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A FLOW-3D STUDY OF THE IMPORTANCE OF FLUID MOMENTUM IN MOLD FILLING

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Abstract

The design of effective runners and gates for filling molds is strongly dependent on the momentum of the incoming liquid metal. Because of momentum effects, liquid metal may splash, jet or otherwise flow in undesirable ways into a model cavity. To understand such behavior and to aid in the design of better runner/gate systems, researchers are beginning to explore the use of computational models of the filling process. It is shown in this paper that models for most metal casting applications must be based on the full momentum conservation equation if realistic results are to be obtained.

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Introduction

The filling of molds or dies with molten materials is subject to many fluid dynamic phenomena that influence the quality of the cast product. For instance, such things as premature solidification, air entrapment and weld seams often lead to unacceptable results. Unfortunately, filling processes involve strongly nonlinear dynamic effects and large deformation free boundary motions, which make them difficult to predict or even approximate by simple means. Because of this, a variety of computer programs have appeared in the past several years that are designed to model mold filling processes. One such program, FLOW-3D, is the subject of this paper.[1] In particular, we shall use the program to model a simple thin-wall die casting that was selected to illustrate several important consequences of how fluid momentum can significantly influence the filling of a die.

The generation of die cast parts having thin walls is often done by high pressure (i.e., high speed) injection of molten metal into the die. Rapid filling is desirable in this case because it reduces the chance for premature solidification that could shut off the flow to portions of the die. High filling and cooling rates also imply a shorter production time, which can lead to competitive advantages for a manufacturer. On the other hand, the high velocities associated with this type of casting also mean that it is essential to consider fluid momentum effects when designing runner-gate systems to feed the dies.

Even in investment casting, where slower velocities are usually the norm, fluid momentum can still be a source of concern. One very simple example illustrating this is given in Fig. 1A (reproduced from Ref. 2). Here molten lead has been poured into a mold for a hemispherical shell. The photograph, which is a flash x-ray picture, shows how the initial impact of lead onto the inner surface of the mold leads to a thin radial splash of metal. For comparison, Fig. 1B shows a FLOW-3D computational result for a similar case. The computed case does not exactly correspond to the experiment because the experimental details were not recorded. The physical thinness of the splash and the fact that it has a short life span makes it difficult to capture by a discrete computational model. Nevertheless, the FLOW-3D program indicates a tendency for a small amount of metal to separate from the surface of the mold. This example serves as a qualitative demonstration of FLOW-3D's capabilities for modeling complex free-surface flows under conditions where fluid momentum has a significant influence on the flow dynamics.

In contrast to the above cases, consider the situation associated with injection molding of plastics. Viscous effects usually dominate these flows so that momentum effects can generally be ignored. In fact, this assumption is made in virtually all the specialized modeling programs available for plastic injection molding. But the neglect of momentum is not always correct, particularly in situations involving high injection speeds or in locations where the thin wall assumption is violated. An illustration of this is provided by a plastic bottle cap. The cap has a thin wall everywhere except in the region of the threads. Injection points for making caps are typically located at the top center of the caps. This means that plastic must enter the threads after turning the corner connecting the top with the sides of the cap, see Fig. 2. To the extent that momentum influences the flow, its tendency will be to direct the flow along the outside cap wall and to hinder the filling of the thread region.

In the next section we attempt to clarify the essential difference between low and high Reynolds number flows from the point of view of mold filling. Following that, we describe a generic mold design that exhibits several important consequences of fluid momentum. A comparison between the filling characteristics of the mold using an inviscid fluid versus a very viscous fluid clearly demonstrates the profound influence exerted by momentum on the filling process.

High Versus Low Reynolds Number Flows

It shall be assumed for present purposes that the Navier-Stokes equations are a valid mathematical representation for the flow of molten material:

$$\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u} = -\frac{1}{\rho} \nabla p + \vec{g} + \overrightarrow{\nabla \cdot \sigma} \qquad (1)$$

The relative importance of different terms in this equation can be evaluated by introducing nondimensional variables. Using L for a characteristic length and U for a characteristic velocity, it is readily found that the ratio of the momentum advection term to the viscous stress term is expressed by the flow Reynolds number,

$$R = LU/\nu \qquad (2)$$

Its precise value is unimportant since it depends on the evaluator's choice of L and U; however, a value of 10 or greater would strongly suggest that inertia of the flow is more significant than viscous stresses. Conversely, a Reynolds number of order 1 or less would strongly suggest a flow dominated by viscous stresses.

Consider the low Reynolds number flow associated with a highly viscous material such as a thermoplastic flowing in a narrow gap of thickness H between two mold walls (i.e., a thin wall casting). Let us further assume that we have no interest the velocity profile between the walls, but only in the average flow velocity parallel to the mold walls. If the Reynolds number based on this average velocity and gap thickness, HU/ν, is sufficiently low, the flow will possess a Poiseuille velocity profile across the gap. In this case the average flow velocity in the gap is given by,

$$\vec{U} = -H^2/(12\nu\rho)\nabla p \qquad (3)$$

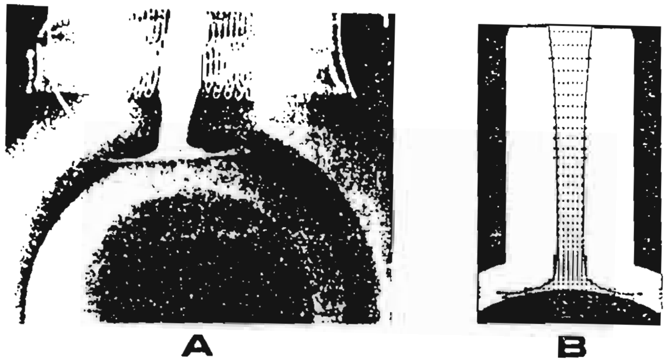

Figure 1 - (A) X-ray of lead poured into hemispherical mold. (B) FLOW-3D simulations of early splash.

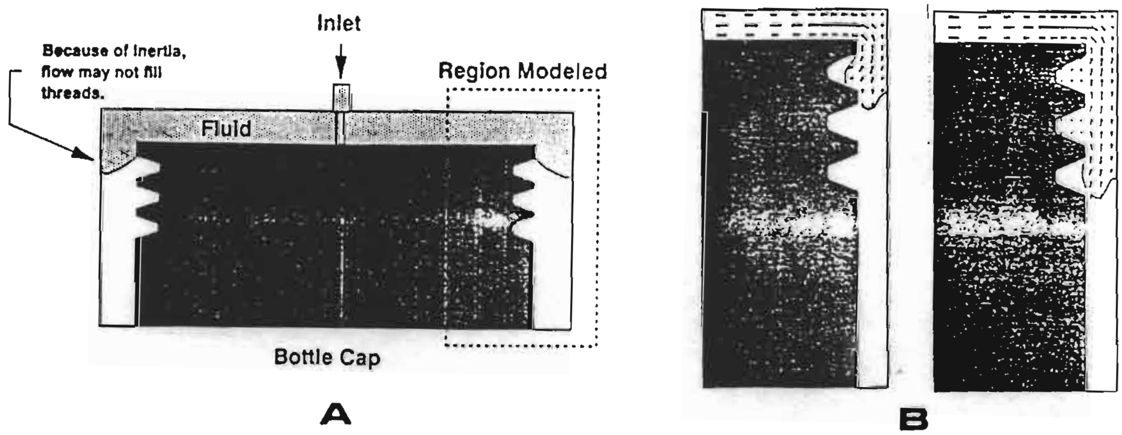

Figure 2 - Viscous flow in axisymmetric bottle cap die. Reynolds number of order unity. (A) Schematic. (B) FLOW-3D calculation showing possible air entrapment in thread.

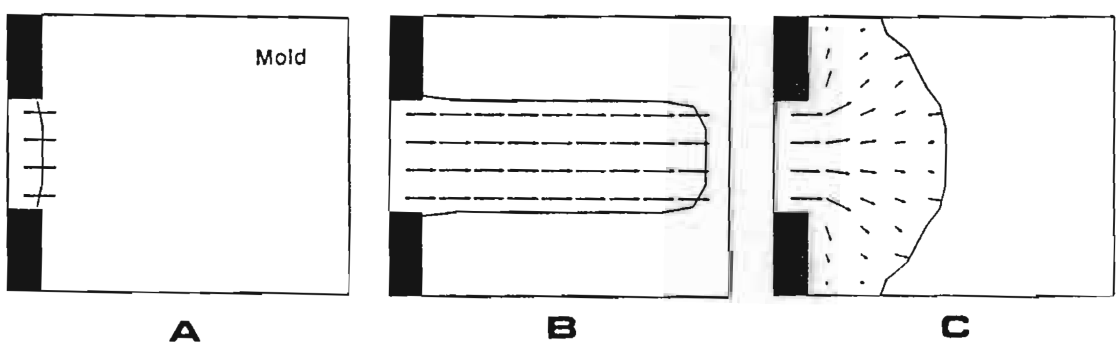

Figure 3 - Illustration of high vs. low Reynolds number flow behavior. (A) Initial condition. (B) Inviscid flow. (C) Very viscous flow.

where ν and ρ are the viscosity and density of the fluid. This result states that the average flow velocity is proportional to, and in a direction opposite to, the local pressure gradient.

This result is the low Reynolds number limit of the Navier-Stokes equations under the assumed conditions. Inspection shows that it is identical to the Darcy flow assumption for porous media in which the permeability is given by $H^2/(12\nu)$. Equation (3) is the basis of most thin-wall plastic molding programs.

A simple problem may be used to contrast the different flow characteristics implied by Eq. (1) and Eq. (3). Figure 3A shows a schematic of the flow region, which is a two-dimensional box (mold) having an inlet port at its left side. The thickness of the mold in the third direction is small compared to all other dimensions, i.e., it is a thin-wall mold. A constant flow velocity is specified at the inlet. When this problem is modeled using the Navier-Stokes equations, Eq. (1), in the limit of vanishing viscosity (Euler approximation), there is no viscous stress anywhere in the mold. In this limit the Reynolds number is infinite and the incoming flow is seen to simply jet straight across the mold, Fig. 3B.

When the calculation is repeated with a large Darcy-type drag coefficient, the results approximate a large viscous shear stress between the mold walls. In this low Reynolds number limit, the flow, which is shown in Fig. 3C, is seen to be completely different from the high Reynolds number case. Molten material flows outward filling the entire width of the mold; most importantly, there is no tendency for the flow to jet as it did at high Reynolds numbers.

Of course, these results are not too surprising since Eq. (3) explicitly states that the flow velocity will be directed parallel to the pressure gradient. At the free surface there is a constant pressure (i.e., air pressure) so that the flow at the surface must be directed normal to the surface. This fact explains why the incoming material immediately flows out toward the top and bottom of the mold.

It should now be obvious that the fluid dynamics of mold filling must be different at low versus high Reynolds numbers. At low Reynolds numbers typical for thermoplastic injection molding, flow will be normal to the free surface causing the material to fill in all voids (in the absence of solidification). Under high Reynolds number conditions, which would be true for most metal casting processes, the metal can jet, splash, and flow in considerably more complex ways that may lead to incomplete mold filling. These effects are a direct consequence of the momentum of the molten material and must be accurately treated in any realistic mold-filling computer program.

Consequences of Fluid Momentum in Die Casting

The best way to illustrate the difficulties associated with fluid momentum is to consider a simple, generic die casting problem. In particular, let us consider a box-shaped die with a central partition, Fig. 4, that is to be filled with aluminum. All walls of the cast box are to have a thickness of 0.0032 m (1/8 inch). The aluminum is assumed to be driven by a cylinder/piston arrangement, which is not included in the model. Instead, an injection velocity is specified at the upstream end of the inlet runners where they intersect the boundary of the computational region. The vertical thickness of the inlets is 0.0032 m and the width of the side runner is 0.0095 m (3/8 inch).

Since the box has left-right symmetry with respect to the inlets, we have elected to model only one symmetric half. Figure 5 shows the inlet runner-gate system located in the top surface of the box. The principal flow enters a slightly diverging gate and must then turn a 90 degree corner (downward) as it enters the box along its upstream edge. Along the top of the box sidewall there is a secondary inlet runner that is positioned to inject metal down the side of the box as well as into the middle partition. In fact, the end of the runner was cut at an angle in an attempt to deflect flow into the partition because it was anticipated that this would be a difficult region to fill.

Particulars of Die Cast Model

Outside dimensions of the box are 0.1016 by 0.1016 by 0.2032 m (or 4 by 4 by 8 inches). The box die (symmetric half) has been placed in a computational grid having dimensions 0.2286 by 0.0603 by 0.1016 m. The grid subdividing this region into rectangular control volumes (cells) is nonuniform and consists of 36 by 14 by 19, or 9576 total cells including boundaries.

An injection velocity of 20.00 m/s is assumed for aluminum having density 2700 kg/m^3 and no viscosity. The no-viscosity assumption is consistent with the idea of a very high Reynolds number. Furthermore, because of the coarseness of the numerical resolution, it would not be possible to resolve viscous boundary layers in any case. Thus, it is better to neglect viscous stresses and, in so doing, reduce the computational effort.

Thermal effects have not been included in the model because the entire box is expected to fill with metal in approximately 0.05 s, a time too short for any significant amount of heat transfer to occur. On the other hand, gravity effects are included even though they too are negligible.

Finally, for use as an alternative graphic display method, a set of eight marker particle sources were defined across the inlets to the two gates. Marker particles move with the fluid but do not influence the flow. In the present case we have also given the markers a small diffusional motion so that they will spread out in a random way instead of remaining on lines emanating from the source points. (A complete input file for the problem can be obtained from the author.)

Preliminary Flow Results

If no further additions are made to the model, the computed filling patterns would not be especially realistic. The reason can be seen from the computed results at 0.015 s shown in Fig. 6A. We note that the incoming flow has turned

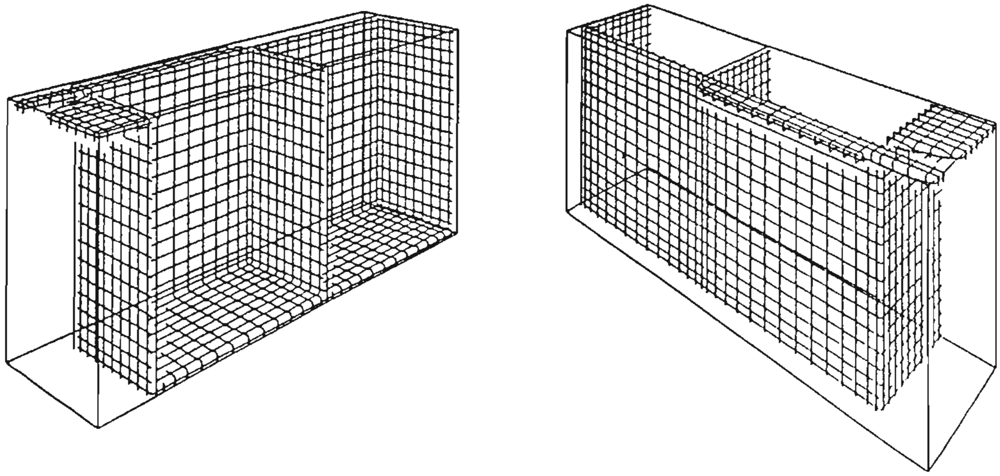

Figure 4 - Perspective of box die with runner-gates at top leading edge and side.

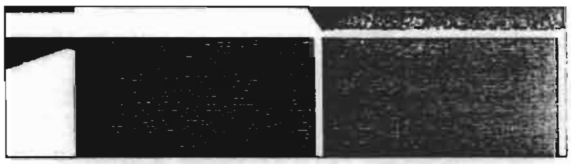

Figure 5 - Top view of inlet runner-gate system (white areas left and top left).

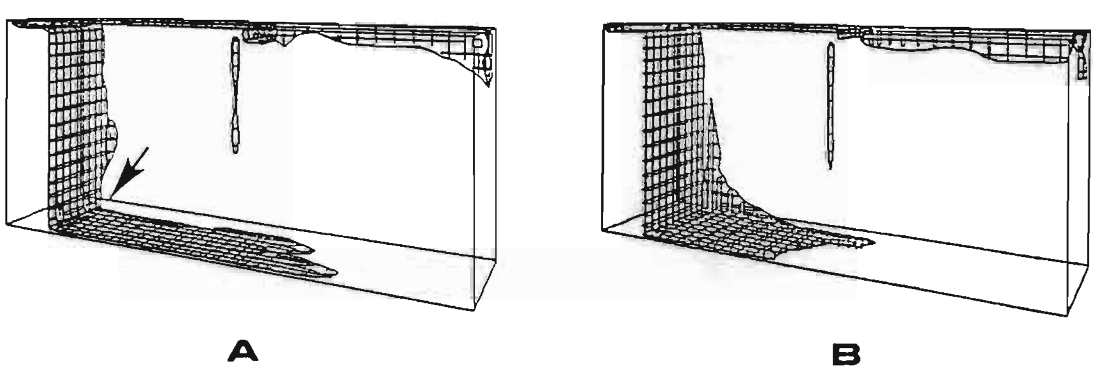

Figure 6 - Comparison of computed results showing effect of turning losses at arrow. (A) No turning losses. (B) With turning losses.

90 degrees down the left edge of the box and then turned another 90 degrees to flow out along the bottom of the box (see arrow for second turning location). What is odd is that the flow makes the turn (at arrow) without spreading laterally. In reality one expects flow losses to arise in the turning process that would generate a back pressure and force fluid toward the back side of the box.

Flow losses do not appear here because there are no losses in the computational method when the grid resolution is insufficient to resolve a flow profile across the flow channel. For instance, in the present case the channel width is defined by only one grid cell. However, even a small number of cells spanning the width would not be sufficient to resolve realistic secondary flows and losses associated with the 90 degree turn in the channel. To get a realistic simulation, it is essential to add turning losses to the computational model. In FLOW-3D we can do this using a baffle flow loss option. The idea is to define special baffles at the turning locations that don't obstruct the flow but have flow losses proportional to the square of the fluid speed. Since actual losses are unknown, we have used a loss coefficient equal to 1.0, which appears to be reasonable for a 90 degree turn in a rectangular channel, see Fig. 6B. All subsequent calculational results were made using these losses.

The need for turning flow losses is a direct consequence of fluid momentum, which is responsible for the losses, and constitutes our first important finding from this study.

High Reynolds Number Results

Computational results were obtained out to a time of 0.05 s at which time the die was 97% filled. Two small void regions remained trapped in the side of the box. The computation required 1490 time cycles and consumed 17.8 hours (about 15.27 hours without marker particles) of CPU time on a MicroVAX II computer. (Corresponding times on a SUN SPARC 1 station would be about 3.5 hours and on a DECstation 3100 about 1.8 hours.)

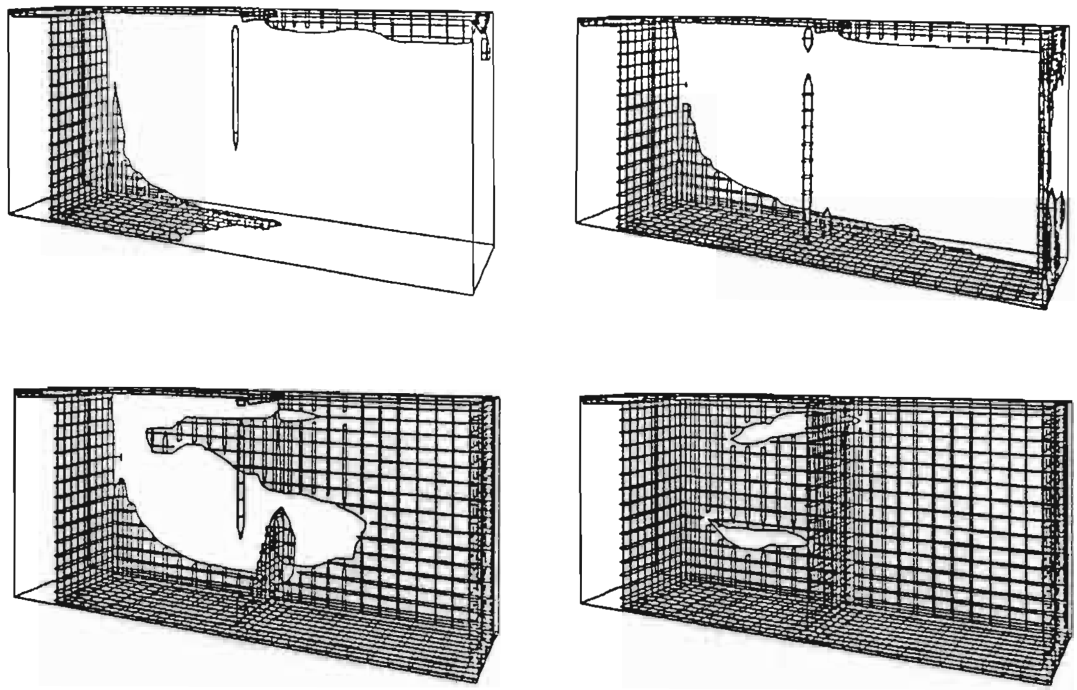

Figure 7 - Filling history for molten aluminum shown at times 0.015, 0.025, 0.04 and 0.05 seconds.

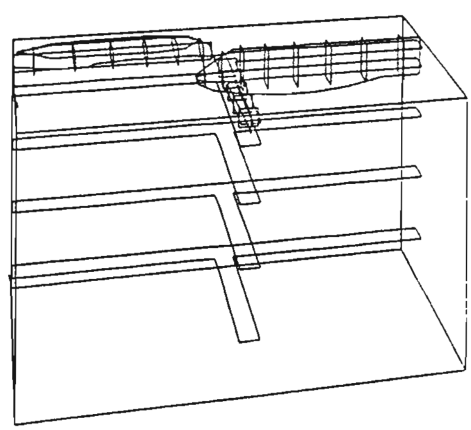

Figure 8 - Blowup showing early side runner flow at junction with control partition. Majority of flow continues downstream rather than being deflected into partition.

A selection of filling patterns covering the 0.05 s time period is presented in Fig. 7. Careful review of these plots, as well as other output, reveals several features of the filling process dominated by fluid inertia effects.

For example, the diagonal taper placed at the end of the side runner, which was intended to divert flow into the partition, did not work very well. The high inertia of the metal directed toward the rear of the box was only displaced into the side of the box downstream of the partition. This is shown more clearly in the enlargement of the deflector region displayed in Fig. 8. The computed results, therefore, have been useful in revealing a deficiency of the runner-gate system. This is the second main conclusion drawn from the computer model.

Another observation that can be made from the computed results is that flows from both the main gate and from the secondary runner-gate have reached the far end of the box long before the filling of the main portion of the box is complete. At t=0.025 s, for example, portions of the two inlet streams have already interacted at the far end of the box, but the box is only 48.6% filled. This feature is a consequence of fluid inertia, which allows the incoming flows to jet across portions of the die. Jetting of metal across the length of the die and the interaction of these jets from different gates indicates that the filling process is far from well behaved.

Reviewing the filling history after t=0.025, in fact, indicates that the fluid reaching the end of the box does not stay there but is actually diverted back upstream toward the inlets. This upstream flow occurs primarily along the outside wall of the box, as can be seen from the plots in Fig. 9. When this reverse flow reaches the inlet end of the box, it separates - some flowing up toward the top while the rest flows downward toward the bottom. A consequence of the flow separation and subsequent interaction with the incoming flows is that two void regions are trapped in the sidewall of the box. In a real situation these void regions would contain air; but since air effects were not included in the computation, we cannot accurately continue the simulation.

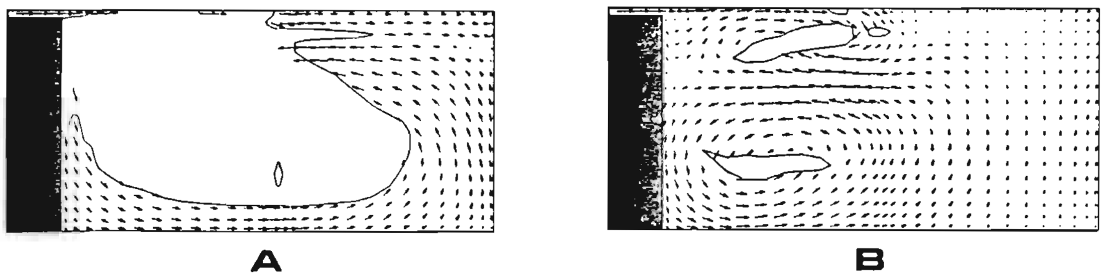

Figure 9 - Flow velocities in side wall of box (inlet is at left end) at time (A) 0.035 s and (B) 0.05 s. Note that reverse flow probably leads to trapped air.

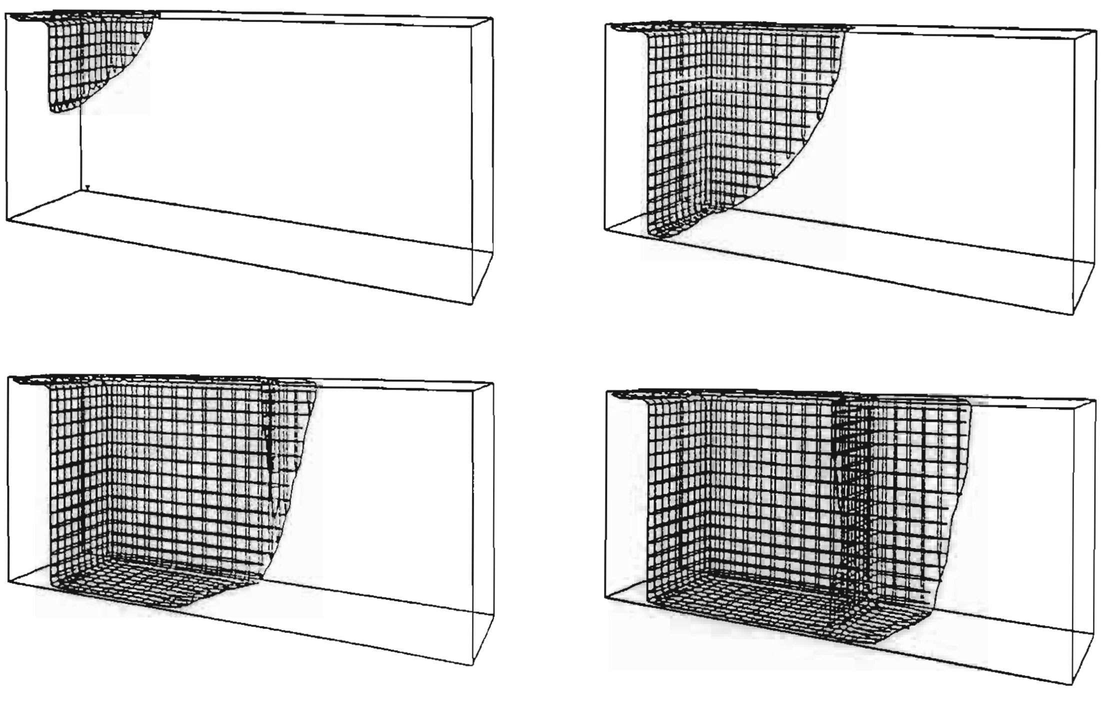

Figure 10 - Filling history for very viscous fluid shown at times 0.005, 0.015, 0.025 and 0.035 seconds.

Showing the probable occurrence of trapped air regions on the side of the box, which are caused by a reverse flow, which in turn was caused by the jetting of metal across the length of the die, is another important finding. This result is clearly a consequence of fluid inertia.

It would be useful to include some experimental data at this point that would substantiate these conclusions. Such data does exist; unfortunately it is proprietary and cannot be presented in this paper. The data in question is not for the same conditions used in the present model, hence, the use of the designation "generic" die cast problem. Nevertheless, the generic problem does possess the salient features found in actual experimental tests. Those tests confirm the likelihood of trapped air regions on the sides of box-like dies near the inlet gates.

Low Reynolds Number Results

It is instructive to compare the previous results to those that are obtained when the filling fluid is very viscous, in particular, when the viscosity is so large that the viscous shear stress on the walls of the die completely dominates the dynamics. In this limit the Darcy law formulation, Eq. (3), can be used to describe the flow processes.

To make comparisons easier, the inlet velocity has been kept the same as in the previous case. Therefore, at any given time the volume of fluid in each calculation will be the same and only its distribution will be different. Selected output for this case is presented in Fig. 10. This calculation was only carried out to a time of t=0.035 s, as the filling was extremely regular and no surprises were expected. It is immediately obvious that the low Reynolds number case fills very smoothly compared to that at the higher Reynolds number. Instead of flowing straight in, as its initial inertia would dictate, the flow spreads out around corners and completely fills all upstream portions of the die. In particular, the center partition also filled smoothly and completely. This is in agreement with the earlier observation that in low Reynolds number situations the flow is normal to the free surface, which insures the smoothness of the filling process.

Inertia is unimportant in this case, but is the only other possible contribution of significance to momentum changes besides viscous and pressure forces. We can infer, therefore, that the relative influence of inertia is the principal reason for the difference in filling patterns between the low and high Reynolds number cases. Strictly speaking, gravity also contributes to momentum changes but has been implicitly ignored here because of the high velocities and/or high fluid pressures.

If gravitational accelerations are dominant, for example in a bottom-filled mold with low velocity, then fluid inertia will again be negligible and the filling process should be well behaved. In this case gravity causes fluid to pack into all spaces below an approximate horizontal free surface that moves slowly upward.

Summary

Using the computational fluid dynamics program FLOW-3D, we have modeled the filling of a generic die shape. For high Reynolds number situations the computational model has clearly demonstrated that fluid inertia plays a crucial role in the filling of the die cavity.

One result from this study is the importance of accounting for turning flow losses when they would not otherwise be included in the computational model. Another finding is the possibility that incoming flow will jet through the die and may even be reflected back toward the inlet region. The occurrence of this type of reverse flow makes the possibility of entrapping air highly probable.

Comparisons between low and high Reynolds number cases have been used to demonstrate the importance of fluid inertia in a particularly graphic way.

An essential conclusion from this study is that the full Navier-Stokes equations should be used in computational models of mold-filling processes whenever the flow Reynolds number is of order 10 or greater.

References

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2. L.E. Bryant, Jr., "Portable Flash X Ray at the Los Alamos Scientific Laboratory," Los Alamos Scientific Laboratory report LASL-78-19 (May 1978).