MATHEMATICAL MODELING OF MOLD POWDER INFILTRATION AND HEAT EXTRACTION NEAR MENISCUS IN CONTINUOUS CASTING

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INTRODUCTION

The infiltration of mold powder between the strand and mold near meniscus affects operational problems such as breakout and surface quality of the strand in continuous casting [1)-5)]. Although the mechanism of powder infiltration has not been fully understood, various problems in slab quality and casting operation have been overcome by optimizing such factors as powder properties, oscillation condition, molten steel flow near meniscus, etc. It is, however, still considered important to understand the infiltration mechanism of mold powder, because much improvement in operational and quality-related problems is required in higher casting velocity.

Under these circumstances, some cold or hot model experiments have been reported in the literatures [6)-8)], but none of them fully succeeded in simulating the features of powder infiltration phenomenon, probably because most of the factors near meniscus such as heat extraction, solidification of steel shell and powder, withdrawal of solidified shell, temperature distribution in the mold, meniscus profile near the mold, etc. are all related in affecting the infiltration of mold powder.

Theoretical approaches to understand the powder-related phenomenon near meniscus have also been reported in the literatures [9)-11)], but most of them focused their efforts on explaining the mechanism of oscillation mark formation, where at least a part of the geometry of powder channel were treated as a given condition for the calculation. As a result, there has been few previous works that succeeded in theoretically calculating liquid and solid film thickness between the strand and mold and heat extraction in the mold.

In the present study, mathematical model has been developed that can predict powder film thickness of both liquid and solid phase, thereby predicting heat extraction in the mold.

MATHEMATICAL MODEL

Schematic illustration near meniscus is shown in Fig. 1. Near the meniscus, the surface of molten steel near the mold bends toward the inward of the bulk liquid due to the interfacial tension [9)]. Steel begins to solidify at its surface below the meniscus, with substantial starting point of solidification at M and reaches the closest to the mold at the point P in Fig. 1. The regions above and below the point M are called region 1 and region 2 respectively in Fig. 1. The pressure inside the powder channel between the shell and mold varies depending on the mold oscillation, withdrawal velocity of shell, dimension of powder channel and static pressure of molten steel, etc. Although the pressure inside the powder channel is greater than atmospheric pressure near meniscus, there will be a certain position in the longitudinal direction between the point P and mold exit where the pressure equals to the atmospheric pressure due to the shrinkage of solidified shell. The region between this position and meniscus is the area taken into consideration in this model.

Mathematical Model for Liquid Film Thickness

Assuming one-dimensional movement of powder between the shell and mold, Navier-Stokes equation is given by equation (1).

$$\eta \frac{\partial^2 u}{\partial y^2} = \frac{dp}{dx} - \rho_f g \qquad (1)$$

where, x : axis in the longitudinal direction

y : axis in the thickness direction

η : viscosity of mold flux

p : pressure inside the flux channel

ρ_f : density of flux

g : acceleration of gravity

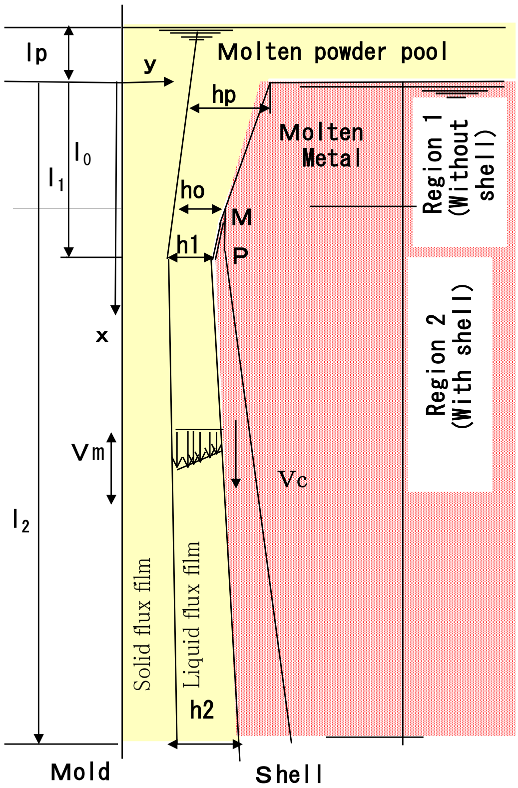

Fig. 1 Schematic illustration near meniscus.

If powder channel profile, h(x), is given, equation (1) is solved by the boundary conditions given in equation (2) and one can obtain pressure gradient at any position x as a function of h(x) as shown in equation (3), where Q is powder consumption rate which is independent on x.

$$u = V_m \quad \text{at } y = 0$$
$$= 0 \ \text{ or } V_c \quad \text{at } y = h(x) \quad \text{in region 1 or region 2} \qquad (2)$$

where, V_m : mold velocity, V_c : casting velocity, $h(x)$: liquid thickness of flux film

$$\frac{dp}{dx} = (V_c + V_m)\frac{6\eta}{h(x)^2} - \frac{12\eta}{h(x)^3} Q + \rho_f g \qquad (3)$$

where, $Q = \int_0^{h(x)} u(x,y)dy$: Flux consumption rate

$$p = \rho_f g l_p \quad \text{at } x = 0$$
$$= 0 \quad \text{at } x = l_2 \qquad (4)$$

Integrating equation (3) under the boundary condition shown in equation (4), the pressure inside the powder channel is expressed as shown in equations (5) and (6) for region 1 and region 2 respectively, where powder consumption rate is expressed as equation (7).

According to equations (5) and (6), it is easily found that pressure in the region between the point P and channel exit is less than static pressure of molten steel unless h2 is far less than h1. Since the pressure at the channel exit equals to atmospheric pressure, which is less than static pressure of molten steel, it will be reasonable to assume that substantial pressure of molten steel acting on the channel is decreased due to the rigidity of solidified shell. Similarly, at the point P where shell rigidity might be very small, substantial pressure acting on the channel could be smaller than static pressure of molten steel, due to either the interfacial tension or shell rigidity.

Based on the above–mentioned discussions, it is assumed in the present study that there exists some factor such as shell rigidity which decreases the static pressure of molten steel acting on the channel. Namely, equations of pressure balance are defined as shown in equations (8) and (9), taking into account of pressure decrease due to shell rigidity or interfacial tension. The values of liquid film thickness at the point P (channel inlet) and at channel outlet, h1 and h2, were determined by solving equations (5), (6), and (7) under the boundary conditions of equations (8) and (9), assuming linear profile of powder channel and neglecting mold oscillation. Δ p and G are assumed constant and their values are determined so that calculated behavior of powder infiltration will be basically consistent with actual phenomena as well as the rough calculations of pressure difference due to interfacial tension and thermal stress of shell. The thickness of molten powder pool and channel thickness at meniscus used in the calculation are 10mm and 5mm respectively. The values of the distance from meniscus to the point M (l_0) and to the channel outlet (l_2) are

$$p(x) = p(0) + 6\eta V_m \varepsilon(0,x) - 12\eta Q \xi(0,x) + \rho_f g x \qquad for\ 0 \le x \le l_0\ (region\ 1) \tag{5}$$

$$p(x) = p(l_0) + 6\eta (V_m + V_c)\varepsilon(l_0,x) - 12\eta Q \xi(l_0,x) + \rho_f g(x - l_0) \qquad for\ l_0 \le x \le l_2 (region\ 2) \tag{6}$$

$$where, \qquad Q = \frac{\{p(0) + 6\eta V_m \varepsilon(0,l_0) + 6\eta(V_m + V_c)\varepsilon(l_0,l_2) + \rho_f g l_2}{12\eta\xi(0,l_2)}, \tag{7}$$

$$\varepsilon(a,x) = \int_a^x \{1/h(x)^2\}dx, \qquad \xi(a,x) = \int_a^x \{1/h(x)^3\}dx,$$

assumed as l_1-0.5mm and l_1+100mm, respectively and channel thickness at the point M is assumed to be h_1+0.2mm. Here, l_1 is the distance from meniscus to the point P in Fig. 1 and h_1 is the channel thickness at the point P. l_1 is assumed to be 10mm in the mathematical model for liquid film thickness, but in the final model where models for liquid film and solid film are combined, l_1 is determined by the condition of thermal equilibrium.

$$p(l_1) = p(0) + \rho_f g l_1 - \Delta p \qquad at\ \ x = l_1 \tag{8}$$

$$\int_{l_1}^{l_2} p(x)dx = \int_{l_1}^{l_2} (p(0) + \rho_{Fe} g x)dx - G \qquad at\ \ x = l_2 \tag{9}$$

$$where,\ \Delta p = 4.25 \times 10^{-3} atm: \ pressure\ decrease\ due\ to\ \text{interfacial}\ tension\ or\ \ shell\ rigidity$$

$$G = 1.5\rho_{Fe} g(l_2 - l_1)^2/2: \quad average\ shell\ rigidity\ in\ region\ 2.$$

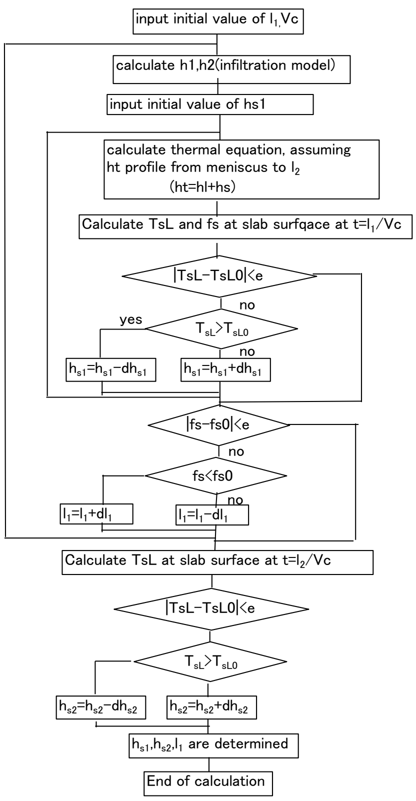

Fig. 2 Algorithm of model for solid film thickness.

Mathematical Model for Solid Film Thickness

In the above-mentioned model for liquid film thickness, l_1, distance from meniscus to the position of channel inlet P, was assumed constant. However, this position would vary during casting due to casting velocity, meniscus perturbations such as level fluctuation etc., being influenced by heat extraction through infiltrated liquid and solid powder film.

In the present study, it is assumed that thickness of solid film as well as the position of channel inlet (l_1) is determined by thermal equilibrium between molten steel and mold. In other word, thickness of solid film was calculated by iteration so that the temperature of the interface of liquid and solid film (hereafter abbreviated as TSL in figures) equals to the solidification temperature of mold powder for a given value of liquid film thickness. The position of channel inlet was calculated by iteration so that the fraction solid of shell surface at the position P equals to 0.8. When the position of channel inlet changes, calculated liquid film thickness would be changed. Therefore, calculation of solid film thickness and position of channel inlet are combined with the calculation of liquid film thickness by iteration. Calculations of heat flow and solidification are numerically conducted by one-dimensional finite difference method 、 where steel composition were assumed as 0.12%C-0.2%Si-1.2%Mn-0.01%P-0.005%S.

RESULT OF CALCULATION

Influence of Casting Velocity on Powder Infiltration

An example of calculated powder consumption is shown in Fig. 3 as a function of casting velocity. Calculated powder consumption decreases with increasing casting velocity as expected from actual casting behavior. Fig. 4-a and Fig. 4-b show calculated liquid film thickness and total film thickness at channel inlet and channel outlet as a function of casting velocity. It is noted that both liquid film thickness and solid film thickness decrease with increasing casting velocity. Fig. 5 shows the liquid film thickness at channel inlet and channel outlet. As shown in Fig. 5, Liquid film thickness drastically decreases with increasing casting velocity especially at channel outlet, resulting in drastic decreasing tendency of powder consumption with increasing casting velocity.

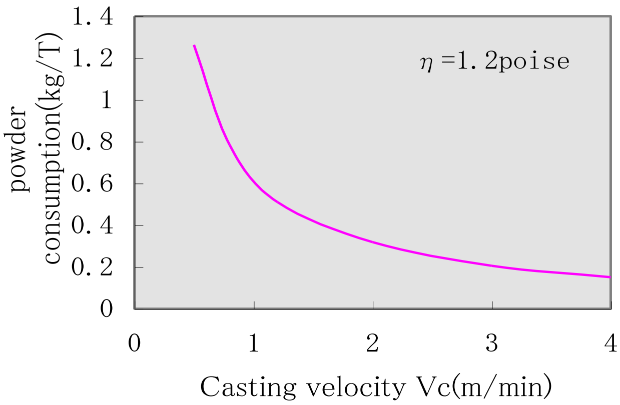

Fig. 3 Calculated powder consumption as a function of casting velocity.

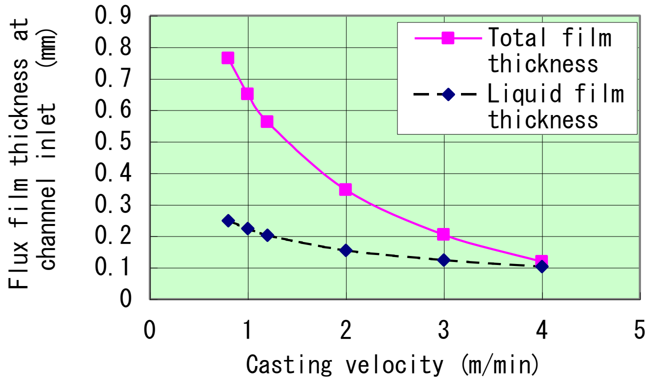

Fig. 4-a Film thickness as a function of casting velocity at channel inlet. (1.2poise, TSL=1170℃)

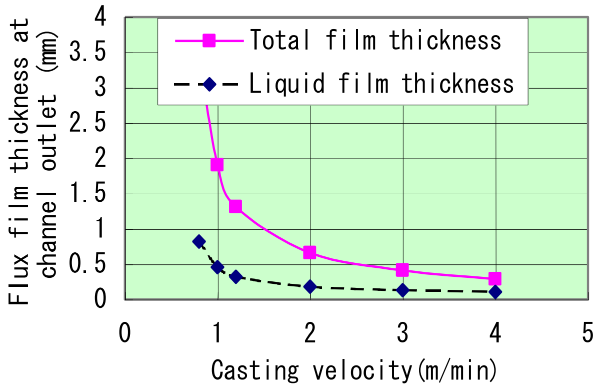

Fig. 4-b Film thickness as a function of casting velocity at channel outlet. (1.2poise, TSL=1170℃)

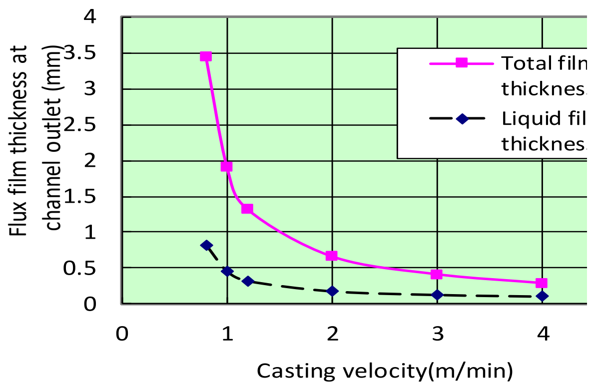

Fig. 5 Liquid film thickness as a function of casting velocity. (Viscosity=1.2poise, TSL=1170℃)

Calculated heat flux is shown in Fig. 6 for channel inlet and channel outlet as a function of casting velocity. Calculated heat flux decreases with increasing casting velocity. Heat flux at channel outlet, which is located 100mm downward from channel inlet in this calculation, is smaller than that at channel inlet. Decreasing tendency of heat flux with decreasing casting velocity and with increasing distance from meniscus shows good agreement with actual phenomenon. This is caused because film thickness of both liquid and solid phase decreases with increasing casting velocity as shown in Fig. 4a and Fig. 4b.

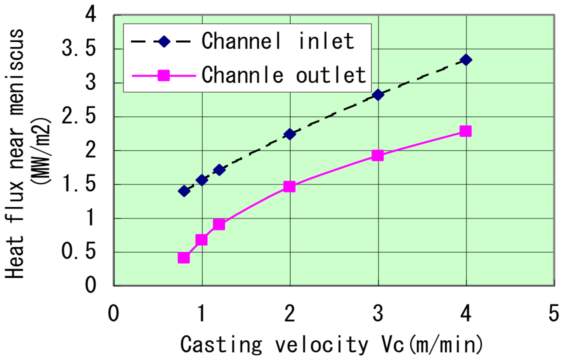

Fig. 6 Heat flux near meniscus as a function of casting velocity. (1.2poise, TSL=1170℃)

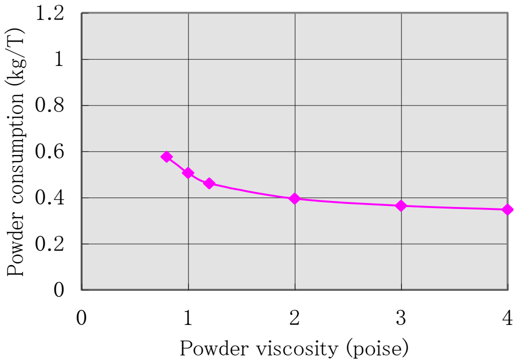

Fig. 7 Powder consumption as a function of powder viscosity.
(Vc=1.2m/min, TSL=1170℃)

Influence of Powder Viscosity on Infiltration.

Influence of powder viscosity on powder consumption and liquid film thickness are shown in Fig. 7 and Fig. 8 respectively. Powder consumption decreases with increasing powder viscosity but its dependency is rather small compared with that of casting velocity. This is because the dependency of liquid film thickness on powder viscosity is very small at channel inlet as shown in Fig. 8. The heat flux increases with increasing powder viscosity but its dependency is also small compared with that of casting velocity as shown in Fig. 9.

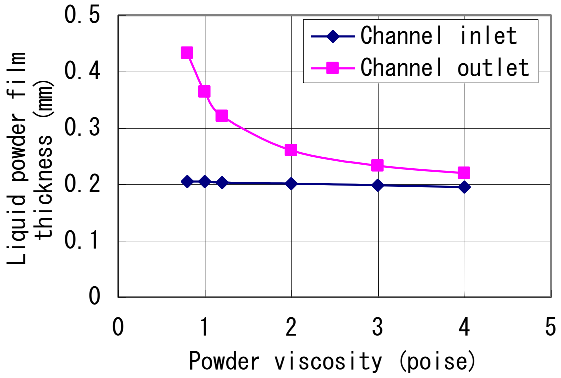

Fig. 8 Liquid film thickness as a function of powder viscosity.
(Vc=1.2m/min, TSL=1170℃)

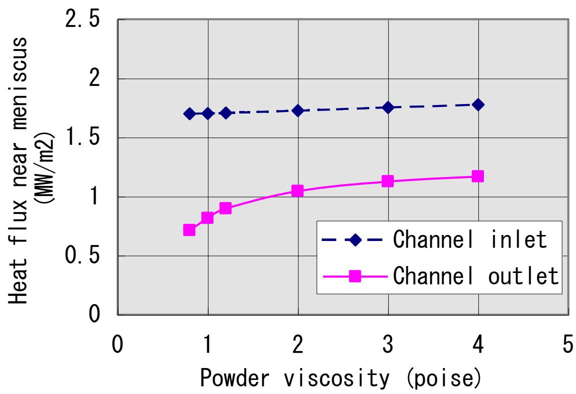

Fig. 9 Heat flux near meniscus as a function of powder viscosity.
(Vc=1.2m/min, TSL=1170℃)

Influence of Solidification Temperature of Mold Powder on Infiltration.

Relationship between powder consumption and solidification temperature of mold powder is shown in Fig. 10. Powder consumption decreases with increasing solidification temperature, showing good agreement with actual phenomenon[2)]. This tendency is due to the decreasing tendency of liquid film thickness at both channel inlet and channel outlet with increasing solidification temperature as shown in Fig. 11.

Solid film thickness near meniscus, on the other hand, increases with increasing solidification temperature, resulting in slight increase in total film thickness and slight decrease in heat flux near meniscus as shown in Fig. 12 and Fig. 13. The calculated result that heat flux slightly decreases with increasing solidification temperature of mold powder agrees with actual phenomenon[2)], but its dependency is rather smaller than actual phenomenon, the reason of which is considered that interfacial heat resistance between solid film and mold is assumed constant regardless of the variation of solidification temperature in the present work.

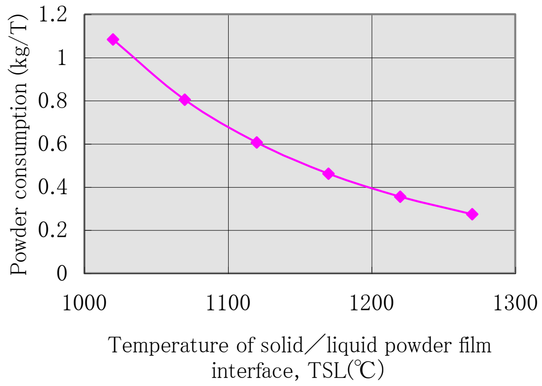

Fig. 10 Powder consumption as a function of solidification temperature of mold powder. (1.2m/min,1.2poise)

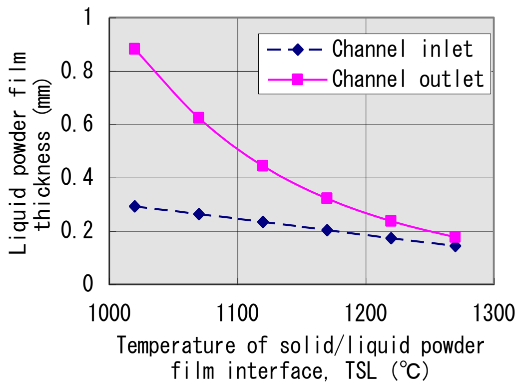

Fig. 11 Powder consumption as a function of solidification temperature of mold powder. (1.2m/min,1.2poise)

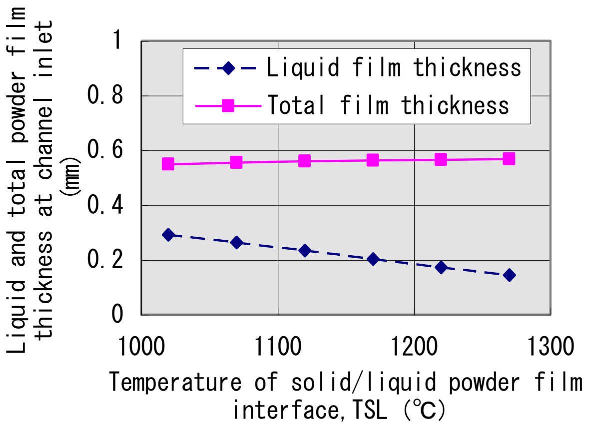

Fig. 12 Total film thickness at channel inlet as a function of solidification temperature of mold powder. (1.2m/min,1.2poise)

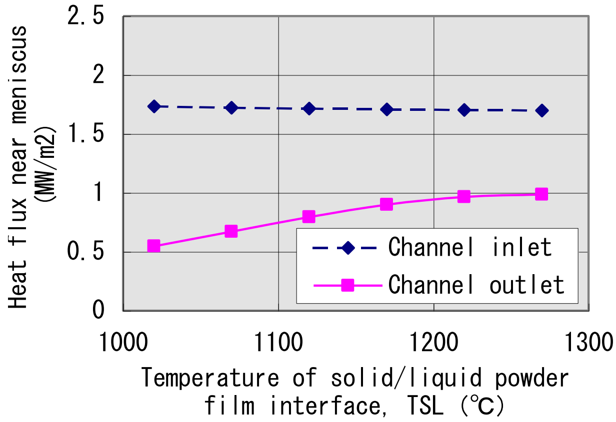

Fig. 13 Heat flux near meniscus as a function of solidification temperature of mold powder. (1.2m/min,1.2poise)

Influence of Meniscus Perturbation in Infiltration

The mold powder infiltration for unsteady state condition was analyzed in such way that solid film thickness was first calculated under steady state condition, and then liquid film thickness was calculated using the calculated solid film thickness as a constant parameter, and influence of the fluctuations of meniscus level and meniscus temperature was analyzed.

Influence of abrupt change in meniscus temperature on liquid film thickness at channel inlet is shown in Fig. 14. Liquid film thickness for steady state is also shown in Fig. 14 as a reference. In the case of steady state where thermal equilibrium is achieved between molten steel and mold, liquid film thickness slightly decreases with increasing superheat at meniscus. On the other hand, when superheat at meniscus suddenly varies with solid film thickness being constant, mold powder infiltrates excessively when superheat decreases and too little when superheat increases as shown in Fig. 14. The reason is that the position of channel inlet becomes shallower or deeper when superheat at meniscus decreases or increases, which affects the pressure balance between molten steel and powder channel.

Influence of meniscus level fluctuation on powder infiltration is shown in Fig. 15. Mold powder infiltrates excessively or too little when meniscus level suddenly moves downward or upward. This result shows qualitative agreement with actual phenomenon, but quantitatively speaking, influence of meniscus level fluctuation seems to be too sensitive when compared with actual phenomenon. The reason is considered that actual meniscus shape due to interfacial tension is not taken into account in the present work. In order to explain the influence of level fluctuation more quantitatively, it is considered that more precise calculation of temperature field near meniscus will be required.

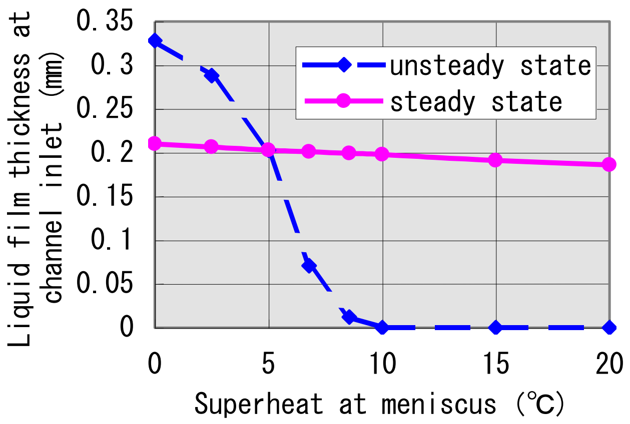

Fig. 14 Liquid film thickness at channel inlet for unsteady state where superheat at meniscus suddenly varies from 5℃.(Vc=1.2m/min, Viscosity=1.2poise,TSL=1170℃)

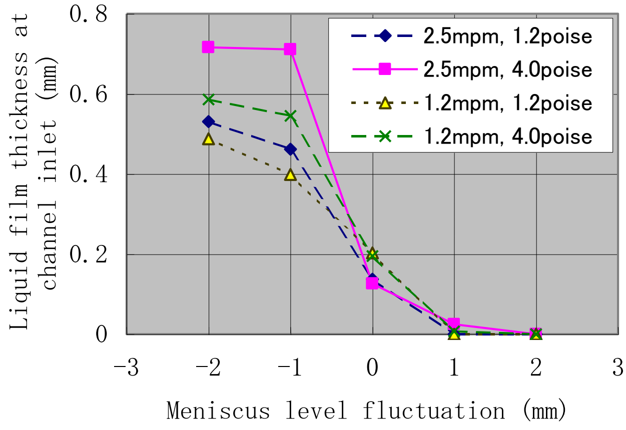

Fig. 15 Liquid film thickness at channel inlet when meniscus level suddenly varies from 0mm.(Vc=1.2m/min,Viscosity=1.2poise, TSL=1170℃)

DISCUSSIONS

Calculation Conditions to Reproduce Realistic Powder Infiltration Behavior in the Model.

Mathematical simulation has been made under various assumptions and the conditions to explain the powder infiltration behavior of actual phenomenon in the model has been examined.

As a result, it was revealed that the following conditions are necessary to obtain quantitatively similar result of powder consumption of actual phenomenon as a function of casting velocity and powder viscosity.

a) Liquid film thickness is determined by pressure balance.
b) There is a factor such as shell rigidity that decreases substantial pressure of molten steel acting on the channel.
c) There is a place well below the meniscus where pressure inside the powder channel is equal to atmospheric pressure.
d) There exists a steel shell above the point p where the thickness of powder channel would be its minimum in the longitudinal direction.
e) There is a region near the meniscus where shell substantially does not exit.

Among the factors stated above, conditions a) to c) are the most essential factors to simulate actual phenomenon, and conditions d) to e) are necessary to quantitatively account for the actual behavior of powder consumption. For instance, we cannot obtain similar result of actual powder consumption as a function of casting velocity and powder viscosity if conditions a) to c) are not applied in the calculation. Similarly, dependency of powder consumption on casting velocity becomes too small compared with actual phenomenon if conditions d) and e) are neglected. In addition, if h1 is assumed constant by neglecting the condition a), powder consumption tends to be a constant value in higher casting velocity which is also inconsistent with actual phenomenon.

Mechanism of Powder Infiltration

Powder infiltration has been often discussed with mold oscillation. It has been experimentally verified, however, that mold powder can infiltrate even though the strand is not subjected to mold oscillation [12)-14)]. When neglecting mold oscillation, it is clear from equation (7) that mold powder infiltrates due to drag force imposed by the moving strand and the force of gravity as stated in the literature [10)]. This is true if we consider the channel profile as a given condition. But the question is how channel profile is determined by the nature. The key word for the answer to this question seems to be the pressure inside the powder channel. Fig. 16 shows an example of the calculated pressure inside the powder channel. Because of the conditions a) to c) state above, the pressure in most of region2 is negative, being smaller than atmospheric pressure. This is caused due to the drag force imposed by the moving strand and existence of shell rigidity. When casting velocity and viscosity are larger, the pressure in region 2 becomes lower, resulting in smaller film thickness at both channel inlet and channel outlet. Due to this negative pressure in region 2, mold powder at channel inlet is sucked downward, resulting in powder infiltration with the help of the existence of shell rigidity or interfacial tension at channel inlet which decreases static pressure of molten steel acting on the channel.

Fig. 16 Longitudinal distribution of pressure inside powder channel .(Vc=1.2mpm, Viscosity=1.2 poise,TSL=1170℃)

SUMMARY

A mathematical model that can predict powder film thickness of both liquid and solid phase as well as heat extraction in the mold has been developed. As a result of analyzing powder consumption and heat extraction as a function of casting velocity, powder viscosity, and solidification temperature of mold powder, it was revealed that calculated results well agree with actual phenomenon. In order to explain the actual phenomenon more quantitatively, additional studies for the improvement in the model are remained to be done such as more precise calculation of temperature field near meniscus, taking into consideration of slag rim near meniscus and mold oscillation, etc.

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