Finite Element Model of a complex Glass Forming Process as a Tool for Control Optimization

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Introduction

In a wide variety of industrial processes the underlying physical phenomena have to be regarded as spatial distributed and strongly nonlinear. Examples are rheological forming processes in industrial glass furnaces. For understanding, controlling and optimizing such industrial processes, numerical simulation models have become increasingly important over the last few decades. The realization of experiments is often expensive and complicated. Thus, these simulation models offer a promising alternative for the design of process control strategies and process optimization.

The industrial process that is considered in this paper is a complex rheological forming process producing thin-walled glass tubes from thick walled cylinders. The process setup is visualized in **Fig. 1**. The cylinder is fed with slow velocity v_f in an oven where it is heated up to its forming temperature. Below the oven the tube is pulled with a higher velocity v_s resulting in thin-walled glass tubes. In the cylinder the pressure p_s can be adjusted by the flow of a gas. The geometry of the resulting tubes strongly depend on the velocities v_f and v_s, the pressure p_s and the oven temperature T_{oven}. The main physical phenomena arise from radiation, heat conduction, and fluid dynamics. These processes are strongly nonlinear due to the impact of radiation and nonlinear material parameter laws. In addition, the forming process involves a wide temperature range and is characterized by large deformations.

There are several objectives of this paper. First, we present the extension and further development of our finite element model to be used for more realistic and complex process investigations. Second, several completely different stages of the glass forming process are investigated using numerical simulation and the results are compared with available measurements. In the future, the realistic simulation model will be used to compare different control strategies and process optimizations.

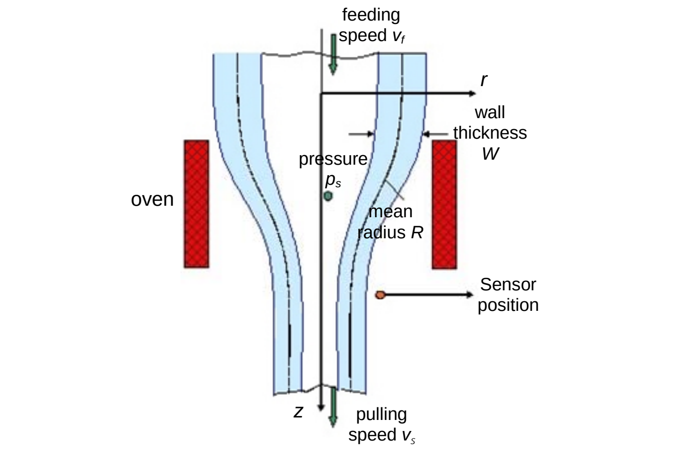

Fig. 1: Axisymmetric setup of the rheological forming process

Use of COMSOL Multiphysics

a.) Governing equations The state that uniquely describes the complex rheological forming process does not only depend on time but also on spatial coördinate $\underline{r}$. By assuming the process setup to be axisymmetric, the spatial coördinate $\underline{r} := [r, z]^T$ consists of the radius r and the height z. The main goal consists in the calculation of the velocity field $\underline{u}(\underline{r},t)$ of the fluid, the pressure $p(\underline{r},t)$ and the temperature distribution $T(\underline{r},t)$ inside the fluid. The corresponding equations are derived using a fluid dynamics approach, i.e., the forming is regarded as a Newtonian fluid with free surfaces. The mathematical model consists of two parts that describes **(a)** the actual glass motion and **(b)** the heat flow in the glass.

For the actual motion of the rheological material, the governing equations are the *incompressible Navier-Stokes and the continuity equation* as represented in the following

$$\rho \frac{\partial \underline{u}}{\partial t} = \nabla\left[-pI + \eta\left(\nabla \underline{u} + (\nabla \underline{u})^T\right)\right] - \rho(\underline{u} \cdot \nabla)\underline{u} + F$$

$$\nabla \underline{u} = 0$$

The fluid velocity field is represented by $\underline{u}(\cdot)$, the fluid pressure distribution is $p(\cdot)$, the fluid density and strongly temperature-dependent viscosity are respectively denoted as ρ and η. The first equation is the momentum balance; the second one is simply the equation of continuity for incompressible fluids. The boundary conditions are the velocities v_f and v_s respectively at the top and the bottom of the cylinder and the pressure inside the tube.

The heat flow in the glass can be described by the *convection-diffusion equation* for an incompressible fluid as follows

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) - \rho c_p \underline{u} \cdot \nabla T \quad .$$

Here c_p denotes the heat capacity at constant pressure, λ is the thermal conductivity of the working fluid, and T is the temperature. The conditions on the outer and inner boundary of the tube are respectively given by the heat transition by radiation and convection.

b.) Nonlinear Material Parameter Laws The material parameters characterizing the forming process vary strongly with the relevant temperature range from $20^\circ C$ up to more than $1800^\circ C$. Temperature variations within this range cause significant changes in the mechanical properties of the glass. Thus, tremendous nonlinearities are introduced into the system equations.

In general, the dynamic viscosity η represents the fluids resistance to the flow. In the case of glass, the viscosity strongly depends on the temperature and the range for varying temperature is relatively large. It increases rapidly as a glass melt is cooled, so that its shape will be retained after the forming process. Typically the temperature dependence for the viscosity of glass is given by the Vogel-Fulcher-Tammann (VFT) relation. However, in order to consider a wider temperature range, the following extended relation can be deduced

$$\log(\eta) = k_\eta^1 + k_\eta^2 \tanh\left(k_\eta^3 T + k_\eta^4\right) \ ,$$

where k_η^1, k_η^2, k_η^3, and k_η^4 denote model parameters to be identified. The temperature dependency of the heat conductivity and capacity respectively are given by a cubic and linear relation.

Literature

[1] Bernard, T.; Blanco, I. H.; Peters, M.: "Model Predictive Control of a complex rheological forming Process based on a Finite Element Model", FEMLAB Conference (2005)