



# Experimental determination of heat transfer coefficients during squeeze casting of aluminium

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## ARTICLE INFO

### Article history:

Received 14 May 2007

Received in revised form

7 March 2008

Accepted 31 March 2008

### Keywords:

Heat transfer coefficients

Squeeze cast

Applied pressure

## ABSTRACT

Heat transfer coefficients during squeeze cast of commercial aluminium were determined, by using the solidification temperature versus time curves obtained for varying applied pressures during squeeze casting process. The steel mould/cast aluminium metal interface temperatures versus times curve obtained through polynomial curves fitting and extrapolation was compared with the numerically obtained temperatures versus times curve. Interfacial heat transfer coefficients were determined experimentally from measured values of heating and cooling temperatures of steel mould and cast metal and compared with the numerically obtained values and found to be fairly close in values. The values of the heat transfer coefficients were found to increase with increase in applied pressures and to decrease with fall of solidifying temperatures corresponding to three distinct solidification stages namely, liquidus, liquidus–solidus and solidus stages. Below temperatures of 500 °C, the effect of the increase in heat transfer coefficients with applied pressure application becomes less significant and the drop in values of the heat transfer coefficients with solidification temperatures at any applied pressures remains fairly constant. The peak values of heat transfer coefficients obtained for as-cast (no pressure application) and squeeze cast (pressure application) of aluminium are 2975.14 and 3351.08 W/(m<sup>2</sup> K), respectively. Empirical equations, relating the interfacial heat transfer coefficients to the cast aluminium surface temperatures and applied pressures at three distinct temperature range intervals, were also derived and presented.

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## 1. Introduction

Casting operation involves the process of melting and pouring of the molten metal into the mould, followed by solidification that takes the shape of the mould cavity as Burns (1986) reported. With casting process, it is possible to cast large and intricate shapes which cannot be economically formed in one piece by either forging or welding. Higgins (1983) noted that the inefficiency of casting operations of the past has been improved upon through numerous innovations that have taken place so that precision cast components can be pro-

duced. One method that has gained acceptability in casting processes is the squeeze casting as reported by Franklin and Das (1983). Squeeze casting is one of the improved casting techniques used for the production of engineering components mostly in non-ferrous metals by the application of pressure on the cast metal to eliminate defects associated with shrinkage cavities and/or gas porosity. By squeeze casting operation, the liquid molten metal is compressed under pressure inside the mould cavity of a re-usable metal mould, usually made of steel (see Fig. 1). Squeeze casting offers considerable saving in cost for large production quantities when

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doi:10.1016/j.jmatprotec.2008.03.071

### Nomenclature

|                 |                                                     |
|-----------------|-----------------------------------------------------|
| $c$             | specific heat                                       |
| $h_{al}(T)$     | interfacial heat transfer coefficient of cast metal |
| $K$             | thermal conductivity of the steel mould             |
| $K_{al}(T)$     | thermal conductivity of the cast metal              |
| $P$             | applied pressure                                    |
| $q$             | heat flux                                           |
| $\Delta r$      | elemental distance                                  |
| $T$             | temperature                                         |
| $T_{al}$        | cast metal temperature                              |
| $T_M$           | mould temperature                                   |
| $T_1 \dots T_4$ | measured temperatures                               |
| $\Delta T$      | temperature difference                              |
| Greek letter    |                                                     |
| $\rho$          | density of aluminium                                |

the size of the casting is not very large. Chatterjee and Das (1972) observed that for large castings and alloys of high melting temperature, permanent-mould casting method becomes impracticable. Mould used in squeeze casting apart from being re-usable and its economic advantage, it has the advantage of producing good surface finish, close dimensional tolerance and defect free products. The solidification process of the molten aluminium in the steel mould takes a complex form as Stevanovic et al. (1994) indicated in their work. Das and Chatterjee (1981) noted that during solidification of metals all mechanisms of heat transfer are involved and the solidifying metal undergoes state and phase changes.

Krishnan and Sharma (1996) indicated that the final structure and properties of the cast specimen obtained depends on the casting parameters. Such parameters as studied by Aniyi (1994) include applied pressures, die pre-heat temperature while Abifarin and Adeyemi (2003) introduced delay time and

period of applied pressures as parameters also having effects on the final structure of the solidifying aluminium metal.

Kim and Lee (1997) studied time varying heat transfer coefficients between a tube-shaped casting and metal moulds. In their investigation, they found that the heat transfer coefficients at the interface of the inner mould decreases temporarily and then increases, while the one at the outer interface of the mould decreases monotonously to a quasi steady state. Kobryn and Semiatin (2001) determined the interface heat transfer coefficients for permanent-mould casting of Ti–6Al–4V and found that the values of heat transfer coefficients for shrink-off and shrink-on mould alter with interface type. Browne and O'Mahoney (2001) carried out experimental determinations of interface heat transfer coefficients relating to solidification range, metallostatic head, investment shell thickness, pre-heat and interface geometry and concluded that effect of metallostatic head was only significant for long freezing-range alloys while increasing shell mould thickness and pre-heat also had effects that were alloy dependent. Martorano and Capocchi (2000) investigated and determined the heat transfer coefficients at the metal–mould interface of a unidirectional solidification system using algorithm method on the whole domain. Cho and Hong (1996) studied heat transfer coefficients at the casting/die interface in squeeze casting and applied a single load (50 MPa) with die heating and concluded that heat transfer coefficient increases with the application of pressure.

There are published information on the study of the interface heat transfer coefficients between cast metal and metal mould, as given above, but there are few or no published work yet on the effects of varying applied pressures and metal solidification temperatures on the values of the heat transfer coefficients of molten aluminium in squeeze casting operation.

The comparison between numerically and experimentally derived values of interface steel mould/cast temperatures versus times, cast aluminium solidification temperatures versus times curves, and interface heat transfer coefficients with times determined experimentally and numerically by inverse method are presented in this work.

Empirical equations, relating the heat transfer coefficients of solidification of molten metal aluminium to applied pressures and solidification temperatures are presented for the three distinct stages of phase changes for solidification of aluminium during squeeze casting.

## 2. Numerical evaluation of interface heat transfer coefficients

The method of calculating heat transfer coefficients is based on the knowledge of known temperature histories at the interior points of the casting or mould together with the numerical models of heat flow during solidification which was adopted by Krishnan and Sharma (1996). Santos et al. (2001) observed that these temperatures are difficult to measure due to the difficulty in locating accurate position of thermocouple at the interface. Therefore, the inverse heat conduction method based on non-linear estimation technique as developed by Beck (1970) has been adopted to determine the values of

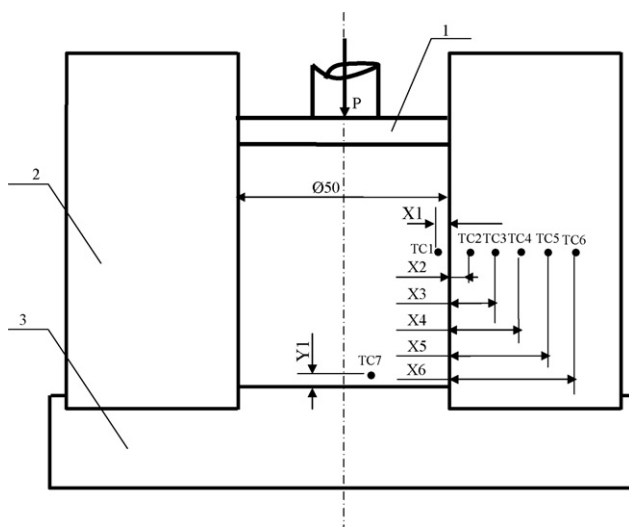


**Fig. 1 – Schematic diagram of squeeze casting test rig. 1, upper punch; 2, cylindrical steel mould; 3, lower die ( $X_1 = 2$ ,  $X_2 = 4$ ,  $X_3 = 8$ ,  $X_4 = 12$ ,  $X_5 = 16$ ,  $X_6 = 20$ ,  $Y_1 = 2$  (mm)).**

interface heat transfer coefficients as a function of time during solidification of squeeze casting. Solidification of squeeze casting of aluminium involves phase change and therefore thermal properties of aluminium are temperature dependent, making the inverse heat conduction problem non-linear.

The governing heat transfer equation in one-dimensional cylindrical coordinates is given by:

$$\rho c_p \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( K_{al}(T) r \frac{\partial T}{\partial r} \right) \quad (1)$$

Eq. (1) holds with the boundary condition at the interface expressed as

$$q = K_{al}(T) \frac{\partial T}{\partial r} = h_{al}(T) [T_{al} - T_M] \quad (2)$$

The works of Ozisik (1985) and White (1991) have shown that thermal conductivity of aluminium metal varies with casting temperature. The relationship between the thermal conductivity and casting temperature of aluminium is therefore expressed in an equation thus:

$$K_{al}(T) = 241.84 - 0.041T_{al} \quad (3)$$

Santos et al. (2001) related the average interface heat transfer coefficient  $h$  with heat flow across the casting/steel mould interface and the equation is as given by:

$$h_{al}(T) = \frac{q}{[T_{al} - T_M]} \quad (4)$$

The heat transfer coefficient  $h$  at the interface is estimated by minimizing the errors between numerically estimated and measured temperatures defined by:

$$F(h) = \sum_{i=1}^n (T_{est} - T_{exp})^2 \quad (5)$$

where  $T_{est}$  and  $T_{exp}$  are the estimated and experimentally measured temperatures at various thermocouples location and times;  $n$ , iteration stage.

### 3. Experimental procedures

#### 3.1. Material used and squeeze casting rig

##### 3.1.1. Material used

The material used for the present investigation was commercially pure aluminium, of percentage composition of 99.5% of aluminium and traces of other elements.

##### 3.1.2. Squeeze casting rig

Chromel–Alumel thermocouples TC2, TC3, TC4, TC5 and TC6 were positioned on the sides of the cylindrical steel container, while TC1 and TC7 were positioned in the cast aluminium metal in the cylindrical and bottom flat surfaces respectively as shown in Fig. 1.

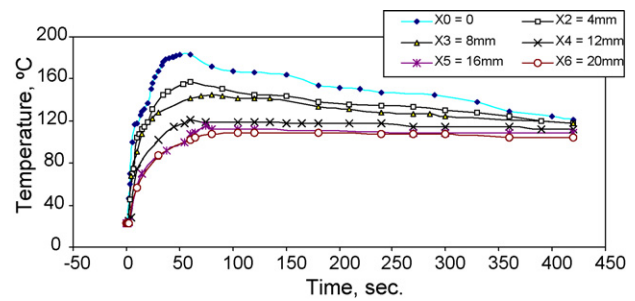


Fig. 2 – Effect of distance on the heating temperatures of steel mould with time (extrapolated heating curve at the cast specimen/steel mould interface i.e.  $X = 0$ ).

#### 3.2. Experimental molten aluminium and steel mould interface temperatures determinations

Thermocouples of chromel–alumel type 3 mm in diameter were used to determine the solidifying temperatures of the cast molten metal and heating temperatures of the steel mould at the various positions in the cylindrical steel container of Fig. 1. The solidifying temperatures at both the cylindrical and flat bottom surfaces of the cast molten aluminium metal were monitored at a position  $X1 = 2$  mm (from the surface of the steel mould/cast aluminium metal interface) into the cast molten aluminium metal.

At the steel mould wall in the cylindrical surface, thermocouples were positioned at  $X2 = 4$  mm,  $X3 = 8$  mm,  $X4 = 12$  mm,  $X5 = 16$  mm and  $X6 = 20$  mm measured from the cast aluminium metal/steel mould interface to monitor the heating temperatures at these positions of the steel mould wall (see Fig. 1). From the temperature versus time curves obtained for each position in the steel mould, the interface heating temperature versus time curve at the cast aluminium metal/steel mould, for position when  $X = 0$  was obtained by using the polynomial curve fitting method (see Fig. 2).

This was done by selecting a particular time of heating of steel mould, say  $t = 10$  s and drawing vertical lines cutting across the heating temperature versus time curves at various thermocouples' distances within the steel mould. At the point of intersection with each curve, the value of temperature was read against distance  $X$ , for the chosen time,  $t = 10$  s. The value of interface steel mould/cast temperature at time say,  $t = 10$  s was determined at the steel mould/cast metal interface by substituting the value of  $X = 0$  in the polynomial curve fitting Eq. (6) obtained from the values of temperatures at various distances in the steel mould at a chosen time,  $t = 10$  s.

$$T = 0.0031X^4 - 0.168X^3 + 3.263X^2 - 22.812X + 117.8 \quad (6)$$

The temperature obtained by this method corresponds to the interface steel mould/cast metal temperature at a distance  $X = 0$  for the chosen time say,  $t = 10$  s. This procedure was repeated for a number of time increments to get series of such temperatures with corresponding times.

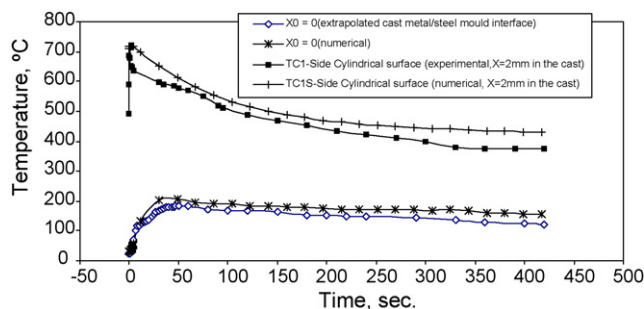


**Fig. 3 – Comparison of experimental measured temperatures with numerical values of aluminium metal without pressure application ( $P = 0$ ).**

The graph of extrapolated temperature versus time was drawn for position when  $X=0$  to represent the heating temperature versus time curve at the steel mould/cast aluminium metal interface (see Fig. 2, corresponding to curve  $X=0$ ), which indicated the dynamic effect at this surface.

Numerically, the steel mould/cast aluminium metal interface temperature with time were also obtained using the inverse method and compared with the extrapolated interface temperature versus time curve (see Fig. 3).

### 3.2.1. Without pressure application

A metered quantity of molten metal was poured into the steel mould cavity at a temperature of about 720 °C to attain a height of about 75 mm. The upper die was released to close the mould cavity without applying any load on the upper die. Thermocouples inserted into the hole drilled through into the cylindrical and flat bottom die (TC1 and TC7) were made to penetrate 2 mm into the cast specimen at both surfaces. These thermocouples measured the solidification temperature with time of the cast specimen at both the cylindrical and flat bottom surfaces. The other thermocouples were inserted into the blank hole in the steel mould, measuring the heating temperature with time of the cylindrical wall of the die. The terminals of the thermocouples were connected to the chart recorder/plotter (set at the highest speed of 10 mm/s and voltage 100 mV) through the cold junction apparatus, maintained at 0 °C throughout the measuring period.

### 3.2.2. With pressure application

The procedure for no pressure application was repeated, except for the application of pressure on the solidifying molten aluminium metal. The molten aluminium was carefully poured into the mould cavity within 3 s so as to avoid turbulence of molten metal flow. The punch was lowered to close the die and the Vega Compression Machine, model UTM 3C, serial no. 1061 with a capacity of 89,000 N, was actuated to compress the solidifying molten metal. The compression loads were applied at a delay time of about 7 s after pouring molten aluminium and retained on the solidifying molten metal for a period of about 100 s, until total solidification was achieved. During pressure applications, the solidification temperature with time were recorded on the chart recorder by

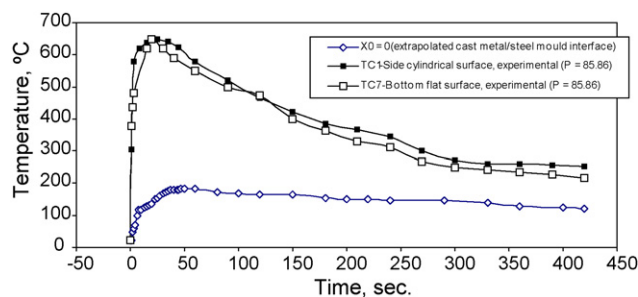


**Fig. 4 – Effect of pressure on the experimental measured temperatures of solidification of aluminium metal with time ( $P = 85.86$  MPa) for side and bottom moulds' surfaces.**

thermocouples positioned at the cylindrical and bottom flat surfaces of the steel mould.

### 3.2.3. Interface heat transfer coefficients determination

Extrapolated temperature versus time curve of Fig. 2 for position when  $X=0$  (i.e. cast aluminium metal/steel mould interface) was used to determine the heat transfer coefficients of solidifying molten aluminium metal. It was used to determine the interface heat transfer coefficients in the cast aluminium metal/steel mould for no pressure and with pressure applications at both the cylindrical and bottom flat surfaces of the steel mould.

The interface heat transfer coefficients between the steel mould and cast aluminium metal at the cylindrical and bottom flat surfaces were determined from the extrapolated experimental heating temperature versus time curve obtained for position  $X=0$  and aluminium cast solidification temperature versus time curves obtained for the cylindrical and bottom flat surfaces, using Eqs. (2) and (3).

The interface heat transfer coefficients were determined also numerically by the inverse method using the finite difference method (FDM) and the obtained results were compared with the experimentally derived values.

## 4. Results and discussions

### 4.1. Temperature versus time curves

Fig. 3 shows typical temperature versus time curves for solidifying molten aluminium metal and steel mould respectively without the application of pressure.

This figure shows the comparison of the numerical method usually applied by Cho and Hong (1996) to determine interface steel mould/cast metal temperature versus time curve with the extrapolated experimental method of this present work. The heating curve, as obtained through extrapolations of polynomial curves fitting equations and numerical methods are in close agreement and the deviations from the numerically obtained values ranges from 1.26 to 19.31%.

Typical result obtained under pressure is also shown in Fig. 4, indicating the solidification and heating curves generated for solidifying molten aluminium metal and steel mould which follow the same patterns to the curves in Fig. 3.

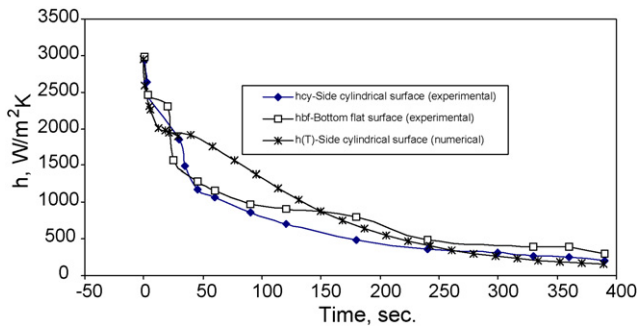


**Fig. 5 – Comparison of numerical values of interface heat transfer coefficients with calculated experimental values.**

With the application of pressure, the peak temperatures recorded are about the same 649 and 648 °C for a pressure of 85.86 MPa at the bottom flat and cylindrical surfaces of the steel mould, respectively (see Fig. 4). The peak temperature (649 °C) obtained at the bottom flat surface of the steel mould under applied pressure is found to be higher than that temperature (607 °C) without pressure application. This effect may be associated to additional internal heat generated, resulting to higher temperature during pressure application on the solidifying molten aluminium.

#### 4.2. Interface heat transfer coefficients with time

From the temperature with time curves of Fig. 3, the heat transfer coefficients for both cylindrical and bottom flat surfaces were determined for both numerical and calculated values and shown in Fig. 5. The maximum heat transfer coefficients of 2927.92 and 2975.14  $W/(m^2 K)$  are obtained at the cylindrical and bottom flat surfaces respectively for no pressure application, which is close in value to 2900  $W/(m^2 K)$  as obtained for pure aluminium by Kim and Lee (1997). The values of heat transfer coefficients decrease rapidly for both the cylindrical and bottom flat surfaces to a level of 866.70 and 969.50  $W/(m^2 K)$  respectively in 90 s. These values further decrease to 361.80 and 478.80  $W/(m^2 K)$  at these surfaces in another 150 s and further decrease then becomes not so noticeable.

From Fig. 5, the peak values of interface heat transfer coefficients are 2927.92 and 2956.73  $W/(m^2 K)$  as obtained by experimental and numerical determinations respectively at the cylindrical surface for no pressure application. For times within 40–120 s the values of the interfacial heat transfer coefficients obtained numerically and experimentally are found to show higher values of about 19.83% for numerical results to experimental results.

With the application of pressure on the solidifying aluminium metal, the heat transfer coefficients reach maximum values of 3085.34 and 3351.08  $W/(m^2 K)$  in the cylindrical and bottom flat surfaces, respectively (see Fig. 6). These values also decrease to 847.80 and 783.63  $W/(m^2 K)$  in 240 s in the cylindrical and bottom flat surfaces respectively, while further decrease with time of solidification is no longer pronounced.

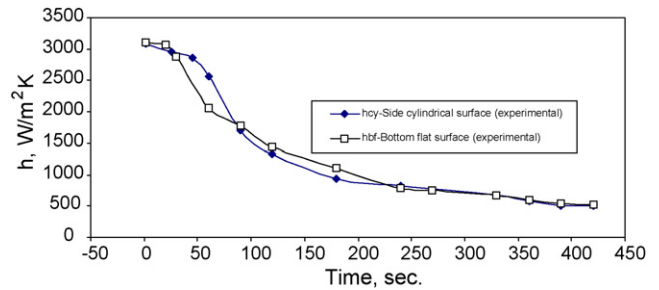


**Fig. 6 – Effect of time of solidification of aluminium metal on heat transfer coefficients with pressure application ( $P = 85.86$  MPa) at side and bottom surfaces of steel mould.**

#### 4.3. Interface heat transfer coefficients with solidification temperatures

Figs. 7a and 8 show the calculated experimental interface heat transfer coefficients for solidifying molten aluminium metal as a function of solidification temperatures of the solidifying molten aluminium metal. Fig. 7a shows the variation of heat transfer coefficient with solidification temperatures of aluminium at the cylindrical surface, while Fig. 8 is the interface heat transfer coefficients with solidifying temperature at the bottom flat surface with and without the application of pressure on the solidifying metal. From the two graphs, the maximum interface heat transfer coefficients obtained without pressure and with pressure application in the bottom flat

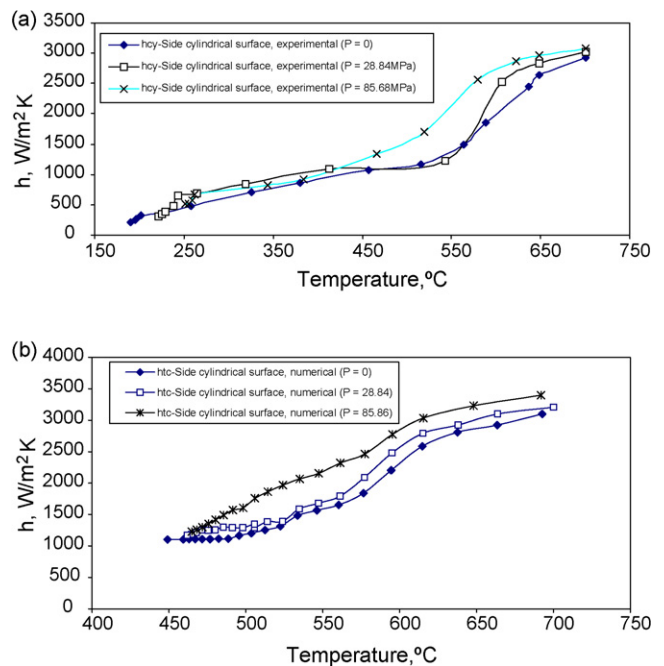


**Fig. 7 – (a) Typical effects of pressure application on the heat transfer coefficients with solidifying temperature at the side cylindrical mould surface by experimental method. (b) Typical effects of pressure application on the heat transfer coefficients with solidifying temperature at the side cylindrical mould surface by numerical method.**

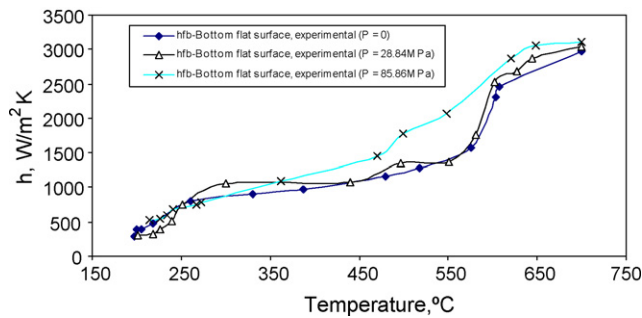


**Fig. 8 – Typical effects of pressure applications on the heat transfer coefficients with solidifying temperature at the bottom flat mould surface.**

surface of the steel mould are 2975.14 and 3351.08 W/(m<sup>2</sup> K) for no pressure and with pressure, respectively.

Fig. 7b shows the numerical values of the variation of interface heat transfer coefficients with the solidification temperature of aluminium metal at the cylindrical surface with the application of pressure. The maximum value of heat transfer coefficient of 3397.29 W/(m<sup>2</sup> K) at applied pressure of 85.86 MPa as compared to 3351.08 W/(m<sup>2</sup> K) obtained through the experimental procedure.

At solidifying temperature above 600 °C, a sharp reduction in the interface heat transfer coefficients is noticed at both surfaces as is seen from Figs. 7a, b and 8.

For temperatures below 500 °C, the interface heat transfer coefficients for both no pressure and pressure applications are close in values. This shows that at temperature below 500 °C, the effect of applied pressure is no longer significant on the interface heat transfer coefficient values. The drop in temperature results in solidification of the molten aluminium, which in turn leads to a drop in the heat transfer coefficient values. The effect of applied pressure on heat transfer coefficients of aluminium becomes more pronounced at solidifying temperatures above 500 °C which was also reported by Cho and Hong (1996). Below this temperature, the effect of applied pressure on interface heat transfer coefficient values becomes less pronounced.

Therefore, from Figs. 7a, b and 8, it is observed that the effect of applied pressure becomes more significant at temperature close to the liquidus temperature of aluminium as measured along the bottom flat surface of the steel mould (see Fig. 8). The maximum value of 3397.29 W/(m<sup>2</sup> K) is obtained for pressure level of 85.86 MPa as compared to 2975.14 W/(m<sup>2</sup> K) for no pressure at the bottom flat surface of the steel mould.

#### 4.4. Peak interface heat transfer coefficients with applied pressures

Fig. 9 shows the variation of peak values of interface heat transfer coefficients with and without pressure applications. Higher experimental values of heat transfer coefficients are obtained at the bottom flat surface than at the cylindrical surface of the steel mould (see Fig. 9). This effect can be associated to greater effect of pressure application experienced at the bottom flat surface than at the side cylindrical surface, thus leading possibly to greater additional internal heat

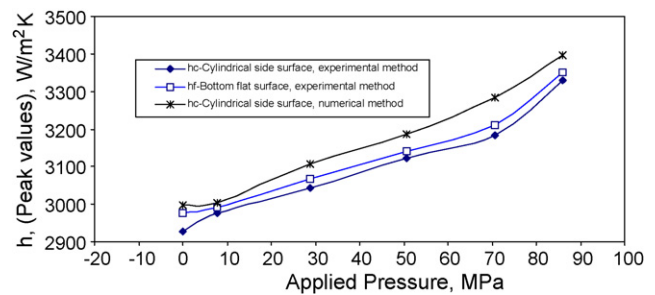


**Fig. 9 – Effect of pressure on the peak values of heat transfer coefficients of aluminium metal at liquidus stage at side and bottom flat moulds' surfaces.**

energy generated, and hence higher values of heat transfer coefficients obtained. The results of numerical determination of heat transfer coefficients as shown in Fig. 9 shows higher values as compared to the experimental obtained values. At applied pressure of 85.86 MPa, the heat transfer coefficients obtained is 3397.29 and 3351.08 W/(m<sup>2</sup> K) by numerical and experimental procedures, respectively. From the curves of heat transfer coefficients obtained with temperatures (see Figs. 7a, b and 8), three distinct portions are noticed. These portions are easily differentiated by the aluminium solidification temperature. These temperatures are below 500 °C, solidus phase, 500–660 °C, liquidus–solidus phase, and above 660 °C liquidus phase of solidification of molten aluminium.

The liquidus–solidus phase, which occurs over a solidification temperature range of 500–660 °C, instead of a constant solidification temperature of 660 °C can be attributed to the presence of impurities such as silicon, magnesium and manganese in the commercially pure aluminium a fact supported by Higgins (1983).

The empirical equations for each of the distinct phase changes as a function of applied pressures and solidification temperatures are determined for both the experimental and numerical methods. The empirical equations obtained are for mean average values of heat transfer coefficients based on the experimental method at the cylindrical and flat bottom surfaces. These are

Temperatures below 500 °C (solidus phase),

$$h_S = 3.081T + 1.303P - 232.942 \quad (7)$$

with coefficient of correlation  $r = 0.9545$ .

Temperatures between 500 and 660 °C (liquidus–solidus phase),

$$h_{LS} = 10.420T + 5.641P - 4176.022 \quad (8)$$

with coefficient of correlation  $r = 0.9884$ .

Temperatures above 660 °C (super heat, liquidus phase),

$$h_L = 2.769T + 2.518P + 988.921 \quad (9)$$

with coefficient of correlation  $r = 0.7825$ .

The empirical equations obtained through the numerical methods are from the results of the computer simulations of heat transfer coefficients at the cylindrical cast metal/steel

mould interface by the application of various applied pressures. The empirical equations are

Temperatures below 500 °C (solidus phase),

$$h_{\text{Snum}} = 3.849T + 3.643P - 700.427 \quad (10)$$

with coefficient of correlation  $r = 0.969$

Temperatures between 500 and 660 °C (liquidus–solidus phase),

$$h_{\text{LSnum}} = 9.027T + 3.414P - 3000.625 \quad (11)$$

with coefficient of correlation  $r = 0.964$ .

Temperatures above 660 °C (super heat, liquidus phase),

$$h_{\text{Lnum}} = 2.489T + 2.787P + 1342.19 \quad (12)$$

with coefficient of correlation  $r = 0.772$ .

## 5. Conclusion

From the present investigation, the following conclusions can be made:

- The temperature versus time curves deduced by extrapolating to steel mould/cast metal interface by polynomial curve fitting to heating temperatures at various steel mould heating times with distance locations in the steel mould are found to be close in values to the usual numerical methods applied by other authors. The interfacial heat transfer coefficients obtained by the numerical and experimental methods under no pressure application are found to agree within 2975 and 2998 W/(m<sup>2</sup> K) from the numerical obtained values.
- Effect of pressure application on the solidifying molten aluminium is more pronounced at solidification temperature above 500 °C of the cast aluminium specimen on the values of the interface heat transfer coefficients obtained. Interface heat transfer coefficients are found to decrease with increase in solidification time in both the cylindrical and bottom flat surfaces of the steel mould and thereafter remain fairly constant at temperature below 500 °C.
- Values of experimental peak heat transfer coefficients at the bottom flat surface are found to be higher with pressure application on the solidifying aluminium metal than at the cylindrical surface.
- The empirical equations, relating interface heat transfer coefficients to the applied pressures and solidification temperature at three distinct stages of solidifying molten aluminium are also given.

## Acknowledgements

The authors wish to acknowledge the assistance rendered by the Authority of the Institute of Technology, Kwara State Poly-

technic, Ilorin, Nigeria for making their laboratory available for use.

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