Fifth International Conference on CFD in the Process Industries
CSIRO, Melbourne, Australia
13-15 December 2006

MECHANISM OF THE DRIFT FLOW IN CONTINUOUS CASTING AND THE EFFECT ON THE DRIFT FLOW USING THE ELECTROMAGNETIC FIELD

Kentarou SATOU[1], Ryu HIRAYAMA[2], Keisuke FUJISAKI[1,2], Shouji TANIGUCHI[1], Shouji SATOU[3],

[1] Graduate School of Environmental Studies, Tohoku University, Sendai, Miyagi 980-8579, Japan`
[2] Environment & Process Technology Center, Nippon Steel Corporation, Futtsu, Chiba, 293-8511, Japan
[3]N-Tec Oita Engineering Corporation, Nishinosu, Oita, 870-0902, Japan

ABSTRACT

The drift flow of the molten steel in the mold of the continuous casting and its influence of the in-mold electromagnetic stirrer(M-EMS) are analyzed using unsteady and three-dimensional magneto hydrodynamic calculation. The drift flow is possible to be generated by the influence of only turbulence in the mold. Nozzle clogging also causes the drift flow and the meniscus shape fluctuation. Flow of non-clogging side is larger than that of clogging side at any time. Fluctuation of the drift flow by the influence of turbulence is twice as large as that of the nozzle clogging. Sliding gate makes one-sided flow in the nozzle and causes the drift flow. The meniscus height of open side tends to be higher than that of close side. Fluctuation range of the meniscus height to result from the sliding gate is smaller than that to result from turbulence from the viewpoint of moving average. The M-EMS makes the drift flow larger.

NOMENCLATURE

$\boldsymbol{v}$ velocity(m/s)
ρ density(kg/m^3),
η viscous efficient (kg/m･s)
$\boldsymbol{F}_{em}$ electromagnetic force(N/m^3)
$\boldsymbol{g}$ gravity acceleration (m/s^2)
$\boldsymbol{p}$ pressure (Pa)
μ viscosity(Pa･s)
$\boldsymbol{A}$ vector potential(Wb/m)
$\boldsymbol{J}_0$ current density(A/m^2)
ϕ scalar potential(V/m)
D electric flux density(C/m^2)
P_1 pressure before pressure drop(Pa)
P_2 pressure after pressure drop(Pa)
C_2 coefficient(-)
Δm thickness of the porous film(m)
H meniscus height(m)
ΔH difference in meniscus height(m)
H_L meniscus height of the left side (non-clogging side in nozzle clogging model and open side in sliding gate model) (m)
H_R meniscus height of the right side (clogging side in nozzle clogging model and close side in sliding gate model) (m)

INTRODUCTION

Drift Flow Phenomena

Recently, high quality steel such as high-strength steel is required by a demand of automobile users. In order to produce the high-quality steel, a reduction of non-metallic inclusions is necessary in the solidified steel at the casting process, because it is much harmful to the surface quality in the final production, and their removal is impossible at the later steel making process. Since the non-metallic inclusions are small enough such as less than 0.1mm diameter, they follow the molten steel flow dynamics. Therefore, the dynamics variation of the molten steel flow is considered to cause damage to the attachment of the non-metallic inclusions. One of the reasons for the flow disturbance includes the drift flow which is the asymmetry flow in the mold. The drift flow is considered to be caused by the following phenomena of the molten steel.
(1) Turbulent flow of the molten steel.
(2) Nozzle clogging by the attachment of the non-metallic inclusions to the inside of the nozzle[1][2].
(3) One-sided flow at a sliding gate position of the nozzle[3].
(4) One-sided flow from a tundish through the nozzle.

The degree how these factors makes an effect on the drift flow isn't made clear. This work is intended to explain the quantity of influence of the drift flow occurrence to the considered mechanism. This paper explains the influence of turbulence flow and nozzle clogging which is written in the above paragraph as the drift flow occurrence (1) and (2). The hydrodynamic numerical calculation is used to investigate it, because the on-line flow of the molten steel is almost impossible to measure and ideal phenomena is possible to evaluate in the numerical calculation.

In-Mold Electromagnetic Stirrer

In-mold electromagnetic stirrer (M-EMS) is used as the control tool of the molten steel flow in the mold[4]. The M-EMS is driven by the electrical power source of three-phase alternating current, and produces the traveling magnetic flux to the molten steel. The M-EMS makes some electromagnetic force in the molten steel to obtain some velocity. Some velocity at the molten steel is useful for preventing to attach the non-metallic inclusions which cause the bad steel quality. However, it isn't clear that M-EMS effects the improvement of the molten steel flow in the drift flow condition. Therefore we obtain the molten steel flow characteristics in that condition by using the magneto hydrodynamic calculation[5].

NUMERICAL CALCULATION METHOD

Fluid Dynamics Calculation[5]

Fluid dynamic calculation consists of the Navier-Stokes equation and the equation of mass continuity. To assume that the molten steel is incompressible fluid, the next equations are defined.

$$\rho\left(\frac{\partial \boldsymbol{v}}{\partial t}+\boldsymbol{v}\cdot\nabla\boldsymbol{v}\right)=-\nabla \boldsymbol{p}+\eta\nabla^{2}\boldsymbol{v}+\rho\,\boldsymbol{g}+\boldsymbol{F}_{em} \quad (1)$$

$$\nabla\cdot\boldsymbol{v}=0 \quad (2)$$

Finite volume method is used, and the basic algorithm is SIMPLE method. We use LES (Large Eddy Simulation) method as the turbulence model, because the Reynolds number is enough high to be 8.74×10^{4} in the process.

Electromagnetic Calculation [6]

To obtain the stirring force to the molten steel driven by the M-EMS, we make an electromagnetic field calculation based on Maxwell equations. The method of electromagnetic field is A-φ method and quasistatic method described as [10].

$$\nabla\times\left([\mu]^{-1}\cdot\nabla\times\boldsymbol{A}\right)=\boldsymbol{J}_0-\sigma\left(\frac{\partial\boldsymbol{A}}{\partial t}+\nabla\phi\right) \quad (3)$$

$$\boldsymbol{F}_{em}=\sigma\left(\frac{\partial\boldsymbol{A}}{\partial t}+\nabla\phi\right)\times\left(\nabla\times\boldsymbol{A}\right) \quad (4)$$

Finite element method is applied to the equation (3) for 3-dimensional space and solved by Galerkin method.

Then electromagnetic force of equation (4) is installed in the fluid dynamic calculation as a disturbance force of equation (1) and we calculate the velocity distribution. The effect of the electromotive force is assumed to be ignored in the electromagnetic field calculation of the M-EMS, because the synchronous speed of the M-EMS is much faster than that of the molten steel. Since it is difficult to calculate the same meshes to correspond the finite element mesh of the electromagnetic calculation and the staggered mesh of the hydrodynamic calculation, we interpolate both values of each calculation in the 3-dimentional field[11].

CALCULATION MODEL

Calculation Object

Table 1 shows a calculation model condition and Figure 1 shows a structure of the calculation object. The molten steel is poured through the submerged entry nozzle, and it is cooled down to be solidified gradually. Some powder is floating at free surface to make the casting operation smoothly, though the meniscus is expressed to the stationary wall to simplify the calculation. Boundary condition of the inlet upper the mold is set to the constant velocity and that of the outlet under the mold is set to keep up the same volume in the mold. Shear condition of the wall is applied no slip condition.

Casting Speed	1m/min
Discharged angle	90degree

Table 1 Computational model condition

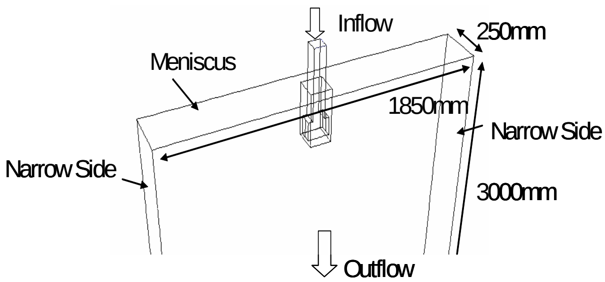


Figure 1. Computational Model.

Three Calculation models

To evaluate the influence of the drift flow to the molten steel flow in the continuous casting using the hydrodynamic calculation, we make three calculation models. There are basic model, the nozzle clogging model, and the sliding gate model.

Basic model shows Figure 1 and it has neither clogging discharge hole nor the sliding gate. This model evaluates the influence of the turbulent flow to the drift flow.

Nozzle clogging model expresses as the pressure drop using the porous jump boundary condition shown as Figure 2[8].Since the porous jump condition is employed when thin film provided pressure drop, the equation of the pressure drop is expressed as follows.

$$P_1-P_2=P_1\,C_2\rho v^2\Delta m \quad (5)$$

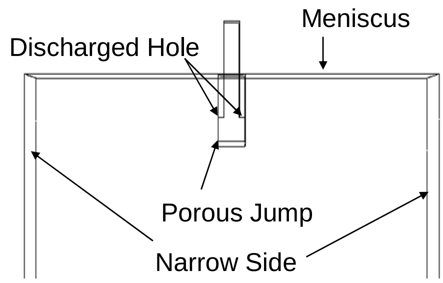


Figure 2. Nozzle Clogging Model

Sliding gate model is shown in Figure 3. Sliding gate is set to 700mm above the meniscus and open rate is 50 %.

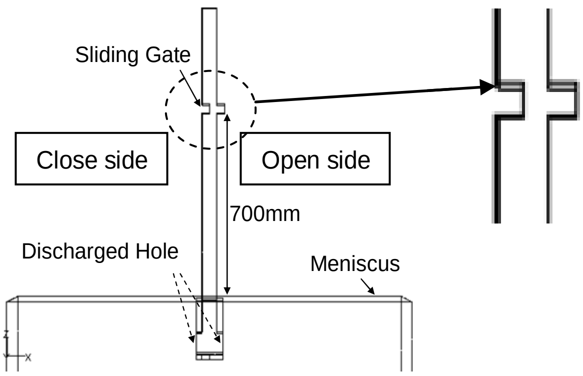


Figure 3 Sliding Gate Model.

Electromagnetic force driven by the M-EMS is applied to the basic model and the nozzle clogging model. Since the result of the basic model with M-EMS is already described in reference [12], we indicate the result of nozzle clogging model with M-EMS in this paper. The electromagnetic coil is set to make the rotating flow of the molten steel in the mold[7]. The electromagnetic force is adopted to the molten steel of all thickness and all width at the mold as shown in Figure 4.

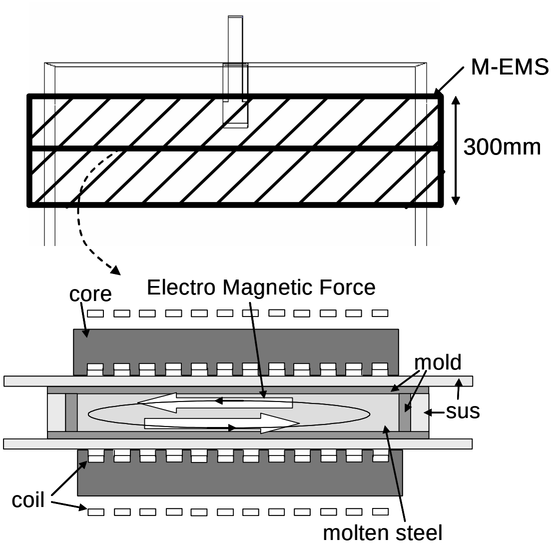


Figure 4. M-EMS Model.

Calculation conditions are chosen in order to evaluate factors of the drift flow and the influence of M-EMS to each factor. As shown in Table 2, Case 1 is the basic model with M-EMS non-applied, and it can evaluate the influence of the turbulence flow to the drift flow. Case 2 and Case 3 are nozzle clogging model where the M-EMS is applied to the Case 3. The influence of the nozzle clogging can be understood by comparing the Case 2 with the Case 1. The influence of M-EMS can be understood by comparing the Case 2 with the Case 3. Case 4 is the sliding nozzle model with M-EMS non-applied. The influence of the sliding gate to the drift flow is understood by comparing the Case 1 with the Case 4.

Case No.	Calculation model	M-EMS
1	Basic model	off
2	Nozzle clogging model	off
3	Nozzle clogging model	on
4	Sliding Gate model	off

Table 2. Calculation condition

CALCULATION RESULTS AND CONSIDERATION

Computational Results

The drift flow is considered to cause the large one-sided downward flow in the mold and the fluctuation at the meniscus. Since the downward flow is almost impossible to be detected directly in on-line condition, the one-sided downward flow seems to cause the difference of the meniscus height between the both narrow sides. To obtain the meniscus height in the stationary wall at the meniscus, the pressure of the meniscus is used by equation (6).

$$H = \frac{P}{\rho g} \tag{6}$$

To evaluate the difference of the meniscus height between both sides, the equation (7) is introduced. ΔH is used as an index of the drift flow.

$$\Delta H = H_L - H_R \tag{7}$$

Figure 5 shows the contour map of the meniscus height adopted by the equation (6) and the velocity vector of the molten steel at the 1/2 thickness of the mold at the time of 200 seconds.

Figure 6 shows the time variation of ΔH in each case. The pale solid line shows an instantaneous value and the dark solid line shows a moving average of 50 seconds. Table 3 shows the fluctuation range of ΔH.

Effect of turbulence flow to the drift flow

The basic model to evaluate the turbulence flow in the mold is the Case 1 in Figure 5. It is shown that the discharged flow from the discharged hole is symmetry, though the mold flow dynamics especially at the narrow sides is not symmetric. It means that the drift flow is possible to occur only by the turbulent flow in the mold.

As shown in the Case 1 of Figure 6 and Table 3, ΔH changes with time, though the time average of ΔH is 0mm at all iteration time. Therefore, meniscus shape is asymmetry instantaneously but symmetry in the time average condition at the case of drift flow caused by the turbulence.

Influence of nozzle clogging to the drift flow

As shown in the Case 2 of Figure 5, the meniscus height and the discharged velocity differ between the clogging side and the non-clogging side in the nozzle clogging model without the M-EMS. The discharged flow of the non-clogging side strikes the narrow side and separates upper and downward flow. Upper flow goes to the meniscus and goes toward the nozzle under the meniscus. The flow pattern of the molten steel at the non-clogging side is the same as that of the basic model. However, the discharged flow of the clogging side spreads near the nozzle because of viscosity resistance.

In the Case 2 of Figure 6, it is found that the meniscus height at the non-clogging side is higher than that of the clogging side, because ΔH has a plus value at any time. However, the fluctuation range of ΔH in the Case 2 has about half value as large as that of the Case 1. This reason is considered that the time fluctuation of the velocity at the discharged nozzle in the nozzle clogging model is smaller than that of the basic model, because the meniscus height is correlated with the velocity just under the meniscus.

Influence of the sliding gate to the drift flow

Sliding gate model changes the flow pattern in the nozzle to other case. Firstly, we describe the flow pattern in the sliding nozzle in the Case 4. Sliding gate brings to the velocity distribution in the nozzle. Figure 7 shows the distributions of the molten steel velocity and the pressure in the nozzle. From this figure, sliding gate makes large velocity of the molten steel at open side. As shown in broken line of (a) of Figure 7, upper flow generates just under the sliding gate because of the pressure gradient by the velocity gap between open side and close side as shown in (b) of Figure 7.

Next, we describe the molten steel flow in the mold and evaluate the influence on the drift flow in the sliding gate model. The influence of the sliding gate to the drift flow can be understood in the computational results of the Case 4. As shown in the Case 4 of Figure 5, the discharged flow runs out only lower side of the discharged hole which runs out all side of the discharged hole at other Case. Figure 8 shows the enlargement of the Figure 5 near the discharged hole. From this figure, the downward velocity in the nozzle speeds up by the sliding gate, and it strikes the bottom of the sliding nozzle before runs out from the discharged hole. Furthermore, Figure 8 shows the angles of the discharged flow are different in both sides of the discharged hole. Comparing the discharged flow of the open side, that of the close side has an upper angle. Since the downward flow in the nozzle is close to the discharged hole of the open side, the discharged flow of the open side runs out with the component of the downward velocity as shown in (a) of Figure 8. On the other hand, the discharged hole of the close side is far from the downward flow in the nozzle. The downward flow goes to the discharged hole of the close side along with the bottom of the nozzle as shown in (b) of Figure 8. Therefore, the discharged flow of the close side runs out from the discharged hole to the horizontal direction.

Meniscus shape of the sliding gate model in the Case 4 is not so changed against the basic model in the Case 1 as shown in Figure 5. Furthermore, meniscus height near the narrow side seldom changes in the both sides in the Case 4.

As shown in the Case 4 of Figure 6, the moving average value of ΔH is all negative. It indicates that the meniscus height of the closed side tends to become higher than that of the open side because of the angle of the discharged flow. On the other hand, though the fluctuation range of the instantaneous value in the Case 4 is almost the same as that in the Case 1, the moving average fluctuation of ΔH in the Case 4 is smaller than that in the Case 1. It is thought that fluctuation time of ΔH in the Case 4 becomes shorter than that in the Case 1 because of increase of the discharged velocity.

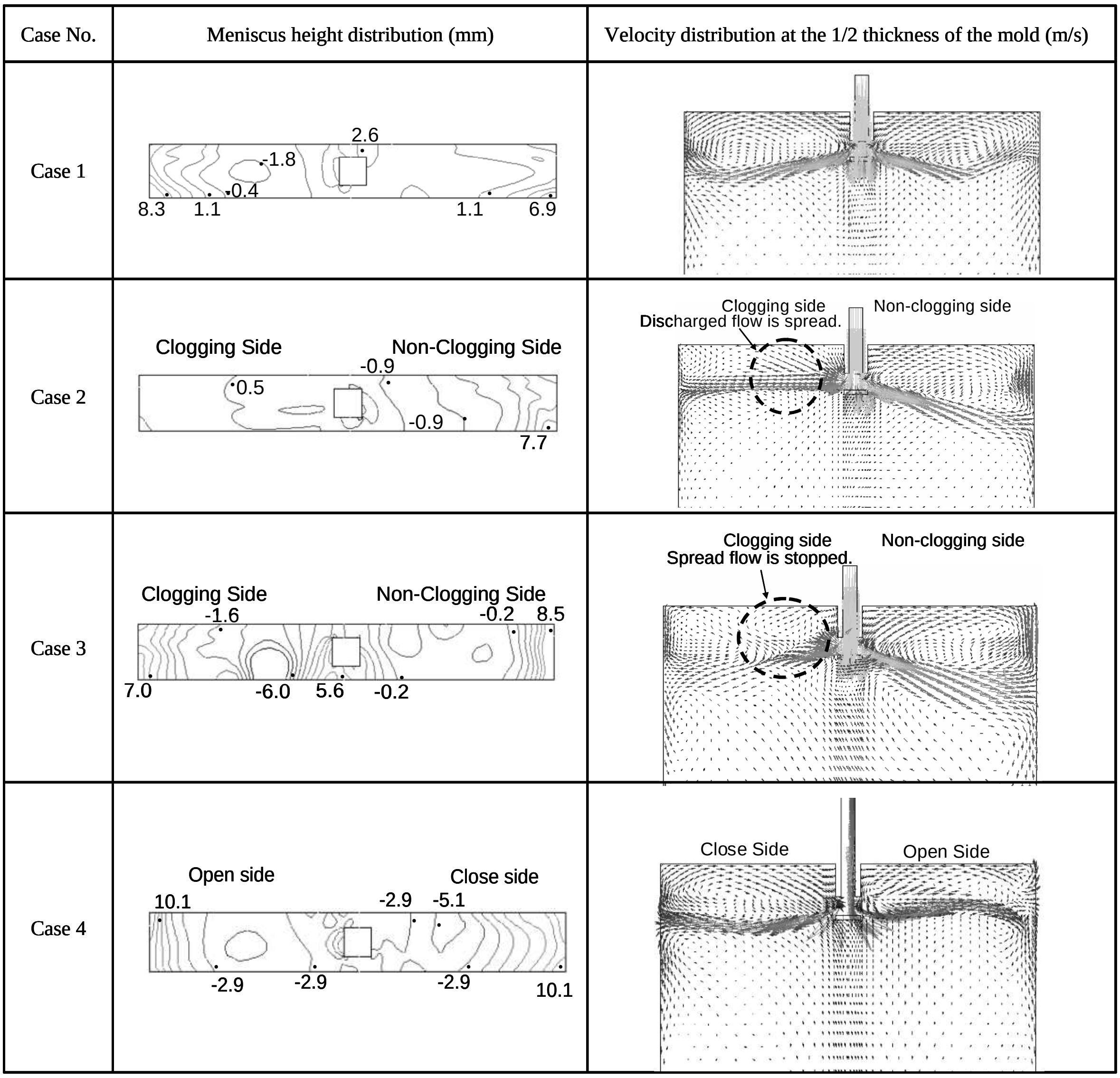
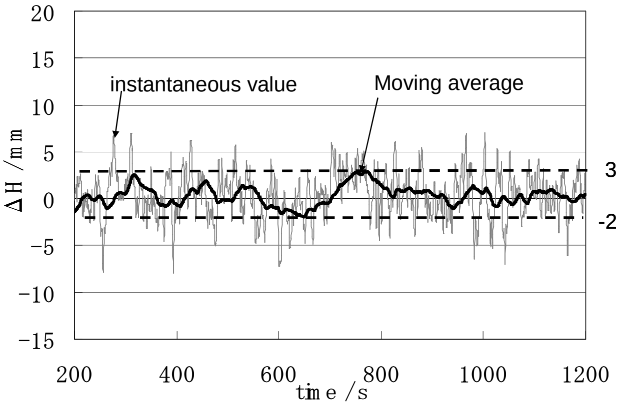
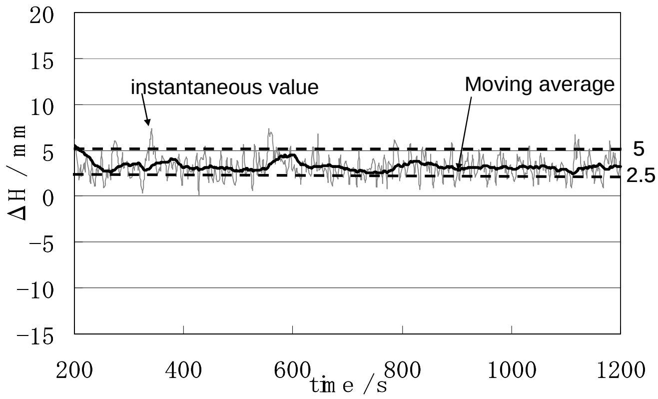


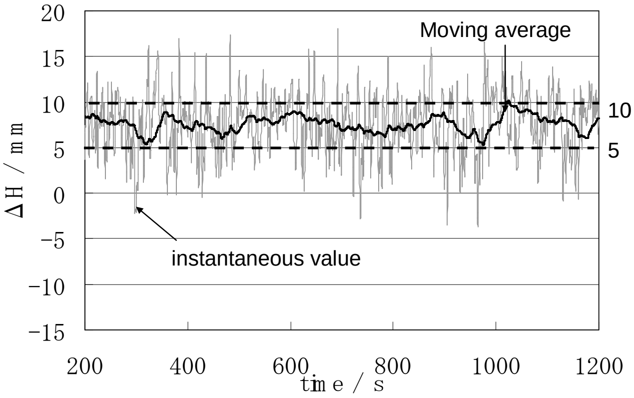
Figure 5. Distribution of meniscus height and the velocity



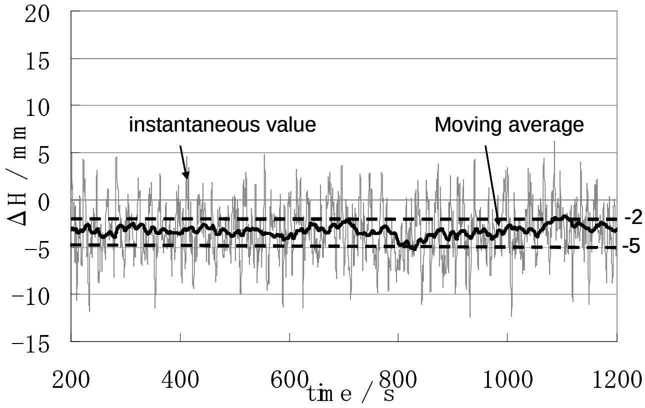
Case 1 Basic model (1200s)



Case 2 Nozzle clogging model (1200s)



Case 3 Nozzle clogging model with M-EMS (1200s)

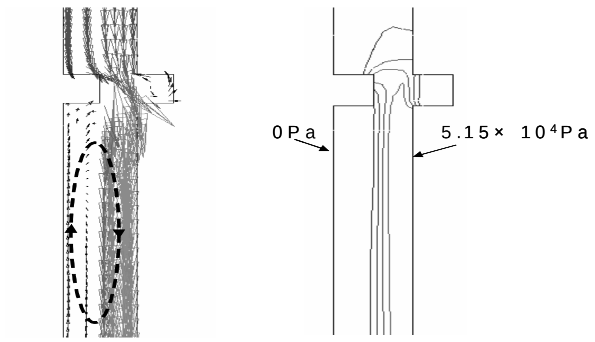


Case 4 Sliding gate model (1200s)

Figure 6. Fluctuation with time of ΔH.

	Case 1	Case 2	Case 3	Case 4
Fluctuation range (mm)	5	2	5	3
Maximum	3	4.5	10	-2
Minimum	-2	2.5	5	-5
Average value	0	3.5	5	-3

Table 3 Fluctuation range of ΔH.



(a) vector of velocity (b) contours map of pressure

Figure 7. Molten steel velocity of the sliding gate.

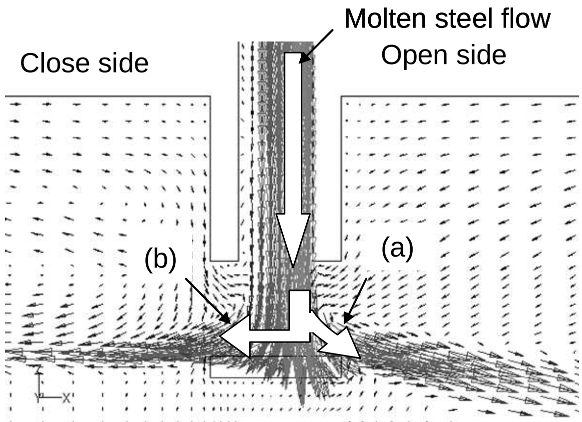


Figure 8. Molten steel velocity of the discharged hole.

Influence of M-EMS to the drift flow of the nozzle clogging model.

We describe the influence of the M-EMS to the nozzle clogging model. As shown in the Case 4 of Figure 5, spread flow near the nozzle of the Case 3 is suppressed by the M-EMS applied in the nozzle clogging model. It is thought the velocity of the discharged flow is increased by the electromagnetic force of the M-EMS and it isn't affected by viscosity resistance.

In comparing the Case 2 with the Case 3 in Figure 6, the average value and the fluctuation range of ΔH of the Case 3 are larger than those of the Case 2. It indicates the M-EMS makes large the drift flow at the nozzle clogging.

CONCLUSION

The drift flow of the molten steel in the mold of the continuous casting and its influence of the M-EMS are analyzed using unsteady and three-dimensional magneto hydrodynamic calculation. The results are as follows.

(1) Turbulent flow generates the drift flow and the meniscus height distribution is symmetry with time averaged.

(2) Nozzle clogging with the attachment of the non-metallic inclusions also causes the drift flow and the meniscus height distribution is asymmetry. Meniscus height fluctuation range to result from the nozzle clogging is half as large as that to result from the turbulence. Furthermore, the velocity of the non-clogging side is larger than that of the clogging side at any time.

(3) The sliding gate also causes the drift flow and the meniscus height distribution is symmetry. Upper flow is generated in the nozzle under the sliding gate. Meniscus height of the closed side tends to become higher than that of the open side. Meniscus height fluctuation range to result from the sliding gate is smaller than that to result from the turbulence from the viewpoint of moving average because of shorter cycle time of the meniscus height fluctuation.

(4) Fluctuation range of the meniscus height becomes large by using the M-EMS. The M-EMS has no effect to frequency of the drift flow in case of the nozzle clogging model.

ACKNOWLEDGMENT

We appreciate Dr. Shin-ichi Shimasaki due to assist of our research especially about technique of numerical calculation.

REFERENCES

[1] Technical paper of Kobe steel: *Steel making conference of ISIJ*, **104**(4), 1991,(in Japanese).

[2] Technical paper of Nippon steel: *Steel making conference of ISIJ*, **104**(2), 1991,(in Japanese).

[3] N.Kubo, T.Ishii, J.Kubota, N.Aramaki, *ISIJ international,* **41**(10), 1221-1228, 2001.

[4] K.Fujisaki, *IEEE Trans. on Industry Applications*, **37**(4), 239-240, 2003.

[5] K.Takatani, *ISIJ international,* **43**(6), 915-922, 2003.

[6] S.Satou, K.Fujisaki, T.Furukawa, *International Journal of Applied Electromagnetic and Mechanics* **19**(1-4), 653-658, 2004.

[7] R.Hirayama, K.Fujisaki, T.Yamada, *IEEE Trans. on Magnetics*. **40**(4), 2095-2097, 2004.

[8] Fluent Inc., Fluent User's Guid, 6.22, 2002.

[9] Y.Miki, S.Takeuchi, *ISIJ international*, **43**(10), 1548-1555, 2003.

[10] T.Ueyama, K.Shinkura and R.Ueda, *IEEE Trans. on Magnetics*, **25**(5), 4153-4155, 1989.

[11] K. Fujisaki, T.Ueyama and K.Okazawa, *IEEE Trans on Magnetics*, **33**(2), 1642-1645, 1997.

[12] K.Satou, R.Hirayama, K.Fujisaki, *Proceedings of EPM2006*, 51-56, 2006.