Is Fluid Flow Important for Predicting Solidification?

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ABSTRACT

Simulating fluid flow is usually the most computationally expensive part of the casting modeling process and casting designers often wonder if they should do it at all. The answer to this question clearly depends on the situation. One needs to model filling with conjugate heat transfer to get accurate temperature distributions for subsequent solidification, but how different would the results be if an instantaneous filling was assumed? How important is the residual flow after filling, or natural convection generated during solidification? Are these processes likely to affect the location of shrinkage defects?

In this paper we address these questions through a series of examples that compare different modeling assumptions. One conclusion is that it is advantageous for an engineer to have access to a range of numerical and physical models. These models can be combined to carry out simulations of varying complexity, but a proper engineering judgment must be used in the selection of what is and what is not important for an application.

1. Introduction

Filling models have become an essential part of most casting simulation tools [1]. Using these models helps to analyze mold erosion, gas porosity, cold shuts, seams, the evolution of foreign inclusions and other phenomena that can directly cause defects in castings.

A common alternative to a filling simulation is the assumption of an instantaneous filling. The system of equations describing flow is reduced from five (the continuity, momentum in three directions and energy equations) to just one (the energy equation), significantly simplifying the computational effort in modeling solidification. In that case the initial conditions are a full mold cavity and uniform temperatures in metal and mold. By ignoring filling we lose information about the temperatures in the metal and mold at the end of the filling process. The temperature distribution depends on the sequence in which the mold cavity surface gets wetted by the hot metal, the filling rate and, of course, the gating and casting geometry.

The residual metal flow after filling is also ignored when an instantaneous filling is assumed. The residual flow can play an important role in the redistribution of heat in the metal during the first stages of solidification. However, fluid flow is excluded in most solidification models, even when a complete filling simulation is carried out. Buoyancy effects have a similar fate although solutal convection has to be modeled if macrosegregation is important.

2. Filling vs. No Filling

Suppose the filling rate is constant and t_f is the filling time. Given that initially the mold cavity is empty, we can estimate the thermal energy that goes into the mold during filling as

$$\Delta E_f = \frac{1}{2} t_f h A (T_i - T_m) \tag{1}$$

where h is the interfacial heat transfer coefficient, A is the mold total wetted area at the end of the filling and T_i and T_m are the initial metal and mold temperatures, respectively. We assume here that the filling time is small so that T_m can be used to represent the mold surface temperature during filling.

For longer filling time the heating of the mold has to be taken into account. In that case an estimate of the interfacial heat flux can be made using a one-dimensional analytical solution [2]. If the flux is limited by the thermal resistance of the mold, which can be assumed if $h\sqrt{a_m t}/k_m > 3$, then

$$q \approx \frac{k_m(T_s - T_m)}{\sqrt{\pi a_m t}} A \quad , \tag{2}$$

where a_m and k_m are the mold thermal diffusion and conduction coefficients, respectively, t is the time elapsed from the beginning of the cooling process and the solidus temperature, T_s, is used to represent the interfacial metal temperature. In typical sand and steel molds Eq. (2) can be used when $t > 10\ s$. Equation (1) then transforms into

$$\Delta E_f = \frac{k_m(T_s - T_m)t_f^{1/2} A}{2\sqrt{\pi a_m}} \; . \tag{3}$$

The ratio of energy loss during filling, Eq. (1) , to the total superheat of the metal, E_{sh}, is

$$a = \frac{\Delta E_f}{E_{sh}} \doteq \frac{t_f h(T_i - T_m)}{\delta \rho C(T_i - T_l)} \quad , \tag{4}$$

where $E_{sh} = V\rho C(T_i - T_l)$, V is the total casting volume, ρ and C are the metal density and specific heat, respectively, T_l is the liquidus temperature, and $\delta = 2V/A$ is a measure of the characteristic casting section thickness.

E_{sh} is an estimate of the amount of energy that must be extracted from the metal before the fluid flow is affected by solidification. Unless a is much smaller than one, filling *is* important for an accurate evaluation of temperature distribution at the beginning of solidification. If $a \geq 1$, then freezing is likely to occur during filling and an instantaneous filling assumption cannot be employed. It can be seen from Eq. (4) that a larger superheat or preheated mold will reduce the difference between the results of the full and instant filling models, while a filling simulation is likely to be needed for longer filling times or for a casting with thinner walls.

If an instantaneous filling is assumed, then the amount of energy equal to ΔE_f is lost by the metal in the period of time approximately equal to $t_f/2$, or twice as fast as during the actual filling. Therefore, the energy loss is overestimated when filling is ignored, at least during the first stages of solidification, before the mold geometry starts affecting the cooling pattern. The difference in the total solidification times, t_s, predicted by the two models is of the order of t_f. The latter normally is much smaller than t_s; thus, ignoring filling should have only a small effect on the overall cooling rates.

Let us estimate the variation of temperature in the metal at the end of filling, ΔT_f. During filling thermal energy is mostly distributed in the metal by convection as opposted to diffusion since the Peclet number in a typical casting, $Pe = UL/a$, is large (> 100). Here U is the characteristic flow velocity, L is the length scale for metal temperature variation, $a = k/\rho C$ is the metal thermal diffusion coefficient and k is the metal thermal conduction coefficient. The thermal boundary layer thickness in the metal at the end of filling, d, can be estimated as $d = \sqrt{a t_f}$, and the temperature change in the boundary layer during filling as $\frac{h(T_i - T_m)t_f}{d\rho C}$. At the same time convection mixes the cold fluid at the walls into the bulk of the fluid, distributing the heat over the distance $d + Ut_f$. The resulting temperature drop can be estimated as

$$\frac{\Delta T_f}{t_f} = \frac{h(T_i - T_m)}{d\rho C} - \frac{U\Delta T_f}{L} \tag{5}$$

One can expect that the product of t_f and U in the denominator is nearly constant for a given casing geometry. Therefore, according to Eq. (5) and the definition of d, temperature variation at the end of filling grows linearly with t_f for short filling times, while for longer filling times $\Delta T_f \sim \sqrt{t_f}$.

3. Heat Conduction vs. Residual Flow

A residual flow continues to move the heat around reducing temperature gradients in the liquid metal for some time after filling, thus delaying the onset of solidification. The characteristic time for the decrease of the residual flow due to viscous effects can be estimated as

$$\tau_r = \frac{\delta^2}{4\nu} \tag{6}$$

where ν is the metal kinematic viscosity. For example, in an aluminum casting with a 5 *mm* wall thickness $\tau_r \approx 6.0\,sec$, which usually is significantly smaller than the total solidification time. With the onset of solidification the remaining fluid flow will die away even faster due to additional flow losses in the mushy region.

As the mold temperature increases, the metal cooling rate decreases. If there is still significant recirculation present, reheating and remelting of metal can occur in areas, where it was cooled most during filling. Typically, fluid flow will continue for longer periods of time in thicker sections, therefore, solidification in thick sections may be affected proportionally more than elsewhere in the casting.

Residual flow increases thermal mixing in the liquid metal with the effective thermal diffusion coefficient is $a_e = a + UL = a(1 + Pe)$. Residual circulation can be neglected after the Peclet number becomes small. However, in most cases it is excluded from the models altogether since a significant computational effort is required to simulate residual flow.

4. Buoyancy Driven Convection

At the same time as the residual flow intensity decreases, natural convection may develop due to variations in temperature and solute concentration in the liquid metal.

The magnitude of temperature variation at this stage of the process is defined by the combined effect of heat transfer, thermal conduction and convection. The importance of thermal convection in redistributing heat relative to thermal diffusion can be characterized by the thermal Rayleigh number

$$R_T = \frac{g\beta_T \Delta T \delta^2 L}{4\nu a}, \tag{7}$$

where g is gravity, β_T the liquid metal thermal expansion coefficient and ΔT the typical liquid metal temperature variation during solidification. Thermal convection flow is more significant when R_T is large, *i.e.*, in large, bulky castings with small thermal and viscous diffusion.

Similar estimates can be made for the solutal buoyancy if β_T is replaced with the solutal expansion coefficient, β_c, and ΔT with the average solute concentration variation, ΔC, plus a with the solute diffusion coefficient, D. Generally, the solutal Rayleigh number

$$R_C = \frac{g\beta_C \Delta C \delta^2 L}{4\nu D} \tag{8}$$

is large implying that solute redistribution on the scale of the casting (macrosegregation) occurs due to convection rather than diffusion [3].

One can expect that buoyant flow is only important in purely liquid metal, however, solutal convection in mushy regions can also be significant and lead to the formation of freckles [4]. Generally, thermal convection dominates during the first stages of solidification, when temperature gradients are large and no significant segregation has developed. The situation changes to the opposite at later times during solidification, when temperature gradients diminish due to the release of latent heat and solute concentration gradients build up. Therefore, the transport of heat by solutal convection usually is minimal.

How important is macrosegregation for solidification? The transport of solute by convection is proportional to $U\Delta C/L$ and $\Delta C \approx C_0(1-p)$, where C_0 is the initial composition and p the partition coefficient. The dimensionless number

$$s = \frac{UC_0(1-p)}{L\frac{dT}{dt}} \left| \frac{dT_l}{dC} \right| \tag{9}$$

characterizes the ratio of the segregation and cooling rates during solidification. If $s << 1$, then segregation can be neglected. For steep liquidus lines (dT_l/dC is large) small compositional changes are more important for solidification. In thin wall sections U will generally be small due to frictional flow losses while the cooling rate, dT/dt, large. Therefore, segregation should be less important in thin sections than in the rest of the casting.

If the solute rejection at liquid/solid interface leads to an increase in the liquid phase density, then the solute convection enhances the thermal convection. Otherwise, the two types of convection work in the opposite directions and the ratio $\beta_T\Delta T/\beta_C\Delta C$ defines which one prevails (assuming that temperature and solute concentration vary on the same length scale).

5. Numerical Analysis

The general purpose computational fluid dynamics code FLOW-3D was used for the numerical simulations presented in this section [5]. Those simulations serve to demonstrate some of the above considerations.

The influence of the filling time on the occurrence of a shrinkage defect has been demonstrated in the first series of simulations of a pure aluminum casting in a sand mold [6]. The casting geometry is shown in Fig. 1. Four filling times are considered: 0.0 s (instantaneous filling), 6.0 s, 7.0 s and 22.5 s. The experimental filling times are controlled by the size of the choke at the bottom of the sprue. The metal is poured at 80^0C superheat into the mold, which is initially at room temperature. The shrinkage cavity in the horizontal section of the casting, near the vertical section (at T-junction), is observed. Both sections of the T-junction have the same thickness so that the size and location of the shrinkage should be sensitive to small temperature and solidification rate variations in the casting. No residual or thermal convection is included in the simulations.

The results of the simulations show that the predicted location of the shrinkage defect in the T-junction is close to the experimental result shown in Fig. 2, and has little dependence on the filling time (Fig. 3). However, the size of the cavity decreases with an increase of the filling time, as shown in Fig. 4. In particular, there is no shrinkage at the T-junction for the longest filling of t_f =22.5 s. A possible explanation is that longer filling times result in a more directional solidification, from the T-junction towards the feeder, thus providing a better feeding for the volumetric shrinkage in the T-junction.

According to Eqs. (2) and (3), $a = 0.2$ for $t_f = 6.0$ s and $a = 0.38$ for $t_f = 22.5$ s, indicating that the energy loss is significant during filling. Simulations showed that metal in the vertical section was already solidifying during the longest 22.5 s filling. It is interesting to note that the time from the beginning of pouring to complete solidification is practically constant in all four cases and equal to 475 s, which is within 5% of the average experimental time of 500 s..

Unfortunately, the predicted dependence of the shrinkage size on the filling time could not be directly related to the experiment since variations in the experimental cavity sizes for a given filling time were larger than the variation in the predicted sizes for the four filling times.

A second series of simulations were designed to analyze the influence of the modeling assumptions on the location of the last spot to solidify. The casting is a plate 90 *mm* wide, 200 *mm* high and 5 *mm* thick, which is filled with a Al-10%Mg alloy through a 10×5 *mm* gate positioned in the middle of the bottom section of the casting with a velocity of 1.6 *m/s*. In a second set of simulations, the basic geometry was modified by increasing the plate thickness to 20 *mm*. Initially the sand mold is at 25^0C and metal at 650^0C. Four simulations each were carried out for the thin and thick plates with the following physical model assumptions (in the order of complexity):

1. Instantaneous filling, no fluid flow;
2. Full filling, but no flow during solidification;
3. Full filling and residual flow during solidification;
4. Full filling and residual flow with thermal convection during solidification.

Solutal buoyancy was not included in the calculations for the reasons of limited length of this paper, although the simulation software does contain a segregation model.

Figure 5 shows the variation in the location of the last place to solidify predicted for the thin and thick plates. For the thin plate this variation is negligible. The last place to solidify is at the geometrical center of the plate. Fluid flow is not important in cooling and solidification of the metal. For the thick plate the result of model 1 is at the geometrical center, while those of models 2 and 3 are slightly below the center. This shows that the thermal center of the plate is shifted towards the gate due to heat losses during filling. Model 4 prediction is 25 *mm* above the geometrical center of the 200 *mm* high plate, showing that there was sufficient space ($\delta = 20$ *mm*) and time ($t_s = 190$ *s*) for thermal convection to develop and redistribute the heat towards the upper section of the plate.

6. Conclusions

Fluid flow can influence solidification in a number of ways. Filling defines metal and mold temperature distributions when the mold is full and sets up a residual flow, which continues to distribute heat in the casting. The residual flow dies away due to viscous forces, giving way to thermal convection that continues to convect thermal energy in liquid metal. Solute buoyancy generates additional convective flow that contributes more to solidification kinetics rather than to the distribution of heat in the metal.

A number of dimensionless parameters are suggested in this paper that may be used to estimated the relative importance of those processes during solidification. These estimates can be made for a whole casting or its different sections. However, it may be difficult to apply these parameters to complex castings. In general, a comprehensive computational tool is needed. Such tool can be used to test modeling assumptions and, ultimately, optimize and improve the casting design.

References

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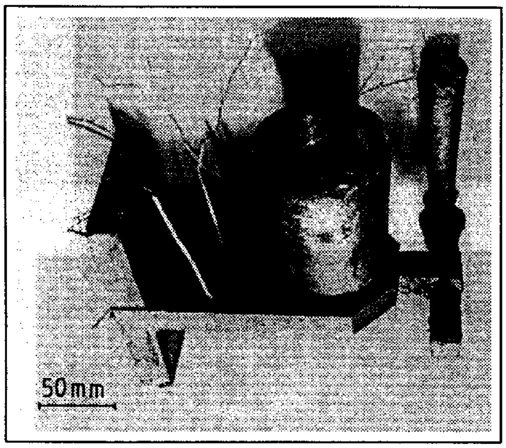

Fig.1 The overall view of the T-shape casting.

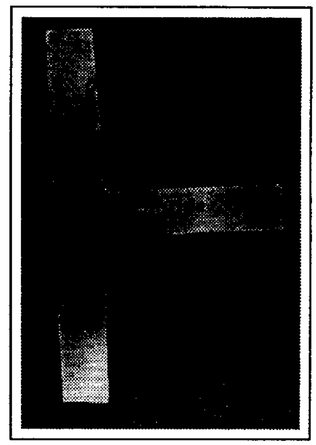

Fig. 2 Shrinkage defect at the T-junction.

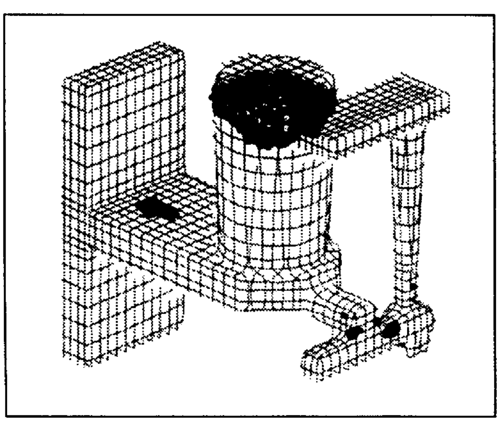

Fig. 3 Predicted shrinkage defects for $t_f = 7\ s$

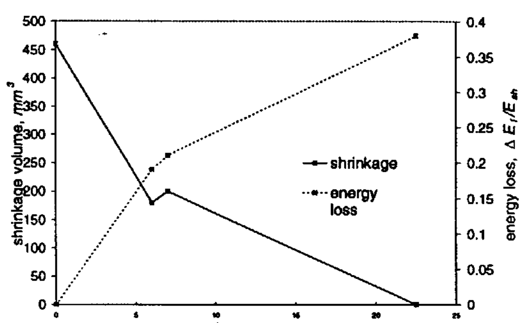

Fig. 4 Shrinkage volume at T-junction and energy loss during filling as functions of filling time.

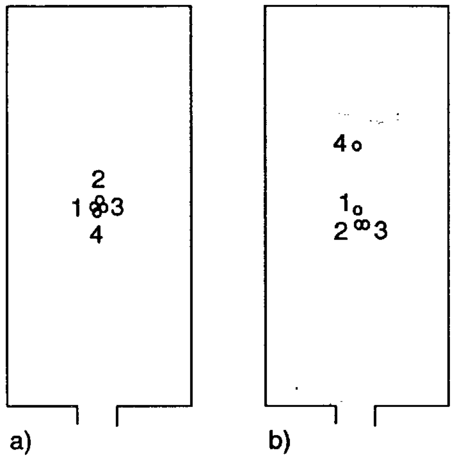

Fig. 5 Locations of the last place to solidify for the 5 *mm* (*a*) and 20 *mm* (*b*) plates predicted by models 1, 2, 3 and 4 (see text).