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MODELLING CENTRIFUGAL CASTING: THE CHALLENGES AND VALIDATION

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Abstract

Components which best utilise the properties of high temperature titanium alloys are characterised by thin sections of a few millimetres thickness and hundreds of millimetres length. These alloys however are difficult to work with, being highly reactive in a molten state, necessitating a low superheat during processing. Centrifugal casting is therefore utilised as a production method, as under the centrifugal force, metal can fill thicknesses substantially less than a millimetre. However, due to the high liquid metal velocity developed there is a high risk of turbulent flow and of the trapping of any gas present within the liquid metal.

This challenging application involves a combination of complex rotating geometries, significant centrifugal forces and high velocity transient free surface flows, coupled with heat transfer and solidification. Capturing these interacting physical phenomena, free surface flows, trapped air and associated defects is a complex modelling task. The authors have previously described the efforts needed to capture the bulk flow and liquid/solid coupling. This contribution will describe development and enhancements required to enable conventional free surface algorithms to capture the details of the flow: by maintaining a sharp metal-gas interface and reducing numerical diffusion whilst maintaining solution stability, on what are inevitably complex three dimensional geometries. Validation of the model has been done using a series of water experiments to capture the flow dynamics. Key observations arising from the work, such as capturing the dynamics of the pour conditions, were incorporated within the computational model.

Modelling the casting, flow-thermal-solidification, of a TiAl alloy adds another layer of complexity. A bench-mark test case is employed to validate the effect of solidification on the fluidity of an aluminium alloy.

Introduction

In recent years, two requirements have received a high priority from aircraft engine manufacturers: the reduction of noise and emissions. By replacing heavy components in aircraft engines with lightweight titanium alloys, significant increases in efficiency can be achieved. Traditional casting methods however, cannot be applied to these alloys, due to low superheat, and therefore low overall fluidity, arising from melting in an induction skull furnace. Mould rotation can improve the castability of the alloy, as centrifugal forces, orders of magnitude greater than gravity, drive the metal into very thin sections. However, defects can arise from the high liquid metal velocity and air entrainment, due to turbulent mixing of liquid and gas in an unconstrained pour.

The fluid filling process plays a crucial role in a centrifugal casting system and understanding the complex flow process is crucial for determing the casting integrity and performance. A number of researchers have investigated the filling process during centrifugal casting [1-3]. Numerical simulations have investigated the effectiveness of different filling methods, including bottom fill versus top [4], angular velocity [5] and evolution of microstructure [6-7]. However, in order to fully model the centrifugal system the gas and liquid phases need to be adequately resolved in order to portray bubble and gas entrainment, transport within the liquid metal and capture during solidification.

The aim of the work, reported here, is to develop a comprehensive computational model of the centrifugal casting system that can adequately capture the liquid-gas flow dynamics allowing reliable predictions of the macro-defects that can arise from the process.

Computational Model

The model is implemented within PHYSICA [8] where the numerical procedures are based upon finite volume methods on unstructured heterogeneous meshes suitable for complex 3D geometries [9] and with scalable speed-up in parallel [10].

The metal and air is represented as a Newtonian fluid by the Navier-Stokes equations:
for fluid momentum

$$\frac{\partial(\rho\underline{u})}{\partial t} + \nabla.(\rho\underline{u}\,\underline{u}) = \nabla.\left(\mu_{eff}\nabla\underline{u}\right) + \underline{S}_u - \nabla p \tag{1}$$

for mass conservation

$$\frac{\partial\rho}{\partial t} + \nabla.(\rho\underline{u}) = S_m \tag{2}$$

where $\underline{u}$ is the fluid mixture velocity, ρ is the fluid mixture density, p is pressure and μ_{eff} is the effective viscosity. These equations may well be augmented by turbulence models to calculate the effective viscosity.

The governing equations are solved in a non-inertial reference frame, where the co-ordinate system moves with the rotating equipment. To account for the acceleration of the fluid the centrifugal and Coriolis forces enter the momentum equations as fictitious forces. The velocity of the fluid relative to the co-ordinate system can be expressed as;

$$\underline{u}_r = \underline{u} - (\underline{\Omega} \times \underline{r}) \tag{3}$$

where u_r is the relative velocity, Ω is the angular velocity and r is the position vector.

Substituting (3) into (1) and re-arranging the left hand side of (1) can be written as;

$$\frac{\partial}{\partial t}(\rho\underline{u}_r) + \nabla.(\rho\underline{u}_r\underline{u}_r) + \rho\left(2\underline{\Omega}\times\underline{u}_r + \underline{\Omega}\times(\underline{\Omega}\times\underline{r})\right) \tag{4}$$

and equation (2) as;

$$\frac{\partial\rho}{\partial t} + \nabla.(\rho\underline{u}_r) = S_m \tag{5}$$

When the fluid is rotating at the same velocity as the rotating frame the forces should balance and the relative velocity is equal to zero. The differencing scheme employed in the numerical discretisation of the governing equations determines the accuracy of the flux calculations and hence the correct time period for a stationary fluid to achieve its rotational velocity. A first order scheme is not sufficient and a higher order scheme, such as, SMART [11] is required.

The heat transfer and solidification are described by:

$$\frac{\partial}{\partial t}(\rho cT) + \nabla.(\rho\ c\ \underline{u}\ T) = \nabla.(k\nabla T) + S_h \tag{6}$$

where c is the mixture specific heat capacitance and k the conductivity.

The source term S_h can represent viscous dissipation, of heat due to fluid bulk motion, boundary heat transfer and the latent heat release during phase change. If only change of phase is considered, the source into the heat equation due to the solidification process is equal to:

$$S_h = -\frac{\partial(\rho f_L L)}{\partial t} - \nabla.(\rho \underline{u} f_L L) \tag{7}$$

where L is the latent heat of solidification and f_L is the liquid fraction of the metal component of the fluid. The liquid fraction is typically a function of the metal temperature. A Darcy like flow retardation is applied to the fluid momentum once solidification begins. [12]

Capturing the metal-air interface employs a fixed grid solution procedure, employing the concept of volume of fluid, GALA scheme and the SEA TVD capturing scheme [13-15]. The advection of the scalar,

$$\frac{\partial \phi}{\partial t} + \underline{u}_r.\nabla(\phi) = S_\phi \tag{8}$$

is solved numerically and the interface is captured as a discontinuity in the solution field via an appropriate non-diffusive scheme. Methods that work well for relatively quiescent mould filling, such as, van Leer [16] based surface capturing algorithms smear unacceptably for the dynamic flow conditions arising during centrifugal casting. Methods which are better at surface capture, such as, donor-acceptor algorithms [17] are much more sensitive to mesh quality and so make demands on the element quality throughout the whole mesh – one poor quality element can cause the whole procedure to fail [18]. A switching algorithm has been implemented that calculates the orthogonality of a cell face and switches from donor-acceptor to van Leer interpolation scheme on highly non-orthogonal faces.

The inclusion of surface tension effects, on the interface between materials, is accounted for by a source term in the momentum equations which depends on the value of the surface tension, the curvature of the interface and any effects caused by the interaction of the free surface and a boundary [19].

Flow Validation

A series of water model experiments were performed using a transparent cylinder to represent a casting mould, filled in a controlled manner through a funnel or a less controlled manner by hand, with the resulting fluid flow recorded using high-speed video image capture. It was evident from observations of the video footage that a tranquil pour is not achieved and there is significant fluctuation in the flow (Figure 1a), with similar effects observed previously in bulk liquid metal flows [20]. Capturing the pour dynamics in the model inlet boundary conditions is required in order that the physics are reflected in the model in order to accurately predict the flow dynamics. For the simple case of a surface patch constant mass flow inlet, the pour profile will typically be symmetrical around the axis of pour. In a constrained geometry, this will cause the liquid to spread up the wall, before collapsing back upon itself. In such cases, the symmetrical form will cause a volume of gas to be trapped beneath a flawless blanket of liquid in a way that is not physically correct (Figures 1b,c): in reality, any hole or defect in the surface of the liquid will allow the gas to escape. These volumes of gas will typically be entrained, as their buoyancy is overcome by turbulent recirculation of the liquid.

For the case of filling a cylinder, correctly modelling the volume of trapped gas cannot be achieved using a fixed inlet condition. The volume of trapped gas, taking the shape of a torus around the incoming flow, may have a volume five orders of magnitude greater than a typical sub-millimetre bubble. The total volume of the gas/liquid mixture will therefore be greatly overestimated. Figures 1b and 1c show an attempt to introduce instability into the system by modelling the liquid entering the cylinder through the funnel. It would appear, however, that the residual momentum of the liquid before the pour, and the turbulent removal of the stopper have a greater influence on the flow condition than the delivery method. The 3D funnel model cannot therefore be said to be an improvement on a simple 2D wedge (Figure 1d) in terms of realistic inlet condition.

By tracking the discrete fluctuation in the flow against a gridded background, equations were derived to characterize the pour profile; the variable mass flow rate gave a much reduced error in describing the mass flux of the pour compared to a fixed mass flow rate. Results of the experimental flow validation case were presented in [21]. In order to incorporate such fluctuations for a range of pouring conditions, an oscillating inlet diameter and variable inlet velocity were implemented in such a way as to conserve the mass transfer rate. Figure 1e illustrates how, by introducing the variable inlet condition, the large re-circulating volume was broken up into smaller bubbles, which easily escaped the bulk volume, better representing the physical process (Figure 1a)

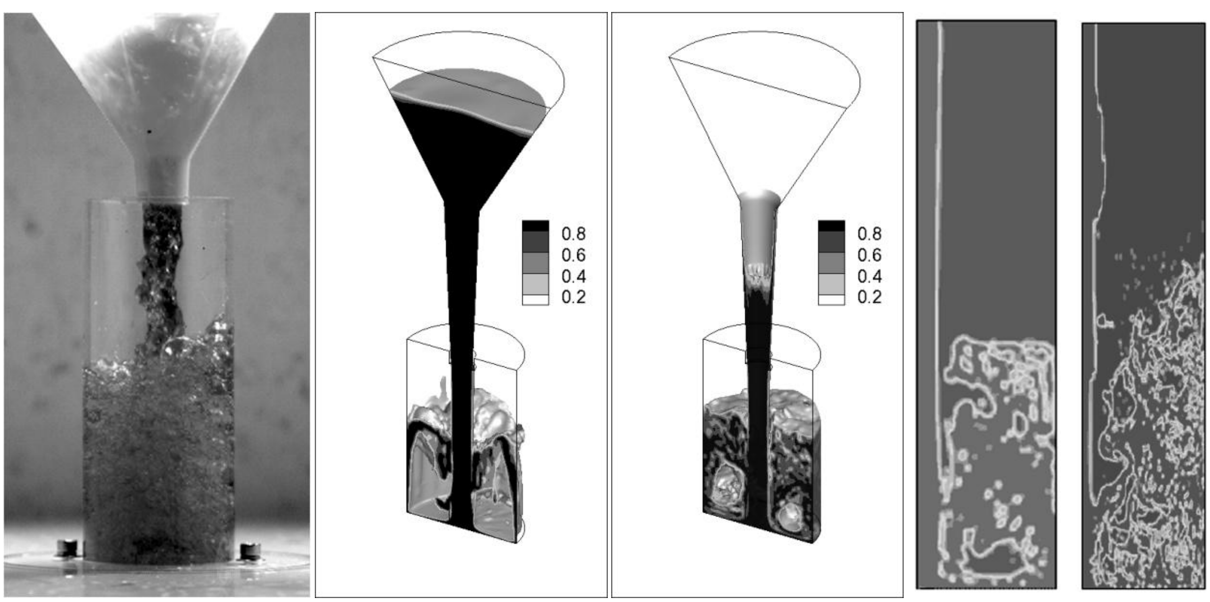

Figure 1: a) Experimental pour b,c) Funnel inlet d) Constant inlet e) variable inlet

Further improvement to the flow condition was achieved by positioning the inlet inside the model domain. When the volume patch lies inside the fluid domain, a smeared liquid/gas region is formed behind the flow. The induced velocity at the inlet patch drags the smeared region through the flow, introducing gas into the pour. In combination with the variable inlet condition, this creates an incoming liquid stream that accurately mimics the observed flow. The introduction of instabilities to the flow in the form of additional gas might be expected to increase the gas entrainment in any subsequent running system, however, similarly to the cylinder case, the ability to break up the otherwise physically idealised entrainment events in the flow allow the resulting filling to show greater fidelity in terms of free surface capture, and greater clarity of the bubble entrainment process. Figure 2 shows the effect of introducing an offset inlet, note in particular the lack of smeared liquid in the runner in Figure 2a compared to 2b.

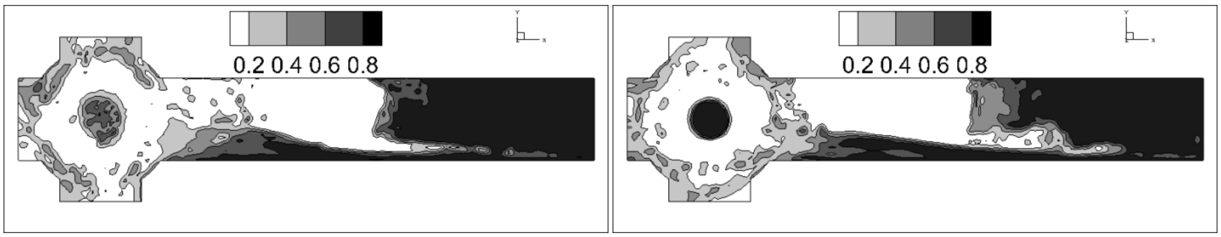

Figure 2: Test geometry filling 1s a) Offset inlet b) Surface inlet

In order to calibrate and validate the model, a series of aluminium alloy castings, employing the variable inlet conditions, were undertaken. A detailed description of the experimental setup and comparison of the liquid metal flow dynamics, using real-time x-ray against model predictions were presented in [20]. The experiments showed close correlation of the fraction of gas incorporated into the liquid during pouring when a perturbed inlet boundary condition was applied. The highly variable liquid dynamics and unconstrained pour conditions introduce slight variations into the inlet stream that can not be exactly measured or hence, accurately modelled. However, the validation work has shown that the perturbed inlet condition can improve the prediction of the locality of air entrapment, transport of air bubbles within the system and give a reasonable estimate of the volume of air entrained within the liquid.

Fluidity Test Case

To test the effectiveness of the model in predicting the fluidity of cast metal, the vacuum method described by Ragone et.al [22] was chosen, with results taken from the related work of Feliu et. al [23] The method was chosen, as the liquid metal is subject to high pressure and velocities, before freezing in thin channels, which represents the centrifugal casting process the model is aimed towards.

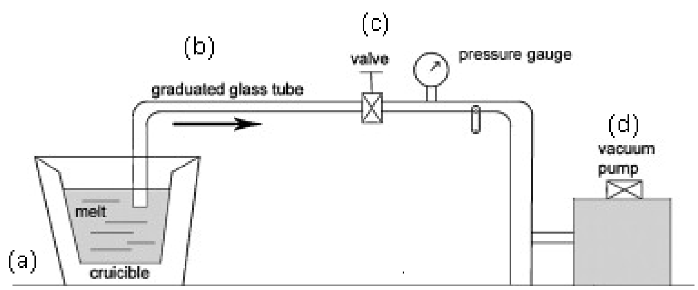

Figure 3: Fluidity test apparatus (redrawn from [23])

The apparatus is shown in Figure 3 and consists of (a) a crucible, (b) a heat resisting glass fluidity test channel, (c) a solenoid valve, (d) a pressure reservoir. Fluidity tests were performed by drawing liquid metal from a crucible through a test channel by means of a partial vacuum. Metal flow ceases when any section of the flowing stream becomes sufficiently solid to prevent passage of more liquid. In the investigation, charge metals consisted of Al (99.99 % pure). The fluidity test channel consists of a glass tube 4.80 mm bore with a wall thickness of 1.02 mm.

The crucible and pipe were meshed, and the simulation performed assuming a ‘virtual wall’ of single ‘dummy’ elements, 1.02 mm thick. The temperature was solved explicitly in the dummy elements thus incorporating the transient heat capacity of glass whilst reducing the memory and computational time.

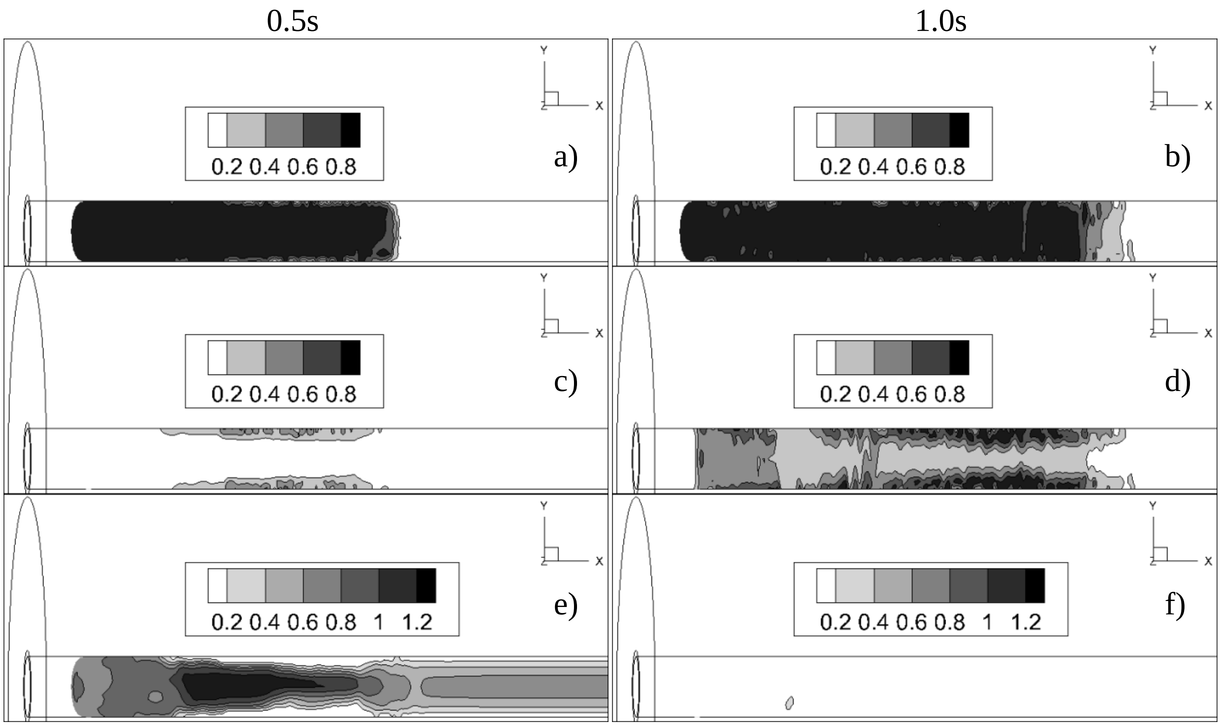

Figure 4: Fluidity model – Fraction metal (top), Fraction solid (middle) x-axis velocity (bottom)

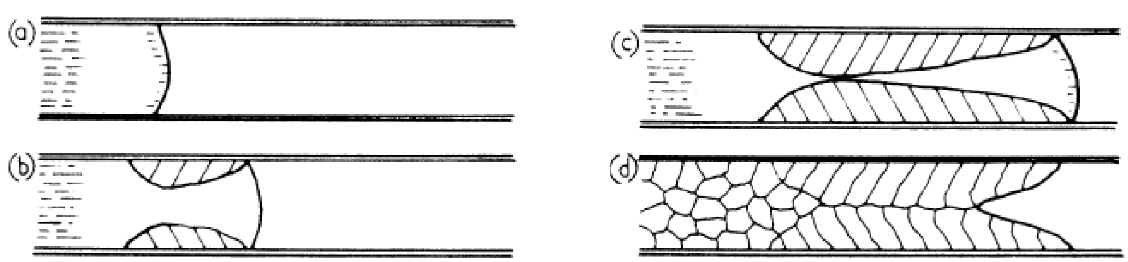

Figure 5: Mode of solidification of pure alloys with superheat [21]

In the experiments, the metal was heated to 1033 K and fluidity tests performed as the metal cooled to solid. The pressure is held constant at the pipe outlet, giving a pressure drop equivalent to a 254mm (10”) head of metal. In the second test the temperature was held constant at liquidus plus 50 K and the pressure drop was varied. Figure 4 shows a cross-section of the fluidity tube during, and at cessation of, the flow. Plots are scaled by a factor of 10 in the y direction to allow clearer visualisation of the results. It can be seen that as the liquid flows along the pipe Figure 4a, it loses heat at the walls Figure 4c, and the mushy liquid/solid restricts the metal to a pseudo-laminar flow in the centre of the pipe Figure 4e. Nearer the crucible, where the mould has heated up, the metal does not freeze as quickly, and heat is distributed by more turbulent metal flow. At the tip of the flow therefore, where new metal is dragged through the reduced section pipe, a strong thermal gradient develops, indicating columnar grain growth. In the remainder of the pipe, a more even distribution of temperature would suggest equiaxed grain growth Figure 4d. Figure 5 shows a summary of the findings from Feliu et. al [22] that are in excellent agreement with the model; Figure 6 plots the data of pure metals from the same work, in comparison to the model predictions.

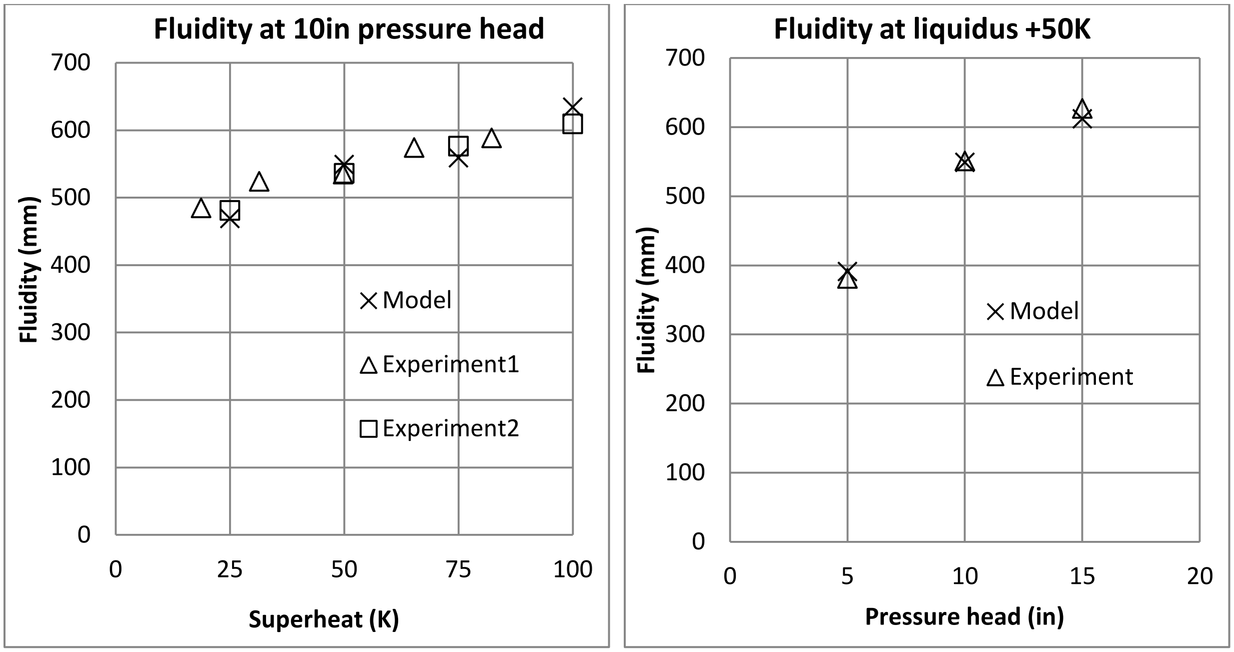

Figure: 6: Experimental and model results

Conclusion

This contribution describes a comprehensive computational fluid dynamics model suitable for centrifugal casting systems. The free surface algorithm maintains a sharp metal-gas interface allowing detailed resolution of air entrapment and transport of bubbles. Newly implemented techniques for representing the inlet flow conditions have been shown to be necessary in order to predict the overall flow dynamics, air entrainment and bubble transport. The validation of heat transfer and solidification, employing Darcy type flow retardation and virtual moulds, has achieved excellent agreement with experimental results for the fluidity test case.

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