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# Slag adhesion on the refractory sensor for molten steel level measurement

Qing He *, Zhi Xie

*Institute of Automation Instrument, College of Information Science and Engineering, Northeastern University, Shenyang 110819, China*

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ABSTRACT

A novel principle for molten steel level measurement in tundish by using temperature gradient was proposed in our previous work. A refractory sensor was inserted into the tundish to sense the temperature distribution of the slag and the molten steel. However, during the lifting process, the slag usually adhered to the refractory sensor, impairing the temperature readings of the CCD camera. While in contrast, molten steel was never found adherent to the sensor. In order to study the mechanism of this phenomenon, slag/-molten steel adhesion on the sensor was analyzed in view of dynamics. Dynamic differential equations were established based on a one dimensional axisymmetric model. Steady-state solution of the equations was obtained in an analytical form. For the transient solutions, the differential equations were transformed into a heat conduction problem and were computed via the thermal module of the finite element software ANSYS. It is found that the adhesive thickness of the slag/molten steel on the sensor depends on the lifting velocity of the sensor, the viscosity and the density of the slag/molten steel. Because of the differences in density and viscosity, the adhesive thickness of the molten steel is very small, while the adhesive thickness of the slag is noticeable and increases with the decrease of its temperature. Experimental data at the steel plants is used to validate the theoretical analysis.



## 1. Introduction

Molten steel level in tundish is responsible for melt cleanliness in steelmaking [1,2], and the ever increasing demands for high quality and stringent cleanliness requirements have encouraged steelmakers to seek for the measurement of molten steel level supporting inclusions removal. But, molten steel level measurement in tundish is still a problem because of the following factors:

(1) The harsh environment and the high-temperature medium. The molten steel is up to 1500 °C, disabling the applications of contact measuring methods, i.e. pressure gauges [3,4], fiber laser sensors [5], etc.
(2) The covering slag of unknown thickness and compositions floats on top of the molten steel, limiting the usage of non-contact measuring techniques such as ultrasonic waves [6,7], optical measurement [8,9] and microwaves [10,11]. Although radioactive gamma rays [12] have been commonly used for molten steel level measurement in the mold, they are not suitable for open places because of high energy radiation. Eddy current [13,14] and electromagnetic induction [15,16] methods are effective only over a narrow range of measurement distance (50–200 mm) as a result of severe attenuation of the electromagnetic signals.

A novel principle for molten steel level measurement in tundish by using temperature gradient was proposed in our previous work [17]. The differences of temperature gradients between different layers were examined to distinguish between the molten steel and the covering slag as follows: A refractory bar/sensor is inserted into the tundish to sense the temperature distribution of the different layers. After adequate heat transfer, the refractory bar/sensor is lifted, and an area CCD camera is used to capture the temperature distribution of the bar via radiation temperature measurement. Then significant differences in temperature gradients between the molten steel and the covering slag are utilized to identify the molten steel level. The measuring method has been put into applications at several different steel plants [18,19]. The temperature distribution of the lifted bar/sensor and the interfaces between different layers obtained from experiments carried out in steel plants are shown in Fig. 1.

However, the covering slag usually adheres to the sensor during the lifting process, impairing the temperature readings of the CCD camera. The adhesive thickness of the slag on the sensor is not

* Corresponding author.
*E-mail address:* heqing@ise.neu.edu.cn (Q. He).

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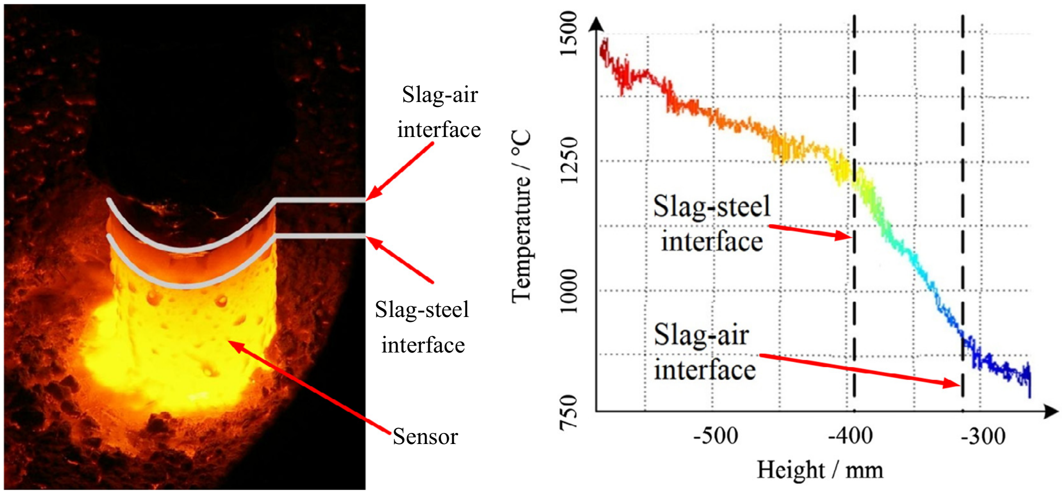


(a) Thermal image (b) Temperature distribution of the lifted bar/sensor

**Fig. 1.** Thermal image and temperature distribution of the lifted bar/sensor [17]. (a) Thermal image. (b) Temperature distribution of the lifted bar/sensor.

constant and varies with different locations on the sensor. In general, with a higher position, the temperature of the sensor is lower, and the adhesive thickness of the slag is larger. In contrast, molten steel can never be found adherent to the sensor.

In order to study the mechanism of this phenomenon, in this article, slag/molten steel adhesion on the refractory sensor is analyzed in view of dynamics. Firstly, properties of the slag and the molten steel especially the slag viscosity are investigated. Then, slag/molten steel adhesion on the refractory sensor is simplified into a one dimensional axisymmetric model and dynamic differential equations are established for the model. Next, steady-state and transient solutions of the equations are obtained in analytical and numerical forms. According to the solutions, the mechanism of slag/molten steel adhesion on the refractory sensor is studied and the affecting factors of slag/molten steel adhesion are found out. Experimental data from the actual on-site applications at the steel plants is used to validate the theoretical analysis. At last, reasonability of the theoretical model is discussed at the end of this article.

## 2. Properties of the slag and the molten steel

The refractory sensor needs to be lifted from the slag and the molten steel in the tundish to complete the measure work. The material of the refractory sensor is selected as a commonly used alumina-based material containing 67 wt.% alumina, 23 wt.% graphite and 10 wt.% additives. The melting point of the sensor is higher than 1900 °C.

During the lifting process, the fluids, molten slag and steel, will adhere to the outer surface of the refractory sensor. The physical properties of the fluids, such as viscosity and density, directly influence the adhesion process. Viscosity and density of the fluids are temperature dependent. In the tundish, the temperature variation of the molten steel in the whole tundish is less than 4 °C while the temperature drop in the covering slag reaches 500 °C. Therefore, viscosity and density of the molten steel can be considered as constants, but viscosity and density of the slag should be treated as functions of temperature.

The viscosity and density of the slag have been extensively studied by many researchers [20–24]. The temperature dependence of the slag viscosity is frequently represented by the Weymann equation [22]:

$$\eta(T) = ATe^{\frac{B}{T}} \tag{1}$$

where $\eta$ is the viscosity, dPa s; A and B are constants and can be calculated based on the compositions of the slag according to the Riboud model [22], dPa s/K and K respectively; and $T$ is the absolute temperature, K.

The tundish slag composition largely depends upon the tundish operation and the grade of steel being cast, including CaO, MgO, $Al_2O_3$, $SiO_2$, $Fe_2O_3$, etc. Via X-ray fluorescence spectroscopy, the investigated slag in the current study contains 42 wt.% CaO, 6 wt.% MgO, 12 wt.% $Al_2O_3$, 21 wt.% $SiO_2$, 2 wt.% $Fe_2O_3$ and 17 wt.% others. According to the Riboud model [22], the constants of the viscosity model in Eq. (1) can be calculated as $A = 8.1 \times 10^{-11}$ dPa s/K and B = 27452 K.

Meanwhile, viscosity of the slag was measured via the concentric cylinder method and the experimental procedure is detailed in [25]. Comparisons between the measured data and the results predicted by the Riboud model are presented in Fig. 2(a). It is observed that the Riboud model is effective in predicting the slag viscosity with the current slag composition. Note that the measured viscosity in Fig. 2(a) is obtained with the reference shear rate $D_r$ = 16.0 $s^{-1}$ as following:

$$\eta = \tau / D_r \tag{2}$$

where $\tau$ and $D_r$ are the shear stress (Pa) and the reference shear rate ($s^{-1}$) respectively.

It is well-known that crystallization of some phases in the slag is possible when temperature of the slag decreases. The typical feature of crystallization is a rapid rise in viscosity as the slag is cooled, and the slag turns from Newtonian fluids into non-Newtonian fluids [26]. The Herschel-Bulkley model, which is known as the yielding-power law model, is widely used to determine the rheological constitutive equations of fluid:

$$\tau = \tau_y + kD^n \tag{3}$$

where $\tau_y$, $k$, $D$ and $n$ are the yield stress (Pa), viscosity factor (Pa·$s^n$), shear rate ($s^{-1}$), and the flow index, respectively. On the principle of conservation of energy, the value of $\tau_y$ should keep 0. Thus, it is a Newtonian fluid for $n$ = 1.0 and it is a non-Newtonian fluid when $n$ takes other values.

In the current study, crystallization of the slag occurs around 1100–1200 °C, and the relationship between the shear stress $\tau$ and the shear rate $D$ are given in Fig. 2(b). It is observed that, the