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Effect of Heat Transfer and Solidification on High Pressure Die Casting

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ABSTRACT

The effects of heat transfer, including conduction, surface radiation and latent heat on high pressure die casting are examined. The SPH formulation of the enthalpy equation, the latent heat and surface radiation are described. Solidification is modelled via a temperature dependent viscosity and has a significant effect on the fluid dynamics. The choice of thermal boundary conditions is also important.

INTRODUCTION

High pressure die casting (HPDC) is an important process for producing light and strong cast automotive components from aluminium and magnesium. Liquid metal is injected into the mould at high speeds and pressures. The fluid flow is fast and the behaviour of the free surface is very complex. HPDC dynamics are not well understood and incorrect filling can lead to high rejection rates.

In the first of this sequence of papers (Cleary and Ha, 1998) we presented smoothed particle hydrodynamics (SPH) simulations of HPDC for two moulds with Reynolds numbers (Re) varying from 50 to 50,000. These results were shown to be insensitive to the particle resolution. In the second paper (Ha *et. al.* 1998) an isothermal SPH simulation was compared favourably with a water analogue experiment. These simulations all neglected important heat transfer processes. In this paper we extend the modelling to include these. Conduction modelling using SPH has been systematically explored by Cleary and Monaghan (1998) and found to be very accurate with only modest numbers of particles. The modelling of coupled heat and mass flows using SPH was similarly tested in Cleary (1998a).

SPH HEAT EQUATION

A new form of the SPH heat equation based on internal energy was developed in Cleary and Monaghan (1998). For solidifying metals, it is more appropriate to use an enthalpy formulation, giving an SPH energy equation for particle a:

$$\frac{\mathrm{d}H_a}{\mathrm{d}t} = \sum_b \frac{4\, m_b}{\rho_a\, \rho_b} \frac{k_a\, k_b}{k_a + k_b}\, T_{ab}\, \frac{\mathbf{r}_{ab} \,.\, \nabla_a W_{ab}}{\mathbf{r}_{ab}^2 + \eta^2} \quad (1)$$

where $H = \int_0^T c_p(\theta)\, d\theta + L[1 - f_s(T)]$ is the enthalpy per unit mass, c_p is the specific heat, L is the latent heat and $f_s(T)$ is the volume fraction of the metal that is solid at temperature T. Also k_b is the conductivity, ρ_b is the density and m_b is the mass of particle b. Here $\mathbf{r}_{ab}$ is the position vector from particle b to particle a, $T_{ab} = T_a - T_b$ and $W_{ab} = W(\mathbf{r}_{ab}, h)$ is the interpolation kernel with smoothing length h (see Cleary and Ha, 1998). Equation (1) has an explicit conductivity which can be temperature dependent and ensures that heat flux is automatically continuous across material interfaces. This allows multiple materials with substantially different conductivities and specific heats to be accurately simulated.

FREE SURFACE RADIATION MODEL

The mould in these applications has a large thermal mass so we need only consider the radiation that is emitted from the free surface as a thermal sink. An SPH implementation of this simple model requires the free surface to be identified. The smoothed particle number density $N_a = \sum_{b \neq a} m_b\, W_{ab} / \rho_b$ is constant throughout a continuous material but which declines rapidly as any free surfaces are approached. Particles for which $N_a < 0.84\, N_{max}$ are classified as being surface particles. The radiative flux emitted for such a particle is:

$$\Phi_a = \epsilon\, \sigma\, T_a^4 \,, \quad (2)$$

where ϵ is the emissivity of the surface and $\sigma = 5.67 \times 10^{-8}$ is the Stefan-Boltzmann constant. The perimeter of fluid (in 2D) that is radiating with this flux is approximated by $2\,(1 - N_a)\,\Delta x$, where Δx is the initial particle spacing. This estimate is surprisingly good for all but the most extreme cases, such as droplets of one or two particles. The heat loss for a particle is then given by the product of the flux and the perimeter, so the radiative heat loss rate per unit mass applied to a free surface particle a is:

$$2\,(1 - N_a)\,\Delta x\, \epsilon\, \sigma\, T_a^4 / m_a \quad (3)$$

At each timestep this is subtracted from the rate of change of enthalpy for the free surface particles. Details of this radiation model and its accuracy are given in Cleary (1998b).

SOLIDIFICATION MODEL

For HPDC modelling, the coupling between the heat transfer and the fluid flow occurs via a strongly temperature dependent viscosity which varies from very small values in the fully liquid metal for temperatures above the liquidus T_l to extremely viscous adjacent to the walls for temperatures below the solidus T_s. Here dendrite growth produces solid fractions above 60% and the material is either rigid or slowly deforming. For temperatures in between the metal is a complex slurry of metallic solids contained in liquid metal, known as the mushy zone. For the aluminium alloy used here $T_s = 520°\mathrm{C}$ and $T_l = 572°\mathrm{C}$, respectively. To begin, we test the SPH model on a Couette flow. Here fluid is sheared between parallel infinite plates moving in opposite directions. The plates are isothermal and cold and the fluid is initially hot T_0 and stationary. The viscosity dependence on the temperature is exponential:

$$\nu(T) \;=\; \nu_r\, exp\{\, a\,(T_0 - T)\} \;, \qquad (4)$$

where ν_r is the lowest viscosity occurring at $T = T_0$. Here we choose $\nu_r = 0.001$ corresponding to a peak Reynolds number (Re) of 1000.

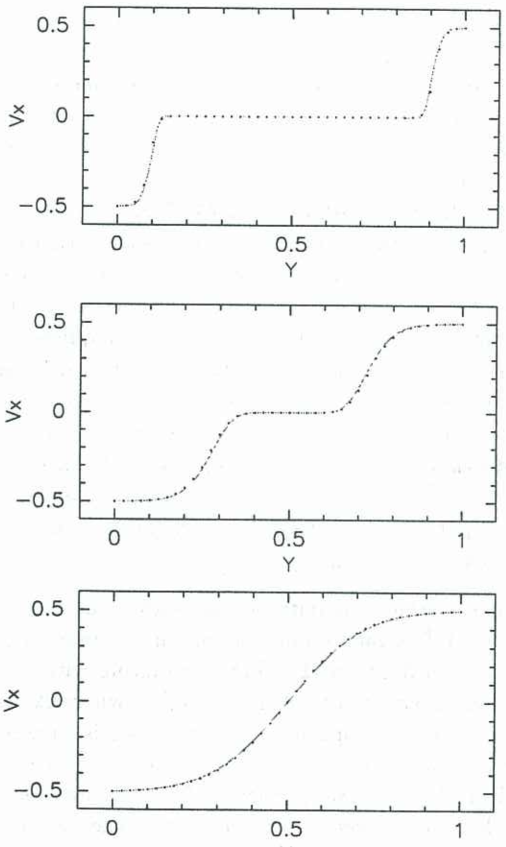

Figure 1: Velocity for a Couette flow with cold walls and an variable viscosity with ratio 10,000 at a) $t = 0.1$ s, b) $t = 0.2$ s, c) $t = 0.4$ s.

The accuracy of the SPH simulations is determined by comparing them to high resolution finite element solutions using the package *Fastflo*. Figure 1 shows the velocity profile across a Couette flow when the viscosity varies by a factor 10^4 between the cold 'solidish' regions near the walls and the hot free flowing central region. The SPH velocities (points) are very close to the *Fastflo* solution at all times, demonstrating the high accuracy of the SPH method for this application. Kinematic viscosities of between 1 and 10 appear to be sufficient to make the 'solidified' material whose temperature is below the solidus behave effectively as a solid and move with the walls.

Viscosity variations of 5 orders of magnitude (from a minimum kinematic viscosity of 10^{-4}) in a Couette flow of hot fluid between isothermal cold walls can be modelled accurately with as few as 40 particles across the channel. This frequently means that there are only 3 or 4 particles in the very high viscosity gradient regions, but the temperature and velocity profiles remain quite accurate. Details are contained in Cleary and Mooney (1998)

HPDC WITH CONDUCTION

The coupled heat and mass transfer SPH model is applied to HPDC for the C shaped mould (used in the preceding papers). Figure 2 shows the temperature distribution of the liquid metal at four times during the filling process for a viscosity ratio of $\mu_r = 100$ between the free flowing and viscous material and a peak Re$= 2500$. The particles are shaded according to their temperature with the lightest grey being the hottest temperatures. Figure 3 shows the same simulation with the particles shaded according to their viscosity. The dark material is free flowing while the light grey material is very viscous (effectively solid). The metal adjacent to the cold mould walls (which are maintained at $27°\mathrm{C}$) cools quickly and slows considerably. At $t = 0.5$ ms the jet of hot metal has filled much of the vertical section on the left. The free flowing material is fragmented with complex free surface behaviour. The filling pattern is substantially different to that of the isothermal case. The solidifying material on the lower right wall of this section pushes the free flowing jet into the middle of the mould section. This eliminates the back flow along the left wall of the mould.

Once the metal fills the left section ($t > 0.5$ ms) and begins to travel along the horizontal section the front of the jet becomes rounded and surface breakup is inhibited. The thermal boundary layers are very small near the front but increase steadily with distance from the front. Between the cold boundary layers is a central jet of hot metal that is pushed to the front and then flows to the sides, solidifying on the walls.

Figure 4 shows the temperatures distributions for the same times when the viscosity ratio between the hot and cold metal is only 10. This flow pattern is closer to that of the isothermal flows. In particular, at $t = 0.5$ ms the jet of material is located on the right of the mould and leaves the left empty to be filled by

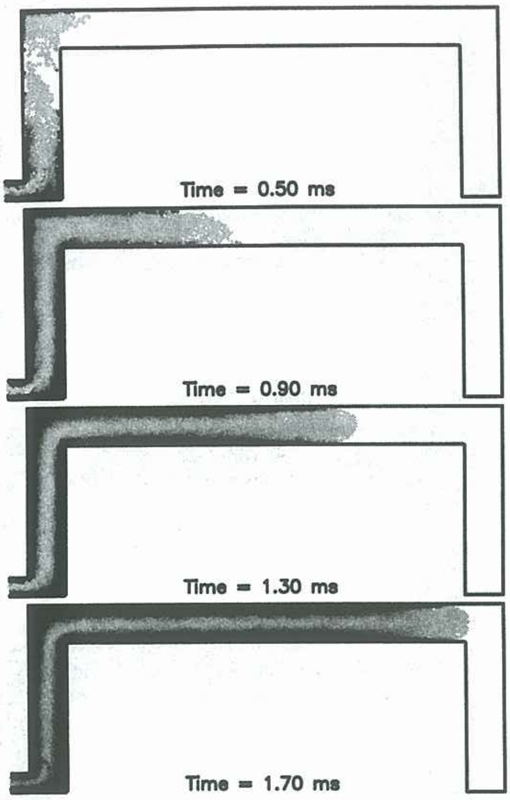

Figure 2: Temperature for $\mu_r = 100$ with an isothermal mould.

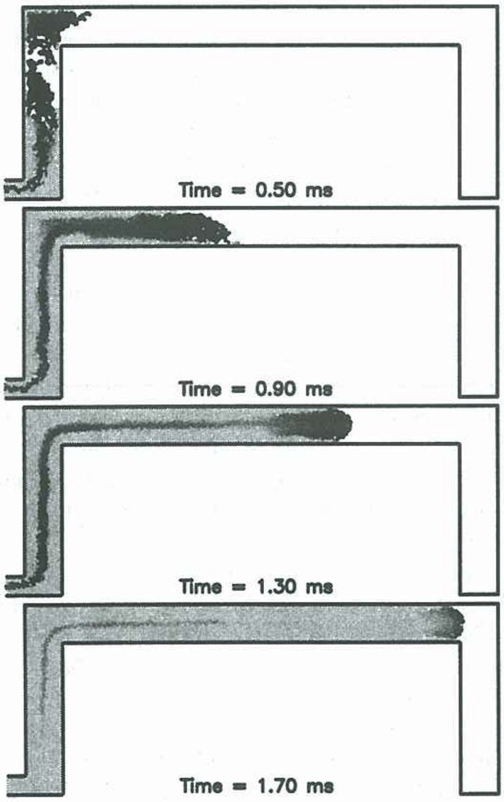

Figure 3: Viscosity for $\mu_r = 100$ with an isothermal mould.

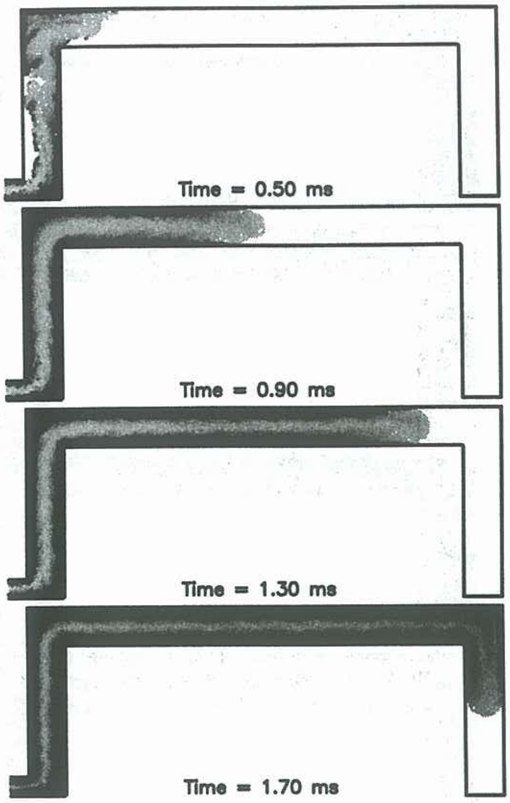

Figure 4: Temperature for $\mu_r = 10$ with an isothermal mould.

the familiar back filling process. The lower viscosity in the cold metal near the walls allows it to be sheared more, so the distance travelled by the jet increases by around 25%. The flow for a viscosity ratio of 1000 is qualitatively similar to the 100 case, but the higher viscosity near the walls concentrates the shear in the hot core of the jet and slows the speed of the jet front by around 25%.

EFFECT OF THERMAL BCs

The thermal diffusivity of the mould walls is around 10 times lower than for the liquid metal. This means that isothermal mould walls remove far too much heat from the flow. A more realistic configuration involves simulating the heat conduction in the mould, which is represented by five layers of SPH particles with properties of steel and an isothermal boundary condition of $T = 350°\text{C}$ on the outside. The filling process, shown in Figure 5, reveals that substantially less heat is removed and the fluid remains much more free flowing with surface breakup and splashing. This flow is much closer to the original non-heat transfer solutions and demonstrates that the choice of thermal boundary conditions is critical to obtaining realistic solutions.

EFFECT OF LATENT HEAT ON HPDC

The latent heat released during solidification of aluminium is 495 kJ/kg. This is comparable to the heat lost in cooling from T_l to T_s and is therefore quite im-

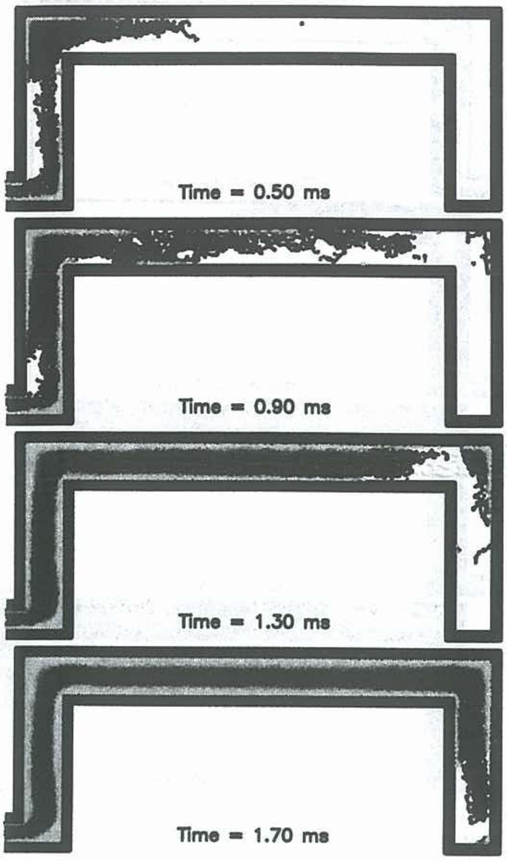

Figure 5: Viscosity distribution when the conduction in the mould is also simulated.

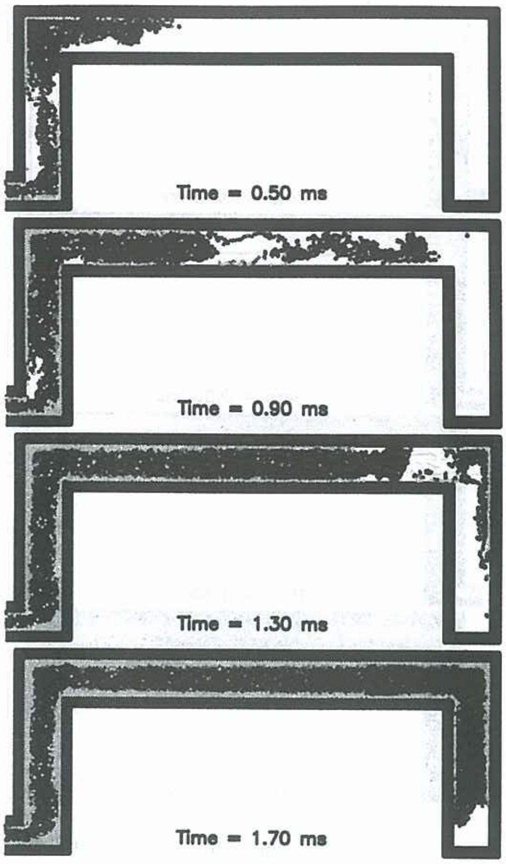

Figure 6: As in Figure 5 but including latent heat.

portant. The latent heat release was tested by solving a Stefan problem. The SPH solution is highly accurate. A linear release of latent heat within the mushy zone was then used for the same configuration as the one shown in Figure 5. The viscosity (Figure 6) shows that the amount of solidified metal on the inside of the mould is reduced modestly. More importantly the temperature of the viscous metal a little further from the walls is raised sufficiently to reduce the viscosity of this material to close to the minimum value. This significantly sharpens the region of large viscosity variation, concentrating it at the edge of the solid metal. Also a sprinkling of viscous partially solidified material is now visible within the hot jet. This is caused by the hot jet stripping solidified material from the now much more exposed solid surface and the latent heat preventing this material from rapidly re-melting, thus leaving a slurry. The overall filling pattern is little changed by these effects.

EFFECT OF RADIATION ON HPDC

The predominant effect of radiation in HPDC is to provide cooling of the free surfaces, particularly for droplets. For the case with the isothermal mould the radiative cooling was found to be insignificant.

CONCLUSIONS

HPDC with heat transfer has been simulated using SPH. The choice of thermal boundary conditions has a significant effect on the flow pattern as does the viscosity ratio between the free flowing core of the jet and the cold viscous material near the walls. The inclusion of latent heat leads to a sharpening of the viscosity gradients and to solid metal particles being embedded in the liquid metal jet. Surface radiation seems to be unimportant.

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