

CASTING PROCESSES WITH CHANGING GEOMETRY

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Introduction

In recent years casting modeling has become an accepted and even required part of the design process. Modern simulation tools are capable of modeling flow, thermal and structural aspects of the many casting processes. In these cases most of the modeling work involves fixed geometry of the mold. However, there are casting practices that involve moving parts directly in contact with liquid metal. For example, metal handling before and during pouring involves moving furnaces and ladles, in high pressure die casting a plunger propels metal into the die cavity, in centrifugal and tilt pour castings the molds move, and in squeeze casting pieces of the die move together to form the metal into a shape.

FLOW-3D[®]'s new model, called General Moving Object (GMO), provides a robust and accurate way to simulate three-dimensional motion of arbitrary shapes in a fixed computational grid. Multiple moving objects can exist in the same domain and each of them can have a different type of translational and rotational motion, either prescribed or dynamically coupled with metal flow [1]. This fixed-mesh GMO method has advantages over the moving and deforming mesh methods because of its efficiency and flexibility. The shape and the motion of each moving object are not restricted in their complexity.

The GMO model is based on the Fractional Area-Volume Obstacle Representation (FAVOR[™]) technique to describe the mold geometry in fixed rectangular meshes by means of area, A_f , and volume fractions, V_f [2]. In each computational cell, or control volume, V_f is defined as the ratio of the volume open to metal flow relative to the total cell volume, and A_f is defined as the ratio of the open area of the cell face relative to the total area of the face (see Fig. 1). At each point in time, A_f and V_f are updated in accordance with the object's motion to reflect its changing position.

Mathematical Model

General motion of a rigid body can be divided into translation and rotation around a reference point. For a six-DoF (Degrees-of-Freedom) motion, it is convenient to select the object mass center as the reference point. Equations governing the two kinds of motion for each moving object are [3]

$$\vec{F} = m \frac{d\vec{U}_G}{dt} \quad (1)$$

$$\vec{T}_G = [J] \cdot \frac{d\vec{\omega}}{dt} + \vec{\omega} \times ([J] \cdot \vec{\omega}), \quad (2)$$

where \vec{F} is the total force, m is the mass of the moving object, \vec{T}_G is the total torque about the mass center in a body-fixed reference system, \vec{U}_G is the mass center velocity, $\vec{\omega}$ is the angular velocity, and $[J]$ is the moment of inertia tensor about the mass center. Equation (1) is solved in an inertial reference system associated with the computational grid, while Eq. (2) is solved in a body-fixed system which has its origin at the mass center of the moving object. Each moving object has its own fixed coordinate system. For each moving object a coordinate transformation matrix between the inertial (*i.e.*, fixed with the computational grid) and the object's coordinate system is computed as a function of time to track the position and orientation of the object in the space system. The transformation matrix, together with the original definition of the moving object (*e.g.*, a CAD data file), is used to regenerate the moving object's representation in the computational grid at every time step during solution [4].

The continuity equation, with the area and volume fraction factors included, is

$$\frac{V_f}{\rho} \frac{\partial \rho}{\partial t} + \frac{1}{\rho} \nabla \cdot (\rho \vec{u} A_f) = - \frac{\partial V_f}{\partial t} \quad (3)$$

where ρ is the fluid density, and \vec{u} is the fluid velocity. The source term on the right-hand side of Eq. (3) represents the effect of the moving boundary (*e.g.*, the wall of the mold) on the flow. It can be expressed in terms of the velocity, \vec{U}_{obj} , and surface normal, \vec{n} , of that boundary and is

$$-\frac{\partial V_f}{\partial t} = (\vec{U}_{obj} \cdot \vec{n}) \cdot s_{obj} \quad (4)$$

where s_{obj} is the specific surface area (area per unit volume) of the moving object boundary in a control volume (see Fig. 1). The representation of the source term in the form of Eq. (4) is useful when tracking the moving boundary in a fixed computational grid.

No additional terms associated with the moving boundary exist in the momentum equations when they are written in the non-conservative form:

$$\frac{\partial \vec{u}}{\partial t} + \frac{1}{V_f} (\vec{u} A_f \cdot \nabla \vec{u}) = -\frac{1}{\rho} [\nabla p + \nabla \cdot (\tau A_f)] + \vec{G} \quad (5)$$

Here p is pressure, τ the viscous stress tensor and \vec{G} gravity. Of course, the tangential velocity of the moving object must be taken into account in the shear stress terms at wall boundaries.

The volume-of-fluid, VOF, method is used to track metal free surfaces [5]. The fluid fraction function, F , is defined as equal to 1.0 inside fluid, and to 0.0 otherwise. Averaged over a control volume containing free surface, the value of the fluid fraction falls into the range between 0.0 and 1.0, and, in general, will vary in time and space as the fluid moves through the computational domain. The kinematic transport equation for the VOF function is

$$\frac{\partial F}{\partial t} + \frac{1}{V_f} \nabla \cdot (F \vec{u} A_f) = -\frac{F}{V_f} \frac{\partial V_f}{\partial t} \quad (6)$$

Equation (6) is solved using a high-order interface tracking numerical scheme that employs geometric reconstruction of the interface to maintain accuracy during its advection [4].

For an object moving in a coupled fashion, its linear and angular velocities are obtained from the equations of motion, Eqs. (1) and (2). The effects of the hydraulic force (pressure and shear stress), gravitational force and control force on the object's motion are considered. Control forces are the extra forces and torques that can be applied to a moving object, for example, the engine thrust on a boat. For prescribed-motion objects, the time-dependent linear and angular velocities are provided as part of the input to the model.

The continuity and momentum equations, Eqs. (3)-(5), are solved in a coupled fashion to obtain the fluid flow solution in response to the motion of the walls of the domain. Locations and orientations of all moving objects are tracked, and area and volume fractions are updated accordingly. Heat transfer between metal and walls, both stationary and moving, can also be included. In this case, the thermal energy transport equation for the moving objects is solved with a second-order numerical scheme to maintain a good accuracy of the solution.

Figure 1 illustrates how the volume and area fraction coefficients are computed in a two-dimensional rectangular mesh, as well as the source term on the right-hand side of Eq. (4). Within a control volume the solid boundary is approximated as a planar interface allowing for a simple evaluation of the unit normal and surface area for each such surface element. The FAVORTM method provides the means to impose accurate boundary conditions for fluid flow and heat transfer. Because of its high-order representation of the geometry, the total surface area and volume of a solid object approach their exact values as the grid spacing is reduced.

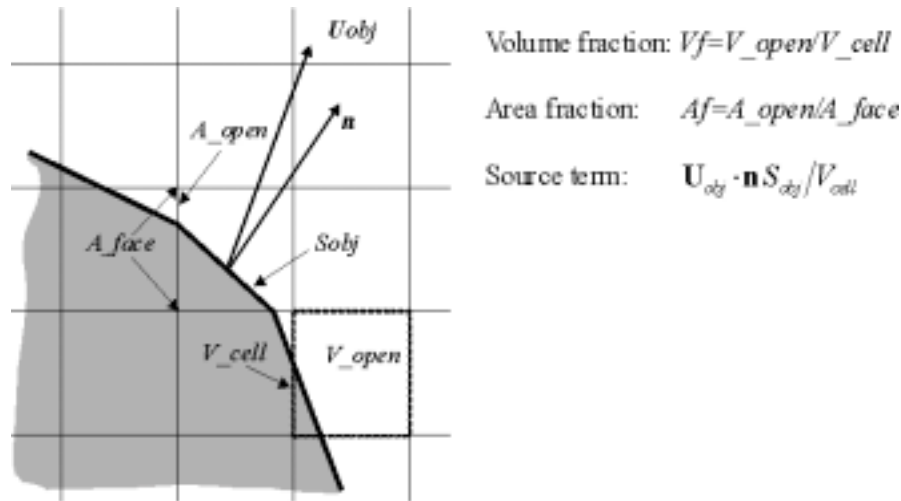


Figure 1. Schematic showing the calculation of the area and volume fraction coefficients, A_f and V_f , for a solid object (shaded area) imbedded in a rectangular grid. The calculation of the source term for the continuity equation is shown for the central control volume.

Examples

Potential applications of the GMO method exist not only in casting, but also in many other engineering problems, such as civil engineering and sea keeping. After a brief description, several examples of the application of the new model to the simulation casting processes are shown below. In each case the motion of the moving part of the geometry is prescribed as if controlled by a programmable machine.

Pouring out of a Ladle

This example employs both translational and rotational time-dependent prescribed motion to simulate the process of pouring liquid metal from a ladle into a sand mold. The ability to model the handling of metal before it gets into the mold is an important extension of the general filling simulation capability. Even though significant metal damage through oxidation and air entrainment can occur during this early stage of the casting process, it is usually left out of the conventional filling analysis, and replaced by a fixed flow rate at the top of the pouring basin. The new model allows engineers to investigate this highly transient and turbulent stage, and, combined with the heat transfer, air entrainment and defect tracking models, the quality of the filling process can be evaluated in more detail.

The metal is initially placed into a vertically oriented ladle, which then moves horizontally to a location above the pouring basin and stops. After stopping, the ladle tilts forward 60 degrees, then recovers and moves back to the initial position—all in the time span of 10 seconds. Selected frames from the simulation are shown in Fig. 2. The color represents the amount of entrained air in the metal, measured by the fraction of the air volume in the air/metal mixture. The entrainment of air is modeled in terms of a competition between turbulent, surface tension and gravity forces [7].

Most of the entrainment of air occurs in the sprue where the free falling liquid metal jet mixes with the metal already in the sprue. This is where the speed of the metal is the highest, and the level of turbulence is also the highest. In addition, the footprint of the jet moves in and around the top of the sprue, adding even more turbulence and variability to the flow in the basin and sprue. If one needs to minimize the metal damage at this point during filling, these aspects of the flow must be investigated closely.

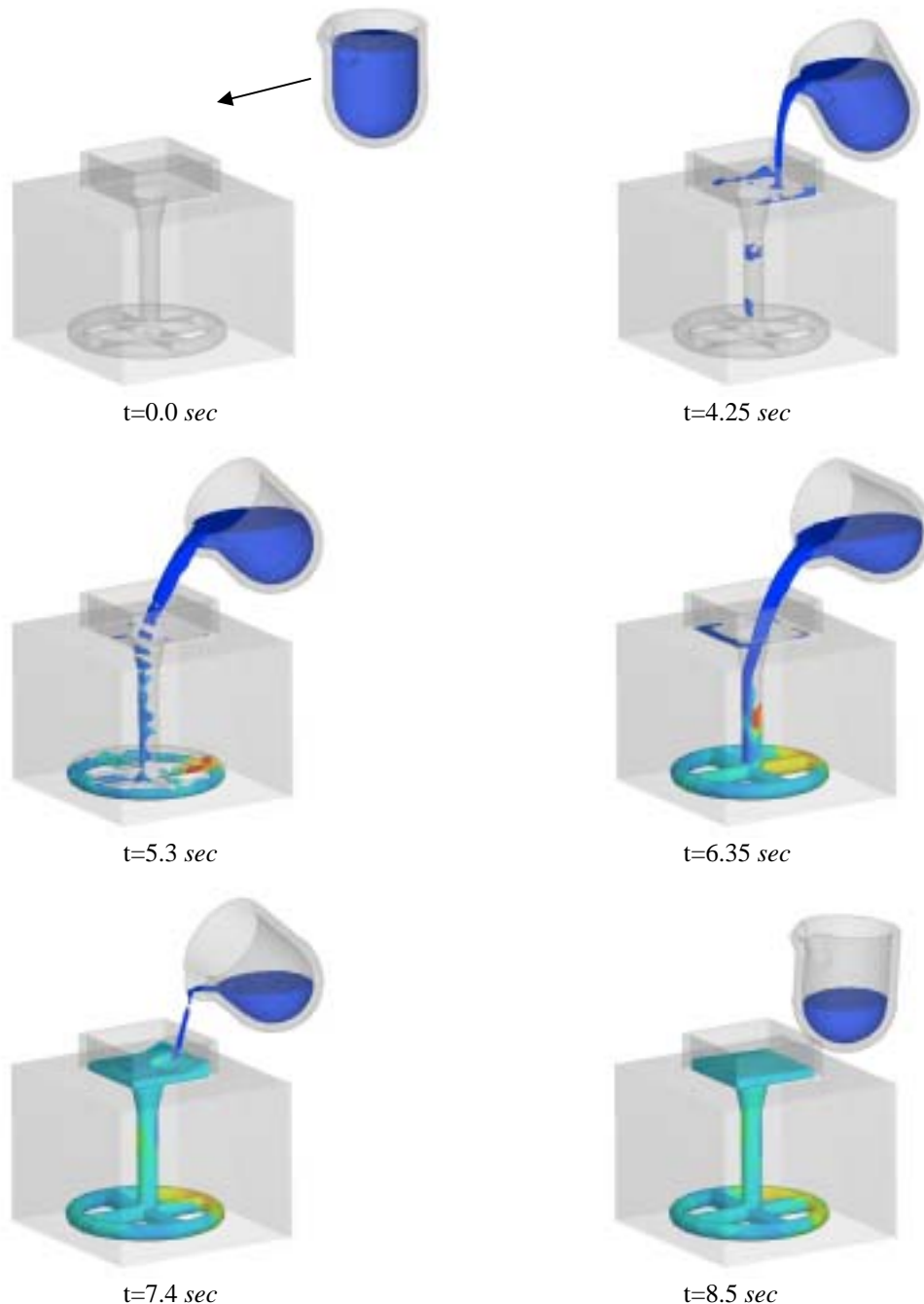


Figure 2. The simulated pouring sequence of a liquid aluminum alloy from a ladle into a sand mold using the prescribed-motion GMO model. Color represents volume fraction of the entrained air with the scale going from 0.0 (blue) to 8.0 % air by volume (red).

Shot Sleeve

In this example we use a linear, one-dimensional, time-dependent prescribed motion of a cylindrical plunger, 0.06 m in diameter, to simulate the process of pushing metal in the shot sleeve into a cavity during high pressure die casting. As with pouring from a ladle, proper handling of metal in the shot sleeve in the cold chamber process is critical to ensure a good quality casting. The speed of the plunger must be carefully programmed to avoid the entrainment of air by overturning surface waves. The speed of the plunger can be defined as an arbitrary function of time.

The shot sleeve is initially half filled by liquid metal. The motion of the plunger is divided into a slow stage, 0.6 second long, with a velocity of 0.2 m/s , and a fast stage, with the velocity of 2 m/s . The transition between the two stages is linear and occurs over a time interval of 0.05 second as shown in Fig. 3. The flow results are shown in Fig. 4, with metal colored by the velocity magnitude. A shallow wave is sent ahead of the plunger during the slow shot stage. Before the wave reaches the end of the sleeve, the plunger accelerates generating a much larger wave.

Pouring into a shot sleeve from a metal transfer cup could also be added to the shot sleeve model for a more detailed description of metal flow. The pouring process may result in a significant residual metal flow in the shot sleeve *before* the plunger starts moving.

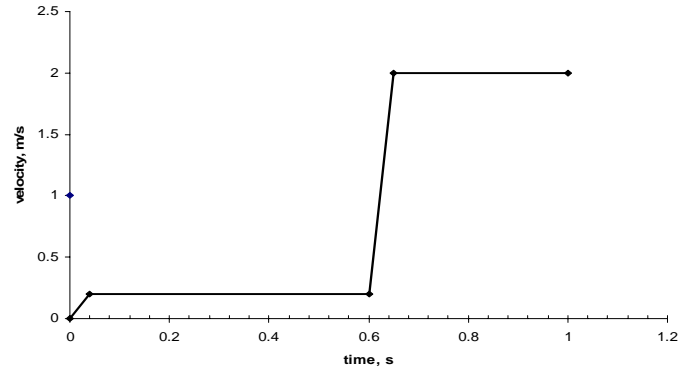


Figure 3. Plunger velocity profile with time for the cold chamber shot sleeve simulation.

Centrifugal Casting

Centrifugal casting process helps to achieve superior grain structure and minimize porosity compared to the conventional gravity casting. However, splashing and turbulence during the initial stages of filling can be excessive due to the high speed of the rotation of the mold. Careful design of the catching basin and the runners is important to minimize the damage to the metal due to oxidation and early solidification.

In this example the whole mold is rotating at a constant speed of 400 *rpm* around its vertical axis of symmetry. There are three identical spherical cavities spaced in the horizontal plane by 120 degrees from each other and connected to the catching basin by rectangular runners. Metal is poured from the top at a constant rate to achieve the filling time of 2.5 seconds.

The results are shown in Fig. 5. The frames are 0.5 second apart, which is equivalent to 3.33 revolutions of the mold. Note the initial splashing of the metal. The centrifugal force due to rotation pushes metal into the runners and mold cavities. A vertical vortex forms along the axis of rotation. In the actual process the rotation would continue until the metal is fully solidified, but is not considered here.

This simulation is the most challenging of the examples because the geometry and its motion are quite complex. The moving solid surfaces sweep the flow area many times during filling. Nevertheless, the overall volume error at the end of filling is less than 1.5% of the total poured volume.

Squeeze Casting

The final example is a squeeze casting, sometimes called liquid metal forming. It consists of two pieces of a die, one of which is moving. The bottom piece is stationary, while the top piece slides up and down to form a cavity in the gap between them. Initially the upper piece is elevated, with the cavity open. Liquid metal is placed in the open cavity of the preheated bottom piece and then the upper piece moves down, squeezing the metal into its final shape of a round, stepped plate with a uniform wall thickness of 5 *mm*. Castings made this way usually have excellent mechanical properties, which are just short of those for a forged casting, but with greater savings in the production costs.

The downward velocity of the upper piece starts with a constant speed of 1 *m/s*, then linearly decreases to zero at the end of the process. It is calculated to leave just the right gap between the two die pieces when the upper piece stops.

Figure 5 displays four frames showing the initial placement of the die pieces and metal, an intermediate stage and the final position of the pieces and the shape of the casting.

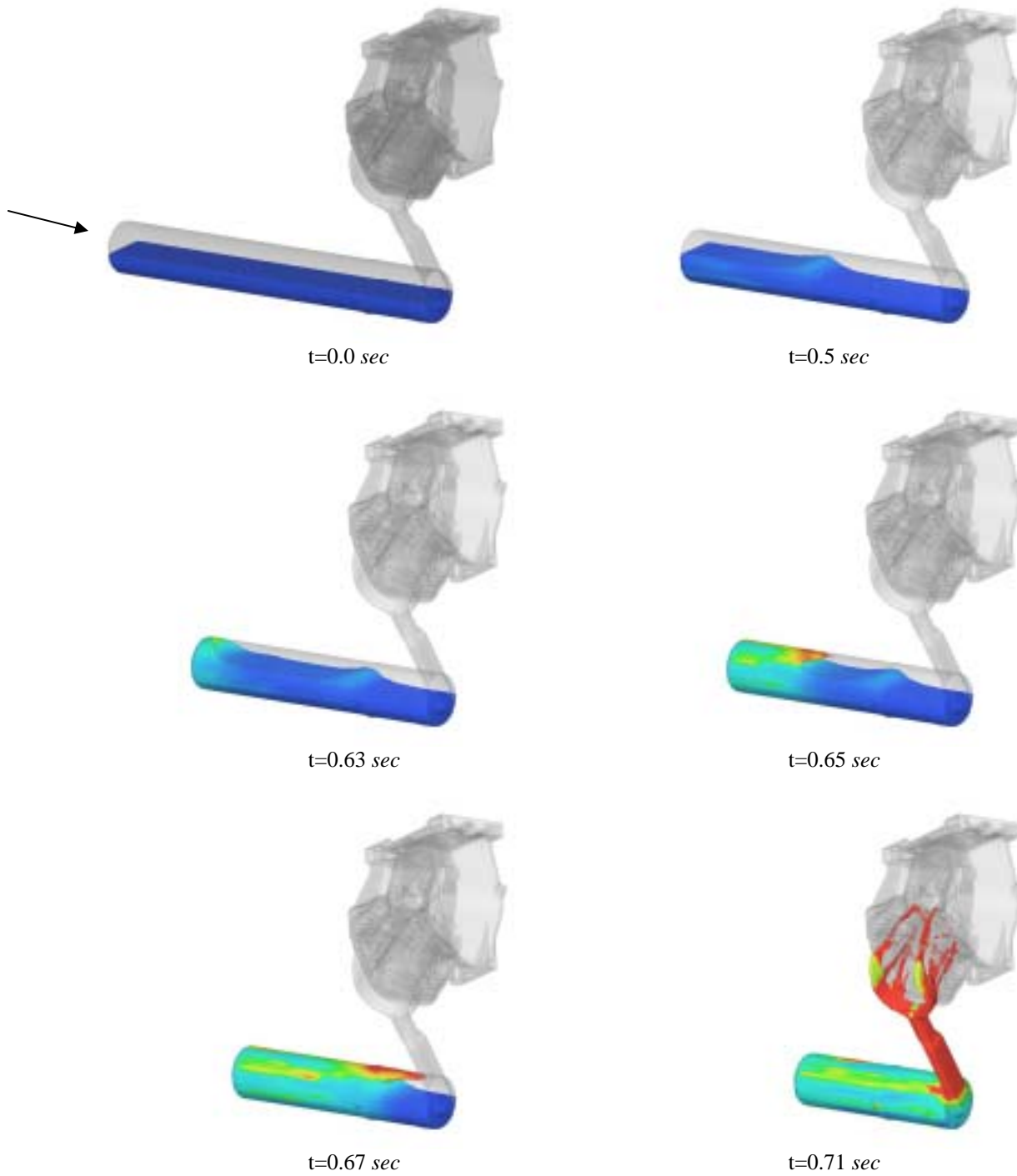


Figure 4. Flow in the shot sleeve during the slow shot and fast shot stages of the filling process. Color represents metal velocity with the scale going from 0.0 (blue) to 10 *m/sec* (red).

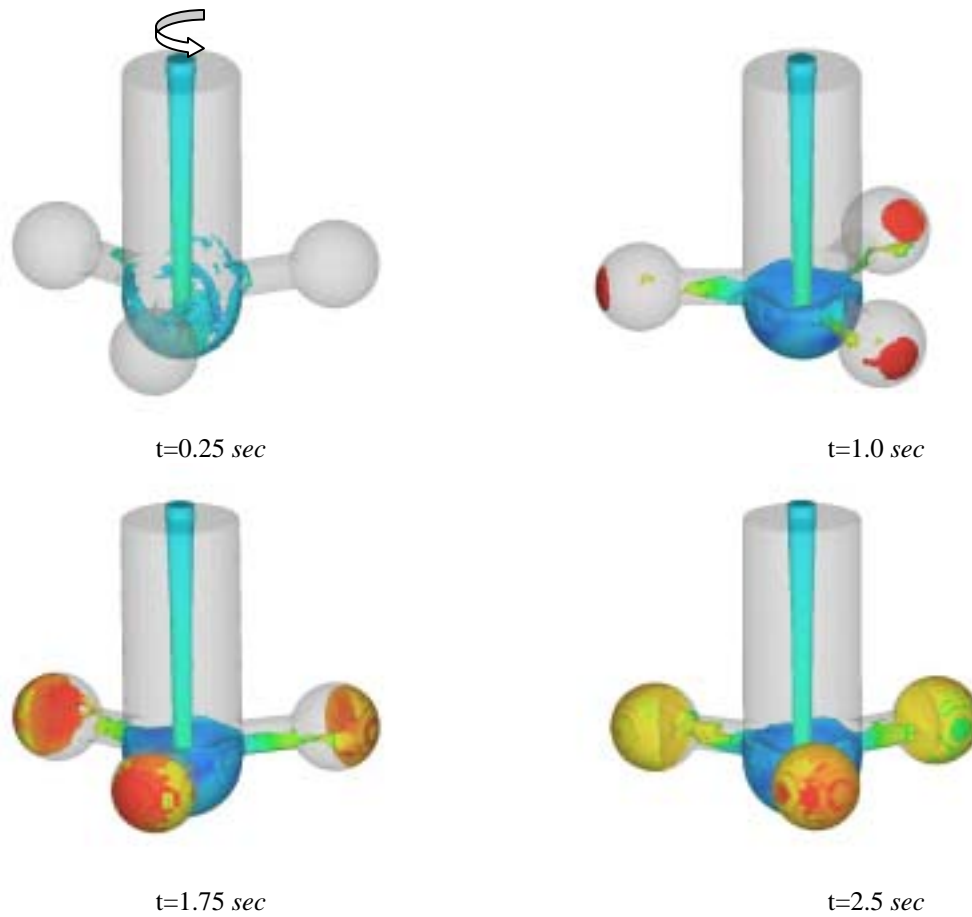


Figure 5. Filling sequence for the centrifugal. Color represents metal velocity with the scale going from 0.0 (blue) to 5.25 *m/sec* (red).

Conclusions

A fixed-mesh-based model for general moving objects (GMO) in fluid has been developed and implemented into the commercial CFD package *FLOW-3D*[®] [6]. It allows for moving solid objects with up to six degree-of-freedom motion fully coupled with fluid flow. The use of fractional area and volume fractions to represent solid geometry in rectangular grids provides an efficient and accurate way to model general motions of complex shapes.

At this time no quantitative experimental data are available for direct comparison with the computational results. In all cases the numerical solution is stable and well converged and looks reasonably accurate. In addition to predicting realistic flow patterns, metal volume is conserved to within less than 1.0% of the total metal volume.

All simulations were run on a dual-processor desktop Opteron[™] computer. CPU times for each case were within several hours.

The GMO model can be applied to simulate a wide range of casting processes that involve moving geometry such as pouring operations, shot sleeves, centrifugal and squeeze casting. Combined with the heat transfer and air and oxide film entrainment models, it can yield detailed insights into these processes and allows engineers to extend their knowledge and understanding of the complex interactions between various process parameters.

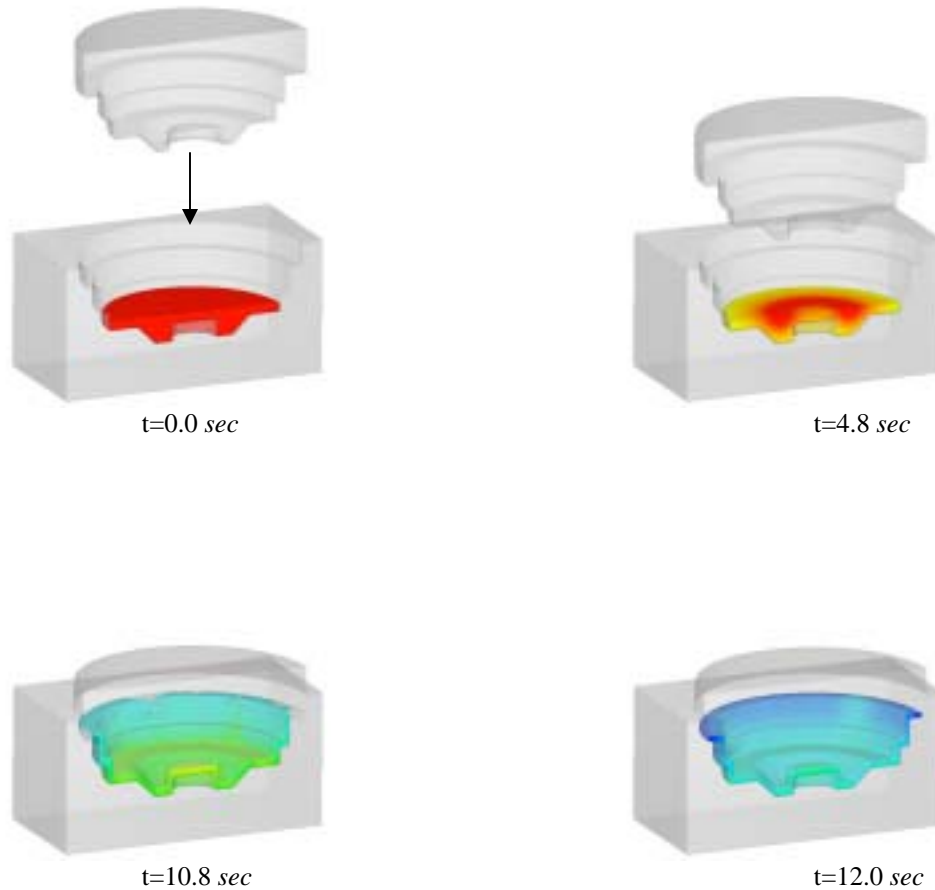


Figure 6. Squeeze casting forming sequence. Color represents metal temperature. A half of the complete geometry is shown for better clarity. Color represents metal temperature, with the scale going from 605 C (blue) to 645 C (red).

References

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