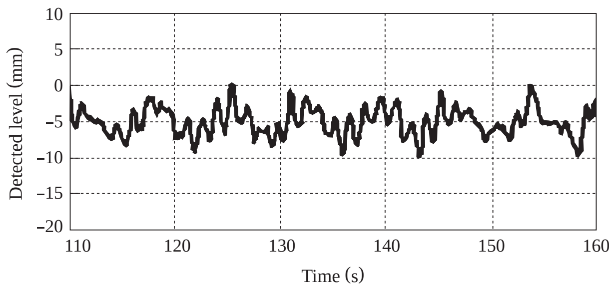

Fig. 6 Detected molten steel level calculated by molten steel flow analysis model

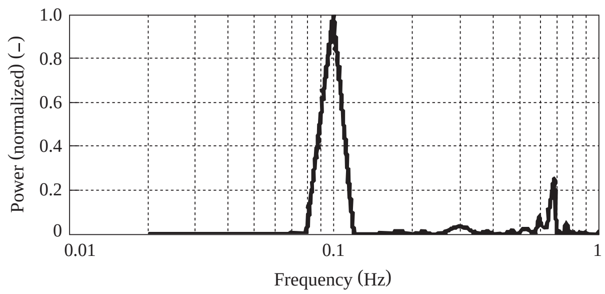

Fig. 7 Frequency characteristic of detected molten steel level fluctuation calculated by molten steel flow analysis model

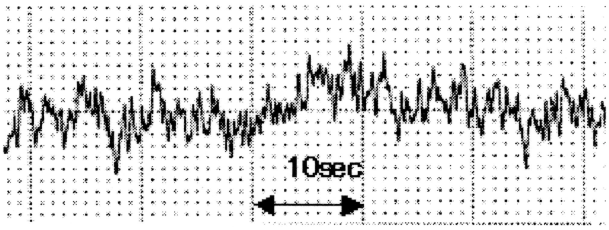

Fig. 8 Mold steel level chart in commercial operation

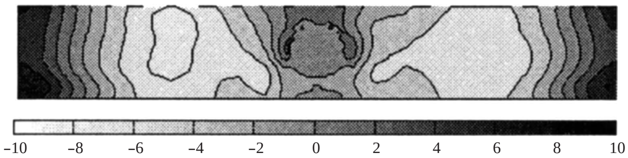

Fig. 9 Average molten steel level in mold (analysis)

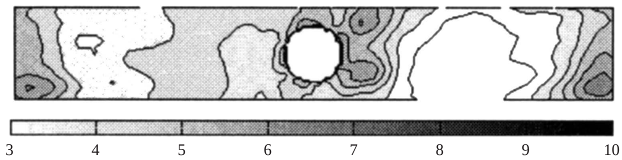

Fig. 10 Standard deviation of molten steel level in mold (analysis)

wherein the darker the area, the larger the value. The white area in Fig. 10 is the area where the mold steel level is detected and controlled with a sensor, and it is seen in the figure that the mold steel level fluctuation is well controlled near the white area. In contrast, the mold steel level fluctuation in other areas is not controlled and especially in the opposite side where no sensor is provided, the fluctuation is large. The above indicates that mold level control suppresses local level fluctuations only.

It is also seen in the figures that the molten steel level is high near the mold narrow faces and around the submerged entry nozzle, and the level fluctuation is also large in these areas. This is considered to reflect the molten steel flow in the mold. **Fig. 11** shows the distribution of the vector of time average flow rate of molten steel at the thickness center of a mold. The molten steel flowing from the entry nozzle hits the narrow faces and strong upward circulating flows are formed there. Here, it is seen that the strong upward flows along the narrow face walls lift the molten steel surface near them. The molten steel level is high also around the entry nozzle, because the circulating flows from both the sides run into each other there, and as a result, the level fluctuation is also large in this area.

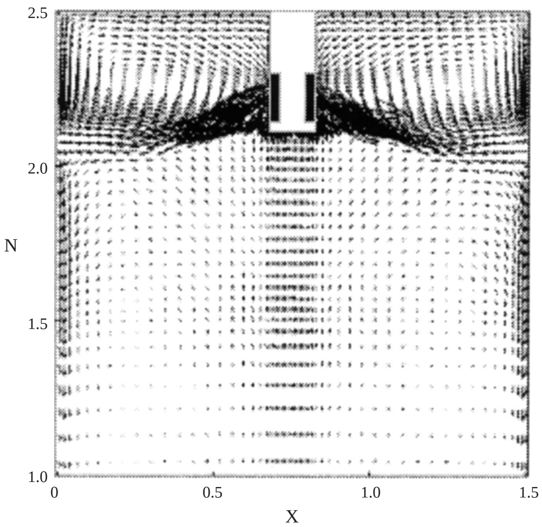

Fig. 11 Distribution of time average of molten steel flow rate at mold thickness center (analysis)

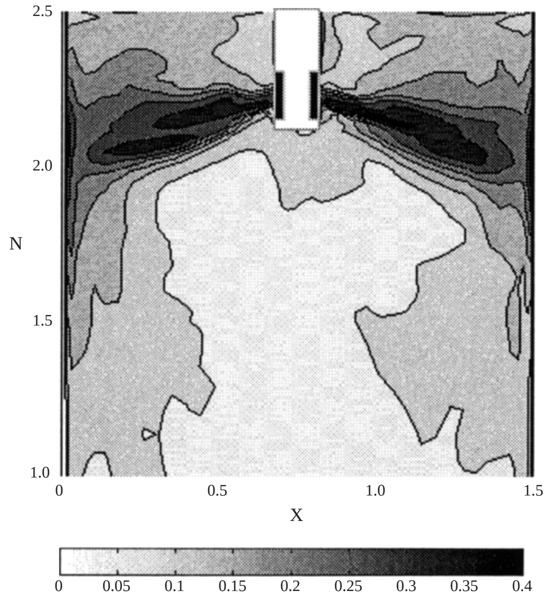

Fig. 12 Distribution of standard deviation of molten steel flow rate at mold thickness center (analysis)

Fig. 12 shows the distribution of standard deviation of molten steel flow rate at the thickness center of the same mold in m/s; the darker the area, the larger the value. It is seen in the figure that the whole molten steel in the mold is significantly disturbed by the influx from the nozzle. It is considered that the turbulence becomes significant as the speed of the incoming flow becomes high, showing itself as the rippling of the molten steel surface.

As stated above, it has been demonstrated that a molten steel flow analysis model enables a realistic mold level control simulation reflecting the turbulence of molten steel flow.

5. Closing

A mold level control model applying molten steel flow analysis has been formulated, and thus a realistic mold level control simulation reflecting the turbulence of molten steel flow has been made possible. The effectiveness of the developed model has been confirmed through simulations. A mold level control system based on the developed model will be designed for application to high-speed casting operation, and its effectiveness will be evaluated through tests in actual operation.

References

1) Suzuki, D. et al.: Level Control Model by Numerical Fluid Dynamics Method. Proceedings of the Fourth International Conference on Intelligent Processing and Manufacturing of Materials. IPMM'03. 2003(CD-ROM)