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MONITORING OF MENISCUS THERMAL PHENOMENA WITH THERMOCOUPLES IN CONTINUOUS CASTING OF STEEL

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Abstract

Many quality problems in continuous-cast steel are related to mold level fluctuations, stickers, deep oscillation marks, and other events at the meniscus. These phenomena may be detected by monitoring temperature signals in the wall of the copper mold. This work applies computational models of transient heat conduction to investigate the potential capabilities of mold thermocouples to detect such phenomena by computing the sensitivity of the detected signal to heat flux variations at the meniscus. The three-dimensional model is first validated with temperature data recorded in a commercial slab casting mold, and in a previous laboratory measurement. The method is capable of monitoring meniscus level, and to detect large surface level fluctuations. However, its ability to detect temperature fluctuations decreases with decreasing magnitude and duration of the level fluctuations and the distance of the thermocouple from the hot-face surface. Sensitivity calculations with the model are presented to quantify these detection limits. Finally, a new inverse heat-conduction model is applied to extract new insights into heat transfer at the meniscus from thermocouple measurements.

Introduction

During continuous slab casting, molten steel flows through a "Submerged Entry Nozzle" (SEN) into a water-cooled copper mold. The steel solidifies a thin shell, which contains the liquid and is withdrawn at a casting speed that matches the flow rate. Fluctuations of the position of the molten meniscus (metal level) disrupts solidification at the meniscus, entrains slag inclusions, and leads to many quality problems. These include deep oscillation marks, stickers, and even catastrophic "breakouts. Liquid level is usually measured with an expensive commercial system to maintain liquid level within +/- a few millimeters, using a suspended eddy-current level sensor (which measures a single spot somewhere between SEN and the narrow face), or a radiation detector (which averages over a volume that is blocked by metal) [1].

Another potential method to quantify the metal level during continuous casting is to utilize the temperatures measured continuously by thermocouples (TC's) embedded in the copper mold. This inexpensive method has been applied commercially by "LevelTherm" to control level within +/-20-30mm in billet/bloom casting [2]. If sufficiently accurate, this method would have the potential advantage of providing information around the entire perimeter of the meniscus, allowing for more precise monitoring of surface quality in addition to controlling liquid level. This paper investigates the potential use of a two-dimensional Inverse Heat Conduction model to interpret the dynamic variations of measured TC temperature signals into the dynamic variation of the metal level in the mold during the process. The ability of a model-based system to achieve this goal is investigated by comparing the predictions of a transient heat-conduction model with actual mold temperature measurements. A parametric study is then performed to determine the theoretical sensitivity of this method to resolve level fluctuations of different amplitudes and frequencies. This work provides important new insights into the use of thermocouples to monitor meniscus heat transfer and liquid surface level in continuous casting of steel.

Model Description

A three-dimensional finite-element model of transient heat conduction has been developed to predict temperature histories in a representative segment of a commercial continuous casting mold. The 132.5mm-wide x 172.5mm-long model domain of a segment of the top portion of the copper mold wall is shown in Fig. 1. This segment domain includes the top portions of 7 water slots (2 deep and 5 shallow) with their curved ends, the molten steel meniscus, and two recessed bolt holes, each containing a thermocouple from the two thermocouple rows used for breakout detection. To match the plant measurements, the thermocouples are modeled as 2.2mm diameter cylinders centered in 2.4mm holes drilled through the bolts, with air in the annular gap and a 0.1mm layer of conductive paste between the TC tip and the copper mold. The vertical boundaries are symmetry planes, as the segment can be repeated to reproduce the entire wide face of the mold. The water slots are constant heat convection boundaries with a coefficient $45kW/m^2K$ to an ambient temperature of 30°C. The mesh contains 24,836 elements and 40,310 degrees of freedom. Further details are given in Tables I and II and elsewhere [3].

Table I. Model Geometry and Simulation Conditions

Copper plate thickness	43mm
Bolt diameter	16mm+2mm threads = 20mm total
Steel grade	441(01) ferritic stainless steel
Casting speed	1.04 m/min
Strand width	1290 mm
Segment width	132.5mm
Base meniscus level below mold top	95mm
Top thermocouple height above meniscus	42mm
Bottom thermocouple below meniscus	115mm
Water channel spacing / spacing across bolts	15mm / 45mm
Water channel thickness	5mm

Table II. Model Material Properties

Material	Thermal Conductivity (W/m ^oC)	Specific Heat (J/kg-K)	Density (kg/m^3)
Copper (Cu-Ag-0.1P)	364.	386.	8960.
Constantan (for K-thermocouples)	216.	416.	8900.
TC conducting Paste	0.9	2800.	2100.
Air (for air gap)	0.028	1040.	1.2

Model Validation

To test the accuracy of the model, it is first applied to simulate the transient temperature variations during a severe level fluctuation at the commercial steel continuous caster [3]. The hot-face is given a heat flux boundary condition which varies with distance down the mold (z-direction) as shown in Fig. 2. This profile is translated vertically up and down the mold according to the surface level history recorded by the eddy-current sensor at the plant. The severe level fluctuation during this time interval dropped ~30mm and lasted ~50s. Results are presented in Figs. 3 and 4.

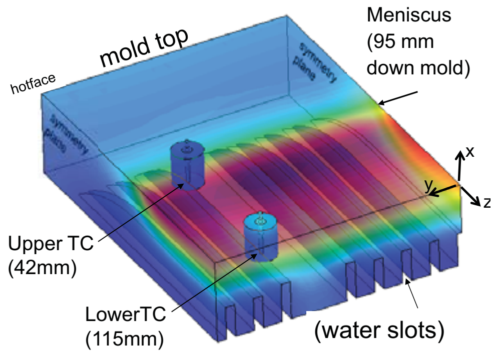


Fig. 1. Model domain and steady temperature distribution

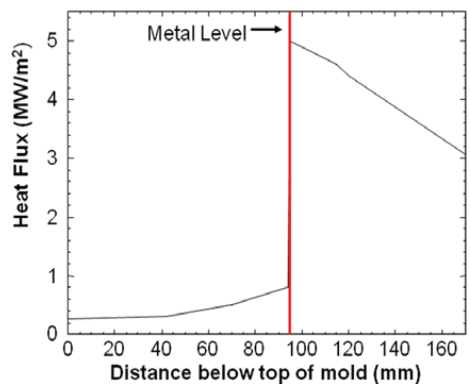


Fig. 2. Heat flux profile on mold hot-face versus distance below top of mold

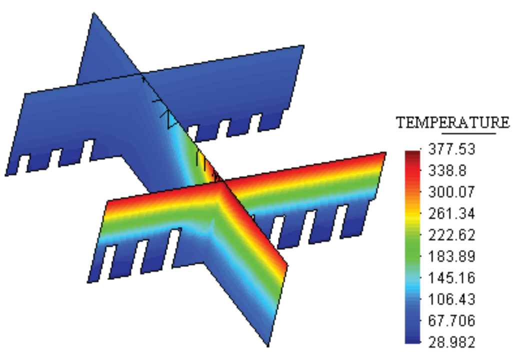


Fig. 3. Steady temperature contours (°C) in mold sections for base mold level (95mm down mold)

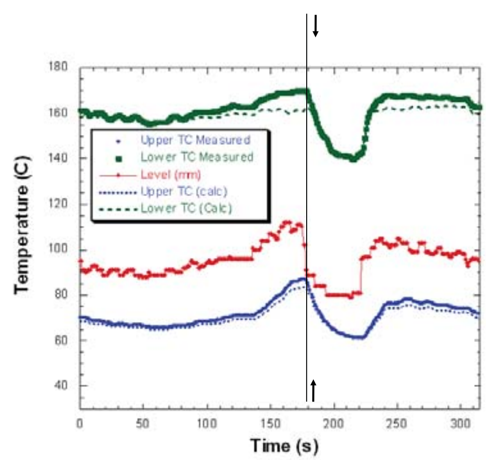


Fig. 4. Transient temperature histories predicted at thermocouple locations compared with measurements. Measured surface level position is also shown (in mm below mold top).

The initial steady-state temperature distribution is shown in Figs. 1 and 3, where the base liquid surface (meniscus) level is 95mm. The bolts require a larger spacing between water slots, which tends to increase the mold temperature in that region. To compensate for this, the two adjacent water slots are machined deeper into the mold beside this region, which tends to lower the temperature in this region. The net result is a surface temperature distribution across the mold (y-direction) which is only slightly larger opposite the bolts. The sharp peak in heat flux at the meniscus diffuses both up and down the mold (z-direction), which causes the mold hot-face surface temperature to reach a peak of ~380°C at about 25mm below the heat flux peak at the meniscus, which is below the lower TC for these conditions. The maximum cold-face temperature at the root of the water slots exceeds the water boiling temperature, which is ~120°C for the pressurized conditions in this mold. The upper and lower TC tip temperatures are 68°C and 159°C.

The transient results in Fig. 4 show that the temperature responses predicted at the location of the thermocouple beads in the mold wall match very well with the actual measurements. This demonstrates that the model is reasonably formulated, including the boundary conditions, and that liquid level variations cause mold temperature variations which can be accurately predicted. Even the small wiggles in the temperature response caused by wiggles in the liquid level can be detected. A slight error is observed for the lower thermocouple location, where the model tends to smooth away the peaks. This may have been due to insufficient mesh refinement. Mesh resolution was improved in the copper hot-face above the TC tips for the later parametric study.

The liquid level drop causes a drop in temperature at both TC locations in this work, owing to the net decrease in heat flux reaching the interior at each location. At the upper TC, heat must always conduct upwards (z-direction) from the meniscus region, so its temperature always drops when the level drops. When the lower TC is positioned lower down the mold, however, a drop in level sometimes causes its temperature to increase, as the peak in the heat flux curve becomes closer. In addition, a level fluctuation may cause changes in mold flux infiltration, leading to changes in the heat flux profile. Thus, temperature response at the lower TC is more difficult to interpret for several reasons. Fig. 4 also shows that the temperature response of both TCs lags behind the level signal by several seconds, as expected, owing to the large thermal inertia of the thick copper mold wall.

Parametric study of TC sensitivity to level fluctuations

The validated model was then run to investigate the influence of level fluctuation severity on the mold thermocouple temperature response. The ability of thermocouples to detect liquid level was found by manufacturing a sinusoidal level fluctuation and varying its duration (1/frequency) from 1-6s, amplitude from 2-20mm, thermocouple detection limit (+/- 1-2 ^{o}C), and thermocouple position beneath the hot-face surface in the mold wall.

A typical manufactured surface level signal is shown in Fig. 5 for a liquid surface level

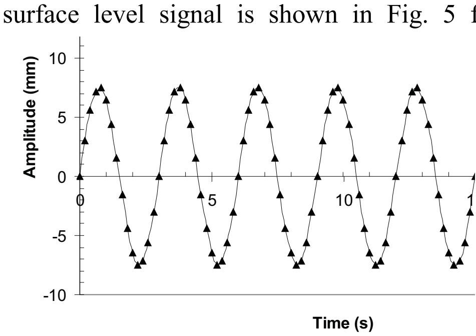


Fig. 5. Liquid level oscillation frequency and amplitude

oscillating with 7.5mm amplitude (15-mm variation from peak to peak), and 3s-duration (0.33 Hz frequency).

Fig. 6 shows the corresponding temperature responses predicted for the two thermocouples. After a brief initial transient, the model converges to a "pseudo-steady state" stably-oscillating temperature profile. The frequency matches the level fluctuation frequency, with a phase lag, as expected. The peak-to-peak magnitude of the fluctuating temperature signal is ~0.2°C (0.1 °C amplitude) at the upper TC and ~1°C at the lower TC. For a TC detection limit of 1°C, this variation at the upper TC is not detectable for this example, while it is at the critical detection limit at the lower TC. Peak-to-peak magnitudes were recorded from the steady converged results of 34 different simulations.

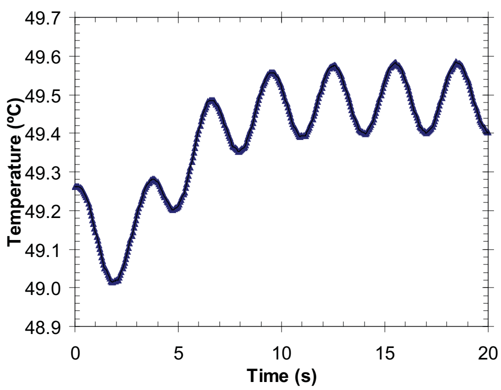


Fig. 6 a). Temperature predicted at upper TC

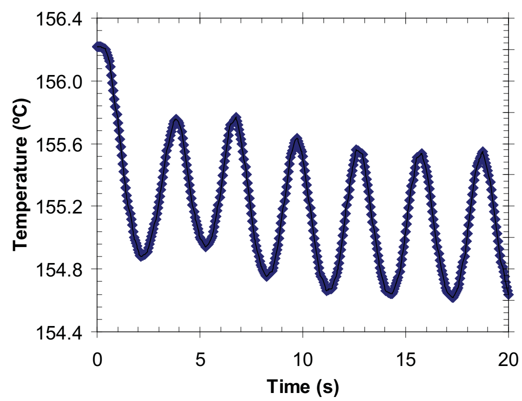


Fig. 6 b). Temperature predicted at lower TC

Fig. 7 shows the critical metal level fluctuation that produces a 1°C temperature fluctuation at the upper and lower thermocouples. Error bars indicate the uncertainty that arises from interpolating these critical detection limits from discreet simulation results. Larger fluctuations of longer duration (upper right of the lines) are detectable, while smaller fluctuations of shorter duration (lower left of the lines) are not. These results show that detecting a level fluctuation requires both a sufficiently-high amplitude and a long-enough duration. Short-duration (< 1s at the lower TC) level fluctuations cannot be detected, even if they are very large. Similarly, small height (<2mm) level changes cannot be detected, even if their duration is long.

The temperature changes at the lower TC are much larger, owing to the larger heat flux below the meniscus. Thus, the effects of a surface level change are predicted to be easier to detect at the lower TC, as indicated by its critical line being closer to the origin in Fig. 7. In reality, however, the lower TC is subject to other sources of temperature variation, such as variations in mold slag infiltration and conductance across the mold-shell gap. Thus, the upper TC might produce more reliable signals for the detection of mold level changes. The upper TC can just barely detect a level fluctuation of 12.5mm-amplitude and 4s duration. Such a level fluctuation is quite severe, and would likely produce a surface quality problem in the cast product. Thus, it would be desirable to find a sensor that is more responsive.

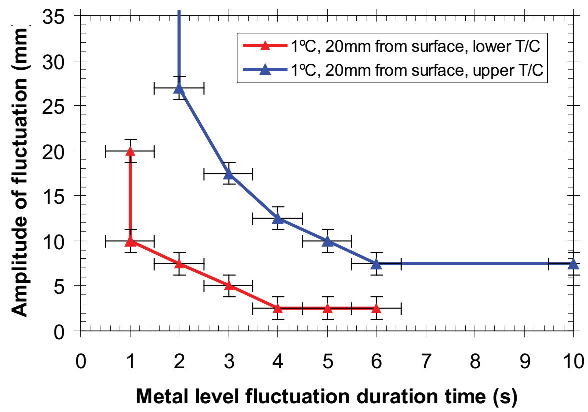
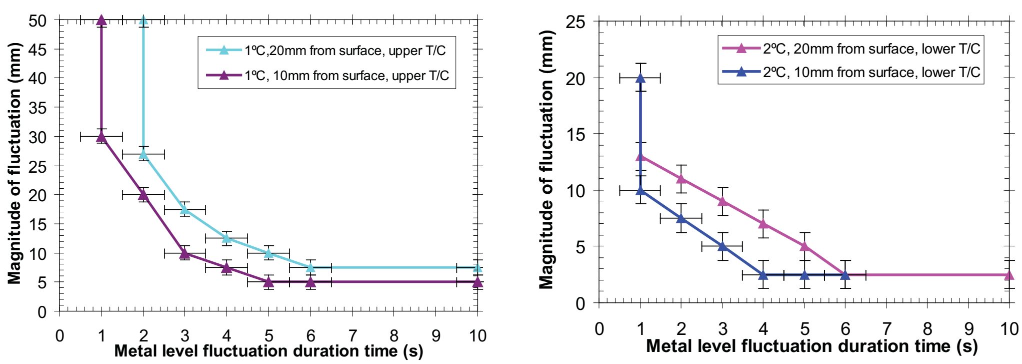


Fig. 7. Thermal response at standard upper and lower TC locations (1°C detection limit)

The opposing effects of decreasing the TC sensitivity and moving the TC closer to the hot-face surface of the mold are shown in Fig. 8 for the lower TC. Moving the TC closer to the hotface makes detection easier. The 10-mm deep TC can detect level fluctuations that are only 2/3 the duration of the detection limit at 20-mm. On the other hand, decreasing the TC sensitivity from 1°C to 2°C almost exactly cancels this improvement, as the 10-mm 2°C case in Fig. 8 almost exactly matches the 20-mm 1°C case in Fig. 7. Naturally, level fluctuations are more easily detected by more sensitive thermocouples located closer to the mold hotface surface. These findings are consistent with findings based on experimental thermocouple measurements with oscillating surface heat flux [4].



a) 1°C detection limit

b) 2°C detection limit

Fig. 8. Effect of TC distance beneath hot-face on critical detectable level fluctuation at lower TC

Inverse Heat Conduction Model

To predict the liquid level change directly from the measured thermocouple history requires inverting the transient heat conduction model used to generate the preceding results. As a first step towards this goal, a two-dimensional inverse heat-conduction model was developed in this work to predict the time-varying heat flux profiles from an array of measured mold temperature histories. To test the model, it was applied to interpret the TC measurements of a mold simulator [5]. The water-cooled mold plate has two columns of embedded thermocouples located 1.5mm and 5mm from the hot-face surface, as shown in Fig. 9. The TC labels represent the TC distance from the plate bottom. This plate is inserted into the molten steel bath at a "casting speed" of 12.7mm/s while being oscillated at a frequency of 1.3Hz (i.e. period of 0.77s) and a stroke of 6.3mm. Property data for the copper is given in Table 1. The nominal meniscus level was adjacent to TC 4. Further details on this experiment and the measured TC temperature histories are published elsewhere [5].

Results from the inverse model are presented in Figs. 10-12. First, a 1-D form of the inverse model was performed by neglecting axial heat conduction, and solving for horizontal heat conduction between each TC pair. As shown in Fig. 10, these predictions agree reasonably with the previous heat flux results, which used a similar 1-D inverse heat conduction model [5].

Predictions using the new 2-D inverse heat conduction model are shown in Fig. 11. The time averages of the 1-D and 2-D results are compared in Fig. 12. Much greater variations in surface heat flux are predicted, owing to the important averaging effect of axial conduction in the copper wall. These wide variations range from very high values, approaching those found in

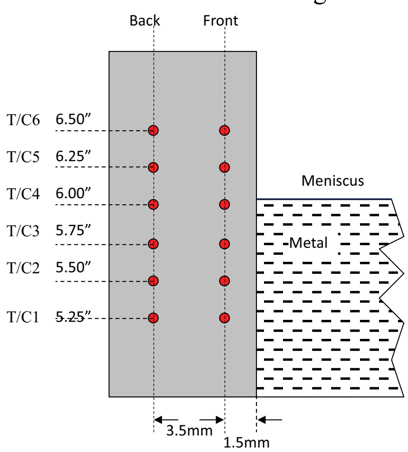


Fig. 9. TC locations in mold simulator [5]

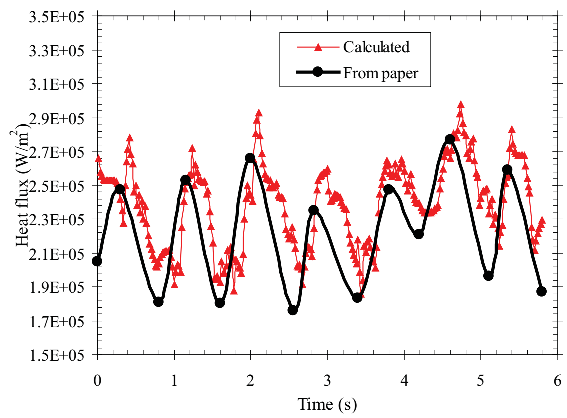


Fig. 10. Comparison of 1-D inverse model results [5]

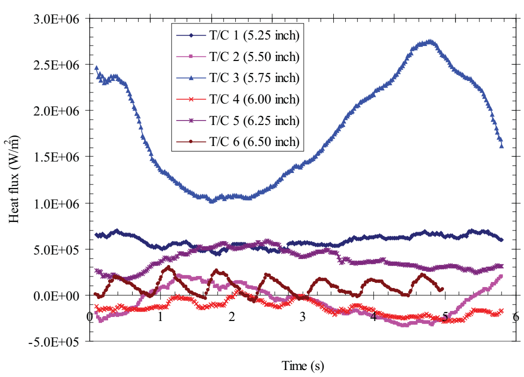


Fig. 11. Calculated heat flux histories on the mold surface (2-D inverse model)

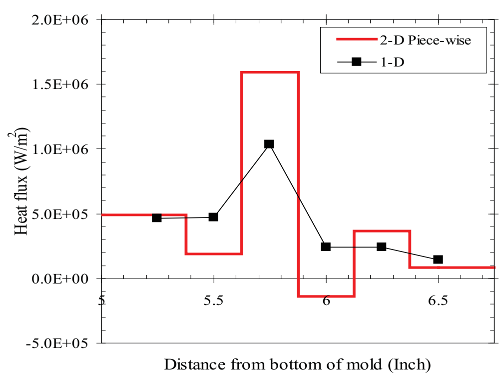


Fig. 12. Time-average heat flux profile down mold (z direction)

commercial casters, to very small – even negative! - values. The negative values are believed to be numerical errors associated with sudden drops to very small heat fluxes, which are expected when the liquid level drops below a given point on the mold wall. These results suggest that surface heat flux variations are much larger than expected from previous work, owing to liquid level variations and related transient behavior.

Conclusions

A new method to understand mold temperature variations near the meniscus has been developed using inverse transient heat-conduction models and has been applied to investigate the measurement of mold level fluctuations using thermocouples embedded in the mold walls. Compared with other techniques used to measure mold level variation, this new inexpensive method is shown to be capable of providing quantitative information on the temporal fluctuation of the metal level in the mold. The method is limited, however, in the amplitude and frequency of the level fluctuations it can detect by the large distance of the thermocouples from the mold surface. For conventional thermocouples used in commercial practice, located 20mm beneath the hot-face surface, temperature response can be accurately related to surface level fluctuations in the mold, at least when they are severe. The minimum level fluctuation that can produce a barely-detectable 1°C variation at a 20-mm-deep upper TC is about 8-mm amplitude (for a low-frequency level fluctuation) or 2s duration (for a high-amplitude level-fluctuation). Thermocouples located above the meniscus are more reliable for level detection, even though they are less sensitive, due to the smaller temperature changes. Locating the thermocouples closer to the hot-face surface of the mold greatly increases their sensitivity. Inverse heat conduction models can be used to transform mold thermocouple temperatures into liquid level and to reveal variations in meniscus heat flux.

Acknowledgements

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