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ASSESSMENT OF CASTING FILLING BY MODELING SURFACE ENTRAINMENT EVENTS USING CFD

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Abstract

The reliability of cast components is dependent on the quality of the casting process. During this highly transient filling phase the prevention of free surface turbulence and consequential oxide entrainment is critical to ensure the mechanical integrity of the component. Past research has highlighted a number of events that lead to entrainment of surface oxides. 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 and compared to experimental data from previously published work. A quantitative criterion is proposed to assess the damage of each type of event. Complete running systems have also been studied to understand how they could be assessed for quality of filling based on the flows within them.

Introduction

It is now generally accepted that the integrity of a casting will be degraded substantially if high levels of free surface turbulence are experienced by the liquid metal during mold filling [1]. This is due to entrainment and breakup of the surface oxide film that is commonly formed on the surface of liquid metals and alloys. A number of mechanisms have been defined for the entrainment of oxide film into the bulk material, namely: back waves, bubble entrapment, colliding fluid fronts and both plunging and rising jets [2]. This work will concentrate solely on liquid metals whose oxide films are solid, such as aluminum.

Over the last decade it has become common practice within the foundry industry to use computational modeling to simulate and qualitatively assess free surface turbulence during mold filling. This has facilitated, with varying degrees of success, optimization of running systems, with the aim to improve component integrity. With both the increase in computational power and the introduction of process optimization software within process simulation software [3], filling system optimization is now accessible to the foundry engineer. However, for this technology to be beneficial, appropriate criterion functions are required [4]. Quantitative assessment of free surface turbulence has proven problematic thus far. To date there are few techniques available to assess oxide film entrainment, those currently available have been largely summarized by Campbell [5]. These techniques do not always give a single quantitative value which is required for optimization, and/or may only be appropriate for quantifying entrainment caused by a single entrainment mechanism. To the authors' knowledge no one has yet attempted to model the entrainment of surface oxides into a bulk liquid in all its complexity, i.e. modeling the bulk fluid flow with solid oxide film on the surface and air above. Such a simulation would need to be capable of modeling three phases (bulk liquid, surface oxide film and atmospheres) in order to model the fluid and air flows as well as the solid properties of the film to ascertain when it folds over, fractures and breaks up. This would be excessively complex and computationally intensive for commercial use.

A number of techniques that have the potential to providing a single, quantitative, value suitable for the assessment of the severity and/or extent of free surface turbulence have been proposed for implementation within commercial software. These include the following, whose capabilities are described in Table 1:

- Excess free surface area [6] – the minimum possible free surface area to fill the mold is subtracted from the actual free surface area encountered during mold filling to define the excess free surface area. The lower the excess free surface area the higher the casting integrity.
- Dimensionless Numbers [7, 8] – both the Froude and Weber numbers have been used to assess flow structures within casting running systems. Entrainment and therefore casting integrity is assumed to be proportional to the magnitude of the dimensionless number above a threshold value.
- Folding of bi-films [9] – the free surface normals and velocity vectors of free surface cells with in the computational domain are assessed to determine whether entrainment has occurred. If so, a marker particle is placed and tracked to describe the entrained film.
- OFET (Oxide Film Entrainment Tracking) [10] – particles are placed on the free surface at a defined intervals. At every time step these are re-positioned. If two particles come together then the surface is deemed to have folded on is self. A marker particle is placed and tracked to describe the entrained film.
- Surface scalar [11, 12] – a scalar value grows within any free surface cell at a rate proportional to the time in contact with the atmosphere. This scalar value is then advected due to the fluids motion.

The single quantitative values for use in optimization are calculated from the above criteria by assessing for example; the total number of particles placed, number of particles in a defined region, total scalar mass, total scalar mass in defined region or by integration of a dimensionless number with respect to time to gain a single 'damage' value.

Table 1 - Summary of entrainment assessment techniques

Technique	**Assess All Entrainment Mechanisms**	**Final Defect Location**	**Computational Expense**	**Notes**
Excess free surface area	No	Not given	Low	Extremely difficult to define base line free surface area value in all but simplest cases
Dimensionless numbers	No	Not given	Low	Not possible to assess all of casting system
OFET	No	Given	High	Currently limited to 2 Dimensional models only
Folding of bi-films	No	Given	Medium / High	Does not assess all entrainment mechanisms
Surface scalar	Yes	Defect contour map given	Medium	Numerical diffusion of scalar means accurate final defect location is not given

It would be desirable to develop a technique to simulate free surface entrainment with the capability to assess all entrainment mechanisms and give a final defect location. As can be seen from Table 1, only the surface scalar technique has the ability to assess all entrainment mechanisms. However, this technique does not give a precise final defect location as the scalar is diffused throughout the fluid as it is advected. This results in regions with differing probabilities of defects being shown with color contours, but no definitive defect location. This is undesirable if the optimization of critical regions within a casting volume is required.

Methodology

A customization to the commercially available FLOW-3D software has been developed. This allows the placing of particles when flow structures likely to entrain double oxide films occur, and the tracking of these particles to their final resting position. To use this technique for quantitative optimization, assessment of the number of particles entrained or number of particles in a defined region allows single quantitative values to be defined. This technique can assess entrainment at all types of flow structures defined within the computational domain and is implemented fully in three dimensions.

The Cartesian mesh used in FLOW-3D allows the definition of the primary normal free surface direction as any one of the six faces of a control volume for a cell containing a free surface. This is defined by the “NF” parameter. To establish if an entraining event occurs within the computation time-step the code uses the NF parameter of each free surface cell and the fluid velocity vectors in adjacent pairs of cells. All free surface mesh cells are scanned for each time-step. Once an entraining event is defined a particle is placed to represent the entrained film. The particles are given an average velocity of the assessed cells in X, Y and Z axes, corresponding to the location of entrainment. It is envisaged that with accurate flow and solidification modeling the final positions of defects can be determined. The particles’ size, density, coefficient of restitution and initial velocity vector can be defined by the user. This allows particle behaviors to be tuned to those defined by past research and theory [1, 2, 13].

It is necessary to set a limit to the frequency of placing particles in any one cell to prevent the time step becoming significantly distorting results, and to reduce the impact on computation time. The code has a low impact on simulation time for a reasonably designed running system. 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.

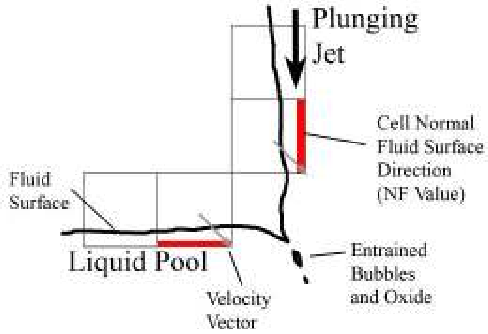

Figure 1 (above) - Plunging jet entrainment schematic

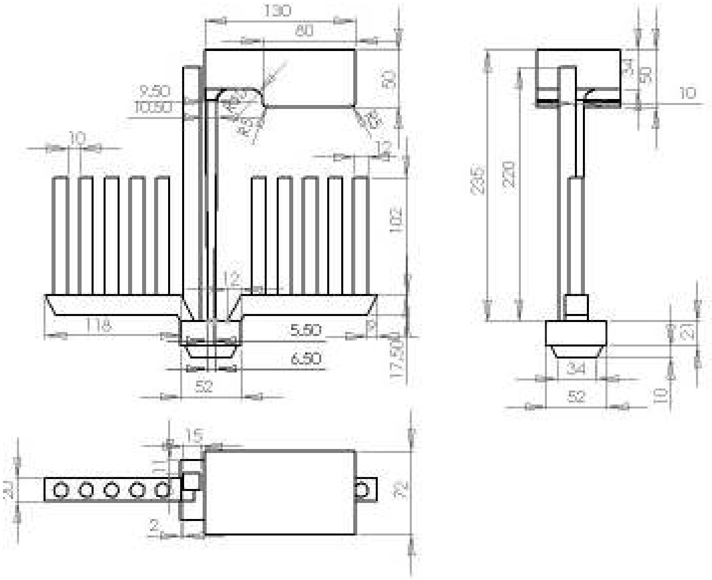

Figure 2 (right) - Mold design

An example of one entraining mechanism, namely the plunging jet, is shown in Figure 1. Here, it can be seen that there is a right and a top free surface and that the velocity vectors are such that the surface oxide film would be drawn into the bulk fluid and thus entrained. Marker particles would be placed in the corner cell to represent this. Further details and example of this methodology are available in a previous publication [14].

Experimental Design

Previously published work by Green and Campbell [1] was used for partial validation of this technique. This work used one mold design to cast ten cylindrical tensile test bars. Once machined and heat treated they were tensile tested and the scatter in measured tensile strengths quantified using a Weibull distribution as a quantitative assessment of casting integrity. Five resin bonded silica sand molds were produced in aluminium alloy A356 and hand poured at a temperature of 735-740 °C for each condition. Details of the molds are shown in Figure 2. The molds were cast both with and without a 10 ppi reticulated foam filter at the base of the runner and also a filter cup. Here the results, both with and without the filter, but no filter cup, are compared. Experiment gave Weibull moduli of 19.7 and 37.7 for the non-filtered and filtered conditions respectively.

Computational Modeling

Two models of the running system design (filtered and unfiltered) as described in Figure 2 were simulated. A uniform 1.25 mm^3 mesh and filter data defined by Lo was used [15]. The flow fields within the model and solidification were simulated throughout the entire simulation to allow accurate tracking of the particles until their final position within the domain is obtained upon solidification. The sand mold and surrounding atmosphere was within the modelled domain. This allowed accurate calculation of heat transfer conditions between the metal and the mold, and the mold and the atmosphere during the simulation. The Renormalised Group (RNG) turbulence model and surface tension model were utilized.

A pressure boundary was used for the inlet condition. A falling stream of circular cross section (36mm diameter) was positioned to impact the bottom of the pour basin after falling vertically. The stream was a representation of pour being initiated 25 mm above the model (pressure boundary of 550 Pa applied) in addition to the 50 mm of free fall the stream experienced within the model domain. The mass flow rate was significantly reduced 0.65 s after the pour being initiated. A moving object was set up to cover most of the inlet, Figure 3, to represent as closely as possible a hand pour, with rapid filling to achieve a full basin, followed by a steady stream to maintain the head height throughout filling.

The entrainment tracking algorithm was used to interrogate the flow structures in the casting systems. The particles were sized randomly between the diameters 25 and 31.25 μm, with a density of 2250 kgm^{-3} and a maximum frequency of placement of 100 particles s^{-1}.

Results

The results presented in Figure 3 show there to be large scale entrainment in the pouring basin due to a persistent plunging jet. The basin filled rapidly along with the down sprue. There was a persistent plunging jet at the bottom of the down sprue for the unfiltered mold (Figure 4). When quantified by the number of entraining events per cell the filtered mold had no obvious entraining features (Figure 5).

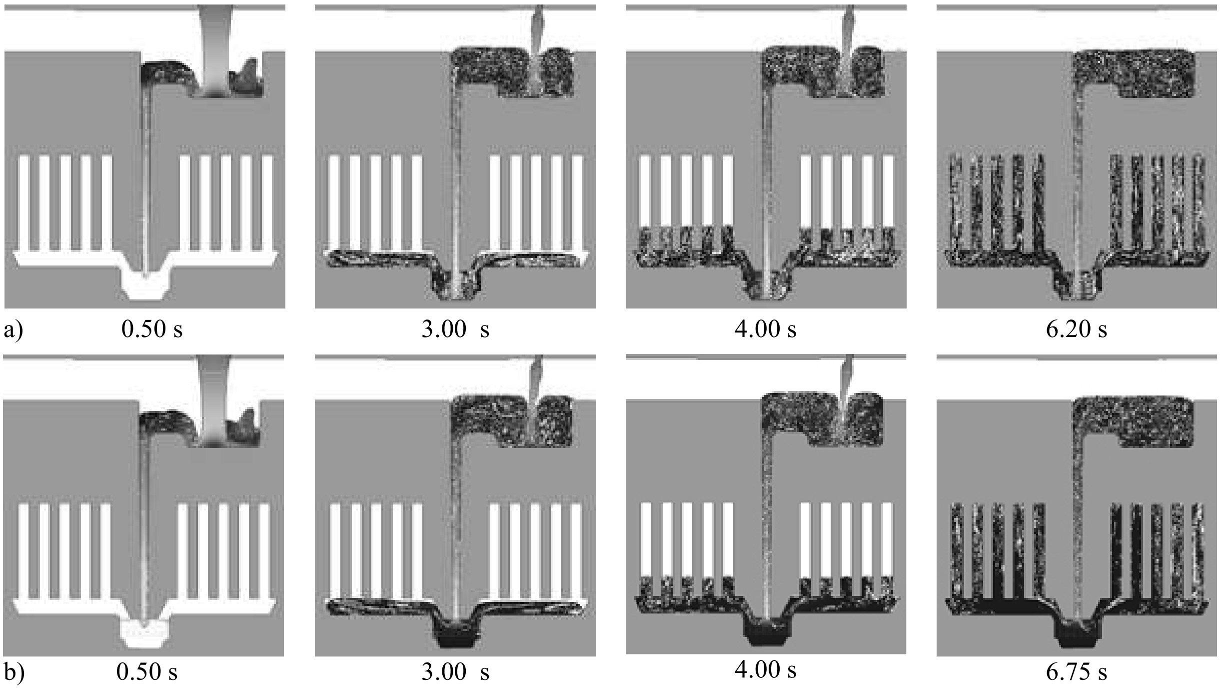

Figure 3 - 2D section of model during filling. a) Unfiltered, b) Filtered

Only the number of particles in the gauge length (central 40 mm portion of the test bar) was assessed; this was to allow direct comparison with the experimental tensile strength distribution data. The filtered condition averaged 1485 particles in the gauge length as opposed to the 1945 particles averaged by the unfiltered condition at the end of solidification. This result of the filtered condition being of greater integrity matches the findings of Green and Campbell [1]. Figure 6 reports the number of particles within each test bar and shows that the outer test bars (1, 2, 9 and 10, as labeled from left to right in Figure 3) are in general of the lowest integrity.

Discussion

The modeled results show agreement with those found experimentally, although further data is required for full validation. Unpublished flow imaging work by Green and Campbell [16] used a 20ppi filter in a modified version of the running system described in Figure 2. Castings were produced using a real-time X-ray flow imaging facility. Images from the footage are presented in Figure 7 and show flow forms within the filter print that match those of the model. In the case of the unfiltered condition Figure 7 shows an initial folding of the surface followed by a persistent plunging jet. The resulting defects are subsequently distributed throughout the material. However, the initial melt material can be seen to contain the highest density of particles. This is especially prevalent in the unfiltered condition where the initial fluid is severely damaged by entrainment in the form of a plunging jet within the filter print (Figure 4). This material finally resides in the outer test bars giving the skewed pattern seen in. This result shows that correctly designed overflows to capture the initial metal streams could be beneficial to casting integrity and reliability.

In this study it was determined that flow within the pouring basin created large numbers of particles which entered the downsprue and remained within the bulk of the flow, traveling through the runners to the test bars. Entrainment levels of approximately 150,000 events during the mold filling were seen in the pour basins of both conditions. This suggests that the plunging jet in the basin is more damaging than the entrainment experienced throughout the rest of the mold, Figure 5. It has been shown previously, using a criterion of excess free surface area, that pouring into a basin is likely to be the most entraining portion of the whole filling of a mold [6]. In [6] this was attributed to splashing and folding of the free surface upon itself, whereas the results presented in this study indicate persistent entrainment by a plunging jet mechanism as illustrated in Figure 4 and Figure 5 .

There are limitations to the accuracy of the modeling technique reported which require further development. These include:

- Oxide films are individually unique, varying in size, shape and density. However, due to the limitations of the FLOW-3D particle model, it is not possible to assign each particle both a unique size and density. The shape of particles within FLOW-3D is limited to spheres only.
- Work has shown that when a filter is used there is the possibility of oxide films being shredded and thus become more numerous and smaller [17]. Currently this is not accounted for in the model.
- The accuracy of the particle tracking model is unknown. Current work by Griffith *et al.* has allowed the possibility of accurately assessing a simulation software particle tracking model [18].
- The models were simulated as accurately as possible using the data available from the published paper [1]. This did not allow full representation of the pouring profile as no data was available. This is unfortunate, as unpublished work at The University of Birmingham has shown the pour conditions impact greatly the fluid flow within the mold, both experimentally and in simulations.

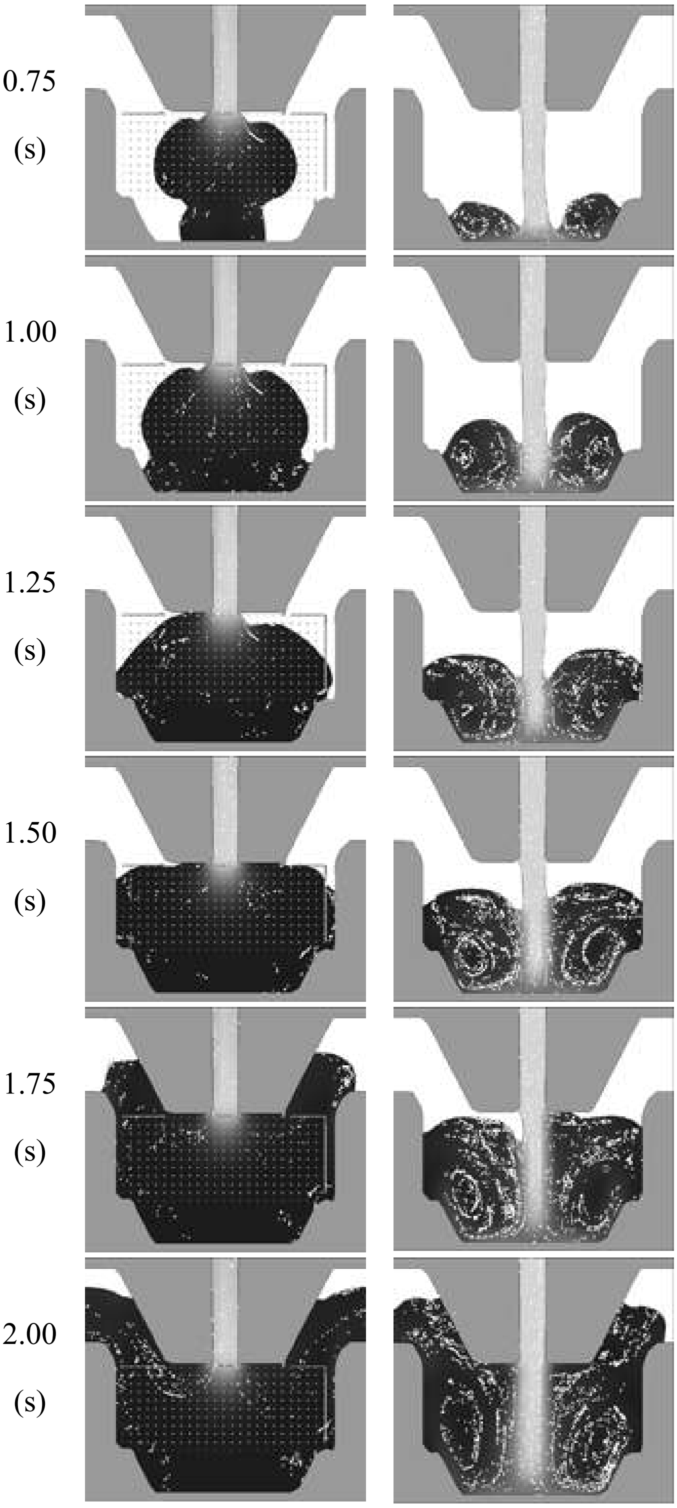

Figure 4 - Comparison of flow in filter print for filtered (left) and unfiltered (right) condition

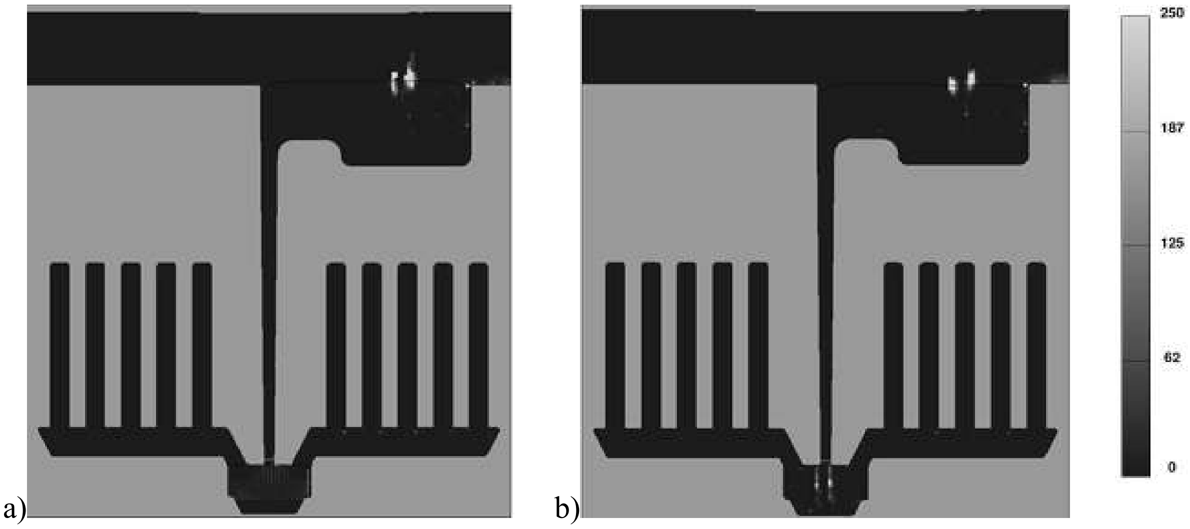

Figure 5 - Total number of entraining events in each cell. a) Filtered. b) Unfiltered

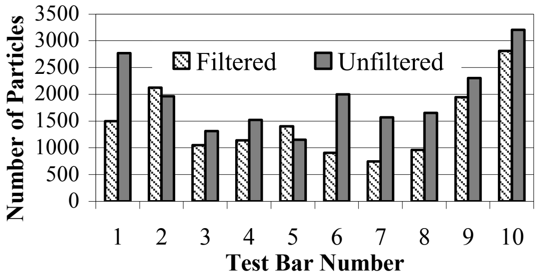

Figure 6 - Number of particles in gauge length

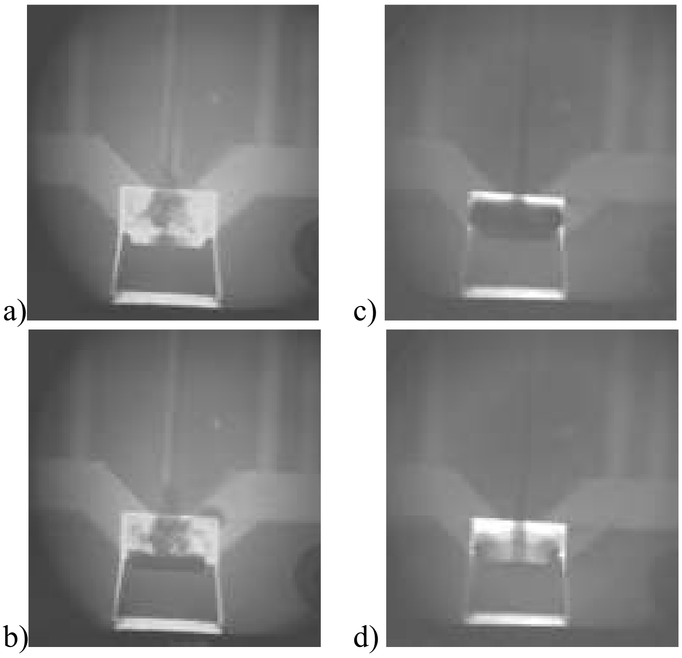

Figure 7 - Real time X-ray data. a) Filtered 0.20 s, b) Filtered 0.64 s, c) Unfiltered 0.20 s, d) Unfiltered 0.64 s

The incorporation and transport of particles within the liquid metal as reported in this paper is not unique, algorithms for doing so having been described previously by Yang *et al.* and Ohnaka *et al* [9, 10]. However, in the technique reported in this paper, entrainment is implemented fully in three dimensions, facilitating assessment of all possible entrainment mechanisms.

Conclusions

A new algorithm has been developed to apply Boolean logic criteria to define free surface entrainment in liquid flows and place marker particles to allow the final defect location to be determined. The algorithm has been shown to match previously published data although further data is required for full validation.

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