MEASUREMENTS OF METAL–MOLD INTERFACIAL HEAT TRANSFER COEFFICIENTS DURING SOLIDIFICATION OF Sn AND Sn-Pb ALLOYS

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A study is reported on the evolution of the thermal resistance at the interface between the mold and the metal during solidification of metal castings. Experiments were performed to measure the interfacial heat transfer coefficient \( h_i \) for solidification of Sn and Sn-Pb alloys from a vertical wall. The experiments with pure Sn were simulated numerically using a constant \( h_i \), and good agreement was found. The variation of \( h_i \) in the presence of a mushy zone at the interface was studied. In the case of a Sn-10wt%Pb alloy it was found that \( h_i \) varied as a function of the liquid fraction at the interface. The interfacial heat transfer coefficient had a higher value during the initial stage of solidification, when the liquid fraction at the interface was high. However, as the temperature at the interface approached the eutectic temperature and the liquid fraction decreased to zero, \( h_i \) dropped to a lower value. Once the temperature at the interface fell below the eutectic temperature, \( h_i \) remained approximately constant. In the case of a eutectic Sn-Pb alloy, the interfacial resistance increased slightly due to thermal contraction of the metal as solidification proceeded. The observed variation in \( h_i \) for the three different metals examined in this study is explained by volumetric contraction upon solidification.

INTRODUCTION

The structure and properties of a casting are influenced by the rate of solidification. The solidification rate in turn depends on the thermal resistance at the metal–mold interface. This thermal resistance is generally modeled as an interfacial heat transfer coefficient \( (h_i) \), which is defined as

\[
h_i = \frac{q}{(T_i - T_w)}
\]

Accurate knowledge of this coefficient is necessary in the design and modeling of casting processes.

The physical mechanisms for the development of the interfacial resistance due to imperfect contact between the solidified metal and the mold have been discussed by Ho and Pehlke [1] and Prates and Biloni [2]. Initially, the metal

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contracts from the mold wall because of volume change upon solidification. After a
stable skin of solidified material has formed at the interface, the interfacial gap can
grow due to thermal contraction of the mold and the casting. Heat transfer at the
interface is by (1) conduction through isolated contacts between the metal and
the mold, (2) conduction through the gases present in the interfacial gap, and (3)
radiation between the surfaces forming the gap. Heat transfer by radiation plays an
important role only when the temperatures are high and the gap spacing is large
[1]. The value of \( h_i \) for a certain metal/mold combination depends on the
geometry and configurational factors controlling the contact pressure between
the mold and the metal [1, 3, 4], the pouring superheat of the metal [5], the mold
coating, and the formation of an oxide layer at the interface [3, 4]. Of all these
factors, geometry has the most significant effect on the value of \( h_i \) [3].

Experimental studies [3, 6, 7] indicate that in the case of pure metals the
interfacial resistance attains an approximately constant value quickly after the
onset of solidification. Constant values of \( h_i \) were used by Durham and Berry [5, 8]
in their numerical simulations of solidification experiments to obtain good agree-
ment with the experimental data. In these experiments, a stable solid shell was
established quickly with respect to the total freezing time of the casting. However,
if the time to form a stable shell is comparable to the total freezing time of a
casting, the dynamic nature of \( h_i \) has to be taken into consideration [3].

In the case of large-freezing-range metal alloys that are slowly cooled, a
mushy zone can be present at the interface for a significant fraction of the total
solidification time of the casting. This mushy zone is characterized by the simulta-
neous presence of solid and liquid. During such solidification it can be expected
that the value of \( h_i \) is higher initially and drops as a solid shell forms. The initially
higher \( h_i \) is due to the liquid present at the interface, which tends to maintain a
better thermal contact with the mold. The variation of \( h_i \) with a mushy zone
present at the interface has not been studied in detail. Experiments for the
determination of \( h_i \) in the case of alloys have been reported [4, 7, 9]. However, in
these experiments solidification was fast and a solid shell formed very early. As a
result, the variation of $h_i$ with liquid fraction at the interface could not be examined. In addition, a direct measurement of the size of the interfacial gap is difficult in the presence of a mushy zone at the interface [1, 9].

In the present study, the variation of $h_i$ during the solidification of Sn-Pb alloys from a vertical wall is investigated experimentally. In addition, solidification experiments with pure tin are performed and simulated numerically using a constant value for $h_i$. The study provides further insight into the nature of the metal-mold interfacial heat transfer in the presence of a mushy zone.

EXPERIMENTS

Experimental Setup

Experiments were carried out in a 50-mm-square cavity (Fig. 1). The third dimension of the test cell was equal to 100 mm. One of the vertical walls of the cell was made of a copper heat exchanger. The other walls were made of 0.625-mm-thick steel plates. The top plate had four holes to allow melt above the top plate (the mold was overfilled by about 3 mm) to feed solidification contraction. The walls of the cell were rendered adiabatic by insulation and the use of guard heaters (see Fig. 1). The temperatures of the guard heaters were maintained close to the temperatures measured on the walls of the test cell. The inner edges of the test cell were sealed using high-temperature RTV silicone adhesive. A thin protective coating of graphite was applied to all the inner surfaces of the cell. Heat was extracted through the heat exchanger by circulating a heat transfer fluid (Siltherm) through it. The heat transfer fluid entered the heat exchanger through four ports on the sides (two on each side) and exited through a port in the center. The heat transfer fluid was circulated through a system of pipes and valves by a Haake HT 400 constant-temperature bath controller. A secondary heat exchanger was installed around a part of the piping system. This heat exchanger was switched on

![Fig. 1 Schematic illustration of the test cell.](image)
to achieve a certain cooling rate. To verify that the heat exchanger cools uniformly, a few preliminary experiments were carried out with reduced heat exchanger area and additional thermocouples. The results of these experiments confirm that the heat exchanger cools almost uniformly. In addition, the temperature rise of the heat exchanger fluid as it passes through the heat exchanger is only about 0.07°C. Therefore, temperature gradients over the face of the heat exchange can be assumed to be negligible.

Temperature measurements were carried out using chromel-alumel (k-type) thermocouples. Two thermocouples were embedded in the heat exchanger wall. These thermocouples measured the wall temperature (\(T_w\)). Four thermocouples were used to measure the temperature of the heat transfer fluid entering the heat exchanger (\(T_f\)). Figure 2 schematically illustrates the experimental configuration and relevant temperatures near the heat exchanger. Temperatures inside the cell were measured by nine thermocouples inserted through the top plate. The locations of these thermocouples are shown in Fig. 3. The thermocouple tubes were bent 4 mm from the thermocouple junction and inserted into the cell with the tip and the length of the tube in a plane parallel to the heat exchanger. Then the thermocouple tubes were rotated slightly so that the tips of all three thermocouples at the same \(x\) location were in one vertical line. The thermocouples inserted into
the cell were sheathed in 1.5-mm-diameter steel tubes. All thermocouples were calibrated at the melting point of tin (232°C). At this temperature the thermocouple readings exhibited fluctuations of about 0.04°C. The range of temperatures measured varied from 205 to 232°C in the experiments with tin and from 160 to 225°C in the Sn-Pb experiments. The accuracy of the thermocouples over this range was estimated to be 0.2°C. It may be pointed out that in the calculation of $h_i$ in the Sn-Pb experiments the temperature differences are more critical than the absolute temperatures themselves.

**Experimental Procedures**

Experiments were performed with Sn (99.99% pure) and Sn-Pb alloys (made from 99.99% pure Pb and Sn). The metal was melted in a crucible and the deslagged, superheated melt was transferred into the preheated test cell. In the case of experiments with the Sn-Pb alloy, care was taken to homogenize the melt before pouring. After establishing a steady, uniform temperature in the melt, solidification was initiated by lowering the temperature setting on the constant-temperature bath and switching on the secondary heat exchanger. Thermocouple readings were collected by a Hewlett-Packard 3852A data acquisition system at a frequency of 10 s and stored on an IBM PC/2 computer.

An additional experiment was performed after the completion of a solidification experiment with pure tin to determine the interfacial heat transfer coefficient ($h_i$). In this experiment the solid block of tin was maintained at a uniform temperature (initial condition) and then cooled by reducing the heat exchanger temperature at an approximately constant rate. During this cooling phase the temperatures of the heat exchanger and temperatures in the test cell were collected at a frequency of 4 s. To determine the interfacial heat transfer coefficient, this experiment was simulated numerically.

![Diagram](image-url)  
**Fig. 3** Location of the thermocouples in the test cell.
Experimental Conditions

The experimental conditions for the experiments reported here are shown in Table 1. In all experiments, a steady, uniform temperature above the melting point (liquidus temperature) was maintained as the initial condition. Five experiments were performed with tin [10]; the results of only one typical experiment are presented here. In this experiment (A) with Sn, the temperature of the heat exchanger was reduced rapidly to a temperature below the melting point and held approximately at the value until the end of the experiment. In the Sn-Pb experiments (B-E), heat was extracted from the test cell by reducing the temperature of the heat exchanger at an approximately constant rate. The cooling rates shown in Table 1 are an average over the duration of solidification.

PURE Sn EXPERIMENTS

Results and Discussion of the Solidification Experiment

Figure 4 shows the temperature data obtained during the course of the solidification experiment with pure tin (Experiment A). It can be observed that the metal undercools by about 2°C before nucleation. After nucleation, the temperature in the cell quickly rises to the melting-point temperature (232°C). The time taken by the solidification front to reach a thermocouple location can be found from Fig. 4. When the front reaches a thermocouple, the reading of the thermocouple starts falling from the melting-point value. It can be deduced from Fig. 4 that the front is not planar. The front takes a longer time to reach T2 when compared to T1 and T3. The next set of thermocouple readings (at x = 25 mm) indicates that the front reaches T4 followed by T5 and T6 in that order. These observations are explained as follows. During the initial stages of solidification, the solidification rate is high and consequently the heat flux through the heat exchanger is also high. This results in an estimated temperature nonuniformity of about 0.15°C in the heat exchanger wall, the temperature at the center of the wall being the highest. This higher temperature at the center decreases the solidification rate, which results in the front reaching T2 at a later time when compared to T1 and T3. As solidification proceeds further, the front grows faster at the bottom than at the top. The faster rate of solidification at the bottom is explained in terms of a vertical variation of $h_i$. A higher value of $h_i$ at the bottom compared to the

<table>
<thead>
<tr>
<th>Experiment designation</th>
<th>Alloy</th>
<th>Heat exchanger cooling rate (°C/s)</th>
<th>Initial superheat (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Sn</td>
<td>—</td>
<td>0.0</td>
</tr>
<tr>
<td>B</td>
<td>Sn-10wt%Pb</td>
<td>0.028</td>
<td>11.1</td>
</tr>
<tr>
<td>C</td>
<td>Sn-10wt%Pb</td>
<td>0.028</td>
<td>1.7</td>
</tr>
<tr>
<td>D</td>
<td>Sn-10wt%Pb</td>
<td>0.065</td>
<td>1.3</td>
</tr>
<tr>
<td>E</td>
<td>Sn-37.8wt%Pb (eutectic)</td>
<td>0.025</td>
<td>6.3</td>
</tr>
</tbody>
</table>
top results in the solidification front being ahead at the bottom. It may be pointed out that heat losses to the bottom would also result in the observed shape of the solidification front. However, the heat losses to the bottom were negligible, as the bottom guard heaters were maintained at slightly higher temperatures than the temperature measured inside the cell. Melt convection would also result in a solid-liquid interface that grows faster at the bottom. However, in the present experiment the melt temperature was uniformly at the melting point (see Fig. 4), and consequently the influence of melt convection can be assumed to be negligible.

**Determination of the Interfacial Heat Transfer Coefficient**

Assuming that the interfacial heat transfer coefficient remains constant during solidification of pure tin [3, 6, 7], it can be determined from a simple cooling experiment after the conclusion of the solidification experiment. In this experiment, heat was extracted from the solidified tin block and the temperatures inside it were recorded. For the determination of $h_{i}$, this experiment was simulated numerically. The one-dimensional transient heat conduction equation was solved using the finite-volume method [14]. A uniform temperature was used as the initial condition, and the right wall of the test cell ($x = 0.05$ m) was taken to be adiabatic. The following convective boundary condition was used at $x = 0$:

$$k \frac{\partial T}{\partial x} = h_{i}(T_{i} - T_{w})$$

(2)

![Graph](image)

*Fig. 4* Measured temperature profiles during solidification in Experiment A.
where $T_i$ is the interface temperature at $x = 0$. The thermal diffusivity in the heat conduction equation was calculated using the following property values: $k = 59.6 \ \text{W/mK}$ [11], $\rho = 7192.46 \ \text{kg/m}^3$ [12], and $c = 258.95 \ \text{J/kgK}$ [13]. The measured wall temperature ($T_w$) variation was used as an input to the numerical simulation. Note that the nature of the boundary condition given by Eq. (2) rules out an analytical solution. As $h_i$ in Eq. (2) was not known beforehand, the calculations were carried out for various values of $h_i$. The resulting temperature profiles (temperature versus time) were then compared with the experimental profiles at the appropriate locations. The value of $h_i$ that resulted in the best temperature profile match with the experiment was assumed to be the desired value of $h_i$. Figure 5 shows the comparison of the measured profiles with the numerically calculated ones for $h_i = 3750 \ \text{W/m}^2\text{K}$. The experimental profiles plotted are the averages of the three thermocouple readings at each $x$ location.

### Numerical Simulation of the Solidification Experiment

The above-determined value of $h_i$ was used in a one-dimensional numerical simulation of Experiment A. A modified version of the FORTRAN program used by Schneider and Beckermann [15] was employed for numerical solution. The initial undercooling was taken into consideration in the numerical model. Again, the measured wall temperature ($T_w$) variation was used as an input.

![Comparison of measured and predicted temperature profiles](image)

**Fig. 5** Comparison of the measured and predicted temperature profiles for the determination of the interfacial heat transfer coefficient in Experiment A.
Figure 6 shows good agreement between the experimental data and the numerical results for Experiment A, indicating that the assumption of a constant $h_i$ is reasonable. The experimental temperature profiles plotted in the figure are those measured by the mid-height thermocouples (T2, T5, and T8). Nonetheless, the difference between the measured and predicted temperatures increases during the course of the experiment, which can be explained by a slight decrease in $h_i$ due to thermal contraction of the solidified metal. The variation of $h_i$ during solidification is examined in more detail in the following section on the Sn-Pb experiments.

**Sn-Pb EXPERIMENTS**

**Determination of the Interfacial Heat Transfer Coefficient**

The interfacial heat transfer coefficient ($h_i$) was calculated using Eq. (1). The temperature of the wall ($T_w$) was measured directly. It can be assumed to be uniform across the wall due to the small wall thickness (1.6 mm) and the high thermal conductivity of the wall material (copper). It was estimated that this assumption results in an error of about 2% in the heat flux calculations. The uniformity of the wall temperature over the face of the heat exchanger was discussed previously. The heat flux ($q$) and the interfacial temperature ($T_i$) in Eq. (1) were determined through separate procedures, which are described in the following.
The heat flux \( q \) was obtained from a simple convective model for the heat exchanger. The model used the measured temperatures of the heat exchanger wall \( T_w \) and the heat transfer fluid \( T_f \) in addition to the heat transfer coefficient between the wall and the fluid (see Fig. 2), according to

\[
q = h_c(T_w - T_f)
\]  

(3)

In Eq. 3, \( T_f \) was taken to be the measured temperature of the heat transfer fluid entering the heat exchanger. This is appropriate due to the small temperature rise (0.07°C) the heat transfer fluid experiences as it passes through the heat exchanger. The heat transfer coefficient \( h_c \) was determined from the experiment with pure tin in which the heat flux \( q \) was available from the numerical simulation. The validity of the model is demonstrated in Fig. 7, where the heat transfer rates calculated using the convective model (with \( h_c = 4100 \) W/m² K) are shown to be in very good agreement with the results of the numerical simulation of Experiment A. To further confirm the validity of the model, the heat removed from the cell to completely solidify the Sn-10wt%Pb alloy was calculated using the model. This heat was compared to a heat-removal calculation based on the enthalpy difference between the liquid and the solid phases of the metal. The calculations using \( h_c \) resulted in 112.2 kJ, which compares very well with the enthalpy calculations of 107.5 kJ.

**Fig. 7** Comparison of the heat removal rates from the test cell as calculated by the convective model and the numerical simulation in Experiment A.
The interfacial temperature ($T_i$) was not measured because of the difficulty in locating thermocouples at the interface. However, it was calculated using the thermocouple readings closest to the interface (i.e., at $x = 5$ mm). For this purpose, the following heat equation was solved in the domain $x = 0$ to $x = 5$ mm:

$$
\frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) = \rho \frac{\partial h}{\partial t}
$$

(4)

where $h$ is the average solid plus liquid enthalpy. The boundary conditions are

At $x = 0$, \quad $k \frac{\partial T}{\partial x} = h_v (T_w - T_i)$

(5)

At $x = 5$ mm, \quad $T = T_{x=5 \text{ mm}}$

(6)

The following approximations were made in the solution of the above equation: (1) the time rates of change of enthalpy and temperature were assumed to be independent of location in the domain, and (2) the thermal conductivity and density were assumed to be constant and uniform over the domain. These assumptions make it possible to analytically integrate the above equation in space. The integration results in a time-varying parabolic temperature distribution in the domain from which $T_i$ can be determined. In the solution of Eq. (4), the enthalpy and density data due to Poilier and Nandapurkar [12, 13] were used. The composition and solid fraction of any temperature were obtained from the Scheil equation using the phase-diagram data due to Poilier [12]. The thermal conductivity in Eq. (4) was taken to be a composition- and solid fraction-weighted mean of the thermal conductivities of pure tin and lead [10, 11].

The above calculations for the determination of the interfacial heat transfer coefficient ($h_i$) were performed at each time that temperature data were collected (every 10 s). An error analysis was performed to estimate the uncertainty in the value of $h_i$ [10]. The uncertainties assumed in the various parameters are (1) 5% error in $q$, (2) 10% error in $k$ for the mushy zone, (3) 10% error in the location of the thermocouples, and (4) 0.1°C in the temperature difference between the wall and the thermocouple at $x = 5$ mm. The error in $h_i$ due to each of these uncertainties was calculated. The total error was obtained by taking the square root of the sum of the squares of these errors. During solidification, the error in $h_i$ was less than 20%. When a solid shell at the heat exchanger wall was established, the error was about 9%. The error in $h_i$ during solidification results mainly from uncertainties in the thermal conductivity in Eq. (4). Since the same procedure for evaluating the thermal conductivity was utilized in all experiments, a comparison between the results of the various experiments can be expected to be more accurate.

**Results and Discussion of the Sn-10wt% Pb Experiments**

Figures 8–10 show the temperature data collected during the course of Experiments B, C, and D, respectively. The temperatures recorded by the thermo-
Fig. 8  Measured temperature profiles in Experiment B.

Fig. 9  Measured temperature profiles in Experiment C.
couples at $x = 25$ mm and $x = 45$ mm exhibit two interesting characteristics. During the initial phase of solidification, these temperatures stay close to the liquidus temperature (liquidus arrest). During the final phase of solidification, these thermocouples register temperatures close to the eutectic temperature for some time before falling further (eutectic arrest). The eutectic arrest occurs because solidification proceeds to completion isothermally after the interdendritic liquid reaches the eutectic composition.

A few qualitative observations regarding the heat flux through the heat exchanger can also be made from the temperature profiles. The heat flux through the heat exchanger is proportional to the temperature difference ($T_w - T_f$) [see Eq. (3)]. From Figs. 8–10 it can be seen that the heat flux through the heat exchanger increases immediately after nucleation. This increase is due to the latent heat released by the solidifying metal. The heat flux increases as solidification proceeds and reaches a maximum value when the temperature gradient in the cell (temperature difference between the thermocouples at $x = 45$ mm and $x = 5$ mm) is about maximum. After the end of solidification the heat flux drops, as expected.

A certain fraction of the temperature difference between the wall and the thermocouples at $x = 5$ mm is due to the interfacial resistance. A few qualitative conclusions can be drawn regarding $h_i$ by comparing the temperature differences ($T_w - T_f$) and ($T_{x=5\, \text{mm}} - T_w$). From Figs. 8 and 9 it can be seen that the heat flux through the heat exchanger starts falling when the temperature at $x = 5$ mm is between 195°C and 185°C (eutectic temperature). During the same time, the average temperature difference, ($T_{x=5\, \text{mm}} - T_w$), increases. Thus it can be concluded that the interfacial heat transfer coefficient decreases during that time. In Fig. 10 (Experiment D), the heat transfer coefficient decreases only after the temperature at $x = 5$ mm is close to 185°C. During the time the heat transfer coefficient decreases, the thermocouple T3 (the top thermocouple at $x = 5$ mm) shows higher readings than the other two thermocouples at the same $x$ location. This observation suggests that the heat transfer coefficient is lower at the top of the heat exchanger compared to the bottom, which can be explained as follows. As solidification proceeds, the interdendritic liquid becomes richer in Pb. The Pb-rich and relatively cold liquid is denser and flows downward, resulting in a higher Pb concentration in the bottom portion of the test cell. The liquidus temperature of the Pb-rich liquid is lower and hence it solidifies last. A solidification reaches completion at the top first and bottom later, the interfacial gap forms at the top at an earlier time than at the bottom. The earlier formation of the interfacial gap at the top explains the higher temperatures recorded by the thermocouple T3. From Figs. 8–10 it can also be noticed that thermocouple T3 shows a higher reading than T1 and T2 even after the temperatures at $x = 5$ mm fall below the eutectic temperature. This suggests that the interfacial heat transfer coefficient remains higher at the bottom than at the top.

The calculated evolutions of the interfacial heat transfer coefficient ($h_i$) and the corresponding solid fraction ($\varepsilon$) at the interface for the three Sn-10wt\%Pb experiments are shown in Figs. 11–13. These quantities were not calculated during the very initial phase of solidification due to inaccuracies introduced by the large transients present during nucleation. Generally, the interfacial heat transfer coefficient decreases with increasing solid fraction, which can be explained by
volume contraction of the melt upon solidification. For low solid fractions, $h_i$ remains approximately constant and at a relatively high value (between 8,000 and 10,000 W/m² K for all three experiments). The solid that forms initially does not contribute to the formation of the interfacial gap, because the interdendritic liquid can feed the solidification contraction. The continued presence of the liquid at the interface thus causes $h_i$ to be high. However, as the solid fraction increases beyond a certain critical value and the melt flow through the mushy zone becomes more restricted, an interfacial gap begins to form and $h_i$ starts to drop significantly. This

Fig. 10 Measured temperature profiles in Experiment D.

$$\text{Time (s)}$$

$$\text{Temperature (°C)}$$

nucleation

T1

T2

T3

T4

T5

T6

T7

T8

T9

Tw

Ty

Fig. 11 Evolution of the interfacial heat transfer coefficient and the solid fraction at the metal–mold interface for Experiment B.
critical value of the solid fraction at the interface is equal to about 0.65 for Experiments B and C, and 0.75 for Experiment D, which was carried out at a faster cooling rate.

In Experiments B and C, the interfacial heat transfer coefficient again reaches a constant level at the beginning of the eutectic reaction, which corresponds to a solid fraction of about 0.75. In Experiment D, on the other hand, $h_i$ does not level off until solidification at the interface is complete. Hence the entire drop of $h_i$ in Experiment D takes place during the eutectic reaction. Accordingly, the transition in $h_i$ from a higher value to a lower level is more abrupt than in Experiments B and C, which can be explained by the faster cooling rate in Experiment D. In all three experiments, the lower level of the interfacial heat transfer coefficient corresponds to a value of about 4500 W/m² K, which remains approximately constant even after solidification at the interface is complete. No significant differences in the variation of $h_i$ in Experiments B and C are observed. The larger initial superheat in Experiment B simply shifts the curves in Fig. 11 to the right (relative to the ones in Experiment C in Fig. 12), due to the longer time period needed to dissipate the superheat before nucleation (see also Figs. 8 and 9).

Fig. 12 Evolution of the interfacial heat transfer coefficient and the solid fraction at the metal–mold interface for Experiment C.

Fig. 13 Evolution of the interfacial heat transfer coefficient and the solid fraction at the metal–mold interface for Experiment D.
Results and Discussion of the Eutectic Alloy Experiment

The temperature data obtained during the experiment with the eutectic alloy (Experiment E) and the calculated variation of $h_i$ are presented in Figs. 14 and 15, respectively. A eutectic alloy solidifies, like a pure substance, isothermally and without a mushy zone. By noting, from Fig. 14, that the thermocouples at each $x$ location record the eutectic temperature (183°C) at about the same time, it can be deduced that the solidification front is relatively vertical. Nonetheless, some thermal convection can be expected to be present in the melt, because the thermocouples indicate the existence of melt superheat during most of the experiment. Figure 15 shows that the interfacial heat transfer coefficient gradually decreases during solidification. Again, the variation in $h_i$ during the very initial stages of solidification could not be calculated. However, in eutectic solidification the solid fraction at the metal–mold interface reaches unity soon after nucleation (no mushy zone). This results in the formation of a certain initial gap due to contraction of the melt upon solidification. The corresponding initial interfacial heat transfer coefficient can be expected to be of a similar magnitude as in the other experiments after the formation of a solid shell at the interface (see also the next section). The subsequent gradual decrease in $h_i$ is due to thermal contraction of the solidified metal, assuming that the heat exchanger wall remains stationary. It was estimated that thermal contraction of the solid increases the size of the interfacial gap by about 17% until solidification in the cell is complete. During the same time, Fig. 15 indicates a decrease in $h_i$ of roughly 13%. Noting the inverse relationship between the gap size and the interfacial heat transfer coefficient, it
can be concluded that the observed decrease in $h_i$ can, in fact, be attributed to thermal contraction of the solidified eutectic material.

**COMPARISON OF THE EXPERIMENTS**

This purpose of this section is to show that the observed differences in the interfacial heat transfer coefficients between the pure Sn, Sn-10wt%Pb, and eutectic alloy experiments can be explained by the amounts of contraction of the three melts upon solidification. The measured values of $h_i$ at the point in time when the solid fraction at the interface has reached unity are given in Table 2. The value for the Sn-10wt%Pb alloy is an average of Experiments B, C, and D. The corresponding solidification shrinkages were determined from the density data due to Poirier [12]. The volume change for the Sn-10wt%Pb alloy in Table 2 represents only that portion of the total solidification shrinkage that contributes to the formation of the interfacial gap and, hence, the decrease in $h_i$ in Figs. 11-13 (see also Results and Discussion of the Sn-10wt%Pb Experiments). It can be seen from Table 2 that the interfacial heat transfer coefficient is, in fact, inversely proportional to the amount of solidification contraction. Estimates of the corresponding sizes of the interfacial gap are also included in Table 2. They were calculated by assuming that the dominant thermal resistance at the interface is due to conduction through the air present in the gap [1].

**CONCLUSIONS**

Experiments were conducted to study the evolution of the interfacial heat transfer coefficient at a vertical heat exchanger surface during solidification of Sn and Sn-Pb alloys. The following conclusions can be drawn.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Comparison of Interfacial Heat Transfer Coefficients and Solidification Shrinkages for the Three Metals Considered in this Study</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Alloy</strong></td>
<td>$h_i$ (measured) ($W/m^2K$)</td>
</tr>
<tr>
<td>Sn</td>
<td>3750</td>
</tr>
<tr>
<td>Sn-10wt%Pb</td>
<td>4500</td>
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<tr>
<td>Eutectic</td>
<td>3000</td>
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</table>
1. In the case of solidification of pure Sn, an interfacial gap forms soon after nucleation, due to contraction of the melt upon solidification. The corresponding interfacial heat transfer coefficient can be determined from cooling experiments after solidification is complete. The use of this constant $h_i$ in a numerical simulation of the solidification experiment resulted in good agreement with measured temperatures.

2. During solidification of Sn-10wt%Pb alloys, a mushy zone exists at the heat exchanger surface for a large portion of the duration of the experiments. From the measured variation of $h_i$, it was determined that for solid fractions at the interface below 0.65, melt flow through the mushy zone is able to feed the solidification contraction, resulting in a relatively high value of $h_i$. Above this solid fraction, an interfacial gap forms and $h_i$ decreases significantly. The interfacial heat transfer coefficient reaches a constant level again during the eutectic reaction at the interface and remains approximately constant until the end of solidification. The initial melt superheat was found to have little effect on the variation of $h_i$ with solid fraction at the interface, whereas a higher cooling rate resulted in a higher value of the solid fraction at which the interfacial gap begins to form (about 0.75) and, subsequently, a more rapid decrease in $h_i$.

3. In the eutectic Sn-Pb alloy experiment, no mushy zone exists, and the solidification shrinkage of the melt causes the formation of an interfacial gap during the very initial stages of solidification. It was shown that the subsequent growth of the interfacial gap, and hence the decrease in $h_i$, can be attributed to thermal contraction of the solidified metal.

4. The differences in the interfacial heat transfer coefficients observed in the various experiments correlate well with calculations of the volumetric change upon solidification of the three melts considered in the study.

Although improved insight into the temporal variation of $h_i$ during the solidification of metal alloys has been obtained, care should be exercised in applying the results to physical configurations other than the one considered here. For example, the spatial variation of $h_i$ across a large heat extraction surface, possible expansion/contraction of the mold material, and the effects of mold coatings and oxide layers have not been investigated here.

REFERENCES