Cold Model Experiment on Infiltration of Mould Flux in Continuous Casting of Steel: Simple Analysis Neglecting Mould Oscillation

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A new cold model of continuous casting is developed to clarify the infiltration of mould flux into channel between a mould and a solidifying shell. In the experiment, silicone oil is poured and infiltrated down into the channel between an acrylic plate and a moving belt. In contrast with most of the previous analyses that assumed a fixed thickness of the liquid flux film, this model is based on an idea that the thickness can be varied depending on the balance of forces acting on the shell: static pressure in the molten steel pool, and dynamic and static pressure in the mould flux channel. Furthermore, a linear gauge sensor that is in contact with the acrylic plate monitors the film thickness of oil, while in continuous casting the thickness of mould flux cannot be measured during the operation.

Simple experiments without oscillating motion clearly reveal that the infiltration behavior is largely dependent on the profile of channel: In the channel that becomes narrower in downward direction, the infiltration of oil is enhanced with the increase of both belt velocity and oil viscosity. In contrast, for the channel that becomes wider along the downward direction, the increase of the velocity and the viscosity reduces the oil infiltration.

In continuous casting operation, the increase of both casting velocity and viscosity of mould flux decreases the mould flux consumption. Those observations indicate that the infiltration of mould flux is strongly governed by the channel that becomes wider in casting direction.

KEY WORDS: continuous casting; mould flux; infiltration; lubrication; modeling; simulation.

1. Introduction

In continuous casting of steel, infiltration behavior of mould flux has a significant effect on the stable operation and the surface quality of the cast slab. It is therefore essential to clarify this phenomenon; many researches have focused on the narrow channel of the flux between a mould and a solidifying shell.

In those works, most of the theoretical models1–6) calculated the flow of viscous liquid between parallel or non-parallel boards. However, they have not reproduced even qualitatively the commonly observed relation7,8) between mould powder consumption and casting conditions such as casting velocity, viscosity of the flux and mould oscillation parameter. Although the origin of this discrepancy is not clear, it should be noted that for the simplicity of the algorithm they assumed a fixed width of the channel between the mould and solidified shell that is not required to be constant.

In order to overcome this problem, a few recent studies have tried to theoretically obtain the thickness of the flux film. Yamauchi et al.9) and Ogibayashi et al.10) calculated the distribution of the film thickness along the casting direction, taking into account the effect of the ferro-static pressure on the solidified shell. But the former model empirically assumed a thickness at a point just below the meniscus as an equation of casting velocity. The latter analysis did not clarify the effect of mould oscillation, although it reproduced the observed dependency of the casting velocity and powder viscosity on mould powder consumption. Accordingly, the current theoretical models do not perfectly reveal the powder infiltration behavior.

In contrast, some interesting laboratory analogues have been performed on the powder infiltration between the oscillating mould and the moving shell. As displayed in Fig. 1, Itoyama et al.11) carried out a cold model experiment in which liquid paraffin was poured into the gap between an oscillating acrylic plate and a rotating belt. In a similar experiment, Anzai et al.4) measured the pressure of the viscous liquid in the channel. In those researches, however, they fixed the horizontal position of both the acrylic plate and the belt surface, which poses the same problem as is found in the theoretical models.

In the preceding paper,12) the authors have described a numerical model presuming that the thickness of liquid flux...
film can be varied. In the present contribution, a new cold model experiment is developed where silicone oil is influxed into the gap between an acrylic plate and a moving belt. Differently from the previous experiments, the width of the gap is not constant and can be varied during the rotation of the belt. It is based on an idea that in continuous casting the film thickness of the liquid flux is mainly dependent on the balance of forces acting on the solidifying shell: the static pressure of the molten steel and the static and dynamic pressure of the liquid slag in the channel. Furthermore, the apparatus is designed so that the film thickness of oil can be measured, while in continuous casting the liquid flux film can never be observed during the operation. This paper reports on simple experiments without oscillating motion, which focus on the shape of the channel between the acrylic plate and the belt.

2. Experimental Procedure

The experimental apparatus is illustrated in Fig. 2 and its photograph is shown in Fig. 3. Silicone oil is poured between an acrylic plate and a moving belt. The rotated belt, acrylic plate and silicon oil correspond to the drawn slab, mould and liquid mould flux, respectively. The oil forms a pool on the top surface of the acrylic plate, and the moving belt partially infiltrates the oil from the pool down into a narrow channel that represents the gap between the mould and shell in continuous casting. Both sides of the pool perpendicular to the belt surface and both vertical edges of the channel are sufficiently sealed using acrylic boards. The belt, composed of polyester, measures 80 mm in width and is rotated by an AC motor at constant velocity. The pouring rate of oil is controlled so that the pool has a depth of 20 mm.

Importantly, this experiment is characterized by the following three mechanisms around the acrylic plate.

Firstly, the acrylic plate, which is not fixed to the frame, moves smoothly along a guide rail in the horizontal direction (see Fig. 2). This indicates that the solidifying shell is not fully constrained in the direction perpendicular to the mould wall. The use of “linear ball slides” as the guide rail made possible the displacement of the plate with very low friction. It is attributed to fine stainless balls that roll and move along needle roller races in this slide unit.

Secondly, an air cylinder located behind the acrylic plate pushes the back surface of the acrylic plate toward the moving belt surface (Fig. 2). This corresponds to the fact that ferrostatic pressure acts on the initially solidified shell toward the mould wall. If silicone oil influxes into the gap during the belt rotation in this state, the distance of the plate from the belt surface is dependent on the relation between the air pressure in the cylinder and the pressure in the oil channel that is generated mainly by the movement of the belt.

Thirdly, a linear gauge sensor that is in contact with the back surface of the acrylic plate monitors the horizontal movement of the plate. The sensor is attached to the frame at the level of the channel entrance that corresponds to the meniscus level in continuous casting. This enables the in-situ observation of the film thickness in the channel that is not realized in continuous casting mould.

It should be noted that for the simplicity of the mechanism in the apparatus, the acrylic plate that corresponds to the casting mould moves in the horizontal direction, while in continuous casting the solidifying shell can displace along the same direction. This inconsistency is assessed in Sec. 4.1.

In order to reveal the effect of channel profile on the infiltration behavior, three types of channel were examined as described in Fig. 4. In Channel (a) the distance between the
belt and the acrylic plate linearly decreases in the downward direction. Oppositely, in Channel (b) the distance increases in the downward direction. In Channel (c), Channel (b) is modified with cutting off the top edge of the acrylic plate in consideration of the real shape of solidifying shell at mould meniscus.

The incline of the plate is 0.5 deg in both Channel (a) and (b). The meniscus-shaped entrance of Channel (c) has a length of 3 mm and an incline of 20 deg. The vertical length of the channel is 100 mm. This should represent the length of the channel that is perfectly filled with the mould flux in the continuous casting mould. The length, 100 mm, is nearly the same as that assumed in the previous reported models.3,4,10) The air pressure in the cylinder with a diameter of 15mm was set to 0.015 MPa. Since the acrylic plate has a surface area facing the moving belt, the static pressure on the acrylic plate is calculated at 0.00033 MPa, which is much lower than the average ferrostatic pressure from the meniscus level to 100 mm below the meniscus in continuous casting (0.0035 MPa). However, this value was chosen for the easier detection of the film thickness of oil using the linear gauge sensor. For each channel, the effect of the moving velocity of the belt and the viscosity of the oil was investigated: the belt velocity, $V_C$ that corresponds to the casting velocity in continuous casting was varied from 0.25 to 0.91 m/min, and the kinematic viscosity of the oil was changed between 500 and 5 000 cs (mm²/s).

3. Results

In the first series of the experiment, the initial width of the channel was set to zero: the acrylic plate was placed in contact with the belt, the oil was poured in, and then the belt rotation was started. The experiments reveal that the infiltration of the oil during the belt rotation is completely different between Channel (a) and (b). For Channel (a), as represented in Fig. 5, the rotation of the belt gradually opened the channel (=increased the film thickness), and then in steady state, the oil continued to flow into the channel that had a certain film thickness of oil. In contrast, Channel (b) remained to be closed during belt movement. This indicates that the rotating belt never infiltrated the oil into Channel (b).

For Channel (a), the effect of belt velocity, $V_C$ was investigated in the same manner. Figure 5 shows that the increase of the velocity provides a rapid increase in the film thickness and also enhances the stable state thickness. The same experiment using oil with two different kinematic viscosities clarifies that higher viscosity also increases the film thickness at steady state (see Fig. 6). In other words, the increase of both belt velocity and viscosity enhances the infiltration of the oil, in Channel (a) that becomes narrower in the downward direction.

In the next series of the experiment, the infiltration behavior in Channel (b) was examined under the condition that the initial width of the gap was set to 0.2 mm at the top of the channel, because the oil does not infiltrate at all if it is 0.0 mm. After filling the gap with the oil, the belt was begun to rotate, and then the acrylic plate was released. As represented in Fig. 7, the movement of the belt decreases the film thickness of oil from 0.2 mm to zero within a few seconds, which makes influx of the oil impossible by closing the gap. Figure 7 also displays the influence of the moving velocity of the belt. The increase of the velocity shortens the period while the film thickness is decreased from 0.2 to 0.0 mm. In order to evaluate the ease of infiltration, this period is defined as $t_0$ (see Fig. 7; large $t_0$ means good infiltration). Figure 8 indicates that the increase in the viscosity of oil, the same as in the velocity, results in the decrease of $t_0$. Those clarified that the increase of the belt velocity and viscosity of the oil reduces influx of the oil for Channel (b). This is also contrary to the result that was obtained in Channel (a).

Furthermore, in order to assess the effect of meniscus
profile, the oil infiltration was examined in Channel (c). The initial film thickness was 0.2 mm, the same as in Channel (b). Figure 9 shows that the meniscus shaped channel prolongs the period $t_0$, which means the enhancement of infiltration. However, it must be noted that the meniscus profile does not change the main feature of the infiltration in Channel (b): the oil does not flow into the channel in the steady state. In addition, the increase of belt velocity shortens the period $t_0$, which shows the reduction of infiltration (see Fig. 10). This also remains the characteristic of Channel (b).

4. Discussion

As described in Sec. 3, the experiment has clarified that the infiltration behavior of the oil is strongly dependent on the profile of the channel: whether it becomes narrower or wider in the downward direction. This result was newly obtained assuming that the film thickness is variable. In contrast, previous analyses that fixed a certain thickness have not provided the same result. Since the shape of the channel seems to be key to understanding the infiltration mechanism of the mould flux in continuous casting, it is theoretically analyzed in Sec. 4.1. Then, the lubrication in continuous casting mould is discussed on the basis of the experimental results in Sec. 4.2.

4.1. Theoretical Analysis on the Infiltration of Oil into Channel

Using the coordinates represented in Fig. 11, conservation of the momentum of the oil in the channel is given by Eqs. (1) and (2):

$$\frac{\partial}{\partial x} P + \frac{\partial}{\partial z} \left( \mu \frac{\partial u}{\partial z} \right) + \rho g = 0 \quad (1)$$

$$\frac{\partial}{\partial z} \left( \mu \frac{\partial w}{\partial z} \right) = 0 \quad (2)$$

where, $P$ indicates pressure, $x, z$ the distance parallel to and perpendicular to the belt surface, respectively, $u, w$ the velocity in the $x, z$ direction, respectively, $\mu$ the dynamic viscosity of oil, $\rho$ the density of oil, and $g$ the gravity constant.

The boundary conditions are written as:

$$u = V_c, \quad w = 0 \quad \text{at } z = 0 \quad (3)$$

$$u = 0, \quad w = 0 \quad \text{at } z = h \quad (4)$$

Equations (1) and (2) are the same as Eqs. (1), (2) in Ref. 12) in which the authors formulated the infiltration of mould flux, if the mould velocity is set to zero. On the other hand, the boundary conditions (3), (4) differ from the ones in Ref. 12), because in the present experiment the acrylic plate that corresponds to the mould is inclined while the numerical model inclines the solidifying shell that is drawn at $V_c$. Solving Eqs. (1)–(4) with the procedure described in

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**Fig. 7.** Change in film thickness of oil by belt movement with various belt velocities, $V_c$ in Channel (b). (Kinematic viscosity of oil = 5 000 mm$^2$/s)

**Fig. 8.** Period $t_0$ as a function of kinematic viscosity of silicone oil. $t_0$ represents the ease of infiltration, as is defined in Fig. 7.

**Fig. 9.** Change in film thickness by belt movement in Channel (b) and Channel (c). (Belt velocity = 0.91 m/min, kinematic viscosity = 3 000 mm$^2$/s)

**Fig. 10.** Relation between belt velocity and period $t_0$ in Channel (b) and Channel (c).

**Fig. 11.** Coordinates used in the mathematical formulation of oil infiltration.
Ref. 12), one can obtain the force \( F \) induced by the oil pressure in the channel that pushes the acrylic plate away from the belt surface.

\[
F = \left[ 6\mu V_C \left( F_1(L) - F_2(L) \frac{f_1(L)}{f_2(L)} \right) + \frac{P_0}{2} \left( L - F_2(L) / f_2(L) \right) \right] + \frac{F_2(L)}{f_2(L)} P_L + \frac{\rho g L^2}{2} - \frac{F_2(L)}{f_2(L)} \rho q L \]

(5)

Where \( L \) represents length of the acrylic, \( P_0, P_L \) the pressure at \( x=0, x=L \), respectively. \( P_0 \) is set to \( \rho gd \) in which \( d \) is depth of oil pool, \( P_L \) is zero.

\[
f_1(x) = \int_0^x \frac{dx}{h^2} \]

(6)

\[
f_2(x) = \int_0^x \frac{dx}{h^3} \]

(7)

\[
F_1(x) = \int_0^x f_1(x) dx \]

(8)

\[
F_2(x) = \int_0^x f_2(x) dx \]

(9)

Equation (5) is exactly the same as Eq. (14) in Ref. 12) that represents the force acting on a solidifying shell that is induced by the pressure in liquid flux channel. This means that the cold model can simulate the infiltration of mould flux into the channel in continuous casting. In detail, movement of liquid flux above the meniscus level is not precisely modeled in this experiment. In continuous casting, the mould wall that keeps the liquid flux pool in this region is oscillated. Thus, in the cold model experiment that assumes the situation without the oscillation, the wall that keeps the oil pool above the channel should be fixed in vertical direction. But for the simplicity of the experiment, the belt that makes the wall in this region is moving down at constant velocity, \( V_C \). This discrepancy was assessed by the preliminary experiments that varied the depth of the oil pool. As a result, the depth of the pool did not essentially change the result that has been described in Sec. 3. This indicates that the discrepancy does not provide critical problem.

For Channel (a) and (b), replacing \( h=h_0+x \tan \theta \) in Eq. (5), where \( \theta \) indicates the angle that the acrylic makes with the belt (\( \theta \) is negative in Channel (a), and is positive in Channel (b)), \( h_0 \) the film thickness at the top of the channel, the force \( F \) is written as:

\[
F = \left[ 6\mu V_C \left( \frac{1}{\tan \theta} \frac{1}{\tan \theta} \log \frac{h_0}{L \tan \theta + h_0} \right) \right] + \frac{L}{h_0} - \frac{L^2 \tan \theta}{h_0(L \tan \theta + 2h_0)} \]

\[
+ \left[ P_0 L(P_L - P_0) \tan \theta \frac{L \tan \theta + h_0}{L \tan \theta + 2h_0} \right] + \frac{\rho g L^2}{2} - \frac{\rho g L^2 \tan \theta}{L \tan \theta + 2h_0} \]

(10)

In this equation, the first term represents the force due to dynamic pressure that is induced by the motion of the belt. The second term shows the contribution of difference in static pressure between the top and the bottom of the channel, \( P_0 \) and \( P_L \), respectively. Since \( P_0 \) is the head pressure of the oil pool, this term depends on the depth of the pool that corresponds to the depth of the liquid flux pool in continuous casting. The third term is related to gravitational force acting directly on the oil that exists as a film in the narrow channel.

On the other side, the air cylinder pushes the acrylic plate with \( F_C \):

\[
F_C = P_c \left( \frac{d_c}{2} \right)^2 \]

\[
\frac{1}{w} = 33 \text{ (N/m)} \]

(11)

where \( P_c \) presents the pressure of the cylinder (0.015 MPa), \( d_c \), diameter of the cylinder (15 mm), and \( w \), width of acrylic plate (80 mm). Thus, the balance of forces, \( F \) and \( F_C \) decides the horizontal movement of the acrylic plate. This indicates that the motion of the solidifying shell, thus liquid film thickness of mould flux, is dependent on the balance between the pressure in the flux channel and the static pressure from the molten steel. Furthermore, the former pressure is attributed to the dynamic pressure induced by the withdrawing of slab, the head of the liquid flux pool, and the force of gravity acting on the liquid flux film.

For Channel (a), the force \( F \) is calculated from Eq. (10) as a function of the film thickness \( (h_0 + L \tan \theta) \), as represented in Fig. 12. In this channel, the force \( F \) always has a positive value. This means that the acrylic plate is pushed away from the belt by the increase of the pressure in the channel. It is due to the positive dynamic pressure mainly induced by the movement of the belt that is represented by the first term in Eq. (10). The contribution of the head of the pool and the gravitational force, the second and third term of the equation, was much smaller than that of the belt movement. On the other side, the air cylinder pushes back
the plate towards the belt with the force $F_{C}$. The relation between $F$ and $F_{C}$, therefore, decides the position of the acrylic plate, and thus the film thickness of oil, as is illustrated in the lower part of Fig. 12.

Figure 12 indicates that small oil thickness provides large $F$ compared to $F_{C}$. In the experiment that is presented in Fig. 5, it enlarges the channel at the non-steady state until $F$ becomes balanced with $F_{C}$, and then the film thickness maintains to be constant. In Fig. 12, film thickness at which $F$ has the same value as $F_{C}$ is 0.28 mm, 0.43 mm for $V_{c}=0.25$, and 0.48 m/min, respectively. These predict in some degree the experimental film thickness at steady state in Fig. 6: 0.42, 0.49 mm on average for 0.25, 0.48 m/min, respectively, with 500 mm²/s of kinematic viscosity. It should be also noted that the increase of both $V_{C}$ and viscosity enhances positive dynamic pressure in the oil channel, which results in the increase of the thickness as represented in Fig. 6. This is due to the enhancement of the first term of Eq. (10) that promotes pulling the oil into the channel.

In contrast, the relation between $h_{0}$ and $F$ for Channel (b) is calculated in Fig. 13. Differently from Channel (a), the force $F$ is negative at all time: the movement of belt generates force that horizontally draws the acrylic plate towards the belt. It is in the same direction as the force provided by the air cylinder, as is schematically indicated in lower part of Fig. 13. This means that $F$ does not balance with $F_{C}$ at any thickness, which results in the closing of the channel. This characteristic in Channel (b) is attributed to negative dynamic pressure induced by the belt movement: the first term of Eq. (10) has a negative value when the channel becomes wider along the direction of the belt movement. In other words, the belt movement that pulls the oil out of the channel decreases the pressure in the channel. In this case, the increase of $V_{C}$ and the viscosity enhances negative pressure in the channel, thus negative value of $F$, which results in more rapid decrease of the film thickness as described in Figs. 7 and 8. It should be noted also in the calculation for Channel (b) that the head of the pool and the gravity force acting on the film have minor effect on the force $F$ than the movement of the belt. Any thickness, which results in the closing of the gap.

Furthermore, it is empirically known in continuous casting that the increase of both casting speed and viscosity of mould flux decreases mould powder consumption, which poses poor lubricity. This is also contrary to the experiment in Channel (a) where increasing $V_{c}$ and the oil viscosity results in the enhancement of the film thickness. In contrast, the empirical knowledge on powder consumption is well explained again by the results obtained in Channel (b): the increase of the belt velocity and the viscosity reduces the infiltration of oil.

Accordingly, those practical observations in continuous casting can be easily understood, if the channel between the mould and solidifying shell is assumed to enlarged along the casting direction, which is modeled by Channel (b).

This assumption is clearly supported by consideration of the thermal shrinkage in a solidifying shell along casting direction except for in the region of meniscus. At mould meniscus, interfacial tension between mould flux and molten metal provides a funnel-shaped entrance to the channel. However, the experiment on Channel (a) reveals that the meniscus has minor effect on the flux infiltration compared with the long channel that is located lower than it, although it promotes the infiltration in some degree.

Consequently, in continuous casting, the infiltration of the mould flux is strongly governed by the profile of the channel below meniscus that becomes wider along the casting direction. In this type of channel, the drawing of slab reduces the pressure in the flux channel, which provokes the closing of the channel (see Fig. 14). This makes impossible the operation without mould oscillation, and makes difficult the higher speed casting even if the mould is reciprocated.

To our knowledge, some researchers have suggested that some amount of mould flux was consumed even without mould oscillation (of course, stable operation has not been realized). Although this observation seems to be inconsistent with the result of this experiment, it can be reasonably explained in the following way. In the cold experiment, the infiltration of oil was investigated in the simple channel that is composed of the flat surfaces of the acrylic plate and polyester belt. Thus, the channel can be perfectly closed by the movement of the belt. On the other hand, the liquid flux channel has a more complex profile in the continuous casting mould. Because of the irregular deformation of the solidifying shell and the variation in solid film thickness of
the mould flux, the width of the channel is irregularly varied in both the vertical and horizontal direction on the mould wall. Thus, the channel cannot be perfectly closed even if the drawing of slab reduces the pressure in the channel. In this case, liquid flux will be infiltrated without mould oscillation through the parts of the channel that are locally wider than the surroundings, that is, liquid pockets and/or streaks between the shell and mould. However, the sticking breakout of the shell will not occur in those parts of the channel. The channel that is relatively narrower than the surroundings, which is essentially important for the sticking, is mainly modeled by this cold experiment.

Next, the strength of the solidifying shell, an important factor that is not apparently considered in this model, will be briefly discussed. In the consideration of this model, the strength of the shell contributes to the flux infiltration as follows: Firstly, the stronger shell will reduce the ferrostatic pressure that acts directly on the liquid flux film. This promotes the infiltration by apparently decreasing $F_c$ in this model. Secondly, the enhancement of the strength will increase the channel width along the casting direction, which provides Channel (b) of the experiment for the continuous casting mould. This contributes to reduce the infiltration of mould flux. Consequently, the strength of the shell will influence the infiltration through the competition of these two opposed contributions. However, further discussion is necessary for quantitative understanding of those effects.

Previously, many studies on flux infiltration and initial solidification have rather focused on the meniscus region. But this model indicates that the infiltration of mould flux is more dependent on the channel that is located lower than the meniscus. Furthermore, differently from the models that assumed a fixed thickness of the channel, the experimental result of Channel (b) and (c), showing that the oil is not stably infiltrated without oscillation, strongly suggests the importance of mould oscillation on flux infiltration. The effect of the oscillation will be investigated in the next paper.

5. Conclusion

In order to reveal the infiltration of mould flux, we developed a new cold model experiment that infiltrates oil down into the channel between an acrylic plate and a moving belt. Differently from the previous models, the apparatus was designed so that the film thickness of the oil that corresponds to the liquid flux in continuous casting can be varied. The simple experiments neglecting the oscillation reveal the importance of the channel profile on the infiltration:

(1) In Channel (a) that becomes narrower along the downward direction, the oil maintains to be infiltrated during the movement of the belt. The film thickness of oil increases with the increase of both belt velocity and viscosity of oil that correspond to the casting velocity and the viscosity of flux, respectively.

(2) In contrast, in Channel (b) that widens along the downward direction, the oil is not infiltrated at steady state. Increase of both belt velocity and viscosity of oil results in a rapid closing of the channel, which means the reduction of infiltration. Even when a meniscus shaped entrance was placed at the top of this channel, this characteristic was remained (Channel (c)).

In continuous casting operation, the increase of casting speed and viscosity of mould flux is observed to decrease mould flux consumption. This observation can be easily explained by Result (2), but not by Result (1). This means that mould flux channel that becomes wider below the meniscus in the casting direction strongly governs the infiltration of mould flux in continuous casting.

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