Simulation of the glass flow in a mould-plunger system : a cooperation between N.V. Vereenigde Glasfabrieken and Eindhoven University of Technology : review of results of the period sept. 96 - sept. 97

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1 Introduction

The cooperation between the N.V. Vereenigde Glasfabrieken and the University of Technology Eindhoven (TUE), department of Mathematics and Computing Science, started in the course of 1995. Since september 1996 a ph.d. position is financed by the Glasfabrieken. The deliverables of this 4-year project are:

- understanding of the dynamics of the glass flow during the forming of a 'parison' and its coupling with heat transport via convection, diffusion and radiation.
- a software package to simulate the forming of a parison numerically, so that the influence of parameters, such as geometry, glass temperature, cooling strategy etc, can be studied.

The tools to be delivered will be indispensable in optimizing the process conditions, especially in view of the requirement of reduction of the amount of glass used per jar.
During the project not only the ph.d. student is involved in the project, but rather a team of staff members. Their names are listed in Appendix 1.

2 Initial situation

In september 1996 initial calculations had been finished and some software to simulate the glass flow was available. This software, under the working name "PARFLOW" had the following shortcomings:

- The time integration method was simple and probably not accurate enough to get the highly reliable results the project aims at.
- The variability of the viscosity of the glass was not taken into account.
- As for the boundary conditions only no-slip conditions had been implemented.
- The energy household of the system (heat transport via convection, diffusion and radiation) was not yet included.
- The movement of the plunger was not yet included. In stead of that the glass was set into motion by an artificially introduced pressure at the bottom of the mould.

3 Results

The first year (september 1996 - september 1997) has yielded a significant number of results in various directions.

3.1 Extension of the software

The numerical problems with the time integration and the calculation of the glass front, which forms a "free boundary", have largely been solved. The software has been extended at several points:

1. Thanks to the integration of the design software package PARVORM, which has been developed earlier, with PARFLOW, the geometry of plunger and mould can be easily adjusted.
2. The movement of the plunger has been built in. This movement is the actual cause of the glass flow between plunger and mould.
3. The boundary condition at the wall of both plunger and mould can be varied. Both no-slip (total velocity at the wall is vanishing) and slip (the normal component of the velocity at the wall is vanishing) conditions have been implemented, and even intermediate conditions can be used.
4. The position and form of the initial glass blob can be chosen freely.
5. The glass flow during pressing can be visualized by computer animation. Several examples have been made available to the N.V. Vereenigde Glasfabrieken.

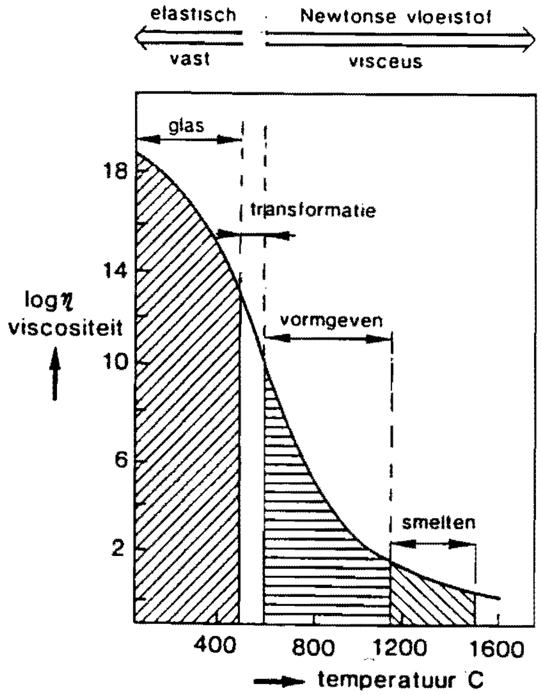
3.2 Modelling of the pressing process

Parallel to the software activities the modelling of the pressing process has been investigated. Attention has been paid to the following aspects:

a) Derivations of analytical solutions of the governing differential equations. In this approach use is made of asymptotic approximations based on the fact that the region of flow is quite long and relatively very thin. The outcome of this analysis has been compared to the results from numerical simulations with PARFLOW and the agreement is striking. This work has been reported in *[Chandra and Rienstra, 1997]*.

b) Analytical expressions have been derived for the force exerted on the plunger by the glass. This force can thus be calculated without numerical flow simulations. Because of this the calculation of the force could be appropriately integrated with the design software PARVORM. The calculation of this force provides information about the dynamical properties of a mould design: if the force is too high, the design has to be adjusted to make production possible.

c) The energy flows during pressing have been studied in order to estimate the influence of temperature variations on the process. Because the glass viscosity is highly temperature dependent (see Fig. 1), it is crucial to know the temperature variations.



Viscositeitsverloop van een glas

The details of the analysis are given in *[Chandra and Rienstra, 1997]*. They applied the method of 'dimensional analysis' to obtain estimates of the relative importance of heat diffusion, heat convection, heat production by friction, and heat exchange with the wall. Important insights gained from their analysis are:

i) As long as the glass moves heat transport is dominated by convection; heat diffusion and heat exchange with the wall are negligible. Since the initial glass blob is at uniform temperature, this observation implies that the glass will remain at uniform temperature, except for a thin boundary layer along the walls if the no-slip conditions are applied. So, the viscosity of the glass may be taken constant in the flow.

ii) The cooling of the glass starts if the glass flow has come to rest. Then the glass will cool down via heat exchange with the wall and via radiation.

iii) The heat conductivity of the metal parts of plunger and mould is a factor of 300 bigger than that of glass. This implies that the heat transport in these metal parts is very fast compared with the velocity of heat diffusion in the glass. So we may conclude that the metal parts are locally at a uniform temperature. Since the intensity of the cooling in the upper parts of the mould is different from that in the lower parts, the mould temperature may vary along the mould. However, geometrical details of the mould and its cooling device are completely negligible.

4 Summary of results

Numerical results
The package PARFLOW can now be used to simulate the physical situation during the pressing phase. With this package the influence of the choice of boundary conditions (slip, no-slip), the geometry of plunger and mould, the temperature of glass, and the position of the initial glass blob can be studied in order to optimize the process. Some examples of such simulations in the form of computer animations are already available.

Analytical results
The force exerted on the plunger by the glass during pressing can be analytically calculated. Further, it has been found that the glass remains at its initial temperature as long as it flows. The details of plunger and mould geometry are not relevant for the calculation of the heat/exchange with the walls.

5 Further research

The following activities have been planned within the project.

- Application of PARFLOW to a great variety of pressing situations.
- Comparison of results of PARFLOW about the flow with experimental data obtained by the N.V. Vereenigde Glasfabrieken.
- Inclusion of the cooling phase into PARFLOW. In this cooling phase the glass is at rest. The mould and the plunger are withdrawn from the parison after some time. The contribution of radiation to the cooling will also be included, though in an approximating fashion, because inclusion of an exact radiation model is both unnecessary and impossible.
- The analytical approach will be continued and its results compared to those of PARFLOW (actually this is done in parallel by TUE as a bonus).
- PARFLOW will be made user-friendly.

Reference

Chandra, T.D. and Rienstra, S.W., *Analytical approximations to the viscous glass flow problem in the mould-plunger pressing process*, Report RANA 97-08, Eindhoven University of Technology, August 1997.

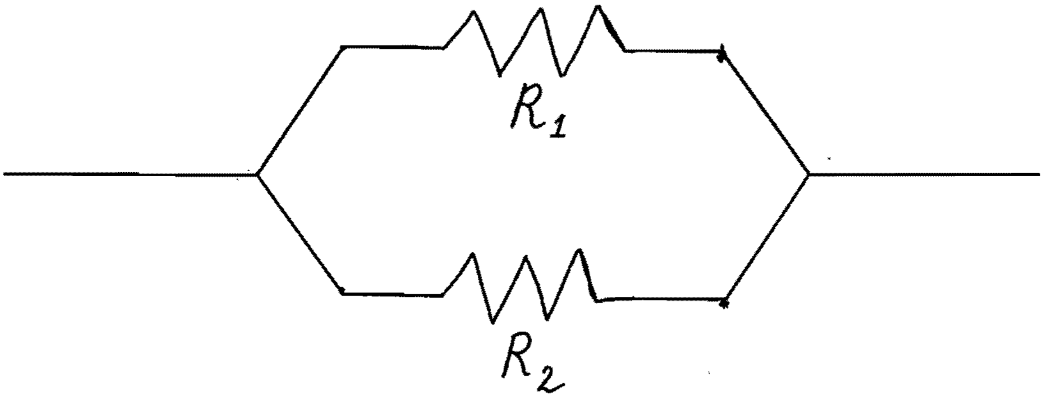
Appendix 1

The team involved in the present project consists of the following staff members:

- Prof.dr. R.M.M. Mattheij (head of the project team)
- Dr.ir. J.K.M. Jansen (daily supervisor)
- K. Laevsky, m.sc. (ph.d. position)
- Dr. J. Molenaar (modeling)
- Dr. S.W. Rienstra (modeling)
- L.G.F.C. van Bree (programmer)
- Ir. A.C. Telea (visualization)

Appendix 2

Dimensional analysis is a powerful method to estimate the relative importance of various effects in a system. In this approach the modeling equations are put into dimensionless form by scaling all variables with characteristic values. This usually leads to some dimensionless numbers. The magnitudes of the numbers allow to draw conclusions about the behaviour of the system before any numerical calculation is performed.
E.g., consider a system consisting of two parallel resistances R_1 and R_2. See the Figure:



The dimensionless number of this simple network is the quotient R_1/R_2, Now we meet with 3 cases:

- $R_1/R_2 \gg 1$: R_2 is relatively most important, R_1 could be ignored.
- $R_1/R_2 \ll 1$: R_1 is relatively most important, R_2 could be ignored.
- $R_1/R_2 \approx 1$: R_1 and R_2 are equally important.

The dynamics and energy balances of the glass flow during pressing are described by the (incompressible) Navier-Stokes equations. The dimensional analysis of these equations is given in *Chandra and Rienstra, 1997.* It has been shown in this report that 3 dimensionless numbers play a role:

- Reynolds number $Re = \dfrac{VL\rho}{\eta}$
- Prandtl number $Pr = \dfrac{\eta c_p}{k}$
- Eckert number $Ec = \dfrac{V^2}{c_p \Delta T}$

The meaning and characteristic values of the quantities at the right hand sides are:

- Plunger velocity $V \sim 10^{-1}\ m/s$
- Length scale parison $L \sim 10^{-2}\ m$

- Glass density $\rho \sim 2500\ kg/m^3$
- Dynamic glass viscosity at $800°C$ $\eta \sim 10^4\ kg\ s/m$
- Thermal conductivity of glass $k \sim 1.7\ J/m\ s\ °C$
- Heat capacity of glass $c_p \sim 1100\ J/kg\ °C$
- Temperature variation $\Delta T \sim\ 300\ °C$.

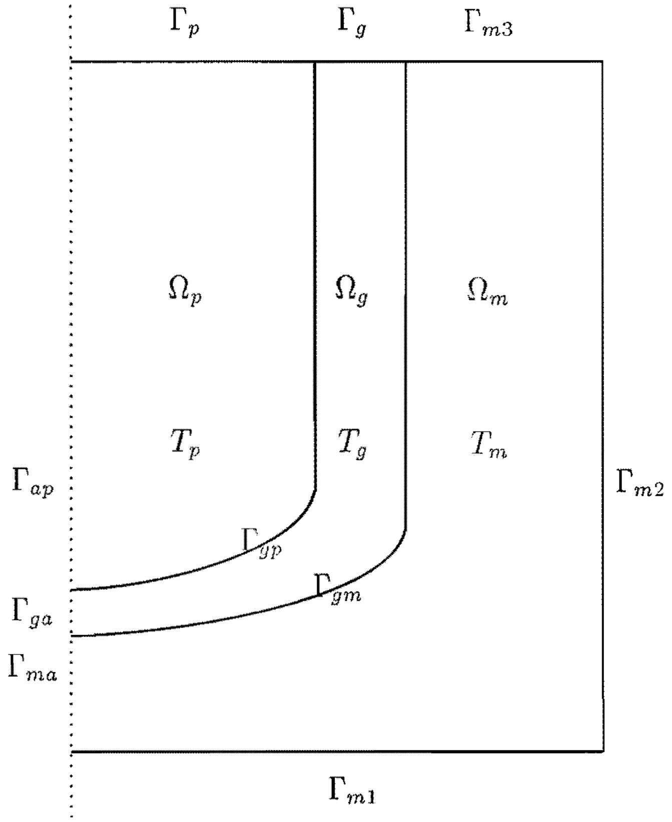
Using these values we find

$$Re \sim 2.5\ 10^{-4},\ Pr^{-1} \sim 1.5\ 10^{-7},\ Ec \sim 3\ 10^{-8}$$

Since $Pr^{-1} \ll Re$ we may conclude that heat transport via *diffusion* is negligible compared to heat transport via *convection*. Since $Ec \ll Re$ we conclude that the heat generation by internal friction may be ignored. The general conclusion is that, during the pressing phase, heat transport is dominated by convection. So, if the initial blob of glass is at uniform temperature this will hold as long as the glass flows.

Appendix 3

The cooling of molten glass in a mould



Ω_p: plunger

Ω_g: glass

Ω_m: mould

T_p: temperature in the plunger

T_g: temperature in the glass

T_m: temperature in the mould

T_{0p}: steady state temperature of the plunger

T_{0m}: steady state temperature of the mould

Heat equations in Ω_p:

$$\frac{1}{\alpha_p}\frac{\partial T_p}{\partial t} = \Delta T_p, \text{ in } \Omega_p; \ \alpha_p \text{ is the thermal diffusivity.}$$

$$\frac{\partial T_p}{\partial n} = 0 \text{ on } \Gamma_{ap}, \ T_p = T_{0p} \text{ on } \Gamma_p$$

$$k_p \frac{\partial T_p}{\partial n} = h_{gp}\left(T_p - T_g\right) \text{ on } \Gamma_{gp}; \ k_p \text{ is the thermal conductivity.}$$

Heat equations in Ω_g:

$$\frac{1}{\alpha_g}\frac{\partial T_g}{\partial t} = \Delta T_g, \text{ in } \Omega_g; \ \frac{\partial T_g}{\partial n} = 0 \text{ on } \Gamma_g \cup \Gamma_{ga}$$

$$k_g \frac{\partial T_g}{\partial n} = h_{gp}\left(T_g - T_p\right) \text{ on } \Gamma_{gp}; \ \alpha_g \text{ is the thermal diffusivity.}$$

$$k_g \frac{\partial T_g}{\partial n} = h_{gm}\left(T_g - T_m\right) \text{ on } \Gamma_{gm}; \; k_g \text{ is the thermal conductivity.}$$

Heat equations in Ω_m:

$$\frac{1}{\alpha_m}\frac{\partial T_m}{\partial t} = \Delta T_m \text{ in } \Omega_m; \; T_m = T_{0m} \text{ on } \Gamma_{m1} \cup \Gamma_{m2} \cup \Gamma_{m3}.$$

$$k_m \frac{\partial T_m}{\partial t} = h_{gm}\left(T_m - T_g\right) \text{ on } \Gamma_{gm}; \; \frac{\partial T_m}{\partial n} = 0 \text{ on } \Gamma_{ma}.$$

α_m is the thermal diffusivity; k_m is the thermal conductivity.

Thermal constants:

$\alpha_g = 6.2_{10}{}^{-7}$ [m^2/s], thermal diffusivity.

$\alpha_p = \alpha_m = 1.7_{10}{}^{-5}$ [m^2/s], thermal diffusivity.

$h_{gp} = h_{gm} = 2_{10}{}^{3}$ [W/m^2/.c], contact conductancy.

We observe that $\alpha_p = \alpha_m >> \alpha_g$, and this implies that when the heat process of the glass starts, the heat processes of the plunger and the mould are already in the steady state. This means that the temperature $T_p = T_{0p}$ and $T_m = T_{0m}$, respectively.
Consequently, the three heat processes are not coupled.
Now we have for the glass process the following boundary value problem

$$\frac{1}{\alpha_g}\frac{\partial T_g}{\partial t} = \Delta T_g \text{ in } \Omega_g$$

$$\frac{\partial T_g}{\partial n} = 0 \text{ on } \Gamma_g \cup \Gamma_{ga}$$

$$k_g \frac{\partial T_g}{\partial n} = h_{gp}\left(T_g - T_{0p}\right) \text{ on } \Gamma_{gp}$$

$$k_g \frac{\partial T_g}{\partial n} = h_{gm}\left(T_g - T_{0m}\right) \text{ on } \Gamma_{gm}$$

h_{gp} is the contact conductance between the glass and the plunger.
h_{gm} is the contact conductance between the glass and the mould.
The contact conductance depends on the surface roughness, the interface pressure and temperature, the termal conductivities of the contacting materials and the type of fluids or gas in the gap.
On the two boundaries Ω_{gp} and Ω_{gm} we have a temperature drop, depending on the contact conductances, and a boundary layer, depending on the thermal diffusivity of the glass. We can prove that the asymptotic behaviour of the boundary layer is the errorfunction $\text{erfc}(r/\sqrt{4\alpha_g t})$.

References

Özişik, M.N., *Heat Conduction*, second edition. John Wiley & Sons inc, 1993, New York.
Simons, P., *The Cooling of Molten Glass in a Mould; A BEM-FEM combination*, 1996. ISBN 90-5282-697-8.