Dynamic Computational Modeling of the Glass Container Forming Process
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Abstract
Recent advances in numerical simulation capabilities have made the modeling of glass container forming processes feasible. In this study, all stages of the gob/container forming processes were modeled in order to predict final bottle thickness and residual stress distributions. In addition to thermo-mechanical coupling capabilities, ‘mesh-to-mesh’ interpolation, mesh superposition, and remeshing techniques were used to allow a continuation of the calculations despite very severe mesh deformations. By modeling the entire forming process, insight into the impacts of the different forming stages on final container quality can be gained for the first time. These insights are can be used to develop new equipment, and control algorithms for increased production and pack rates.

Keywords: Forming Modeling, Numerical Analysis, Process Modeling, Glass Forming

1. Introduction
Glass container producers face the challenge of producing lighter and stronger as a result of increased pressure from the plastics industry. Additionally, the requirements and tolerances on the quality of glass containers are becoming increasingly stringent. As the quality of glass containers is determined to a large extent by their forming processes, the design and optimization of molds and forming processes becomes more and more critical. Despite decades of use in the production of glass containers, the forming process on an industrial IS (individual section) machine is not well understood. Machine timings and mold designs are based on past experience and trial and error. Poor mold designs and forming processes can cause container defects and a loss in container production rates. Due to their high throughput, even small increases in IS machine downtimes or slight decreases in production can result in huge losses for glass manufacturers. Many glass companies have turned to modeling the forming process in order to gain knowledge of the key phenomena which affect container quality.

The forming of glass containers by the ‘press and blow’ process can be roughly divided into five main steps: gob formation at the feeder, transfer and loading of the gob into the blank mold, pressing of the parison, inversion of the parison into the blow mold, and the reheat and final blowing of the container (see Figure 1). After the glass gob is loaded into the blank mold, the plunger presses the gob to create the parison shape. At this point, the parison is upside down, and needs to be inverted before it is blown into its final shape. A swinging arm inverts the parison into the blow mold where the skin of the parison is allowed to reheat before being blown into the desired bottle shape. Once

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the container is blown and has cooled to the point where post-forming deformations will be small, the bottle is removed from the mold and swept onto a conveyor for inspection. The sensitivity of glass to the processing history is such that it is critical to ensure comprehensive modeling to yield accurate design information. In particular, it is important to take an integrated approach that includes the effects of upstream processing conditions in order to control the final thickness distribution in the bottle. To demonstrate how thermal problems in gob forming equipment can affect the consistency of final container quality, a numerical investigation was carried out on the flow and thermal conditions of molten glass during its passage through a container forming IS machine.

2. Description of Modeling

2.1 Governing Equations
For an incompressible fluid, the Cauchy stress tensor $\sigma$ is determined up to an arbitrary isotropic tensor (Crochet, 1982):

$$\sigma = -\rho I + T$$  \hspace{1cm} (1)

where $\rho$ is the pressure, $I$ is the unit tensor, and $T$ is the extra stress tensor. Conservation of mass for an incompressible fluid yields is used as a kinematic constraint imposed on the possible motions of the fluid. Conservation of linear momentum gives:

$$\nabla \cdot \sigma + \rho \mathbf{f} = \rho \frac{D\mathbf{v}}{Dt}$$  \hspace{1cm} (2)

where the operator $D/Dt$ is the material time derivative. Finally the energy equation for an incompressible fluid reads:
\[ \rho C(T) \frac{DT}{Dt} = T : \nabla v + r - \nabla \cdot q \]  

(3)

where \( C \) is the heat capacity, \( \rho \) is the volumetric heat source, and \( q \) is the heat flux. Viscous heating can enter through the term \( T : \nabla v \).

### 2.2 Modeling Glass Flow in the Body of the Container

For most regions of the glass forming domain, the glass was modeled as a generalized Newtonian fluid. In this case, the extra-stress tensor is:

\[ T = 2\eta(\dot{\gamma}, T)D \]  

(4)

where \( D \) is the rate of deformation and \( \eta \) is the shear viscosity which varies with temperature and shear rate, \( \dot{\gamma} \). The non-Newtonian behavior of glass due to shear thinning was characterized using the data of Simmons et al. (1989). The Williams-Landel-Ferry (Williams et al., 1955) equation was used to describe the variation of viscosity with temperature.

### 2.3 Modeling the Glass in the Neckring

The generalized Newtonian fluid model is unable to describe viscoelastic phenomena related to normal stresses and stress relaxation. These phenomena begin to become important as the glass cools near the mold temperatures. During the formation of the parison, viscoelastic effects (as well as shear thinning effects) become important as the glass fills the neckring. The extra-stress tensor was broken down into two components, the viscoelastic contribution, \( T_1 \), and a purely viscous contribution, \( T_2 \).

The viscous component of the extra-stress is given by:

\[ T_2 = 2\eta_2(\dot{\gamma}, T)D \]  

(5)

The viscoelastic component was developed from typical differential models used in numerical simulations:

\[ A(T_1, \lambda) \cdot T_1 + \lambda(\dot{\gamma}, T)D = 2\eta_1(\dot{\gamma}, T)D \]  

(6)

Here, \( \lambda \) is the relaxation time, \( \eta_1 \) is a viscosity coefficient; both are functions of shear rate and temperature. \( A \) denotes a model dependent tensor function. The tensor function used to characterize the viscoelastic stress was the White-Metzner model.

### 2.4 Boundary and Initial Conditions

The boundary conditions for fluid dynamics on the flow domain \( \partial \Omega \) were specified as either velocity components or surface traction components:

\[ v = \vec{v}(x,t) \quad \text{for} \quad x \in \partial \Omega_v \quad \text{and} \quad \sigma \cdot n = \vec{t}(x,t) \quad \text{for} \quad x \in \partial \Omega_t \]  

(7)
where \( n \) is the outward unit normal to the boundary, and \( \mathbf{v} \) and \( \mathbf{t} \) are specified functions. The conditions at the glass mold interface were described as Robin type boundary conditions, where frictional slip is allowed:

\[
(\sigma \cdot \mathbf{n})_t = a(\mathbf{v} - \mathbf{v}^w)^b
\]  

(8)

where the subscript refers to the component tangential to the boundary, \( \mathbf{v}^w \) is the boundary (or wall) velocity, and \( a, b \) are material constants describing the fluid-wall interactions. These constants were determined experimentally using an instrumented plunger that allowed for the determination of the frictional force during pressing. Thermally, a temperature or heat flux must be specified at the boundaries:

\[
T = \overline{T}(x, t) \quad \text{for} \quad x \in \partial \Omega_T \quad \text{and} \quad k(x) \frac{dT}{dn} = \overline{q}_s(x, t) + q_c + q_r \quad \text{for} \quad x \in \partial \Omega_q
\]  

(9)

where \( \frac{d}{dn} \) is the derivative normal to the boundary, \( \overline{q}_s \) and \( \overline{T} \) are given functions. The quantities \( q_c \) and \( q_r \) denote the convective and radiative components of the heat flux. During glass/mold contact the primary mode of heat transfer is contact conductance. In general, the convective heat transfer deviates from perfect contact due to a resistance between the glass and mold. This contact resistance is a thin gas layer consisting of air and combustion products of the lubricant. The gas gap is due to micrononuniformities of the mold surface, thermal contraction of parison, and changes in glass pressure due to pressing/blowing. Expressions for the latter two effects have been previously derived (Hyre, 2003). The gap thickness is determined at each step in the simulation from the local glass temperature distribution and pressure.

2.5 Free Surface

The position of moving boundaries is determined by solving a kinematic equation:

\[
\mathbf{v} \cdot \mathbf{n} = \frac{\partial}{\partial t} \chi(x_0, t) \cdot \mathbf{n}
\]

(10)

where \( n \) is the normal to the free surface described by \( \chi(x_0, t) \), and \( \mathbf{v} \) is the velocity field evaluated at the free surface. The dynamic condition requires that the normal force be prescribed as either zero or a known value (e.g. blowing).

2.6 Numerical Solution

The governing conservation and constitutive equations were solved along with the appropriate boundary conditions. All models are axisymmetric. To account for the movement of the free surfaces during forming, three remeshing techniques were required. The first was simple Lagrangian remeshing where the nodes followed the displacements of the material points. This method was used during gob transfer, parison invert and final blow. During gob formation, inverted reheat, reheat/stretch and parison pressing, the Thompson (1982) transformation remeshing technique was used.
This method is based on the resolution of a partial differential of the elliptic type, and remains robust for large mesh deformations. The final remeshing technique used involved the exporting of the geometry and remeshing the domain external to the numerical solver. This was required when the mesh became too distorted or the time steps became too small to continue.

3. Results

Figure 2 shows an example of the gob forming process. The models are able to accurately predict the glass free surface shape before it is sheared to form the discrete gob of glass that eventually becomes the glass container. This part of the modeling has been used successfully to develop gob forming algorithms to customize the shapes of gobs leaving the feeder (Hyre and Harrison, 2002).

The gobs were then allowed to fall through the gob interceptors, on to the scoops, troughs, deflectors, and into the blank (Figure 3). Heat transfer between the gobs and the transfer equipment was modeled using the contact conductance model described above. The temperature of the transfer equipment was measured experimentally.

The next step in the forming process is the pressing of the parison. Several ancillary models are associated with the pressing processes. Blank mold/neckring and plunger cooling models were developed to provide the appropriate boundary conditions.
An iterative process was used to determine the operating conditions of the mold and plunger. The heat flux computed from the glass to the mold and plunger were cyclically imposed on the mold and plunger models until an equilibrium condition was met. The forming simulation was then run again with the new mold and plunger temperature distributions. This process was continued until the operating temperatures of the mold and plunger did not change. Figures 4, 5, and 6 show typical blank, plunger and blow mold geometries which include axial cooling channels and the parison/bottle cavity.

After pressing (Figure 7) and a small amount of inverted reheat, the parison is inverted to the blow mold (Figure 6) for final blowing. The parison then stretches/reheats and is finally blown into its final shape (Figure 8). The reheat/final blow model is also an iterative, coupled simulation between the mold and glass.

The glass forming physics and ancillary equipment cooling in each of these processes are simulated with advanced numerical tools. A comprehensive approach was used to provide a complete picture of the formation of glass containers process. By modeling all forming processes, insight into the impacts of the various stages in the IS machine on final container quality can be gained. These insights can be used to develop new equipment, and control/cooling schemes for increased production and pack rates.

References