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Depicting Aluminium DC Casting by Means of Dimensionless Numbers

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Abstract

DC casting of aluminium and its alloys is a controlled heat removal solidification process. The rate of heat extraction has strong effects on the microstructure and mechanical properties of the solidified alloy ingots. In view of this strict temperature, control over the ingot as it solidifies should be implemented in order to achieve metal with the best possible properties. In situ direct temperature measurements are complicated; so in this report, the use of dimensionless analysis to predict temperature distributions on the ingots as they are casted is proposed. It is reported that the dimensionless groups that better represent the impact of process variables on the solidification of aluminium and its alloys are the Péclet (Pe) and Biot (Bi) numbers.

Keywords: DC casting, aluminium alloys, dimensionless numbers, solidification, mechanical properties

1. Introduction

Aluminium alloys are widely processed through direct chill (DC) semi-continuous casting. This process was developed almost simultaneously in Europe and in the United States shortly before the Second World War [1].

Nowadays, DC castings can be found in any aluminium casting shop. The process can be described as [2] 'The process involves a short mold of a desired shape to form an ingot by mold cooling. The ingot thus formed is lowered at a predetermined rate and solidification is completed by direct application of water below the mold'.

From the previous description, it is clear that metal solidification strongly depends on cooling water flowrate, casting velocity and mould geometry [3]. Additionally, it is expected that the chemical composition of the cast alloy will influence process parameters [2, 3].

Depending on the aluminium alloy to be casted, different operational problems may arise; for example, consider 1XXX alloys. Given that these alloys are basically constituted of 99% mass aluminium, they require uniform water distribution [2] as well as proper temperature control, since most of the heat losses are attributed to radiation from the metal to its surroundings. Descriptions of problems encountered in DC casting of other aluminium alloying systems can be found elsewhere [2, 4].

As alloying systems get more complex (more components), it becomes more difficult to predict the mechanical properties and structural features of the ingots as they solidify. In view of this, this entry proposes to create a predictive tool to estimate the final alloy properties from dimensionless analysis.

2. Cooling systems in DC aluminium castings

Cooling systems are largely responsible for the solidification of the aluminium ingots. Metal cooling takes place by means of two cooling systems. The primary cooling system is located in the casting mould itself. The mould has a cavity between its walls; thus, cooling occurs as water passes through such cavity. The primary cooling system is used to withdraw the latent heat of solidification; in other words, solidification occurs as a consequence of this cooling system.

The second cooling system consists of water falling from the lower end of the mould. At the bottom of the mould's cavity, there are some holes alongside the length of the mould so water falls from it, forming a water curtain that wets the metal as the ingot is formed. This secondary cooling system removes the sensible heat from the already-solidified ingot. Furthermore, this cooling system completes the solidification of the ingot while it cools down the cast metal. **Figure 1** shows a sketch of the DC casting process.

2.1. Process parameters in DC casting

As sketched in **Figure 2**, during ingot casting three well-defined regions develop: liquid, solid and liquid + solid. The liquid region along with the solid + liquid one is known as sump. The sump is where the actual solidification takes place, and it is bounded between the liquidus and solidus isotherms. The sump itself can be divided into two regions, one known as slurry which is rich in liquid metal and the mushy, which is a mixture between the solid and liquid phases.

Within the sump, as heat is extracted from the liquid, the first solid particles start to appear. These starting solid particles are impinged with liquid metal, leading to a coherent microstructure [1, 5–8]. The microstructure can be altered by changing the process variables.

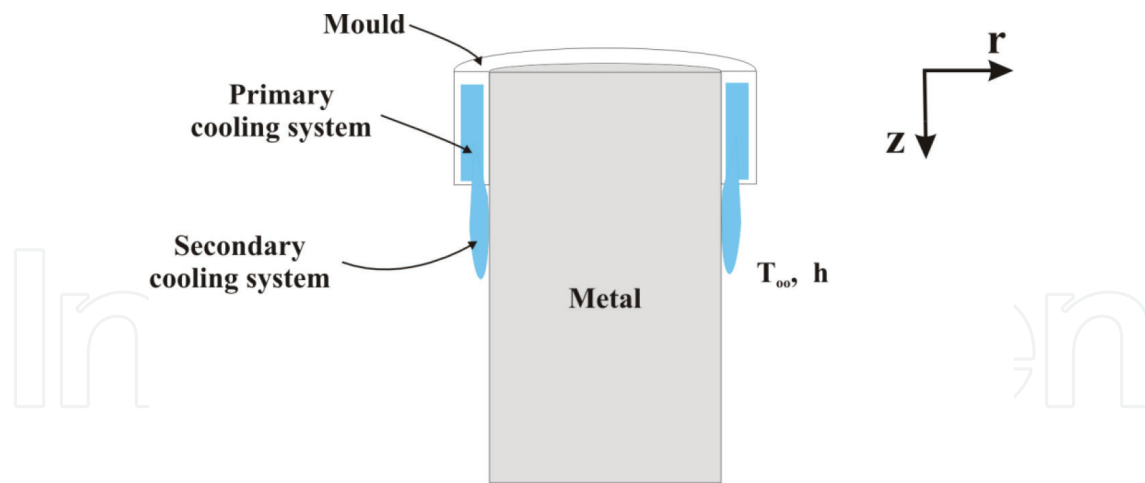


Figure 1. Sketch of an aluminium ingot processed by DC casting.

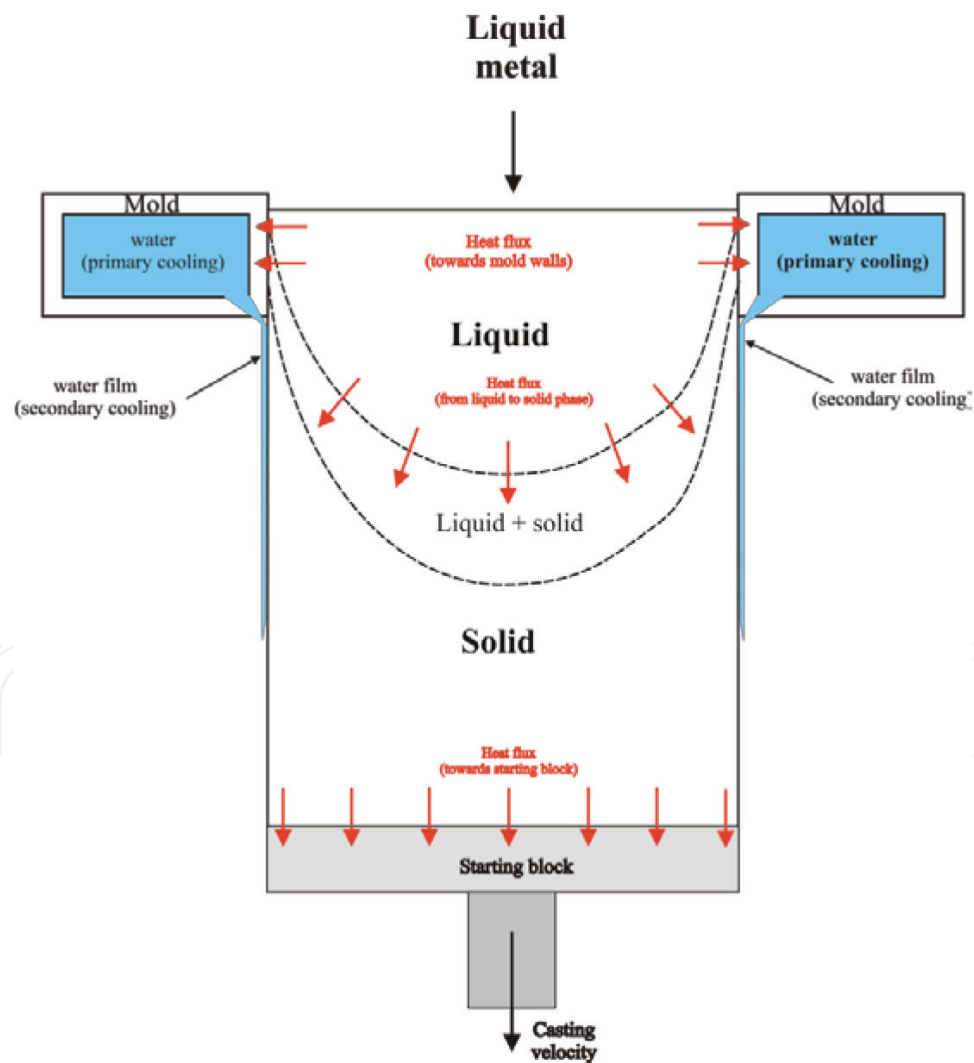


Figure 2. Heat extraction in DC casting; sketch showing main process variables.

The main process variables involved in the DC semi-continuous casting of aluminium and its alloys are:

- Chemical composition
- Cooling water flowrate (cooling rate)
- Casting velocity
- Melt casting temperature (superheat)

2.1.1. Chemical composition

Given the little heat extracted from the liquid phase, most of the heat is withdrawn from the solidification, and the solid phase, thus temperature distribution within the aluminium ingot as it is cooled, might be directly related to the thermal conductivity of the alloy being cast. Depending on the number of alloying elements and the actual aluminium content in the alloy, the liquidus and solidus lines may change accordingly.

Data [9, 10] in **Figure 3** show how the thermal conductivity changes with the aluminium content in different alloys. Such changes directly impact the size and depth of the sump and consequently the local time of solidification; thus, the rate of heat extraction accordingly changes, resulting in modifications to the final microstructure of the solid ingot.

2.1.2. Cooling water flowrate

Cooling water flowrate inside the caster mould is important in the semi-continuous casting of aluminium alloys. Using higher water flow results in higher heat extraction from the melt, and this affects the sump depth.

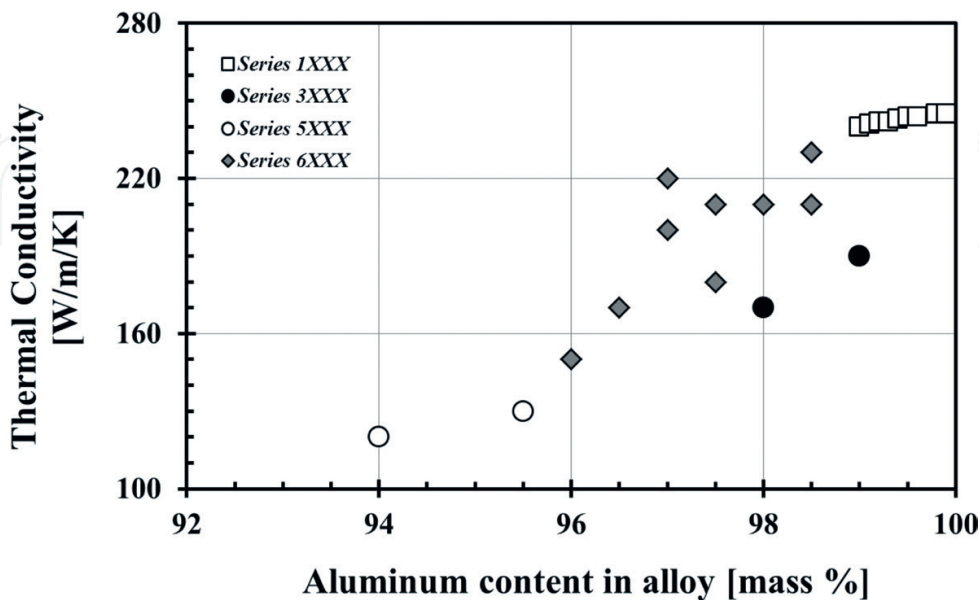


Figure 3. Thermal conductivity of some aluminium alloys [9, 10].

The overall heat balance determines that it must be a minimum water flowrate that can be used during casting to ensure the solidification (enough heat is removed) before the ingot exits the mould, avoiding liquid metal breakout [11, 12].

Increased cooling results in decreasing the sump depth; exhaustive cooling has minimal consequences for the thickness of the solid shell and that of the mushy zone [5]. To prove this, experiments on heated materials (on one side) and cooling down with water spraying on the opposite side of the heating were conducted [13]. From these tests, it was concluded that heat transfer coefficients in the nucleate boiling regime do not change significantly with the water flowrate; however, the cooling flowrate affects the point at which film boiling happens.

Additionally, it has been shown [11, 13] that using cooling water up to 30°C has no effect on the cooling rate of the cast ingot. However, if the cooling water exceeds 70°C, then it may have some negative effects on the depth and thickness of the mushy zone [13, 14].

It has also been found [15] in a stationary laboratory-scale facility that the heat flux is greatly affected by the thermal conductivity of the aluminium alloy. Surface morphology and the initial temperature of the metal sample to be cooled also affect the heat flux. It has been independently concluded [11, 15–17] that the heat flux increases with higher water flowrates, ingots with rougher surfaces and lower cooling water temperature.

In addition to that, it was revealed [18, 19] that there is a strong dependence between temperature distribution and sump depth on casting speed, but also there is a relatively weak dependence on the flowrate of the quenching water striking the outside of the ingot. Furthermore, decreasing the water flowrate by 20% deepens the sump by 4% [19].

2.1.3. Casting velocity

Casting velocity is perhaps the most dominant process variable in aluminium DC casting [5, 16]. Typical values for casting velocities found in industrial shops lie within 3 and 20 cm/min. These velocities depend among other things on chemical composition and ingot size. Also, commercial flowrates are found to be between 0.12 and 0.24 L/min per 1 mm of mould characteristic length [1].

Tests on the casting of magnesium-based alloys [20] showed that casting speed has a large impact on the pool depth. As casting velocity is increased, the metal pool deepens. Casting velocity affects the centre of an ingot the most, with less effect towards the ingot edges. The pool's depth increases proportionally to increments in casting velocity, despite the chemical composition of the casting alloy [14].

Increasing casting velocity conveys into high cooling rates. This is due to high thermal gradients developed inside the ingot. These are provoked by higher energy extraction rates at the water impingement point to keep the system under equilibrium. Faster casting velocities require a corresponding hike in heat flux, as more heat is removed from the ingot [21, 22].

As the casting velocity increases, so does the ingot surface temperature around the secondary cooling, especially at the water impingement point; this affects the water cooling regimes. At the beginning of the casting operation, water film boiling regime occurs, and this increases as the casting approaches steady-state conditions, thus reaching the nucleate boiling regime [22].

Casting velocity can only be increased up to the point in which the cooling water is no longer able to extract heat from the metal surface. If this happens, the ingot shell could remelt, and liquid aluminium may spill and even get in contact with the water. This represents a high risk for an explosion.

2.1.4. Casting temperature

Usually, commercial aluminium alloys are cast between 680 and 730°C; considering that pure aluminium melts at 660°C, the extra heat added to the melt is not as significant as it is in other alloying systems such as alloyed steels.

Casting temperature has very little effect on the overall heat extraction rate; this is because the specific heat of the molten metal at the most represents 7% of the total heat input in the caster. Additionally, the sensible heat of solidification may add another 35–40% of the heat input.

3. Heat transfer in DC aluminium casting

Solidification is the most important process taking place during DC casting. The rate at which solidification occurs directly relates to the roughness of the resulting cast microstructure. The solid microstructure directly relates to the segregation of chemical elements in the alloy matrix, the precipitation of second phases and the occurrence of porosities and inclusions; all of these effects factors into the mechanical properties of the solid metal.

Heat transfer goes from the liquid (hot zone) towards the solid (cold zone). Energy is basically removed by convection and conduction mechanisms. Radiation heat transfer has very little effect on this process and can be neglected. Temperature distribution depends on the balance between heat input and output.

Heat input depends on the amount of thermal energy stored in the melt and the casting rate. The energy content is made up of the specific heat of the liquid (~5–7%), the latent heat of solidification (~30–35%) and the specific heat of the solid (balance) [1, 16]. On the other hand, the solidification of the cast alloys depends on the density of the metal, the casting velocity and ingot size.

As latent heat is removed from the melt, initial solid clusters start to develop in the metal next to the mould wall. The more the extracted heat, the higher the solid fraction present in the melt. As cooling proceeds, the solid fraction increases until reaching full solidification of the metal.

To determine the temperature distribution within the ingot as it is cast, it is necessary to solve the general heat transfer Eq. [23], which for the semi-continuous casting of aluminium has the form [24]:

$$\frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) - u \rho C_p \frac{\partial T}{\partial z} = \rho \cdot C_p \frac{\partial T}{\partial t} \quad (1)$$

In this equation, u is the casting velocity [m/s], ρ is the density of the casting aluminium alloy [kg/m³], C_p is the heat capacity (at constant pressure) of the aluminium alloy [J/kg/K], k is the

thermal conductivity of the alloy [W/m/K], t is the time [s], x and y are spatial coordinates [m] and T is the temperature [K]. The z coordinate relates to the casting velocity through the casting time, so it can be expressed as $z = u \times \text{time}$ [25].

Eq. (1) results from a macroscopic heat balance. The first two terms in Eq. (1) relate to heat conduction within the ingot, whereas the third term is due to heat extraction caused by the ingot motion at the casting velocity.

For calculation purposes it is often assumed that casting proceeds under steady-state conditions and that the heat removed in the z direction is negligible. Thus, heat conduction prevails both in the x and y directions. Additionally, as casting proceeds and the liquid alloy cools down, an additional term involving the latent heat of solidification (ΔH_{solid}) released during phase change from liquid to solid must be added to Eq. (1); this results in

$$\frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) = \rho \cdot \frac{\partial(\Delta H_{\text{solid}})}{\partial t} \quad (2)$$

Eq. (2) applies to either the solid or liquid phase, while the thermal conductivity of the metal along with the latent heat of solidification varies with both temperature and position. It is noteworthy that ΔH_{solid} is a function of temperature; thus, Eq. (2) reduces and takes the form

$$\frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) = \rho \cdot \left(\frac{\partial \Delta H_{\text{solid}}}{\partial T} \right) \cdot \frac{\partial T}{\partial t} \quad (3)$$

The left-hand side of this expression can easily be related to the convective heat transfer due to water cooling. The term on the right-hand side represents the latent heat removal due to the solidification itself [24]. Eq. (3) can be solved numerically [17, 22, 24, 26–29]. Temperature fields can be computed from this equation as well as stress and deformation fields; however, further discussions on the latter are beyond the scope of this entry.

According to Hakonsen and Myhr [24], heat transfer in aluminium casting operation can be described by using the dimensionless Péclet and Biot numbers. Péclet number represents the ratio of convective to conductive heat transfer [30] and is defined as

$$Pe = \frac{Lu}{\alpha} \quad (4)$$

where L is a characteristic length (geometrical factor) [m], u is the casting velocity [m/s] and α is the thermal diffusivity of aluminium [m²/s], which is defined as

$$\alpha = \frac{k}{\rho C_p} \quad (5)$$

Similarly, Biot number is defined as the ratio of the internal thermal resistance to the surface film thermal resistance [30]; this is expressed as

$$Bi = \frac{hL}{k} \quad (6)$$

In Eq. (6), h is the heat transfer coefficient between cooling water and aluminium ingot [W/m²/K]. The other variables in Eqs. (4)–(6) have been already defined.

In view of the former, it has been proposed that Eq. (3) can be rewritten as [24]

$$\frac{\partial^2 T}{\partial X^2} + \frac{1}{Pe} \frac{\partial^2 T}{\partial Y^2} = \Phi \cdot \frac{\partial T}{\partial Y} \quad (7a)$$

$$\frac{\partial^2 T}{\partial R^2} + \frac{1}{R} \frac{\partial T}{\partial R} + \frac{1}{Pe^2} \frac{\partial^2 T}{\partial Y^2} = \Phi \cdot \frac{\partial T}{\partial Z} \quad (7b)$$

Eq. (7a) is defined for Cartesian coordinates, whereas (7b) is for cylindrical coordinates. These last equations are fully expressed in terms of dimensionless variables; thus R , X and Y vary from 0 to 1 and represent r , x and y dimensionless directions, respectively:

$$R = \frac{r}{r_0} ; \quad Y = \frac{y\alpha}{y_0 u} ; \quad X = \frac{x\alpha}{y_0 u} \quad (8)$$

In addition to the dimensionless parameters in Eq. (8), expression 7a and expression 7b present the Φ parameter which represents the actual solidification process. Φ is a function of temperature and accounts for the release of latent heat and the decrease of the liquid fraction as time increases. This function is represented by

$$\Phi = 1 + \frac{\Delta H_{solid}}{\rho C_p} \frac{\partial(\rho f_l)}{\partial T} \quad (9)$$

In (9) f_l represents the liquid fraction within the solidification range. This fraction depends both on the temperature and the cooling rate. However, in DC casting the cooling rate remains fairly constant, meaning that in fact f_l only depends on the temperature.

It has been observed [1, 24] that in aluminium DC casting, the Péclet number typically lies between 1.4 and 4.5, whereas Biot number varies between 2 and 60. These results mean that both convective heat transfer and conduction have strong influence in the heat extraction.

Having determined that both convective and conductive heat extraction play a similar role, it is now necessary to relate these heat removal modes to the actual process variables, so based on the response of them, the expected solidification microstructure and consequently the final mechanical properties achieved by the final ingot can be predicted. To accomplish that, it becomes necessary to have an accurate estimation of the heat transfer coefficient.

3.1. Estimation of the heat transfer coefficient

Heat transfer coefficient is the key parameter in estimating convective heat transfer. As cooling water passes through the mould, it extracts considerable amounts of heat. The secondary cooling system removes the remaining heat from the molten phase.

The problem associated to the heat transfer coefficient is that this single parameter cannot be calculated directly from a specific equation. It depends on multiple factors that exist during the heat exchange: cooling agent flowrate, system geometry, existing thermal gradient, thermophysical properties, etc. Therefore, to determine the heat transfer coefficient as accurately as possible, this needs to be done from experimental measurements and data fit.

In this regard, many studies have been conducted to have precise estimations of the heat transfer coefficients involved in cooling down the aluminium ingots [7, 8, 13, 31–38].

It has been established [13, 31] that the critical convective heat flux is achieved when transitioning from nucleating to water film boiling regime. This transition directly relates to casting velocity. If this velocity reaches a critical speed, the ingot surface may exceed that of the nucleating-boiling transition, reducing the capability of cooling water to extract heat.

Based on this general observation, it has been suggested that typical heat transfer coefficients in DC casting primary cooling system are in the vicinity of 2000–3000 W/m²/K [32, 33].

Independent experiments have provided different expressions to determine the heat transfer coefficient as a function of different process variables. Santos et al. [34] proposed that the heat transfer between aluminium and a water-chilled mould coefficient varies with time as

$$h = 2000 \times t^{-0.17} \quad (10)$$

The time in Eq. (10) refers to the residence time of the melt in the mould. Eq. (10) is valid in the interval $0 < t < 250$ s.

A similar analysis was conducted by Aweda and Adeyemi [35]. They studied the heat transfer coefficient in squeeze casting of aluminium. They found that in the caster mould, the heat transfer coefficient between the melt and the mould is a direct function of the metal temperature and also the squeeze pressure. Assuming a pressure of 0 in the DC caster, there is no external applied force in the caster. The correlation for the heat transfer coefficient as a function of temperature is

$$h = 2.679T + 988.921 \quad (11)$$

Such correlation is valid for temperatures above 660°C.

Figure 4, shows how the heat transfer coefficient changes with these variables. In either case, the heat transfer coefficient decreases with time by exchanging heat with the surroundings (temperature dependency) or by extending its residence time in the mould (time dependency). In any case, the heat transfer coefficient values are in the same order of magnitude.

Correlations (10) and (11) do not account for cooling water flowrate effect. To account for this variable, a series of experiments were conducted [36, 37]. From this setup, it was found that by measuring temperature across the ingot, it is possible to back calculate the values of the heat transfer coefficient during the solidification of the aluminium. From the computations

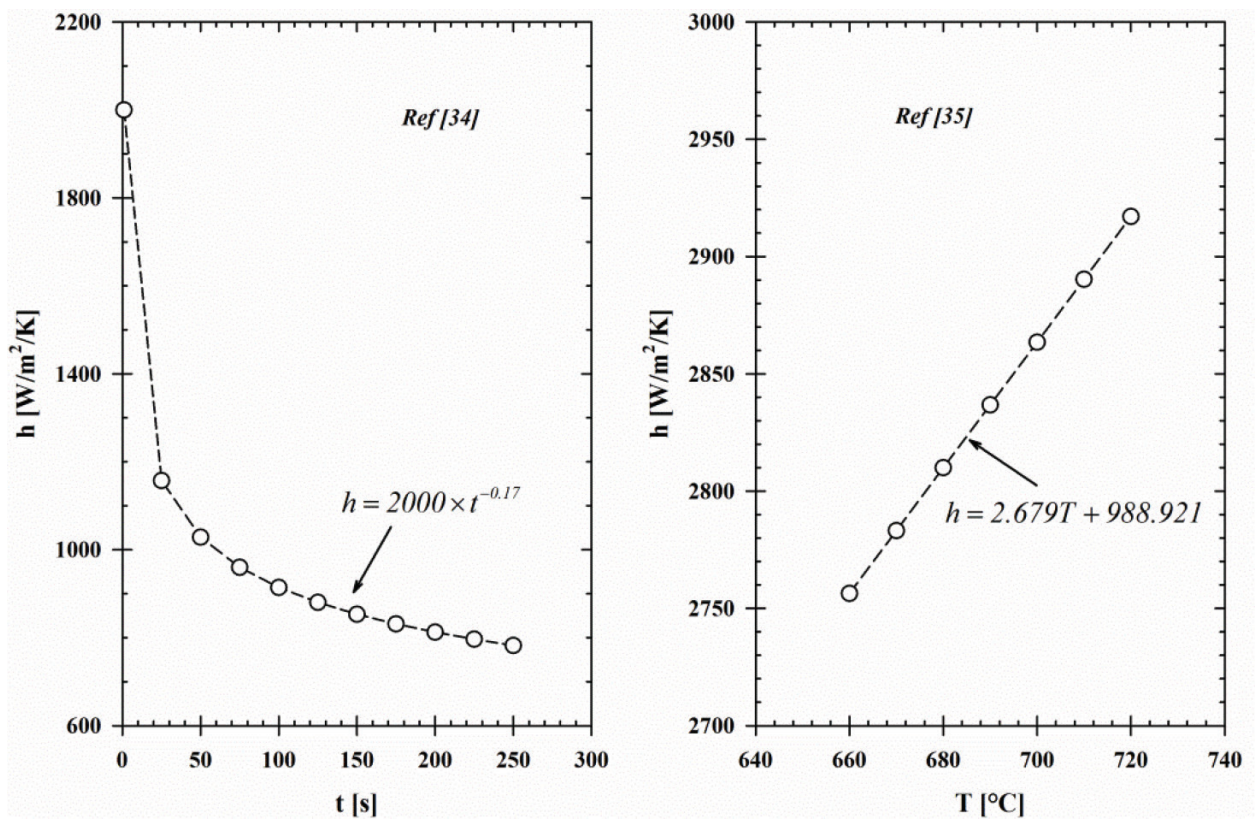


Figure 4. Effect of holding time on the mould [34] and that of the metal temperature in the mould [35] on the heat transfer coefficient during the solidification of an aluminium ingot.

made, it was found that the heat transfer coefficient during the DC casting of aluminium varies between 10^3 and 10^7 $\text{W/m}^2/\text{K}$, which is considerably higher than the values computed with Eqs. (10) and (11).

To determine the accuracy of the values reported, it was decided to evaluate another heat transfer coefficient correlation proposed by Sleicher and Rouse [38]:

$$h = \frac{k_{\text{water}}}{D} (5 + 0.015 Re^{0.82} Pr^{0.83}) \tag{12}$$

Eq. (12) was obtained after conducting many experiments to quantify convective heat transfer in enclosed channels. In applying Eq. (12), it is assumed that cooling water flowrate within the mould wall is in the turbulent regime. In relationship (12), D is the diameter of the water channel; Re is the water Reynolds number at the cooling water temperature; Pr is the Prandtl number of water (~ 7) at the mould; and k_{water} (0.591 W/m/K) is the thermal conductivity of the water.

From **Figure 5**, it can be seen that by increasing the water flowrate within the mould, it increases the heat exchange rate (higher h value), thus reducing the mould's temperature. This is well established in the continuous casting of steel but has not been studied thoroughly in DC casting of aluminium and other light metals (**Table 1**) [31].

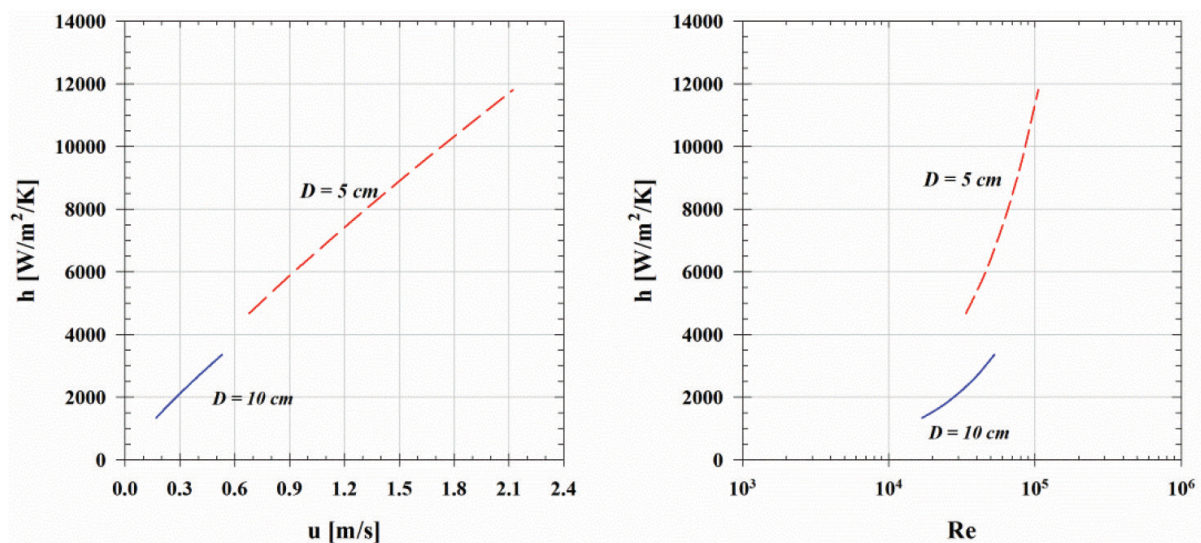


Figure 5. Estimation of the heat transfer coefficient as proposed by Sleicher and rouse [38] as a function of water velocity (u) and Reynolds number (Re).

Water flowrate [L/min]	Water velocity [m/s]	Re	D [m]	h [W/m ² /K]
80	0.17	1.69×10^4	0.1	1337
100	0.21	2.11×10^4	0.1	1599
120	0.25	2.54×10^4	0.1	1852
150	0.32	3.17×10^4	0.1	2219
175	0.37	3.70×10^4	0.1	2513
200	0.42	4.23×10^4	0.1	2801
80	0.68	3.38×10^4	0.05	4675
100	0.85	4.23×10^4	0.05	5602
120	1.02	5.08×10^4	0.05	6496
150	1.27	6.34×10^4	0.05	7788
175	1.49	7.40×10^4	0.05	8829
200	1.70	8.46×10^4	0.05	9844

Table 1. Process variables used in Eq. (12) to estimate the heat transfer coefficients shown in **Figure 5**.

4. Estimation of Pe and bi numbers and their effect on the DC casting process

Estimation of Pe and Bi numbers according to Eqs. (4) and (6), respectively, was conducted for different water channel diameters. This is shown in **Figure 6**.

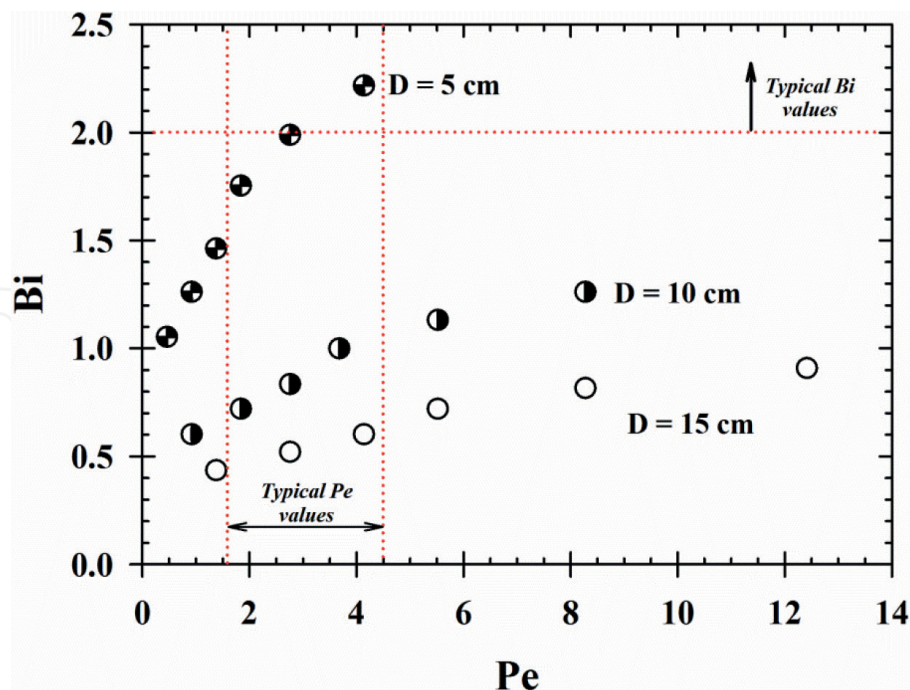


Figure 6. Bi versus Pe plots for different casting conditions and water channel diameters.

Figure 6 indicates typical Pe and Bi values reported in literature [1, 24]. As it can be observed in such figure, a significant amount of data fits well in the reported Pe interval; however, in terms of Bi number, only a few data lie within the observed values.

Péclet number directly relates to the casting velocity, whereas Biot number depends on the heat transfer coefficient.

To increase the value of Biot number, it would be necessary to increase the heat transfer coefficient which in turns means to increase the cooling water flowrate (Re in Eq. 12). If more water is added to the mould (primary cooling system), it may induce thermal stresses due to faster heat extraction rate; such thermal stresses may in turn affect the solidification structure henceforth the mechanical properties of the resulting cast alloy.

On the other hand, if Pe increases it would mean that the casting velocity could be too fast to allow for the initial solidification of the ingot, risking remelting of the initial solidification front and possible leaking of liquid metal. To counteract this effect, more cooling water should be added to the mould to extract as much heat as possible. These effects induce different metallurgical defects that hinder the quality of the solid metal.

The Bi versus Pe diagram represents a compromise between the amount of cooling water added to the mould and the casting velocity. These two process variables have the higher impact on the solidification of the alloys obtained by DC casting. The proper balance between these two variables ensures that a proper temperature distribution within the ingot establishes as it solidifies. Furthermore, such temperature field minimizes the probability of attaining poor mechanical properties and other defects associated to imbalances between these variables.

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