Effect of Feeder Design and Operation on Gob Shape

Matthew Hyre and A. Leven Harrison
Virginia Military Institute, Lexington, Virginia 24450 USA

Large deviations from the ideal gob shape and trajectory can have severe consequences on the penetration of the glass into the transfer equipment and molds. Additionally, asymmetric loading of the gob into the blank molds can cause uneven temperature and wear patterns on the mold interiors. In order to investigate how various feeder design and operating parameters affect gob shape and weight, a numerical study was performed. The numerical simulation modeled the formation of the gob at the feeder. In addition to 'mesh-to-mesh' interpolation, mesh superposition, and remeshing techniques were used to allow a continuation of the calculations in spite of very severe mesh deformations. Of particular interest in this study were the effects feeder plunger motion and shape on gob properties.

Introduction

Since the glass gob represents the transition point from a continuous melting process to the discrete glass forming operation, it is important to control various gob parameters such as weight, geometry, viscosity, temperature, and fall orientation. Traditionally, gob shape control has been conducted by trial and error based on past experience and operator knowledge. Feeder plunger shape, location, and stroke along with feeder orifice size and glass temperature are usually varied until the desired gob shape and weight have been achieved. Recent advances in numerical techniques and computer capabilities have made the numerical modeling of the gob forming processes feasible.

A numerical investigation has been carried out on the flow and thermal conditions of molten glass during its passage through a double gob feeder. Of particular interest were the impacts of plunger stroke profile and shape on gob formation. The models were developed utilizing FLUENT/UNS and POLYFLOW numerical codes.

Previous Work

While a significant amount of numerical work has been performed in the analysis of glass furnaces and forehearths, little has been targeted at the feeder. Most of the early feeder studies used physical modeling (dimensional analysis) to study the effects of geometry and tube height variations.[1,2,3] Attempts at numerical simulation were limited to extremely coarse meshes and subjected to unrealistic assumptions. Advective terms were often neglected in both the energy and momentum equations,[4] and in some cases, the velocity profile was assumed to follow that of tube rotation in an infinite fluid.[5] Only in the last few years have computers and computational techniques advanced to the point where such limitations can be removed.[6]

Governing Equations

Assuming glass is incompressible, the conservation of mass equation is:

$$\nabla \cdot \mathbf{v} = 0$$

v denotes the velocity vector. Conservation of linear momentum gives:

$$\nabla \cdot \boldsymbol{\sigma} + \rho \mathbf{f} = \rho \frac{D\mathbf{v}}{Dt}$$

The operator D/Dt is the material time derivative. Finally the energy equation for an incompressible fluid reads:

$$\rho \mathbf{C}(\mathrm{T})\frac{\mathbf{D}\mathrm{T}}{\mathbf{Dt}} = \mathbf{T} : \nabla\mathbf{v} + \mathbf{r} - \nabla \cdot \mathbf{q}$$

C is the heat capacity, **r** is the volumetric heat source, and **q** is the heat flux. Viscous heating can enter through the term $\mathbf{T} : \nabla\mathbf{v}$. The glass was modeled as a generalized Newtonian fluid. The extra-stress tensor is then:

$$\mathbf{T} = 2\eta(\dot{\gamma}, T)\mathbf{D}$$

D is the rate of deformation tensor and η is the shear viscosity which varies with temperature and shear rate, $\dot{\gamma}$. The Williams-Landel-Ferry (WLF) equation was used to describe the variation of viscosity with temperature.[7] The WLF model fit the experimental viscosity data better than an Arrhenius law for a wider range of temperatures.

Boundary Conditions and Material Properties

The boundary conditions for fluid dynamics on the flow domain were specified as either velocity components (along feeder/plunger walls) or surface traction components (glass surfaces/orifice exits). The position of moving boundaries is determined by solving a kinematic equation:

$$\mathbf{v} \cdot \mathbf{n} = \frac{\partial}{\partial \mathbf{t}} \chi(\mathbf{x}_0, \mathbf{t}) \cdot \mathbf{n}$$

n is the normal to the free surface described by $\chi(\mathbf{x}_0, t)$, and **v** is the velocity field evaluated at the free surface. For the gob surface, the dynamic condition requires that the normal force be prescribed as zero. Surface tension enters the system as a force which has the direction normal to the free surface:

$$\mathbf{f}_{st} = \frac{\gamma}{R}\mathbf{n}$$

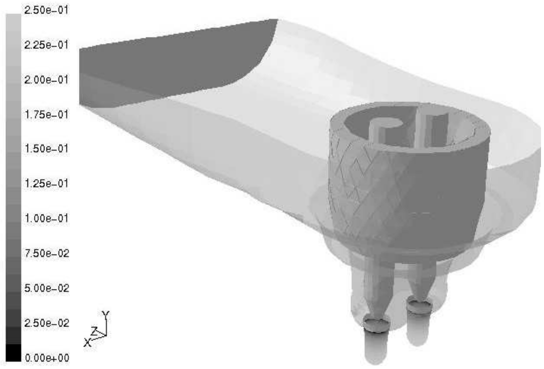
γ is the surface tension coefficient and R is the Gaussian curvature of the surface. This is used as a Neumann boundary condition in the momentum equation.

In addition to the viscosity of glass, the glass density, specific heat, and surface tension properties were specified. The glass density was assumed to be constant with a value of 2540 kg/m^3. The glass surface tension was determined through sessile drop testing. The expression of Sharp and Ginther was used for specific heat. [8] The internal radiation of the glass was approximated using an effective conductivity.

Numerical Solution

In order to determine the thermal condition of the gob as it enters the IS machine, numerical models of a standard double gob feeder were developed. The feeder orifice exits were modeled as free surfaces so that the shape, temperature, and velocity profiles of the gobs exiting the feeder could be ascertained. In order to shorten the computation time, the steady state result of the feeder, with the orifice exits modeled as outlets, was used as an initial condition for a transient simulation that included the actual formation of the gob.

Figure 1: Double Gob Feeder



Mesh Superposition

The effects of the reciprocating plungers in the feeder were taken into account utilizing a mesh superposition technique. The plunger geometries and meshes were created separately from the glass domain. The plunger meshes were then superposed onto the glass domain. This technique results in a much simpler methodology for mesh generation since no complex intermeshing region needs to be generated. Additionally, this method does not require remeshing algorithms within the spout bowl. In general, mesh superposition techniques do not resolve the velocity profile near the moving part very well. However, the velocity profile near the plungers was not of interest in this study.

When imposing the plunger mesh over the glass mesh, the Navier-Stokes equations, the mass conservation equation, and the energy equation must be modified. The modified Navier-Stokes equations are:[9]

$$\mathrm{H}(\mathbf{v}-\bar{\mathbf{v}})+(1-\mathrm{H})(-\nabla\mathbf{p}+\nabla\cdot\mathbf{T}+\rho\mathbf{g}-\rho\mathbf{a})=0$$

H is a step function and $\bar{\mathbf{v}}$ is the local velocity of the moving part. This equation is then discretized for each node of the velocity field. If node *i* (at location **x**) is outside the moving part, H is set equal to 0 and the usual Navier-Stokes equations are solved. Otherwise, H is set to 1 and the Navier-Stokes equations degenerate to $\mathbf{v}=\bar{\mathbf{v}}$.

To calculate a physically meaningful pressure in zones where geometrical penetration occurs, the mass conservation equation is modified to:

$$\nabla\cdot\mathbf{v}+\frac{\beta}{\eta}\Delta\mathrm{p}=0$$

β is a relative compression factor, and η is the local viscosity. To prevent pressure peaks in regions with large numbers of geometrical constraints, the mass conservation equation has been modified so that the fluid is slightly compressible. The loss or gain of fluid volume per unit time is linked to the Laplacian of the pressure through the relative compression factor.

The energy equation is modified in a manner similar to the Navier-Stokes equations:

$$(1-\mathrm{H})\left(\rho \mathbf{C}(\mathbf{T})\frac{\mathbf{DT}}{\mathbf{Dt}} - \mathbf{T} : \nabla \mathbf{v} - \mathbf{r} + \nabla \cdot \mathbf{q}\right)_{\text{fluid}} + \mathrm{H}\left(\rho \mathbf{C}(\mathbf{T})\frac{\mathbf{DT}}{\mathbf{Dt}} - \mathbf{r} + \nabla \cdot \mathbf{q}\right)_{\text{solid}} = 0$$

This equation is discretized for each node of the temperature field. If the node is outside the moving part, the step function H is equal to zero and the energy equation with the glass properties are used. Otherwise, H is equal to 1 and the energy equation with the plunger properties is used. The interpolants for the equations are: mini-elements for velocities, pressure is constant per element, and temperatures are linear.

Adaptive Remeshing

In order to keep good quality elements and avoid unacceptably skewed meshes due to the large deformations of the gob free surface, adaptive remeshing was used on the orifice domains. The newly incorporated automatic remeshing algorithms in POLYFLOW use a triangulation technique that generates a new mesh on the skin of the deformed mesh and propagates the mesh throughout the domain.[10] The entire feeder was not remeshed – only the volumes below the orifice pan were selected for automatic adaptive remeshing. The remeshing criteria were based on the curvature of the gob and the deformation tensor (elongation and distortion). At each step where remeshing was required, a new 4-node tetrahedral mesh was generated and the previous result fields were interpolated back onto the new grid. In this manner, the gob free surface and history dependent variables naturally convect with the glass.

Results

In general, the best gob shape is the shortest one that will load centrally and cleanly into the mold, without dragging on the sides of the mold or funnel. A gob unnecessarily long is likely to cause surface marks and load asymmetrically. A cylindrically shaped gob with hemispherical ends is usually recommended for the IS machine.

The following results give an example of how the model can be used to evaluate different feeder design and operation parameters. It is assumed that both the feeder temperature and speed remain constant. Obviously, hotter glass will increase both the weight and length of the gob. Conversely, colder glass decreases the length and weight. An increase in speed also decreases the length and the weight (the converse is also true).

Effect of Plunger Stroke

Figures 2 and 3 show the effect of a change in plunger stroke profile. Both Figures show the gob shape before the upward stroke of the plungers. Figure 1 represents a sinusoidal stroke over 1 second, while Figure 3 represents a constant plunger velocity in both directions. The sinusoidal profile resulted in a better shaped gob with a more uniform diameter. The constant velocity case resulted in a gob with a larger diameter near the top of the gob. This was due to the larger driving pressure and resultant flow rate near the end of the stroke when compared with the baseline case. The gob volume for the sinusoidal stroke was about 4 percent larger than the constant stroke gob volume. The deviation in left and right gob weights was 1 percent for the baseline case and 1.5 percent for the constant velocity case.

Figure 2: Baseline Model

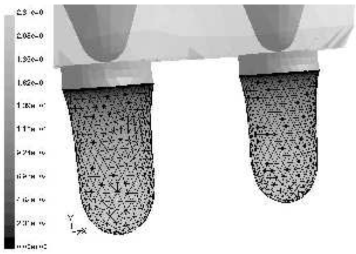


Figure 3: Constant Velocity

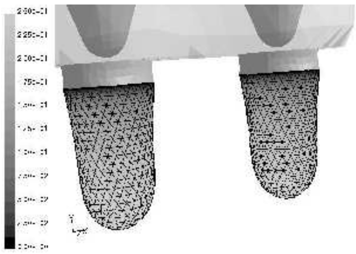
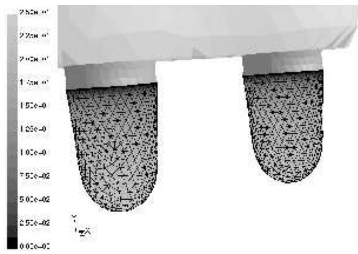


Figure 4: Raised Plunger



Effect of Plunger Position

Figures 2 and 4 show the effect of a change in initial plunger position on gob shape and weight. In Figure 4, the plungers have been raised by a distance of 2.54 cm. The change in gob weight is quite evident. Due to the smaller driving pressure of the raised plungers, the gobs are more than 15 percent lighter than the baseline case. The peak velocities at the gob tips are about 20 percent less than the baseline case. Clearly, the initial plunger positions are critical in determining final gob weight.

Conclusions

By evaluating the extent and manner to which feeder operation and plunger design affects gob shape and weight, a systematic methodology to control these parameters can be developed. Insights gained from the models can be used to develop new gob forming equipment which allows greater gob shape and weight control. Such a system would help eliminate container weight and thickness variations, along with defects created during the container forming process.

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