MultiCraft

International Journal of Engineering, Science and Technology
Vol. 3, No. 1, 2011, pp. 120-135

INTERNATIONAL JOURNAL OF ENGINEERING, SCIENCE AND TECHNOLOGY
www.ijest-ng.com

Vibration improved the fluidity of aluminum alloys in thin wall investment casting

Waleed Abdul-Karem[1], Khalid F. Al-Raheem[2],

[1,2] *Department of Mechanical and Industrial Engineering / Caledonian College of Engineering, OMAN*
[*]Corresponding Author's e-mail: khalid@caledonian.edu.om

Abstract

Misrun is a term used to describe the incomplete filling of the mould cavity. It is a major defect in the investment casting process when used to produce turbine blades, impellers and impulse blades for turbo pumps which have complex profiles, thin walls and sharp edges. From the casting engineering point of view, poor fluidity characteristics are a major factor leading to the occurrence of misrun defects in thin wall casting. The technique to "increase" the metal head during casting and improve the fluidity in thin sections are explored in this paper by the application of vibration during the pouring process. A mathematical model that enable to calculate the fluidity length in thin wall investment casting consider the effect of both mould surface , roughness and vibration has been developed. Surface roughness has been studied with the objective to calculate the Interfacial Heat Transfer Coefficient (IHTC) during liquid contact and subsequent by the IHTC during separation of solidifying metal from the mould (gap formation). The obtained data are applied in a one dimensional model of solidification during filling of a channel. The effect of vibration is quantified and incorporated into the fluidity model, such that the velocity with and without vibration can be considered in the fluidity model. High pouring temperature aluminum alloy in thin wall investment casting, fluidity characteristic is improved by application of vibration.

Keywords: Vibration casting, heat transfer coefficient, investment casting, flowability, fillability, surface roughness.

1. Introduction

Fluidity is one of the most important factors in the casting process. Fluidity is defined by (Fleming, 1974) as the distance covered by quality liquid metal in a channel of fixed geometry before solidifying. This does not involve its physical properties, and it can be measured by using a standardized system of enclosed channels (Beeley, 1972). Kondic (1959) states that it is very difficult to find a definition for the fluidity which can be accepted by metallurgists and foundry-men, the reason being that the fluidity from the point of view of many metallurgists is understood as a matter of flow behavior only, whereas for foundry-men, it is a question of the flow and mould filling. Hence, he defines the fluidity as the ability of the melt to flow and fill the mould. In his definition, Kondic covers all the terminology related to fluidity.

Wachter (1955) investigated the effect of vibration on molten metal and found that there was a pumping force generated at the entrance to the vertical passages used to evaluate the fluidity of the molten metal. Levinson, 1955 observed that a small pinhole in the welded seams of a mold leaked liquid only while vibration was applied. This has been interpreted to mean that vibration can inject liquid metal into a constricted channel, thereby augmenting the fluidity. Flemings (1962) found that vibration increased the distance which the metal runs (its fluidity) into small holes in a casting. These effects were found to be greatest with small metal heads and are again attributable to an increased effective metal head. Campbell, 1980 provided a critical review of more than two hundred studies concerning the influence of vibration during solidification.

From the literature available (Campbell, 1988; Merton C. 1964; and Chandraschariah , 1982) on fluidity in flowability filling type conditions (when the temperature of the mould is less than the liquidus temperature), it is clear that fluidity has a major effect on the filling of the mould. It can be improved by controlling factors relating to flow and heat transfer, including superheat, alloy composition and the resultant mode of solidification. However, fluidity improvement in thin wall investment casting is another matter; the surface tension is an additional factor which should be taken into account when calculating fluidity (Campbell, 1988;

Campbell, 2003 and Flemings, 1962). Analysis of fluid flow and heat transfer are frequently used in modeling to improve the quality and yield of castings by improving their fluidity characteristics (Griffiths and Jones, 2004). To formulate expressions for filling, such as empirical formulas or charts, it is necessary to understand the fundamentals of the heat transfer and fluid flow mechanisms during the filling processes. This is because of the complex nature of the coupling between heat transfer and fluid flow during solidification. Waleed et al. (1996 and 1997) analyzed mathematically the rate of heat loss during casting, The present work, a mathematical model that enable calculation of the fluidity length of thin strips in investment casting has been developed. The developed model taking into account the effect of both mould surface roughness and vibration.

2. Derivation of model for fluidity in thin section

The model comprises a one-dimensional heat transfer model with phase change, under an established flow field in a thin ceramic channel under the influence of low frequency vibration throughout the casting cycle, as shown in Figure 1, below. Where x is the distance which covered by liquid metal.

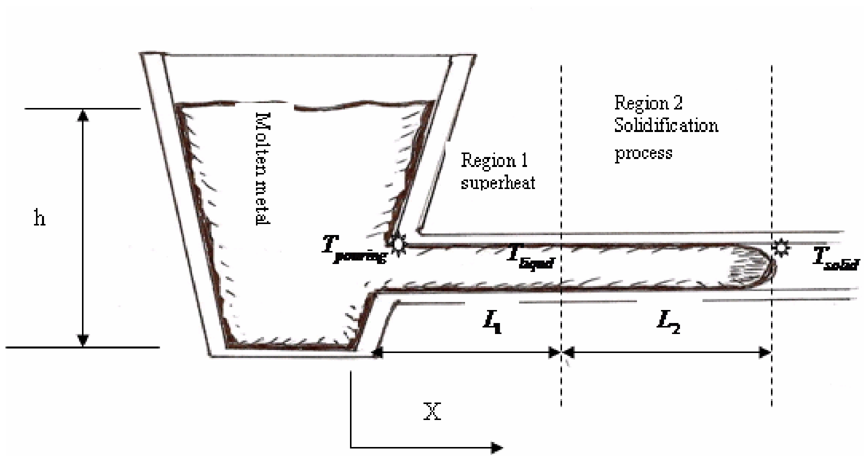
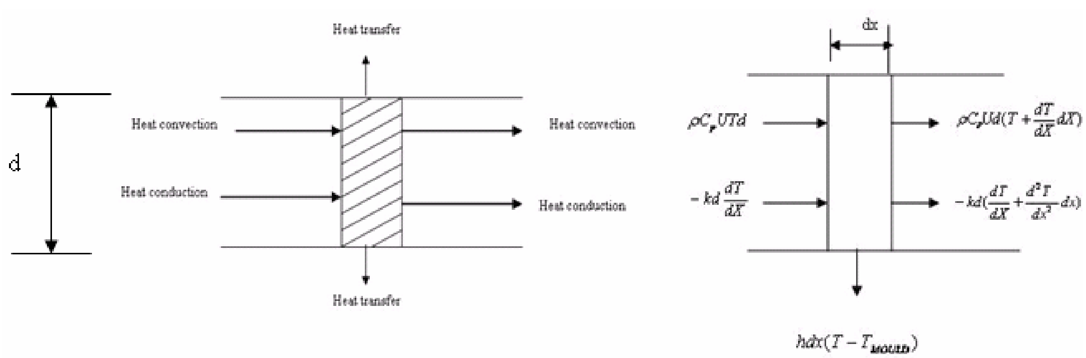


Figure 1: Mathematical geometry used to develop the analytical model

The total fluidity (the distance covered by the metal) can be divided into two main regions of heat loss to the mould, as follows (Al-Sammara and Dows, 1996).

2.1 Heat Loss from Superheated liquid



Heat energy converted in the left face + heat energy conducted in the left face = heat energy converted out of the right face + heat energy conducted out of the right face + heat transfer by convection out of the top and bottom faces of the liquid and conduction between the mould and the liquid surfaces.

Figure 2: Elemental volume for energy analysis of superheated liquid (Al-Sammara and Dows, 1996).

Writing the energy balance to correspond to quantities shown in Figure 2,

$$-\rho C_P U d\frac{dT}{dx}dx + kd\frac{d^2T}{dx^2}dx = 2h_1 dx(T - T_{mould}) \tag{1}$$

Dividing by $\rho C_P ddx$ gives

$$\alpha\frac{d^2T}{dx^2} - U\frac{dT}{dx} - \frac{2h_1}{\rho C_p d}(T - T_{mould}) = 0 \tag{2}$$

When the heat loss reduces the superheat and the metal is still in a completely molten state (single phase), the following equation can be written:

$$\alpha\frac{d^2T}{dx^2} - U_1\frac{dT}{dx} - \frac{2h_1}{\rho C_p d}T = \frac{-2h_1}{\rho C_p d}T_{mould} \tag{3}$$

The boundary conditions are proposed, from Figure (1), to be:

At X=0, T=T_p and at X=L_1, T=T_{liq} where T_p is the pouring temperature.

And the liquid flows a distance L_1 before losing its superheat, where [13];

$$L_1 = \frac{\ln\left\{\frac{T_{Liq} - T_{mould}}{T_P - T_{mould}}\right\}}{\frac{U_1 - \sqrt{U_1^{\,2} + \frac{8h_1\alpha}{\rho C_p d}}}{2\alpha}} \tag{4}$$

2.2 Heat loss with solidification

In this region the metal starts to solidify and becomes a mixture of solid and liquid; the heat content is principally from latent heat, but partly from specific heat. This is illustrated in Figure 3:

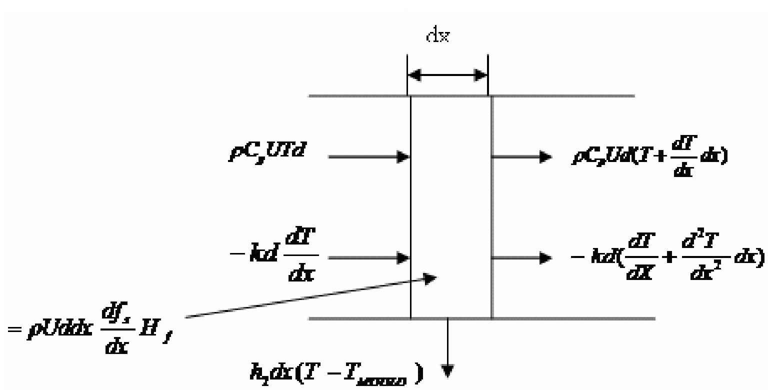


Figure 3: Elemental volume defined for energy analysis in the latent heat region (Al-Sammara and Dows, 1996).

$$\alpha \frac{dT^2}{dx^2} - (U_2 - \frac{UH_f}{C_P}\frac{df_s}{dT})\frac{dT}{dx} - \frac{2h_2}{\rho C_P\ d}T = \frac{2h_2}{\rho C_P\ d}T_{mould} \tag{5}$$

The term $\frac{df_s}{dT}$ in Equation 5 makes the equation a non-linear differential equation, which has no exact solution. To solve Equation 5, the relationship between f_s and temperature is needed. Using the data of Mills and R. F, 1998, for A356 alloys, the relationship was plotted in Figure 4 as a solid fraction vs. alloy temperature.

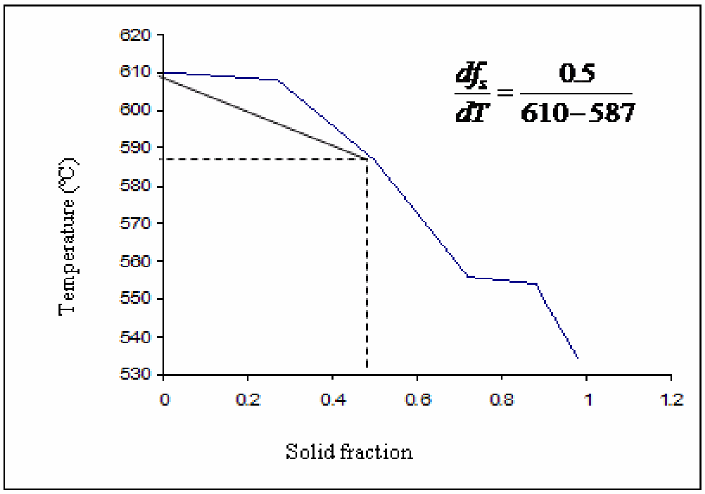


Figure 4: Temperature versus fraction solid in the AlSi7% alloy

From Figure 4 we can estimate the value of $\frac{df_s}{dT}$ to be about (0.0201 K^{-1}) and, when this is substituted into Equation 5, a linear differential equation can be obtained, which has an exact solution;

$$\alpha = \frac{d^2T}{dx^2} - (U_2 - 0.0201\frac{UH_f}{C_p})\frac{dT}{dx} - \frac{2h_2T}{\rho C_p d} = \frac{-2h_2T_{mould}}{\rho C_p d} \tag{6}$$

$$where, G = (U_2 - 0.0201\frac{UH_f}{C_P})$$

To solve Equation 6, we used the procedure which was used to solve Equation 2 for the superheat region was used, of which the result was (Al-Sammara and Dows, 1996);

$$L_2 = \frac{\mathrm{Ln}\left(\dfrac{T_{sol} - T_{mould}}{T_{liq} - T_{mould}}\right)}{\dfrac{G - \sqrt{G^2 + \dfrac{8h_2\alpha}{\rho Cpd}}}{2\alpha}} \tag{7}$$

The analytical solution obtained for L_2 assumes that the flow continues, at constant velocity, until 50% of the latent heat and the sensible heat of the liquid phase has been lost from the metal stream, i.e., $f_s = 0.5$. It is well known that fluid flow is arrested before $f_s = 1$, thus reducing the attribution of the heat of solidification to the total fluidity length. This is a fundamental difference between the flow mode of Fleming (skin freezing) and the present study (pasty freezing). It is therefore necessary to account for the effect of f_s on L_f in particular the effect on L_2. The calculated value of L_2 can be easily adjusted for the relative ratio of the heat lost during semi-solid flow by choosing the solid temperature T_{solid} with respect to the $f_{s(crit)}$, the critical fraction solid at which flow is arrested.

The fluidity of the metal is represented by the total distance covered by the molten metal in a thin channel:

$$L_{TOTAL} = L_1 + L_2 \tag{8}$$

The result from the heat loss model indicated that the velocity of the molten metal and the interfacial heat transfer coefficient (IHTC) in the channel were an important factors affecting fluidity. At this point, it is convenient to specify the velocity of the molten metal and (IHTC) during the filling of the mould.

2.3 Modeling molten metal velocity

It is not necessary to consider frictional energy loss in this context (Hwang and Stoehr , 1988). As set out below a simple modification, including unsteady state continuity and the Bernoulli equation with additional terms, including the quantity of pressure generated due to surface tension (Steven J and Hani, 2005), can be used to derive the velocity of the molten metal in a thin wall casting.

Pressure head = $\rho g H$

Back pressure due to surface tension = $\frac{\gamma}{r}$ (neglecting the second radius of curvature and assumming a perfectly non-wetting system)

Effective pressure = $\rho g H - \frac{\gamma}{r}$

No flow can occur when $\rho g H < \frac{\gamma}{r}$, and thus velocity, $U = 0$

The metallostatic pressure required to cause metal to enter a channel of thickness r i

$$\rho g H = \frac{\gamma}{r} \tag{9}$$

Assumptions:

A strip casting was measured in which only the γ component for one dimension was relevent, as only the channel thickness was considered as significant, (hence not $\frac{2\gamma}{\rho r g}$).

Adding the kinetic pressure head into Equation (9), to calculate the velocity U using the effective pressure head, it becomes:

$$\frac{1}{2}\rho U^2 = \rho g H - \frac{\gamma}{r}$$

$$U^2 = \frac{2}{\rho}(\rho g H - \frac{\gamma}{r})$$

$$2(gH - \frac{\gamma}{\rho r}) = U^2$$

$$U = \sqrt{2g(H - \frac{\gamma}{\rho r g})} \qquad (10)$$

The velocity of the liquid aluminum alloys in a thin section casting was measured in a real-time X-ray machine to compare with the velocity model in the present work this illustrated in Figure 5 and 6 .

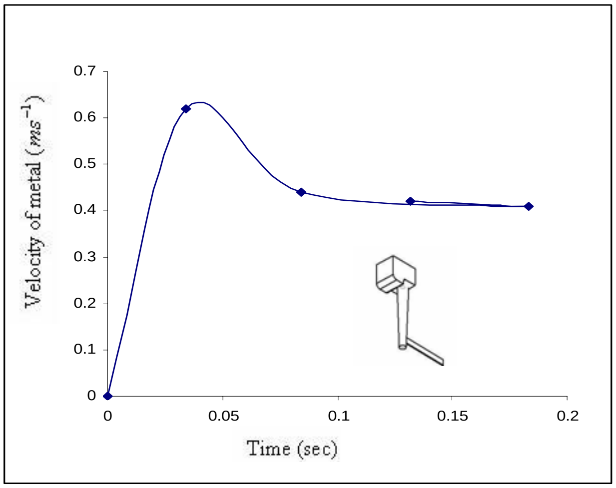


Figure 5: Velocity measurements, flowability filling condition, piece thicknesses 0.75mm, mould Temperature 450ºC, pouring Temperature 750ºC, and metal head 170mm

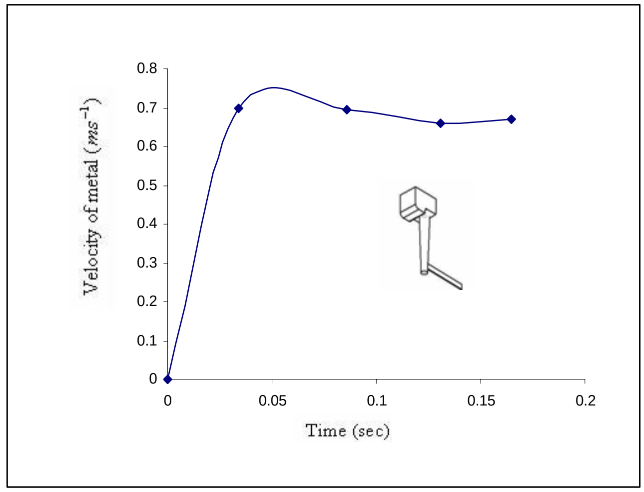
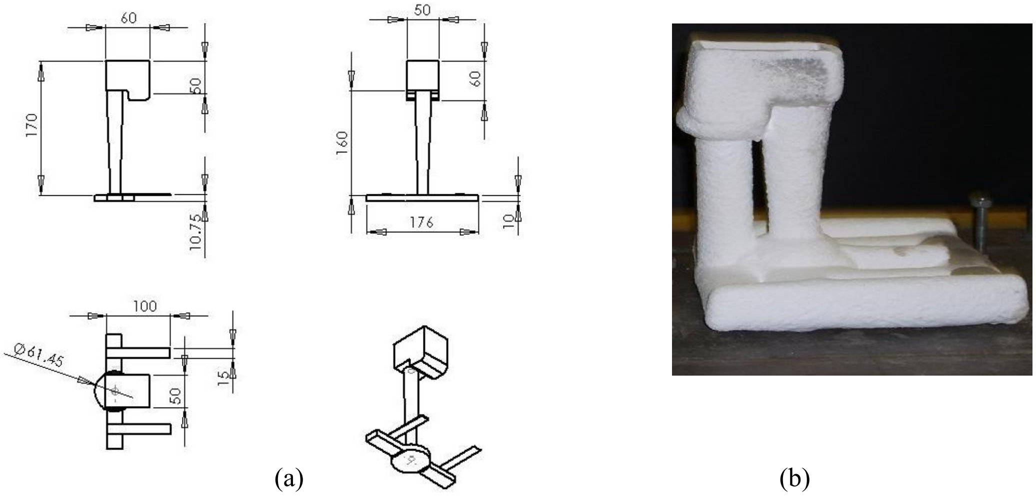


Figure 6 : Velocity measurements, fillability filling condition, piece thicknesses 0.75mm, mould Temperature 660-700ºC, pouring Temperature 750ºC, metal head 170mm

The experimental result in the fillability filling type conditions, (with the mould temperature higher than the liquidus temperature), without vibration, indicated that the average velocity of the liquid metal front was between 0.68 m/s to 0.7m/s, compared with 1.02m/s calculated by Equation (10). Generally, the average velocity measurement results for liquid metals running in a thin section reveal agreement with the value of the velocity estimated by using Equation (10) and they confirm the usefulness of the simple modification of the Bernoulli equation by adding a quantity which represents the back pressure due to surface tension in the thin section, estimated by ($\frac{\gamma}{r}$). The measured velocity was always less than the theoretical velocity, which suggests that an error may result from ignoring the frictional force between the liquid metal and the mould surface when calculating the velocity, or the secondary radius of the curvature.

The result of the experiment carried out in flowability filling type conditions with the temperature of the mould about 420°C, (lower than the liquidus temperature of 610ºC), using the mould design illustrated in Figure 7, and without vibration, is that the velocity of the liquid metal decreased with increasing distance of the meniscus from the channel entrance, until it reached 0.41m/s, when it stopped abruptly.



(a) (b)

Figure 7 (a) Mould design for fluidity test strip thickness 0.75mm metal height 170 mm, pouring temperature 450ºC, mould temperature 660ºC-700C (b) ceramic mould

Fleming (1962 and 1974) described this phenomenon during his explanation of pasty-type freezing in the solidification processes for Al-Si alloys. However, he estimated the flow distance L from the simple equation L = U× t_f , which assumed that the liquid has an approximately constant velocity U, where t_f is a solidification time. In the present work, the result indicates that the mode of solidification has an influence on the velocity of the metal in its semi-solid state during the solidification process.

Consequently, the velocity in a thin wall casting under the influence of vibration at the positive phase (upward with respect to gravity) of the frequency cycle can be calculated by adding to Equation 10, the maximum acceleration generated due to vibration. This then becomes:

$$U_{+p} = \sqrt{2(g+a)(h - \frac{\gamma}{\rho r(g+a)})} \quad (11)$$

$$U_f = \sqrt{2(g - 2\pi^2 f^2 a \sin 2\pi f t)(h - \frac{\gamma}{\rho r(g - 2\pi^2 f^2 a \sin 2\pi f t)})} \quad (12)$$

Equation (12) was applied to calculate the velocity of the liquid metal in the positive phase of the frequency cycle and the resulting flow lengths obtained by step-wise integration, (calculation does not taken in to account, when square root is - ve).

The experiments using a Plexiglas mould, high speed camera and mercury metals, velocity was found to be (0.00983 ms^{-1}) compare with (0.16 ms^{-1}) obtained from velocity of metal in one frequency cycle at maximum acceleration Therefore, the velocity of liquid metal can be quantified by 73% from the theoretical velocity U_f as illustrated in Figure 8 . Hence the velocity under vibration condition is

$$U_v = 0.73U_f \quad (13)$$

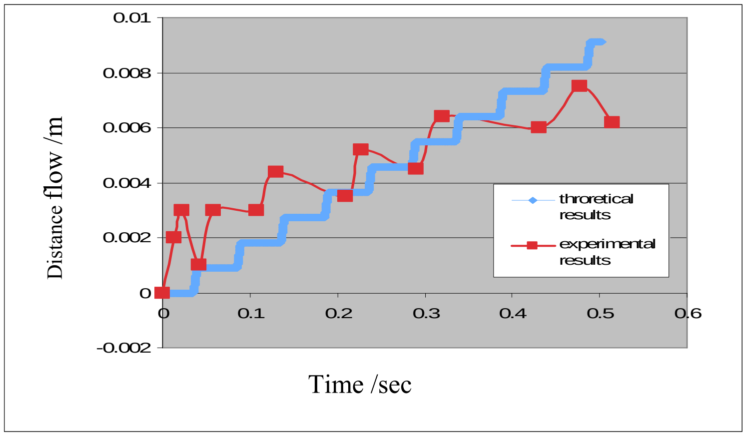


Figure 8 : Comparison between the experimental results and theoretical results of flow velocity of mercury in a strip of thickness 0.060mm, frequency 20 Hz, amplitude 0.5mm

2.4 Calculation of a heat transfer coefficient

From the literature available (Griffiths, 2000, Ho and Pehlke, 1983 and Hallam and Griffiths, 2004), a heat transfer coefficient can then be calculated on the basis of the resistances to heat diffusion that are summed in parallel (See Figure 9). The formation of the air gap occurs next. Deformation, caused by the expansion and contraction of the thin skin of casting would result in an increase in the size of the gap or even complete separation between the casting and the mould.. This is shown schematically in Figure 10.

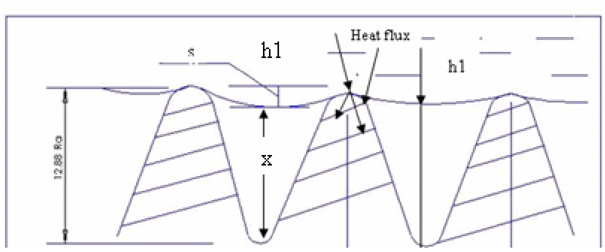


Figure 9: Metal-mould interfaces at the first stage and at the heat flux.

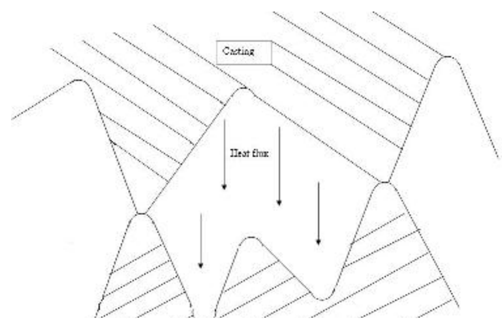


Figure 10: Metal-mould interfaces at the second stage (air gap forming).

From the description above it is clear that there are two different heat transfer coefficient values for a thin wall investment casting during the filling process; one for the superheat region (which would depend on the size of the contact area between the liquid metal and the peaks of the surface roughness of the mould), and another for the latent heat region (which would depend on the size of the gaps forming in the interface between the metal and the mould surface). Therefore, heat transfer coefficient estimates were obtained for a superheat and a latent heat region, separately.

The parameters of the surface roughness of the ceramic shell before casting, and the casting surface, were measured using Taylor Hobson surface profilometer device is shown in Figure 11, and are summarized in Table 1. The table also includes the mean radius b of the asperity peaks of the rough mould surface, measured using the same instrument.

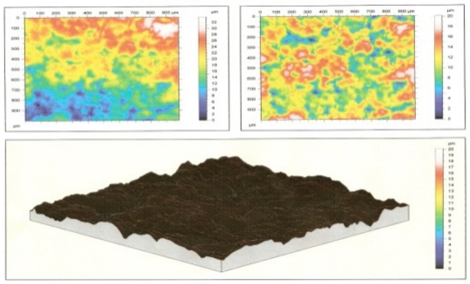


Figure 11 3D-surface roughness profile measured for ceramic mould

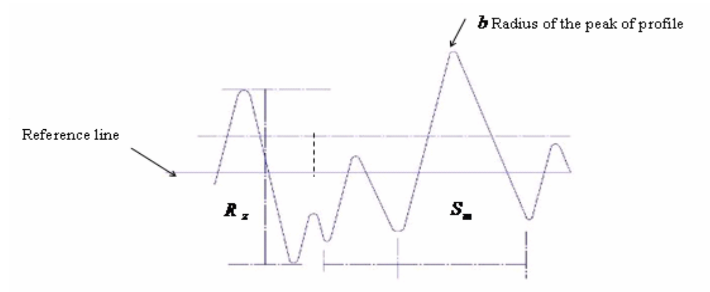


Figure 12 Schematic to show the definition of the surface roughness parameter.

Table 1 Surface roughness data obtained from the ceramic mould and castings.

Surface measured	$R_a\,(\mu m)$	$R_z\,(\mu m)$	$S_m\,(\mu m)$	b (μm)
Ceramic shell	2.2	12.8	58.9	5
Casting (flowability filling type)	4.07	21.9	303	
Casting (fillability filling type)	3.52	17.3	282	
Casting, vibration during filling (fillability filling type)	2.97	15.9	270	
Casting vibration after filling (fillability filling type)	2.75	15.0	170	
Casting vibration after filling (flowability filling type)	2.2	14	185	

R_a is the mean distance between the surface profile and the reference line, R_z is the mean distance between peak height and valley depths in the surface profile, S_m is the mean distance between profile peaks.

The sketch in Figure 12 shows the various surface parameters used during the calculation of the heat transfer coefficient between the ceramic shell and the casting.

2.4.1 Heat transfer coefficient calculation in superheat region

In the present work the heat transfer coefficient in the superheat region was calculated for a condition when the metal was in a liquid state with the contact area of the mould controlled by surface tension, density, metal pressure head and mould surface peak to peak distance in the profile. This enables the heat transfer coefficient between the mould and the casting to be estimated by subtracting the value for the penetration of the liquid metal into the surface roughness valleys, estimated by (Murthy, et. al, 1986) to be;

$$s = \frac{S_m{}^2 h}{8(A^2 + bH)}$$

(Where $A = \sqrt{\frac{\gamma}{\rho g}}$; $b =$ radius of the asperity peaks in surface roughness profile; $H =$ pressure head), from the depths of the valleys in the surface profile of the ceramic mould,

$$x = (R_{z\,mould} - s)/2\,,$$

and the thermal conductivity of the air (k_{air}), which in this case gave a IHTC of $\approx 11800\,Wm^{-2}K^{-1}$ and $\approx 13000\,Wm^{-2}K^{-1}$ for casting with and without vibration respectively, Figure 9.

2.4.2 Heat transfer coefficient calculation in latent heat region

In conditions of semi-solid (latent heat release), an air gap is formed; its growth is related to deformation of the casting skin caused by the expansion and contraction during the process of solidification. This enables the heat transfer coefficient between the mould and the casting to be estimated by the size of the air gap (assumed to be equal to the sum of the depths of the valleys in the surface profile of the ceramic mould and the casting surface;

$$(z = \frac{\sqrt{R^2_{z(mould)} + R^2_{z(cast)}}}{2})$$) and the thermal conductivity of air (k_{air}). Using Griffiths' model ($h = \frac{k_{air}}{z}$) [18], this produced an IHTC of $\approx 6000\, Wm^{-2}K^{-1}$ and $\approx 5000\, Wm^{-2}K^{-1}$ for casting with and without vibration respectively.

The heat transfer coefficient between the casting and the wall of the mould as a function of the liquid metal surface temperature has been shown in Figure 13. It has been assumed that $\frac{dh}{dT}$ is linear relationship between the liquidus temperature and solidus temperatures.

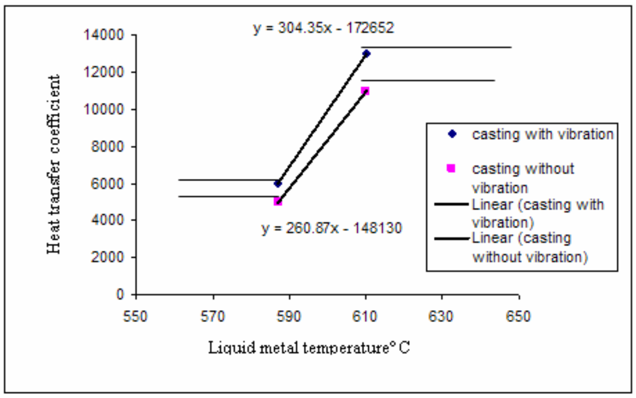
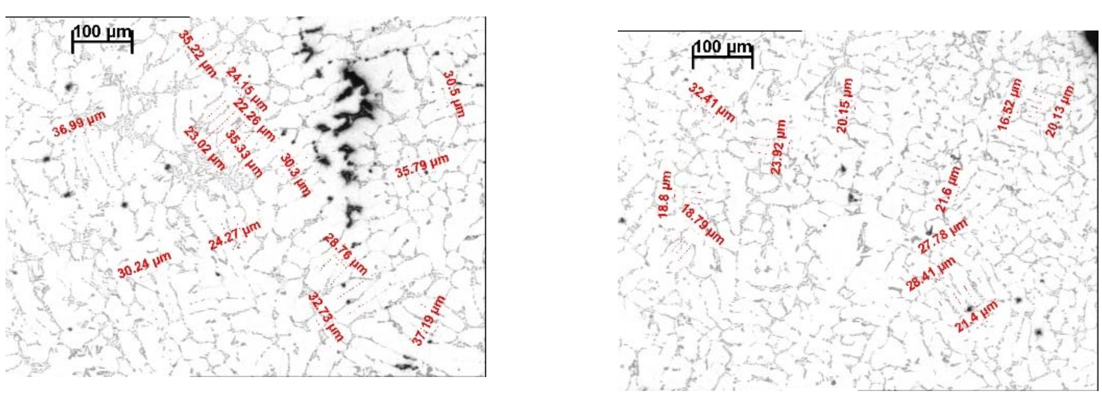


Figure 13: The variance of the calculated heat transfer coefficient with the temperature of the liquid metal

From the calculation of the heat transfer coefficients made above, the heat transfer coefficient is not a constant value in thin wall investment castings, but varies with time and temperature gradient. Stemmler el at. 2001, confirmed this, by estimating the heat transfer coefficient as a function of the temperature during simulation of Al7Si% alloy investment casting.

The solidification time for a casting with vibration under 0.8g conditions, was calculated from the secondary arm spacing's, this is illustrated in Figure 14 (Using the regression relationship of SDAS as a function of the solidification time t_f ($\lambda_f = 10.7 t_f^{0.30}$ (Hamed and R. Elliott, 2006) this time included primary aluminum dendrites growing, or rapid solidification may increase the amount of the primary phase formed.) and was found to be 1.2 s, compared with 1.3 s in the casting without vibration.



(a) (b)

Figure 14 Typical mid-thickness strip microstructures observed at the flow tips of (a) castings filled without vibration and (b) castings filled with 0.8g acceleration (pouring temperature, thickness 0.75mm,750ºC; mould temperature 420ºC; metal head 170mm).

This means that the liquid metal under vibration conditions loses heat faster than liquid metal does without vibration, Kocatepe and Abu-Dheir, 2005, confirmed this observation and found that vibration during casting reduced the solidification time by 24%, compared with a casting without vibration. This indicated that the heat transfer coefficient when vibration is used was greater than without vibration. It is suggested that the reason for the increase in the value of the heat transfer coefficient can be attributed to the increase in the pressure related to the metal head, as a result of the acceleration due to the vibration in the bulk of the metal. This reduced the size of the air gap (ie, reduces its insulation) in the interface between the surface of the ceramic mould and the molten metals and increased the contact area, thereby increasing the heat transfer coefficient. This suggestion was supported by measuring the value of R_a on the surface profile of the casting without vibration, which was found to be 4.07 μm, compared with 2.97 μm for casting with vibration. Pehlke, 1985 confirmed this suggestion: he reported that any increase in the metal head of the liquid in the casting process was associated with an increase in the heat transfer coefficient. The gain from the increased pressure in the bulk of the metal and increased heat transfer coefficient produced a casting with a good surface finish. Alonso Rasgado,2009 confirmed this by using vibration in pressure die casting.

3. Discussion and results

When all the parameters in the heat loss model (velocity of molten metal and interfacial heat transfer coefficient) were calculated, the model was tested and compared with the results of two series of experiments (with and without vibration). The values of the thermo-physical properties for the ceramic shell and the casting, as well as other data used in the heat loss model to calculate the fluidity of the A356 alloys in thin section in vibration conditions, are shown in Table 2.

Table 2. Thermo-physical properties of the A356

Property	Value
Properties of the A356 alloy	
Thermal conductivity ($Wm^{-1}K^{-1}$)	88.6
Specific heat capacity ($Jkg^{-1}K^{-1}$)	917
Density (kgm^{-3})	2394
Coefficient of thermal expansion	24×10^{-6}
Latent heat (Jkg^{-1})	397,490
Liquidus temperature (K)	890
Solidus temperature (K)	850

The physical properties of the A356 alloys were assumed to be independent of temperature.

A series of experiments was conducted in flowability filling type conditions to determine the effect of vibration on the fluidity characteristics of thin wall investment castings, with different pouring temperatures with and without vibration. Investigation of the results of the heat loss model with experimental data for different pouring temperatures (660°C, 700°C and 750°C), channel thickness of 0.75mm and mould temperature 420ºC was carried out. The fluidity was tested by pouring molten A356 alloy into a thin channel casting with thickness of 0.75mm. The cross-sectional area along the thin channel is constant and the distance to which the molten metal flowed was measured. The test mould is illustrated in Figure 7. The mould was insulated by a ceramic fibre blanket to minimize variation in the mould temperature from casting to casting which arose due to differences in the time taken to mount the mould on the vibrating table. Flow distance is illustrated in Tables 3 plotted in Figures 14, using fluidity as a function of the pouring temperature with and without vibration at 0.8g acceleration.

Table 3: The results of fluidity experimental

Pouring temperature °C	Fluidity Casting without vibration, mm	Fluidity Casting with vibrating 0.8g, mm	Vibration condition
660	71	70	During filling
	70	67	
	68	65	
	74	72	
	74	61	
	76		
700	83	91	During filling
	90	89	
	77	93	
	81	87	
	85	93	
750	91	117	During filling
	94	114	
	90	109	
	92	112	
	94	113	
	97	107	
750		90	After filling
		92	
		94	
		88	

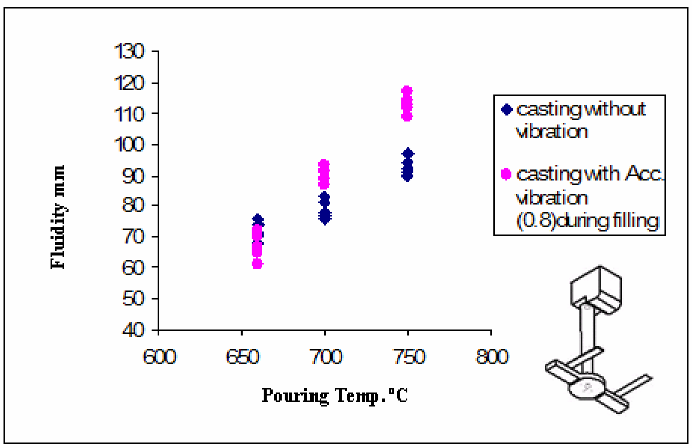


Figure 15: The fluidity of A356 alloy as a function of pouring temperature in the flowability filling type, according to the vibration techniques used during filling and gravity pouring

Figure 15 shows that the fluidity increased in the casting with and without vibration with any increase in the pouring temperature; this result has been confirmed by many fluidity researchers (Surathkal el. 2006, Kondic, 1949 and Adefuye, 1997). The two results (of the fluidity test and model calculation) without and with vibration were found to be comparable, as shown in Figures 16 and 17 with a channel thickness of 0.75mm. Generally, the results are in good agreement in the case without vibration, (see Figure 16), tends to confirm the heat loss model used in the present work. However, in the case of casting with vibration applied during filling the experimental and theoretical results were different see Figure 17. It is suggested that this difference was due to the estimation of heat transfer coefficients, surface tension, and the velocity of the metal in the latent heat region, which are variable parameters. These parameters are change which occurs when the temperature of the molten metal changes, but it was assumed that all parameters are constant values during fluidity calculation.

The specific heat capacity, C_p, is another parameter that would effect on the results of the heat loss model in calculating the fluidity, which was assumed to be a constant value in both the superheat and latent heat regions. However, the specific heat capacity changes with temperature and the state of the metal, whether liquid or solid. Therefore, it is surmised that the value of the specific heat is equal to the sum of the $C_{P(liquid)}$ in the superheat region and the $C_{P(solid)}$ in the latent heat, which can be estimated by the following formula:

$$C_{p(soild+liquid)} = f_s(T) \times C_{psol}(T) + (1 - f_s)C_{pliq} \quad (14)$$

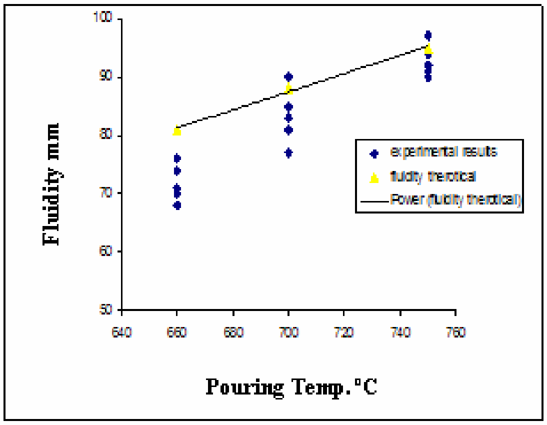


Figure 16 shows the relationship between the fluidity and the pouring temperature, casting without vibration, in a $0.75^{\pm 0.05}$ mm channel. A theoretical line is obtained from the heat loss model.

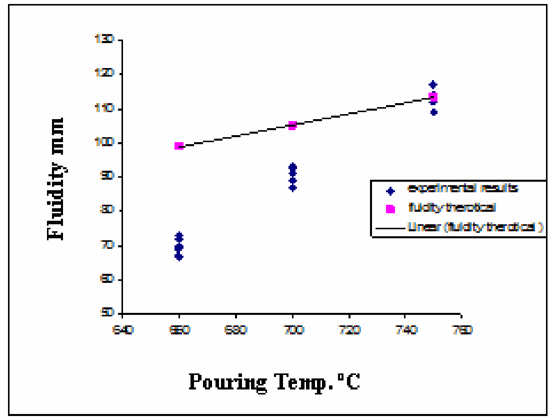


Figure 17 shows the relationship between the fluidity and the pouring temperature, casting with 0.8g acceleration of vibration during filling, in a $0.75^{\pm 0.05}$ mm channel. A theoretical line is obtained from the heat loss model.

In the experiments for the fluidity measurement under vibration conditions, vibration was used in two ways for the purpose of comparison: (i) first, during the pouring process: (ii) second, after the filling process. According to Table 3, the result shows that vibration had no effect on the fluidity when it was applied after the filling process. This is as a result of the heat loss from the molten metal to the mould walls starts when the melt flows through various parts of the mould components, the pouring basin, sprue and gating, before reaching the test piece. This situation caused a drop in superheat and ensured the metal solidified quickly in the thin section and then stopped. Consequently, vibration has no chance to effect the velocity of the molten metal in the fluidity test. Moreover, the solidification time in a thin section was momentary (0.23 s), measured by using a digital video recording real-time X-ray camera and the stabilization time of the vibrating table used in these experiments was 1 second. This means that the liquid metal solidified before the vibration was applied. However, the results showed an improvement in the fluidity when vibration was used during the high temperature pouring (see Figure (15)), because there was sufficient time for the metal to remain in a liquid or semi-solid state. This gave more chance for the vibration action to increase the velocity of the liquid metal during the pouring process, thereby improving the fluidity.

In practice the vibration was observed to have an inverse action on improving the fluidity, in cases when the filling process in thin wall investment casting was carried out at low pouring temperatures (660ºC (see Figure (15)). It may be the case that the vibration motion increases the capacity for crystallization in the liquid metal as the casting temperature declines (nucleation phenomenon) (Boris Ouriev, 2006). This situation led to a reduction in the solidification time, (about 0.16s) if compared with the solidification time in castings without vibration, (about 0.23s). Using Eq. 10 to estimate the velocity of the liquid metal in vibration conditions and obtaining the fluidity from the experiment. With this, the value of the solidification time could be estimated by using the simple equation of velocity, which was found to be 0.16 s. In this regard, it will be necessary to modify the present criteria (mathematical models of fluidity with a low pouring temperature under vibration conditions), Figure 17.

In addition, the increase in the heat transfer coefficient between the molten metal and the mould, as a result of the vibration pressure, is likely to have led to an increase in the heat loss during casting (Flemings, 1974). This caused a reduction in the solidification time and thereby effect on the fluidity value. However, in the case of casting under vibration with a high pouring temperature, the duration of the liquid stage was greater than the duration of the liquid stage when the casting was done at a low pouring temperature. Thus, the improvement in the velocity of the liquid metal in the liquid stage, and the reduction in the viscosity in the semisolid stage as a result of the contact break-up between the particles of the melt (Boris, 2006) during vibration, exceeds the influence of the increased heat transfer coefficient on the fluidity in thin wall casting. For this, the results are in agreement, and this also confirms the heat loss model used in the present work, Figure 16.

4. Conclusions

The general following conclusions can be drawn from the present work:

- A fluidity mathematical model has been developed to investigate the use of mechanical vibration as a parameter to improve the fluidity in thin wall investment casting. Also to characterize the dominant control parameter (frequency, amplitude, pouring temperature, mould temperature, wall thickness, velocity and heat transfer coefficient).
- The ability of the liquid metal to flow in the thin section is controlled by the heat content in the system; increasing the heat content of the system leads to an increase in the fluidity in thin wall investment castings.
- Application of vibration during filling of thin wall investment has no effect on fluidity at pouring temperature less than 700 ^{o}C. At a pouring temperature 750 ^{o}C and applied vibration of 0.8g results an increase in fluidity of 17%.
- Solidification time in thin wall investment castings under vibration conditions is shorter than solidification time in casting without vibration, by 9%.
- A good surface finishing was obtained from the casting with vibration. This was justified, to an increase in the internal pressure in the bulk of the liquid as a result of vibration.

List of Symbols

Q	Initial volume flow rate, $m^3 s^{-1}$
U	Velocity of molten metal, ms^{-1}
H	Metal head, m
A	area, m^2
r	Radius, m
t	Fill time, Sec
L	Length of fluidity in superheat, m
T_p	Pouring temperature, ^0C
K	Thermal of conductivity $Wm^{-1}k^{-1}$
C_p	Specific heat, $Jkg^{-1}k^{-1}$
Acc.	Acceleration (g)
γ	Surface tension, Nm^{-1}
ρ	Density, kgm^{-3}
h_1,	heat transfer coefficient in the superheat region,
U_1	Velocity of liquid metal in the superheat region
$m^{\cdot}$	Mass flow rate
f_s	Solid fraction
H_f	Latent heat of fusion (J/kg)
h_2	Heat transfer coefficient in a latent heat region
U_2	Velocity of metal in latent heat region
$\mathbf{L_s}$	Fluidity
α	Diffusivity

References

Abu-Dhrie N., Khraisheh M., Saito K., Male A., 2005. Silicon morphology, *Science and Engineering* Vol. A393, pp. 109-117.
Adefuye 1997. PhD thesis, (Fluidity of Aluminium-Silicon) Casting Alloys.
Al-Sammara and Dows, 1996. Fluidity of steel in investment casting", Conference Paper, Baghdad University.

Beely, 1972. Foundry Technology, Butterworth and Co (publishers) Ltd London: 88 Kingway, pp. 21-38.

Ouriev B., 2006. Rheology and rheometry of aluminium alloys: influence of shear and vibration on aluminium flow properties, *Solid State Phenomena*, Vol. 116-117, pp.558-564.

Campbell J., 2003. Casting, 2nd Edition, UK.

Campbell J., 1988, Thin Wall Casting, *Material Science and Technology*, March, Vol. 4, p194-204.

Campbell J., Review of fluidity concepts in casting, *Cast Metals*, Vol. 4, pp. 227-237.

Campbell J., 1988. Grain refinement of solidification metals vibration: review, Conference paper, The Metals Society, University of Warwick, Coventry, 15-17 September.

Chandraschariah, 1994. Effect of foundry variables on fluidity of investment-cast nickel base superalloys, AFS Transaction, Vol.2 pp. 94-124,.

Flemings, F. R. Mallard, E. F. Niiyama and H. F. Taylar," fluidity of aluminium", Trans. AFS, 1962, 70, 1029-1039.

Flemings," Solidification Process", McGraw- Hill, 1974 p. 219-229.

Flemings M.C., 1964. Fluidity of metal-techniques for producing altar- thin section, *Casting*, British Foundry, Jul. pp. 312- 323.

Griffiths and Jones S., Laser flash diffusive measurement, *IRC in Materials for High Performance Application*, University of Birmingham.

Griffiths W. D., 2000. A model of the interfacial heat-transfer coefficient during unidirectional solidification of an aluminum alloy, *Mechanical and Materials Transaction*, Vol. 31B, April, pp. 285-295.

Hallam and W. D. Griffiths, "A Model of the Heat-Transfer Coefficient for the Aluminum Gravity Die-Casting Process." Mechanical and Materials Transaction,Vol. 35B, April, 2004, p.1-14.

Hamed and R. Elliott, "The dependence of secondary dendrite arm spacing on Casting Practice", National Institute of Technology Karnataka 22 September 2006.

Ho K. and Pehlke R.D., "Transient method for determination of metal-mould interfacial heat transfer", Paper read at 87th ASF Casting Congress, Rosemont, Illinois, April 10-15, 1983.

Hwang W. E. and Stoehr R. A., "Modeling of Fluid Flow". ASM Handbook, Vol.15, 1988. p 867-876.

Iida T. , 1988. The physical properties of liquid metals, Clarendon Press, Oxford,

Kondic V., 1959. A new test for fluidity, British Foundry, Dec. pp. 75-83.

Kondic V., 1949. Fundamental characteristic of casting fluidity, *J. Institute of Metals*, Vol. 75, No. Part 8, Apr. pp. 665-678.

Levinson. D. W, A. H. and Rostoker; 1955. Influence of vibration on fluidity and filling during investment casting on Aluminium, *AFS Transaction*, Vol.63, p. 686.

Mills and Brooks R. F.. 1998. Measurement of thermophysical properties in high temperature melts, *Material Science and Engineering* A178, pp.77-81.

Murthy, S. S. and Kishore, 1986. CG iron-processing variable, casting characteristic and mechanical properties, *Advanced Casting Technology, Conference Kalamazoo*, Michigen USA, (12-14) November.

Sin L. and Dule D., 2004. Influence of process parameters on fluidity of investment casting, A Zg10 magnesium alloy. *Materials Science and Engineering*, Vol. 386, pp.34-42.

Snowden, J., I, and Sikkenga, L.A. ," Investment Casting", A Growth Industry. Michigan 49441, USA Rep-1988, pp 13-17.

Stemmler G., Laschet L., Hass, M., Schallmo and Hediger F., 2001. Simulation of investment casting: coupling of contact and heat transfer calculation between casting and mold during solidification, *Modeling of Casting, Welding and Advance Solidification Process*.

Steven J. Roach and Hani Henein, 1903. A new method to dynamically measure the solidification condition Al-7Si-0.5Mg alloys, *Cast Metal*, Vol. 6, No.1, pp.36-41.

Surathkal, P.O.Sriniviasnagar, Mangalore. 2005. Science and engineering of aluminum surface tension viscosity, and density of melts, *Metallurgical and Materials Transaction*, Vol. 36B, October, pp. 667-675.

Wachter, W. J, 1955. Influence of vibration on fluidity and filling investment casting on aluminium, *AFS Transaction*, Vol.63, p.686.

Waleed, Al-Sammara, and Daws, 1997. Production of turbine blade using centrifuge investment casting method, Conference paper, Al- Anbir University.

Zushu I., Kenneth C. and Kusuhiro M. 2005. Measurement of the density and surface tension of Ni-based superalloys in the liquid and mushy states, *Metallurgy and Material Transaction*, Vol. 36B, pp. 247-253.

Biographical notes

Khalid F. Al-Raheem received his B.S. (1987), M.Sc. (1990) degree in Production and Metallurgical Engineering from University of Technology, Iraq and PhD (2009) in machine condition monitoring from Glasgow Caledonian University, UK. He is currently a senior Lecturer at Mechanical and Industrial Engineering Department, Caledonian College of Engineering (CCE), Oman. Prior to joining CCE he was a Lecturer at Mechanical Engineering Department, UOT, Iraq (1991–2001). His publications, post-graduate supervisions and teaching interests are in machinery condition monitoring, signal analysis and control system engineering.

Waleed Abdulkarem received his B.S. (1984) in Mechanical Engineering from UOT, M.Sc. (1996) degree in Mechanical Engineering from Baghdad University and PhD/part time (2003) from Baghdad University, Iraq. He has PhD in materials engineering from Birmingham University, UK. He is currently a senior Lecturer

at Mechanical and Industrial Engineering Department, Caledonian College of Engineering (CCE), Oman. Prior to joining CCE he was a fellow researcher in Birmingham University (2004-2010), General Manager for engineering office- Al-Karama establishment (2000-2003), Iraq. He was a Project director in Ministry of Industries and Lecturer in Baghdad University and UOT (1989-1996), Iraq. His publications and teaching interests are in fluid mechanics, casting process and mechanical design.

Received February 2011
Accepted March 2011
Final acceptance in revised form April 2011