Molten Steel Level Measurement in Tundish with Heat Transfer Analysis

Zhenwei HU, Ying CI and Zhi XIE

College of Information Science and Engineering, P.O. Box, No.321, Northeastern University, Shenyang 110819, Liaoning, P.R. China.

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Temperature variation rate is different between “molten steel – tundish cover flux(TCF) – air” layers in tundish because heat transfer between these three materials with different thermal conductivities. Numerical calculation proves that temperature gradient extremums exist at the interfaces of “molten steel – TCF – air” layers in tundish. At the same time the change of initial temperature, thermal conductivity, convection coefficient have no effect on the interfaces locating. Thus temperature gradient extremums can be used for measuring molten steel level in tundish. In the process of measurement, a CCD camera is used to capture the thermal image of measuring sensor which is inserted into tundish to get the temperature distribution. By calculating temperature gradients of the measuring sensor in the thermal images, the interfaces of “molten steel – TCF – air” can be located, finally the molten steel level is obtained. The influence of measuring sensor adhering by TCF is also solved by gray image projection algorithm. Steel metallurgical field experiment shows that the method of molten steel level measurement is authentic and measuring error is less than 5 mm.

KEY WORDS: molten steel level; measurement; heat transfer; temperature distribution; interface location.

1. Introduction

In metallurgy industry field it is significant to get molten steel level in continuous casting tundish for billet quality and safety production.1,2) Harsh measuring circumstance caused by high-temperature of molten metal especially the TCF at top layer makes it difficult to measure molten steel level accurately.

As the different densities between molten steel and TCF, the traditional weighting method can’t give the accurate molten steel level information.3) Many specialists and scholars have done remarkable researches on molten steel level measurement techniques.4–9) The isotope method4,5) has radiation pollution which is quite dangerous. Katakyn and Pokrovskiy using eddy-current transducer to detect steel level,6) the theoretical maximum measuring range is about 300 mm, but the molten steel level is over 700 mm in most tundishes. Ultrasonic waves,7) laser,8) microwave9) methods are also studied to measure molten steel level, but because the uneven TCF layer spatial distribution and the time-varying thickness, obtaining accurate molten metal level and the thickness of TCF layer is still a difficult problem.

In order to overcome the measurement disadvantages of TCF layer, a new method of molten steel level measurement based on temperature gradient analysis is proposed.

2. Measuring Principle

2.1 Measuring Method and Process

There are three layers in tundish: molten steel at the bottom layer, TCF layer at the middle layer and air layer at the top layer. For great different thermal conductivities of these three materials (steel, TCF and air), the temperature gradients at the interfaces between them are obvious characteristics.

In order to obtain the differences of the temperature gradient between the three mediums, we use the method as follow which is shown in Fig. 1(a): insert a measuring sensor made of refractory material (called “measuring sensor” below) into tundish through all the mediums including the air, TCF and molten steel layer to perceive the temperature. When the measuring sensor reaches thermal balance, raise it and use a charge coupled device(CCD) camera to acquire the thermal radiation. When the measuring sensor has been raised, the raising parts drill through the TCF layer and it is adhered by the TCF. Thus the surface of raising parts has the same emissivity, so the distribution of the temperature can be measured due to the distribution of radiant energy. By analyzing the thermal image of the measuring sensor, detect the temperature gradient between the layers by means of image processing and recognition, the molten steel level is measured finally. The temperature distribution of measuring sensor is shown in Fig. 1(b).

The measuring process in this paper is shown in Fig. 2. $L_{MQ}$ is the length of the measuring sensor, $H_D$ is the vertical distance between the top of the measuring sensor and optical center of camera lens, $T_{TCF}$ is the thickness of TCF layer. The interface of air layer and TCF layer is expressed as TCF-level, which is designated as $H_{TCF}$. The interface of molten steel layer and TCF layer is called molten steel level, which is designated as $H_{STEE}$. The molten steel measuring process is separated into two steps as follow:
Step 1: measure TCF-level $H_{TCF}$.

Usually, the measuring system is in the state of TCF-level measurement, as shown in Fig. 2(a). During this time, images of the measuring sensor inserted into molten metal is acquired by the camera; obtain the air-TCF layer interface $P_{AS}$ by pattern recognition; then calculate $H_{HASL}$ (the vertical distance between measuring sensor apex and $P_{AS}$). $H_{DEEP}$ is calculated according to the encoder, the length of measuring sensor and the depth of tundish. Finally, the TCF-level $H_{TCF}$ is expressed as:

$$H_{TCF} = L_{MB} - H_{HASL} + H_{DEEP} \cdots \cdots (1)$$

Step 2: measure molten steel level $H_{STEEL}$.

The mechanism takes the camera and the measuring sensor move upwards when the measuring system is in TCF-level measurement state and measuring sensor has reached thermal balance. The measuring sensor is lift to a position of a setting height which is recorded by the encoder and shown in Fig. 2(b). In the TCF thickness measurement state, images of measuring sensor are acquired by the camera, and then the temperature distribution at surface of the measuring sensor is extract. The character of temperature extremums of TCF-steel layer interface $P_{AS}^*$ and $P_{SS}^*$ are recognized. The distance between $P_{AS}^*$, $P_{SS}^*$ and the top of measuring sensor is designated as $H_{ASL}^*$ and $H_{SSL}^*$. Then the thickness of the slag layer is:

$$T_{TCF} = H_{SSL}^* - H_{ASL}^* \cdots \cdots (2)$$

Finally the molten steel level is:

$$H_{STEEL} = H_{TCF} - T_{TCF} = L_{MB} - H_{ASL} + H_{DEEP} - (H_{SSL}^* - H_{ASL}^*) \cdots \cdots (3)$$

2.2. Physical Parameters of Measuring Sensor

Physical parameters of measuring sensor should meet the following conditions: the time when measuring sensor reaches thermal balance between TCF layer and molten steel layer should be as short as possible. Meanwhile, the temperature distribution of measuring sensor should be maintained as long as possible when being elevated from the TCF and molten steel layer. Therefore the material of measuring sensor needs thermal conductivity and specific heat of the selection, alumina-carbon is a suit one, its thermal conductivity is 8.7 W/(m·K) and specific heat is 1 000 J/(kg·K).

The measuring sensor is made in rod shape; at the same time it is hollow-core for the purpose of measuring internal temperature in order to validate ANSYS calculation results in the following part of this paper. The parameter of measuring sensor is shown as follow: the length is 960 mm, the diameter is 85 mm and the hollow-core diameter is 25 mm.

3. Temperature Distribution Analysis of Measuring Sensor

Finite element analysis is used to prove the validity and reliability of molten steel level measuring method not only in the standard state but also when physical parameter changes. According to the physical parameters of measuring sensor, initial conditions and boundary conditions, the heat transfer differential equation between measuring sensor and three layers, the temperature distributions of the measuring sensor is calculated by the ANSYS software.

3.1. Heat Transfer Differential Equation

The heat transfer differential equation can be described according to the Fourier equation:\(^{10}\)

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial T}{\partial z}\right) + q_{\text{in}} = \rho c \frac{\partial T}{\partial t}$$

\cdots \cdots (4)
For isotropic thermal conductivity of materials, \( k_x = k_y = k_z = k \), formula (4) can be transferred into:

\[
k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + q_m = \rho c \frac{\partial T}{\partial t} \quad \text{(5)}
\]

The temperature distribution analysis of the measuring sensor is three-dimensional unsteady thermal analysis, further more there is no heat source inside the sensor, formula (5) can be simplified to:

\[
\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \frac{\rho c}{k} \frac{\partial T}{\partial t} \quad \text{(6)}
\]

Formula (6) is the heat transfer differential equation of measuring sensor.

3.2. Physical Parameters and Boundary Conditions

Physical parameters of three mediums\(^{11,12}\) in tundish is shown in Table 1 and the thickness of TCF layer is 30 mm.

The initial temperature of measuring sensor is described as formula 7 when heat transfer begins:

\[
\phi(x, y) = \text{function of initial temperature} \quad \text{(7)}
\]

\( \phi(x, y) \) is the function of initial temperature and in this paper measuring sensor is set to 30°C which is supposed to an isothermal body.

Boundary conditions include as follows:\(^{13}\)

(a) boundary between molten steel layer and TCF layer:

\[
-k_s \frac{\partial T_{TCF}}{\partial n} = h_{ss}(T_i - T_{TCF}) \quad \text{(8)}
\]

(b) free surface of TCF layer:

\[
-k_s \frac{\partial T_{TCF}}{\partial n} = h_{sa}(T_{TCF} - T_{ev}) \quad \text{(9)}
\]

(c) ektefine of measuring sensor where contacting with molten steel layer

\[
-k_s \frac{\partial T_m}{\partial n} = h_{m}(T_i - T_m) \quad \text{(10)}
\]

(d) ektefine of measuring sensor where contacting with TCF layer

\[
-k_s \frac{\partial T_m}{\partial n} = h_{TCF}(T_{TCF} - T_m) \quad \text{(11)}
\]

(e) ektefine of measuring sensor where contacting with air layer

\[
-k_s \frac{\partial T_m}{\partial n} = h_{f}(T_m - T_{ev}) \quad \text{(12)}
\]

In formulas (8)–(12), \( k_s \): thermal conductivity of TCF layer which is 0.6 W/(m·K), \( k_m \): thermal conductivity of measuring sensor which is 8.7 W/(m·K), \( T_{TCF} \): temperature of TCF layer which is 1 200°C, \( T_i \): temperature of molten steel layer which is 1 530°C, \( T_{ev} \): temperature of air layer which is 30°C, \( T_m \): initial temperature of measuring sensor which is 30°C, \( h_{ss} \): heat transfer coefficient between molten steel layer and TCF layer which is 200 W/m\(^2\)·K, \( h_{sa} \): heat transfer coefficient between TCF layer and air layer which is 0.4 W/m\(^2\)·K, \( h_{m} \): heat transfer coefficient between measuring sensor and molten steel layer which is 40 W/m\(^2\)·K, \( h_{TCF} \): heat transfer coefficient between measuring sensor and TCF layer which is 40 W/m\(^2\)·K, \( h_{f} \): heat transfer coefficient between measuring sensor and air layer which is 5 W/m\(^2\)·K.

3.3. Temperature Distribution of Measuring Sensor

Using finite element method to solve temperature distribution model based on the heat transfer process and definite conditions, appending loads of temperature, convection, heat conduction and radiation. After the calculation by ANSYS, nephogram of the temperature distribution of the measuring sensor is shown in Fig. 3.

Because of the thermal conductivity difference between air, TCF layer and molten steel, temperature variation rate is different between three materials. Calculating the temperature gradients in the region of \([A, B]\) near the TCF layer, the results are shown in Fig. 4.

There are two obvious inflexions in the temperature gradient curve. According to the geometrical relation the first inflexion at position “a” is the interface of molten steel layer and TCF layer, the second inflexion at position “b” is the interface of TCF layer and air layer. So the position of inflexion can be used as criterion for locating the interface.

In order to demonstrate the universality of the conclusions, change the initial temperature of measuring sensor, Table 1. Physical parameters of three mediums in tundish.

<table>
<thead>
<tr>
<th>Medium</th>
<th>Density (kg/m(^3))</th>
<th>Specific heat (J/(kg·K))</th>
<th>Thermal conductivity (W/(m·K))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1.29</td>
<td>1.004</td>
<td>0.023</td>
</tr>
<tr>
<td>TCF</td>
<td>1.210</td>
<td>1.172.3</td>
<td>0.6</td>
</tr>
<tr>
<td>Molten steel (1 530°C)</td>
<td>7.000</td>
<td>880</td>
<td>48</td>
</tr>
</tbody>
</table>

Fig. 3. Nephogram of calculated temperature distribution of the measuring sensor.
convection thermal conductivity of TCF layer and coefficient between molten steel and TCF layer for calculating.

In metallurgical field, refractory usually preheats before using. So initial temperature of measuring sensor is set as 400°C, the results is shown in Fig. 5.

When initial temperature increases, the thermal equilibrium time decrease and the surface temperature of measuring sensor is different, but position change of two inflexions in the temperature gradient curve is less than 1 mm.

In order to verify the heat conduction between the measuring sensor and different kinds of tundish cover flux, thermal conductivity of TCF layer is changed from 0.8 W/(m·K) to 1.6 W/(m·K). The calculating result is shown in Fig. 6, it can be made out that the change of thermal conductivity has small affect on the temperature gradient, the interface location doesn’t change.

For verifying the heat convection between measuring sensor and different steel grades (including the effect of molten steel flow speed), convection coefficient between molten steel and measuring sensor is changed from 2000 W/(m²·K) to 8000 W/(m²·K). The calculating result is shown in Fig. 7, when the convection coefficient increases the difference of temperature gradients increase, but it has no effect on locating the interface of “molten steel layer - TCF layer” and “TCF layer - air layer”.

Therefore the two position of extremums which are calculated from temperature gradients of ektexine of measuring sensor, have no effect on the initial temperature, thermal conductivity and convection coefficient, the only change is the value of inflection point of temperature gradients. Thus the interface of “molten steel layer - TCF layer” and “TCF layer - air layer” can be identified according to the position of extremums in temperature gradients distribution.

### 3.4 Verification of the ANSYS Calculation

In order to validate the correctness of the model mentioned above, measuring temperature of measuring sensor at metallurgy field is compared with the result of ANSYS. The method is described as follows: the measuring sensor is hollow-core, when being inserted into the molten steel; the hollow-core becomes a blackbody cavity. Then using a radiation thermometer pointed to the hollow-core at the top
of the measuring sensor, the temperature of measuring sensor can be measured by the blackbody radiation from the hollow-core. Field temperature measuring device is shown in Fig. 8.

Depend on this method the temperature of measuring sensor is measured at metallurgy field during the first 400 second after the measuring sensor being inserted into tundish, Fig. 9 shows the comparison with the measuring result and calculating result by ANSYS.

The comparison shows, the maximum difference temperature between the measuring and modeling result is 9°C, relative error is less than 1%, so the model satisfy the application requirements.

The model proves that temperature gradient has extremes at the interfaces between molten steel layer, TCF layer and air layer. At the same time it provide evidence for interface orientation in the image of measuring sensor inserted into the molten steel layer.

4. Result and Discussion

4.1. Interface Locating in Typical Image

Figure 10 shows that the system has been applied to measuring molten steel level of continuous casting tundish in steel metallurgy industry field. During the continuous casting process the CCD camera captures the images of measuring sensor for interfaces locating.

A typical image when the measuring sensor inserts into molten steel is shown in Fig. 11(a), then the system measures the level of TCF layer continuously. Figure 11(b) is an image of the measuring sensor when it was raised up. The temperature distribution of the measuring sensor is shown in Fig. 11(c). The green dots in the figure represent reliable temperature distribution points on the surface of the measuring sensor extracted by system; the white curse represents axial gray distribution of the measuring sensor; and the two vertical white lines acquired by discrimination according to local extremum which \( P_{\text{AS}} \) represents the air-TCF layer interface, \( P_{\text{SS}} \) represents the TCF-steel layer interface. Finally the molten steel level can be calculated by formula 3.

4.2. Influence of TCF Flow

During the measuring process, the surface of the measuring sensor adheres TCF when it rises through the TCF layer, it seriously affects getting reliable temperature distribution.

The TCF has good flowability, it flows downward through the surface of the measuring sensor in the rising process. The interface of TCF layer and molten steel layer are influenced, furthermore, temperature distribution can’t be extracted or formed pseudo interface at the surface. TCF flow images are shown in Fig. 12.

For this case, gray projection method is used to recognize the flow of TCF on the surface of measuring sensor. TCF flows about 10 mm per second. The thickness of TCF layer in tundish is 40–120 mm for different casting conditions. It may cost about 4 seconds that the TCF flow through the part which the measuring sensor is raised up from thinnest TCF layer. So the time interval of two TCF flow feature images can be selected as any one between 1 and 4 seconds. For reliability and resolution, the TCF flow distance is calculated between t second image and \( t+1 \) second image in this.
By comparing with the interface location distance, pseudo interface is identified and removed. The concrete steps are as follows:

**Step 1:** get the TCF flow image of t second and t+1 second.

**Step 2:** calculate the gray projection of the images:

Horizontal gray projection can be calculated as follow:

\[
p(x_i) = \sum_{y=0}^{H-1} g_1(x_i, y) \quad (i = 0 \cdots W) \quad (13)
\]

\[
q(x_i) = \sum_{y=0}^{H-1} g_2(x_i, y) \quad (i = 0 \cdots W) \quad (14)
\]

Which \(x_i\) is the \(i\) position in horizontal coordinates of image pixel, \(y\) is vertical coordinates of image pixel, \(H\) is the height of image, \(W\) is the width of image, \(g_1(x_i, y)\) is pixel-gray value of \(t\) second image in coordinate \((x_i, y)\), \(g_2(x_i, y)\) is pixel-gray value of \(t+1\) second image in coordinate \((x_i, y)\), \(p(x_i)\) is horizontal gray projection of \(t\) second image in column \(i\), \(q(x_i)\) is horizontal projection of \(t+1\) second image in column \(i\), \(\varepsilon\) is noise reduction threshold. The relationship of coordinate system is shown in Fig. 13.

The integration of \(p(x_i)\) and \(q(x_i)\) can be expressed:

\[
S_p(x_i) = \sum_{x=x_0}^{x_i} p(x) \quad (15)
\]

\[
S_q(x_i) = \sum_{x=x_0}^{x_i} q(x) \quad (16)
\]

Which \(x_0\) is integral lower limit, \(x_i\) is integral upper limit

**Step 3:** calculate the distance of TCF flow:

Set \(x_{pi}\) is the abscissa of TCF edge in \(t\) second image, then the integral value can be expressed as \(S_p(x_{pi})\), we can found a point \(x_{qi}\) in the abscissa of \(t+1\) second image that \([S_p(x_{pi}) - S_q(x_{qi})]\) reaches minimum. Finally the flow distance of TCF at the surface of measuring sensor is:

\[
l = x_{qi} - x_{pi} \quad (17)
\]

**Step 4:** Calculate the gradient of temperature distribution of measuring sensor in \(t\) and \(t+1\) second images, search the interface according to the extremum.

**Step 5:** The validity of interface can be compared the measuring interface distance with the calculating result according to formula 18. If the extremum position moves between successive images match the calculating result it can be confirmed that the moving extremum position is a pseudo interface.

According the successive TCF flow images in Figs. 14(a), 14(b), the integration of horizontal gray projection is calculated which is shown in Fig. 14(c). Using formula \([S_p(x_{pi}) - S_q(x_{qi})]\), \(x_{qi}\) is calculated on the curve of horizontal gray projection in \(t+1\) second image. Comparing the position of \(x_{pi}\) and \(x_{qi}\), the flow distance of TCF at the surface of measuring sensor is 9 mm.

At the same time the interface is located which is shown in Fig. 15, taking the distance between real interface and pseudo interface as the research object which is “ab” in Fig. 15(a) and “cd” in Fig. 15(b). “ab” is 8 mm, after TCF flow
“cd” is changed to 16 mm. On the other hand the flow distance of TCF is about 8 mm, that meets the result of the gray projection calculating results. Thus the pseudo interface is identified. By removing the pseudo interface the molten level in tundish is calculated according to interface a and b using formula 3.

### 4.3. Validation of Measuring Results

In order to validate the accuracy of molten steel level measuring system, a manual measurement method is used. A steel bar is insert into the tundish which has the same steel grade as the molten steel casting in tundish. The part of the steel bar is melted which being inserted into the molten steel layer, on the other hand the part in the TCF layer is still solid state, its surface is adhered by TCF, the adhere length is the thickness of TCF layer. Recording the length of steel bar which is from melting position to the top of tundish which expresses as $H_M$, the depth of tundish is known as $H_T$. So the molten steel level is $H_{Steel} = H_T - H_M$. Figure 16 shows the schematic of manual measuring method and its application.

The automatic measuring result and the manual measuring result at a steel corporation is shown in Table 2, for three casting processes which the thickness of TCF layer is cover from 40 mm–60 mm, temperature of molten steel is cover from 1475°C to 1490°C, thickness of TCF layer: 40 mm–60 mm. Deviation between automatic measuring method and manual method is lower than 5 mm.

In casting process 1 the measuring data during two ladle change period is shown in Fig. 17, in the first ladle change period which is 178 seconds long the maximum steel level is 792 mm and the minimum is 711, it is intuitional for operator better than tundish weight. In casting process 2 and 3, the increasing thickness of TCF has no effect to the measuring result and during the end of casting period the measuring range fits the change of molten steel level. In metallurgical

#### Table 2. Comparison of measuring and manual result.

<table>
<thead>
<tr>
<th>Measuring condition</th>
<th>Automatic measuring result (mm)</th>
<th>Manual Measuring result (mm)</th>
<th>Error (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casting process 1:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>temperature of molten steel: 1475°C–1490°C; thickness of TCF layer: 40 mm–60 mm. (around the ladle change period)</td>
<td>784</td>
<td>787</td>
<td>3</td>
</tr>
<tr>
<td>Casting process 2:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>temperature of molten steel: 1511°C–1523°C; thickness of TCF layer: 60 mm–80 mm.</td>
<td>674</td>
<td>672</td>
<td>2</td>
</tr>
<tr>
<td>Casting process 3:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>temperature of molten steel: 1535°C–1548°C; thickness of TCF layer: 100 mm–120 mm. (at the end of casting period)</td>
<td>676</td>
<td>673</td>
<td>3</td>
</tr>
</tbody>
</table>

Fig. 17. The history data of molten steel level measuring system and the manual validation.
field operator believes that exact steel level value is suit for continuous casting process and steel quality control, so this method can meet the requirement of the field well.

5. Conclusion

(1) Temperature gradient analysis method is used to measuring molten steel level in tundish. In measuring process a measuring sensor is inserted into molten steel, after heat balance temperature gradients exist at the “air layer – TCF layer” interface and “TCF layer – molten steel layer” interface.

(2) The initial temperature, thermal conductivity and convection coefficient of the measuring sensor have no effect on locating the “air layer – TCF layer” interface and “TCF layer – molten steel layer” interface.

(3) A CCD camera is used to detect these two interfaces, and then molten steel level can be calculated. At the same time TCF flow is studied and solve by gray projection method.

(4) The measuring error is less than 5 mm comparing to the manual measurement at the steel metallurgical field.

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