JOURNAL OF MATERIALS SCIENCE 27 (1992) 3467–3473

Effect of melt superheat and chill material on interfacial heat-transfer coefficient in end-chill Al and Al–Cu alloy castings

M. A. TAHA, N. A. EL-MAHALLAWY, A.-W. M. ASSAR, R. M. HAMMOUDA
Department of Design and Production Engineering, Faculty of Engineering, Ain-Shams University, Cairo, Egypt

Solidification of metal castings inside moulds is mainly dependent on the rate of heat removal from the metal to the mould. During casting solidification, an air gap usually develops at the interface between the solidfying metal and the surrounding mould or chill. This condition occurs in most casting geometries, except in some cases such as the cast metal solidifying around a central core. An overall heat-transfer coefficient, which includes all resistances to heat flow from the metal to its surroundings can be determined. The objective of this work was to determine the overall heat-transfer coefficient, h, using experimental and computer-simulation results on commercial purity aluminium and Al–4.5 wt% Cu alloy solidifying in a vertical end-chill apparatus. The cast ingots had a cylindrical shape with 12.5 mm diameter and different lengths of 95 and 230 mm. It solidified at different superheats (ranging from 50–110 °C) against two different chill materials: copper, and dry moulding sand. A computer program solving the heat-conduction equation and taking into consideration the convection in the melt, was used to compute the temperature history at numerous points along the ingot length. Different h values were assumed as a function of time, until agreement between experimental and computed cooling curves was obtained. The variation of h as a function of time, surface temperature, specimen length for each melt superheat and chill material was found. The thickness of the air gap was also evaluated. The results indicate that the variation of heat-transfer coefficient with time followed a pattern of sudden increase for the first few seconds, followed by a steady state, after which h decreased and reached another lower constant value. The h values were also found to decrease rapidly when the liquidus temperature was reached in the melt. For longer specimen and higher melt superheat, the heat-transfer coefficient increased. It was also higher for a copper than for a sand chill.

1. Introduction

Improving casting quality and controlling solidification of metals inside the mould is mainly influenced by the rate of heat transfer from the metal to its surroundings through the mould wall. The rate of heat transfer not only depends on the temperature and thermal properties of both metal and mould material, but also on the heat resistance between them. The heat resistance usually exists at the boundary between the metal and the mould during solidification due to the formation of an air gap between the metal and the mould. The formation of the air gap was described elsewhere [1, 2]. The heat resistance is defined as the reciprocal of the interfacial heat-transfer coefficient. It is important to determine this coefficient in order to use it in solving solidification problems. Some values for this coefficient have been reported [2, 3], but recent work indicates that it is variable with time, gap temperature, gap width and type of gas in the gap [1, 2, 4].

An excellent survey of the metal–mould heat-transfer coefficient has been presented by Ho and Pehlke [3] who also found, by solving the heat-conduction problem, that the heat-transfer coefficient, h, for aluminium solidifying against a water-cooled copper chill, decreases with time first rapidly then at a much slower rate. They also found that h increases as the mean interfacial temperature increases for a given gap width. Another study by El-Mahallawy and Assar [1] presented the relation between h and the air-gap formation for a metal–lead end-chill vertical mould bottom chill as follows: first, a high and constant value of h is obtained due to the good contact between the liquid metal and the chill. As the solidification starts near the chill, a drop in h takes place by the liquidus temperature due to the formation of a solid shell. As the temperature drops in the solidified shell, the gap width increases due to shrinkage which is translated by a continuous decrease in h.

It is the purpose of this work to determine the interfacial heat-transfer coefficient between the metal and chill for commercial purity aluminium and

0022–2461

Al–4.5 Cu alloy during cooling and solidification in a vertical tube against three different chill materials: copper, steel and dry moulding sand.

2. Experimental procedure

A special apparatus for unidirectional solidification using end-chill was designed and constructed. The apparatus consists of: (1) a three-coil electrical resistance furnace, (2) a stainless steel cylindrical crucible 12.5 mm i.d., 1.25 mm thick and 280 mm long, (3) a water-cooled chill of either copper, steel, or dry moulding sand, and (4) a closed cooling system, as shown in Fig. 1. The experiments were made using commercial purity aluminium (99.5%) and Al–4.5 Cu alloy which was prepared from the same aluminium together with a high-purity copper (99.99%).

The following procedures were subsequently followed for each experiment.

1. The stainless steel mould was mounted in the cooling head, then the four thermocouples were inserted radially inside it.
2. The melting furnace was positioned around the stainless steel mould with the cooling head at a determined level.
3. When the predetermined superheat was reached, the furnace was turned off and the cooling-water pump was turned on at the same time.
4. When the temperature of the specimen had dropped below the solidus temperature, the cooling-water pump was turned off and the specimen was removed from the furnace.

Temperature–time measurements were obtained through three thermocouples radially inserted in the stainless steel mould located at 6, 90, and 170 mm above the metal/chill interface and the fourth one in the cooling head at 5 mm from the metal/chill interface. The four thermocouples were connected to a chart recorder, and the cooling curve for each location was obtained

3. Heat-flow model

The determination of the heat flux is based on the solution of the transient heat-conduction equation. The experiment was designed to establish conditions of unidirectional heat transfer taking into account the heat conduction within the chill material.

The basic heat-transfer equation used is

$$C\rho(\partial T/\partial t) = K(\partial^2 T/\partial z^2) + q^{\cdot} - Q_r^{\cdot} \qquad (1)$$

where C, ρ, and K are the specific heat, density, and thermal conductivity, respectively, $q^{\cdot}$ is the local rate of latent heat evolved, $Q_r^{\cdot}$ represents the radial heat losses to the mould and surroundings T is the temperature, t is time and Z the space co-ordinate. In order to solve the one-dimensional partial differential equation, the explicit finite difference method is applied. The liberation of the latent heat during solidification of Al–4.5 wt % Cu is handled using the equivalent specific heat method [5] for the liquid–solid mushy zone. The latent heat is added to the specific heat term over the liquid–solid transition range, i.e. in the case of equivalent specific heat, C_e:

$$C_e = C - L_f(\partial F_s/\partial T) \qquad (2)$$

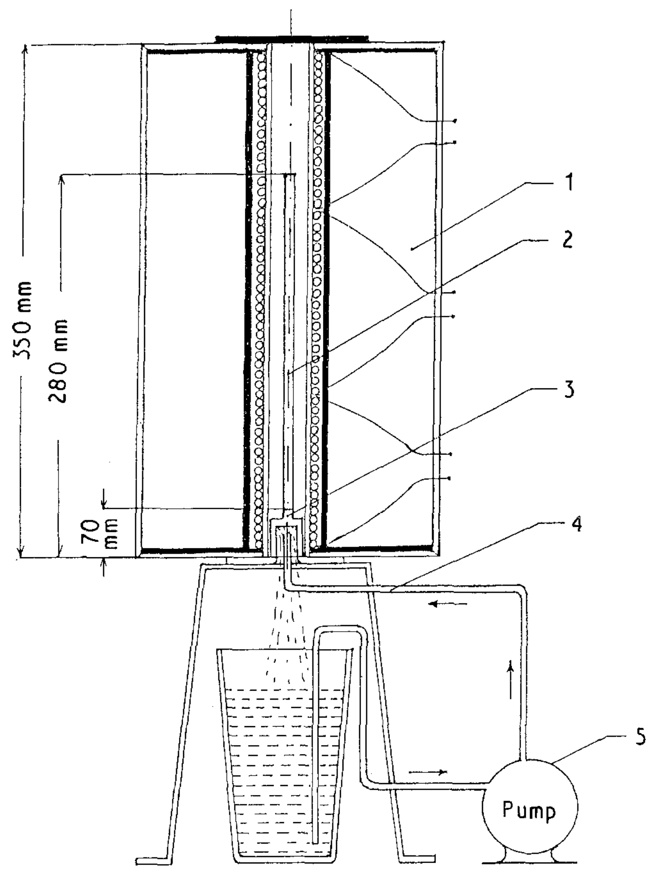

Figure 1 Schematic drawing of the end-chill apparatus which consists of: (1) electrical furnace, (2) stainless steel crucible, (3) end chill, (4) cooling system, and (5) electrical pump.

where L_f is the latent heat of fusion and the value of $\partial F_s/\partial T$ is obtained by differentiating the relationship between the fraction solid, F_s, and temperature, T, known as the Scheil equation

$$F_s = 1 - (T - T_m)/(T_l - T_m)^{[1/(k-1)]} \quad (3)$$

where k is the partition coefficient, T_m the melting point of pure metal and T the temperature.

In the case of commercial aluminium, the liberation of the latent heat occurs isothermally [1]. This isothermal evolution of latent heat is dealt with by artificially maintaining the solidified element temperature equal to the solidification temperature of the pure aluminium. This is done by separately calculating the change in heat content of the element at each time step. The temperature of the element is not allowed to drop below the solidus temperature unless the heat content drops by the latent heat.

3.1. Boundary conditions

The upper boundary condition is determined from the temperature given by the thermocouple readings placed at 170 mm from the chill. At the metal–chill interface, which represents the lower boundary condition, the heat loss per unit volume of the chill is given by

$$h(A_c/V_l)(T_{metal} - T_{chill}) \quad (4)$$

where h is the heat-transfer coefficient, A_c the cross-sectional area of the element with volume V_l, T_{metal} is the temperature of the first element of metal in contact with the chill and T_{chill} is the chill temperature which is taken from the thermocouple readings placed in the chill centre-line at 5 mm from the metal–chill interface.

3.2. Radial heat losses

Radial heat losses, Q, were added to the model as

$$Q = \sigma(T_f - T_i) \quad (5)$$

$$\sigma = H\Delta t/C\rho \quad (6)$$

where H is an overall radial heat-transfer coefficient, which is a function of A_s/V_l where A_s is the surface

TABLE I Thermophysical properties of commercial aluminium used in the computation [6]

Thermal conductivity, K_m ($W m^{-1} °C^{-1}$)	$T<400$ °C; $K_m = 238$ $T>400$ °C; $K_m = 294.693 - 0.1417\,T$ $T>T_l$; $K_m = 95$ $T>700$ °C; $K_m = 72.08 + 3.323\times10^{-2}\,T$
Specific heat, C ($J kg^{-1} °C^{-1}$)	1050
Density, ρ ($kg m^{-3}$)	2700
Latent heat of fusion, L_f ($J kg^{-1}$)	37700

TABLE II Thermophysical properties of Al–4.5 wt % Cu used in the computation [6]

k ($W m^{-1} °C^{-1}$)	$T < 627$; $k_m = 100 + 0.15\,T$ $T = 627$–645; $k_m = 4303.333 - 6.555556\,T$ $T > 645$; $k_m = 62.20238 + 1.984\times10^{-2}\,T$
C_m ($J kg^{-1} °C^{-1}$)	$1096.2 - 1.4\,T + 4.56\times10^{-3}\,T^2 - 0.42\times10^{-6}\,T^3$
ρ ($kg m^{-3}$)	2800
L_f ($J kg^{-1}$)	280000

TABLE III Thermal conductivity of different chill materials used in the computation [6]

Chill material	Thermal conductivity ($W m^{-2} °C^{-1}$)
Copper	395
Iron	70
Sand	2.3

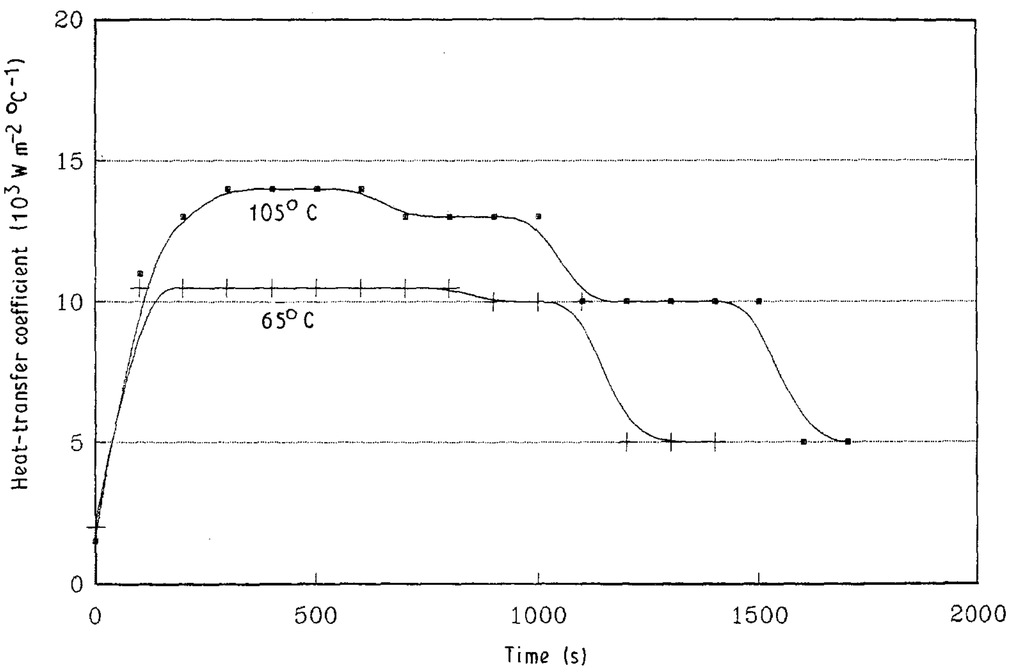

Figure 2 Heat-transfer coefficient versus time in Al–4.5 wt % Cu, cast on a sand chill at 65 and 105 °C superheat.

area of the element, V_l the volume of the element, and T_f is the furnace temperature.

The thermal and physical properties of the commercial aluminium and Al–4.5 wt % Cu alloys as a function of temperature used in computation are taken from Smithells [6] and are given in Tables I–III.

4. Results

4.1. Effect of superheat on h

The variation of h with time for Al–4.5 wt % Cu is represented in Fig. 2 against sand chill at superheats 65 and 105 °C, and for the same alloy against copper end-chill for superheat 50 and 110 °C in Fig. 3. The figures show that h is higher, the higher the superheat. They also show that h for specimens on sand chill starts from a relatively low value (1500 and 2000 W m^{-2} °C^{-1}) for 65 and 105 °C superheat, respectively, then increase to a steady value of 11 000 and 13 500 W m^{-2} °C^{-1} for the same superheats, then decreases again with time. This is again observed from the results in Fig. 3 for the specimens on copper chill. Figs 4 and 5 show h plotted against surface temperature which was given by the temperature on the first element in front of the chill and in direct contact with the gap. This is done in order to avoid the effect of time which may be different from one casting to

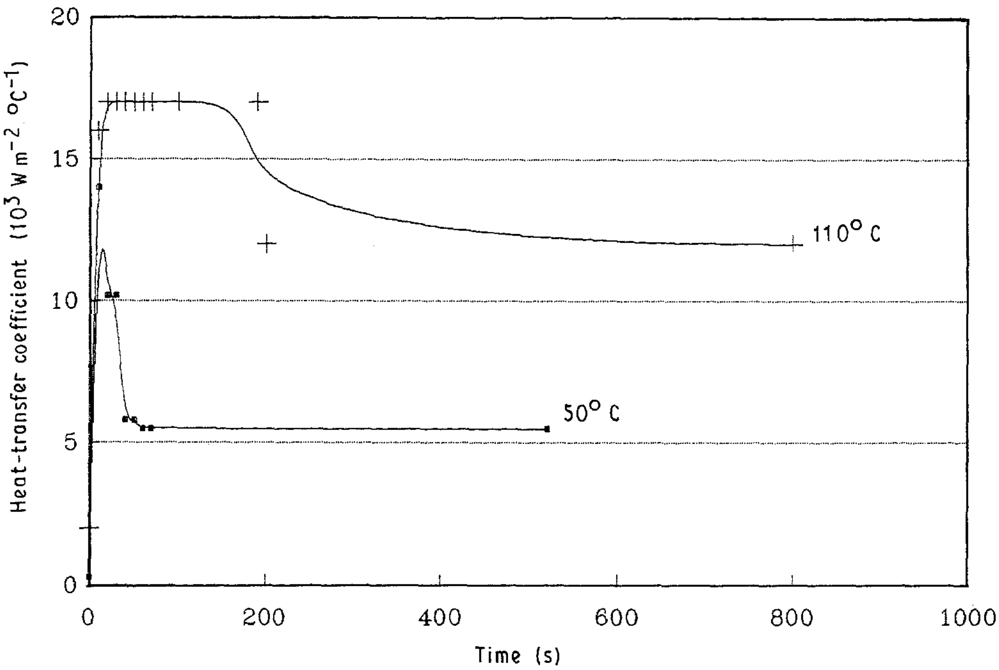

Figure 3 Heat-transfer coefficient versus time in Al–4.5 wt % Cu, cast on a copper chill at 50 and 110 °C superheat.

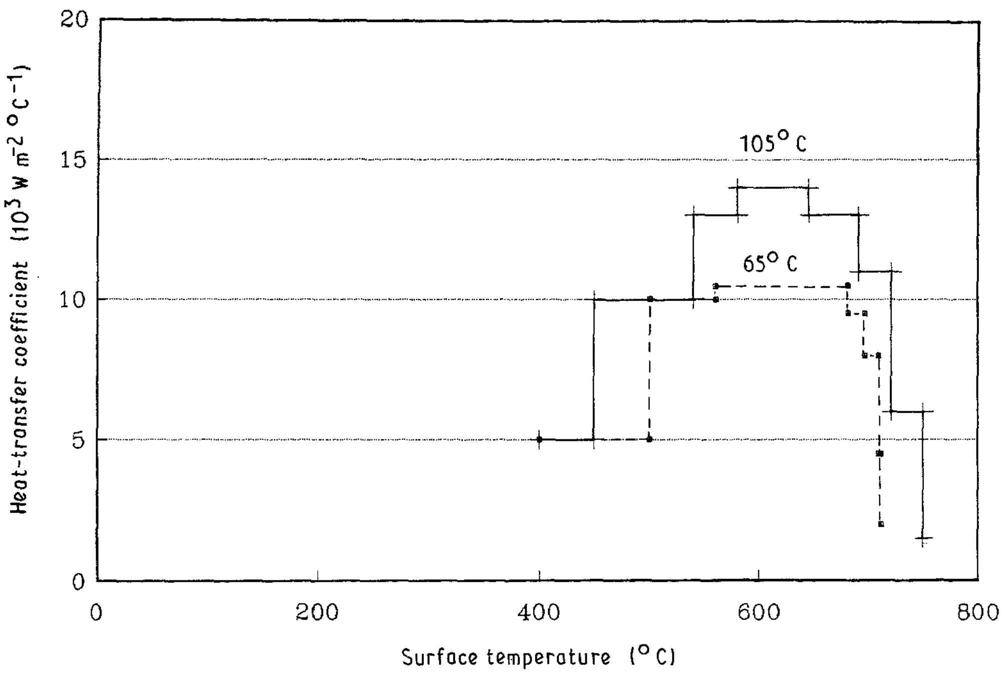

Figure 4 Heat-transfer coefficient versus surface temperature in Al–4.5 wt % Cu, cast on a sand chill at 65 and 105 °C superheat.

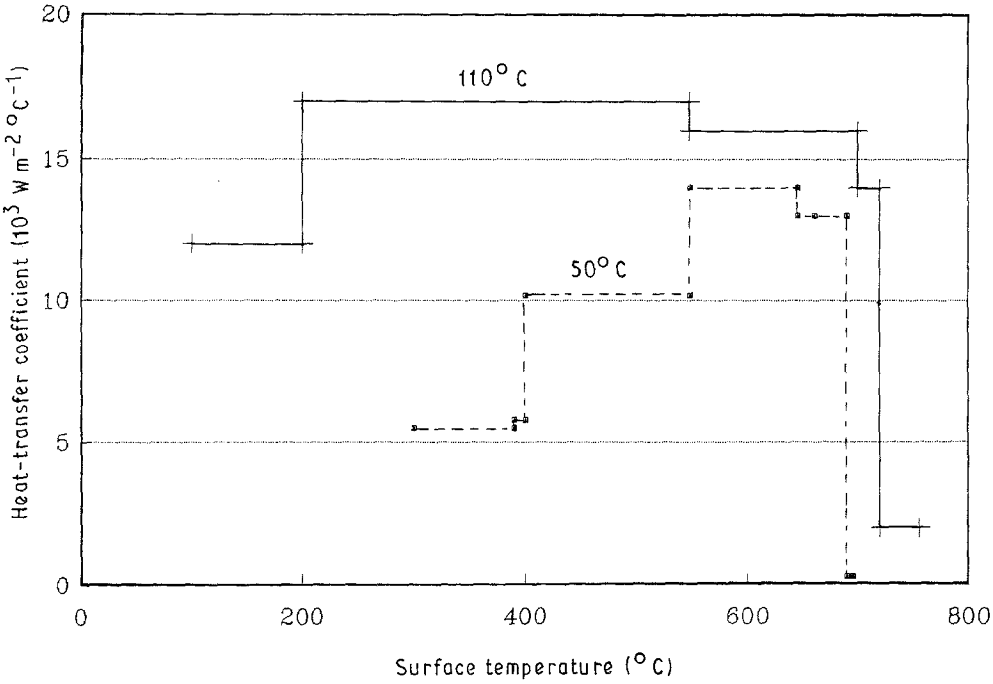

Figure 5 Heat-transfer coefficient versus surface temperature in Al–4.5 wt % Cu, cast on a copper chill at 50 and 110 °C superheat.

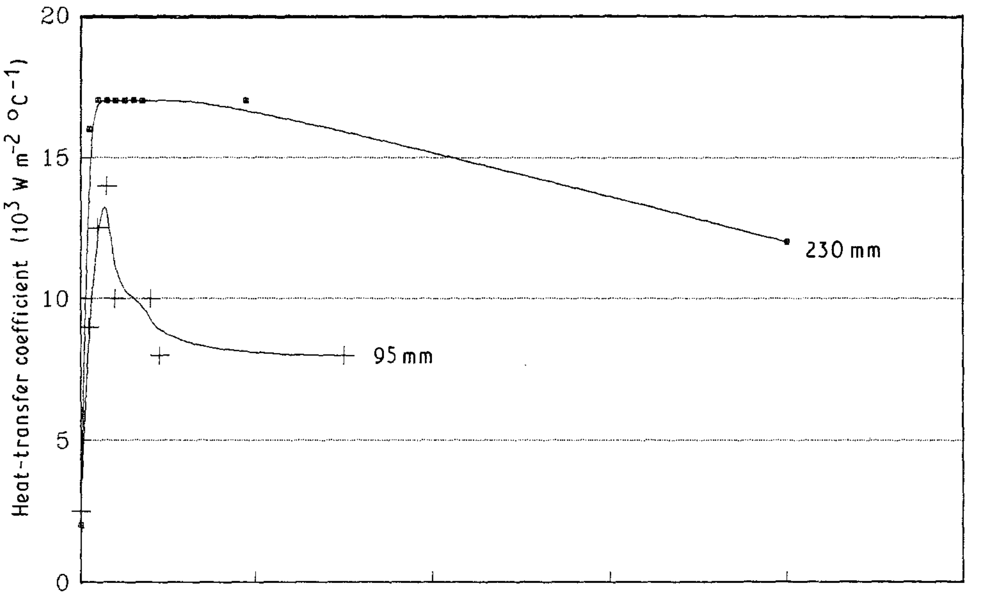

Figure 6 Heat-transfer coefficient versus time using two values of specimen length of 230 and 95 mm in Al–4.5 wt % Cu, cast on a copper chill at 100 °C.

another due to the difference in superheat, cooling conditions, or mould materials. The figures show the same behaviour as in Figs 2 and 3.

4.2. Effect of specimen length on *h*
Fig. 6 shows the effect of specimen length on *h* as a function of time. The specimen lengths were 95 and 230 mm and the superheat was kept constant at 100–110 °C. A copper chill was used for these specimens. The figure indicates that the shape of the curve is similar to that previously described in Section 4.1 and that the longer the specimen the higher is *h*. Fig. 7, representing the relationship between *h* and surface temperature, shows that above the liquidus, *h* is lower than in the solidification range and that for temperature below the solidus, *h* decreases again.

4.3. Effect of chill material on *h*
Figs 8 and 9 show the effect of the end-chill material on *h* for commercial aluminium specimens at 80 °C

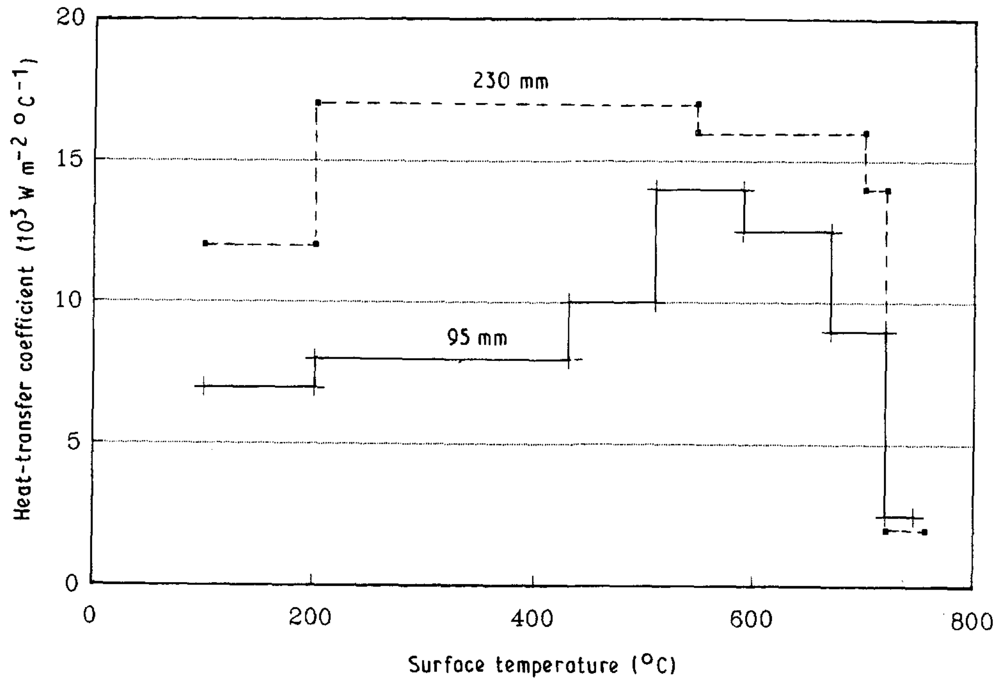

Figure 7 Heat-transfer coefficient versus surface temperature using two values of specimen length of 230 and 95 mm in Al–4.5 wt % Cu, cast on a copper chill at 100 °C.

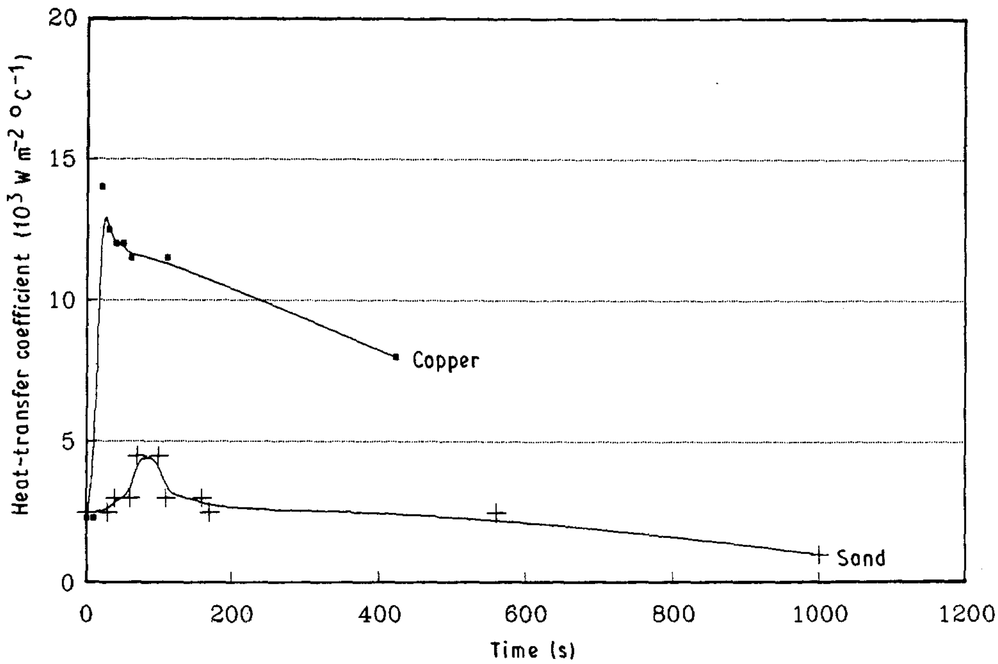

Figure 8 Heat-transfer coefficient versus time using two chill materials of sand and copper for commercial aluminium poured at 80 °C.

superheat. Chill materials used were copper, and sand. It is noted that the highest h is obtained for specimens on copper chill. In general, the value of h in the case of copper chill is three to four times that of sand chill.

5. Discussion

The relationship of h with surface temperature or time shown in Figs 2–9 indicate that the behaviour is similar in all cases. It follows a pattern of a sudden increase in h for the first few seconds (< 10 s) followed by steady state, then a rapid decrease below the solidus temperature. Previous results by Nishida *et al.* [2] have also indicated a sudden increase in h with time in the first few seconds, as shown in Fig. 10, in which the results show that the air gap and h values increase in this first period, indicating that the air-gap formation is not the only parameter affecting h values.

The general behaviour of present results is similar to that of Ho and Pehlke [4] and Nishida *et al.* [2] but with higher h values, due to the smoothness of the chill surface and the effect of the metallostatic pressure which lead to a reduction of the air-gap thickness.

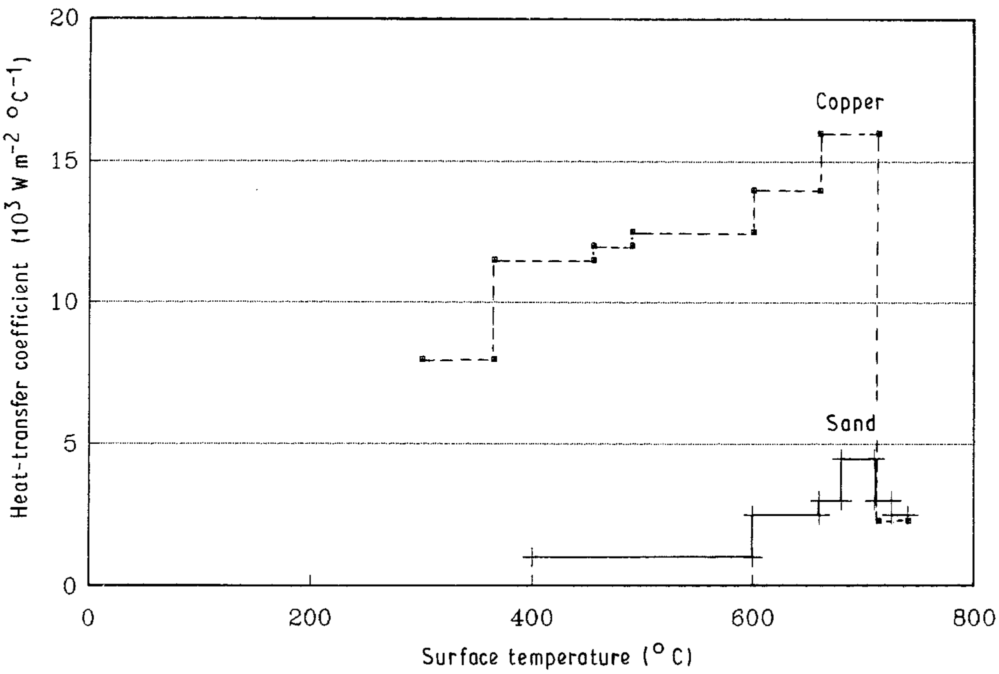

Figure 9 Heat-transfer coefficient versus surface temperature using two chill materials of sand and copper for commercial aluminium poured at 80 °C.

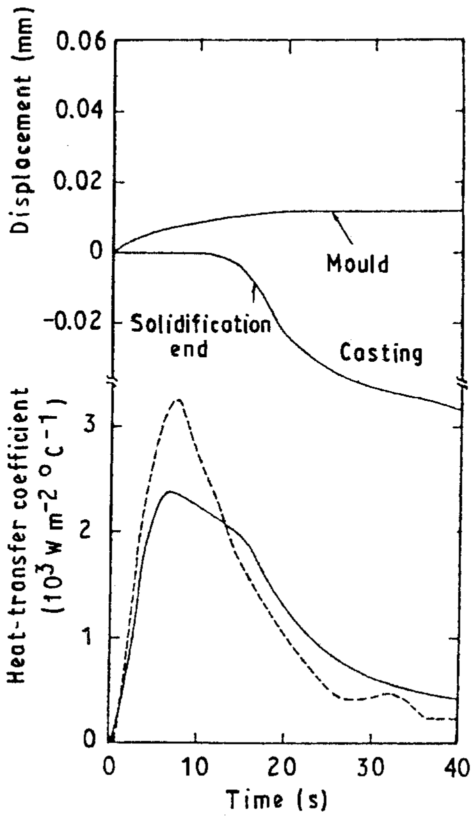

Figure 10 Heat-transfer coefficient (lower curves) (——) approximate calculation, (- - -) simulation compared with mould and casting displacement (upper curves) for cylindrical pure aluminium casting [2].

6. Conclusions

1. h increases with increasing melt superheat.
2. h was found to be higher for copper chill than for sand chill.
3. h increases with increasing specimen length.

References

1. N. A. EL-MAHALLAWY and A. M. ASSAR, *J. Mater. Sci. Lett.* **7** (1988) 205.
2. Y. NISHIDA, W. DROSTE and S. ENGLER, *Metall. Trans.* **17B** (1986) 833.
3. K. HO and R. D. PEHLKE, *AFS Trans.* **83** (1975) 689.
4. *Idem., Metall. Trans.* **16B** (1985) 585.
5. N. A. EL-MAHALLAWY, P. N. HANSEN and P. R. SAHM, in "International Conference on Numerical Methods for Transient and Coupled Problems", Venice, Italy, 9–15 July 1984, p. 100.
6. C. J. SMITHELLS, "Metals Reference Book", 5th Edn (Butterworth, London, 1976).

Received 28 August 1990
and accepted 28 February 1991