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USING THE CALCULATED FROUDE NUMBER FOR QUALITY ASSESSMENT OF CASTING FILLING METHODS

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Abstract

The reliability of cast components is dependent on the quality of the casting process. This can be characterised by the robustness (repeatability) and specific fluid flow characteristics within the running system. During this transient filling phase the prevention of free surface turbulence and thus oxide entrainment is critical to ensure the mechanical integrity of the component. Past research has highlighted that return waves are major causes of free surface entrainment. To reduce the entrainment occurring during the transitional filling of the runner a steady quiescent flow must be developed.

Using *FLOW-3D* the Froude number has been extracted from simulated casting filling to allow the quantitative prediction of air entrainment for a number of different flow conditions. Different running system geometries have been simulated and the overall quality of the running system performance assessed using the Froude number entrainment criterion. The results have been compared to real-time X-ray imaging of transient aluminum alloy flow in running systems.

The results show that, for the designs used, the correctly designed geometry is advantageous. An incorrect design may reduce the Froude number but can greatly increase the persistence of the return wave and entrainment and is therefore extremely detrimental to the cast component. The addition of a filter created a deeper quiescent incoming flow and greatly reduced the persistence giving a low total entrainment value. Additionally, the in-gate design is of utmost importance in controlling the back pressure and thus the persistence of the back wave between the in-gate and the downsprue exit. This has a direct effect on the level of oxide entrainment. The quantitative Froude number data obtained from the *FLOW-3D* model were seen to correlate well with the qualitative real time X-ray data, where as the lowest frequency of bubble occurrence and smallest size was observed in systems containing a filter.

Introduction

It is only in the recent history casting processes that dimensionless numbers have been used by the foundry engineer to assess for turbulence within the metal stream. The Reynolds number was initially used as a criterion for ‘quality’ of filling. However, extensive research has shown that the folding of surface oxide into the bulk fluid is far more important than internal turbulent energy losses and severely degrades materials’ properties [2]. Therefore, Reynolds number is an inappropriate criterion for the prediction of running system performance. Alternatively, the Weber and Froude numbers have been used as criteria for free surface instability and turbulence in hydraulic systems, but it is only recently that this has been proposed as applicable to metal casting [3-5].

Previous research on the Froude number has largely been conducted experimentally by civil engineers. Large hydraulic structures, such as weirs and spill ways, often induce hydraulic jumps and extensive entrainment of gas into the liquid stream. Thus, research has concentrated on assessing the energy dissipation and aeration at these features [6, 7].

The Froude number (*Fr*) is defined as the ratio of inertial and gravitational forces and can be represented by Equations 1 or 2:

$$Fr^2 = \frac{\rho l^2 v^2}{\rho l^3 g} = \frac{v^2}{gl} \tag{1}$$

$$Fr = \frac{v}{\sqrt{gl}} \tag{2}$$

where ρ is density (kgm^{-3}), l is characteristic length, typically a fluid stream's depth (m), v is characteristic velocity of the stream (ms^{-1}), and g is the gravitational acceleration (ms^{-2}). It is generally accepted that when *Fr* exceeds a value of 1 the fluid stream may become energetically unstable, initiating an undular jump whilst a full hydraulic jump develops when $Fr \approx 1.7$ [8] which we define as the entrainment threshold. The relative severity of such jumps is summarised in Figure 1.

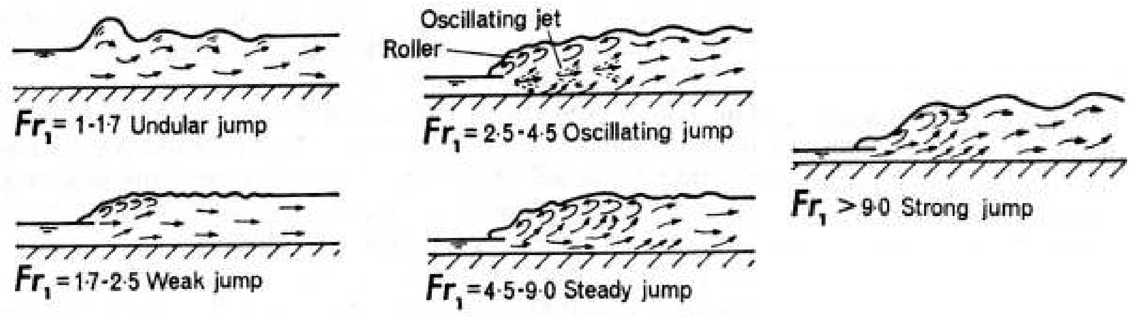


Figure 1. The dependence of hydraulic jump structure on Froude number (from [8])

In the case of transient fluid flows during casting it is also common to observe flow structures similar to hydraulic jumps, although in this case the 'jump' does not take the form of a standing wave, but is instead itself moving along the runner [9, 10]. With manipulation these waves can be assessed as standing waves in the same manner as a hydraulic jump as seen in equation 3 where v_2 is the returning wave velocity; as depicted in Figure 2.

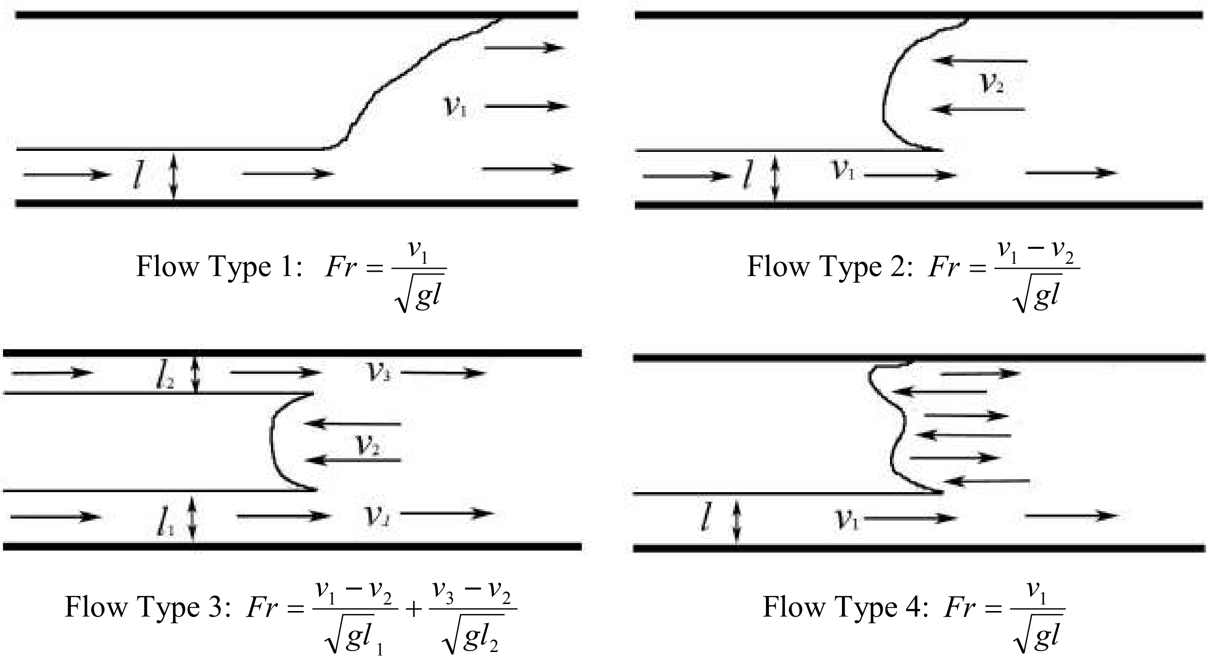
$$Fr = \frac{v_1 - v_2}{\sqrt{gl}} \tag{3}$$

The performance of casting filling systems, and specifically formation of hydraulic jumps in runners, has previously been researched using computational fluid dynamics software such as *FLOW-3D* [1]. With such tools it has been shown that flow structures similar to hydraulic jumps may be predicted and experimental observations of molten aluminium streams poured onto and spreading across flat sand cores as high velocity jets show jumps [11]. However, recent unpublished work conducted by ourselves has not been able to validate experimentally the jumps modelled for open channel flows.

This difficulty has led us to consider again the problem of prediction of free surface entraining flows in runners and the quantitative (numerical) representation of the performance of a casting filling system. In this paper we report development of a numerical methodology based on *Fr* number analysis and the initial experimental validation of this approach.

Assessment Criterion Methodology

Following on from previous work at the University of Birmingham in which a large number of 3D flow conditions were simulated in the horizontal runners of large castings [12] it has been possible to categorise the flow regime under which a runner is 'primed' (the initial filling transient before it is completely filled) as belonging to one of four sub-types. These are represented schematically in Figure 2.



Flow Type 1: $Fr = \frac{v_1}{\sqrt{gl}}$

Flow Type 2: $Fr = \frac{v_1 - v_2}{\sqrt{gl}}$

Flow Type 3: $Fr = \frac{v_1 - v_2}{\sqrt{gl_1}} + \frac{v_3 - v_2}{\sqrt{gl_2}}$

Flow Type 4: $Fr = \frac{v_1}{\sqrt{gl}}$

Figure 2. Flow type schematics and associated calculation formula (downsprue exit / runner entrance to left of figure)

These 4 flow types have also been observed experimentally and captured using real time X-ray flow imaging, using techniques described elsewhere [13]. In general each flow type exhibits the following characteristics and locations:

- Type 1: The shallow and deeper flows are both travelling away from the downsprue exit and commonly occurs in the section between the downsprue exit and the in-gate. This occurs when there is insufficient back pressure induced by the in-gate to force the return wave towards the sprue exit.
- Type 2 is often seen between the end of the runner bar and the in-gate and is characterised by well structured counter-directional metal streams.
- Type 3 is most commonly seen at the start of the runner next to the sprue exit, where the fluid impacts the bottom of the runner then proceeds to roll around the runner roof and meets a returning wave of flow type 2.
- Type 4 is used to define any flows which are not described by and of the previous flow regimes. These are highly chaotic type flows often entraining large air bubbles and often occurs as the initial fluid stream impacts the end of the runner bar.

More than one flow type commonly occurs during casting.

For calculation of *Fr* it is clear that in each instance the flow can be reduced to a standing wave and definitions of Fr for Types 1 to 4 are given in Figure 2. Flow type 3 is calculated by splitting to the flow into two standing waves, an upper and lower wave. Providing both the upper and lower wave exceed the entrainment threshold ($Fr \geq 1.7$) then the *Fr* numbers for both waves are summed together. If only one portion of the wave exceeds the threshold then this value is taken.

A sub-routine has been developed to assess the waves found in casting running systems. Using *FLOW-3D* to model the liquid metal filling of a casting a sub-routine has been developed and implemented to allow calculation of *Fr* (in accordance with the definitions in Figure 2) at predetermined, regular, time steps. To obtain the Froude number the following are defined in the sub-routine input file: the cell plane and mesh block in which to undertake the calculation, the cell values for both the top and bottom of the runner, the height at which to scan to find the metal front and also the predetermined time step at which to undertake the operation.

The sub-routine takes the following steps to obtain the Froude number for each predetermined time step (Figure 3):

1. The cells along the predefined plane at the defined height are scanned until a cell with fluid is detected.
2. The cells in successive downstream columns are then scanned until a column with every cell containing a fluid fraction of 1 is found. This is selected as the calculation column.
3. The column is scanned from the bottom cell searching for a change in flow direction. The number of changes of flow direction and velocity is used to identify a flow type.
4. The distance from the runner boundaries (floor and roof) to changes in fluid direction allow parameters l_1, l_2 and l_3 to be calculated.
5. The average velocities v_1, v_2 and v_3 are calculated between these boundaries.
6. The *Fr* number is then calculated and output to a text file.

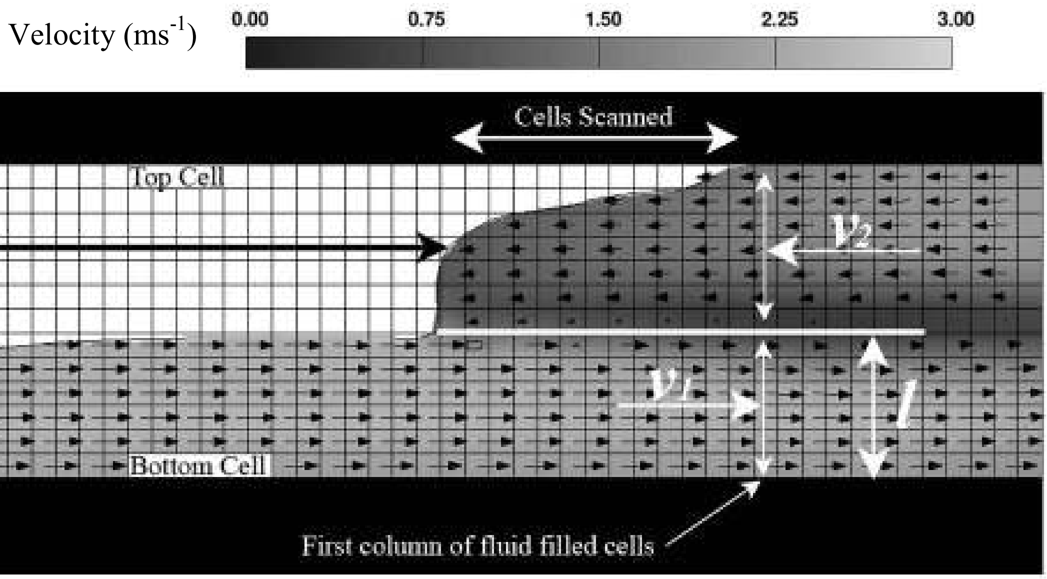
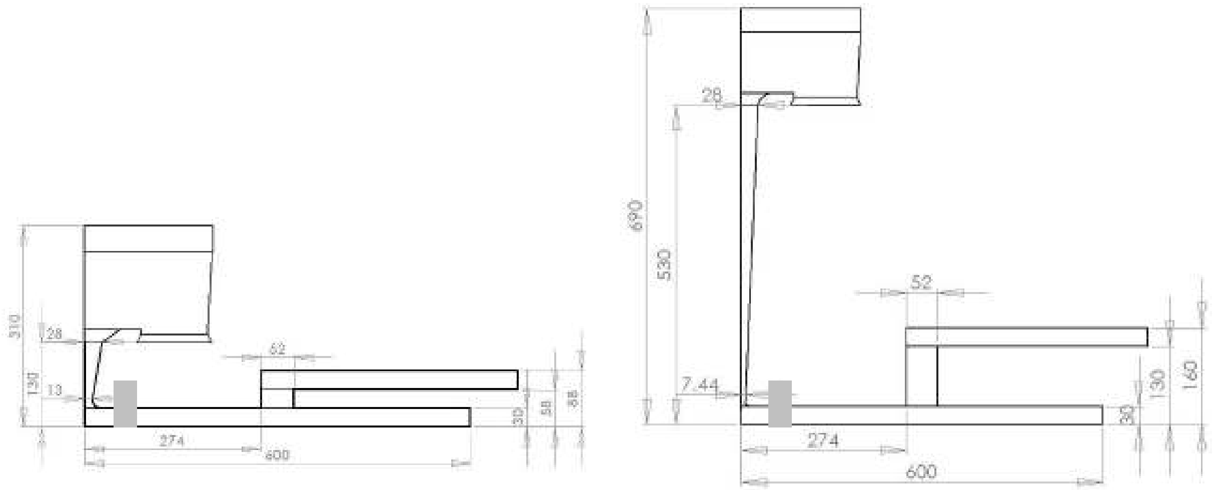


Figure 3. 2D Return wave showing Fr calculation method

Experimental Validation

Four experimental castings were poured in resin bonded silica sand moulds (AFS grade 60 sand) using commercial purity aluminium alloy LM0. The cast weight was 11 kg, the pouring temperature 760 ºC and the pouring was controlled using a robotic system. Details of the crucible position relative to the basin, crucible geometry and crucible rotation profile were recorded and replicated within models. Filling was viewed using real-time X-ray radiography to allow the qualitative assessment of the flow transient. Flow images were captured at a rate of 100 s^{-1} and resolution 800×600 pixels over a field of view of approximately 250×200 mm.

Two simple running systems were designed. Each conformed to known 'best practice principles' for a large sized aluminium casting [4]. Each system was expected to allow the creation and propagation of return waves and featured a blind end runner with an in-gate positioned half way along the length to generate a filling back pressure. The designs are shown in Figure 4; both systems have the same volumetric flow rate at the downsprue exit. Each was cast with and without a 20ppi 50×50×20 mm reticulated foam filter placed vertically 26mm from the left side of the runner bar (down sprue end).



a) Low Condition b) High Condition

Figure 4. Running system (runner thickness 35mm)

Each of the castings was modelled using *FLOW-3D* and the filling transient in the runner analysed using the Froude number sub-routine. A Froude number of 1.7 has previously been reported as threshold above which a direct rather than undular jump (and hence entrainment) occurs and was applied as a criterion within this study. From the calculation the following data were determined:

- Froude number within the runner as a function of time,
- Flow type,
- Persistence – duration of the flow transient prior to complete filling of the runner, and
- Total damage, defined as the integral area of the Froude-time plot above the threshold value of Fr=1.7.

Results

The results obtained by calculation are shown in Figures 5 to 7. Figure 5 shows the instantaneous Froude number as a function of time, Figure 6 the distribution of flow forms by experiment and Figure 7 the persistence and total damage. The results show the high condition mould to be the most entraining and the high condition mould with filter to produce the least entraining flow regime. Flow types 1 and 2 were the dominant regimes within all experiments.

Typical examples of flow simulation results and equivalent the real-time X-ray images are shown in Figures 8-12.

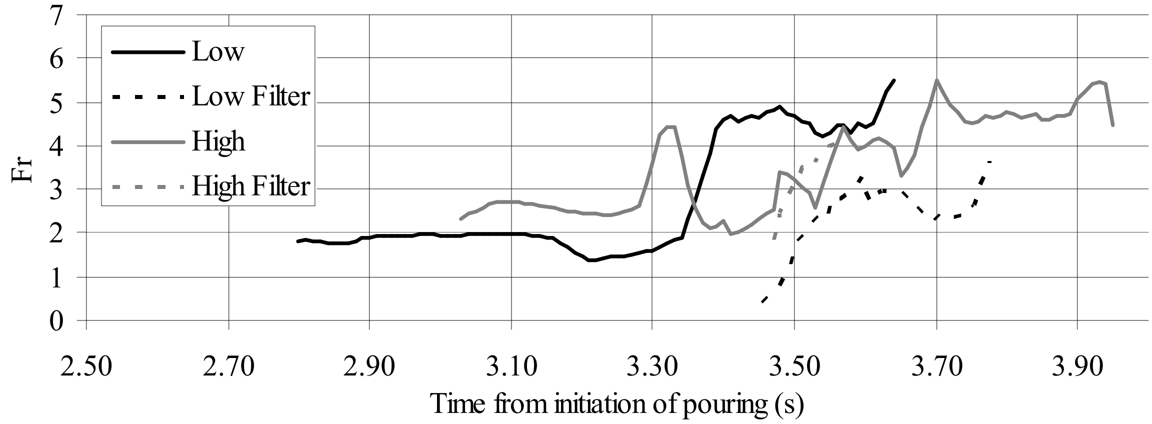


Figure 5. *Fr* versus Time chart (5 point rolling average used)

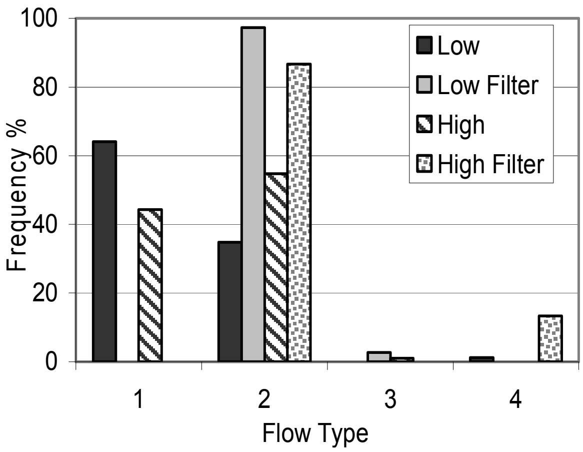


Figure 6. Flow type distribution for each filling system

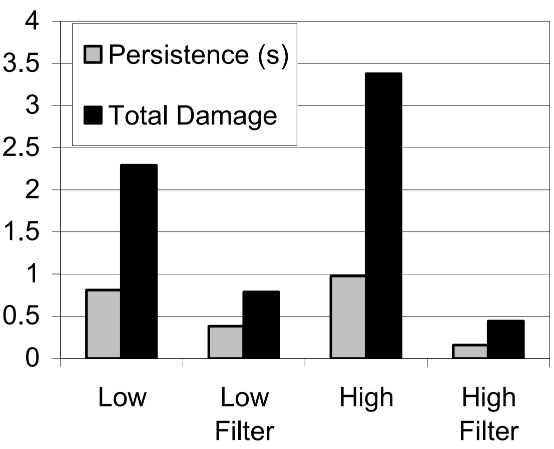


Figure 7. Calculated persistence and total damage for each filling system

Discussion

Figures 8 to 11 are examples of how the experimental results were consistent with those numerically modelled, showing the same flow types. The X-ray data was qualitatively compared to the persistence and total damage function. The results were appeared to correlate well with the unfiltered condition moulds showing a greater persistence, the highest frequency and largest size of visibly entrained air bubbles at the returning wave interface, Figure 12. It was not unexpected that the high condition produced the highest rate of entrainment as the system has the most energy; the system generated a Fr number of 6.46. This mould produced the most persistent wave which was also the most highly entraining. The best mould was the high condition with a filter; this was due to the filter producing a more quiescent fluid front, with a deeper initial stream. This stream took most of the depth of the runner in its first pass and proceeded to rapidly fill the remaining runner with a returning back wave of very short persistence, taking just 1/200 of a second to propagate from the location shown in Figure 11 to the in-gate. It can be seen from Figure 5 and 7 that minimising the persistence of a returning wave is crucial to the effective design of running systems. It is assumed in this research that the rate of oxide entrainment varies in direct proportion to the Froude number. No investigations on this topic could be found in the literature therefore this assumption needs further investigation and validation. Figure 7 shows how each of these flow types was present at some point during this investigation; however flow type 2 was predominant (Figures 8 through 11) with flow types 3 and 4 (Figure 12) being extremely infrequent.

It can be seen by comparing Figures 10 and 11 how the addition of the filter increases the depth of the initial fluid stream. Figure 7 shows that persistence is also reduced with the addition of a filter, this is due to the fluid stream being deeper with less volume to fill by the returning wave. It was seen from the model and also the real-time X-ray how the use of a taller in-gate causes a backpressure of magnitude large enough to propagate the wave back towards the down sprue such faster than when a lower in-gate is used. This suggests that taller in-gates are beneficial to casting quality.

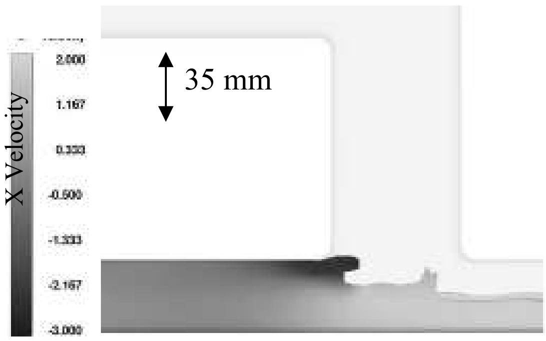


Figure 8. High Condition Model

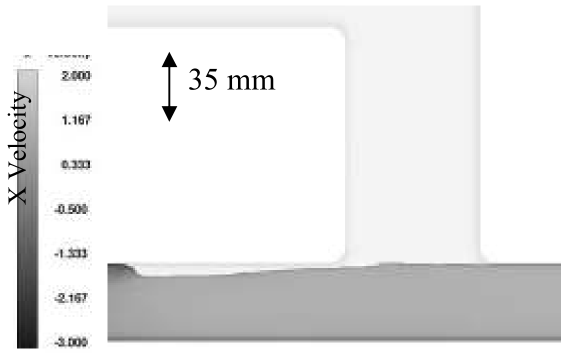


Figure 9. High Condition Filter Model

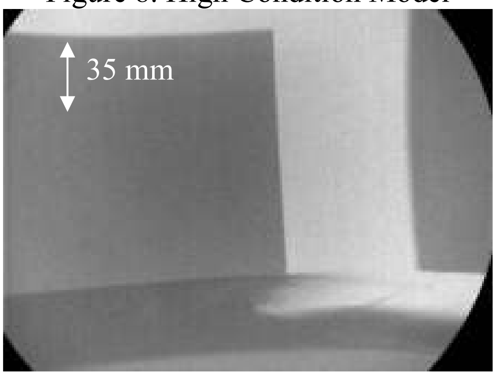


Figure 10. High Condition

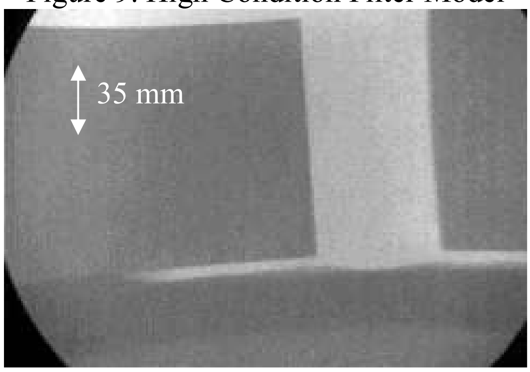


Figure 11. High Condition Filter

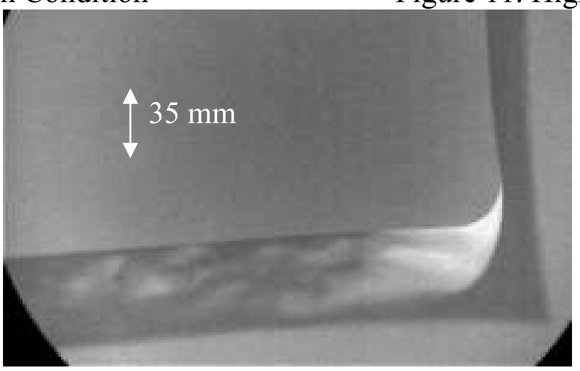


Figure 12. High Condition, type 4 flow

Whilst these preliminary results appear encouraging, the technique remains qualitative and further development of this criterion is required. Elements for development will include definition of the entrainment threshold in liquid metal as opposed to water, confirming the method for assessing multiple (simultaneous) entrainment events, establishing a better relationship between Froude number and degree of oxide entrainment and experimental validation to establish a correlation between damage criterion and casting reliability.

Conclusions

1. A numerical method has been developed whereby the instantaneous Froude number can be extracted from casting filling simulations.
2. An integral damage function has been defined, calculated and compared to direct observation of transient flows.
3. Preliminary results suggest a good correlation between direct experimental imaging of entrainment and the calculated damage function.

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