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INVESTIGATING SURFACE ENTRAINMENT EVENTS USING CFD FOR THE 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 and mould cavity. During this highly transient filling phase the prevention of free surface turbulence and consequential oxide entrainment is critical to assure the mechanical integrity of the component. Past research has highlighted a number of events that lead to entrainment of surface oxides, including plunging jets, waterfalls and returning back waves. Using *FLOW-3D*, flow structures that result in surface entrainment events have been simulated and an algorithm developed that allows entrainment and defect motion to be tracked. This enables prediction of the quantity and motion of oxide film generated from each event. The algorithm was tested experimentally using real-time X-ray radiography to directly image transient liquid metal flows. A quantitative criterion is proposed in order to be able to assess the damage of each type of event. Complete running systems have also been studied in order to understand how they could be assessed for quality of filling based on the geometric features of the flows within them.

Introduction

It is now generally accepted that high levels of free surface turbulence during mould filling lead to formation of extensive double oxide film casting defects which ultimately degrade the reliability of a material [2, 3]. Sources of free surface turbulence in casting include plunging jets, reflected waves and rising metal streams [4]. Runyoro *et al*. [5] rationalised entrainment at rising jets as controlled by Weber number, whilst Reilly *et al*. [6] suggest Froude number as an appropriate tool for the quantification of degree of entrainment by reflected waves. It is clearly a major challenge to represent adequately within a computational fluid dynamics framework all possible sources of entrainment.

Recent work to predict the performance of casting filling systems using computer modelling have utilised calculation of excess fluid free surface area [7, 8], modelling and tracking of entrainment through the folding of surface oxide for film forming alloys [1] and the nucleation, growth and transport of oxides in cast irons [5]. The ability to calculate and represent quantitatively the degree of entrainment and location of defects is central to advancing the application of numerical techniques to process optimisation. However, to date, the limited number of examples of the application of optimisation techniques have been forced to concentrate on conventional metrics for example local filling time or velocity within individual control volumes. One such example is given in [9].

Here a new technique which is amenable to application in numerical process optimisation is presented for the modelling and tracking of entrainment in film forming alloys such as aluminium.

Methodology

Bifilm tracking: Using *FLOW-3D* [1] (a finite difference fluid dynamics package) a customisation has been developed to allow the placing of particles when a flow structure likely to entrain a double oxide film has occurred. The particles' density, size, co-efficient of restitution and initial velocity vector can be defined by the user. This allows particle behaviour to be tuned to exhibit behaviour as defined by past research and theory, *i.e.* positively buoyant, commonly 1-5um in size, adherent to mould surfaces upon contact and travelling naturally within the fluid. The number of particles entrained and the positions in which they come to rest within the casting system allows the system to be quantitatively assessed, making this a powerful tool for optimisation.

Interface identity: *FLOW-3D* utilises a cartesian mesh allowing a free surface to be defined on any one of the six faces of a control volume. The code uses an "NF" parameter for each cell at every time step throughout the simulation domain. This defines firstly, if a cell has a fluid fraction of either 1 or 0 or has a free surface. Secondly, if the cell has a free surface, the primary normal direction to the free surface is reported. As shown in Table I, depending on its attributes, each cell is given an NF value from 0 to 8.

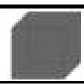
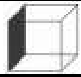
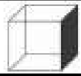
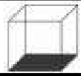
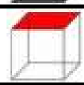
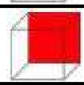
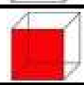
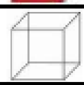
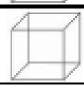
NF Value	Cell Description	Diagram
0	Interior fluid cell	
1	Fluid at left	
2	Fluid at right	
3	Fluid at bottom	
4	Fluid at top	
5	Fluid at back	
6	Fluid at front	
7	Cavitating cells (e.g Bubble)	
8	Void cell	

Table I : Definition of NF cell

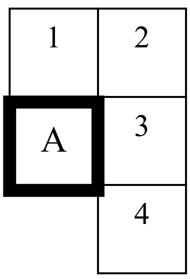


Figure 1. Cells scanned

Identification of entrainment locations: Every cell in the mesh domain is scanned in every time step of the simulation. For each cell in the mesh with a free surface (NF value ≥1 and ≤ 6) the following analysis is performed to determine if an entraining event has occurred.

1. Four surrounding cells, as depicted in Figure 1, where cell A is the current cell under assessment, are analysed to see if they also contain a free surface. If no other free surface if found then the next cell in the mesh is analysed.

2. When one of the four cells surrounding the object cell also contains a free surface then both are assessed to determine if an entraining flow structure is occurring. For both cells the NF values, fluid velocities and vector, and the fluid fraction of the cell at the end of the time step are the main constituents of the logic used to define an entrainment event. Two examples from the many different permutations of logic used to determine an entraining situation are shown in Figure 2 and Table II.

3. If it is determined that an entraining event has occurred then, providing that the predefined number of particles within the cell has not been reached, a marker particle of size and density defined by the user is placed in the most relevant position within the cell. The particles are given an average velocity in X, Y and Z axes corresponding to the location of entrainment. It is envisaged that with accurate flow and solidification modelling this should allow the final positions of defects to be determined.

It is necessary to set a limit to the number of particles present in each cell to prevent the time step becoming a significant factor on results, and to reduce the impact on CPU time. The code has a low impact on simulation time, with a typical simulation incorporating entrainment of defects taking 8% longer to run. However, when a large number of entrainment events have occurred due to a highly entraining system, the tracking of very large numbers of particles can be detrimental to simulation speed.

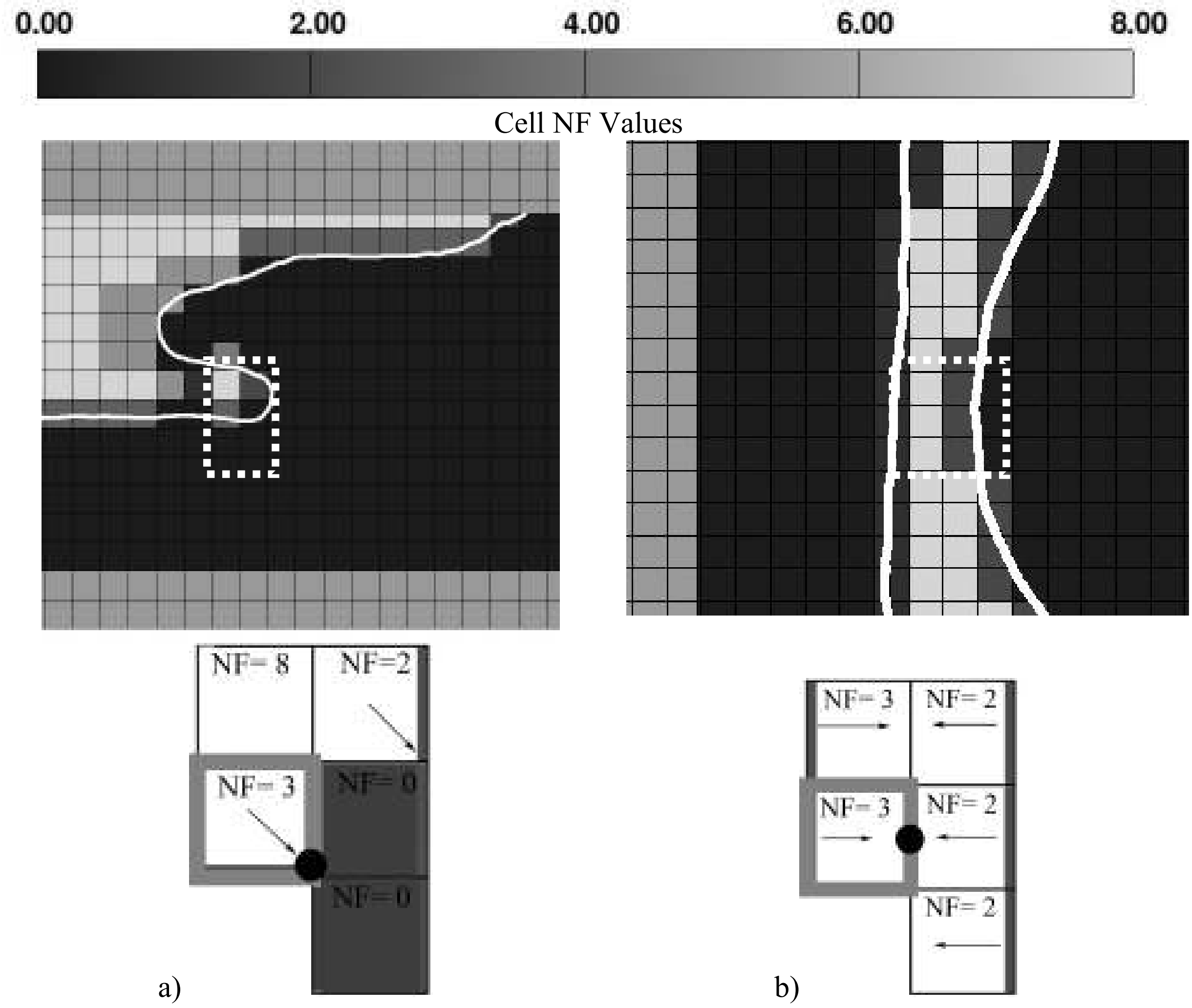


Figure 2. Example of entrainment logic. (Arrows represent velocity vector)
a) Returning wave as seen in Figure 8. b) Colliding fronts as seen in Figure 6b.

As described above, each cell within the computational domain is checked against a series of logic criteria deemed entraining. Currently 2D logic is applied to each cell plane in the remaining dimension to give a semi 3D effect. Further development will give a full 3D code. Figure 2 shows schematics for two example cases of the logic used to determine an entrainment event, and Table II describes their logic properties.

Table II. Example of entrainment logic

Example	Cell	NF Value	Fluid Fraction at end of Time Step	Velocity
Returning Wave	A	3	>0, <1	X = Positive, Y= Negative
	2	2	>0, <1	X = Positive, Y= Negative
Colliding Fronts	A	1	1	X = Positive
	30	2	1	X = Negative

a) Returning Wave (as also illustrated in Figure 8) – Here it can be seen that Cell A as has an NF value of 3 and is therefore has a free surface with fluid at the bottom. Cell 2 also has a free surface with the fluid to the right. If the velocities of these cells are entraining defects into the bulk material as depicted by the velocity vector then it can be deemed that this is an entraining event. Therefore providing that there are currently no other particles in cell A, a particle, as depicted by the circle in the schematic, can be placed with an appropriate velocity vector, in this case equal to the velocity vector of cell 3.

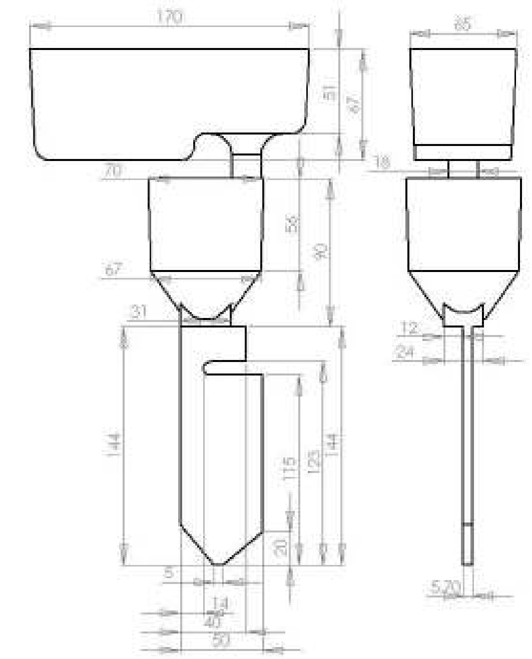
b) Colliding Fronts (as also illustrated in Figure 6b) – In this example Cells A and 3 have NF values of 1 and 2 and their velocities are positive and negative, respectively. Therefore if both cells have a fluid fraction of 1 at the end of the time step it can be deemed that the fronts collided, entraining a double oxide film. A cold lap, otherwise known as a cold shut, is a classic example of this. Once this event has deemed to have occurred a particle is placed on the centre of cell A's right boundary with velocities equal to the average of cells A and 3 in the X, Y and Z axis.

Experimental Design

Two simple moulds were cast in a real-time X-ray flow imaging facility, the principles of which have been reported previously [10]. The resin bonded silica sand mould designs were selected as they would generate entraining events including returning waves, plunging jets and colliding fronts. Details of the moulds are shown in Figure 3. Castings were produced in aluminium alloy A356 and poured at a temperature of 750 °C. Video sequences of the filling were captured at a frame rate of 100 s^{-1}, resolution 800×600 pixels, field of view approximately 250 x 188 mm and rotation profile of the crucible captured throughout pouring.

Modelling

The extended horizontal runner mould was modelled using *FLOW-3D* with a pressure boundary at the top of the downsprue. For the vertical plate the pour from the crucible into the basin was also modelled. The entrainment tracking algorithm was used to interrogate the flow structures in the plate and channel of the respective castings, not the running systems. This was done to increase the clarity of the results. The inclusion of the pouring basin and running system creates large numbers of particles which remain in the bulk material concealing other entraining regimes. It has been shown previously that pouring into a basin is likely to be the most entraining portion of the whole filling of a mould [8]. High levels of turbulence are present within the basin which has a persistent plunging jet of high energy (incoming stream from the crucible) impinging on a large volume of fluid in the basin.



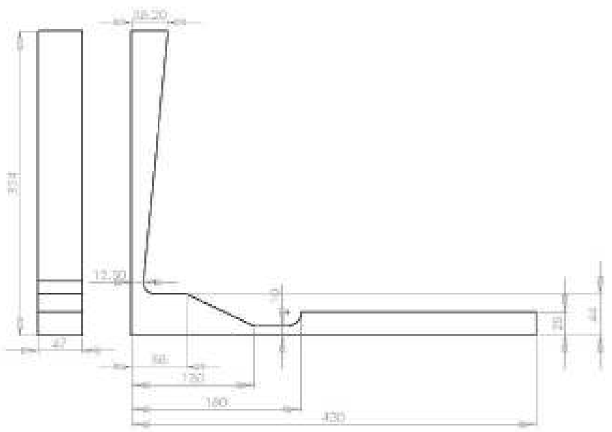
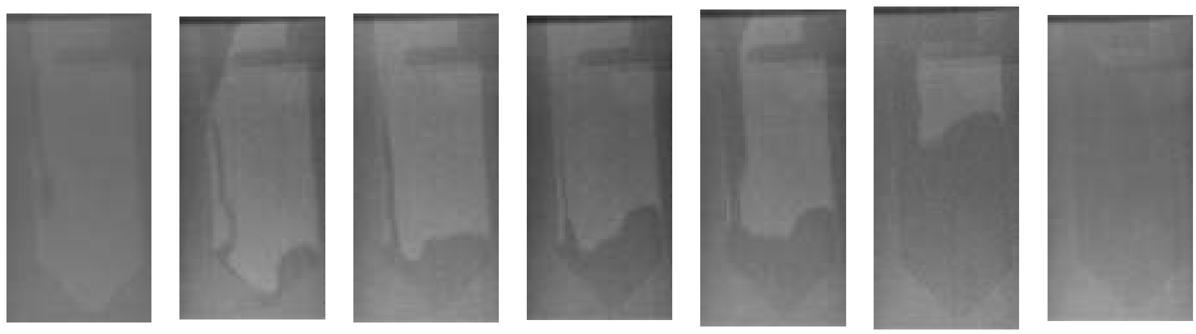


Figure 3. Geometries of the cast and modelled geometries, (a) vertical top filled plate and (b) extended horizontal runner.

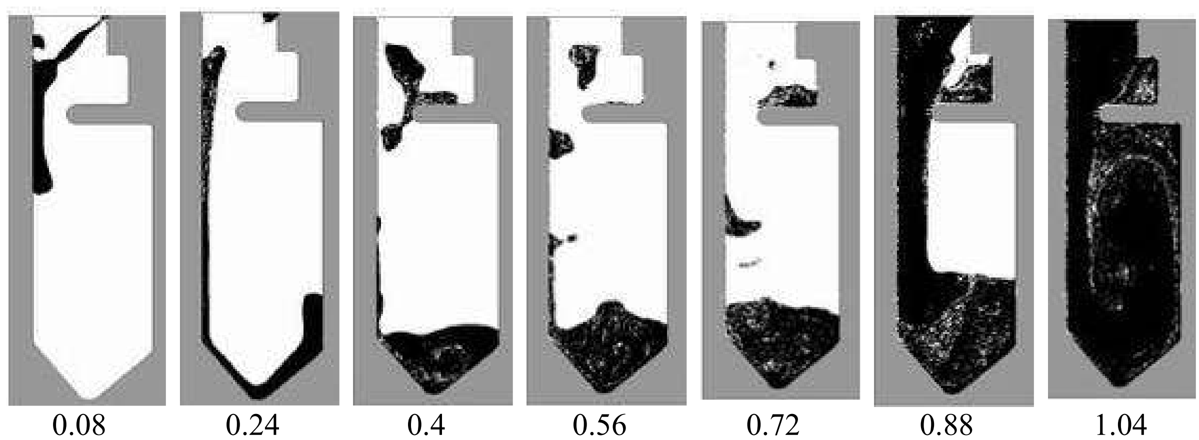
Results

The real time X-ray results of the vertical plate and extended horizontal runner can be seen in Figures 4 and 7 respectively. These show highly entraining flow regimes. The modelled results for the same castings are shown in Figures 5, 6 and 8.



0.08 0.24 0.4 0.56 0.72 0.88 1.04

Figure 4. Real time X-ray of plate casting. Time (s)



0.08 0.24 0.4 0.56 0.72 0.88 1.04

Figure 5. Modelled plate using entrainment criterion. The Particles representing entrained oxide films are represented as white dots. Time (s)

In the case of the horizontal runner the modelled filling pattern correlates closely with the experimental data. Markers indicating entrainment of the surface oxide film are introduced into the fluid stream at the counter directional interface. The model of the plate filling shows a less exact correlation to the experimental data. However, it can be seen that marker particles were incorporated at flow confluences (Fig 6b), shearing interfaces (Figure 6c) and plunging jets (Figure 6a) and subsequently transported within the flow. Examples of particle attachment to the mould wall are clearly visible in Figure 6(c).

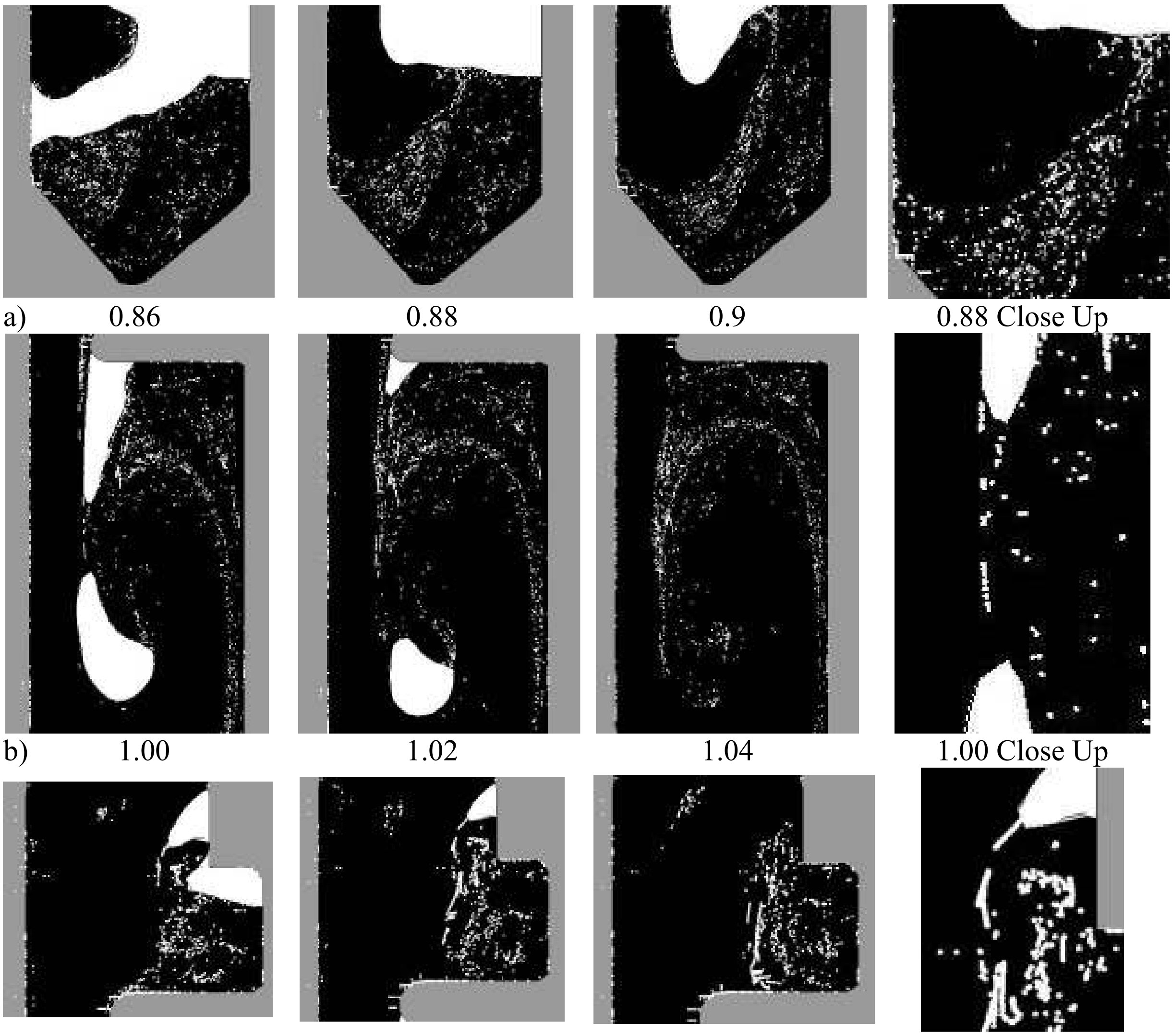


Figure 6. Three examples of entrainment mechanisms from plate model. a) colliding of surfaces b) colliding of surfaces c) Impinging jet

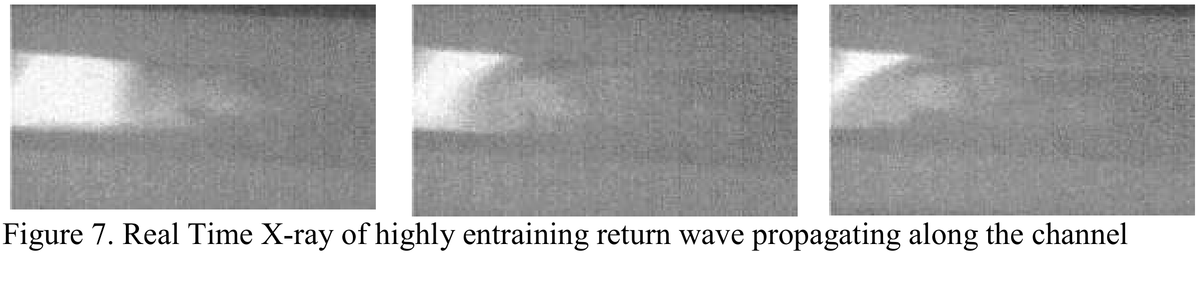


Figure 7. Real Time X-ray of highly entraining return wave propagating along the channel

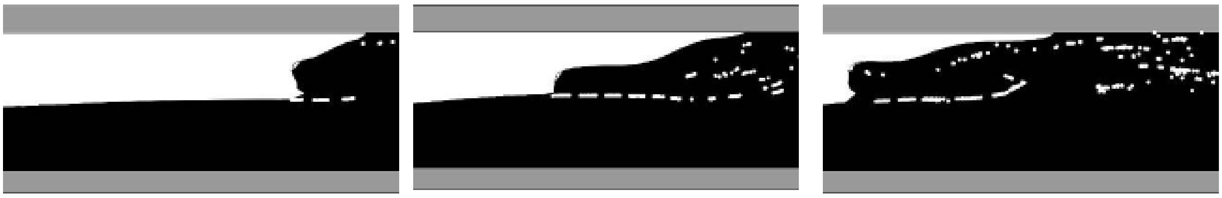


Figure 8. Entraining return wave propagating along the channel showing marker particles

Discussion

It has been shown that it is possible to determine, through analysis of the local free surface motion, the locations of oxide (and bubble) entrainment during the transient phase of casting mould filling. However, differences were identified between the calculated and observed filling, particularly that of the vertical plate. This was investigated and repeated simulation has shown that, due to the very small casting volume (35.5 cm^3) and high pouring rate, the filling pattern varied significantly with minor variation in pouring position and basin to mould alignment (estimated to be ±8 mm and ±2 mm respectively). The effect of inlet conditions of modelled flow has been shown in previously published work [11]. When simulating the larger scale horizontal running system the model was observed to correlate more closely with experiment. However, it should be noted that the present simulations are for single phase flow and if, as is observed in the horizontal runner, there exists significant levels of air incorporation, changing the local fluid density, the calculated local flow pattern will again be in error. Despite this the model appears to predict accurately the occurrence of entrainment.

The incorporation and transport of particles within the liquid metal as reported in this paper is not unique, an algorithm for doing so having been described previously by Yang et al [12]. However, in that case the model was restricted to operating in 2D and was computationally intensive, requiring the fluid free surface to be covered with a distribution of particles that could be entrained within the liquid. The new approach is numerically more efficient as the requirements for placement and tracking of surface particles has been obviated.

This is on going work and requires further development. A crucial aspect is defining the threshold for entrainment of oxide films in events such as plunging jets and returning waves. These are not currently known, but defining these accurately is critical to the accuracy of the code. Once the thresholds have been established and programmed then the code can be transformed into 3D from the 2D shown here, before validation against experimental data.

It is clear that whilst the application of geometric rules to analyse the flow structure has some validity and the experimental and model results show a good level of correlation it must be noted that the fluid properties may influence the entrainment characteristics. In the case of liquid metals this is presently unknown but it has been reported in [6] that the density, surface tension and viscosity of a fluid affects the entrainment threshold of jets and waves. Studies accounting for all 3 factors showed that with an increase in any of these properties comes in increase in the entrainment threshold. To date there is no theoretical or experimental study unifying all three parameters. However, it is known that entrainment at a free surface is controlled strongly by Weber number whilst within a horizontal runner Froude number appears more important [6]. In future work it will be necessary to assess the model sensitivity to these material properties.

Conclusions

1. A series of rules for identification of free surface entrainment have been defined. These are based on the local 2 dimensional geometric identity of free surface flow structures
2. A new algorithm has been developed to apply the rules, enabling introduction of marker particles into the fluid stream at locations where surface entrainment occurs.
3. Qualitative comparison and assessment of the model against real-time X-ray data shows a good correlation, particles marking regions where highly entraining flow regimes were observed.

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