Mold Simulator Study of Effect of Mold Oscillation Frequency on Heat Transfer and Lubrication of Mold Flux

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The heat transfer and lubrication behavior of the slag film infiltrated into the mold/shell gap have a significant effect on the surface quality of continuous casting of steel slabs. With the mold simulator technique, the effect of mold oscillation frequency on the heat transfer and lubrication behavior of the infiltrated mold/shell slag film was studied in this article. The experiment results showed that the increase of the mold oscillation frequency from 1.00 to 2.00 Hz would cause the thickness of the infiltrated mold/shell slag film decreased by 8.08 pct. As a result, the thermal resistances between the mold and the shell decreased by 9.81 pct, and then the shell solidification factor increased by 3.98 pct due to the mold heat flux increased. Moreover, the thickness of liquid slag film decreased by 17.50 pct, and the liquid slag consumption decreased by 20.69 pct.

KEY WORDS: continuous casting; mold flux; mold oscillation frequency; heat transfer; slag lubrication.

1. Introduction

Many of the surface defects in the final rolled product have been found to be associated with the surface defects of the strands (i.e., oscillation marks and depressions), and the formations of these surface defects are attributed to the heat transfer and lubrication behavior of the slag film infiltrated into the mold/shell gap. In continuous casting of steel, mold flux is usually added on the top of liquid steel surface to protect the steel meniscus from oxidation, lubricate the newly formed shell, and control the heat transfer between the shell and the mold. During each cycle of mold oscillation, the liquid slag from the mold top surface slag infiltrates into the mold/shell gap and lubricates the newly formed shell. Then the liquid slag is getting cooled quickly and leads to the formation of a solid slag film against the shell, and a liquid slag film next to shell, where the slag film controls both mold heat flux and mold lubrication.

Enough slag film must be infiltrated into the mold/shell gap to provide the mold lubrication, prevent the sticking and decrease the shell surface defects. As the liquid slag is consumed into the mold/shell gap, a certain amount of slag has to be added to the mold top surface over time. The slag consumption per unit area of shell surface \( Q_{\text{slag}} \) is frequently used as a measure of the lubrication supplied to the shell, where a high \( Q_{\text{slag}} \) is necessary for good lubrication in a mold. Based on the measurements in the industry and/or the experimental, many empirical equations have been developed to estimate the required value of slag consumption, and the formulas were expressed as a function of casting speed, mold oscillation conditions. There is a general agreement that the slag consumption is increased with the decrease of casting speed, slag viscosity, and slag crystallization temperature. However, the effect of mold oscillation frequency on the slag consumption is the full of controversial. Some experimental studies indicated that \( Q_{\text{slag}} \) increases with decreasing frequency, but other studies showed \( Q_{\text{slag}} \) increases with increasing frequency. Another works on the slag consumption is by the mathematical modeling, where the gravity, the shear and the interfacial frictional forces between mold and shell were regarded as the driving force for the slag consumption. Some mathematical modeling studies suggested the slag infiltration occurs during Negative Strip Time when the mold moves downward faster than the casting speed (NST = \( \arccos(V_c/2\pi/4)/\pi; \) where the casting speed is \( V_c \), mold oscillation frequency is \( f \) and stroke is 2.4), which is the results of the increase of pressure in the flux channel near the meniscus due to the descendant of slag rim. Meanwhile, some researches argued that it is difficult for slag infiltrating into the mold/shell gap during the NST period due to the gap getting blocked by the bending of the shell, thus the slag infiltration largely occurs in Positive Strip Time (PST, where NST + PST = one cycle of mold oscillation). Whereas most models reported slag consumption per unit cycle of mold oscillation \( Q_{\text{cycle}} \) increases with increasing both PST and NST, and exhibits a stronger correlation with PST than NST. Although mathematical models provided a reasonable description of the effects of the casting speed and slag viscosity on the slag consumption, and they also predicted that \( Q_{\text{slag}} \) increases with increasing oscillation frequency, which disagrees a few observations from plant and cold model experiment.

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The surface quality of slabs is associated with the unevenness solidification of initial shell. It is found that the unevenness solidification of initial shell could be suppressed by lowering the mold heat flux. The suppression of heat flux can be achieved by applying mold fluxes with high crystallization due to the scattering radiation at the grain boundaries. While crystallization of slag may lead to the formation of cracks and voids in the slag film and the surface roughness of slag at the mold side that will act as additional barriers for heat transfer. Besides, the casting conditions also have effect on the mold heat flux. It is generally reported that the heat flux increased with the increase of casting speed and superheat. But few studies have been conducted to investigate the effects of mold oscillation frequency on the mold heat flux. Works byBadri et al. and Wang et al. have studied the relationship between the fluctuations of mold heat flux and temperature and mold oscillation by using a mold simulator under laboratory conditions. They confirmed that the heat flux at the meniscus area rises rapidly during NST period and the presence of each oscillation mark on the shell surface is corresponding to a peak value of the heat flux variation rate. Numeric works by Ramirez-Lopez, Jonayat and Moinet obtained the similar results. Additionally, Pinheiro et al. found that the average mold heat flux increased about 8 pct when mold oscillation frequency increased from 2.50 to 2.83 Hz. They attributed the enhancement of heat transfer to the shallower oscillations marks caused by decreasing NST when mold oscillation frequency was increased, and it resulted in a narrower mold/shell gap. Kumar also observed that the mold heat flux was increased by about 15 pct when mold oscillation frequency was increased from 1.67 to 2.67 Hz. However, Chandra observed the mold heat flux was decreased with increasing the frequency (1.6 to 2.4 Hz). Therefore, it is inconsistent about the effect of mold oscillation frequency on the mold heat transfer.

In this paper, the effect of mold oscillation frequency on the heat transfer and lubrication behavior of the infiltrated mold/shell slag film was studied. Firstly, four trials with different mold oscillation frequency were conducted by using a mold simulator that could replicate the initial shell solidification and the lubrication of liquid mold flux with similar to the real scenario of continuous casting mold under laboratory conditions. Then, the initial shell and the infiltrated mold/shell slag film were obtained. Finally, the mold heat flux, the thermal resistances of slag film and the slag consumption were analyzed from the measurements of in-mold wall temperature, the thicknesses of shell and slag film.

2. Methodology – Brief of Mold Simulator Technique

2.1. Schematic of Mold Simulator

The mold simulator applied to this study is an inverse-type water-cooled copper mold (30 mm×50 mm×350 mm) with oscillation ability and is shown in Fig. 1(a). The simulator system mainly includes: induction furnace, copper mold with oscillation ability, extractor and temperature acquisition system. A U-type water-cooling groove with 10 mm diameter is manufactured inside the mold that consists of one water inlet and one water outlet at quarter-width and three-quarters width positions of mold, respectively. The mold is equipped with an extractor that makes only one face of the mold exposed to the liquid melt. As the liquid steel contacts the mold surface and forms an initial shell, the extractor withdraws the solidifying shell downward and makes the fresh molten steel contact with mold for subsequent solidification that is similar to what the dummy bar does at the start-up of a continuous casting. The responding mold temperatures during casting are measured by a fast thermal monitoring system at the sampling rate of 60 Hz, which consists of 16 highly sensitive T-type thermocouples. As shown in Fig. 1(b), along the centerline of mold, two columns of thermocouples (2×8) are embedded at different depth inside the mold wall. Two columns of thermocouples are spaced 3 mm and 8 mm away from the mold surface respectively, and the dots points represent the fixed locations of thermocouples’ tips.

2.2. Experimental Process

For the mold simulator runs, about 25 kg Interstitial-Free steel (IF steel, the composition of steel is analyzed by plasma–atomic emission spectrometry (ACROS, SPECTRO) and listed in Table 1) was firstly melted in an induction furnace (MgO lining) in argon atmosphere (with purify of 99.99 pct). After the charge was molten, the metal Al (−100 g) as a deoxidizer was added to the molten steel. Next, the temperature of the melt was adjusted to the target value (to control the superheat), mold flux designed for IF steel (about 0.6 kg, composition listed in Table 2, before the experiment the added mold flux has been decarburized by placing it into a furnace to avoid the C pickup in molten steel during the casting) was added to the surface of the liquid bath, so that there would be a layer of molten flux about 7 mm thick on the top of liquid steel (the selected thickness of liquid slag layer could be comparable to that thickness of liquid slag on the mold top of an industrial continuous casting mold). Secondly, the copper mold covered with extractor was descended toward the melt, while the mold was kept oscillated. The mold and extractor were lowered to the preset depth into the melt bath so that the liquid mold flux surface and meniscus of liquid steel would
be located in the mold thermocouple-measuring zone. After the mold and extractor reached the target location, it was held for several seconds to form an initial shell on the mold to ensure the initial shell is strong enough to prevent tearing during extraction. Thirdly, the extractor withdrew the solidifying shell downward at a constant speed to simulate the continuous casting. While the mold moved upward at a certain speed to compensate for the rise of mold level, so that the liquid mold flux surface and meniscus could be kept at the same position with respect to the mold. When the casting was completed for the desired length (about 55 mm), the mold and extractor were withdrawn out of the furnace and then cooled in air. From the time the mold started to lower into the bath to the completion of casting, the mold was kept oscillating sinusoidally at the pre-set frequency and stroke. Finally, the position of the shell tip with respect to the mold was measured and then the solidified shell and the slag film next to mold were cut away for the further study.

To measure the shell thickness, Fe–S alloy was added into the molten steel just before the end of casting. After the casting, the slab was cut along the centerline of mold. By analyzing the result from the sulfur print of the longitudinal section of the shell, the white area was regarded as the solidified shell formed before the Fe–S alloy addition. Finally, the shell thickness was measured by a Vernier micrometer.

In the present work, four different experiments were conducted successively to study the influence of mold oscillation frequency on the heat transfer and lubrication of infiltrated mold/shell slag film. The experiment conditions, such as melt temperature, casting speed, mold oscillation frequency and stroke, for each experiment are listed in Table 3. The mold oscillation frequency \( f \) is selected in the interval between 1 and 2 Hz when the casting speed \( V_c \) is 10 mm/s. As one oscillation mark will be formed during each cycle of mold oscillation, the pitch of oscillation marks \( P \) could be calculated from \( P = V_c/f \). According to the practical experience of continuous casting, the oscillation mark pitch from 5 to 15 mm is the optimal, and the oscillation marks may also act as nucleation sites for the transverse cracks of slab surface. Because a higher mold oscillation frequency is associated with the shorter oscillation mark pitch that brings more chances for the transverse cracks during the straightening process in the second cooling region of continuous casting. Conversely, a lower mold oscillation frequency would lead to the longer negative strip time that will cause the formation of deeper oscillation marks, and even lead to the absent of mold negative strip which will bring the mold sticking breakout. In this study, the oscillation mark pitch is also set as 5 to 10 mm and thus the mold oscillation frequency selected is reasonable. Furthermore, the melt temperature of the liquid steel is measured at first and then the mold simulator system is started, and the measurement error is within \( \pm 2 \) K (by Tungsten-Rhenium thermocouple). Besides, as those four experiments were conducted one by one, the main difference in the composition of mold flux (analyzed by X-ray fluorescence) was MgO due to the dissolution of MgO at the slag line from the induction furnace. MgO content was \( \sim 3 \) pct before experiments, and was 4 to 6 pct after experiments. Therefore, its effect on the heat transfer and lubrication of mold flux is ignored in this study.

### 2.3. Determination of Mold Heat Transfer

In this study, a Two-Dimensional Inverse Heat Conduction Problem (2D-IHCP) mathematic model\(^{(49)}\) was used to recover the heat flux and temperature of the mold surface from the measured temperatures. In Fig. 1(b), rectangle ABCD is the computational domain of 2D-IHCP mathematic model, where AB is the mold surface that close to the hot shell and CD is another side that close to the cooling channel. Once the measured temperatures were delivered to 2D-IHCP mathematic model, and then the heat flux and temperature on the mold surface could be recovered. The 2D-IHCP mathematic model is capable of recovering the mold hot surface heat flux from the limited number of in-mold wall temperature measurements by using Conjugate Gradient Method to find a heat flux function that approaches to the real boundary heat flux, and the detailed description of this mathematic model has been well illustrated in our previous study.\(^{(40)}\)

### 2.4. Determination of Initial Shell Solidification Process

A one-Dimensional Inverse Heat Transfer Problem for Solidification (1DITPS) mathematic model was adopted to determine the temperature distribution of the solidifying shell from the measured shell thickness.\(^{(33)}\) In Fig. 1(b), the initial temperature of steel is melt temperature (Table 3), and the boundary conditions are set as heat flux \( q(t) = 0 \) at the shell surface \( x' = 0 \) side and is insulated at \( x' = l \) side where the liquid steel is in contact with the wall of furnace (MgO). Once the measured shell thickness was delivered to 1DITPS mathematic model, and then the temperature distribution of the solidifying shell could be recovered. The 1DITPS mathematic model is capable of determined the heat-transfer process of solidifying shell from the measured shell thickness and shows a good anti-interference ability of inverse results to the thickness measurement noise, and the detailed description of this mathematic model has been well

### Table 1. Chemical composition of steel (wt%).

|      | C     | Si    | Mn    | P     | S     |
|------|-------|-------|-------|-------|-------|
| Value| 0.0011| 0.004 | 0.107 | 0.0093| 0.0048|

### Table 2. Chemical composition of mold flux (wt%).

|      | CaO | SiO₂ | Al₂O₃ | MgO | Na₂O + Li₂O | P | Basicity CaO/SiO₂ |
|------|-----|------|-------|-----|-------------|---|------------------|
| Value| 36  | 37.5 | 6     | 3   | 7           | 6 | 0.96             |

### Table 3. Mold oscillation setting and casting conditions.

| Trials | Melt temperature, K (°C) | Frequency \( f \), Hz | casting speed \( V_c \), mm/s | Stroke 2A, mm | NST 2A, s | PST (s) |
|--------|--------------------------|-----------------------|-------------------------------|---------------|-----------|---------|
| E1     | 1 833 (1 560)            | 1.00                   | 10                            | 6             | 0.32+0.68|         |
| E2     | 1 833 (1 560)            | 1.33                   | 10                            | 6             | 0.28+0.47|         |
| E3     | 1 833 (1 560)            | 1.67                   | 10                            | 6             | 0.24+0.36|         |
| E4     | 1 833 (1 560)            | 2.00                   | 10                            | 6             | 0.21+0.29|         |
3. Results and Discussion

3.1. Observation of Mold Surface Temperature and Heat Flux during Casting

A typical evolution of responding temperatures inside the mold during a mold simulator run when mold oscillation frequency is 1.0 Hz (trial E1) is shown in Fig. 2, where the distribution of thermocouples is shown in Fig. 1. The mold surface temperatures are in the range from 310 to 384 K. The temperature tendency of the first column of thermocouples (Fig. 2(a)) shows the same variation pattern as those of thermocouples at the second column (Fig. 2(b)), and the temperatures of the first column of thermocouples are about 15–21 K higher and showing a larger variation amplitude. The fluctuations of the mold temperature were introduced by the mold oscillation with respect to the level of liquid melt. The detailed description of the variation of mold surface temperatures could be found in our previous studies.\textsuperscript{38–40}

The measured mold temperatures were delivered into 2D-IHCP\textsuperscript{49} model, then the temperature (\(T_{\text{mld}}\)) and the heat flux (\(q_{\text{int}}\)) of mold surface during casting were recovered. For the trials of E1, E2, E3 and E4, the average \(T_{\text{mld}}\) and \(q_{\text{int}}\) along the casting direction during the last cycle of mold oscillation when the continuous casting is completing are shown in Fig. 3. The position with Z equals to zero is the location of the shell tip. The maximum mold surface temperatures occur at the locations 7 to 8 mm below the shell tip, and they are 387, 389, 393 and 396 K for E1, E2, E3 and E4 respectively (Fig. 3(a)). Moreover, the maximum mold surface heat fluxes occur in the locations 5 to 6 mm below the shell tip where the thermal resistance between mold and shell in this range is lowest (Fig. 9), and they are 2.09, 2.19, 2.30 and 2.40 MW/m\(^2\) for E1, E2, E3 and E4, respectively (Fig. 3(b)). In addition, the locations of maximum mold surface temperature (Z is 7 to 8 mm) are found to be lower than those of maximum mold surface heat flux (Z is 5 to 6 mm) since the heat transfer in the mold wall at the mold meniscus is two dimensional (along horizontal and vertical direction).\textsuperscript{49,50} In summary, the observed temperature and heat flux of mold surface increases with the increase of mold oscillation frequency.
3.2. Thickness Measurements of Shell and Slag Film

Figure 4 shows the longitudinal sections of the solidified shells along the centerline of mold for the trials E1, E2, E3 and E4 respectively, where the top of those shells exhibits a carve shape due to the frozen meniscus of each shell.

The measured shell thickness (s) of each trial along the casting direction is shown in Fig. 5. The shell thickness (s) is fitted with a square root function, \( s = K \cdot t_s^{1/2} \), where the solidification time \( t_s \) (second) is calculated using the equation \( t_s = Z/V_c \) (Z is the distance below the shell tip, and \( V_c \) is casting speed). The shell solidification factors \( K \) are calculated as 2.26, 2.28, 2.32 and 2.35 mm/s \(^{1/2} \) for E1, E2, E3 and E4 that are corresponding to mold oscillation frequency of 1.00, 1.33, 1.67, and 2.00 Hz respectively. It could be observed that the shell thickness tended to increase with the increase of mold oscillation frequency. This is because the infiltrated mold/shell slag film thickness decreases with the increase of mold oscillation frequency, and a thicker slag film in between mold and shell will cause a more thermal resistance to the heat transfer from the shell to the mold (Figs. 6 and 10). The detailed discussion about the heat transfer of slag film would be given later.

As shown in Fig. 6, the thickness of the infiltrated mold/shell slag film along the centerline of mold is in the range of 1.86 to 3.19 mm, 1.80 to 3.07 mm, 1.74 to 2.99 mm, and 1.73 to 2.84 mm for E1, E2, E3, and E4 respectively. The infiltrated slag film is observed to be thicker for the locations corresponding to oscillation marks and the surface depressions as well as for the location corresponding to the shell tip. Moreover, the average thickness of the infiltrated mold/shell slag film for the distance 5 to 25 mm below the shell tip is 1.98, 1.93, 1.85, and 1.82 mm for the trials of E1, E2, E3, and E4 respectively. It is implied that the average infiltrated slag film thickness (include solid slag film and liquid slag film) decreases with the increase of the mold oscillation frequency. This might be attributed to an increase in mold oscillation frequency decreases mold flux consumption (Fig. 13), therefore, reducing the lubricating slag film between the mold and the shell (Fig. 12), and also reduces the negative strip time, which reduces the oscillation mark depth. Both effects lead to a decrease in the mold/shell gap and then the thickness of slag film as demonstrated by Samarasekera and Brimacomb.
to the fact that the heat transfers from the shell to the mold $q_{int}$ is much larger than that of heat accumulated in slag film. According to the superposition principle, the mold surface heat flux ($q_{int}$) would be regarded as the horizontal component of heat flux across the slag film which can be expressed as follows,

$$q_{int} = T_{ss} - T_{sl} = \frac{T_{sol} - T_{sol}}{R_{int} + \frac{1}{h_{lr}}} = \frac{T_{sol} - T_{sol}}{R_{int} + \frac{1}{h_{lr}}}$$

(1)

Where $R_{int}$ is the conductive thermal resistance, which equals to $d/l_{k, eff}$. And the radiative thermal resistance $1/\epsilon_{sh}$ can be expressed as follows,$^{13}$

$$R_{int} = \frac{1}{1/R_{int} + \frac{1}{h_{lr}}}$$

(2)

$$R_{int} = \frac{1}{1/R_{int} + \frac{1}{h_{lr}}}$$

(3)

Where $R_{int}$ is the conductive thermal resistance, which equals to $d/l_{k, eff}$. And the radiative thermal resistance $1/\epsilon_{sh}$ can be expressed as follows,$^{13}$

$$\frac{1}{h_{lr}} = \frac{0.75a \delta d_{s} + \epsilon_{sh}}{m^{2} \sigma_{0}(T_{sh} + T_{sl})(T_{sh} + T_{sl})}$$

(4)

Where $a_{0}$ is the absorption coefficient of liquid slag, $d_{s}$ is the liquid slag film thickness ($d_{s} = d_{m}$, $d_{m}$ is the solid slag film thickness and $d_{m}$ is the measured slag film thickness), $\epsilon_{sh}$ is the shell emission, $\epsilon_{cry}$ is the crystalline slag emission, $m$ is the slag refractive index, $\epsilon_{sh}$ is the Stefan-Boltzmann constant.

The slag film from the mold simulator trials consists of glass, crystals, gap and cracks, which are also found in the industrial’s caster ones.$^{58}$ It is very hard to determine the physical properties of solid slag, and the gray body heat transfer model is not applied to study the heat transfer in solid slag film, which is a discontinuous medium.$^{57}$ For simplification, an effective thermal conductivity $k_{eff}$ which takes both of the conductive and the radiative heat transfer into account, is used here to study the heat transfer in the solid slag film. Therefore, solid slag film thermal resistance $R_{s}$ can be expressed as follows,

$$R_{s} = \frac{d_{s}}{k_{eff}}$$

(5)

The liquid slag film mainly acts as the lubrication func-

### Table 4. Physical properties of IF steel.

| Property                  | Value      | Unit     |
|---------------------------|------------|----------|
| Density, $\rho_{\text{solid}}$ | 7400$^{(3)}$ | kg/m$^3$ |
| Specific heat, $c$        | 820$^{(3)}$ | J/kg/K   |
| Latent Heat, $L_a$        | 272 000    | J/kg     |
| Conductivity in solid $k_s$ and Liquid $k_l$ | 35, 35 | W/m·K |
| Liquidus temperature, $T_l$ | 1 811 | K        |
| Solidus Temperature, $T_s$ | 1 802 | K        |

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tion for mold and shell, the slag film thickness and the liquid consumption per unit area of shell surface \((Q_{\text{slag}})\) are frequently used as the key parameters to evaluate the lubrication behavior of a mold flux. The liquid consumption \((Q_{\text{slag}})\) could be estimated by Thomas-Meng expression \(^{58}\) once the solid slag film thickness \((d_l)\), the downward velocity of solid slag layer \((V_s)\) and liquid slag layer \((V_l)\) are given.

\[
Q_{\text{slag}} = \frac{\rho_{\text{slag}}}{V_f} \int_0^1 \left( \int_0^d V_l dx + V_l d_y \right) dt \quad \text{.............. (6)}
\]

Where the solid slag layer in the vicinity of meniscus area can be assumed to stick to the mold wall, \(^{58}\) so \(V_s\) equals to \(2\pi a d\cos(2\pi f)\) and the liquid slag layer \((V_l)\) is,

\[
V_l = \frac{-(\rho_{\text{slag}} - \rho_{\text{steel}})g x^{n+2}}{\mu_s (n+2) d_y^2} d^2 + \left( \frac{V_s - V_x}{d_f} + \frac{\rho_{\text{slag}} - \rho_{\text{steel}}}{\mu_s (n+2)} \right) \frac{x^{n+1}}{d_f^2} + V_x \quad \text{.............. (7)}
\]

Where \(x\) is the horizontal distance between the crystal/liquid slag interface and the location within liquid slag film, \(\rho_{\text{slag}}\) is density of slag, \(\rho_{\text{steel}}\) is density of steel, \(g\) is acceleration of gravity, and \(n\) is temperature-dependent viscosity exponent that is obtained by fitting viscosity-temperature \((\mu_i-T)\) curve of slag with function \(\mu_i = \mu_1 100 \times [(1 300 - T_{\text{sol}})/(T_{\text{sol}})]^n\).

For simplification, the thermal resistance and liquid slag thickness of slag film at the location 22 mm below the shell tip were chosen to characterize the effect of mold oscillation frequency on heat transfer and lubrication behavior of slag film, where the thermal resistance reaches to a relatively stable value from this position (Fig. 9). Firstly, according to Eq. (1), \(R_{\text{tot}}, R_{\text{int}}, R_s, R_l, R_t\) and \(R_s\) could be estimated from the \(q_{\text{int}}, T_{\text{sol}}\) and \(T_{\text{mld}}\). By knowing \(R_s, T_{\text{sh}}\) and \(T_{\text{sol}}\), the liquid slag film thickness \(d_l\) is calculated from Eqs. (3) and (4), and then the solid slag film thickness \(d_s\) \((= d_{\text{mld}} - d_l)\). Next, by knowing \(d_l\), liquid consumption \((Q_{\text{slag}})\) is estimated for Eq. (6). During the calculation, the physical properties of mold flux, such as shell emission \(\varepsilon_{\text{sh}}\) and crystallization temperature \(T_{\text{sol}}\) et al., are listed in Table 5. \(^{24,30,54,55,59-61}\)

### 3.3.1. Heat Transfer Behavior

A typical evolution of the thermal resistances in between the mold and the shell along the casting direction (trial E1 with mold oscillation frequency is 1.0 Hz) is shown in Fig. 9. The total mold/shell thermal resistance \(R_{\text{tot}}\) of E1 is 8.90×10\(^{-4}\) m\(^2\)·K/W at the location of shell tip \((Z = 0 \text{ mm})\), and decreases to the minimum \((5.98×10^{-4} \text{ m}^2\cdot\text{K}/\text{W})\) at 5 mm below the shell tip that corresponds to the location of maximum mold heat flux (Fig. 3(b)). The \(R_{\text{tot}}\) reaches to a relatively stable value from the position 22 mm below the shell tip. Next \(R_{\text{tot}}\) begins to increase, and finally reaches 11.90×10\(^{-4}\) m\(^2\)·K/W at 25 mm below the shell tip due to the increase of the mold/slag interfacial thermal resistance \(R_{\text{slag}}\) and the slag film thermal resistance \((R_s + R_l)\). The detailed description of the variation of slag film thermal resistance could be found in our previous study. \(^{31}\)

The solid slag film thermal resistance \(R_s\) is 4.21×10\(^{-4}\)
m²·K/W at the location of shell tip (Z = 0 mm), and decreases to the minimum (3.24 × 10⁻⁴ m²·K/W) at 5 mm below the shell tip due to the reduction of slag film thickness, then it begins to increase and finally is 6.45 × 10⁻⁴ m²·K/W at 25 mm below the shell tip due to the further crystallization of mold flux. In addition, the mold/slag interfacial thermal resistance \( R_{int} \) is 1.96 × 10⁻⁴ m²·K/W at the location of shell tip (Z = 0 mm), and decreases to the minimum (1.46 × 10⁻⁴ m²·K/W) at 5 mm below the shell tip, then begins to increase and finally is 3.02 × 10⁻⁴ m²·K/W at 25 mm below the shell tip. Besides, the percentages of the solid slag film thermal resistance \( R_s \) and the liquid slag film thermal resistance \( R_l \) and the mold/slag interfacial thermal resistance \( R_{tot} \) over the total mold/shell thermal resistance \( R_{tot} \) are 47.37 to 54.52 pct (\( R/R_{tot} \)), 20.82 to 24.71 pct (\( R_l/R_{tot} \)) and 22.04 to 25.34 pct (\( R_{int}/R_{tot} \)) respectively. Therefore, \( R_{tot} \) and \( R_l \) could be regarded as the dominative factors to control the heat transfer from the shell to the mold.

Figure 10 shows the slag film thickness at the location 22 mm below the shell tip. The slag film thickness is 1.88, 1.77, 1.72 and 1.66 mm for the trials of \( E_1 \), \( E_2 \), \( E_3 \), and \( E_4 \) that are corresponding to the mold oscillation frequency of 1.00, 1.33, 1.67, and 2.00 Hz, respectively. It is implied that the thickness of liquid slag film decreases with the increase of mold oscillation frequency. Therefore, the infiltrated mold/shell slag film decreases (Fig. 6) that would lead to the reduction of the total mold/shell thermal resistance \( R_{tot} \). While the solid slag film thermal resistance \( R_s \), the liquid slag film thermal resistance \( R_l \) and the mold/slag interfacial thermal resistance \( R_{int} \) (Fig. 10) decrease, which would result in a thicker initial shell (Fig. 5) and thus a colder shell surface (Fig. 7) as well as a smoother surface of slag film next to the mold side (Fig. 11).

### 3.3.2. Lubrication Behavior of Mold Flux

Figure 12 shows the thickness of liquid slag film \( d_l \) at the location 22 mm below the shell tip. \( d_l \) is 0.40, 0.39, 0.35, and 0.33 mm for the trials of \( E_1 \), \( E_2 \), \( E_3 \), and \( E_4 \) that are corresponding to the mold oscillation frequency of 1.00, 1.33, 1.67, and 2.00 Hz, respectively. It is implied that the thickness of liquid slag film decreases with the increase of mold oscillation frequency. The decrease of liquid slag film is also associated with the surface temperature of solidifying shell that is 1 652.13, 1 648.81, 1 642.05, and 1 636.85 K for \( E_1 \), \( E_2 \), \( E_3 \), and \( E_4 \) respectively (Fig. 7), where a hotter surface temperature of solidifying shell would lead to a thicker liquid slag film that is in favor of mold/shell lubrication.

Figure 13 shows the liquid slag consumption \( Q_{slag} \) at the location 22 mm below the shell tip. \( Q_{slag} \) are calculated as 0.29, 0.28, 0.24 and 0.23 kg/m² for \( E_1 \), \( E_2 \), \( E_3 \) and \( E_4 \) that are corresponding to the mold oscillation frequency of 1.00, 1.33, 1.67, and 2.00 Hz. PST of 0.68, 0.47, 0.36, and 0.29 seconds, and NST of 0.32, 0.28, 0.24, and 0.21 seconds, respectively. Increase in mold oscillation frequency from 1.00 to 2.00 Hz resulted in the decrease in NST and/or PST. Furthermore, the liquid slag thickness is calculated as 0.40, 0.39, 0.35 and 0.33 mm for \( E_1 \), \( E_2 \), \( E_3 \) and \( E_4 \) respectively (Fig. 12). Thus, the liquid slag consumption increases with the increase of the mold oscillation frequency. The decrease in \( Q_{slag} \) with increasing the frequency may be attributed to the reduced pumping effect (produced by the downwards movement of the mold and slag rim) as a result of a shorter NST, and to the less infiltration of slag into the mold/shell gap during PST. 12,19,41,62 By linear fitting analysis, the liquid slag consumption seems to have a more correlation with...
mold oscillation frequency than NST and PST, owing to the adjusted coefficient of determination ($R^2$) that is 0.9445, 0.9451 and 0.8061 for fitting lines of frequency, NST and PST respectively.

In summary, with the increase of the mold oscillation frequency, the total mold/shell thermal resistance $R_{tot}$ decreases (Fig. 10) due to the reductions of the infiltrated mold/shell slag film (Fig. 6) that would lead to the formation of a thicker initial shell (Fig. 5) and a colder shell surface (Fig. 7), and then the liquid slag film gets thinner (Fig. 12) and the liquid slag consumption decreases (Fig. 13).

4. Conclusions

The effect of mold oscillation frequency on the heat transfer and lubrication of infiltrated mold/shell slag film during continuous casting of IF steel were studied by using the mold simulator technique. The major conclusions are summarized as follows:

(1) The increase of the mold oscillation frequency from 1.00 to 2.00 Hz is associated with the reduction of slag film infiltrated into mold/shell gap by 8.08 pct (1.98 to 1.82 mm), which leads to the increase of mold surface temperature and heat flux, and thus results in the increase of shell solidification factors by 3.98 pct (2.26 to 2.35 mm/s$^{1/2}$).

(2) Increasing frequency from 1.00 to 2.00 Hz would decrease the total mold/shell thermal resistance by 9.81 pct (11.82×$10^{-4}$ to 10.66×$10^{-4}$ m$^2$·K/W), in which the solid slag thermal resistance decreases by 13.41 pct (2.46×$10^{-4}$ to 2.13×$10^{-4}$ m$^2$·K/W) and the mold/slag interfacial thermal resistance decreases by 10.10 pct (2.97×$10^{-4}$ to 2.67×$10^{-4}$ m$^2$·K/W). Moreover, the decrease of mold/slag interfacial thermal resistance is associated with the decrease of the air gap thickness (9.50 to 8.54 µm) between slag film and mold.

(3) Increasing frequency from 1.00 to 2.00 Hz will decrease the thickness of liquid slag film by 17.50 pct (0.40 to 0.33 mm), and the liquid slag consumption by 20.69 pct (0.29 to 0.23 kg/m$^2$).

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