Simulation of Solidification Time of Commercially Pure Aluminium Casting in Metallic Moulds

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Abstract

Solidification of metals poses many practical problems associated with phase transformation, shrinkage and heat transfer processes. Evaluation of solidification time is one of the important parameters used for assessing the properties of the metal castings. A mathematical model based on the control volume method with fixed mesh was selected in order to simulate the solidification of cast aluminium in permanent steel moulds. A mathematical model was developed which allowed obtaining of solidification time and the temperature fields at any time during solidification of commercially pure aluminium casting and in the metallic mould. An experimental casting of commercially pure aluminium was carried out in rectangular metallic mould. The temperature fields in both the cast and the mould to a very high accuracy were recorded using RD8600 digital temperature recorder. Solidification times in castings and metallic moulds were determined from the cooling and heating curves at various locations in casting and mould. The results showed that the solidification time obtained by experimental study compares favourably well with that determined by the analysis made through simulation modelling.

Key words

Simulation, Solidification, Metallic mould, Aluminium, Casting, Heat transfer, Temperature.

1. Introduction

Solidification is a phase transformation process from liquid to solid state. It is a process accompanied by the release of latent heat at the solid-liquid interface. When molten metal is poured into a mould, heat is extracted from the molten metal by the mould, resulting in a decrease in the molten metal temperature at the mould surface, thus initiating the process of solidification [1]. The primary and most obvious phenomenon controlling casting is the heat transfer rate from the cooling metal to the mould.

Solidification differs depending on whether the metal is a pure element or an alloy. When molten metal is poured into a mould, a series of events take place during solidification of the casting and its cooling to ambient temperature. These events greatly influence the size, shape, uniformity, and chemical composition of the grains formed throughout the casting, which in turn influences its overall properties. The significant factors affecting these events are the type of metal, thermal properties of both the metal and the mould, the geometric relationship between volume and surface area of casting, and the shape of the mould.

The solidification process can be represented using cooling curves showing a variation of temperature with respect to time. A cooling curve is a line graph that represents the change of phase of matter, typically from a gas to a solid or a liquid to a solid. The independent variable (x-axis) is time and the dependent variable (y-axis) is temperature [2]. Cooling rates are important in controlling the quality of a casting since by monitoring the cooling rate and the thermal gradient solidification shrinkage defects can be detected. The most important part of the cooling curve is the cooling rate which affects the microstructure and properties.

Rate of heat transfer between solidifying casting and mould is critical for achievement of a high quality casting. This is especially important in permanent mould casting where the heat transfer between the casting and the mould are primarily controlled by conditions at the mould-metal interface. The solidification of metals, and in particular aluminium and its alloys are prone to defects, such as porosity, one of the chronic problems, as well as shrinkage cavity which impact on the quality of the castings and degrade the mechanical properties, such as tensile strength and fatigue life [3]. Solidification mechanism plays a vital role and forms the basis for influencing the microstructure of castings and hence improving the quality of the cast products. Solidification defects tend to persist throughout subsequent operations. Therefore, good control of solidification process at the outset is of utmost importance [4].

In recent years, the development of digital computer technology and applied numerical methods has provided a powerful means for simulating casting solidification. As computer-aided design and manufacture experience increasing use in industries, computer modelling of solidification process in foundry appears to be of great interest since it enables the microstructure, final shape, residual stresses, and defects to be predicted. Numerical simulation has become a fast indispensable tool in technological discovery and development and a strong driving force in the development of science and technology [5].

Numerical simulation is playing an increasingly important role in support of industrial casting processes. The goal of simulation is to accurately capture solidification dynamics in pure and in alloy materials. To achieve this goal, numerical algorithm must accurately evolve the latent heat in an isothermal solidification process [6]; and it must also accurately couple the temperature and concentration fields in the non-isothermal solidification of multi-component alloys. Many researchers have used the numerical methods to model the casting process [7, 8, 9]. Also, both the finite difference method and the finite element method have been used to model casting and solidification process [10].

This research studied the temperature distribution in aluminium cast as well as that in the metallic mould by simulating the governing heat transfer models and developing a computer programme to predict solidification time and rate of heat transfer in aluminium castings.

2. Material and Method

In the simulation of the solidification process, the partial differential equation (1), [12], was applied to the volume occupied by the molten metal and indeed the mould by partitioning into finite number of control volumes and then applying the energy conservation equation (2), [13], to each control volume to obtain a discrete heat balance.

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + \rho L \frac{\partial f_S}{\partial t} \tag{1}$$

Where ρ is the density; c is the specific heat capacity; T is the temperature; t is the time; k is the thermal conductivity; L is the latent heat of fusion; f_S is the fraction of solid of cast metal; ∇ is the gradient operator.

$$\int_{t_n}^{t_{n+1}} \frac{\partial}{\partial t}\left(A \int_{x_{i-\frac{1}{2}}}^{x_{i+\frac{1}{2}}} E(x,t)dx \right) dt = -\int_{t_n}^{t_{n+1}} A \int_{x_{i-\frac{1}{2}}}^{x_{i+\frac{1}{2}}} \vec{q}(x,t)dxdt \tag{2}$$

Where, E is the energy per unit volume in the molten metal; $\vec{q}$ is the heat flux; x is the spatial coordinate; i is the nodal point; A is the surface area.

Therefore,

$$E(x,t) = \int_{T_m}^{T(x,t)} \rho c_S(T)dT \qquad T(x,t) < T_m \qquad (solid) \tag{3}$$

$$E(x,t) = \int_{T_m}^{T(x,t)} \rho c_L(T)dT + \rho L \qquad T(x,t) > T_m \qquad (liquid) \tag{4}$$

Where T_m is the melting temperature of metal; c_s, c_L are the specific heat capacity of solid and liquid metal respectively.

If c_S , c_L = constants, then

$$E = \rho c[T - T_m], \qquad T < T_m \tag{5}$$

$$E = \rho c[T - T_m] + \rho L, \qquad T > T_m \tag{6}$$

Solving for the temperature T, we have:

$$T = T_m + \frac{E}{\rho c_S}, \qquad E < 0 \qquad \text{Solid} \tag{7}$$

$$T = T_m, \qquad 0 \le E < 0 \qquad \text{Interface} \tag{8}$$

$$T = T_m + \frac{E - \rho L}{\rho c_L}, \qquad E \ge \rho L \qquad \text{Liquid} \tag{9}$$

To be able to update from any time t_n to the next ($t_n + \Delta t_n$) the phase or the state of the metal must be known. This was achieved by considering the phase indicator – liquid fraction (f_L) of the control volume defined as follows:

$$f_L^n = 0, \qquad E_i^n < 0 \qquad \text{Solid} \tag{10}$$

$$f_L^n = \frac{E_I^n}{\rho L}, \qquad 0 \le E_i^n < 0 \qquad \text{Interface} \tag{11}$$

$$f_L^n = 1, \qquad E_i^n \ge \rho L \qquad \text{Liquid} \tag{12}$$

If, $0 < f_L^n < 1$; the control volume is mushy with liquid volume ($f_L^n \Delta x_i$) and the solid volume $(1 - f_L^n)\Delta x_i$ per unit cross-sectional area. Knowing the enthalpy, temperature and phase of each control volume, the resistances and the fluxes can be computed which are then used to update the enthalpies, which in turn yield new temperatures and phase states.

Chvorinov's equation [2] for solidification time (t_s) in sand moulds was modified for metallic moulds by considering the heat balance across the metal/mould interface to yield solidification time for casting in a metallic mould as:

$$t_s = \frac{\rho_m \left[L + C_m \left(T_p - T_m\right)\right] V_m}{h\left(T_m - T_o\right) A_m} \tag{13}$$

Where, T_o is the initial temperature of the mould; T_p is the pouring temperature of metal; L is the latent heat of fusion; *h* is the interfacial heat transfer coefficient; ρ_m is the density of the metal; c_m is the specific heat of the metal; V_m is the volume of metal; A_m is the surface area of metal.

Computer codes for the simulation of solidification of commercially pure aluminium were written in VISUAL BASIC language by considering equations (1) to (13).

3. Results

The results of the simulation for the solidification of commercially pure aluminium casting obtained from the developed computer programme are presented in the Figures 1 to 3 below showing the temperature fields at specify locations in the aluminium cast during solidification, heating and cooling of the metallic mould.

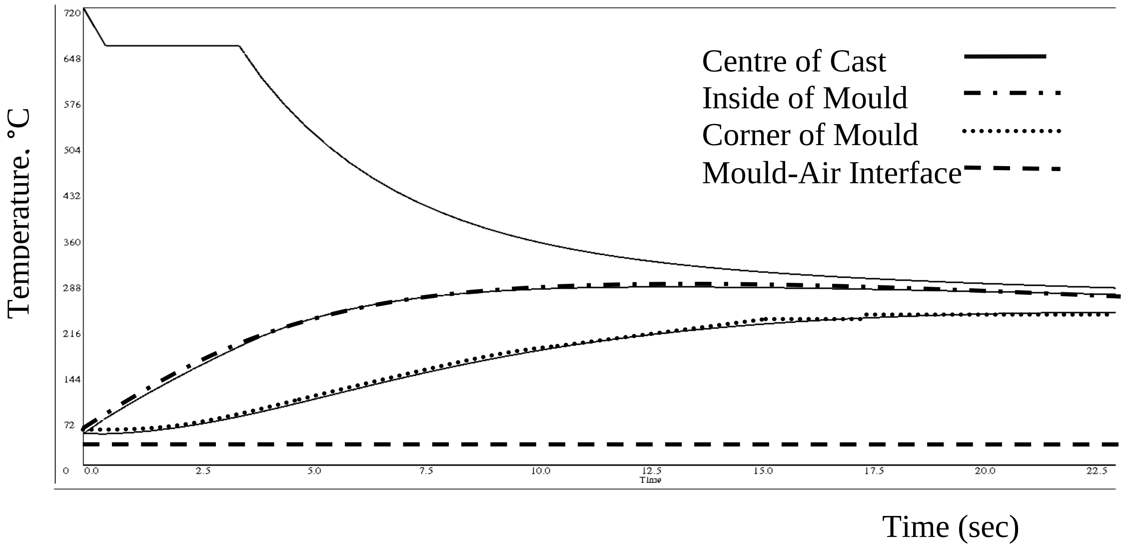

Fig.1. Cooling curve during the solidification of the aluminium metal and the heating curve of the mould at the 50th iteration at time interval of $\Delta t = 0.5$ seconds for the complete cast.

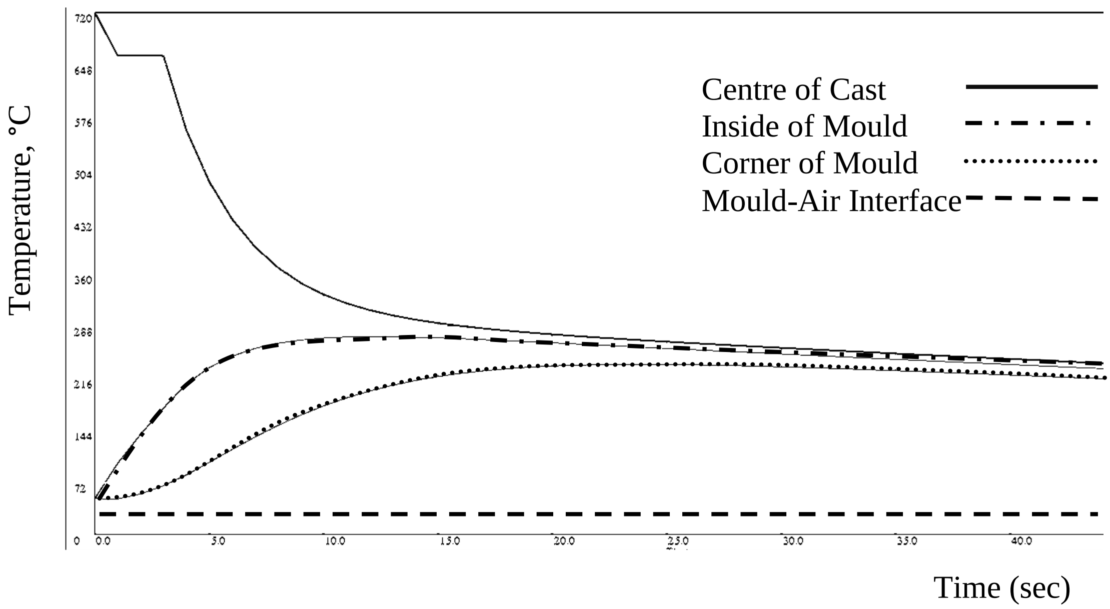

Fig.2. Cooling curve during the solidification of the aluminium metal and the heating curve of the mould at the 50th iteration at time interval of $\Delta t = 1.0$ seconds for the complete cast.

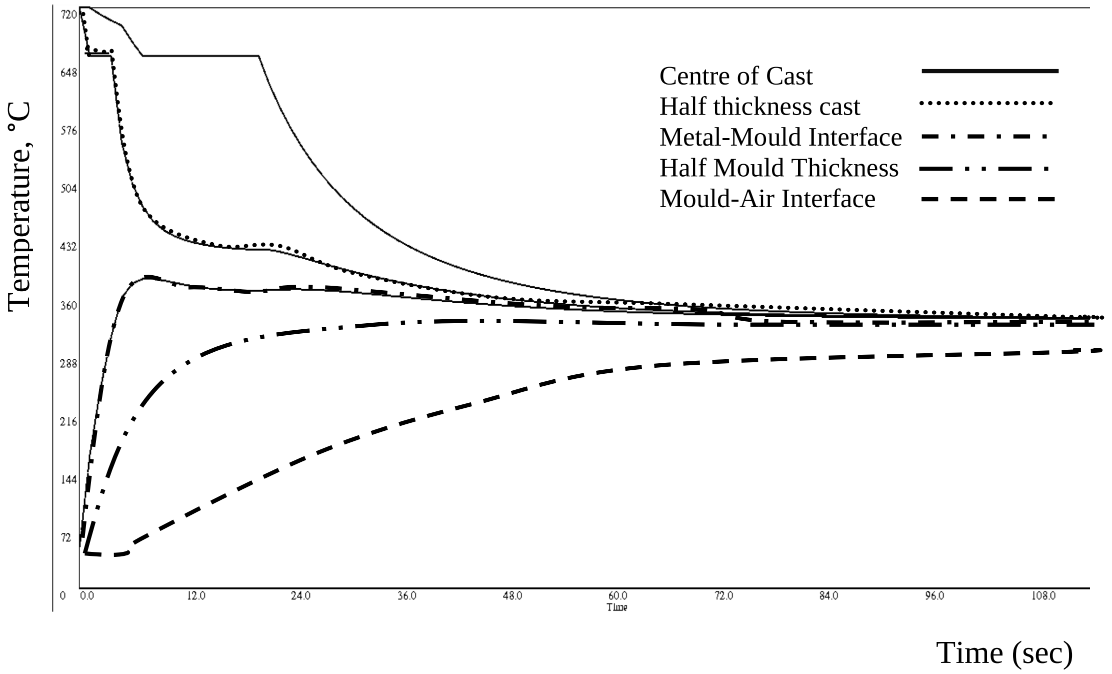

Fig.3. Cooling and heating curves during the solidification of the aluminium metal at the 100th iteration and time interval of $\Delta t = 1.2$ seconds for four nodes of the aluminium cast at a mould initial temperature of 50°C, showing a solidification time of 21.6seconds.

The solidification times are shown in Table 1. From these varied solidification times it is evident that the process of solidification of the aluminium metal is slower when the mould is preheated.

Table 1. Variation of Mould Temperature with Solidification Time during Simulation for Pure aluminium

Mould Temperature (°C)	Pouring Temperature (°C)	Solidification Time (seconds)
50	720	21.6
100	720	22.8
150	720	26.4
200	720	28.8
250	720	36.0
300	720	42.0
350	720	52.8

Experimental Results

In order to validate the simulation results, experiments were performed to obtain quantitative data during the solidification of commercially pure aluminium. The experiments were to establish the solidification time as well as the temperature profiles within the cast while it cools and also in the mould as it heats up. The experiments were conducted in top poured, vertically parted rectangular of varying thicknesses of 12.5mm, 25.0mm and 37.5mm respectively.

Figure 4 shows the cooling curves of the centre of aluminium cast for the various thicknesses of rectangular moulds for the commercially pure aluminium during experimentation.

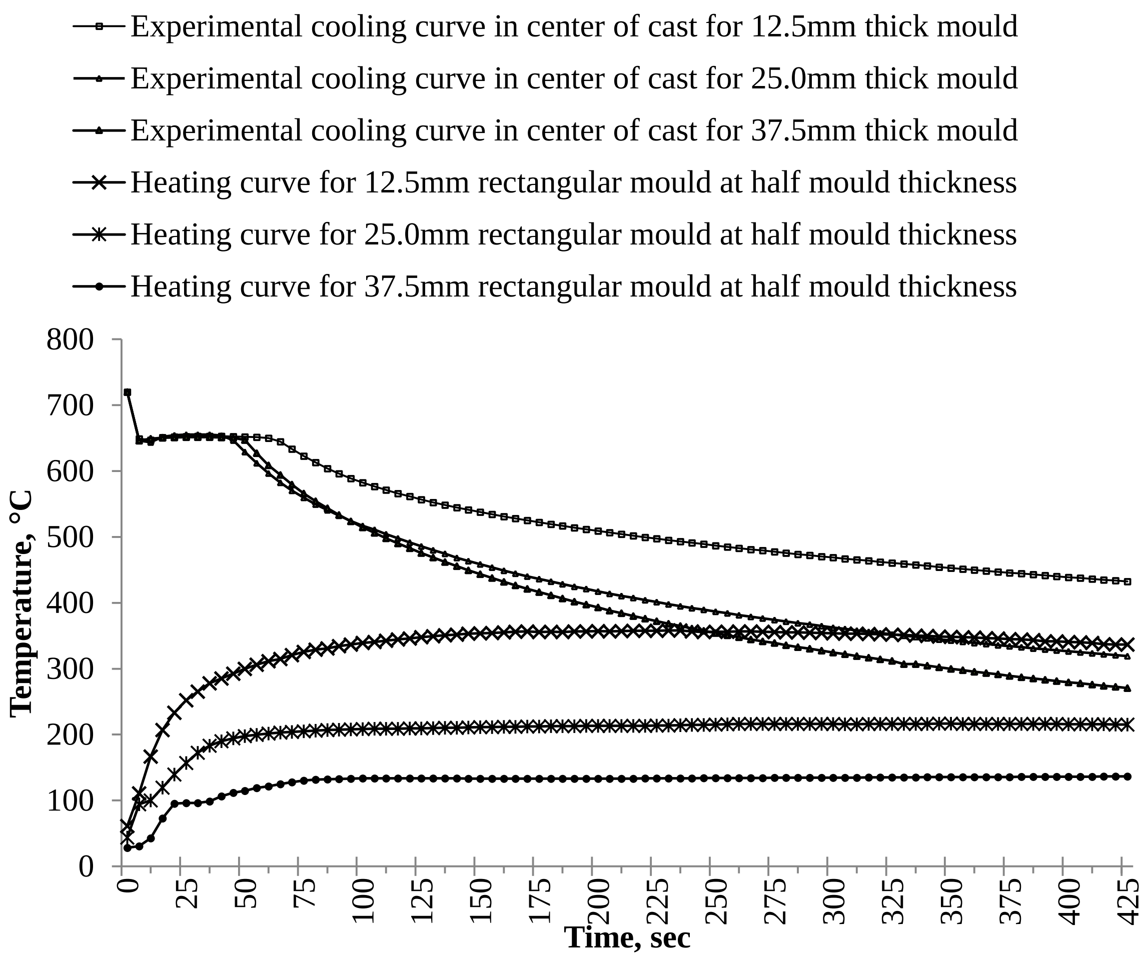

Fig.4. Experimental cooling curves for the solidification of commercially pure aluminium cast and the heating curves of the metallic moulds

Table 2 presents the solidification time of the aluminium cast with increase in mould thickness. The moulds were kept at an initial temperature of 50°C and the molten aluminium poured at 720°C. The solidification time for each thickness was obtained from the plot of graphs from the paperless temperature recorder at the point when the solidified aluminium cast started reducing in temperature from the constant value of fusion temperature.

Table 2. Variation of Solidification Time with Mould Thickness in Rectangular Mould for Commercially Pure Aluminium

Mould Temperature (°C)	Pouring Temperature (°C)	Mould Thickness (mm)	Solidification Time (seconds)
50	720	12.5	21.8
50	720	25.0	22.4
50	720	37.5	23.8

Validation of Simulated and Experimental Results

Figure 5 shows a typical comparison of the temperature versus time curves for the solidifying molten aluminium metal.

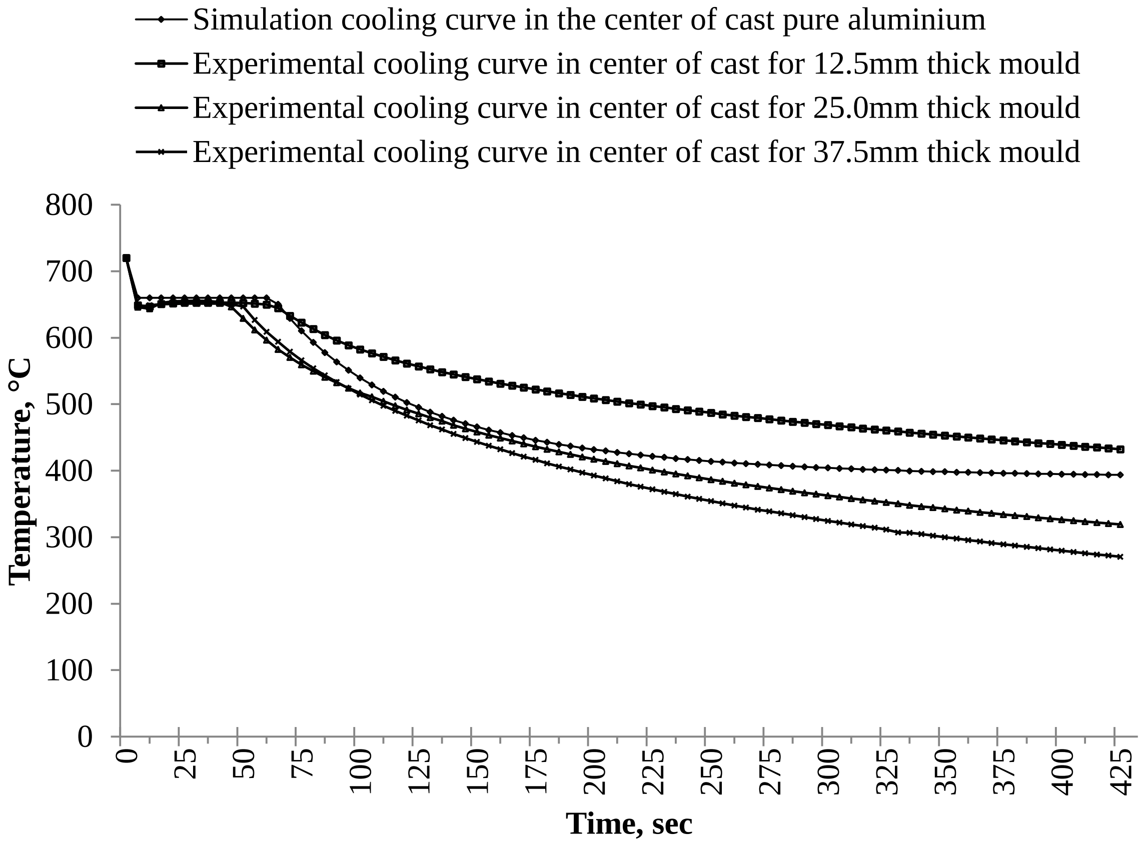

Fig. 5. A comparison of simulated and the experimental cooling curves for the solidification of commercially pure aluminium cast

Figure 5 shows the comparison of the simulated results obtained from the developed programme and the experimental results obtained from experiment performed using the commercially pure aluminium. The results obtained from experimentation using the commercially pure aluminium was compared with the simulated results obtained from the computer programme and were found to be in close agreement. The slight variation is that, while in the simulated results, solidification was completed at a constant temperature of 660°C and the experimental case had solidification temperature lowered to about 655.9°C, due to impurities.

4. Discussion

Figure 1 is the graph of the simulated temperature of the entire molten aluminium metal within the mould time after the 50th iteration. The graph depicts the cooling of the molten aluminium metal from its superheated temperature of 720°C to the fusion temperature of 660°C and subsequent cooling of the aluminium cast to the ambient temperature. It also shows the heating curves for the mould as it extracts heat from the aluminium metal, rising to a maximum and gradually decreasing until it becomes slightly constant. From the graph the aluminium metal solidified at a total time of 4.0 seconds.

The graph of Figure 2 shows cooling curve of the aluminium cast and the heating curve of the metallic mould at 1.0 second time interval, the rate of heat dissipated to the mould is higher and faster thereby resulting in raising the mould’s temperature to a maximum of 270°C. The number of nodes was increased to four as shown in Figure 3 and the centre of aluminum cast solidified at approximately 21.6 seconds. The solidification times for the cast was also demonstrated by preheating the mould to varying temperatures of 50°C 100°C, 150°C, 200°C, 250°C, 300°C and 350°C respectively. The results give significant variation of the solidification times as shown in Table1.

Figure 4 gives the solidification (cooling curves) of the aluminium cast and the mould heating curves during the casting process using the commercially pure aluminium of 99.846% in rectangular moulds of thicknesses of 12.5, 25.0, and 37.5mm respectively. A close examination of the cooling curves shows that at the centre of the aluminium cast, the liquid aluminium metal cools quickly to the freezing temperature of approximately constant temperature of 655.5°C for the three mould thicknesses. There is a measurable thermal arrest at this location indicating the solidification time of the aluminium cast. It also shows the mould heating curves obtained at the half mould thickness. Temperature rises rapidly in the 12.5mm thick mould from the beginning of solidification until it reached a maximum value, it then start decreasing. Whereas a progressive rise in temperature is observed for the thicker moulds of 25.0mm and 37.5mm the temperature increase to a maximum point and then remain slightly constant indicating slow extraction of heat. The results of solidification times shown in Table 2 at 50°C mould temperature indicate the solidification times are quite close.

5. Conclusion

The simulation has shown that by considering the molten aluminium metal as a single volume, the solidification time remains the same. As the numbers of nodes are increased, the solidification time was affected significantly. Considering the entire molten aluminium metal as a single volume, solidification time is shorter as against when the numbers of nodes were increased. The simulation of solidification of commercially pure aluminium for preheated moulds of 50°C to 350°C at an increment of 50°C shows that the solidification time is more when mould preheat temperature is increased. The simulated results of the temperature fields and the experimental values for cooling and heating curves have shown a good agreement, and consequently good reliability for determining solidification time.

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