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Lagrangian finite element model for the 3D simulation of glass forming processes

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ABSTRACT

We propose here a numerical model for a three-dimensional simulation of glass forming processes. Using the basic philosophy of the Particle Finite Element method (PFEM), we introduce several new features adapting the strategy to suit the problem of interest. A modified fractional step method for the solution of the flow equations is applied. This approach, on the one hand, inherits the computational efficiency of the original fractional step approach, and on the other hand shows better mass conservation features. These features are particularly attractive taking into account the importance of the correct prediction of the glass product's wall thickness. A smart mesh update strategy and a simple mechanical contact scheme are introduced. In order to account for temperature-dependent viscosity, the heat equation is coupled to the mechanical model. Viscosity is obtained from the temperature field via an empirical law. The model is validated and an example modeling the processes in the final blow mold of the bottle manufacturing process is proposed.

1. Introduction

In spite of its very long history, bottle manufacturing remains a challenging process and requires further improvements. The continuously growing competition calls for the optimization of the existing processes, diminishing the risks of producing deficient bottles. Thus, such optimization must be based upon a detailed knowledge of the process variables (such as the final topology, wall thickness, stress and temperature distribution) and their dependence upon the input parameters (inlet pressure, cooling conditions, etc.). The typical questions that need to be answered are: How can the container weight be reduced without compromising on its strength? What are the optimal operation conditions (air pressure, mold temperature) and duration of the different forming stages? Up-to-date the answers to these and similar questions are predominantly based upon the experience and craftsmanship rather than scientific knowledge.

Numerical modeling and simulation can serve as an efficient tool for answering many questions arising when facing unexpected effects in the real products. Apart from being considerably cheaper than conducting expensive and time-consuming trial-and-error procedures common to factories, only numerical simulation can provide such (otherwise impossible or difficult to obtain) results as: stress distributions within the solidifying melt and temperature distribution.

Up-to-date, there exist several computational tools used by industries for bottle manufacturing simulation. Usually these software model the glass manufacturing process using axis-symmetric formulations. This approximation greatly reduces the associated computational costs. However, it over-simplifies the process: even though many bottle molds are purely axis-symmetric, nearly all containers produced do have non-symmetrical thickness distributions. Additionally, axisymmetric formulations cannot be applied to modeling bottles with non-circular cross-sections, such as e.g. fragrance containers. Thus, 3D simulations appear to be obligatory for obtaining reliable predictions. However, 3D simulations are typically characterized by excessive computational times.

Generally, two classes of methods can be applied to the problem at hand: the fixed mesh (Eulerian) and the mesh-moving (Lagrangian or Arbitrary Lagrangian Eulerian (ALE)) ones. Eulerian formulations require excessively fine meshes for the correct representation of the domain evolution and typically introduce errors in mass conservation (whenever the Level Set method is used for representing the glass-air interface evolution). On the other hand, Lagrangian approaches lead to strongly non-linear systems of equations and large mesh deformations. Thus, a robust and

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computationally efficient 3D model still presents a major challenge.

In the present work a 3D viscous incompressible fluid formulation using an updated Lagrangian framework is proposed, where the current configuration is the reference one. It adopts the basic features of the Particle Finite Element Method (PFEM) [1]. The key idea of the PFEM is that the variables of interest are stored at the nodes instead of the Gauss points. This results in a hybrid between a standard FE and a mesh-free method. A finite element mesh is created at every time step of the transient problem and the solution is then stored at the nodes. At every time step the governing equations are solved in the standard Finite Element (FE) fashion. The discrete operators are updated at every non-linear iteration step according to the newly obtained domain configuration, ensuring excellent convergence of the iterative procedure. The nodes obtain their new positions and the mesh is regenerated using an unconstrained Delaunay technique. The approach is adapted to the problem at hand introducing a simple but efficient contact algorithm, boundary tracking and a remeshing strategy. In terms of the method for solving the governing equations, we use a modified fractional step approach, combining the classical technique with a quasi-incompressible prediction [2,3]. The approach on the one hand allows for a highly computationally efficient solution and, on the other hand, leads to an accurate mass conservation, which is essential for the problems of interest.

The paper concludes with two numerical examples. The first one is used for the validation of the model. The second one shows the potential of the method. Moreover, it can be used as a reference for the comparison and validation of the future models for the bottle forming simulation. Even though several glass forming simulation results are published in literature [4–7], there exist no well-established benchmark up-to-date. The example we propose focuses on the modeling of the *final blow* stage of a glass manufacturing process. The material and geometrical data as well as all the boundary conditions necessary for reproducing the example are specified.

2. Glass forming

2.1. Industrial process

Prior to presenting the model for the glass (in particular, bottle) forming, let us review the industrial process and introduce the corresponding terminology. The standard bottle manufacturing process is sketched on Fig. 1.

Typically, high speed machines are fed a stream of molten glass[1] that is cut with a shearing blade into "gobs" of predetermined weight. These gobs fall into the first blank mold as shown in Fig. 1a, where the temperature drops to the so-called "working temperature range" (some 1150 °C for soda-lime glasses). At the base of the mold a cylindrical plunger for shaping the bottle neck is inserted. Air pressure or a plunger is applied in order to push the gob to the bottom of the mold (Fig. 1b). Afterwards, air compressed to ≈0,15 MPa is blown from the bottom of the mold forcing the gob to rise and take the shape of the mold (Fig. 1c). This stage is known as a *counter-blow* process, suggesting that the "blow" is performed against gravity. The intermediate product of the counter-blow is known as "parison".

Afterwards, the parison is removed from the first mold, turned upside down (Fig. 1d) and transferred into the second mold, where it is hung in order to stretch due to gravity (Fig. 1e), usually until the contact with the mold bottom is established. Finally, air pressure (slightly lower than the one used in the counter blow mold) is applied leading to the final shape of the bottle (Fig. 1f). This stage is known as *final blow* process. The bottle is then removed from the mold and is transferred to the annealing oven where it is reheated to remove the residual stresses produced during forming and finally it is cooled to the ambient temperature. The forming process, from the time when the gob is dropped into the first mold until the final product is removed from the second mold takes around 6 s.

[1] The most prevalent glass used for glass containers is soda-lime Na_2O—CaO—SiO_2 glass.

2.2. Material properties

Glass is a visco-elastic material. At low temperatures (roughly, below 400 °C) elastic effects dominate, while above 550 °C elastic effects are negligible. One can also consider the transition zone where both effects are important (see Fig. 2a). In the following we shall consider the temperature dependent properties of a typical soda-lime glass.

2.2.1. Mechanical properties: viscosity and density

The viscosity is the most important property in the glass forming process. For example, in a typical temperature range encountered in glass forming processes (between approximately 700 and 1200 °C) glass viscosity varies from $140 \cdot 10^6$ Pa s at 700 °C to some 400 Pa s. The dependence of glass viscosity upon temperature is typically given by Fulcher expression [8]:

$$log_{10}\mu = A + \frac{B}{T - T_0} \tag{1}$$

where T_0, A and B are constants from experiments. In the present work, the following parameter values are considered (except for example 1): $T_0 = 220$ °C, $B = 4700$, $A = -2.8$. The glass viscosity as a function of temperature is shown in a logarithmic scale on Fig. 2b. Due to very large variations of viscosity during the forming process it is mandatory to include thermo-mechanical coupling in the model in order to obtain realistic predictions.

The temperature distribution in the glass is non-uniform at any stage of the glass manufacturing process. Thus, the viscosity is also non-homogeneous both in space and time. In the context of numerical modeling, Lagrangian formulations are very advantageous when dealing with non-constant properties: the property (for example, viscosity) is automatically transported being "attached" to the moving nodes. In the Eulerian framework, the representation of each non-constant property evolution would require solving the corresponding transport equation.

Glass density does not undergo considerable changes (2438 kg/m^3 at 700 °C and 2367 kg/m^3 at 1100 °C), thus constant density is an acceptable approximation.

2.2.2. Thermal properties

Heat transfer in the glass is governed not exclusively by conduction, but also by the radiation, which may even be predominant. For strongly absorbing semi-transparent materials this radiation can be modeled as a diffusion process, thus an effective conductivity taking into account both processes is often defined [4]. Real radiation models are complex and computationally expensive. In the scope of this work they are not discussed.

Variation of the specific heat in the temperature range of interest is negligible (1400–1420 J/kg K between 700 and 1200 °C). The value of the diffusivity D changes from 0.0000015 m^2/s at 700 °C to 0.0000065 m^2/s at 1100 °C.