Simulation and Characterization on Heat Transfer through Mould Slag Film

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As one of the most important factors on product surface quality and casting practice, the heat transfer across the interfacial layers in continuous cast mould is greatly affected by the formation of mould slag film between the solidifying shell and the mould. So far, many methods have been presented to measure the heat transfer of mould slag; however, few of them could be easily applied to represent the real heat transfer across the mould interfacial gap. An apparatus used for mould slag film heat transfer measurement is presented in the current paper. The apparatus is used to simulate the heat transfer across the mould slag film. According to the measurement, four parameters are selected as a standard to characterize the heat transfer of the mould slag. The parameters include maximum heat flux (liquid slag), characteristic time, heat flux at meniscus, and average heat flux. Two measurements on different mould slags verify that: 1) the standard could represent the difference in heat transfer between medium carbon steel and low carbon steel mould slag; 2) the average heat flux is a key factor to indicate the overall heat transfer in casting mould; 3) the formed solid slag film in experiment is identical to the real mould, including the morphology, composition, grain size, and thickness. The experiment simulation offers an effective approach to study the formation and evaluation of slag film inside the mould.

KEY WORDS: mould slag; slag film; heat transfer; slag film heat flux simulator; characterization.

1. Introduction

Mould slag plays very important role in the lubrication and heat transfer between the solidifying shell and cast mould. The slag is added from the top of the mould and three layers are formed on the top by the sequence of powder layer, sinter layer, and liquid slag layer. Liquid slag infiltrates the interfacial gap between cast mould and strand during the negative strip and a solid slag film (include both glass layer and crystallization layer) was formed near the mould. The thickness of the liquid slag film near the strand is around 0.1 mm and the thickness of the solid slag film is around 2 mm. Generally, the liquid slag film affects the lubrication between strand and mould, and the solid slag film dominates the heat transfer across the interfacial gap. The heat resistances between the strand and mould include liquid slag heat resistance, solid slag heat resistance, and solid slag film/mould interface heat resistance. Among these heat resistances, the last two play a dominant role. The thicker solid slag film with a certain amount of crystal could reduce the heat transfer in mould effectively; and hence prevent the longitudinal crack on medium carbon steel. However, the sticker break out might happen if the heat transfer is greatly reduced. So an optimized heat transfer is very important.

The properties of mould slag on heat transfer can be tested by different methods. Taylor and Shibata measured the heat diffusivity of mould slag by laser flash method to present the capability of heat transfer. Coto, Ozawa, and Susa tested the heat conductivity of both liquid slag and solid slag by hot wire method. Riboud measured the heat diffusivity of liquid slag using one-dimensional unsteady slag column method. However, all these measurements could only test either liquid slag or solid slag, which have large deviation to real world. Also, the test cost is high and it is difficult to get the testing sample. Ohmiya and Yamauchi measured both heat conductivity and interface heat resistance by the method of one-dimensional steady state plate. Cho introduced numerical calculation based on the plate method to calculate the interface heat resistance between the solid slag film and mould wall. But the method requires to get the reflection coefficient, absorb coefficient, and extinction coefficient of the mould slag, which limit the application of such method since the properties vary with the composition of mould slag. Yovermeulen dipped a copper finger into the liquid slag. The surface temperature on the copper finger can identify the heat transfer of the mould slag. However, the method could only perform qualitative test instead of quantitative measurement.

Although many measurements were purposed in the previous study, few of them could offer an accurate measurement on heat transfer in cast mould. Wen developed a slag film heat flux simulator based on Yovermeulen's dip testing. The method covers the heat transfer between mould and mould slag, including interface heat resistance, solid slag film heat resistance, and liquid slag heat resistance. It is easy to use and has high accuracy.
to get high replicable measurements, which makes it become a good tool to study the thermal properties of mould slag. However, the parameters used to characterize the heat transfer properties of mould slag in the continuous casting process deserve further investigation. In the current paper, several parameters were selected to characterize the heat transfer properties of the mould slag according to the measurements. Two measurements on different industrial mould slags were made to verify the applicable of these parameters. The purpose of the study is to create a guideline to study the heat transfer of mould slag.

2. Methodology

2.1. Testing Principle and Apparatus

The schematic of the apparatus is illustrated in Fig. 1. The continuous casting mould surface was simulated by water cooling copper sensor (or copper detector). At the beginning of the experiment, around 350 gram mould slag was melted in the MoSi2 furnace. The temperature has to be controlled at 1673 ± 1 K. The copper detector was dipped into the liquid mould slag at 1673 K. The solid slag film is formed around the copper detector. The heat across the film was taken away by the cooling water and the temperature difference of the cooling water in/out was recorded by computer. Therefore, the heat flux between the copper detector and mould slag can be calculated by the following equation:

$$q = \frac{W \cdot C \cdot \Delta T}{F \cdot 1000} \quad (1)$$

where, $q$ is the heat flux across the slag film, MW/m$^2$; $W$ is the flow rate of the cooling water; $\Delta T$ is the temperature difference of cooling water at in/out, K; $F$ is the effectively heat transfer area on the copper detector, m$^2$; $C$ is the specific heat capacity of the cooling water, kJ/(kg·K).

Once the time reaches the target time, the copper detector can move upward automatically; meanwhile, the solid slag film can be collected from the surface of copper detector, as shown in Fig. 2.

The heat transfer from the high temperature liquid slag to cooling water can be represented by heat resistances, including solid slag, liquid slag, interface (air gap), copper detector, and cooling water. It is similar to the real case inside the continuous casting mould. As illustrated in Fig. 3, the heat flux decreases with the increase of the copper detector dipping time, which is identical to the condition in the real cast mould (heat flux is reduced by the increase of residence time or the distance below the meniscus, as shown in Fig. 4). Therefore, the heat flux measurement at different dipping time can reflect the heat flux at different location inside the mould from top to bottom.

2.2. Slag Film Observation

Mills mentioned both slag film thickness and crystallization ratio have great effect on the heat transfer of mould slag. The solid slag film can be collected easily on the copper detector. The average thickness of the slag film is calculated by the three measurements on thickness of both wide face and narrow face. The microstructure of the slag film was observed under the SEM scope, including the crystal distribution, size, morphology, and etc. XRD was
employed to identify the crystal type inside the film. The thickness ratio between the crystal area and slag film area was used to represent the crystallization ratio of the mould slag.

3. Standard of Mould Slag Characterization

From Fig. 3, the measured heat flux varies with time can be classified by three stages: 1) from 0 to \( t_1 \), heat flux increases with the increase of the time dramatically. The heat flux reaches the peak at \( t_1 \); 2) from \( t_1 \) to \( t_2 \), heat flux sharply decreased with the increase of residence time; 3) after \( t_2 \), the heat flux decrease with the increase of time slowly. More details on these stages are as following:

1) From time 0 to \( t_1 \), the copper detector is dipped into the mould slag for a short time. The heat from the high temperature liquid slag moves to the copper detector, which cause the increase of heat flux. At this moment, the thickness of the solid slag film is tiny; therefore, the heat resistance of the liquid slag is the major contributor to the heat transfer. After the heat flux reaches the maximum point, the thickness of the solid slag keeps increasing and the air gap is formed. Then, the heat flux turns to drop. So, the maximum heat flux at \( t_1 \) could be defined as a parameter to represent the capability of liquid slag on heat transfer;

2) From \( t_1 \) to \( t_2 \), the thickness and crystallization ratio of the slag film increase with the increase of time, which cause the increase of the heat resistance between the solid slag and detector. Accordingly, the heat flux is decreased. This period reflect the formation of the interface heat resistance and solid slag heat resistance;

3) After \( t_2 \), the heat flux decrease with the increase of time slowly. Cho\(^{13}\) pointed out the interface heat resistance (air gap heat resistance) can be employed to identify the t 2 (45°), which is defined as heat flux at meniscus and can be calculated by the following equation,

\[
\bar{q}_a = \frac{q_{11} + q_{14} + \ldots + q_{15}}{t_2 - t_1}
\]

4) Mould slag average heat flux, \( \bar{q} \), \( 10^4 \text{ W/m}^2 \), represents the overall heat transfer capability of slag in the mould. According the previous study,\(^{19}\) the structure of the slag film is similar to the slag film sample from the real mould. Therefore, the average heat flux is taken from \( t_1 \) to 45 seconds:

\[
\bar{q} = \frac{q_{11} + q_{14} + \ldots + q_{15}}{45 - t_1}
\]

5) Total heat resistance \( R_T \), \( 10^{-4} \text{ K·m}^2/\text{W} \). After \( t_2 \), the air gap is formed and the change of the heat flux is small. It is a quasi-steady heat transfer process. Therefore, the heat resistance after \( t_2 \) could reflect the heat transfer capability of the slag film. Figure 5 shows the temperature distribution between the copper detector and slag film, the total heat resistance \( R_T \) is calculated by,

\[
R_T = \frac{\Delta T}{q_T}
\]

where, \( q_T \) is the total heat flux, according to Eq. (1); \( \Delta T \) is the temperature difference between liquid slag and copper detector. It can be calculated by Eq. (6)

\[
\Delta T = T_s - T_c
\]

where, \( T_s \) is the interface temperature of the solid slag and liquid slag, representing the flowing temperature of mould slag; \( T_c \) is the temperature at copper detector, approximately

\[
t = t_2 - t_1
\]
represented by the average temperature of in/out cooling water (Tw).

4. Verification of Mould Slag Characterization

4.1. Mould Slag Sample from the Industry and the Experiment Result

To study the reliability of the characterization method, two types of typical mould slag (low carbon steel, LC and medium carbon steel, MC) from a slab strand were selected. The slag samples were obtained from the No.2 slab caster at Chongqing Steel Company. The casting cross-section size is 230 × 1530 mm². The basic chemical composition of the mould powder is listed in Table 1.

To compare the testing result at the laboratory, the slag films were obtained directly from the caster and the mould heat extraction was recorded at the same time. The procedure of the sample collection follows: start to count the time after clear up the slag film at the center of mould; get the slag sample at the sample place when the time arrives to 45 seconds. Table 2 shows the comparison of slag thickness and crystallization ratio between the industrial sample and experiment.

Figure 6 illustrates the testing result of heat flux varies with time for both LC and MC mould slag. According to Fig. 6, the characterization parameters were calculated and listed in Table 3. Meanwhile, the heat extraction of broad face in mould from the industrial measurement for both LC and MC mould slag under 1.0 m/min casting speed were posted in Table 3 for comparison. From Fig. 6 and Table 3, the heat flux for LC is obviously higher than the case of MC.

4.2. Discussion

4.2.1. Structure of the Slag Film

The heat transfer capability of the slag depends on the thickness and structure of the slag film. The consistency of these two key factors between laboratory slag film and plant’s is the focus to determine whether the slag film heat flux simulator can reflect the real heat transfer inside the mould.

Figure 7 shows the structure of the solid slag film from both industrial sample and laboratory experiment. From Fig. 7, it is easy to distinguish that three layers remaining in the MC mould slag: Layer A, close to the mould. Due to the low temperature and high cooling rate, the crystal got less opportunity to grow up. The grain size is relatively small in this area. Layer C, close the liquid slag, the temperature is higher; it is easy to form large size crystal. Layer B, transition layer, the grain size is between the layer A and layer B, it has thin crystal. Figure 8 gives the XRD results for both industrial sample and laboratory experiment on MC mould slag. It shows that the main crystal is cuspidine (3CaO·2SiO2·CaF2) with low heat conductivity. About LC mould slag, three layers also can be observed, including layer A with small size crystal, layer C with glassy, and layer B, narrow transition layer with different crystal appearance from layer A’s. Figure 9 shows the appearance of both cuspidine and a few CaF2 in the LC mould slag. It is shown that diffraction intensity of MC mold slag is much greater than that of LC mold slag from Figs. 8 and 9. That is to say MC mould slag has greater crystallization capacity. This is well proved by Fig. 7 SEM images, and is identical with the value of crystallization ratio in Table 2.

The comparison of industrial sample and laboratory experiment is listed in Table 2. Overall, the slag film obtained from the experiment is identical to the industrial sample on aspect of crystal type, morphology, grain size, film thickness, and crystallization ratio.

4.2.2. Total Heat Resistance

Cho applied plate method to get the relationship between heat resistance and the thickness of slag film for both low carbon and medium carbon steel mould slag. The total heat resistance obtained by slag film heat flux simulator was compared with the result from previous literatures.

According to the previous analysis, the slag film has small change rate on heat flux from t2 to 45 second. And calculated results of t2 for LC and MC mould slag are 23 s and 19 s, respectively. Therefore, the slag film at 25 s was selected to measure the thickness and calculate the total heat resis-

Table 1. Chemical composition and physical properties of industrial mould slag (mass%).

| Mould slag | SiO₂ | CaO | Al₂O₃ | R₂O | F | MgO | Fe₂O₃ | Basicity | Viscosity (Pa·s) | Melting Point (K) | Flowing Point (K) |
|------------|------|-----|-------|-----|---|-----|-------|---------|---------------|-----------------|-----------------|
| MC         | 28.41| 34.33| 1.43  | 7.85| 5.07| 3.29| 0.26  | 1.21    | 0.091         | 1 393           | 1 418           |
| LC         | 31.11| 27.58| 4.28  | 11.64| 7.59| 1.41| 1.03  | 0.89    | 0.147         | 1 363           | 1 403           |

Table 2. Slag film thickness and crystallization ratio of MC and LC.

| Mould slags | Slag thickness (mm) | Crystallization ratio (%) |
|-------------|---------------------|--------------------------|
| MC          |                     |                          |
| Industry    | 2.75                | 89                       |
| Laboratory  | 2.70                | 84                       |
| LC          |                     |                          |
| Industry    | 1.80                | 35                       |
| Laboratory  | 1.83                | 29                       |

Fig. 6. Heat flux varies with time measured by laboratory experiment.

Fig. 7. SEM images of the slag film.
At 25 s, the slag film thickness of the LC and MC is 1.79 mm and 1.5 mm, respectively. The total heat resistance is 19.86 and 15.69 (10⁻⁴ K·m²/W), respectively. The total heat resistance of MC mould slag is higher than that of LC mould slag, which is identical to the finding from Cho’s study, as shown in Fig. 10. From the comparison above, it indicates that the slag heat flux simulator can properly reflect the heat transfer properties of mould slag.

4.2.3. Mould Slag Characterization Parameters

(1) Maximum (liquid slag) Heat Flux

From the Table 3, the maximum heat flux of MC mould slag (950 kW/m²) is lower than that of LC mould slag (1 140 kW/m²). That is because the heat resistance of the liquid slag dominates the heat transfer process when the solid slag starts to grow. The heat conductivity of the liquid slag depends on Debye equation,
The heat conductivity of the sodium silicate decreases with the increase of basic oxide. From Table 1, the basic oxide content of the medium carbon steel mould slag is 1.21, which is larger than that of low carbon steel mould slag; therefore, mean free path of phonon and heat conductivity of MC mould slag is low. According to the test result, the capability of heat transfer of MC mould slag is weaker than that of LC mould slag.

(2) Mould Slag Characteristic Time

The large shrinkage of medium carbon steel during the solidification cause the uneven heat transfer and may result in the longitudinal crack on the slab surface. The crack occurs at the meniscus region. To prevent the longitudinal crack of the medium carbon steel, it requires the mould slag has an excellent capability to control the heat transfer, which means the formation time of air gap should be short. Conversely, the longer air gap formation time is required for low carbon steel mould slag.

From Table 3, the characteristic time of MC mould slag is 14 s, which is lower than the time of LC mould slag (18 s). There are two reasons for MC mould slag has shorter characteristic time: 1) the thickness of MC mould slag is larger than that of LC mould slag. It indicates that the solidification capability of MC mould slag is stronger than that of LC mould slag. The solidification and shrinkage of the mould slag occurs in a short time, and the air gap is quickly formed; 2) the crystallization ratio of MC mould slag is higher than that of LC mould slag, causing the rough surface on the MC slag film and accelerating the formation of air gap. So the characteristic time could reflect the solidification capability of mould slag. Also, it could indicate the formation rate of air gap near the meniscus region.

(3) Heat Flux at Meniscus Region

Besides the short characteristic time of mould slag, lower heat flux is expected at meniscus region to prevent the longitudinal crack. From Table 3, the average heat flux (730 kW/m²) of MC mould slag from t₁ to t₂ is lower than the average heat flux (850 kW/m²) of LC mould slag. It indicates the capability of MC mould slag on heat transfer is weaker than that of LC mould slag. The lower heat transfer rate of MC mould slag depends on the thicker slag film and higher crystallization ratio.

(4) Average Heat Flux

Although the three parameters above can represent the difference between MC mould slag and LC mould slag on heat transfer, they cannot be used to match the heat transfer in mould directly. It is well known that the heat extraction can be easily collected from a caster. It represents the average heat transfer from the top to the bottom of the mould and it is comparable to the heat flux varies with time measured by slag film heat flux simulator. From Table 3, the average heat flux (720 kW/m²) of LC mould slag is 17% above the heat flux (600 kW/m²) of MC mould slag. From the industrial measurement (under the casting speed 1.0 m/min), the average heat extraction of LC mould slag is 1380 kW/m², which is 19% above the heat extraction of MC mould slag (1120 kW/m²). It shows the result from the laboratory experiment is identical to the industrial measurements.

So, the average heat flux from the laboratory experiment could properly reflect the heat transfer of mould slag. It is a key parameter to judge the capability of mould slag on heat transfer, like using the viscosity at 1573 K for the fluidity of mould slag.

5. Conclusions

The variation of heat flux with time was measured by the mould slag film heat flux simulator. Two kinds of mould slag (LC and MC) were measured to verify the purposed characteristic parameters can represent the capability of mould slag on heat transfer. According to the study, the following conclusions can be drawn:

(1) By the analysis on the variation of heat flux with time, four parameters were purposed to represent the heat transfer property of mould slag, including maximum (liquid slag) heat flux, characteristic time, heat flux at meniscus, and average heat flux;

(2) Two kinds of mould slag from the industry were selected to verify the parameters can be properly used to represent the difference in heat transfer between medium carbon steel mould slag and low carbon steel mould slag. Meanwhile, the application of average heat flux can reflect the heat transfer in the real mould; therefore, the parameter is a key factor to judge the capability of mould slag on heat transfer;

(3) The slag film collected from the simulator is identical to the slag film sample from the industry from the view of crystal morphology, composition, grain size, thickness, and etc. It indicates that the formation of slag film under the laboratory experiment is similar to the real world, which creates the opportunity to study the formation and evolution of the slag film inside the mould;

(4) The slag film heat flux simulator is expected to be a reliable method to test the capability of mould slag on heat transfer. It has important meaning for the design and selection of mould slag.

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