Mechanism of Heat Transfer Reduction by Crystallization of Mold Flux for Continuous Casting

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The mechanism by which crystallization of mold flux reduces the heat transfer between the steel shell and the mold has been investigated from the viewpoint of physical properties and characteristics of mold flux and air gap on the basis of a heat transfer model involving conduction and radiation processes. It has been found that, in mold fluxes for medium carbon steel, the reflectivity of the crystalline slag layer formed in mold flux film is an efficient factor for further reducing the total heat flux in the film. The heat transfer reduction based on this finding would be possible according to the following mechanism: Crystallization of mold flux film increases the reflectivity of the crystalline slag layer in the film owing to enhanced scattering of light by introduction of crystal grain boundaries, and thereby more radiation energy returns from the crystalline slag layer to the steel, leading to reduction in the total heat flux across the film.

KEY WORDS: continuous casting; mold flux; heat transfer; crystallization and reflectivity.

1. Introduction

Mold flux plays a very important role in continuous casting of steel, and one of the main functions of the flux is to infiltrate between the solidified shell and the water-cooled copper mold to provide lubrication. Another function is to control the heat transfer between the shell and the mold. For medium carbon steel, for example, improper conditions of casting cause a serious problem called ‘longitudinal cracking’ on the steel surface, which is considered to be due to thermal stresses in the steel resulting from non-uniform solidification shrinkage during the δ–γ transformation.1,2) To prevent surface defects such as longitudinal cracking, it is necessary to provide uniform heat extraction from the shell, which can be attained by reducing the heat transfer across the mold flux layer.3,4) In practice, this reduction in heat transfer is being made by forming crystals of cuspidine (3CaO·2SiO2·CaF2) in the flux film5) and, for further improvements of mold flux, it is very important to know how crystallization of mold flux reduces the heat transfer.

Against this background, many researchers have studied the mechanism by which crystallization reduces the heat flux across the mold flux layer. Mechanisms proposed so far fall into two and are briefly summarized as follows:

(i) The solidification shrinkage due to crystallization produces an air gap layer at the interface between the mold flux film and the mold, which brings about interfacial thermal resistance to reduce the total heat flux.

(ii) Crystallization lowers the transmissivity of the flux film, which causes the radiation heat flux to be small, leading to the reduction in the total heat flux.

With respect to mechanism (i), the presence of interfacial thermal resistance has been experimentally shown by a few researchers6,7). Yamauchi et al.8) have reported that crystallization gives rise to the interfacial thermal resistance corresponding to an air gap of 20–50 μm thickness, and Cho et al.9) have indicated that the interfacial thermal resistance increases linearly with increasing the thickness of the crystalline slag layer. The interfacial thermal resistance has also been studied from the viewpoint of the surface roughness of the flux film10–14): for example, Tsutsumi et al.15) have shown that the interfacial thermal resistance increases as the surface roughness increases, and Yamauchi et al.16) have pointed out that the surface roughness, in turn, increases as the solidus temperature of mold fluxes increases. In addition, there have been several investigations15–19) made on the magnitude of the interfacial thermal resistance, which have shown that the interfacial thermal resistance has a high proportion of the total thermal resistance of the mold flux layer. On the contrary, Hanao et al.15) have pointed out that the previous studies might have overestimated the thickness and interfacial thermal resistance of the air gap layer, because static pressure from the molten steel onto the mold flux layer has not been taken into consideration.

For mechanism (ii), on the other hand, several workers16–20) have investigated the effect of crystallization of mold flux on the radiation heat flux. Shibata et al.16) have reported that, owing to increases in absorption and scattering of light associated with crystallization, the radiation heat flux decreases while the conduction heat flux increases, and Taylor et al.17) have pointed out that scattering by pores and absorption by graphite have the same effect of
reducing the radiation heat flux. It has also been reported that the radiation contribution takes up 6–20% of the total heat flux \cite{15,16}, however, Hanao et al. \cite{16} have suggested that the radiation thermal resistance of the crystalline slag layer is comparable to the interfacial thermal resistance of the air gap layer.

Thus, there has been no consensus obtained on the mechanism of heat flux reduction across the mold flux film by crystallization, further study on which is highly required. Other than this problem, it is also important to investigate what factor is efficient to further reduce the total heat flux across the film. It is certain that the total heat flux depends on physical properties and characteristics of mold flux and air gap. Consequently, the aims of the present work are:

(i) to investigate factors affecting the heat transfer between the steel shell and the mold by calculating the total heat flux on the basis of a heat transfer model involving conduction and radiation processes

(ii) to find an efficient factor for further reduction in the heat transfer to understand the mechanism by which crystallization of mold flux reduces the heat transfer.

2. Model for Heat Transfer Analysis

The molten mold flux film consists of a molten slag layer (next to the steel shell) and a crystalline slag layer (next to the molten slag layer) with an air gap layer (between the crystalline slag layer and the mold) introduced by crystallization. Figure 1 shows a heat transfer model on the basis of the above mold flux structure. In this model, it is assumed:

(a) The total thickness \(d_{\text{flux}}\) of the mold flux film (not including the air gap layer) is 1 mm.

(b) The whole system reaches a steady state, and the temperatures at the interfaces between the steel and the molten slag layer and between the air gap layer and the mold are 1 800 and 500 K, respectively.

(c) Heat is transferred in one direction from the steel to the mold by radiation and conduction; convective flow is neglected since the total thickness is sufficiently small. The molten and crystalline slag layers have respective radiation and conduction resistance components, whereas the air gap layer has only a conduction resistance component since temperature is low enough to neglect radiation, as described later.

\[
q_{\text{conduction (molden)}} = - k_m \frac{T_{c/a} - T_{\text{m/c}}}{d_{\text{molden}}} \tag{1}
\]

\[
q_{\text{conduction (crystalline)}} = - k_c \frac{T_{c/a} - T_{c/a}}{d_{\text{crystalline}}} \tag{2}
\]

\[
q_{\text{conduction (air)}} = - k_a \frac{T_{\text{mold}} - T_{c/a}}{d_{\text{air}}} \tag{3}
\]

where \(k_m\), \(k_c\), and \(k_a\) are, respectively, the thermal conductivities of the molten slag, crystalline slag and air gap layers, \(d_{\text{molden}}\), \(d_{\text{crystalline}}\), and \(d_{\text{air}}\) are, respectively, the thicknesses of the molten slag, crystalline slag and air gap layers \((d_{\text{molden}} + d_{\text{crystalline}} = d_{\text{flux}} = 1 \text{ mm})\), \(T_{\text{mold}}\) is temperature at the steel/slack interface, \(T_{1\ 800}\), and \(T_{500}\) are, respectively, temperatures at the molten slag/crystalline slag and crystalline slag/air gap interfaces, and \(T_{\text{mold}}\) is temperature of the mold (500 K).

The radiation heat flux through an absorbing medium between two infinite parallel plates \((q_{\text{radiation}})\) is generally calculated using Eq. (4).

\[
q_{\text{radiation}} = \frac{n^2 \sigma}{0.75 \alpha d + \varepsilon_1^{-1} + \varepsilon_2^{-1}} (T_1^4 - T_2^4) \tag{4}
\]

where \(n\), \(\alpha\) and \(d\) are the refractive index, absorption (or extinction) coefficient and thickness of an absorbing medium, respectively, \(\varepsilon_1\) and \(\varepsilon_2\) are the emissivities of two parallel plates 1 and 2, \(T_1\) and \(T_2\) are temperatures of two parallel plates 1 and 2, and \(\sigma\) is the Stefan–Boltzmann constant.

When this equation is applied to the air gap layer, the radiation heat flux across the air gap layer \((q_{\text{radiation (air)}})\) can be expressed by Eq. (5).

\[
q_{\text{radiation (air)}} = \frac{n_{\text{air}}^2 \sigma}{0.75 \alpha_{\text{air}} d_{\text{air}} + \varepsilon_{\text{crystalline}}^{-1} + \varepsilon_{\text{mold}}^{-1}} (T_{c/a}^4 - T_{\text{mold}}^4) \tag{5}
\]

According to Eqs. (3) and (5), in the air gap layer, the ratio of radiation heat flux to conduction heat flux \((q_{\text{radiation (air)}}/q_{\text{conduction (air)}})\) has been calculated as about 0.02, where \(\alpha_{\text{air}}=0 \text{ m}^{-1}\), \(d_{\text{air}}=30 \mu\text{m}\), \(\varepsilon_{\text{crystalline}}=0.6\), \(\varepsilon_{\text{mold}}=0.4\), \(n_{\text{air}}=1\), \(T_{c/a}=1\ 200 \text{ K}\) and \(k_{\text{air}}=0.0472 \text{ W} \text{ m}^{-1} \text{ K}^{-1}\). This calculation confirms the reasonability of the previous assumption that the air gap layer has only conduction heat flux.

Radiation heat fluxes across the molten slag layer and the
crystalline slag layer \( q_{\text{radiation(molten)}} \) and \( q_{\text{radiation(crystalline)}} \) can be expressed by the respective equations.

\[
q_{\text{radiation(molten)}} = \frac{n_{\text{molten}}^2 \sigma}{0.75 \alpha_{\text{molten}} d_{\text{molten}} + \varepsilon_{\text{steel}}^{-1} + \varepsilon_{\text{crystalline}}^{-1}} (T_{\text{steel}}^4 - T_{\text{m/c}}^4)
\]

\[
q_{\text{radiation(crystalline)}} = \frac{n_{\text{crystalline}}^2 \sigma}{0.75 E_{\text{crystalline}} d_{\text{crystalline}} + \varepsilon_{\text{crystalline}}^{-1}} \times (T_{\text{m/c}}^4 - T_{\text{c/a}}^4)
\]

where \( n_{\text{molten}} \) and \( n_{\text{crystalline}} \) are the refractive indices of the molten and crystalline slag layers, respectively, \( \varepsilon_{\text{steel}} \) and \( \varepsilon_{\text{crystalline}} \) are the emissivities of the steel and the crystalline slag layers, \( \alpha_{\text{molten}} \) is the absorption coefficient of the molten slag layer, and \( E_{\text{crystalline}} \) is the extinction coefficient of the crystalline slag layer. The value of \( \varepsilon_{\text{crystalline}} \) can be determined via Kirchhoff’s law, \( \varepsilon_{\text{crystalline}} = 1 - R_{\text{crystalline}} - T_{\text{crystalline}} \) which is briefly explained here. Figure 2(a) schematically shows a mold flux layer in the cylindrical coordinate system. The molten and crystalline slag layers exist in the regions \( 0 < r < r_1 \) and \( r_1 < r < r_2 \), respectively, where \( r_1 = 1 \) mm from the assumption in the previous section. Figure 2(b) shows thermal and mechanical stresses operative onto the crystalline layer: the former is due to the shrinkage by solidification and the latter is due to both static pressures from molten steel and molten slag and shear stress of molten slag. On the basis of this model, the deformation \( u \) of the crystalline layer at position \( r \) is given by Eq. (13).

\[
u = \frac{1 + \nu}{1 - \nu} \frac{l}{r} \int_{r_1}^{r_2} r \Delta T dr + \frac{1}{2} C_1 r + C_2 \frac{r}{r}
\]

where \( l \) and \( \nu \) are the linear thermal expansion coefficient and Poisson’s ratio of the crystalline slag layer, respectively, \( \Delta T \) is temperature difference, and \( C_1 \) and \( C_2 \) are constants which can be determined by the following boundary conditi-

![Fig. 2.](image-url)
and this function also contains the term $r\cdot s$ representing small.

cause the shell thickness is so thin that the shell strength is molten steel is operative to the flux film immediately be-

tu

the value of $d\cdot m\cdot l\cdot y$ with increasing the thickness of the crystalline slag layer:

Figure 3 shows the relationship between thicknesses of crystalline slag and air gap layers.

### Table 1. Parameters used for calculations on thickness of air gap layer.

<table>
<thead>
<tr>
<th>properties</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>linear thermal expansion coefficient of crystalline slag</td>
<td>$1/\mathrm{K}$</td>
</tr>
<tr>
<td>Poisson's ratio of crystalline slag</td>
<td>$118\times 10^{-5}$ $^{20}$</td>
</tr>
<tr>
<td>total flow rate of molten slag</td>
<td>$\nu$</td>
</tr>
<tr>
<td>viscosity of molten slag</td>
<td>$0.2$ $^{26}$</td>
</tr>
<tr>
<td>rate of steel</td>
<td>$Q/\mathrm{m}^2\cdot\mathrm{s}^{-1}$ $^{11,14,15,27,28,29}$</td>
</tr>
<tr>
<td>density of molten slag</td>
<td>$1.66\times 10^{-3}$ $^{11,14,15,27,28,29}$</td>
</tr>
<tr>
<td>density of steel</td>
<td>$\eta/\mathrm{Pa}\cdot\mathrm{s}$</td>
</tr>
<tr>
<td>$V_{\text{m}}/\text{min}^{-1}$</td>
<td>$2$ $^{30}$</td>
</tr>
<tr>
<td>$\rho_{\text{molten}}/\text{g/cm}^3$</td>
<td>$2.71$ $^{18}$</td>
</tr>
<tr>
<td>$\rho_{\text{steel}}/\text{g/cm}^3$</td>
<td>$7.20$ $^{25}$</td>
</tr>
</tbody>
</table>

where $Q$ is the total flow rate of the molten slag layer, $V_{\text{m}}$ is the flow rate of the steel, $\eta$ is the viscosity of molten slag, $\rho_{\text{molten}}$ is the density of molten slag, $\rho_{\text{steel}}$ is the density of steel, $g$ is the acceleration of gravity and $y$ is the position in the $y$ direction. It is also assumed that the static pressure of molten steel is operative to the flux film immediately because the shell thickness is so thin that the shell strength is small.

Consequently, Eqs. (13)–(15) give $u$ as a function of $r$, and this function also contains the term $r\cdot m\cdot l\cdot y$ representing $d_{\text{molten}}$. Thus, when the value of $d_{\text{molten}}$ is given, the value of $u_{\text{f}y treating the deformation at the ‘crystalline’/mold interface, i.e., $d_{\text{molten}}$ can be derived using parameters listed in Table 1. Furthermore, the value of $d_{\text{crystalline}}$ can also be obtained from the relationship $d_{\text{molten}} + d_{\text{crystalline}} = d_{\text{fuc}}$. Figure 3 shows the relationship between calculated $d_{\text{crystalline}}$ and $d_{\text{fuc}}$ at 8 mm below the meniscus (where the molten steel is covered with solidified shell), and supports the experimental fact$^{19}$ that the thickness of the air gap layer increases with increasing the thickness of the crystalline slag layer: the value of $d_{\text{fuc}}$ is roughly 10 $\mu$m.

### 3.2. Physical Properties

To investigate effects of the physical properties on the total heat flux, it is very important to determine the variation ranges of the physical properties. In particular, the physical properties of mold flux strongly depend on the chemical composition and, thus, the present work focuses on the chemical composition range for commercial mold fluxes for medium carbon steel.

#### 3.2.1. Thermal Conductivity

Thermal conductivities of molten slags have been measured using the hot wire method$^{20,31,32}$ and values reported are in the range 0.2–0.4 $\text{W m}^{-1}\text{K}^{-1}$. Thermal conductivity values ($k$) can also be derived using thermal diffusivity values ($a$) measured by the laser flash method from the relation $k = a\rho C_p$ where $\rho$ is the density and $C_p$ is the specific heat capacity at constant pressure. The conversion using $a = 4.5\times 10^{-3} \text{m}^2\text{s}^{-1}$ $^{14}$ can be 0.25–0.26 $\text{W m}^{-1}\text{K}^{-1}$, from the fact that the value of NBO/(Si + Al) lies in $0.25–0.26 \text{ W m}^{-1}\text{K}^{-1}$, which are as high as those for crystalline melt. This would be because the measurement by the laser flash method was affected by radiation and, hence, the variation range of thermal conductivity is determined on the basis of the values produced by the hot wire method.

However, the chemical compositions of slags used in the measurements using the hot wire method are not in agreement with those of commercial mold fluxes for medium carbon steel. Thus, the variation range of thermal conductivity is determined on the basis of the relationship between thermal conductivity and NBO/(Si + Al) (number of non-bridging oxygens per tetrahedrally coordinated atom such as Si and Al), which relationship has been proposed by Mills. $^{33}$ Figure 4 shows thermal conductivity values$^{20,31,32}$ reported for molten slags plotted against NBO/(Si + Al). On the basis of this figure, the variation range of thermal conductivity of the molten slag layer has been determined to be 0.25–0.26 $\text{W m}^{-1}\text{K}^{-1}$, from the fact that the value of NBO/(Si + Al) for commercial mold fluxes for medium carbon steel is in the range 3.26–3.45 using reported chemical compositions. $^{14,28,29}$

For the crystalline slag layer, the variation range of thermal conductivity has been determined to be 1.61–1.63 $\text{W m}^{-1}\text{K}^{-1}$, based upon the values reported by Ozawa et al.$^{34}$ who measured on crystalline commercial mold fluxes with NBO/(Si + Al) = 2.51 at about 900 K using the hot wire method. A value of 2.51 of NBO/(Si + Al) lies in
the range of NBO/(Si+Al) of commercial mold fluxes for medium carbon steel. On the other hand, thermal diffusivity values of 5.4–5.6 × 10^{-7} m^2 s^{-1} recorded by the laser flash method are also available; however, thermal conductivities converted using $p = 2.8 \, g \, cm^{-3}$ and $C_p = 1.4 \, J \, K^{-1} \, g^{-1}$ are as high as 2.12–2.19 W m^{-1} K^{-1}, probably owing to the effect of radiation.

### 3.2.2. Absorption and Extinction Coefficients

The absorption and extinction coefficients are usually derived via Lambert’s law from the transmissivity measured as a function of wavelength using a spectrophotometer. According to Planck’s law of radiation, the blackbody radiation has the maximum energy around 2 μm in wavelength at 1800 K which is close to the temperature of the steel shell in continuous casters. The situation is the same even at 1800 K which is close to the temperature of the steel shell in continuous casters. The situation is the same even when gray-body approximation is applied to mold flux and, thus, the absorption and extinction coefficients of molten and crystalline slags are determined for a wavelength of 2 μm. However, there are no extant data for absorption coefficient of molten slags relevant to mold fluxes due to difficulties in measurement; alternatively, data for glassy fluxes are used.

For the absorption coefficient of glassy mold fluxes for a wavelength of 2 μm, there have been two reports by Cho et al. and Susa et al.; the variation range reported are 100–350 m^{-1} and 90–300 m^{-1}, respectively. Recently, one of the authors has made stricter measurements on glassy mold fluxes using a spectrophotometer with an integrating sphere and produced a value of 51 m^{-1}, which measurements have enabled us to collect and detect scattered light at the sample surfaces as well as transmitted light. Thus, the variation range of absorption coefficient of glassy slags, i.e., molten slags has been determined to be 51–350 m^{-1}.

For the extinction coefficient of crystalline mold fluxes as well, Cho et al. and Susa et al. have reported to be 8 000–18 000 m^{-1}, 3 500–13 000 m^{-1} and 24 444–30 000 m^{-1}, respectively, for a wavelength of 2 μm. However, it is likely that these measurements were affected much more seriously by scattering effects because scattering by crystal grain boundaries joins and dominates. Such a situation can be avoided using a spectrophotometer with an integrating sphere, using which Seko has produced values ranging 1 356–2 625 m^{-1} for crystalline mold fluxes having the degree of crystallinity between 51 and 64%. From the viewpoint of higher reliability in measurement, the variation range of extinction coefficient of crystalline slag has been determined to be 1 356–2 625 m^{-1}.

### 3.2.3. Emissivity

As mentioned earlier, the emissivity can be derived from Eq. (8) via Kirchhoff’s law using the reflectivity and the transmissivity. Seko has measured both reflectivity and transmissivity for crystalline mold fluxes using a spectrophotometer with an integrating sphere to obtain emissivity values in the range 0.38–0.60. To the best of our knowledge, there are no experimental data on the emissivity of commercial mold fluxes and thus the variation range of emissivity of crystalline slags has been determined to be 0.38–0.60. His experimental data of reflectivity and transmissivity also gives a value of 0.01 for the emissivity of glassy slag as an alternative to molten slag. This finding supports the previous assumption in Chap. 2 that radiation from crystalline slag is predominant at the molten slag/crystalline slag interface.

### 3.2.4. Refractive Index

There have been two reports by Susa et al. and Ozawa et al. about the refractive index of glassy mold fluxes: values reported are 1.57–1.58 (546 nm) and 1.55 (633 nm), respectively, for fluxes with NBO/(Si+Al) = 2.88 and 2.51—these values of NBO/(Si+Al) lie in the range of NBO/(Si+Al) of commercial mold fluxes for medium carbon steel. The variation range of refractive index of glassy slag as an alternative to molten slag has been determined to be 1.55–1.58 since the refractive index of glass generally shows negative dependencies on wavelength and temperature but these dependencies are not very strong. For the refractive index of crystalline slag, on the other hand, there is only one value reported by Susa et al. 1.59 for a wavelength of 546 nm. Thus, the range of the refractive index of the crystalline slag on the total heat flux is not discussed in the present work. Table 2 summarizes the variation ranges of all the physical properties investigated, with the respective default values in calculations of the total heat flux.

### 3.3. Interface Temperatures

The interface temperatures have been determined on the basis of Eq. (12). This equation contains many variables; however, the thicknesses and physical properties of the respective layers can be fixed using values in Table 2, and the temperatures $T_{\text{steel}}$ and $T_{\text{molten}}$ have also been given as 1800 K and 500 K, respectively. Accordingly, Eq. (12) contains only two unknown variables $T_{\text{molten}}$ and $T_{\text{crystal}}$, and thus the solutions of the simultaneous equations give values to these variables. Table 3 gives the interface temperatures calculated using the default values of the physical properties as functions of $d_{\text{crystalline}}$, where $d_{\text{molten}}$ and $d_{\text{steel}}$ are uniquely fixed from the relationships of the equation $d_{\text{crystalline}} + d_{\text{molten}} = d_{\text{steel}}$ (1 mm) and Fig. 3, respectively. The interface temperature between the molten and crystalline slag layers has been calculated as 1388–1507 K with variation in $d_{\text{crystalline}}$ from 900 to 940 μm, which temperature should be equivalent to the liquidus temperature of mold flux. The liquidus temperature has been previously reported to be 1398–1513 K for commercial mold fluxes for medium carbon steel, and this agreement supports the rea-
sonability of the calculation and the determination of the variation range of thickness of the crystalline slag layer. Thus, in the present work, the ranges of \( T_{m/c} \) and \( T_{c/a} \), have been determined to be 1388–1507 K and 772–807 K, respectively. Correspondingly, the values of \( d_{\text{crystalline}} \), \( d_{\text{molten}} \) and \( d_{\text{air}} \) are in the ranges 900–940 μm, 60–100 μm and 10.17–10.21 μm, respectively. Table 2 also summarizes the variation ranges of the interface temperatures and the thicknesses, along with the respective default values in calculations of the total heat flux.

### 4. Calculations and Discussion

Using the default values of the thicknesses, the physical properties and the interface temperatures determined in Secs. 3.1–3.3, the total heat flux across the mold flux layer has been calculated on the basis of the model described in Chap. 2, resulting in Fig. 5 showing the total heat fluxes in the molten slag, crystalline slag and air gap layers. Since the steady-state condition applies as given by Eq. (12), the total heat flux is kept constant, irrespective of the layer. Terracehni et al. \( ^{41} \) have made in-situ measurements of heat flux across the mold flux layer near the meniscus level in continuous casters, and reported that the heat flux at 8 mm below the meniscus is about 1.3 MW m\(^{-2}\) for a mild cooling operation. The total heat flux calculated in the present work is about 1.2 MW m\(^{-2}\), which is close to the value measured for a mild cooling operation. Additionally, Hanao et al. \( ^{15} \) have observed the cross-sectional microstructure of a mold flux having the liquidus temperature of 1509 K at 8 mm below the meniscus, and reported that the thickness of the molten slag layer is about 50 μm. As shown in Table 3, the present work also finds that an interface temperature between the molten slag and crystalline slag layers (\( T_{m/c} \), corresponding to the liquidus temperature) of 1507 K has been

### Table 2. Variation range of parameters used for calculations based upon heat transfer model.

<table>
<thead>
<tr>
<th>property</th>
<th>variation range</th>
<th>default value</th>
</tr>
</thead>
<tbody>
<tr>
<td>steel shell</td>
<td></td>
<td>0.23</td>
</tr>
<tr>
<td>molten slag layer</td>
<td></td>
<td>0.25 - 0.26</td>
</tr>
<tr>
<td>crystalline slag</td>
<td></td>
<td>1.55 - 1.58</td>
</tr>
<tr>
<td>air gap layer</td>
<td></td>
<td>1.63</td>
</tr>
<tr>
<td>mold</td>
<td></td>
<td>0.48</td>
</tr>
</tbody>
</table>

### Table 3. Interface temperatures and thicknesses of layers.

<table>
<thead>
<tr>
<th>thickness of crystalline slag layer, ( d_{\text{crystalline}} ) μm</th>
<th>thickness of molten slag layer, ( d_{\text{molten}} ) μm</th>
<th>thickness of air gap layer, ( d_{\text{air}} ) μm</th>
<th>( T_{m/c} ) K</th>
<th>( T_{c/a} ) K</th>
</tr>
</thead>
<tbody>
<tr>
<td>900</td>
<td>100</td>
<td>10.17</td>
<td>1388</td>
<td>772</td>
</tr>
<tr>
<td>910</td>
<td>90</td>
<td>10.18</td>
<td>1415</td>
<td>780</td>
</tr>
<tr>
<td>920</td>
<td>80</td>
<td>10.19</td>
<td>1443</td>
<td>788</td>
</tr>
<tr>
<td>930</td>
<td>70</td>
<td>10.20</td>
<td>1474</td>
<td>797</td>
</tr>
<tr>
<td>940</td>
<td>60</td>
<td>10.21</td>
<td>1507</td>
<td>807</td>
</tr>
</tbody>
</table>

Fig. 5. Total heat flux in molten slag, crystalline slag and air gap layers.
The crystalline slag layer leads to the decrease in the trans-actuality. On the other hand, the increase in the thickness of energy transport to the mold side and does not lead to heat

The reflectivity of the crystalline slag layer is an ef-

where \( T, E \) and \( d \) are the transmissivity, extinction coefficient and thickness of crystalline slag. Accordingly, both the decrease in the emissivity and the increase in the thick-

In addition, it can also be seen in Fig. 6(b) that changes in the thermal conductivities of molten slag produces relatively large decrease in the total heat flux with respect to small variation in this value. Further work is required about the effects of these parameter, including the possibility of extending variation ranges of the parameters in actual flux systems.

5. Conclusions

To find a measure for further reducing the heat transfer across the mold flux for medium carbon steel, the total heat flux has been calculated on the basis of a heat transfer model involving conduction and radiation processes, with variation in parameters such as physical properties of mold flux.

(1) The heat transfer across the mold flux film is primaries dominated by thermal conduction and the contribution from radiation is less than 20% of the total heat flux in the molten and crystalline slag layers.

(2) The reflectivity of the crystalline slag layer is an efficient factor for further reducing the heat transfer. The reflectivity can be increased by crystallization of mold flux due to enhanced scattering of light by introduction of crystal grain boundaries.

(3) Increased reflectivity by crystallization causes more radiation energy to return from the crystalline slag layer to the steel shell, resulting in the reduction in the total heat flux across the flux film, leading to mild cooling.

calculated from a thickness value of the molten slag layer \( d_{\text{molten}} \) of 60 \( \mu \)m. These agreements in the total heat flux and the thickness of the molten slag layer indicate that the model used in the present work well describes the heat transfer across the mold flux in continuous casting and that the parameters used are also reasonable. Figure 5 also indicates that the heat transfer across the mold flux film is primarily dominated by thermal conduction and that the contribution from radiation is less than 20% of the total heat flux in the molten and crystalline slag layers.

To investigate an efficient factor reducing the heat transfer, the total heat flux has been calculated again using parameters summarized in Table 2: values changed from the default values to the fullest extent were used for this calculation, but in one calculation only one parameter was changed while the others were unchanged—this means that the steady-state condition is no longer maintained exactly in this calculation. Figure 6(a) shows effects of parameter variations on the total heat flux and Fig. 6(b) shows a close-up of part of Fig. 6(a). The changes in parameters result in the reduction in the total heat flux in all cases. In particular, large decreases of about 0.05 MW m\(^{-2}\) have been obtained in the two cases: (i) the decrease in the emissivity of crystalline slag from 0.60 to 0.38 and (ii) the increase in the thickness of the crystalline slag layer from 900 to 940 \( \mu \)m.

The decrease in the emissivity is a reflection of the increase in the reflectivity or transmissivity according to Eq. (8). However, increased transmissivity results in more energy transport to the mold side and does not lead to heat transfer reduction. Thus, the decrease in the emissivity should be a reflection of the increase in the reflectivity in actuality. On the other hand, the increase in the thickness of the crystalline slag layer leads to the decrease in the trans-

**Fig. 6.** (a) Effects of parameter variations on total heat flux and (b) close-up of part of (a).
REFERENCES

1) A. Grill and J. K. Brimacombe: *Ironmaking Steelmaking*, 3 (1976), No. 2, 76.