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SIMULATION OF DIE FILLING IN GRAVITY DIE CASTING USING SPH AND MAGMAsoft

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ABSTRACT

This paper reports on the application of smoothed particle hydrodynamics (SPH) and MAGMAsoft to model die filling in gravity die casting and the favourable comparison of SPH simulation results with experiments. The simulation results were able to capture the fine detail of the free surface motion, including plume shape, frequency and phase of oscillation and the correct relative heights of the surface levels at all free surfaces.

INTRODUCTION

Gravity die casting (GDC) processes are capable of making complicated high integrity components, such as wheels, cylinder heads, engine blocks and brake callipers, at lower cost than most other casting methods. Cycle times for gravity die casting are shorter than for the sand casting process leading to larger quantities of castings produced per unit time. Surface finish and internal quality (particularly pertaining to porosity) are also better using the GDC process. Improvements to both product quality and process productivity can be brought about through improved die design. These include developing more effective control of the die filling and die thermal performance.

Numerical simulation offers a powerful and cost effective way to study the effectiveness of different die designs and filling processes. For such simulations to be useful, their accuracy must first be assessed. The validation of numerical simulations is commonly done using water analogue models because of the relative difficulties of visualising the flow of hot molten metal in a die. Nevertheless, the water analogue modelling technique was successfully used to highlight flow features in the die cavity in several die casting processes (Perkins and Bain, 1965, Davis and Asquith, 1985, Nguyen and Ito, 1995).

There are a number of available software packages for casting simulation and analysis. These packages are grid-based and employ the volume-of-fluid method. In the die casting community, a popular commercial software package for simulating mould filling is MAGMAsoft. Smoothed particle hydrodynamics (SPH) is a Lagrangian method (Monaghan, 1992) and does not require a grid. It is suited for modelling fluid flows that involve droplet formation, splashing and complex free surface motion. Recently, Cleary and Ha (1998), Ha, et al. (1998) and Ha and Cleary (1999) reported on the application of SPH to high pressure die casting and the favourable comparisons of these SPH results with experiments. This paper is concerned with the application of SPH and MAGMAsoft to simulate the flow of a single fluid at constant temperature during gravity die casting. The effects of heat transfer, solidification and material deformation on GDC will be the subject of future work.

In this paper, the accuracy of SPH and MAGMAsoft in meeting our modelling needs in GDC are examined. The SPH methodology, the MAGMAsoft model and the experimental set-up for GDC are described. These are followed by the numerical simulation results for two dies using SPH and MAGMAsoft and their comparisons with experimental results from the corresponding water analogue models.

THE SPH METHOD

SPH is a Lagrangian method that uses an interpolation kernel of compact support to represent any field quantity in terms of its values at a set of disordered points (the particles). The fluid is discretised, and the properties of each of these elements are associated with its centre, which is then interpreted as a particle. A particle b has mass m_b, position $\boldsymbol{r}_b$, density ρ_b and velocity $\boldsymbol{v}_b$. In SPH, the interpolated value of any field A at position $\boldsymbol{r}$ is approximated by:

$$A(\boldsymbol{r}) = \sum_b m_b \frac{A_b}{\rho_b} W(\boldsymbol{r} - \boldsymbol{r}_b, h) \quad (1)$$

where W is an interpolating kernel, h is the interpolation length and the value of A at $\boldsymbol{r}_b$ is denoted by A_b. The sum is over all particles, b with a radius $2h$ of $\boldsymbol{r}_b$. $W(\boldsymbol{r},h)$ is a spline based interpolation kernel of radius $2h$. It is a C^2 function that approximates the shape of a Gaussian function and has compact support. This allows smoothed approximations to the physical properties of the fluid to be calculated from the particle information. The smoothing formalism also provides a way to find gradients of fluid properties. The gradient of the function A is then given by:

$$\nabla A(\boldsymbol{r}) = \sum_b m_b \frac{A_b}{\rho_b} \nabla W(\boldsymbol{r} - \boldsymbol{r}_b, h) \qquad (2)$$

In this way, the SPH representation of the hydrodynamic governing equations can be built from the Navier-Stokes equations. These equations of motion are given in Cleary and Ha (1998). The simulation progresses by explicitly integrating this system of ordinary differential equations.

In summary, the SPH method requires no computational grid. The SPH particles carry all the computational information and they are free to move. The Lagrangian nature of SPH means that the particles will automatically follow complex flows. This makes the method particularly suited for fluid flows involving complex free surface motion. It is relatively easy to apply the method to multi-dimensional problems. Cleary and Ha (1999) presents 3D modelling of high pressure die casting using SPH.

MAGMAsoft

MAGMAsoft 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 staircases along curved and sloping boundaries and the VOF formulation for modelling the free surfaces leads to artifical diffusion and mass conservation problems in these region.

THE EXPERIMENTAL SETUP

Water analogue modelling is widely used in gravity and low pressure die casting to study the characteristics of the molten aluminium flow in die cavities. To investigate the flow pattern in a cavity with typical features found in dies (ie sudden transitions in section thicknesses, bends, branches, etc) a transparent die has been built. Figure 1a shows the cavity geometry and Figures 1b and 1c show two of the designs of the gate and runner system which were tested under different flow conditions and gate sizes. These are the two models considered in this paper and they are called Model 1 and Model 2. Several blocks of clear perspex 20mm thick were used to assemble the mould between two clear flat support plates.

A constant head tank situated above the sprue was used to supply the flow of coloured water into the cavity. Four nozzles with different diameters were located above the sprue to produce four different flow rates in the cavity. The water flow was initiated by a stopper connected to a solenoid valve. The outflow for each nozzle has been calibrated and it was found that the flow rate was constant.

A conventional Panasonic VHS video camera has been used to record the real time images of the flows. At a later stage, the video images were converted to digital format with the use of a Matrox Mystique frame grabber and software on a Pentium II personal computer.

The flow in the cavity was recorded for a number of different flow rates and gate sizes. One case of each experimental model geometry was chosen to validate the SPH code and MAGMAsoft.

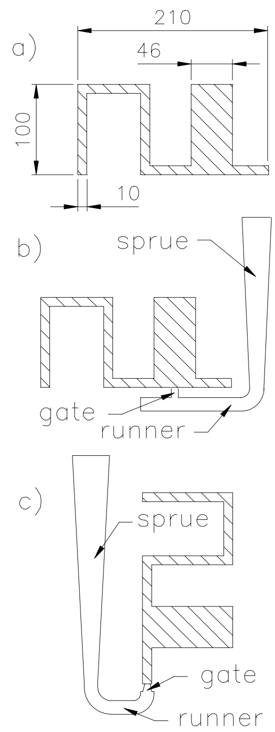

Figure 1: Transparent die models. (a) Die cavity geometry. The lengths are in mm and the third dimension is 20 mm thick; (b) Model 1: Bottom gating, single gate; (c) Model 2: Vertical orientation, bottom gating.

NUMERICAL RESULTS

The differences between the Model 1 and Model 2 are in the orientation of the mould cavity and in the design of the gate and runner system. This enables us to examine the effect of different set-ups on the filling pattern. The experimental results and their comparisons with simulation results obtained using SPH and MAGMAsoft for the two models are presented in the next two subsections.

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) were those of water. No surface tension or turbulence models were included in these simulations. The SPH code can simulate flows in either 2D or 3D. Since the experimental flow is essentially 2D, we chose to perform the SPH simulation in 2D. The MAGMAsoft simulations are done in 3D since MAGMAsoft is a 3D casting package.

In the SPH simulations, a standard spacing of 22 particles per centimetre was used. Test runs at coarser and finer resolutions show little difference in the results. Figure 2 shows that the simulation result at the coarser resolution is similar to that of the standard resolution. To simulate the inlet boundary condition, a row of particles are regularly generated at the inlet boundary and move downward with the specified inlet velocity so that a set of regularly spaced particles flow vertically down from the inlet location accelerating under gravity. The number of particles thus increases steadily with time as fluid falls in the sprue from the inlet nozzle. As the SPH simulations are 2D, the width of the inlet is chosen to give the same volumetric flow rate as used in the experiment. For Model 1, the total number of particles is around 52000 at the end of the simulation. Similar numbers of particles were also used for Model 2. These SPH simulations took about 28 hours on a 500 MHz Alpha XP1000 workstation.

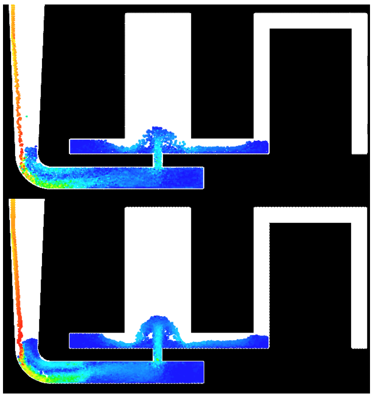

Figure 2: Low (top) and high (bottom) resolution SPH simulations of Model 1.

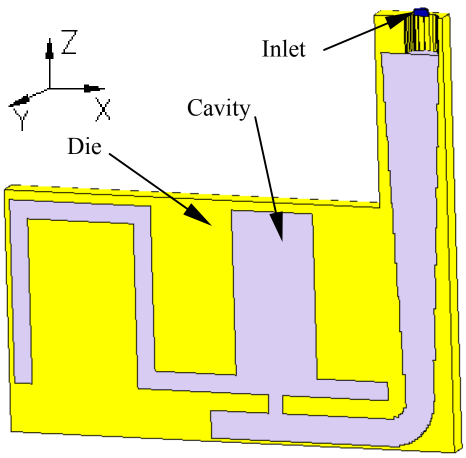

Figure 3: MAGMAsoft model of bottom gating die.

In the MAGMAsoft simulations, the 3D model consisting of the die cavity and inlet is shown in Figure 3. The inlet is located above the sprue and has an area which corresponds to the cross-sectional area of the particular nozzle used in the experiments. A constant flow velocity was set at the inlet as the inflow boundary condition. Only half of the model in the Y-direction has been considered due to the symmetrical nature of the geometry. A typical grid contains around 750,000 control volumes of which 165,000 represent the cavity. On a 200 MHz SUN Ultra 2 workstation, the average MAGMAsoft runtimes were 55 hours for Model 1 and were about 140 hours for Model 2.

Model 1

For Model 1, the diameter of the inlet nozzle was 9.5 mm and the velocity of fluid flow through the nozzle was kept constant at 1.02 m/s giving a flow rate of 0.072 l/s. The corresponding filling time for the cavity of the die is about 4 seconds.

Figure 4 shows the fill patterns obtained numerically and experimentally at selected times. In the experimental images, the number near the top right hand corner is the time in seconds. At 1.2 s, the runner and gate have filled and the fluid squirts through the gate forming a small symmetrical plume which spreads along the bottom of the mould. The SPH result compares very well with the experiment. In particular, there is close agreement in the shape of the plume and the height of the free surface at the base of the sprue. The only perceptible difference is that the SPH fluid spreads out further along the horizontal bottom of the die cavity on either side of the gate. The MAGMAsoft result is qualitatively similar to the experiment but has a wider range of differences than does the SPH solution. In particular, the plume above the gate is stronger and higher than in the experiment and there is a much higher fluid level in the sprue. Also, floating above this free surface is a collection of large smeared droplets. This artefact is characteristic of MAGMAsoft's free surface VOF implementation.

Between 1.6 s and 2.0 s, the thin horizontal lower sections of the die fill completely. As the rectangular central part of the die fills progressively, the plume oscillates first to the right (1.6 s) and then to the left (1.8 s). The SPH results reproduce this motion and the levels of fluid reached in the various part of the die very well. In particular, it correctly captures phase and frequency of the plume oscillation. The MAGMAsoft results again qualitatively capture the flow but do not quite capture the complete filling of the horizontal sections (1.6 and 1.8 s). The fine details of the plume structure and motion are also not quite captured.

As the amount of fill increases, the sloshing motion in the rectangular section of the cavity is increasingly dampened down and the free surfaces become increasingly flat. Both the SPH and MAGMAsoft simulation results reproduce the later stages of the filling well. However, the MAGMAsoft result shows a lower fluid level in the sprue than the experiment. By 3.4 s, the rectangular section above the gate is completely filled and the horizontal section of the C-shaped cavity to the right is beginning to fill. This is reproduced very nicely by both SPH and MAGMAsoft solutions. The SPH simulation slightly over-predicts the height of water in the sprue whereas the MAGMAsoft result slightly under-predicts this level.

Model 2

Figure 1c shows the geometry of Model 2. For this model, the diameter of the inlet nozzle is 6.9 mm and the velocity of fluid flow through the nozzle is kept constant at 1.12 m/s giving a flow rate of 0.042 l/s. The filling time for the cavity of the die is about 8.5 seconds.

In Figure 5, the fill patterns obtained numerically and experimentally at selected time instances are compared. In the experimental images, the number at the bottom left corner is the time in seconds. The filling process for Model 2 is somewhat similar to that of Model 1 in that the early part of die filling is dominated by sloshing free surface wave motion. This sloshing motion is damped after a certain time. We thus restrict our discussion to the early part of the die filling when the process is much more dynamic.

At 1.6 s, the large rectangular section of the cavity is just starting to fill. Both the MAGMAsoft and SPH simulation results reproduce this well. The shape of the fluid front was well predicted by the SPH simulation but less well by the MAGMAsoft simulation. The MAGMAsoft result shows a lower fluid level in the sprue than that of the experimental result, while the SPH result shows a marginally higher level than the experiment. Both methods have some minor problems with jet stability near the free surface in the sprue at this stage.

At 2.1 s, the front of the fluid almost reaches the left wall of the rectangular section of the die cavity. The SPH simulation predicts the overall height of the fluid and the closeness of the fluid front to the left wall very well. In particular, it is able to capture the fine details of the shape of the free surface where the upward jet entering the die slumps under gravity to give the stepped profile observed. The MAGMAsoft simulation under-predicts the level of fill and the closeness of the fluid front to the left wall. MAGMAsoft qualitatively reproduces the elevation of the fluid surface near the right wall of the rectangular section. The simulation results show the slight under prediction by MAGMAsoft and over prediction by SPH of the fluid level in the sprue.

At 2.2 s, the fluid shows a surface wave having just reflected off the left wall of the rectangular section of the cavity. The wave is the result of original wave of fluid travelling to the left hitting the left wall and returning to the right. The upward motion of the fluid from the vertical section above the gate still has sufficient momentum to maintain the elevated surface mentioned above. The SPH solution captures this free surface remarkably well, while the MAGMAsoft result shows the fluid has just reached the left wall.

At 2.4 s, the left half of the free surface in the rectangular section has become flat as the free surface wave from the left moves further back to the right. SPH again reproduces the shape of the free surface of the fluid very well. The MAGMAsoft result is just beginning to show motion of the wave from the left at this stage. However, it predicts the fluid level in the sprue better than SPH does. Soon after 2.4 s, the fluid surface loses its wave-like structure and flattens out. Both MAGMAsoft and SPH simulations reproduce this feature well.

CONCLUSION

In this paper, we have described the SPH method and the application of SPH and MAGMAsoft to simulate GDC for a complex die in two orientations. The agreement with experiment for both numerical methods is good with each being able to predict the overall structure of the filling process. In general, the natural free surface capability of SPH allows it to better capture the free surface wave behaviour and the fine details of the flow. Conversely, MAGMAsoft generally predicts the level of the fluid in the sprue slightly better.

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REFERENCES

CLEARY, P.W. and HA, J., (1998), "SPH modelling of isothermal high pressure die casting*", Proc. 13th Australasian Fluid Mechanics Conference*, Melbourne, Australia, December 663-666.

CLEARY, P.W. and HA, J., (1999), "Three dimensional modelling of high pressure die casting*", Proc 2nd Int. Conference on CFD in Minerals and Process Industries*, Melbourne, Australia, December.

DAVIS, A.J. and ASQUITH, S.J. (1985). "Water Analogue Studies of Fluid Flow in the Die Casting Process". *Trans. 13th SDCE Congress, Milwaukee, USA*, Paper G-T85-063.

HA, J., CLEARY, P. and AHUJA, V., (1998), "Comparison of SPH simulation of high speed die filling with experiment", *Proc. 13th Australasian Fluid Mechanics Conference*, Melbourne, Australia, December, 901-904.

HA, J. and CLEARY, P., (1999), "Comparison of SPH simulations of high pressure die casting with the experiments and VOF simulations of Schmid and Klein", *Int. J. Cast Metals Res*., submitted.

MONAGHAN, J.J., (1992), "Smoothed particle hydrodynamics", *Ann. Rev. Astron. Astrophys.*, **30**, 543-574.

NGUYEN, T.T. and ITO, F. (1995). "Simulation of Mould Filling in a Cylinder Head Casting", *Proc. Int'l Conf. on Casting and Solidification of Light Alloys*, Gold Coast, Queensland, 101-106.

PERKINS, N.D. and BAIN, C.J. (1965). "Transparent Water Models as An Aid to Gating Design for Permanent Mould Aluminium Alloy Castings". *J. Aust. Inst. Metals*, **10**, 160-168.

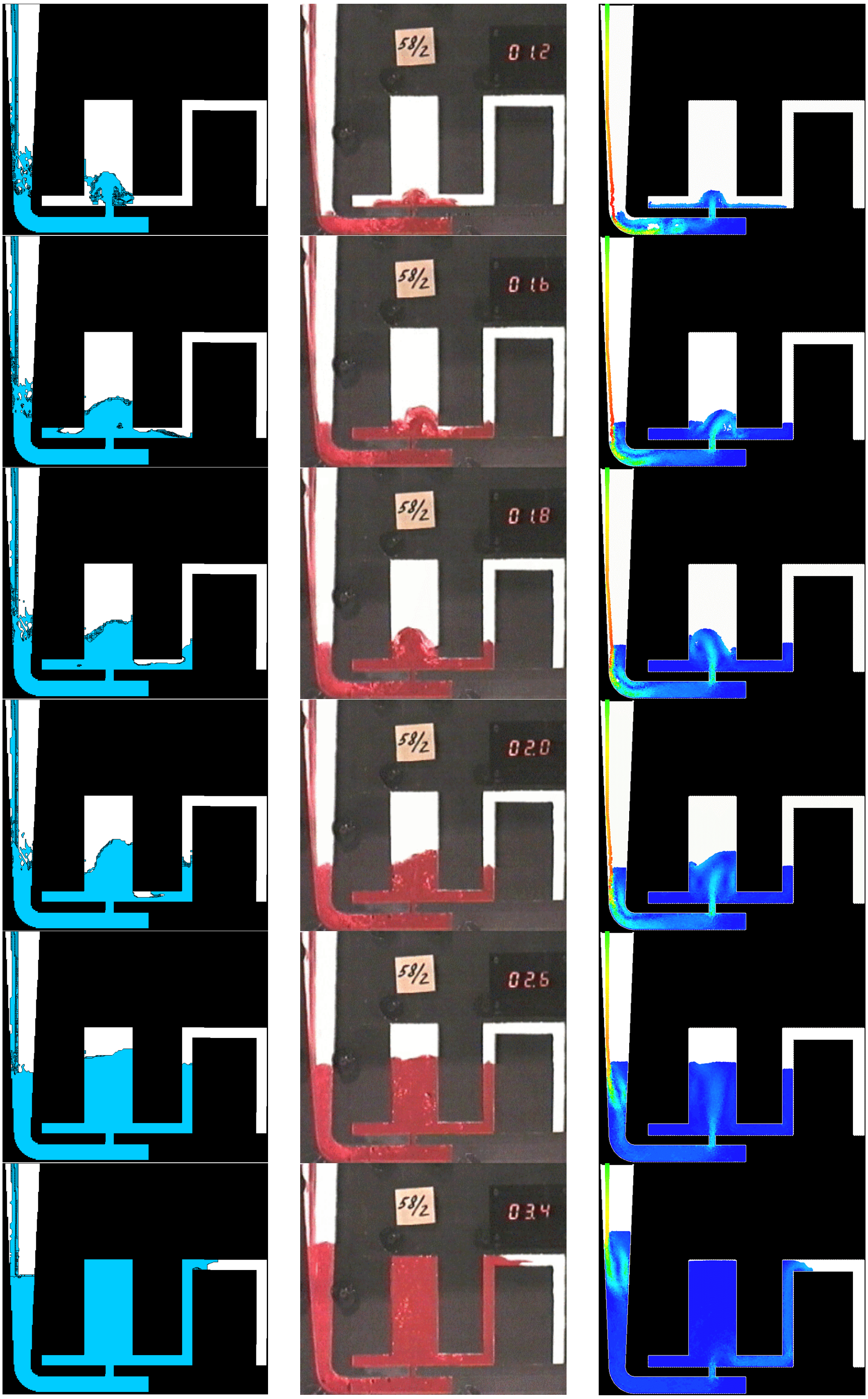

Figure 4: Filling of Model 1. Left: MAGMAsoft. Middle: experiment. Right: SPH.

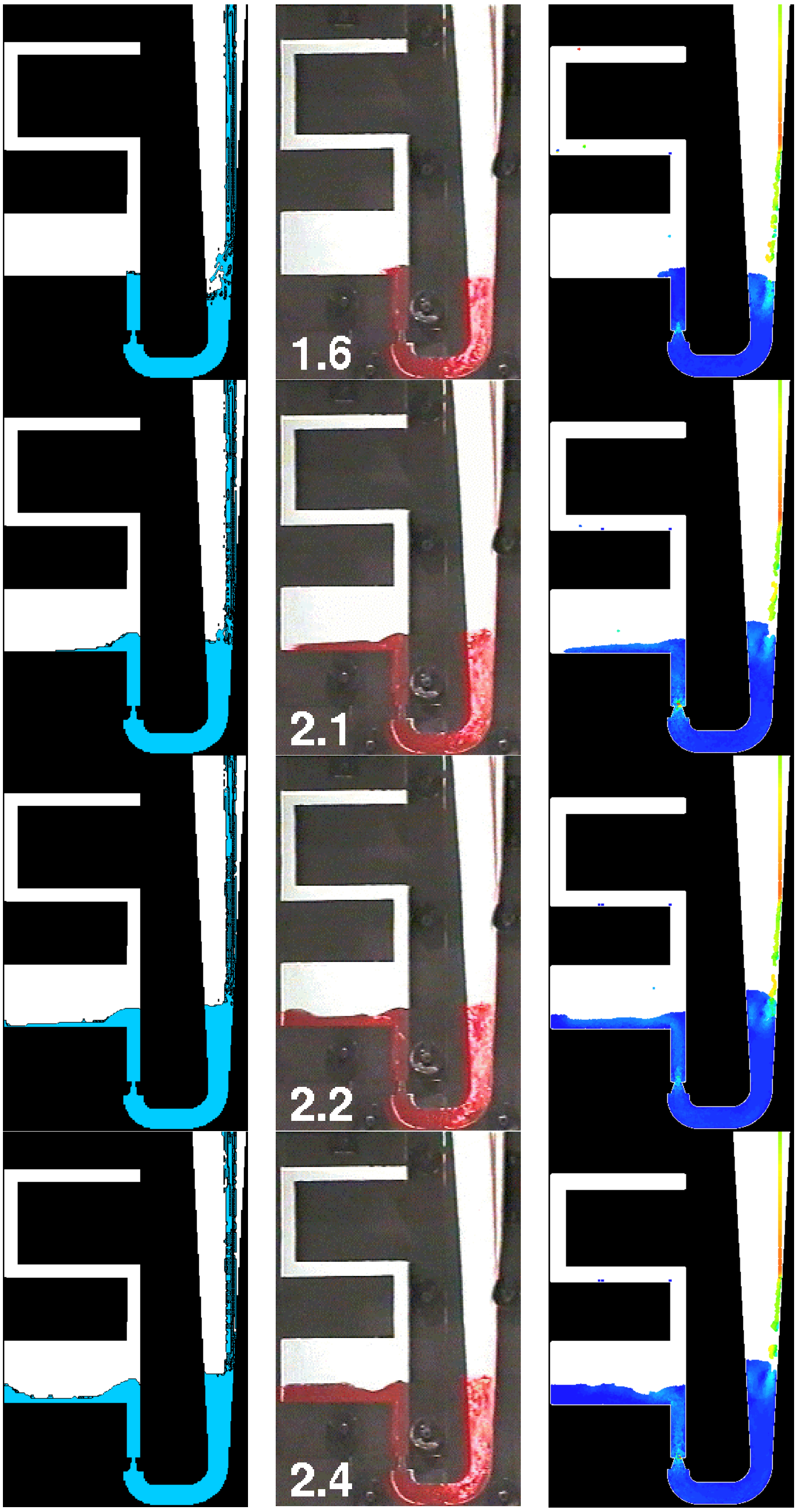

Figure 5: Filling of Model 2. Left: MAGMAsoft. Middle: experiment. Right: SPH.