Numerical Simulation of Foam Expansion in a Mold by Using a Finite Volume Method

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Introduction

Reaction injection molding (RIM) is a widely used process for producing various kinds of complex parts including automobiles, furniture, appliances, and housings. In RIM, products are made from two or more chemical components through mixing, chemical reaction, and molding [1]. Liquid reactants from two supply tanks flow at high pressure into a mix head, where they impinge at high velocity. After impingement mixing, the mixture flows out into the mold cavity and the polymerization is initiated. During the process, foaming can occur. Chemical and/or physical blowing agents are generally used in RIM for foaming. There are many advantages of foamed materials, including low cost, light weight, enhanced thermal and electrical insulation, and high impact strength.

Arai et al. [2] conducted experiments and pre-mixed foam reactants were poured into an L-shaped mold where the cavity was filled as the mixture was foamed and expanded. The distribution of the foam density was then evaluated in the solid part. In spite of some variations due to the amine catalyst used, the density varied from about 30 to 40 kg/m^3 depending on the location in the mold, while the density of the free-rising foam was about 22 kg/m^3. Their research showed that foam density is affected by the pressure of the foam fluid, although this is not the main factor that controls foam density.

Lefebvre and Keunings [3] simulated numerically the continuous flow of chemically reactive polymeric liquids in two-dimensional geometries using a finite element method. The gelling reaction which leads to the formation of polyurethane, and a blowing reaction from a chemical blowing agent, were taken into account. A spine method was used to treat the free surface, however, this method is not appropriate for filling molds of complex geometry. The density of the foam was a function only of temperature, which varied because the reactions are exothermic.

In this study, we propose a model and predict mold filling with a variable-density fluid that fills a mold by self-expansion. We deal with two-dimensional cases as a basic investigation. With the assumptions of ideal mixing and rapid bubble nucleation, the foam is modeled as a continuum with a time-dependent density that is reduced by bubble growth. The continuum is assumed to be a Newtonian fluid. Reaction and temperature variation are neglected.

For numerical calculations, we develop a pressure-based finite volume scheme for unstructured meshes [4] that includes the SIMPLE algorithm with treatment of the fluid compressibility. Cell-based, co-located storage is used for all physical variables. For treating the moving interface, an explicit high-resolution scheme that is similar to the CICSAM (compressive interface capturing scheme for arbitrary meshes) method [5, 6] is used.

Modeling

The governing equations for the foam fluid are

$$\nabla \cdot \mathbf{v} = -\frac{1}{\rho}\left[\frac{\partial \rho}{\partial t} + \mathbf{v}\cdot(\nabla \rho)\right], \tag{1}$$

$$\frac{\partial}{\partial t}(\rho\mathbf{v}) + \nabla\cdot(\rho\mathbf{v}\mathbf{v}) = -\nabla p + \mu\nabla^2\mathbf{v} + \frac{1}{3}\mu\nabla(\nabla\cdot\mathbf{v}) + \rho\mathbf{g}. \tag{2}$$

The third term on the right-hand side of Eq. (2) represents a viscous stress from density variation, and does not appear for the incompressible fluid.

To treat the empty domain which is actually filled with air, some additional assumptions are needed. The air is assumed to be an incompressible Newtonian fluid. Laminar flow is assumed. The density of air is about 1 kg/m^3 and its viscosity is about 10^{-5} Pa·s. If the air is replaced with a fictitious fluid whose viscosity is approximately 1 Pa·s, then transient, inertia, and gravity effects can be neglected in the fictitious fluid, but the solution in the foam fluid is essentially unchanged. Then the governing equations for the empty space are reduce to

$$(\nabla \cdot \mathbf{v}) = 0, \tag{3}$$

$$-\nabla p + \mu\nabla^2\mathbf{v} = 0. \tag{4}$$

Results and Discussion

As a test problem, foam flow in a rectangular slit was solved. This problem has an approximate analytic solution for the case of creeping flow. The length L of the slit used for numerical calculations is 1 m and the height $2H$ is 0.1 m. The mesh of this slit is unstructured and has 2,170 elements and 1,196 nodes. The slit is initially filled completely with expanding foam whose density decays exponentially with time. The right-hand side of the slit has a free surface boundary condition while the other sides are walls. In this case, the viscosity is 10,000 Pa·s, the initial density is 100 kg/m^3, and the rate of exponential decay (κ) is 1 s^{-1}. This makes the Reynolds number 2.5×10^{-5}, so inertia is negligible. We also neglect gravity. Figure 1 shows the pressure profiles of the analytical and numerical solutions for expanding foam. The analytical pressure solution is given as follows

$$p = -\frac{3\mu\kappa}{2H^2}(x^2 - L^2). \tag{5}$$

The maximum pressure of the analytical solution at $x = 0$ is 6.00×10^6 Pa, while the numerical solution gives $p = 5.90\times10^6$ Pa. The reason is that, near the left wall, the x-direction velocity is so small that it is not the dominant velocity component. Therefore, the assumptions that are used for deriving the analytical solution are invalid. The numerical velocities are in excellent agreement with the analytical solution except at $x < H$ and $x > L - H$, where the analytical solution is not accurate.

In order to verify the method of interface capturing and to compare the flow behavior of an expanding foam with that of a fluid with constant density, we obtained advancement of the moving flow front in a two-dimensional rectangular cavity. Figure 2 shows the profiles of the flow front at different times. The flow fronts for the expanding foam are slightly flatter than those of the Newtonian fluid, because the foam expands at every point, including the flow front tip. The expansion compels foam to flow away from the wall, altering the streamline and front shape, as shown in Fig. 3.

More differences in between the constant-density fluid and expanding foam are found in the traces of fluid particles. Figure 4 shows the traces of some particles in the fountain flow. The normalized length ξ is defined as x/l, where l is the average distance of flow front from $x = 0$. The normalized height η is also defined as y/H, where H is the half height of the cavity and $y = 0$ is the midplane. For the constant-density fluid, the average position l of the flow front increases linearly with time, because the inlet condition is a constant flow rate. In the internal flow region, where there is no effect of the fountain flow, the particles move forward parallel to the walls. But when the particles approach the flow front, they experience fountain flow. These particles go outside to the wall, and subsequently flow slowly. For the expanding foam, the average position l of the flow front increases exponentially with time by assuming exponential decay of the density. In the internal region, every particle moves toward the midplane of the cavity. At the same time, each particle moves toward the flow front and, if the flow continues for enough time, will catch up to the flow front. As the particle reaches the flow front, it experiences the fountain flow and moves out toward the wall, where the particles move more slowly in the x direction. Thus, every particle can experience the fountain flow many times, provided the cavity is long enough.

As a demonstration problem, filling of a mold with complex geometry by an expanding foam is simulated. A two-dimensional mold with an insert is selected. Foam is poured into the mold and expands to fill the mold. Figure 5 shows the fill time contours. Although there is no big difference between filling time contours of expanding foam and constant-density fluid, the traces of some fluid particles during the mold filling show different behaviors between the two cases as shown in Fig. 6.

References

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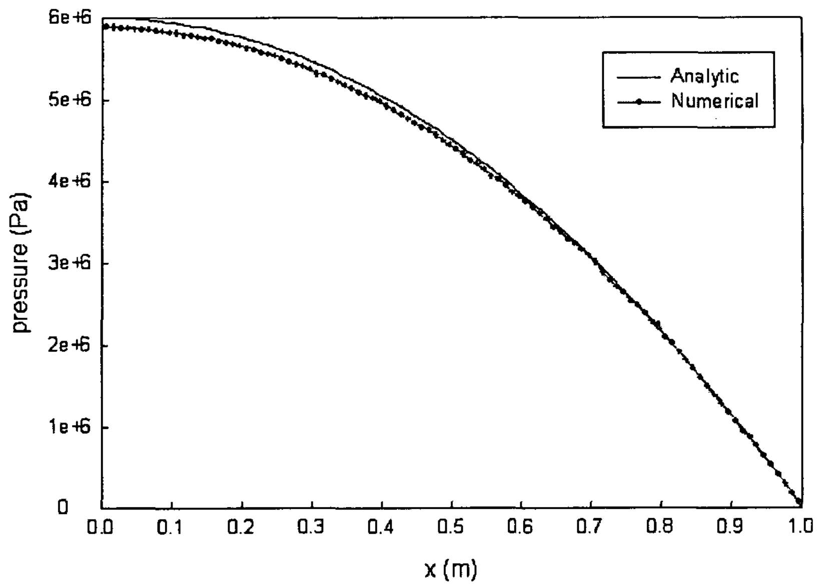


Fig. 1. Pressure profiles for expanding foam in the thin slit. $\mu = 10000$ Pa.s, $\rho_0 = 100$ kg/m^3, and $\kappa = 1$ s^{-1}.

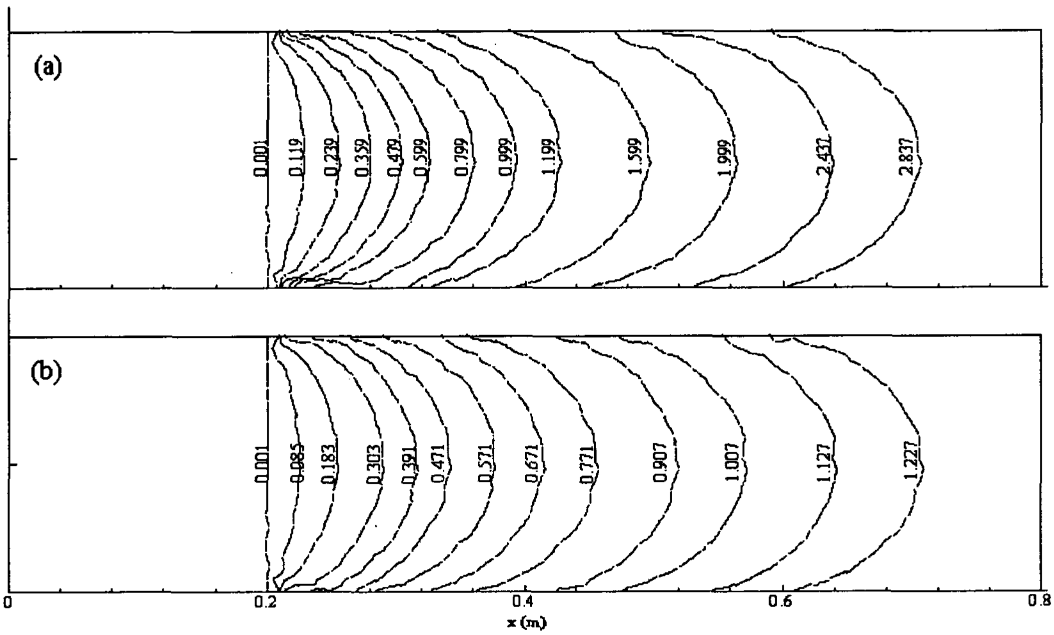


Fig. 2. Profiles of the flow front ($f = 0.5$) at different times (s) for (a) constant-density fluid and (b) expanding foam in fountain flow.

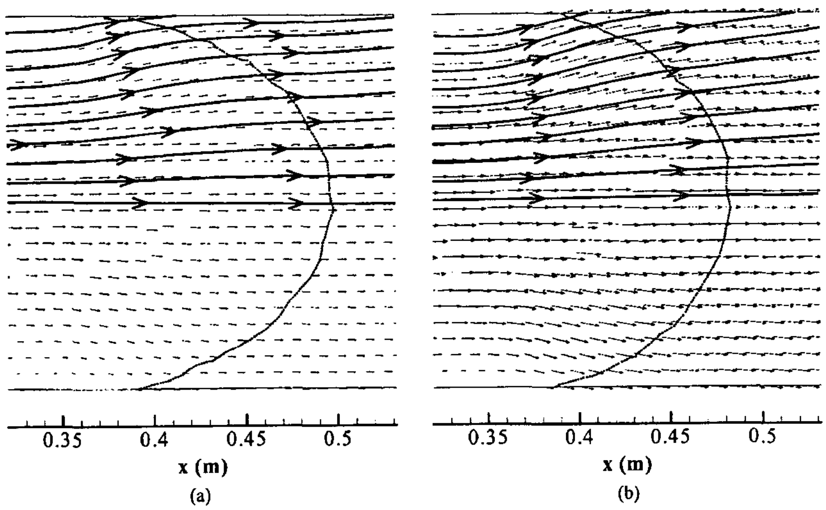


Fig. 3. Velocity vectors and streamlines in fountain flow for (a) constant-density fluid at $t = 1.60$ and (b) expanding foam at $t = 0.83$. Dotted line is the line where fractional volume $f = 0.5$.

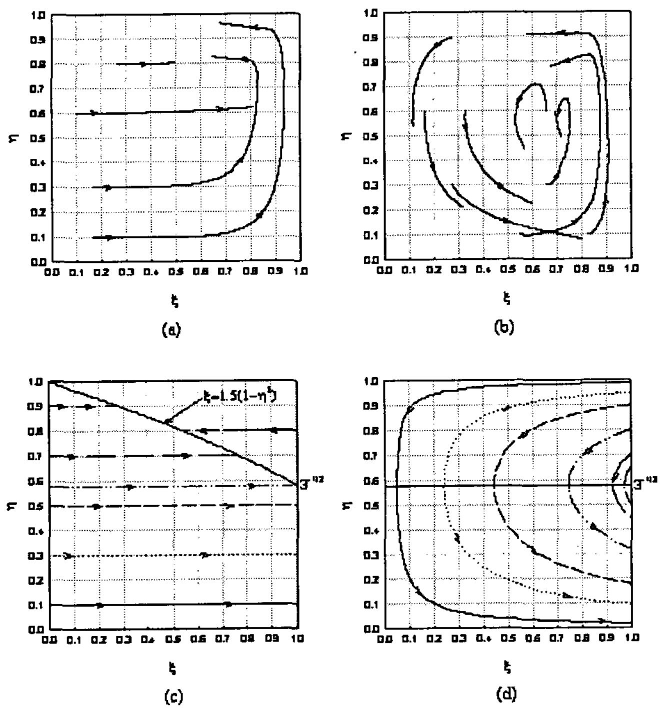
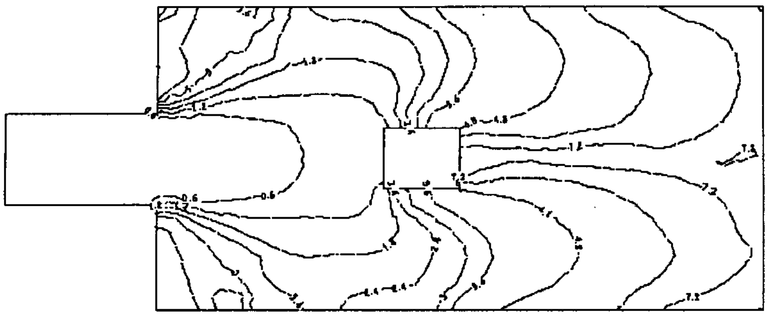
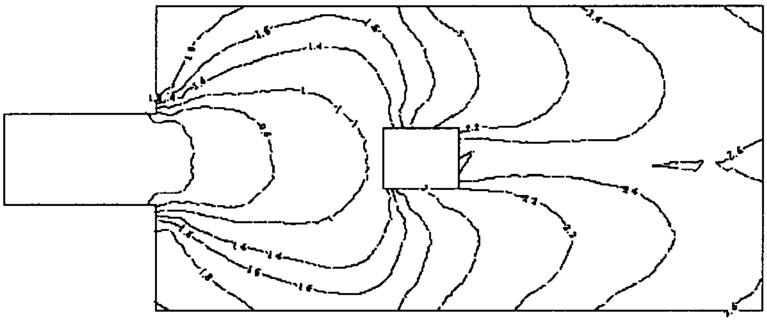


Fig. 4. Traces of some particles in the fountain flow. Note that $\xi = x/l$ and $\eta = y/H$.(a) Numerical results of constant-density fluid. (b) Numerical results of expanding foam. (c) Analytical results of constant-density fluid in the internal flow region. (d) Analytical results of expanding foam in the internal flow region.



(a)



(b)

Fig. 5. Fill time (s) contours of mold filling in (a) constant-density fluid and (b) expanding foam.

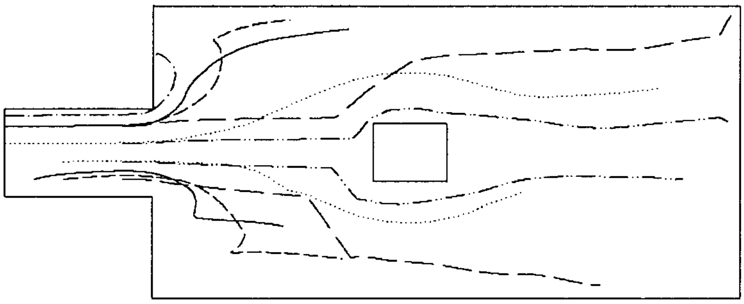


Fig. 6. Traces of some particles during the mold filling. The upper half of the mold is for the constant-density fluid and the lower half is for the expanding foam.