Using Computational Models to Account for Thermocouple Conduction Error in Cast Metal/Mold Interfacial Heat Transfer Experiments

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ABSTRACT

The metal/mold interfacial heat transfer of solidifying castings is a subject that has been investigated by many researchers. The most common experimental approach to this problem, very generally, is to measure the temperature near the interface with thermocouples and then use an inverse method to obtain the interfacial heat transfer coefficient. However, the presence of the thermocouple tends to result in a disturbance of the temperature field near the location where the measurement occurs. This yields bias error in the temperature measurements which are rarely considered in metal/mold interfacial heat transfer studies. In this paper, 3-D computational thermocouple models are used in conjunction with a method for generating correction kernel functions. These kernel functions are used in a form of Duhamel’s superposition integral to account for the bias when estimating surface heat fluxes. This correction method is applied to temperature data obtained from horizontal aluminum plate sand casting experiments. The correction scheme results in an increase in the heat flux estimates of up to 65%.

INTRODUCTION

In an effort to realize the potential of casting solidification simulation, researchers have been working for decades to gain a more complete understanding of the phenomena that occurs during solidification. One of the most important phenomena that must be understood is the heat transfer at the metal/mold interface. Metal/mold interfacial heat transfer is a complex phenomenon to evaluate experimentally. This subject has received much attention from researchers over the past few decades (Woolley and Woodbury, 2007). While prior research has contributed much to our understanding of the phenomena at the metal/mold interface, much work remains to complete our understanding of the subject. Two very general areas that should receive attention from researchers are the investigation of various alloy/mold material combinations and the advancement of techniques for the experimental evaluation of metal/mold interfacial heat transfer.

There are many challenges that contribute to the complexity of evaluation of the metal/mold interfacial heat transfer (Woolley et al., 2006), but one of the challenges which tends to be neglected by researchers is accounting for the conduction error which occurs due to the presence of the thermocouples in the experimental setup. It has been widely documented that bias error influences thermocouple measurements, particularly in a system with large temperature gradients (Attia and Kops, 1986) (Tszeng and Saraf, 2003) (Woodbury and Gupta, 2008).

In a previous work (Woolley and Woodbury, 2008b), a numerical experiment was conducted to demonstrate the utility of the temperature correction method. In the numerical experiment, a detailed 3D model was developed that represented a thermocouple imbedded in a sand mold. Two thermocouple configurations were modeled. The first was a model of a thermocouple configured perpendicular to the heated surface (the inner mold wall) and the other was a model of a sensor parallel to the heated surface. A prescribed heat flux similar to what might be expected at the surface of an aluminum casting was applied to the surface. A simulated “measured” temperature was obtained from the modeled thermocouple. This “measured” temperature was compared to the simulated undisturbed temperature which is present at a large distance away from the sensor. For both configurations, the root mean squared (RMS) errors for the temperature histories improved by 93%. Heat fluxes calculated with the simulated “measured” temperatures, with the simulated undisturbed temperatures, and with the corrected temperatures were compared to the exact (applied) heat flux. The RMS errors for the heat fluxes improved by 72% for the perpendicular case and by 57% for the parallel case.

An effort to correct experimental temperature measurements from aluminum sand castings is presented in the current investigation. A description of the casting experiment, including details of the temperature measurement, is provided. In the current paper, only thermocouples oriented parallel to the inner mold surface are considered. Experimental temperatures were obtained for various casting thicknesses using thermocouples imbedded near the inner mold surface. The temperature correction method is described, including details of the mathematical formulation and the computational model. The
experimentally obtained temperatures are corrected and then used to estimate the heat flux at the metal/mold interface. The heat flux values estimated with the corrected temperatures are determined and compared with the heat flux estimates obtained with the original temperature data.

**EVALUATION OF THE METAL/MOLD INTERFACIAL HEAT TRANSFER**

Inverse methods in heat conduction are frequently employed in the field of materials processing because these methods can be used to reveal information that is difficult or impossible to measure directly. Thermal properties of materials or heat transfer at the surface of a body are among the information pertinent to materials modeling which might be found by inverse methods. In the case of metal castings, the inverse heat conduction problem is useful in the determination of the metal/mold interfacial heat flux or interfacial heat transfer coefficient. In order to characterize interfacial heat transfer with this method, additional information, usually in the form of the temperature measurements at one or more points within the body, must be available. The most common solution methods used in solidification processes were developed by J.V. Beck (Beck, 1970; Beck et al., 1985).

With knowledge of the temperature history, \( T(x_1, t) \), at a known interior location, \( x_1 \), the transient surface heat flux, \( q(t) \), can be estimated by inverting Duhamel’s integral in the form

\[
T(x_1, t) - T_i = \int_0^t \frac{\partial \phi(x_1, \tau) - \lambda}{\partial \tau} d\lambda
\]

where \( \phi(x_1, \tau) \) is the temperature response at point \( x_1 \) due to a unit step increase in the surface heat flux and \( T_i \) is the initial temperature. This inversion can be accomplished with the sequential function specification method (Beck et al., 1985). The heat flux is estimated as

\[
\hat{q}_M = \sum_{i=1}^{r} K_i \left( T_{M+i-1} - \hat{T}_{M+i-1} \right) \phi_i
\]

where the hat (‘) indicates an estimated value, subscript \( M \) represents a general time index, and \( K_i \) is given by

\[
K_i = \frac{\phi_i}{\sum_{j=1}^{r} \phi_j^2}
\]

and \( \hat{T}_{q=0} \) is given by

\[
\hat{T}_{q=0} = \left[ \sum_{i=1}^{M-1} \hat{q}_i \Delta \phi_{M-i} + T_0 \right]
\]

\[
\sum_{i=1}^{M-1} \hat{q}_i \Delta \phi_{M-i+1} + T_0
\]

\[
\sum_{i=1}^{M-1} \hat{q}_i \Delta \phi_{M-i+r-1} + T_0
\]

**DESCRIPTION OF EXPERIMENTS**

The interfacial heat transfer of solidifying aluminum alloy A356 in resin-bonded sand molds was the subject of previous investigations (Woodbury et al., 1998a) (Woodbury et al., 1998b) (Woodbury et al., 1998c) (Woodbury et al., 2000). The 600 mm x 600 mm cast aluminum plates varied in thickness from 6.25 mm to 25 mm. This simple geometry facilitates analysis using one-dimensional parameterization. The broad flat surfaces resulted in nearly one-dimensional heat conduction in the direction perpendicular to the surfaces. The plates were gated from one side, were fed through two runners and were generously vented. In an effort to minimize any disturbance of the heat flow from the faces of the plates into the mold, no risers were used.

The heat fluxes at the metal/mold interface were estimated using an inverse heat conduction solution. Measured temperatures from within the sand mold were used as inputs to the inverse solver. Temperature measurements obtained in the aforementioned investigations are revisited in the current work.
The thermocouples used to obtain the temperature histories from the mold were integrated into the sand before the sand/resin mixture completely bonded. The temperature sensors were positioned near the center of the broad plate surface. Thermocouples considered in this work were arranged either perpendicular or parallel to the interface surface. Two casting/mold combinations have been selected from the previous works for consideration in the current investigation. One mold contained thermocouples positioned perpendicular to the heated surface while the sensors in the other mold were parallel to the heated surface. Castings considered in this work were 6.25 mm, 12.5 mm, and 25 mm thick and solidified in a horizontal position. The variables considered in this study are the thermocouple configuration, the location of the thermocouple in either the cope or drag, the distance of the thermocouple tip from the inner mold surface, and the casting thickness. The variables for each experimental casting and the associated casting identification label are tabulated in Table 1.

### Table 1. Experimental Variables for Castings Considered in this Study

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Plate Thickness</th>
<th>Pour Temp.</th>
<th>Sensor Location</th>
<th>Sensor Distance from Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-25</td>
<td>25 mm</td>
<td>674°C</td>
<td>Top of Mold</td>
<td>3.00 mm</td>
</tr>
<tr>
<td>B-25</td>
<td>25 mm</td>
<td>674°C</td>
<td>Bottom of Mold</td>
<td>4.90 mm</td>
</tr>
<tr>
<td>T-12.5</td>
<td>12.5 mm</td>
<td>738°C</td>
<td>Top of Mold</td>
<td>3.83 mm</td>
</tr>
<tr>
<td>B-12.5</td>
<td>12.5 mm</td>
<td>738°C</td>
<td>Bottom of Mold</td>
<td>4.77 mm</td>
</tr>
<tr>
<td>T-6.25</td>
<td>6.25 mm</td>
<td>746°C</td>
<td>Top of Mold</td>
<td>2.84 mm</td>
</tr>
<tr>
<td>B-6.25</td>
<td>6.25 mm</td>
<td>746°C</td>
<td>Bottom of Mold</td>
<td>4.74 mm</td>
</tr>
</tbody>
</table>

**TEMPERATURE CORRECTION**

A technique for determining the undisturbed transient temperature is used to develop a kernel function which can be readily implemented into an inverse algorithm. This technique is based on methods originally reported by Beck (1968). This technique can be applied to various geometries and physical conditions. A Laplace transform analysis is the basis for the development of the correction kernel function used to determine the undisturbed transient temperature based on temperature measurements. The mathematical formulation results in a kernel function in the Laplace domain which must be inverted to the time domain. The correction kernel is found by numerical inversion of the convolution integral using an adaptation of Beck’s sequential function specification method (Beck et al., 1985).

In the aforementioned work (Beck, 1968), the mathematical formulation of the correction kernel method was very generally outlined. In this section, a very detailed account of Beck’s original formulation is provided. The result of the formulation is a convolution integral with a kernel function expressed in the Laplace domain. Following the correction integral formulation, a method for numerically inverting the convolution is presented.

A computational model was developed to estimate the bias present in thermocouple measurements embedded in a sand mold exposed to a unit step heat flux. The model, to be described later, is used to estimate the measured temperature from the thermocouple as well as the undisturbed temperature which exists some large distance from the sensor. The thermocouple tip temperature is expressed as \( T_p(t) \), the undisturbed temperature is \( T_{p\infty}(t) \) and the initial temperature of the system is \( T_0 \). The temperature rise at the thermocouple tip, \( T_p(t) - T_0 \), at a point \( p \) some distance \( E \) from the surface is related to the surface heat flux \( \dot{q}(t) \) by the convolution integral

\[
T_p(t) - T_0 = \int_0^t \dot{q}(\lambda) \frac{\partial h(0,E,t-\lambda)}{\partial t} d\lambda
\]

where \( h(r,z,t) \) is the temperature rise at a point \( (r, z) \) due to a unit step increase in the surface heat flux \( \dot{q} \).

The dimensionless temperature error, \( \phi \), is given as

\[
\phi = \frac{f(T_p - T_{p\infty})}{\dot{q}R/k}
\]

where \( f \) is the conductivity ratio, \( f = k/k_w \), \( k \) is the parent material thermal conductivity, \( k_w \) is the wire thermal conductivity, and \( R \) is the wire radius. Calculation of \( \phi \) required Beck to use a finite difference two-dimensional solution of the transient, axisymmetric heat conduction equation. The dimensionless temperature rise for the undisturbed temperature \( T_{p\infty} \) for a semi-infinite body exposed to a constant heat flux is given as
\[
\theta_w = \frac{T_{wx} - T_0}{qR/k} = \tau^2 \text{erf} \left( \frac{1}{2\tau} \right)
\]

where \( \tau \) is the dimensionless time and \( \text{erf} \) is the integral complementary error function. The kernel \( h(t) \) in (5) is given by

\[
h(t) = \frac{R}{k} \phi' + f\theta_w
\]

The convolution integral in (5) can be inverted to find \( q(t) \) which can then be used to calculate the undisturbed temperature rise \( T_{wx} - T_0 \) with

\[
T_{wx} - T_0 = \frac{R}{k} \int_0^t q(\lambda) \frac{\partial \theta_w(t - \lambda)}{\partial t} d\lambda
\]

Then Beck describes a procedure for avoiding the repeated inversion of the convolution integral each time that a new experimental temperature history \( T(t) \) is provided. The Laplace transform of (5) can be taken to obtain

\[
\tilde{T}_p - \tilde{T}_0 = \tilde{q} \tilde{m}'
\]

Here the bar indicates that the Laplace transform has been taken and the prime on \( h \) indicates differentiation with respect to time. Also, take the Laplace transform of (9) to get

\[
\tilde{T}_{wx} - \tilde{T}_0 = \tilde{q} \tilde{m}'
\]

Subtracting (10) from (11) yields

\[
\tilde{T}_{wx} - \tilde{T}_p = \tilde{q} \left[ \tilde{m}' - \tilde{h}' \right]
\]

In the next step, (10) is solved for \( \tilde{q} \) which is used to replace \( \tilde{q} \) in (13).

\[
\tilde{T}_{wx} - \tilde{T}_p = \tilde{T}_p - \tilde{T}_0 \left[ \frac{\tilde{m}'}{\tilde{h}} - 1 \right]
\]

This simplifies to

\[
\tilde{T}_{wx} - \tilde{T}_p = \left[ \frac{\tilde{m}'}{\tilde{h}} - 1 \right] \left( \tilde{T}_p - s\tilde{T}_0 \right)
\]

Then this is divided and multiplied by \( s \), the variable associated with the Laplace domain

\[
\tilde{T}_{wx} - \tilde{T}_p = \frac{\tilde{m}'}{s\tilde{h}} - \frac{1}{s} \left( \tilde{T}_p - s\tilde{T}_0 \right)
\]
Since $T_0$ is a constant, we can substitute $\bar{T}_0 = \frac{T_0}{s}$

\[ \bar{T}_{p\infty} - \bar{T}_p = \left[ \frac{m^*}{sh'} - \frac{1}{s} \right] (s \bar{T}_p - T_0) \]  

(17)

Note that, in general, the Laplace transform of the first derivative of a function is

\[ L \left[ f'(x) \right] = sF(s) - f(0) \]  

(18)

Apply this to the case of $F(s) = \bar{T}_p$, where $f(0) = T_p(0) = T_0$, and the result is

\[ L \left[ \frac{\partial T_p(t)}{\partial t} \right] = s\bar{T}_p - T_0 \]  

(19)

Therefore, the inverse Laplace of $s\bar{T}_p - T_0$ is

\[ L^{-1}[s\bar{T}_p - T_0] = \frac{\partial T_p(t)}{\partial t} \]  

(20)

Note also that, in general, for $L \left[ f(x) \right] = F(s)$ and $L \left[ g(x) \right] = G(s)$

\[ F(s)G(s) = L \left[ \int_0^t f(\lambda)g(t - \lambda) d\lambda \right] \]  

(21)

Therefore the inverse Laplace transform of $F(s)G(s)$ is

\[ L^{-1}[F(s)G(s)] = \int_0^t f(\lambda)g(t - \lambda) d\lambda \]  

(22)

So, using the relations shown in (18) - (22), the inverse Laplace transform of (17) can be taken to get

\[ T_{p\infty}(t) - T_p(t) = \int_0^t H(\lambda) \frac{\partial T_p(t - \lambda)}{\partial t} d\lambda \]  

(23)

where

\[ H(\lambda) = L^{-1} \left[ \frac{m^*}{sh'} \right] - 1 \]  

(24)

Equation (23) is the basic equation used to determine the undisturbed temperature, $T_{p\infty}(t)$. Beck explains that the function $H(t)$ is independent of the time-variation of the surface heat flux and, therefore, can be determined for $\dot{q}(t)$ equal to a constant.

In order to use the correction equation (23), an inversion procedure is necessary to find the values of $H(\lambda)$. One procedure is the numerical inversion of the convolution integral. This requires knowledge of $T_p$ and $T_{p\infty}$ from a computational. Another approach is to numerically invert the Laplace transform in (24). This approach requires knowledge of $m$ and $h$ from a computational model. Several different numerical inversion techniques were evaluated in a previous work (Woolley et al., 2008a). The most effective technique was found to be a convolution inversion technique adapted from Beck’s sequential function specification method (Beck et al., 1985).
THERMOCOUPLE MODEL

The system under investigation is a thermocouple imbedded in a resin-bonded sand mold. The transient temperature response of an imbedded thermocouple is governed by the thermal interaction of the sensor components adjacent to the junction(s), the mass of the surrounding material, and the contact with the surrounding material. Earlier axisymmetric models represented the thermocouple as a single wire with effective thermal properties (Beck, 1962). These models were adequate for demonstrating the disturbance in the temperature field and for estimating the magnitude of the thermocouple error. However, only the thermocouple configured perpendicular to the heated surface can be represented by the axisymmetric model.

The model employed in this investigation is a detailed three-dimensional model. Beck’s original analysis (Beck, 1968) was developed for an axisymmetric model. However, the thermocouple geometry may be more accurately modeled in three dimensions and, thus, the Beck’s methodology (Beck, 1968) has been adapted for the three dimensional model. Each wire and even the welded bead of the thermocouple are modeled as unique entities with distinct thermal properties.

The sensor considered (Figure 1) is a 24 AWG (American Wire Gauge) type K (chromel-alumel) thermocouple. The wire radius, \( r_w \), is 0.25 mm. The dimensions of the welded bead of a 24 AWG type K thermocouple were measured with calipers. The geometry of the bead is approximated in the model as an ellipsoid with a major axis radius, \( r_{maj} \), of 0.625 mm and a minor axis radius, \( r_{min} \), of 0.42 mm. The wire is covered with glass braid insulation. The insulation leaves 5 mm of the tip of the thermocouple exposed.

In order to maintain linearity in the above correction kernel formulation, the thermal properties of all of the materials used in the model were considered as constant. The individual thermocouple wires were modeled with distinct thermal properties. The thermoelements for a type K thermocouple are chromel \(( k = 19.25 \text{ W/m-K}, \rho c_p = 3.91 \times 10^6 \text{ J/m}^3\text{-K})\) and alumel \(( k = 29.71 \text{ W/m-K}, \rho c_p = 4.50 \times 10^6 \text{ J/m}^3\text{-K})\). The thermocouple bead is formed by welding the two wires together, and thus the properties are an average of the properties of the constituent materials \(( k = 24.48 \text{ W/m-K}, \rho c_p = 4.20 \times 10^6 \text{ J/m}^3\text{-K})\). The properties for the glass braid insulation were taken as \( k = 0.036 \text{ W/m-K} \) and \( \rho c_p \approx 8.35 \times 10^4 \text{ J/m}^3\text{-K} \). The properties for sand \(( k = 1 \text{ W/m-K} \) and \( \rho c_p \approx 1.596 \times 10^6 \text{ J/m}^3\text{-K} \) fall within the range of published data.

The model was used with commercial computational software to simulate and evaluate the heat flow and the distortion of the thermal field. The mesh elements within and adjacent to the thermocouple bead volume are tetrahedral elements. Everywhere else in the mesh, hexahedral (brick) elements are used.

NUMERICAL INVERSION OF CONVOLUTION INTEGRAL

The method used in the current work to numerically invert the convolution integral is an adaptation of Beck’s function specification method by sequential estimation (Beck et al., 1985). This procedure is used to evaluate the integral in (23) to estimate \( \hat{H}_m \) based on numerical data.

\[
\hat{H}_M = \sum_{i=1}^{M} K_i \left( \hat{T}_{p_i} - T_p \right)_{H_{M+1}} \hat{T}_{M+i-1} \bigg|_{H_{M} \ldots H_{M+i-1} = 0} \phi_i
\]

(25)

where \( M = 1, 2, \ldots, n, n = \) number of time steps, \( r \) is the number of future times, \( \phi_i = T_{p_i} - T_0 \), \( K_i \) is the gain coefficient given by
\begin{equation}
K_i = \frac{\phi_i}{\sum_{j=1}^{r} \phi_j^2}
\end{equation}

and \( \hat{T}_{H=0} \) represents the calculated temperature for the model at time \( t_M \) for the estimated kernel components \( \hat{H}_1 \) to \( \hat{H}_{M-1} \), but \( \hat{H}_M \) is set equal to zero.

\begin{equation}
\hat{T}_{H=0}\bigg|_{H=0} = \left[ \sum_{i=1}^{M-1} \hat{H}_i \Delta \phi_{M-i} + T_0 \right] \\
\sum_{i=1}^{M-1} \hat{H}_i \Delta \phi_{M-i+1} + T_0 \\
\vdots \\
\sum_{i=1}^{M-1} \hat{H}_i \Delta \phi_{M-r+1} + T_0
\end{equation}

The use of future time data has a regularizing effect on the sequential estimation of the correction kernel values.

**RESULTS AND DISCUSSION**

In the current work, a 3D computational thermocouple model was employed to simulate temperature data which was used to generate values for correction kernel functions. The kernel values were used with equation (23) to correct temperature measurements which were experimentally obtained from sand casting experiments. These corrected temperatures were then used to estimate the heat fluxes at the casting mold surface.

The heat flux estimated with the measured and corrected data (for \( r = 8 \) to \( 10 \)) are shown for the 25 mm plate in Figure 2, for the 12.5 mm plate in Figure 3, and for the 6.25 mm plate in Figure 4. The heat flux estimates calculated with the original measured data are shown in these figures with solid lines and the heat fluxes estimated with the corrected temperatures are shown with dashed lines.

![Figure 2. 25 mm plate top (T-25, left) and bottom (B-25, right) heat fluxes estimated from measured and corrected temperatures](image-url)
Due to the correction of the thermocouple temperatures from the 25 mm plate, a maximum change in the heat flux of over 33% was achieved for the mold bottom and of about 48% for the mold top. The heat flux corrections were greater than 5% in the mold bottom for nearly 30 seconds and in the mold top for just over 30 seconds. The $RMS$ difference between the heat fluxes estimated with the measured temperatures and the heat fluxes calculated with the corrected temperatures was 27.3 kW/m$^2$ for the bottom and 18.8 kW/m$^2$ for the top.

For the bottom surface of the 12.5 mm plate, a maximum change in the heat flux estimate of over 49% was achieved while a change of at least 5% continued for over 38 seconds. For the heat flux into the top of the mold, a maximum change of 47% was attained and a change of at least 5% was still observed after 35 seconds. The $RMS$ difference between the heat fluxes estimated with the measured temperatures and the heat fluxes calculated with the corrected temperatures was 53.7 kW/m$^2$ for the bottom and 27.4 kW/m$^2$ for the top.

The correction procedure resulted in a maximum change in the heat flux estimate of over 65% for the bottom of the 6.25 mm plate mold and of 50% for the top. The heat flux corrections exceeded 5% for over 45 seconds for the mold bottom and for nearly 60 seconds for the mold top. The $RMS$ difference between the heat fluxes estimated with the measured temperatures and the heat fluxes calculated with the corrected temperatures was 5.3 kW/m$^2$ for the bottom and 65.4 kW/m$^2$ for the top.
CONCLUSIONS
In the current work, temperature measurements from a sand casting experiments underwent a method for correcting thermocouple bias. The temperature measurements were obtained for use in an inverse heat conduction solver to estimate the heat flux at the mold surface. In a previous work, the kernel method of temperature measurement error correction was demonstrated for thermocouples configured perpendicular to the flat mold surface as well as parallel to the surface (Woolley and Woodbury, 2008).

The impact of the correction technique was found to be greatest during the early part of the experiments. For the 25 mm castings, the heat flux estimates increased by over 33% in the bottom portion of the mold and by nearly 48% in the top of the mold while the RMS differences between the heat fluxes estimated with the measured and corrected temperatures were 27.3 kW/m² for the bottom and 18.8 kW/m² for the top. For the 12.5 mm castings, the heat flux estimates increased by 49% in the bottom portion of the mold and by 47% in the mold top while the RMS differences between the heat fluxes estimated with the measured and corrected temperatures were 53.7 kW/m² for the bottom and 27.4 kW/m² for the top. For the 6.25 mm castings, the heat flux estimates increased by over 65% in the bottom portion of the mold and by 50% in the top of the mold while the RMS differences between the heat fluxes estimated with the measured and corrected temperatures were 5.3 kW/m² for the bottom and 65.4 kW/m² for the top.

All of the thermocouples in the current investigation were oriented parallel to the inner mold surface. It should be noted that the maximum change in the heat flux estimates were observed for the thinnest plate (6.25 mm). In a previous work (Woolley and Woodbury, 2008b), thermocouples in a perpendicular orientation with respect to the heated surface of a sand mold were considered for 25 mm thick plate castings. The maximum observed change in the heat flux estimates for the perpendicular sensor orientation reached up to 85%. Perhaps the correction procedure could have an even greater impact on experimental results for thinner castings with thermocouples arranged perpendicular to the surface.

It has been well-established that thermocouple temperature measurements at or near the metal/mold interface are subject to significant bias due to the sensor’s own influence on the temperature field. Many researchers have conducted experiments in the past and reported results without considering the influence of this source of error. The current study shows that this error can have a very significant impact on the evaluation of the metal/mold interfacial heat transfer using experimentally measured data. It is imperative that, in any future interfacial heat transfer experimentation, researchers account for such a bias error.

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