Problem 2: Predicting Glass Ribbon Shape in the Tin Bath

Industry: Glass

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Problem Statement

During the forming process, the glass-melt flows on top of a bath of molten tin. The forming of glass is essential to the final dimensions of the glass ribbon. The interaction of the bath (tin flows, heating, cooling and forming equipment) with the ribbon is complex and bi-directional i.e. the ribbon shape can affect the bath flow and vice versa. The final dimension of the ribbon is set by customer requirements. The final glass ribbon can suffer optical distortion, related to the forming of the ribbon in the tin bath, which impacts negatively on the quality of the glass product.

A model is required that will predict the ribbon shape in the bath based on typical operational parameters. This will help determine better operating parameters for prevailing conditions in the bath or to trouble shoot optical distortion.

Modeling Goals

- The differential equation describing the ribbon deformation.
- The method of supplying the boundary conditions.
- A method of solving for the ribbon shape given operational parameters.
- A method of coupling the ribbon shape with commercial CFD solvers.

Summary of Float Glass Manufacturing and Forming

Float Process

A furnace is used to melt raw materials to form a glass melt. The glass is conditioned (cooling of the melt to the required temperature) and homogenized (stirred). The pouring end is an overflow into the tin bath.

The tin bath section includes a metal container roughly 50m long, 7m wide and 0.5m deep. This inner side is insulated with refractory leaving a depth of 100mm. This volume is occupied with tin because of its surface tension, vapour pressure and melting temperature. The tin bath is covered by a gas tight roof structure, also protected with refractory. Within the roof, electrical heating elements are located in order to be able to maintain the proper temperature for the forming process. Through the roof a mixture of nitrogen and hydrogen is blown into the chamber to prevent tin oxidation.

At the end of the tin bath the glass ribbon is lifted onto a roller conveyor. The glass ribbon passes through an annealing lehr (controlled cooling) at the end of which it is cut into sheets.

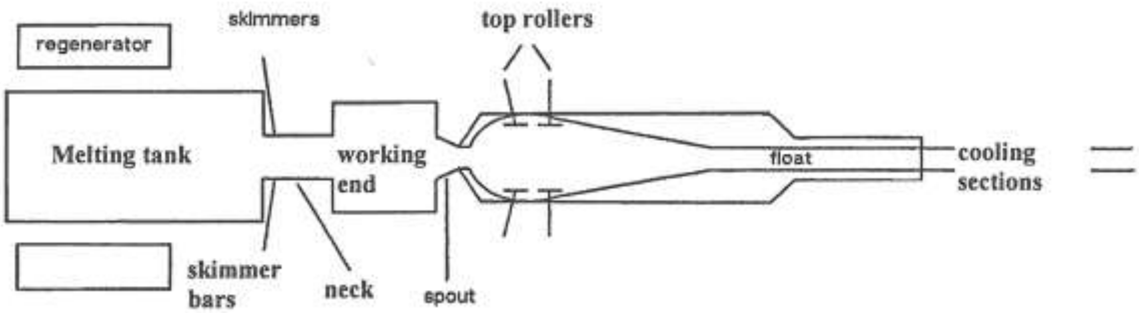

FIGURE 1: FLOAT-GLASS PROCESS

Forming Process

The glass is poured via the spout on top of the tin at around 1100°C. The glass flows out in the width direction and might be cooled with cooling bars above the glass until the proper working temperature is reached. At a temperature of about 900°C the glass is formed by top rolls. These are toothed wheels which are inserted from the side into the flowing glass ribbon, rotating with a specific angular velocity. The angle, the velocity and the pressure on the glass can be varied. Also the number top rolls in use is important. Without top rolls, an equilibrium thickness of about 6mm will be obtained because of the difference in surface tension between tin and glass.

In order to get a thinner glass, the glass flow should be widened. When the rotation of the top roller is slower than the glass flows, the glass flow is slowed down so the ribbon is widened. Thinner glass requires more top rolls with a slow rotation speed and a large angle. Because the amount of glass poured is constant, a higher velocity is required to obtain a wider glass flow. This will constrain the glass ribbon resulting in a thinner glass ribbon. In this manner, thin glass requires more top rolls. The amount of poured glass is reduced because of optical quality and limited cooling rates in the lehr.

For thicker glass the forming process operates in the opposite manner.

Rotation speed, number of rolls, angle of the rolls and pull velocity can be adjusted to obtain the required glass ribbon dimensions. After the glass ribbon has its final width and thickness, the glass is cooled down further to 600°C and lifted from the tin onto the roller conveyor.

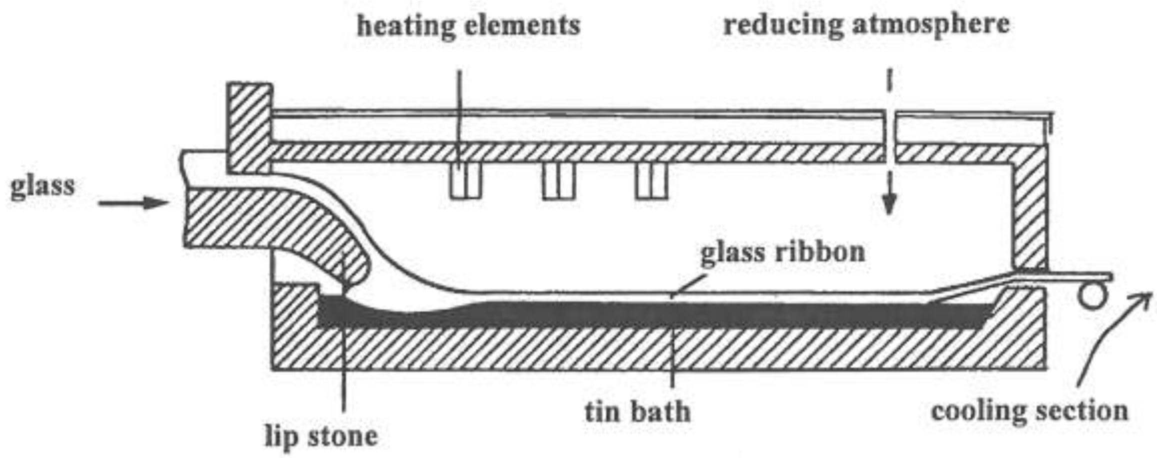

FIGURE 2: TIN BATH

EQUILIBRIUM THICKNESS

During free flow of the glass on the tin, a certain equilibrium glass thickness will be formed. The glass thickness is determined by the surface and interface tensions of the glass, tin and air on the one hand and the glass weight on the other. The resultant surface- and interface- tensions determine the degree to which the glass is pulled sideways or pushed inwards.

OPTICAL QUALITY

This is the degree to which the light is diffracted during transmission through the glass. This phenomenon is greatly influenced by the surface smoothness, which is determined by the contraction after the top rolls and the temperature of the glass.

GLASS FORMING

The shape of a piece of hot glass can be changed by an external force which can cause viscous deformation. The forming process is based on this phenomenon. In industrial forming techniques the external force is applied by:

- Drawing
- Blowing
- Pressing
- Centrifuging
- Rolling
- Casting

The degree of transformation depends on the magnitude of the force and the actually prevailing glass viscosity. A low viscosity will impart a high rate of deformation. After forming, a high viscosity is required so the product retains its shape. During forming, the glass should be cooled down precisely to achieve these conditions.

The degree of cooling depends on the heat content of the glass product and the rate of production. Most forming processes take place in the working range (viscosity range of 10^2 to 10^5 Pa·s). During forming the glass has an isotropic behaviour (properties are independent on direction). At very high deformation rates, the viscous behaviour can change into a brittle behaviour.

Viscosity

The viscosity is one of the most important properties of glass. With the proper forming process conditions, the viscosity just after forming has become so high that the product will retain its shape. Glass behaves like a Maxwell material which can be described by

where is the shear, is the shear stress, is the viscosity, is Young's modulus and is time. At high temperature when , the equation reduces to that of a Newtonian fluid:

The viscosity is a measure of the resistance against shear and describes a kinetic process. Kinetic processes are mostly described by the Boltzmann-relation. However, because of structural changes within the glass above, an adapted Boltzmann-relation is used to describe the glass transformation temperature:

The constants depend on the glass composition.

Viscous Deformation

A distinction is made between two types of transformation processes:

- Extension:

  Deformation by a normal force (push/pull). Distance between two surfaces change.

- Shear:

  Deformation by a shear stress. Two surface shift relative to each other.

Extension

Under the load of a normal force a body will become longer or shorter. The deformation after a certain time is expressed in an elongation per unit length, ε. A body with a length in the x-direction of will have a length of after deformation:

Similar relations apply for the other two directions. The components of the deformation therefore are

The relationship between the rate of deformation and the applied stress is described by:

where μ is the viscosity and σ is the normal stress. For an incompressible liquid the sum of the total deformation rates should be zero.

Therefore the following relations for extension transformation are obtained:

SHEAR

The deformation caused by a shear is defined as

The relationship between the shear stress and the shear rate is given by

In a float bath both transformations of the glass ribbon occur. In the sections where there are no top rollers, the glass is pulled in one direction. At the positions of the top rollers the glass is not only pulled in one direction but at the same time the width is kept constant. Keeping the width constant requires a certain force. The top rollers pull sideways at the glass ribbon to maintain a constant width.

Extending a glass plate in the -direction:

Extending a glass plate in the -direction while keeping the width (in the -direction) constant: