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Estimation of surface heat flux in continuous casting mould with limited measurement of temperature

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ABSTRACT

Continuous casting mould is exposed to high heat flux due to its contact with the hot molten metal. The state of heat transfer in a mould and steel solidification depends on the magnitude of the mould boundary heat flux. In the present study, a mathematical model is developed to determine the heat flux across the hot surface of continuous casting mould from limited temperature measurement. The model is based on two-dimensional inverse heat transfer technique that was solved using the conjugate gradient method. Direct problem which involves two-dimensional conduction in the mould is first solved and validated. The inverse problem was tested by using the simulated temperature data obtained from the solution of a direct problem, where good agreement between the actual and estimated boundary heat flux is found. The Gaussian noises are added to the simulated temperatures to mimic the temperature measurement errors for testing anti-noise ability of the inverse problem model. Further, boundary heat flux is also estimated for a continuous casting mould using actually measured plant data. The model is applied to three test cases with temperature data obtained under different operating conditions and the results are analyzed. It has been observed that the proposed methodology results in accurate boundary heat flux estimation. Higher boundary heat flux are obtained for cases with higher casting speed as compared to cases with lower casting speed.

1. Introduction

In the continuous casting of steel, the heat transfer affects many of the quality and operational problems. Due to the non-uniform heating of the mould wall during casting, the resulting temperature distribution gives rise to differential thermal expansion leading to the mould distortion, cracks and breakout. Temperature distribution in mould depends on heat flux at the hot surface of the mould, cooling water velocity, mould wall material and its thickness, casting speed, and carbon content in the steel [1]. Out of the abovementioned parameters, heat flux distribution in the mould is a critical parameter which could provide important information regarding mould performance and product quality. In order to determine the state of heat transfer in continuous casting mould, so as to improve the operational performance and produce defect-free products, accurate calculation of heat flux forms the basis of an advanced control.

Several studies on heat transfer behavior in a continuous casting mould have been conducted in the past. Various mould heat flux formulas were developed utilizing the industrial mould conditions and casting practices. Such empirical formulas for the mould heat flux are given as a function of casting speed only [2–4]. Later on, experimental and theoretical studies indicated that the boundary heat flux is a function of many other casting parameters as well [5,6]. Some of the factors which may influence the heat flux variation include steel composition, superheat, mould powder, cooling water volume, nozzle type etc. [7]. These are usually not known and difficult to measure during continuous casting, thereby giving rise to uncertainties and inaccuracy in the heat flux calculation. Absence of any reliable and general correlation for boundary heat flux as a function of casting variables led to the development of mathematical models to estimate boundary heat flux based on inverse heat transfer techniques [8].

In the past, various approaches [9–13] were adopted to develop inverse heat transfer algorithms and computational method. A good amount of literature is devoted to the determination of boundary heat flux [14,15]. A one-dimensional (1D) inverse heat

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transfer model was developed to determine boundary heat flux [16]. Inverse methodology was used to estimate mould boundary heat flux using experimental temperature data obtained from a mould simulator [17]. Later, Ko et al. [18], Park and Sohn [19] and Zhang et al. [20] developed a heat transfer model for mould considering 1D transient heat conduction and estimated boundary heat flux from experimentally measured temperature in a mould simulator. They also used the commercial 1D inverse heat conduction software [16] for this purpose. A two-dimensional (2D) transient heat transfer model was also developed for mould and boundary heat flux was calculated [20]. Boundary heat flux estimated by the 1D [20] and 2D [21] approaches were compared later [22]. Heat fluxes given by 2D model were found to be 1.2 to 2 times higher than heat fluxes estimated by 1D model. Wang et al. [23] also developed a 2D transient heat transfer model and estimated boundary heat flux along mould width using experimental data. Ranut et al. [24] modeled heat transfer through mould as a 2D steady state problem. Experimental temperature measurements were used along with a mathematical model based on conjugate gradient method (CGM) to estimate boundary heat flux. Good agreement with the experimental observations was found. A comprehensive model was developed by Hebi and Man [25] involving 2D transient heat conduction in the mould in case of a round billet. Thermal resistance between billet and mould along with boundary heat flux were estimated based on inverse heat transfer using experimental temperature data. Yin et al. [26] developed a coupled thermo-mechanical model where estimated heat flux is used as boundary condition for the problem. Heat flux was determined based on inverse heat transfer calculations using various sensors located in the transverse and longitudinal sections of the mould. Gonzalez et al. [27], Dvorkin et al. [28] and Nowak et al. [29] coupled solution of a direct problem involving calculation of temperature distribution with an inverse heat transfer code for determining mould heat flux to model solidification process during continuous casting.

It may be mentioned here that in order to accurately compute the heat flux variation in a mould, it is important to receive large number of temperature data from the on-line measurement in the mould. However, such provisions of placing large number of temperature sensors in a real production setup are difficult and tedious task [30], and often limited numbers of measured data are available in practical operating conditions which may not reflect the real heat transfer state of the mould. In some cases, temperature data used for inverse heat flux estimation is required to be measured either at mid-section [26] or near the hot face of mould [17,18,25,30,31] which is again very inconvenient and difficult to realize in practice.

The present study proposes a methodology wherein boundary heat flux can be estimated using limited temperature sensors which may be placed conveniently away from hot face of the continuous casting mould, without sacrificing the accuracy of the calculation. Accordingly, in the present work, a mathematical modeling exercise has been undertaken to develop a new methodology wherein a two-dimensional inverse heat transfer algorithm based on conjugate gradient method is used to determine the heat flux variation in a continuous casting billet mould. Input condition of temperature profile is provided using theoretical calculation and also the experimental measurement from the continuous casting shop of Tata Steel, India in the operating condition. The study provides valuable insight towards heat transfer analysis in real continuous casting process.

2. Problem description

Present study deals with estimation of boundary heat flux across the hot surface of a billet mould in contact with the molten steel during continuous casting process. Schematic of the problem is shown in Fig. 1. A 2D longitudinal section of the mould is considered as boundary heat flux varies significantly along this direction. It is to be noted here that the mould is assumed to be straight unlike the tapered mould in actual conditions. Hot (right) side of the mould is in contact with the molten steel and exposed to a heat flux (q_s'') below the meniscus. This boundary heat flux is a function of y and varies along the mould height. Convection heat losses takes place above the meniscus as shown in Fig. 1. Height of the meniscus is H from the bottom. Total height of the mould is $H + H_1$ and width is L. Outer surface (left) of the mould is cooled with the help of water flowing in channel of width, L_1. Water enters at a velocity (U_w) and temperature ($T_{w,in}$) which results in convection heat loss from the cold side. As cold water flows through the channel, it absorbs heat from the hot mould and its temperature increases. Temperature of the water flowing through the channel is hence a function of distance, y. Objective of the present problem is thus to obtain mould boundary heat flux which varies along the mould height using an inverse heat transfer technique.

3. Mathematical modeling

Estimation of boundary heat flux for the mould involves solution of direct problem which includes 2D conduction through mould and solution of inverse problem. Both direct and inverse problems are explained below:

3.1. Direct problem

Direct problem involves analyzing temperature distribution throughout the mould with a known boundary heat flux. Heat transfer through mould is considered to be two dimensional as shown in Fig. 1 and steady state condition is assumed. Governing equation for heat transfer in the mould is as follows [1]:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = 0 \tag{1}$$

where, T is temperature, x and y are coordinate directions. It can be observed from Fig. 1 that the right boundary of the mould (below meniscus) is exposed to a spatially varying heat flux. It is basically the heat removed from the hot liquid metal during it downward movement where solidification of liquid metal slowly begins. Corresponding boundary condition below meniscus at the right wall of the mould (x = L) is as follows:

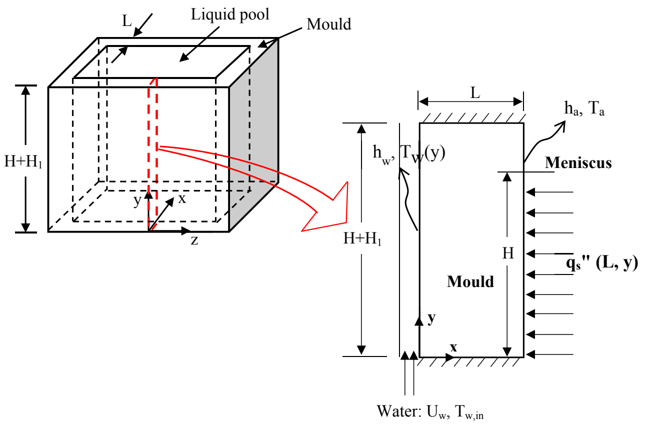

Fig. 1. Schematic of the problem.