# Application of Mathematical Modeling in the Process Development of Glass Forming

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## Introduction

The combination of efficient numerical techniques with user friendly commercial software packages and powerful computer hardware has broadened the possibilities to represent the entire glass manufacturing process as well as resulting product properties by realistic computer models tremendously in the last decade. Thus, simulation opens up possibilities that connot be realized on a purely experimental basis: it enables us to look into otherwise hidden internal processes , try out many variants under entirely different conditions and study critical situations without any danger for people or production plants. With respect to industrial applications, simulation offers the possibility to take important decisions concerning the development of new processes or products early on a solid basis, in order to reduce the overall costs.

Today, simulation normally is used to look at the forward behaviour of a system, i.e. one carries out numerous forward simulations with intuitively or systematically choosen initial and boundary conditions to find the best result for the process or product considered. However, actually process engineers are interested to solve the inverse problem by formula-analytic methods, which ideally leads to a complete analytic survey of the possible system behaviour. In practice, the first method in most cases only leads to local optima, and the second method often reaches its limits due to reasons of required CPU time or general complexity. The paper presents some typical problems of the glass manufacturing process and its analysis and improvement by means of mathematical simulation and optimization.

## Conditioning and Homogenization

Conditioning is mainly the controlled cooling of a glass melt from furnace temperature down to the required forming temperature taking into account specified needs of temperature homogeneity. Depending on the specific glass and desired pull rate various forehearth systems are used. Open ducts heated by burners and / or various types of electrodes dipped into the glass or systems of platinum pipes heated electrically by the Pt-skin. The temperature and flow calculation of these systems is a standard task with available CFD tools (s. ***Fig.1***).

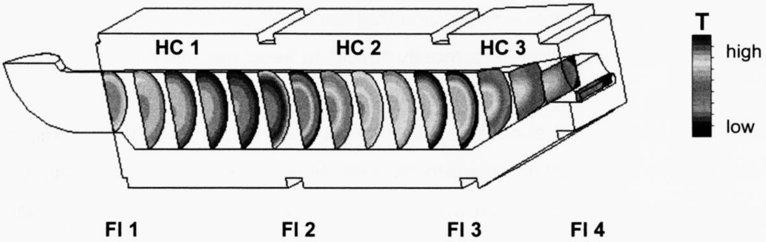


***Fig. 1:*** Temperature distribution in a Pt-Forehearth with 3 heater circuits (HC)

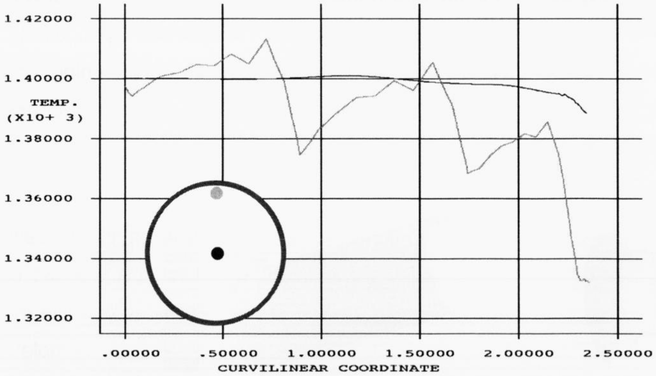


***Fig. 2:*** Temperature history of 2 trajectories along the forehearth axis with different radii (red = centre; blue = close to wall)

From the radial temperature distribution in vertical cross sections along the pipe axis a strong cooling of the glass close to the flanges (Fl) can be seen. Following 2 tracer trajectories from the inlet cross section at flange Fl 1 down to Fl4 (s. ***Fig.2***) a temperature difference between the center and the border up to 60 Kelvin can be observed which entails a difference in residence time by a factor of about 2.5 and is thus a potential source for striae. To reduce the thermal influence of the flanges a finite-dimensional shape optimization was applied for the flange geometry. The new flange concept consists of three concentric rings around the heated pipe, each with a specific function:

- exterior ring: electrical contact and distributor
- middle ring: thermal barrier
- interior ring: pipe contact area and thermal distributor

The exterior and interior rings are mostly "thick" to keep the electrical and thermal resistance small, which has a positive effect on the distribution whereas the cross section of the middle ring should be "thin" to generate a larger Joule effect and to minimize the thermal coupling between the exterior and interior rings. Therefore, the entire cross section of the middle ring is reduced by slots. The concept presented here obviously offers the following degrees of freedom:

- thickness of the three rings
- radii of the rings
- number, position and size of the spokes in the barrier ring
- number, position and size of the electrical contacts at the exterior ring

A result of the flange optimization together with the tube/ flange temperatures can be seen in ***Fig.3***. where the minimum temperature at the tube surface could be raised by about 40 Kelvin.

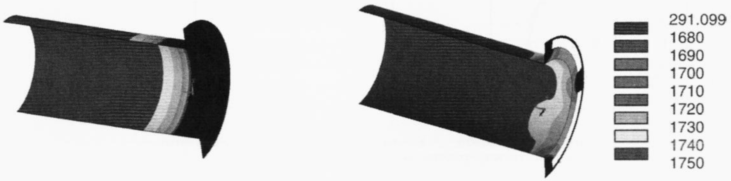


***Fig. 3:*** Initial (left) and optimized (right) flange geometry and surface temperatures

As mentioned above striae in the glass manufacturing process might arise from cold spots but several other sources are known such as depletion of surface glass due to evaporation of volatile species or dissolution of refractory material. However, for high quality glasses striae in the bulk glass would entail rejects, i.e development and improvement of efficient mixing devices is essential for high quality glass manufacturing.

Predicting the homogeneity of glass melts quantitatively after the mixing process is difficult if all parameters of influence, such as diffusion and chemical reactions, are taken into account. However, statements about the absolute mixing quality are not necessarily required in practical process development. It is usually more important to improve and standardize already existing stirrers. The relative evaluation of the mixing efficiency can be done by physical as well as mathematical models. In tracer experiments the dispersion of the tracer particles either can be inspected simply by visualization (e.g. tracer pattern in the exit cross section) or in the mathematical model additionally by means of deformation statistics of specified fluid volumes.

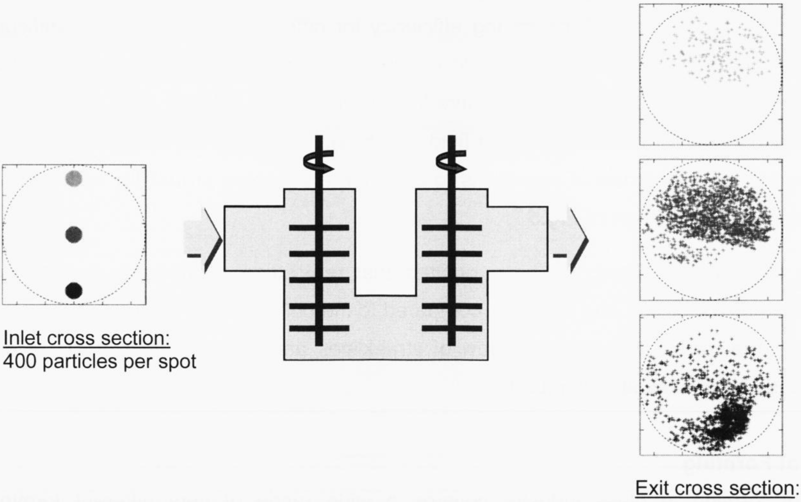


***Fig. 4:*** Initial and resulting tracer pattern in a twin mixer (particles in exit cross section were integrated for 2000 s)

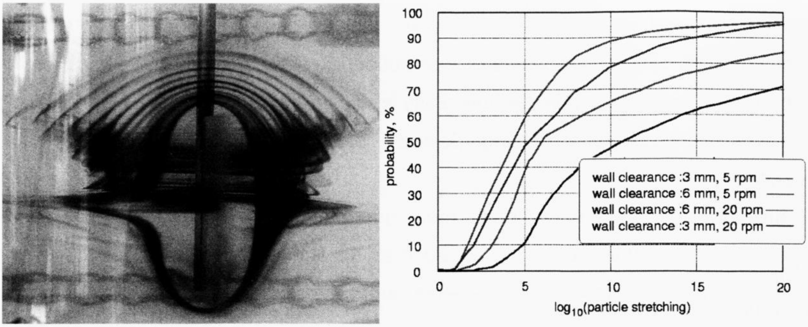


***Fig. 5:*** Tracer pattern (left physical model) and streching numbers (right: calculated)

By the vizualization of particle distributions either in the entire volume or e.g in the exit cross section we can learn a lot about the glass flow in the mixer system but as it can be seen from ***Fig.4*** and ***Fig.5*** resulting tracer patterns are ususally compelex and an assessment of the mixing efficiency for different mixer designs is difficult. The most elementary mechanism to obtain good mixing intensities in high viscous fluids is a strong shearing of the entire fluid volume which induces local streching of infinitesimal test bodies (specified fluid volumes). To assess the streching we have developed mathematical algorithms to calculate a streching probability as it can be seen in the right part of ***Fig.5*** .

In the previous work, we have omitted that real striae might have, in general, different viscosities and densities compared to the bulk glass. Therefore, reals paths of striae might differ from the flow of straeklines and the relevance of this effect needs to be evaluated in future.

## Hot Forming

Hot forming in glass industry coveres a wide range of very different forming processes such as casting, rolling, pressing, blowing, drawing and floating. The outcome of this are various requirements to mathematical modeling – some of them are listed below:

- treatment of free surfaceces (drawing processes)
- large grid deformations (pressing processes)

- transient glass-metal contact (rolling-, blowing- and pressing processes)
- transient heat transfer between glass and molds or cooling air
- coupling of totally different fluids like glass – tin – air (float process)
- handling of totally different scales: microscopic scale for surfce defects vs macroscopic scale of the product geometry
- specific material properties of glass, like stress- and structural relaxation phenomena

For this paper a simple pressing process for a flat, circular glass disc was selected to demonstrate current capabilities of mathematical modeling in the process development. The process consists of four basic steps: (1) pouring of the glass into the mold (2) pressing (3) cooling (4) inductive heating of the mold (s. ***Fig.6***)

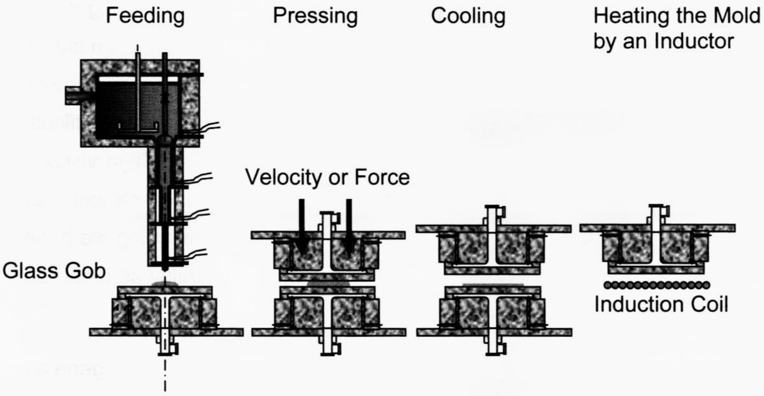
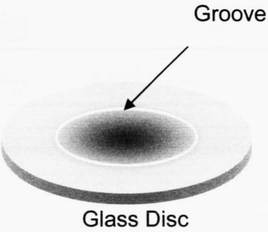
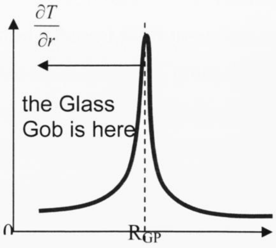


***Fig. 6:*** Process steps flat disc pressing



This process was arranged and operated in a test facility to produce a flat disc of specified geometry and surface quality and it was the final goal to minimize the cost-intensive postprocessing of the surfaces. In first test runs all discs showed a characteristic groove at a certain radius of the bottom side of the disc.



An explanation for the groove formation was found by results of an earlier casting simulation (s. ***Fig.7***). The combination of low mold temperatures and the strong temperature dependence of the viscosity creates immobilized regions at the edge of the emanating glass. The calculated temperature distribution in the left part of ***Fig.7*** shows clearly the cold regions in the glass / mold contact area for different time steps and in the right part the filled area of the glass indicates velocities below 1 e-05 m/s. An analysis of the top side temperature of the bottom mold in the pressing process showed up a steep temperature gradient exactly at the observed groove radius $R_{GP}$.

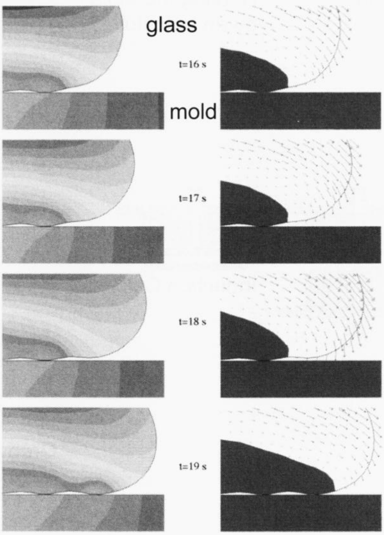


***Fig. 7:*** Temperatures (left) and velocities (right) in a casting process

By means of mathematical modeling a new mold design should be found, i.e. the mold thickness as function of radius, to avoid groove formation by minimizing dT/dr at $r = R_{GP}$ (s. ***Fig.8***).

First a detailed model of all process steps was developed to calculate the quasi-stationary temperature field by doing forward simulations using ANSYS and FIDAP software. It took about 60 pressing cycles to achieve a quasi stationary solution and the required CPU time was in the order of 60 hours.

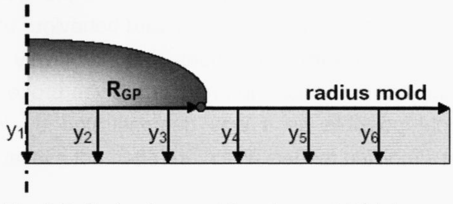


***Fig.8*** Optimization problem for mold thickness

To apply algorithmic optimization techniques the detailed model was reduced to a fast, simplified model with complex boundary conditions which could be obtained from the detailed model.

Again, about 60 cycles were calculated using the simplified model and the results were compared to the detailed model. The CPU time for one cycle could be reduced to approximately 10 seconds, i.e. the model was appropriate for algorithmic optimization. Using the fast model and a modified Levenberg-Marquardt algorithm, which is available in public numerical libraries, the optimization problem could be solved and it took about 500 steps of the optimization procedure and approximately 14 hours CPU time. The calculated geometry and temperature distribution is shown in ***Fig.9***.

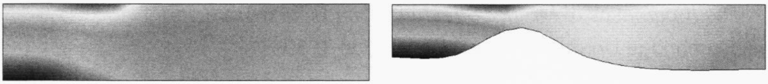


***Fig.9:*** Initial (left) and optimized (right) mold geometry and temperature distribution after feeding (only right half of vertical cross section is displayed)

By test runs with the new mold geometry in our test facility a significant reduction of the groove formation could be demonstrated , i.e. it can be stated that the mold optimization problem was solved successfully. However, in general, algorithmic optimization is not available as a standard tool in glass manafacturing processes today because it requires ususally hundreds or thousands of forward calculations which is not feasible with full CFD / FEM models due to the tremendous demand of CPU time. Only if simplified and fast models are available or can be developed algorithmic optimization is possible in an industrial framework.

## Conclusions

Today, mathematical simulation is an established engineering tool in the glass manufacturing process. In most cases it is used to look at the forward behaviour of a system, i.e. one carries out numerous forward simulations with intuitively or systematically choosen initial and boundary conditions to improve a given process. Algorithmic optimization is in pricipal possible as it was demonstrated by the pressing example but, it requires fast simplified models which are often not available yet.

## Acknowledgements

The author would like to acknowledge H. Eisermann, A. Möller, H. Loch, U. Lange, and G. Weidmann for their contributions and for enabling this paper to be written.

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