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Evaluation of metal–mould interfacial heat transfer during the solidification of aluminium –4.5% copper alloy castings cast in CO_2–sand moulds

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In this study, two methods were employed to measure the heat transfer coefficient h at the metal –mould interface during casting. The first method measured the size of the gap formed between the metal and mould during the casting process and estimated the value of h based on the gap size. The second method measured the temperature at certain locations of the metal and mould, and derived h at the gap by using a reverse method. A procedure is also developed to use temperature measurement data in order to obtain h as a function of casting temperature near the interference. This data is very useful for the mathematical modelling of solidification for casting. In the present study, the casting material is an Al–4.5% Cu alloy and the mould material is CO_2 sand. The results of measurements show that h is not constant, but varies with time and temperature during casting. With the measurement of gap size, h is very large in the beginning and keeps dropping afterwards. As the gap is fully developed, h approaches a constant value between 130 and 40 W/(m^2·°C). By the inverse method, along with temperature measurement, the value of h increases in the beginning stage, reaches a peak value of approximately 710 W/(m^2·°C), and then drops rapidly approximately to the solidification temperature, and rises again until the end of solidification. After that, h keeps dropping until the end of casting.

Key words: *CO_2–sand mould; interfacial heat transfer; heat transfer coefficient; gap size.*

1. Introduction

In recent years, the development of digital computer technology and applied numerical methods has provided a powerful means for simulating casting solidification. One of the main interests of the casting process is to produce parts near net shape and with complex geometry, for instance with internal cavities. Shape casting consists of two stages, the first of which is mould filling – the mould cavity is filled with liquid

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metal; the second is cooling, which continues until the part has solidified. Controlling both stages is of major importance for obtaining sound parts with the required geometry and mechanical properties. As computer-aided design and manufacture experience increasing use in industry, computer modelling of the cooling stage in casting processes appears to be of great interest since it enables the microstructure, final shape, residual stresses, and defects to be predicted.

Since molten casting metal is poured into the mould cavity, it is initially in the liquid state with a high fluidity. It quickly becomes very viscous, in the early stage of solidification, and later completely solidifies. During this process, a gap is formed between the casting metal and the mould. This gap forms due to the following reasons. First of all, the thermal expansion coefficients of the casting metal and mould are different. Second, some of the air initially in the mould cavity cannot escape through the mould and is trapped between the metal and the mould. Third, the binder in the mould materials and the coatings on the inner surface of the mould may evaporate or burn due to high temperature, which contributes as an additional source of gases between the metal and mould. These combined factors affect the size of the gap formed.

As the gap is formed, it presents a resistance to heat transfer from the casting metal to the mould. This is due to the fact that heat can be transferred through the gases in the gap. The heat flux is much smaller compared to the conductive heat transfer in a metal, or even in the mould. It is generally believed that the resistance to heat transfer at the gap increases with the size of the gap. The resistance to heat transfer at the interface will naturally be reflected in the solidification of the casting metal. It is thus very desirable to know the magnitude of this resistance to heat transfer, which is represented by an interfacial heat transfer coefficient. Especially for the mathematical modelling of solidification phenomena in casting, which is gaining much popularity in recent years, it is very critical to have accurate data concerning the amount of heat transfer at the interface in order to build an accurate and reliable solidification model.

The effect of accurately assessing interfacial heat transfer on the accuracy of the thermal analysis of casting has been demonstrated by several previous studies. Zeng and Pehlke have not been able to obtain accurate cooling curves for copper alloy [1] and grey cast iron [2] castings until they made accurate measurements on the gap formed in a sand casting of cylindrical shape. Issac et al. tried to predict the solidification time for casting with a metallic mould. They made an assumption concerning the interfacial gap. The prediction was 24% off from the measured data. They then designed an apparatus to measure the interfacial gap in a metallic mould and used that data for prediction. The accuracy was within 5% of the measured solidification time [3, 4].

Hou and Pehlke tried to calculate the solidification pattern for a casting of a particular shape. They initially used an assumed value to account for the interfacial heat transfer and failed to obtain an accurate prediction either for sand casting [5] or for casting with a metallic mould [6]. Then they proceeded to measure the interfacial gap in cylindrical casting [7]. When they applied the measured data to the predictions, they managed to obtain predictions within 1% of the measurements. All these studies demonstrate how important an accurate assessment of interfacial heat transfer is on the accuracy and reliability of solidification analysis.

Reviewing literature, it can be found that there are basically two methods to measure the interfacial heat transfer coefficient. One is to measure the size of the gap formed between the casting metal and the mould and convert this gap size to an appropriate heat transfer coefficient. The other is to conduct temperature measurements in the casting and mould and convert the mould at several designated locations, and use the inverse method to derive the interfacial heat transfer coefficient.

Using the first method, as early as in 1920, researchers noticed that both the casting metal and mould moved during casting. It was not until 1973, however, that Engler proposed a reliable method to simultaneously measure the amount of movement of the casting metal and mould. In the eighties, Winter and Pehlke systematically measured the variation of the air gap and volume shrinkage for various alloys in a cylindrically shaped casting by using Engler's method. The casting alloys they measured included copper alloys, various cast irons, and aluminium alloys. In the same period, Issac et al. made use of self-designed equipment to measure the size of the gap in a casting with metallic mould. Results showed that the formation of the gap was related not only to the mould material, but also to the shape of the casting and the location of the measurement.

The second method is to derive the interfacial heat transfer coefficient h by using the inverse method. Ho and Pehlke [9–11] studied the mechanisms of heat transfer phenomena at the interface and adapted the inversed method to calculate s. The same method was employed by Hao [12] to study the solidification of cast iron.

Nishida et al. [13] measured the sizes of gaps formed in cylindrical and flat castings. They also used two calculation methods to calculate the variation of h: finite difference method (FDM) simulation and heat flow approximation calculations. Their results showed that the movements of the mould wall and casting alloy depended largely on the shape and location of the casting. They also evaluated the relationship between the size of the gap and h.

More recently, Lukens, Hou, and Pehlke [14] measured the size of the air gap for a cylindrical casting placed horizontally, and showed that the size of the gap was affected by gravity, hydrostatic pressure exerted by the rise, and by the mould material. They found that the casting sections near the bottom formed larger gaps. The movement of the mould wall was smaller if the mould was rigid, and, therefore, a smaller gap was formed.

Chiesa [15] measured the temperature variation of molten metal during the solidification of casting. Comparing with a theoretical model, he obtained h under various coating conditions. His results also demonstrated that interfacial heat transfer resistance existed even in the filling period when the metal was still in the liquid state. Kumar [16] found that the heat flux was actually an exponential function of time. Kulkarni and Radhakrishna [17] studied the thermal behaviour of hollow cylindrical castings for aluminium base alloys using the FEM technique.

The purpose of this study is to employ the two methods, namely gap size measurement and temperature measurement with the inverse method, to estimate the heat transfer coefficient *h* at the metal–mould interface for a hollow cylindrical casting of Al–4.5% Cu alloy cast in a CO_2–sand mould. The results obtained from the two methods were then compared and evaluated. To make the data useful for the mathematical modelling of solidification phenomena in casting, a procedure is also developed to obtain the relation between h and the casting temperature near the interface.

2. Experimental

2.1. Measurements of gap size

It is generally believed that heat transfer resistance at the interface originates from imperfect contact or even separation of the casting and mould. This means a gap is formed between the casting and the mould during casting. The main reason for the formation of a gap is the difference between the thermal expansion coefficients of the casting and mould. When the gap is formed, it is filled by a mixture of air and mould gases. Heat transfer in this stage proceeds mainly by the conduction of the air–gas mixture, since convection and radiation effects can be neglected. Therefore, if the size of the gap formed and the thermal conductivity of the air–gas mixture can be established, the interfacial heat transfer coefficient can then be estimated simply from $h = k/x$, where k is the thermal conductivity of the air–gas mixture and x is the size of the gap.

The main step in this method is measuring the size of the gap formed. In this study, two very sensitive displacement gauges are used to measure the movements of the casting and mould. When the casting is filled, the mould is heated and starts to expand. As heat is extracted from the casting to the mould, the casting solidifies and shrinks, while the mould keeps being heated and expands. The difference of the two movements is defined as the size of the gap formed. Since the displacement gauges can reflect the two movements, the size of the gap can be measured.

2.2. Inverse method

For the analysis of a heat transfer problem, an appropriate set of equations is first determined to describe the heat transfer behaviour. With the boundary conditions, initial conditions, and thermo-physical properties of the materials being known, it is possible to obtain the temperature and variation of the whole system. However, if one of the thermo-physical properties of the materials is not known, but temperature information can be obtained, then it is possible to calculate this unknown property by a reverse scheme, which is the basic idea of the inverse method.

To make use of the inverse method for determining h, temperature measurements need to be made. In order to make the analysis of the inversed method easier, a one-dimensional heat transfer system is devised. It serves as the boundary conditions and as the calibration point. Naturally, more temperature measurements make the analysis more accurate. A brief description of the inverse method for analysing the temperature data of h follows.

The metal–mould heat transfer coefficient is determined basically by solving Fourier's heat conduction equation. The one-dimensional heat conduction equation is:

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

where k, ρ, and c are the thermal conductivity, density, and specific heat, respectively. The initial and boundary conditions are as follows:

- Initial condition

$$T(x,0)=T_i(x) \text{ at } t=0$$

- Boundary conditions

$$T(0,t)=T_{B1}(t) \text{ at } x=0$$

$$T(1,t)=\mathrm{T}_{B2}(t) \text{ at } x=L$$

Where $T_i(x)$, $T_{B1}(t)$, and $\mathrm{T}_{B2}(t)$ are obtained by actual measurements. The configuration of the one-dimensional system is shown in Fig. 1.

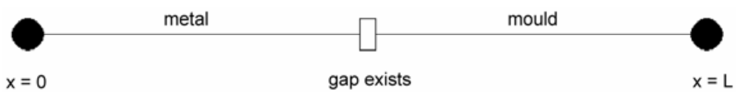

Fig. 1. Configuration of the one-dimensional system

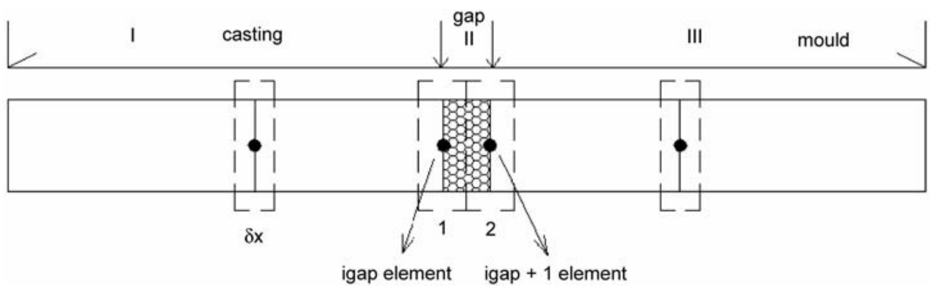

Fig. 2. Regions I, II, and III considered in the model

Notice that the equations are applied to solve the temperature distribution of regions I and III, where gaps do not exist. Region II, where the air gap exits, is treated as two elements. One includes the gap and casting, the other includes the gap and mould, as shown in Fig. 2.

In this study, the principle of enthalpy conservation is used to calculate the temperature history of the system. By the finite difference method, the system can be treated as two parts, regions I and III, and region II.

For regions I and III

$$\rho c \delta x \frac{T_i - TN_i}{\delta t} = k \frac{TN_{i-1} - TN_i}{\delta x} - k \frac{TN_i - TN_{i+1}}{\delta x} \tag{1}$$

from which it follows that

$$T_i = TN_i + \frac{k\delta t}{\rho c \delta x^2}(TN_{i-1} - 2TN_i + TN_{i+1}) \tag{2}$$

For an element in region II (denoted by the index i_{gap}),

$$\rho c \frac{\delta x}{2} \frac{T_{i\mathrm{gap}} - TN_{i\mathrm{gap}+1}}{\delta t} = k \frac{TN_{i\mathrm{gap}-1} - TN_{i\mathrm{gap}}}{\delta x} - h(TN_{i\mathrm{gap}} - TNS) \tag{3}$$

which gives

$$T_{i\mathrm{gap}} = TN_{i\mathrm{gap}+1} + \frac{2k\delta t}{\rho c \delta x^2}(TN_{i\mathrm{gap}-1} - TN_{i\mathrm{gap}}) + \frac{2h\delta t}{\rho c \delta x}(TN_{i\mathrm{gap}+1} - TN_{i\mathrm{gap}}) \tag{4}$$

For the element with the index $i_{\mathrm{gap}+1}$ of region II,

$$\rho c \frac{\delta x}{2} \frac{T_{i\mathrm{gap}+1} - TN_{i\mathrm{gap}+1}}{\delta t} = h(TN_{i\mathrm{gap}} - TN_{i\mathrm{gap}+1}) - k \frac{TN_{i\mathrm{gap}+1} - TN_{i\mathrm{gap}+2}}{\delta x} \tag{5}$$

and

$$T_{i\mathrm{gap}+1} = TN_{i\mathrm{gap}+1} + \frac{2k\delta t}{\rho c \delta x_2}(TN_{i\mathrm{gap}+2} - TN_{i\mathrm{gap}+1}) + \frac{2h\delta t}{\rho c \delta x}(TN_{i\mathrm{gap}} - TN_{i\mathrm{gap}+1}) \tag{6}$$

where: T_i – temperature at the i-th node, TN_i – temperature of the previous time step at the i-th node, δt – time increment, δx – dimension of an element, i_{gap}, $i_{\mathrm{gap}+1}$ – nodes at which the air gap exits, h – heat transfer coefficient of the air gap.

To calculate the temperature history of the casting and mould, some thermal physical properties were needed. The data necessary to calculate the heat transfer coefficient n is given in Table 1.

To calculate the heat transfer coefficient h the temperature distribution was estimated by first minimizing the function

$$F(h) = \sum_{m=1}^{M} \sum_{i=1}^{I} (T_{\eta+1}, m - Y_{\eta+i}, m)^2 \tag{7}$$

Table 1. Thermal physical properties of the casting and mould

Properties	Al–4.5% Cu alloy [18]	CO_2–sand mould [17]
Thermal conductivity *k*, W/(m·s·K)	192	152
Density, kg/m^3	2380	1580
Heat capacity, W/(g·K)	1086	1045
Latent heat, kJ/kg	395.041	

The value of h was obtained when the sum of the squares of the experimental temperature deviations from the estimated temperatures was minimized. The terms $T_{\eta+1,m}$ and $Y_{\eta+1,m}$ are the measured and calculated temperatures. The meanings of the subscripts η, m, and i are the starting time, time, and location, respectively. The value of m was set to 1 in this study, which means there was only one verifying point. The heat transfer coefficient was calculated as a function of integer times recorded time interval, and the superscript I was used to determine the time range for the value of h at a given time.

The minimal value of $F(h)$ could be calculated by setting the partial derivative to zero:

$$\frac{\partial F(h)}{\partial h} = 0 \tag{8}$$

when calculating $h_{j+\mathrm{I}}$ it was assumed that $h_{j+2} = h_{j+3} = \ldots = h_{j+\mathrm{r}} = h_{j+1}$ (r was the index value after which h was the "undetermined h" of the future domain). Equation 8 was approximated by an explicit FDM as follows

$$\sum_{i=1}^{I} (T_{\eta+1}, m - Y_{\eta+i}, m) \frac{\partial T_{\eta+i}}{\partial h_{j+1}} = 0 \tag{9}$$

Using the Taylor series expansion

$$T_{\eta+1}^{1} = T_{\eta+1}^{\mathrm{I}-1} + \left(\frac{\partial T_{\eta+1}}{\partial T_{j+1}} \right)^{\mathrm{I}-1} \left(h_{j+1}^{1} - h_{j+1}^{\mathrm{I}-1} \right) \tag{10}$$

$$\delta h_{j+1}^{1} = h_{j+1}^{1} - h_{j+1}^{\mathrm{I}-1} \tag{11}$$

The superscript 1 denotes the first iteration step, the initial value of h when $I = 0$ and, generally speaking, h_1^0 was set to 1 and h_{j+1}^0 was set to converse value of h_j.

The sensitivity coefficient ϕ was defined as:

$$\phi_{n+1}^{n-1} = \left(\frac{\partial T_{\eta+1}}{\partial T_{j+1}} \right)^{I-1} = \frac{T_{\eta+1}\,[(1+\in).h_{j+1}^{I-1}] - T_{\eta+i}\,(h_{j+1}^{I-1})}{\in .h_{j+1}^{I-1}}$$

where $\in$ is a very small value, always set as 0.001. In the I-th iteration:

$$T_{\eta+1}^{1} = T_{\eta+1}^{I-1} + \phi_{\eta+i}^{I-1} \delta h_{j+1}^{1} \tag{12}$$

Replacing $T_{\eta+1}^{1}$ in Eq. (9) by Eq. (11) we have

$$\sum_{i=1}^{I} \left(T_{\eta+1}^{I-1} + \phi_{\eta+i}^{I-1} \delta h_{j+1}^{1} - i \right) \phi_{\eta+i}^{I-1} = 0 \tag{13}$$

and the procedure was not repeated for a new coefficient value until

$$\frac{\delta h_{j+1}^{1}}{h_{j+1}^{1}} \le 0.001$$

The calculation of the heat transfer coefficient as a function of time was continued until the end of the desired period.

2.3. Experimental procedures

CO_2–sand moulds were used in the present work. Sodium silicate (Na_2CO_3) of 4% by weight was mixed with silica sand and used for making the moulds. The moulds were hardened using CO_2 gas. The dimensions of the moulds were selected to establish a good interference. Figure 3 shows a schematic sketch of the CO_2 sand mould used in the present investigation. The particle size of the silica sand was 50 mesh. Moulds were prepared with a regular hand moulding technique for the different configurations (Table 2). CO_2 gas was then passed through the mould at a pressure of 2 kg/cm^2. In this study, the gap size and temperature measurements are conducted in the same casting. The casting was hollow and cylindrical in shape. To make sure that the heat transfer in the casting is one-dimensional, heat-insulating material was placed on the two sides and bottom of the casting mould. Two thermocouples were then inserted in the mould cavity, one at the centre and the other near the mould surface. Another three thermocouples were inserted in the mould, one near the inner surface, one near the centre, and the other near the outer surface.

In the other half of the casting, two ceramic tubes for displacement measurement were inserted. One was in the cavity near the inner mould surface and the other was in the mould near the inner mould surface. The two ceramic tubes and four thermocouples were carefully placed at the same level. The dimensions of the casting, the placement of the ceramic tubes for displacement measurement, and thermocouples are illustrated in Figs. 4–6. Special care must be taken to make sure that the ceramic tubes move along with the casting and mould, so that the readings from the optical displacement gauge scan actually reflect the expansion–shrinkage of the casting and mould. The apparatus set up for gap size measurement is shown in Fig. 7.

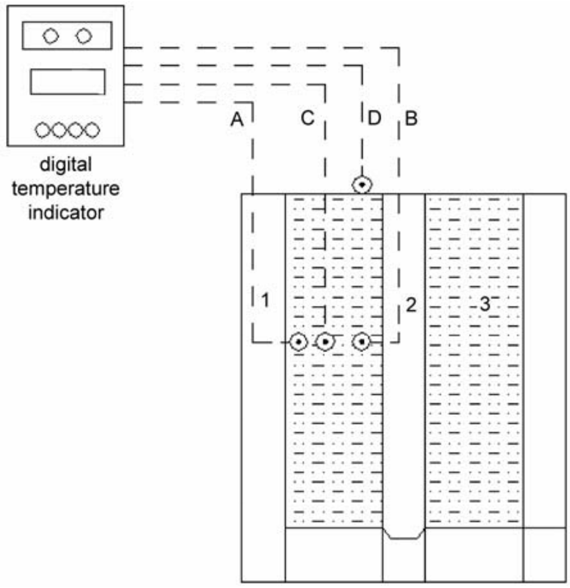

Fig. 3. Experimental setup and thermocouple locations: A – thermocouple placed at the molten metal–mould interface, B – thermocouple placed at the molten metal–core interface, C – thermocouple placed at the centre of the molten metal, D – thermocouple placed at the surface of the molten metal; 1 – CO_2–sand mould, 2 – CO_2–sand core, 3 – molten metal

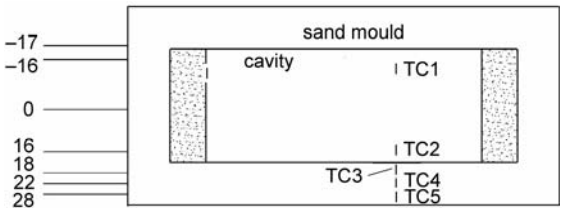

Fig. 4. Locations of the thermocouples
and ceramic tubes for displacement measurements

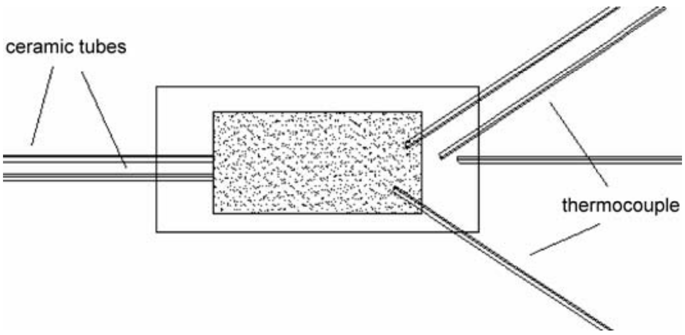

Fig. 5. Top view showing how the thermocouples
and ceramic tubes were placed for displacement measurements

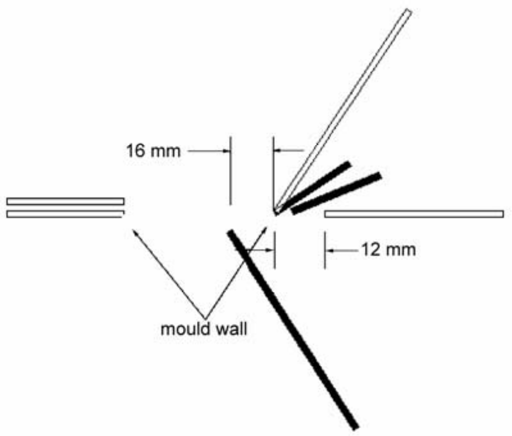

Fig. 6. Isoparametric view showing how the thermocouples and ceramic tubes were placed for displacement measurements

Table 2. Dimensions of hollow, cylindrical castings[1]

Sl.No	OD D, mm	ID d, mm	Thickness t, mm	Height of casting h, mm
1	75	25	25	250
2	125	25 50>	50 37.5	250
3	175	25 50 75	75 62.5 50	250

[1]OD – outside diameter of casting, ID – core or inner diameter of casting, t – thickness of casting.

Alloy Al–4.5% Cu (commercial) was used. Details of its chemical composition are given in Table 3.

Table 3. Details of the chemical composition of the alloy

Composition (%)										
Si	Fe	Cu	Mn	Mg	Zn	Ni	Pb	Sn	Ti	Al
0.343	0.602	4.36	0.683	0.480	0.038	0.006	0.007	0.005	0.013	Remainder

As molten Al–4.5% Cu alloy was poured into the mould cavity with a constant flow rate of approximately 5m/s, heat-insulating material was quickly placed on top. The pouring temperature was about 750 °C. The thermal histories of the five thermocouples were then recorded for the whole period of filling, solidification, and subsequent cooling with a high-speed data acquisition system. The displacements of

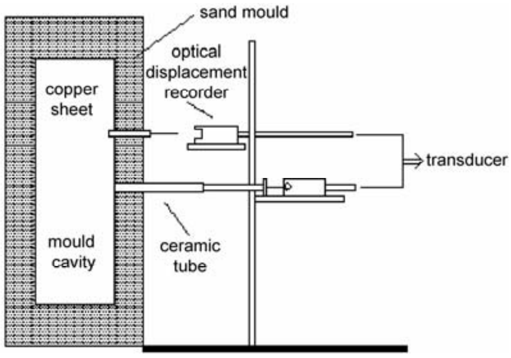

Fig. 7. Apparatus setup for gap size measurements

the casting and mould were also detected by the displacement gauges and recorded through a transducer during the same period.

3. Results and discussion

3.1. Heat transfer coefficients obtained from gap size measurement

The amount of movement of the casting and mould measured during the whole casting period is shown in Fig. 8. The difference between the two movements is believed to be the gap formed at the interface. As can be seen from the figure, when molten metal is first poured into the cavity, both metal and mould expand outward. This is due to the outward movement of the mould when it is heated up by the metal.

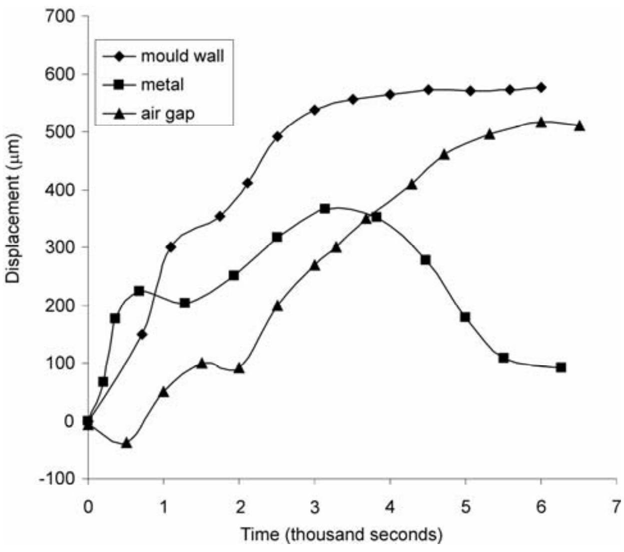

Fig. 8. The displacements of the casting and mould, as well as the corresponding gap size during the whole casting period for a CO_2–sand mould 25 mm thick (75 mm OD, 25 mm ID)

At this time, molten metal is still flexible and moves outward along with the mould. At approximately 340 s, the movement of metal starts to slow down while the mould still moves at the same pace. This is the instant when gap starts to form. At approximately 1240 s, the outward movement of the metal stops and starts to move inward while the mould keeps moving outward. This is believed to be caused by the shrinking of the solidifying metal. At this point, the size of the gap abruptly increases. The rate of increase of the gap slows down when the mould stops expanding, at approximately 1675 s. The metal, however, keeps shrinking until the end of the recording.

To convert the gap size to the interfacial heat transfer coefficient, data for the thermal conductivity of the air–mould gas mixture is needed. Ho made the assumption [10] that the thermal conductivity of the air–mould gas mixture in the gap is equal to that of stagnant air in the atmosphere. Under this assumption, the thermal conductivity of the gap can be expressed as follows:

$$k = 10533\times10^{-5} + 10563\times10^{-7}T \quad [\mathrm{W/(m\cdot s\cdot K)}]$$

where T is the gas temperature in the gap in kelvins, Nishida, however, used another expression to estimate the thermal conductivity of the gas mixture in the gap [13]:

$$k = 1.38733\times10^{-4}T \qquad [\mathrm{W/(m\cdot s\cdot K)}]$$

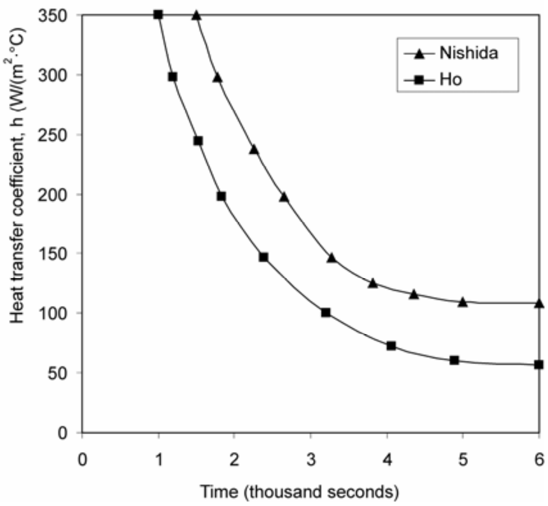

Fig. 9. The interfacial heat transfer coefficient obtained from thermal conductivity data by Ho and Nishida

In this study, both Ho's and Nishida's data were used to estimate the interfacial heat transfer coefficient, and the result is shown in Fig. 9. It can be seen from the figure that the value of h obtained from Nishida's thermal conductivity is always higher than that of Ho's data.

3.2. Heat transfer coefficient obtained from temperature measurement and the inverse method

The temperatures five thermocouples during the whole period are shown in Figs. 10, 11. From these figures it can be seen that the temperature histories of two thermocouples in the casting (#1 metal and #2 metal surface) are almost identical. Therefore, when analysing the temperature data with the inverse method, the temperature readings of T.C. #1 and #3 (metal–mould interface) were used as the boundary conditions. The temperature readings of T.C. #1 to #3 were used to set up the initial conditions, while that of T.C. #3 was used as the verifying condition.

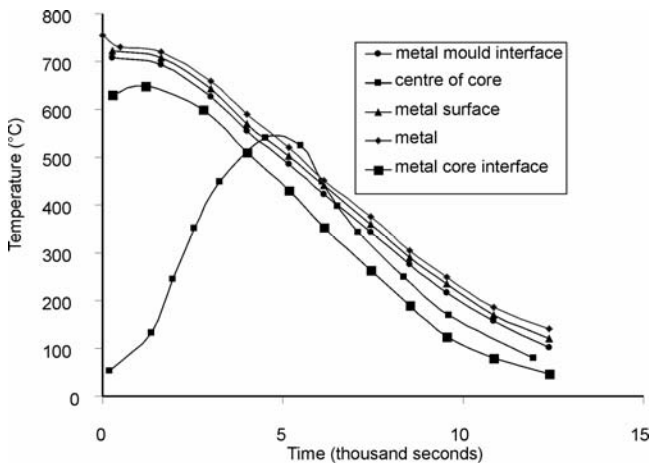

Fig. 10. The thermal histories of the five thermocouples in the 25 mm thick CO_2–sand mould (75 mm OD, 25 mm ID)

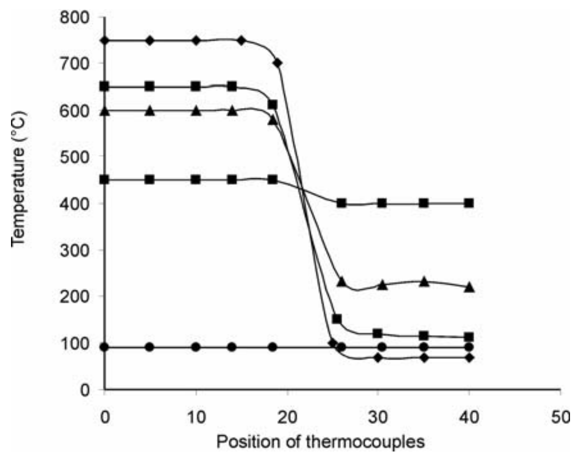

Fig. 11. Temperature distributions in the casting and mould for certain instants of casting operations, obtained from temperature measurements for a 25 mm thick CO_2–sand mould (75 mm OD, 25 mm ID)

The obtained interfacial heat transfer coefficient is shown in Fig. 12. The figure shows that *h* starts from a finite value and gradually increases to about 710 W/(m^2·°C), and then more sharply decreases to approximately 590 W/(m^2·°C). As *h* reaches its peak value, the heat flux reaches a maximum across the interface. Then the metal temperature drops more rapidly and the metal shrinks more and forms a larger gap, resulting in a smaller *h*. After that, *h* increases to about 670 W/(m^2·°C) and keeps dropping until the end of casting.

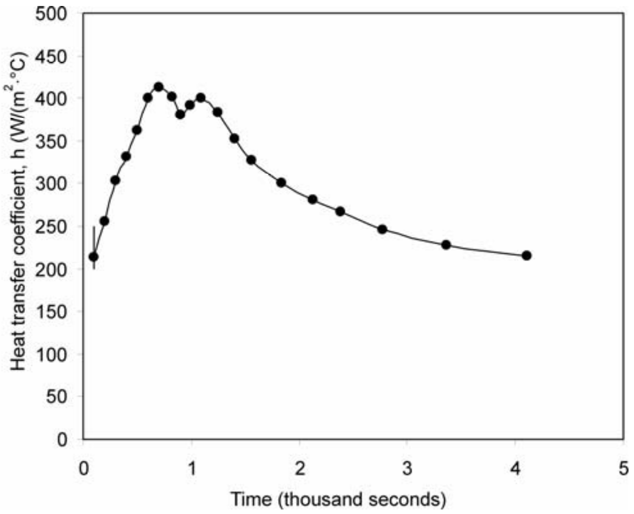

Fig. 12. The interfacial heat transfer coefficient obtained from temperature measurements for a 25 mm thick CO_2–sand mould (75 mm OD, 25 mm ID)

It is noted, however, that the data for *h* are useful only when its relation to the metal temperature near the interface is known. During the analysis of the temperature data by the inverse method, the temperatures of the casting metal and the mould very near the interface were obtained. The data is shown in Fig. 13. Combining the data in Figs. 11, 12, the interfacial heat transfer coefficient, as a function of metal temperature very near the interface, can be obtained, as shown in Fig. 14.

With the metal temperature very near the interface known, it is also possible to convert the gap size and *h* as functions of time obtained from the gap size measurement to functions of metal temperature. The results are shown in Figs. 15, 16. From Fig. 14, it can be seen that no gap is formed between the casting metal and the mould until the solidification temperature is approximately 590 °C. At that temperature a gap starts to form. The gap does not grow, however, and maintains a size of about 70 μm until the end of solidification, at approximately 550 °C and then starts to grow quickly. No gap is formed before the formation of the solidification phase, because the liquid–solid mixture in this stage still maintains good contact with the mould wall.

The moment solidification starts, however, the strength of the solid shell increases. The shell is strong enough to resist the hydrostatic pressure of the molten metal, which tends to push the metal shell outward. It is not until the end of solidification that the metal is completely separated from the mould. Correspondingly, in Fig. 14, the interfacial heat transfer coefficient is rather high before the solidification temperature and drops significantly at the solidification temperature.

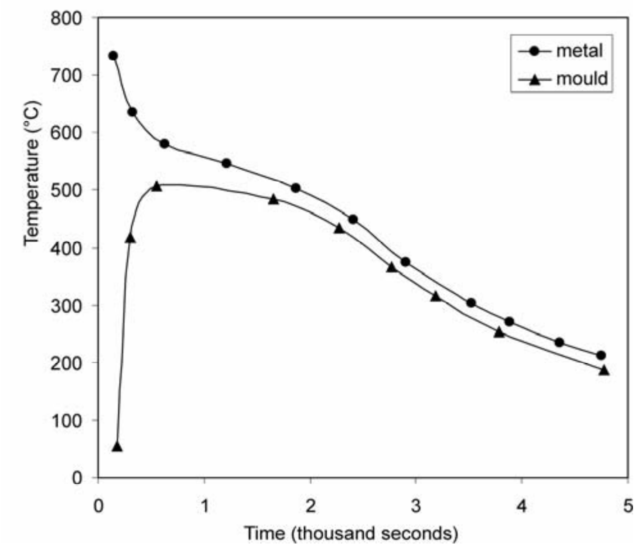

Fig. 13. Temperature of the casting metal and mould very near the interface during the entire casting period, obtained from the inverse method for a 25 mm thick CO_2–sand mould (75 mm OD, 25 mm ID)

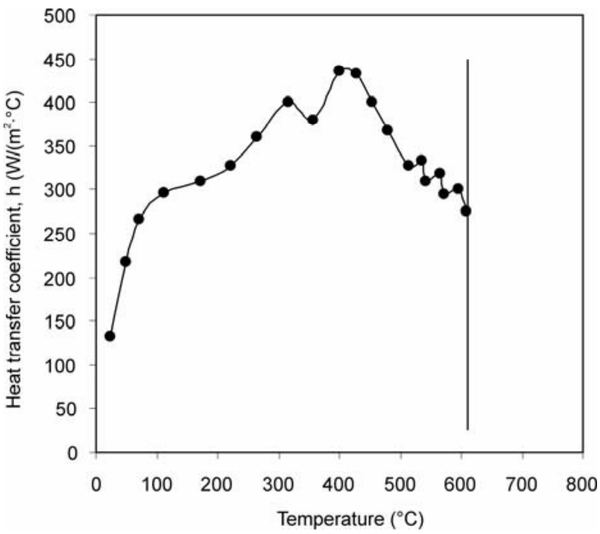

Fig. 14. The interfacial heat transfer coefficient as a function of metal temperature very near the interface, obtained from temperature measurements and the inverse method for a 25 mm thick CO_2–sand mould (75 mm OD, 25 mm ID)

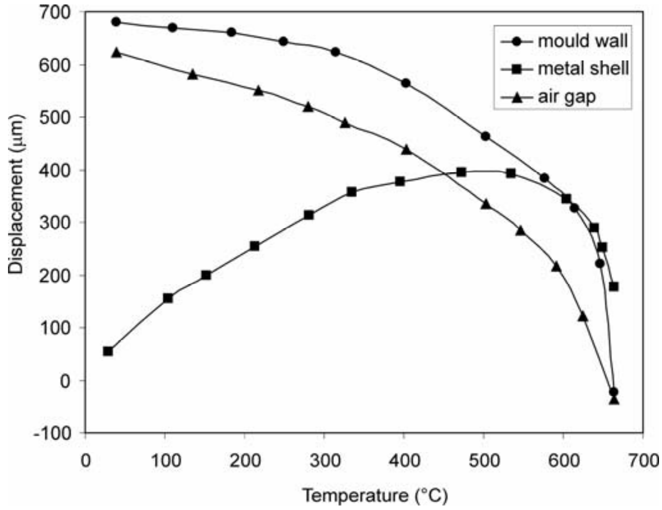

Fig. 15. The displacements of the casting and mould, as well as the corresponding gap size, as functions of the metal temperature very near the interface, for a 25 mm thick CO_2–sand mould (75mm OD, 25 mm ID)

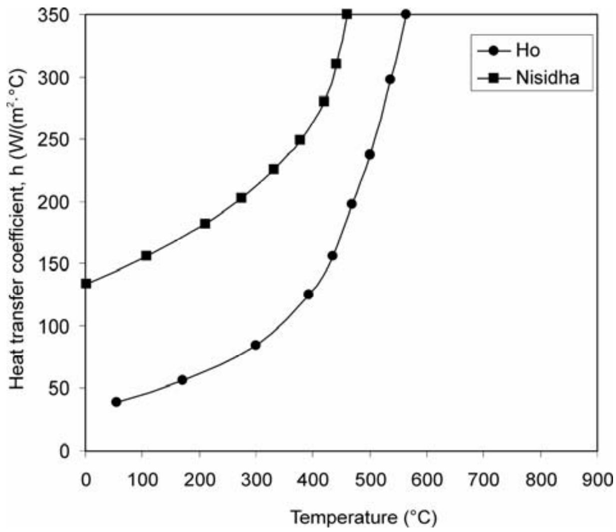

Fig. 16. The interfacial heat transfer coefficient as functions of metal temperature very near the interface, obtained from Nishida's and Ho's thermal conductivity values, for a 25 mm thick CO_2–sand mould (75mm OD, 25 mm ID)

The value of *h*, however seems to increase again to a higher value, still smaller than the peak value. The source of this phenomena is unknown. It may be due to reversal heat transfer from the core. It is speculated that, when cooling first starts, the core forms a solid network and resists the hydrostatic pressure of the inner molten metal from pushing it outward. The network is still porous enough, however, for the melt to penetrate through it until the end of solidification, when a complete solid shell is formed.

Then the value of h drops again and keeps dropping as the gap grows. At a higher temperature above the solidification temperature, the value of h obtained from temperature measurements and the inverse method maintains a certain value – even somewhat lower that the peak value, while the gap size method shows a very high value. The former is believed to be more reliable than the latter since very high values result from a very small gap size. At this stage, it is not reasonable to assume that the relation of $h = k/x$ still holds.

An increase of h during the beginning stage can result from the imperfect contact of the molten metal and the mould when the metal is first poured into the casting. Due to the roughness of the mould, it takes a certain time for the molten metal to wet the mould and establish a close contact.

4. Conclusions

Two methods were employed to measure the heat transfer coefficient at the metal –mould interface during the casting of Al–4.5% Cu alloy in a CO_2–sand mould. One was to measure the size of the gap formed between the casting metal and the mould and using the relation $h = k/x$, where k is the thermal conductivity of the air–mould gas mixture in the gap and x is the size of the gap. The other method was to take temperature measurements at certain locations of the casting and mould and, by using the inverse method, to obtain the value of h. The results of measurements and observations can be summarized as follows:

- The determination of h through the measurement of gap size greatly depends on the assumed thermal conductivity of the gas mixture in the gap.
- The relation $h = k/x$ is not appropriate for the beginning stage of the casting, when molten metal is poured into the mould cavity.
- The value of h derived from temperature measurements and the inverse method is about ten times higher than that obtained from gap size measurements and Ho's and Nishida's values of k.
- With temperature measurements and the inverse method, h starts at about 210 W/(m^2·°C), increases to 710 W/(m^2·°C) at the solidification temperature, abruptly drops to about 590 W/(m^2·°C), and then increases again to about 670 W/(m^2·°C) at the end of solidification. After that, h keeps dropping until the end of casting.

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