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SPH, MAGMASOFT AND WATER ANALOGUE MODELLINGS OF DIE FILLING OF A SERVO PISTON

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ABSTRACT

This paper reports on the application of Smoothed Particle Hydrodynamics (SPH) and MAGMAsoft to model the High Pressure Die Casting (HPDC) of an automotive piston head. The geometric complexity and high speed involved in HPDC lead to strongly three dimensional fluid flow with significant free surface fragmentation and splashing. SPH is a Lagrangian simulation technique that is particularly well suited to modelling HPDC, whilst Magmasoft is a commercial finite volume based casting package. In SPH, materials are approximated by particles that are free to move around rather than by fixed grids.

Validation of SPH and MAGMAsoft predictions for the casting of a servo piston head using water analogue experiments are presented. The overall flows predicted by both methods are broadly similar, but the SPH simulation results were better able to capture the fine detail of the fluid motion and splashing, particularly the relative rates of flow around sharp bends and through thin sections. This demonstrates that SPH modelling of HPDC has now reached a level where simulations can be performed in reasonable computation times and provide a high degree of predictive accuracy.

INTRODUCTION

High pressure die casting (HPDC) is one important method for manufacturing high volume and low cost metallic components. In this method molten metal is injected at both high speed (50 to 100 m/s) and under high pressure through complex gate and runner systems and into the die. Due to the highly irregular and complex nature of the die one can have fluid flowing with significant free surface fragmentation, splashing and spraying. In order to obtain homogeneous cast componens with minimal porosity and void formation one needs to have a good die design with accurate positioning of air vents which enable the release most of the entrapped air. The position of the air vents in turn depends on the gating system used and the geometry of the die. Numerical simulation offers a powerful and cost effective way to study the effectiveness of different die designs and filling processes. However, for such simulations to be useful it is important to assess their accuracy.

MAGMAsoft is a popular commercially available software package for casting simulations and analysis. It is grid based and employs the Volume-Of-Fluid (VOF) method for tracking interfaces.

An alternative simulation technique that appears to have potential to further improve the level of modelling of HPDC is SPH, which is a Lagrangian (grid-free) method of modelling heat and mass flows. It is well suited to modelling free surface flows of the present kind. In this method materials are approximated by particles that are free to move around rather than by fixed grids or meshes. The governing partial differential equations are converted into equations of motion for these particles. The particles are basically moving interpolation points that carry with them (convect) physical properties, such as the mass of the fluid that the particle represents, its temperature, enthalpy, density and any other properties that are relevant, such as stress and strain history dependent rheology. The inter-particle forces are calculated by smoothing the information from nearby particles in a way that ensures that the resultant particle motion is consistent with the motion of a corresponding real fluid, as determined by the Navier-Stokes equations. A detailed description of the method can be found in Monaghan (1992) and Cleary and Monaghan (1999). A recent paper by Cleary et al. (2002) has a desciption of the important governing equations used in this method.

SPH has several advantages over other competing methods for modelling some industrial heat and mass flows.

- Complex free surface and material interface behaviour, including fragmentation, can be modelled easily and naturally with low resolutions and produce accurate predictions with no mass lost or numerical diffusion of the interfaces.
- The Lagrangian framework means that there is no non-linear term in the momentum equation, so the method simulates momentum dominated flows very well with no numerical diffusion associated with the material advection.
- Complicated physics such as multiple phases, realistic equations of state, compressibility, solidification, fracturing, porous media flow, electromagnetics and history dependence of material properties are easy to implement.

Recently, Cleary, et al. (2000) and Ha and Cleary (2000) reported on the application of SPH to high pressure die casting in 2-dimensions and the favourable comparison of these SPH results with water analogue experiments. Particularly good resolution of the small scale fluid structures was obtained as well as accurate predictions of voids in the flow. Ha, et al. (1999) compared 2-dimensional SPH simulations with MAGMAsoft simulations and water analogue modelling of gravity die casting for a complex die in two different orientations. They were able to show that SPH captured the free surface wave behaviour and the fine details of the flow very well. In this paper, we report the results of comparison of SPH simulation results with MAGMAsoft simulation results both in 3-dimensions and experimental results from water analogue modelling. The automotive component used in this study was a servo piston shown in Figure 1.

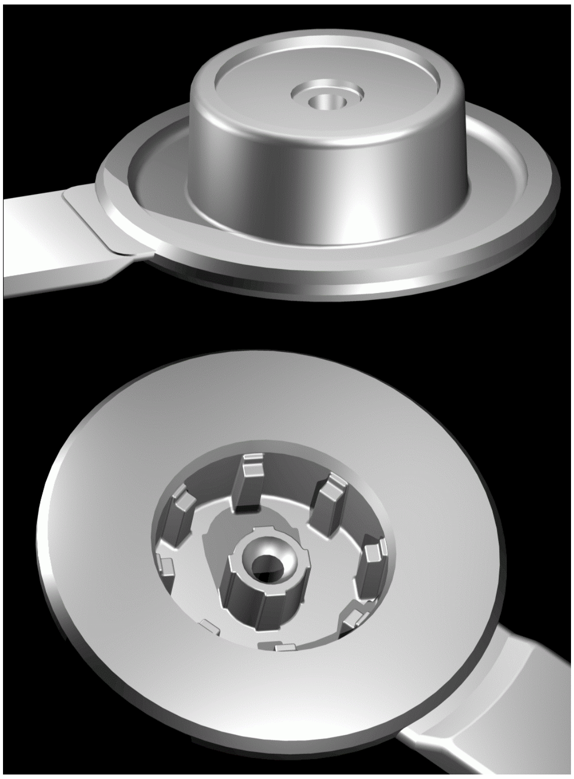


Figure 1: Two views of the servo piston attached to the runner through a 3 mm gate.

In the next section, the experimental set-up for the water analogue modelling and the image capturing of the die filling of the servo piston are described. This is followed by the numerical simulation results using SPH and MAGMAsoft, and the comparison of these results with those of the water analogue measurements.

EXPERIMENTAL SET-UP

In the actual manufacturing process of the servo pistons, a set of 4 pistons are cast at a time. Figure 2 shows two views of the die configuration used, including the shot sleeve, runner and venting system. The filling predictions for this full system are presented in Ha, et al. (2003) of this conference. In this study, only one servo piston is employed in the die configuration used in our numerical and water-analog modelling of the die filling process.

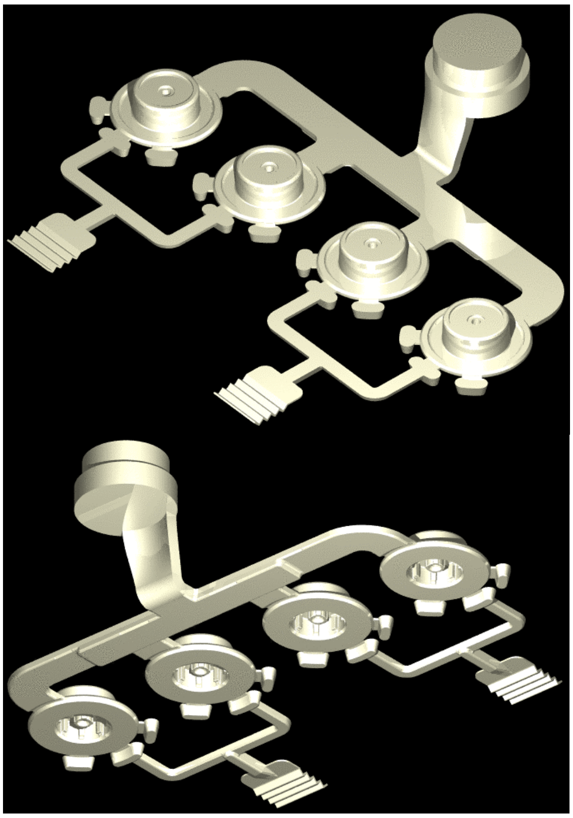


Figure 2: Two views of the configuration for die casting the servo piston.

Figure 3 shows the schematic of the experimental set-up for the water analog equipment and the image capturing by high speed video camera. The flow of water into the die is controlled by the valve in the pipe joining the vessel and the perspex die. The opening and closing of the valve is carried out by hand. The flow rate is controlled by the pressure in the vessel. The manner of operation means that the flow rate is not well characterised and the fill time estimation has a reasonable range of uncertainty. This makes detailed comparison with either MAGMAsoft or SPH more difficult. In all the simulations presented in this paper, an average flow rate of 1.5 litres per second is used.

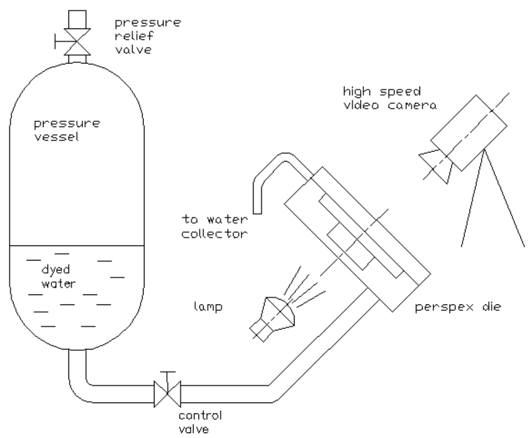


Figure 3: Experimental set-up for water analog experiment.

The filling process is captured by a high speed video camera, operating at a shutter speed of 1/20000 second. Figure 4 shows the view of the die as seen by the camera. An example of the images captured by the camera is shown in the insert of Figure 5. In both figures, the die is shown filled with coloured water.

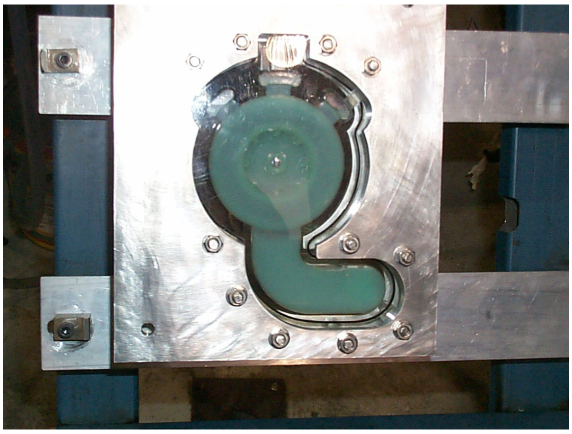


Figure 4: Perspex model of the die viewed by the camera.

The water analogue experiment is difficult to perform due to a number of factors. These relate to the capture of images by a high speed video camera, lighting restrictions, the entrainment of air in the high speed fluid flow and the generation of bubbles in the water during flow through the shot sleeve. This means the images captured are not as clear and definitive as one might like and any obstruction that affects the transmission of light to the camera appears as some shade of grey.

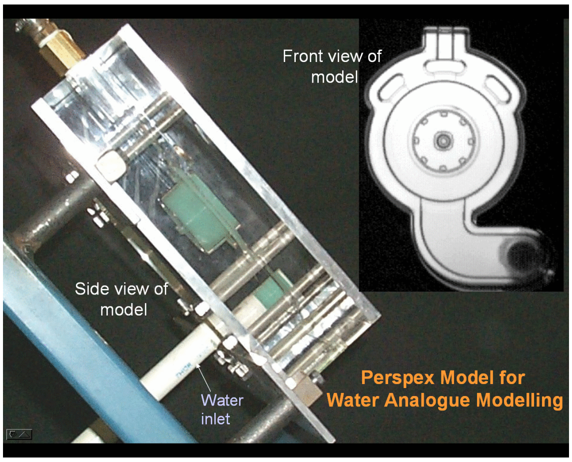


Figure 5: Perspex model of the die viewed from the side. Insert shows an image captured by the camera.

SPH SIMULATION

In both SPH and MAGMAsoft simulations, the filling processes were assumed to be isothermal and the fluid properties (density and viscosity at the temperature of 20°C) used were those of water. No surface tension or turbulence models were included in either form of simulation. Both the SPH and MAGMAsoft simulations were performed in 3D. Figure 5 shows two views of the geometry of die used for numerical simulations.

In the SPH simulations, a particle spacing of 1.44 mm was used. Test runs at coarser and finer resolutions showed little difference in the results. Note that the gate height of the system is 3.0 mm. To simulate the inlet boundary condition, particles were periodically generated at the inlet of the pipe and moved upward with the specified inlet velocity creating a flow of regularly spaced particles travelling up towards the runner. The number of particles in the simulation therefore increases steadily with time. When full the SPH solution has 50,000 particles.

For comparison with the experiment, the SPH particles were depth averaged and the shading made proportional to the fluid depth in order to mimic the shading effect captured by the camera. This was found to be the fairest representation of the simulation that could be produced for a reasonable comparison with the experimental results.

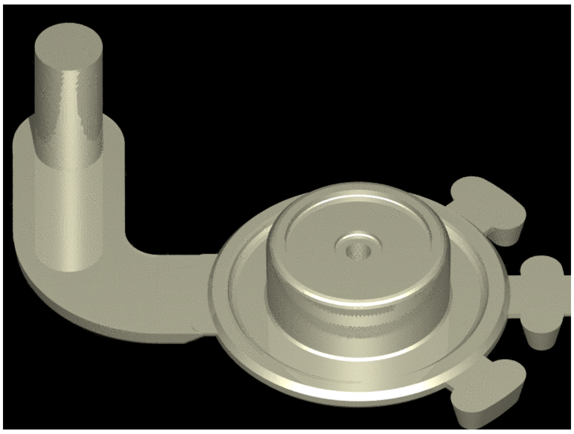


Figure 6: Geometry of die for the simulations.

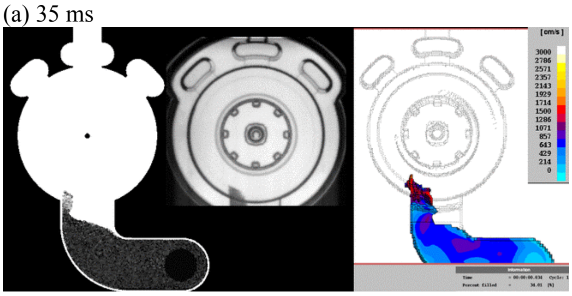
MAGMASOFT SIMULATION

MAGMAsoft (MAGMA, 2000) is a 3D solidification and fluid flow package used in the die casting industry to model the molten metal flow and solidification in dies. MAGMAsoft employs the finite difference method to solve the heat and mass transfer on a rectangular grid. It is a useful tool for simulating molten metal flow in a permanent mould since it can provide useful information about the filling pattern. It also produces reasonably accurate data on casting-related features such as premature solidification, air entrapment, velocity distribution, runner and gate effectiveness. MAGMAsoft, however, has some limitations. The rectangular grid artificially introduces stairstep artefacts along curved and sloping boundaries (refer to Figure 7) and the VOF formulation for modelling the free surfaces leads to artificial diffusion and mass conservation problems in these regions (see, Ha, et al., 1999).

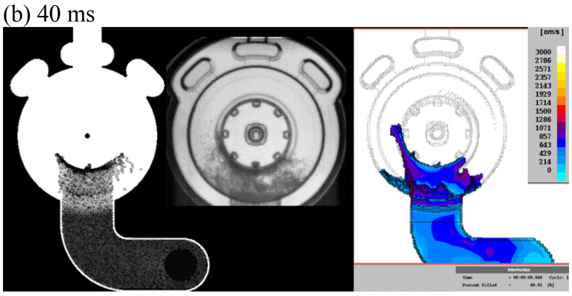
The die geometry used for the MAGMAsoft simulation was exactly the same as that for SPH simulation. The grid used contained 3,373,812 elements or control volumes. A constant flow rate was set at the inlet. The visualisation of MAGMAsoft results was done by shading the elements according to their velocity.

COMPARISON WITH EXPERIMENT

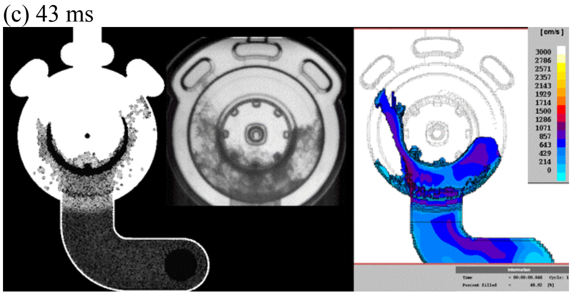
(a) 35 ms



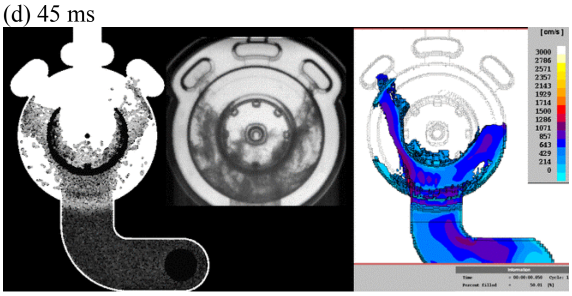
(b) 40 ms



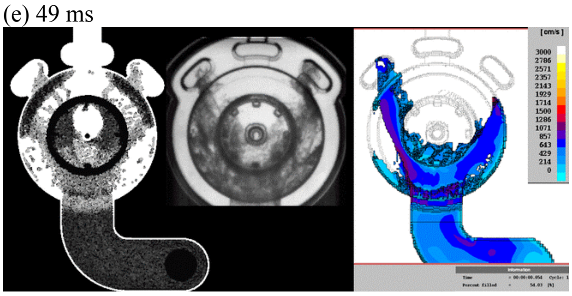
(c) 43 ms



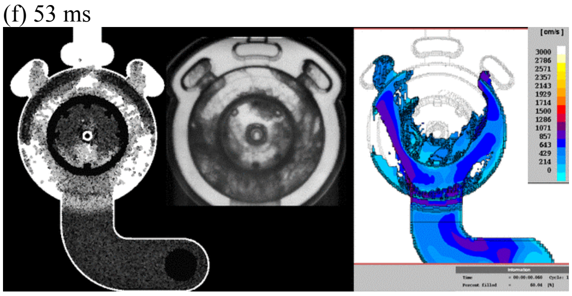
(d) 45 ms



(e) 49 ms



(f) 53 ms



(g) 58 ms

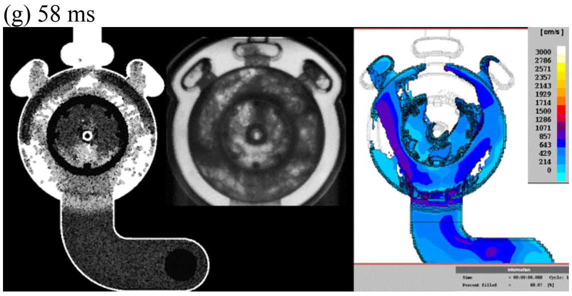


Figure 7: Comparison between SPH (left), experiment (middle) and MAGMAsoft (right) results at given times.

In Figure 7, the results of SPH and MAGMAsoft simulations at selected stages of filling are compared with results obtained from the water analogue experiment. A degree of caution is required when interpreting the results. In the experimental images, the flow features are necessarily somewhat blurred due to the 1/20000 frame exposure time. This is because a drop of fluid moving at say 20 m/s makes a 1 mm long streak during the period of frame exposure. For a part of around 110 mm this introduces errors of the order of 1% for the fluid position and blurs the image slightly. On the other hand, SPH draws precise volumes for the fluid particles whilst MAGMAsoft shows the smoothed projected volume of fluid which can appear more solid than it actually is.

In the first frame (at 35 ms) fluid has just started entering the die in all three cases. To maximise the use of camera resolution, only the die itself was imaged so there is no photographic information about the runner part of the flow. In this first frame, the volume of fluid that has entered the die is slightly too large for MAGMAsoft but slightly too small for SPH.

By 40 ms (frame b) the jet of fluid entering the gate has broadened to fill the width of the gate. This wide but thin (in the third dimension) jet then strikes the inside surface of the raised cylindrical section and starts to flow both up and around its sides. This frame shows the widest variance between all three flows. The experimental fluid is very wispy in appearance indicating that the fluid is very fragmented and is blurred by its motion during the frame exposure time. The fluid in the sides of the cylindrical section can be clearly discerned by the solid dark grey between the 5 o'clock and 9 o'clock positions. In the SPH solution, the fluid has not been sprayed as widely but remains as a more coherent jet. The SPH prediction for the fluid in the vertical cylindrical section covers about the correct area but is too symmetric. This is thought to result from the ommission of air in the simulation, which leads to somewhat different filling dynamics in the last part of the runner leading up to the gate. The MAGMAsoft prediction appears more realistic for this particular time with better predictions of the fluid flow in the cylindrical section and with the filling to the right of the gate. Two important issues with this solution though are the very strong nature of the jet of fluid that has glanced from the left side of the cylindrical central section and also the filling on the outside of the die on the left adjacent to the gate. This later part of the filling was examined in detail and found to be an erroneous reflection from one of the stairstep cells at the base of the central section.

At 43 ms (frame c) there are increasing differences between the MAGMAsoft solution and the experiment, whilst the SPH solution compares progressively more favourably. A key point of comparison are the front locations of the fluid in the vertical side walls of the central cylindrical section. In the experiment, the fluid occupies a region from about 3 o'clock to 9 o'clock. This region can be seen to be substantially filled since the shade of the fluid is very dark. In the same way, the SPH shading (representing the depth of fluid) is also quite dark and the leading edges are in quite similar positions (perhaps a little too advanced on the right). The SPH fluid has now become fragmented and scattered throughout the front half of the horizontal circular base plate in much the same way as the experiment. The leading fragments though are more advanced on the right than on the left which is opposite to that observed in the experiment. This is again thought to be a legacy of the absence of air in the pressurisation of the runner system, which has led to the leading egde of SPH fluid being directed preferentially to the right instead of to the left.

The MAGMAsoft solution has some important difficulties at this point. It clearly predicts an overly strong primary jet on the left side of the cylindrical central section. This very coherent jet has already reached the left vent well in advance of the experimental flow. There is also an absence of fragmented fluid to the left of the main jet and in advance of the leading solid edge of fluid on the right. In the vertical cylindrical section the fluid occupies a region from 4 o'clock to 10 o'clock. This is the correct amount of area filled, but it is biased to the left side by the overly strong primary jet.

At 45 ms, the contrasts are becoming stronger. The key points of comparison are that the SPH and experimental fluid are just reaching both the left and the right vents and this fluid is moderately fragmented in both. In both cases the fluid fronts in the central vertical section are at 2 o'clock and 10 o'clock and match closely. The amount of fluid that has entered the horizontal top section of the die (in the middle of the pictures) is closely matched and the fraction of die volume in the horizontal base plate behind the leading jets are quite similar. In contrast, the overly strong left jet of the MAGMAsoft solution has now entered the left vent, but the fluid on the right is significantly short of the right vent. The locations of the fronts in the vertical cylindrical sections are now between 3 and 4 o'clock on the right and 10 o'clock on the left. There is insufficient fluid entering the horizontal raised central section of the die and to the left of the primary jet.

At 49 ms, the fronts of fluid in the vertical cylindrical section are just joining in the experiment. The SPH solution correctly predicts this merging. This demonstrates that the SPH solution is predicting the correct fraction of fluid entering the vertical section of the die with the correct velocities. In contrast, the MAGMAsoft solution is still predicting front locations that are around 3 o'clock and 10 o'clock. SPH is also very accurately predicting the size of the circular entrapped void on the top surface of the raised central section. The SPH solution is now indicating moderate flow in the left and right vents and is in very close agreement with the experiment. Conversely, the SPH solution seems to be predicting moderately too much accumulation of fluid around the rim of the base plate in front of the two vents and also moderately too little fluid in the regions of the base plate on either side of the gate. This suggests a slightly too rapid flow of fluid across the horizontal base plate. Our conjecture here is that this results from the absence of air in the SPH solution. The inclusion of air could be expected to produce a moderate back pressure which would slow this fluid a little and delay the rate at which it leaves the front part of the base plate near the gate and the rate at which it acculumates around the vents. The MAGMAsoft solution is now poorly representing the fragmented fluid on the left side of the die to the left of the main jet. Neither does it correctly represent the fluid progress on the right of the die or over the horizontal raised central part of the die.

The same trends previously described continue in the remaining frames. The SPH solution is much closer to the experiment, but both simulations have some erroneous features. The SPH solution continues to have substantially correct predictions for the fraction of the die filled, but with a clear predisposition for the fluid to progress through the die a little too fast leading to a modest over-prediction in the amount of fluid on the vent side of the base plate and a corresponding under-prediction of fluid on the gate side. This is again attributed to the absence of back pressure due to air, but also due to the absence of entrained gas from both the filling flow and from the shot sleeve. This trapped air in the experiment slows the passage of the fluid from one side of the die to the other. The MAGMAsoft solution continues to have significant errors in key aspects of the flow.

Examining the final frame of the figure, we again see very good agreement between the experiment and the SPH solution, with similar amounts of fluid in the left and right vents, in the horizontal base plate and in the raised central section. Dark bands of fluid are now forming around the rim of the base plate in the experiment as the air is forced out and the fluid fills the full depth of the die. These dark bands in the rim are quite similar to the ones observed in the SPH solution. On the negative side, the SPH solution has yet to predict the start of flow through the central vent and is still mildly under-predicting the fraction of fluid filling in the gate half of the base plate.

The MAGMAsoft solution is still exhibiting serious divergences from the experimental flow. The leading egdes of fluid on the sides of the vertical cylindrical section have still not met and a reasonable portion of the central horizontal section of the die is yet to be filled. A large section of the base plate opposite the central vent still has no fluid filling it. The leading edges of the fluid moving around the base plate towards the central vent have also not yet made contact. When they do so, there will be an erroneous prediction of a large void region in the base plate directly opposite the central vent due to the unphysically slow flow into this region. Finally, there are reasonable size coherent but unrealistic voids in the base plate on either side of the incoming jet. The SPH solution has also under-predicted the filling in these last regions, but the distribution of fluid is more realistic as is the prediction of the more fragmented nature of that fluid.

Summarising the comparison above, we see that the MAGMAsoft solution is arguably slightly better in the very early stages, but that the SPH solution rapidly overtakes it and is able to make quite accurate predictions for the rates of motion of fluid fronts and the times at which voids are trapped (which will provide good quality predictions of porosity locations). The SPH solution is also able to reasonably accurately capture the fragmented nature of the fluid flow and many of the finer scale features. The SPH solution though fails to deliver full accuracy with two main discrepancies, both of which can be attributed to the absence of air in the simulation. At the start of the filling, the leading fluid is initially pushed into the die with a slight bias to the right side. This is a legacy of the pattern of filling of the runner in the lead up to the gate. If air were present then this would pressurise in the runner before it was filled and would prevent the sideways flow to the right which fills the runner in the absence of air. This would result in an initial fluid jet path that was directed to the left rather than the right. This explains the early differences in the SPH solution. The second discrepancy is that fluid tends to travel across the base plate a little too fast leading to a modest over-prediction of the fluid build up on the vent side of the base plate and a matching under-prediction on the gate side. This indicates that the presence of air in this particular die filling experiement is moderately important to determining the detailed flow.

For MAGMAsoft, we observe significant quantitative divergences from the experimentally observed flow after the early stages. The key features are the prediction of a significantly too strong jet on the left of the base plate and the substantial under-prediciton of fluid entering and the rate of flow around the curved and raised central cylindrical shell. We attribute these problems to the ‘stair-step’ approximation for the curved surfaces. Since MAGMAsoft uses a regular grid, the curved surfaces are represented by a series of steps as specific grid cells that might or might not be included in the computational domain. These geometry artefacts lead to artificial resistance to flow around curves and bends. This is akin to an additional artifical viscosity in regions of curvature. The size of this resistance decreases with the fineness of the grid used. The grids used for HPDC though are typically quite coarse leading to significant resistance. This preferentially and strongly keeps fluid flowing in the flat horizontal base plate leading to overly strong predictions of the jets on either side of the core. It also leads to significant under prediction of flow into the raised central section and particularly delays the filling around the vertical sides of the raised section. This is likely to result in erroneous deductions of locations of porosity. An important consequence of this is that the precise details of the porosity predictions will then be potentially quite sensitive to the details of the grid used for a specific simulation. Different grids are likely to lead to changes in the relative strengths of the jets into the various parts of the die leading to mesh/grid dependent predictions.

CONCLUSIONS

In this paper validation of 3D SPH simulations was carried out by making comparisons between 3D simulations of a single servo piston using SPH and MAGMAsoft and water analogue experiments. In the earlier stages of the simulations MAGMAsoft shows slightly better agreement with the experimental observations. However in the mid to late stages of the filling process, the SPH simulations show very good agreement with the fill pattern shown in the experiment with accurate predictions of the speed of propagation of fluid fronts and the times at which voids are trapped. The MAGMAsoft simulation rapidly diverges from the experimental flow, with significant errors predicted in the strengths of the base plate jets and of the fluid flow around the sides of the central raised cylindrical section. Since the fundamental reason for using simulations in die-casting applications is to study the order of fill and to make predictions of voids, it is essential for a simulation to predict these features accurately and in a mesh independent manner. The SPH predictions of fill pattern and regions of possible voids in the die show good to excellent agreement with the experimental observations for this die. The SPH solution does display two minor types of discrepancies, both of which we attribute to the omission of air (and therefore back pressure from the air) on the fluid flow. This study demonstrates the ability of SPH to make accurate solutions and to potentially offer the die-casting industry a new way of making better predictions of the HPDC process.

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