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NUMERICAL SIMULATION OF 3D GLASS SAGGING PROCESS

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Abstract: *The article deals with possibilities of using the tools for computer modelling in glass industry with the intention on the sagging process. Possibilities of usage are demonstrated in 3D-models of rectangular glass sheets supported by simple mould. Numerical outputs are compared with verifying experimental results under laboratory conditions. Mentioned analysis allows identifying individual stages of the sagging process. Results of sensitivity analysis of chosen parameters are submitted in brief in the end of the article.*

Keywords: ***Glass, forming, sagging, bending, slumping.***

1. Introduction

Glass sagging process is ranked among the expanded glass technologies. It is used firstly for windscreen production; known is also a usage for a production of spherical optical elements and complex building elements, but also in an art glass manufacture. Glass sagging is a relatively complex technological process (Hyre, 2002), whereas its principle is based on the glass temperature dependence on glass rheological properties.

The principle of the method is notorious – glass sheet placed on a frame changes its shape under the influence of the gravity force at a given temperature corresponding to a viscosity under the deformation point (10^{10} Pas). The required shape is obtained through an interaction between the glass sheet, exposed to the viscous flow due to gravity forces, and the frame. The final shape is fixed due to viscosity increasing during the annealing process.

Glass products with more a more complex shapes and stricter dimension tolerances are required and products quality is more and more emphasized, so it is more and more difficult to obtain required aims through those traditional techniques of the product preparation. Therefore the need of an effective and accurate predictive computational model becomes increasingly crucial.

2. Experiment

For the purpose to analyze basic parameters of the glass sheet sagging process a special fixture, simple ring symmetrical along both vertical planes, has been projected (Fig. 1). Measurements were realized in the laboratory furnace with a special design (Fig. 3). Samples of glass sheet made of clear float soda-lime glass (Float glass by AGC with deformation point corresponding to the temperature of 593 °C) of an oblong shape with dimensions 100 x 150 x 2.1 mm has been put on the ring and subsequently they have been inserted together to a preheated laboratory furnace, in which sample has been heated up to the working temperature. As soon as the temperature in the whole cross section of the glass sheet exceeds deformation point sagging process starts. During the experiment a surface temperature of the glass sheet were measured by thermocouples from the top and the bottom side.

After a defined period of time (10, 20 and 40 minutes) the frame with the sagged sample was taken out of the laboratory furnace and annealed by the air. Consequently, the deflection along three basic curves (Fig. 2) was evaluated by means of a special gauging device with an optical laser sensor.

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The aim of experiments was the identification of boundary conditions, concretely the course of temperatures for a virtual model specification and an experimental evaluation of influence of chosen parameters on a course of sagging process. The measurement of samples sag was also used for the verification of computer model results.

Fig. 1: Experimental frame with sagged glass

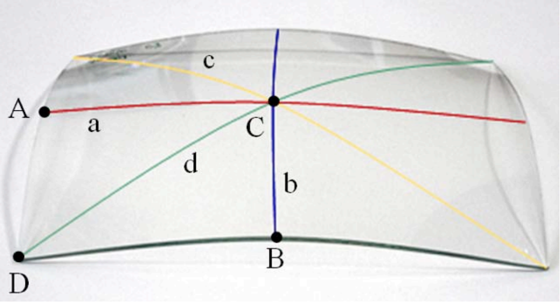

Fig. 2: Sample with measured lines and points

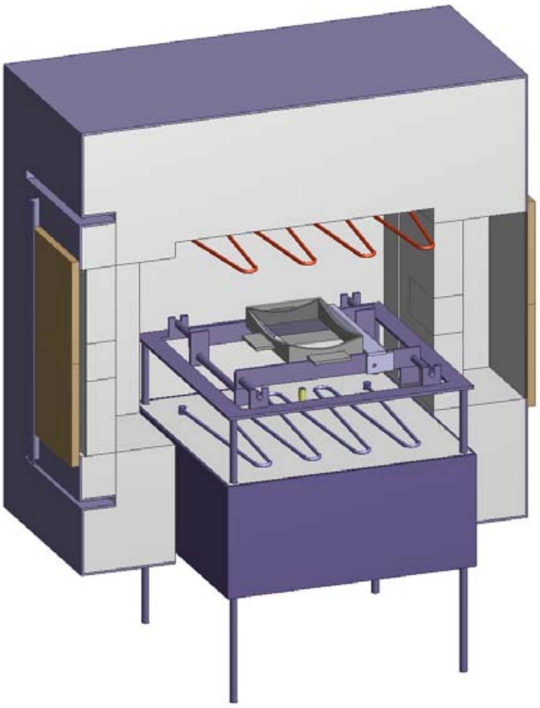

Fig. 3: Broken-out section of laboratory kiln

3. Virtual model

The flat glass gravity process is a complex couple thermo-mechanical problem characterized with strong interaction between the heat transfer and viscous flow of molten glass. Basic phenomena of the forming process are the distribution and the course of temperature fields in the sheet being shaped as well as viscosity changes with temperature.

Numerical modeling of glass forming is based on couple non-linear thermo-mechanical solution, described in the Lagrangian coordinate system by conversation equations, as follows:

$$\frac{\partial \sigma_{ij}}{\partial x_j} = b_i \tag{1}$$

$$\mathrm{div}\left(\lambda\ \mathrm{grad}\,T\right) = \rho\ c\ \dot{T} \tag{2}$$

where: σ_{ij} - the stress tensor, b - body force, T - temperature, λ - effective conductivity, c - specific heat.

Above temperature corresponding to the deformation point molten glass can be considered to be incompressible ($\varepsilon_{ii} = 0$). In this temperature interval the elastic part of the total strain is near insignificant and therefore constitutive behaviour of glass can be characterized by Newtonian model. Relation between equivalent von Misses $\bar{\sigma}$ stress and equivalent strain rate $\dot{\bar{\varepsilon}}$ is then defined through the Newtonian viscoplastic isochoric law, as follows:

$$\bar{\sigma} = 3\eta(T)\dot{\bar{\varepsilon}} \ . \tag{3}$$

The viscosity of glass is highly dependent on temperature. In the glass forming range this dependence can be expressed by V-F-T model (Fulcher, 1925):

$$\log\eta(T) = A + \frac{B}{T - T_o} \tag{4}$$

where: A, B - temperature coefficients.

The critical factor of solved problem is the distribution of temperature fields in formed glass sheet. The sample is in the laboratory furnace heated by convection and radiation, which has a dominant influence. The heat transfer in the furnace is complicated by specific (molten) glass properties. Clear silica are semitransparent for infrared radiation, especially for near-infrared radiation and above the temperatures of 500 °C begins at heat transfer exert radiation (Fig. 4).

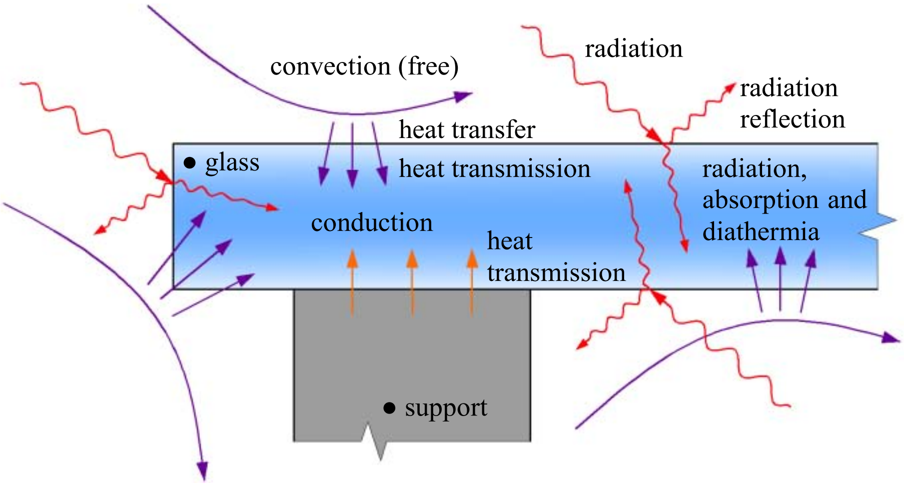

Fig. 4: Thermal transmittance at the sagging process

Considering the thickness of analyzed glass samples, there was used an effective conductivity and heat transfer in the system were realized by means of external subroutine. Geometrical characteristics were chosen according to the experimental model (Fig. 1), material properties of shaped glass were described through the rigid plastic model. The ring mould is assumed to be rigid (Fig. 5).

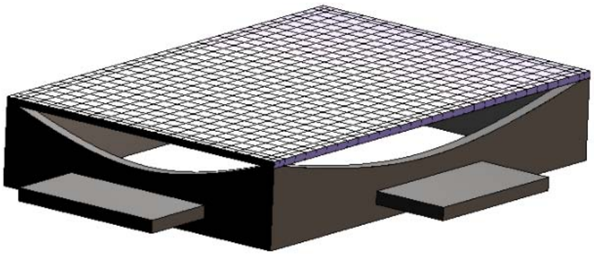

Fig. 5: Virtual model (FEM)

4. Results of virtual modelling

Numerical model allowed analyzing the course of the glass gravity bending process (Fig. 6 and 7).

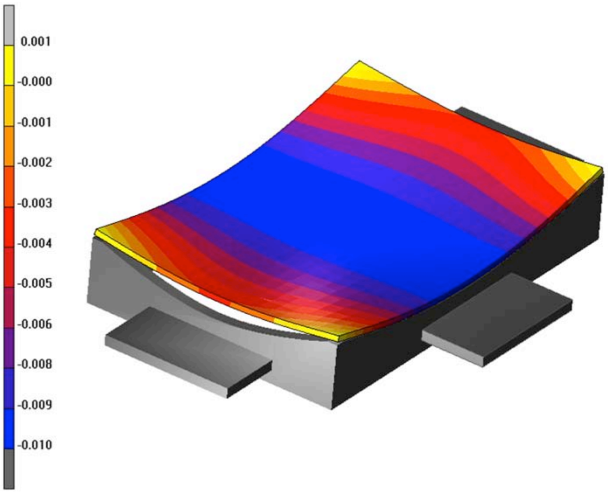

Fig. 6: Sagging on the ring at time 600 s

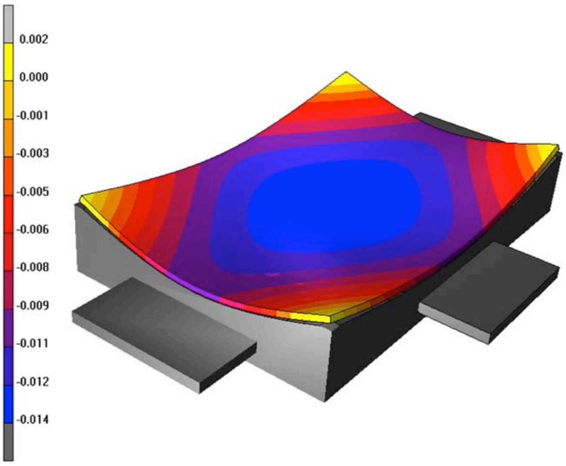

Fig. 7: Sagging on the ring at time 2400 s

Shaping behavior is demonstrable on Fig. 8 where the time flow of displacements is shown in four chosen points (see Fig. 2) for the defined boundary conditions. The sagging process (on the support ring shown in Fig. 1) itself consists of three different stages (see Fig. 9).

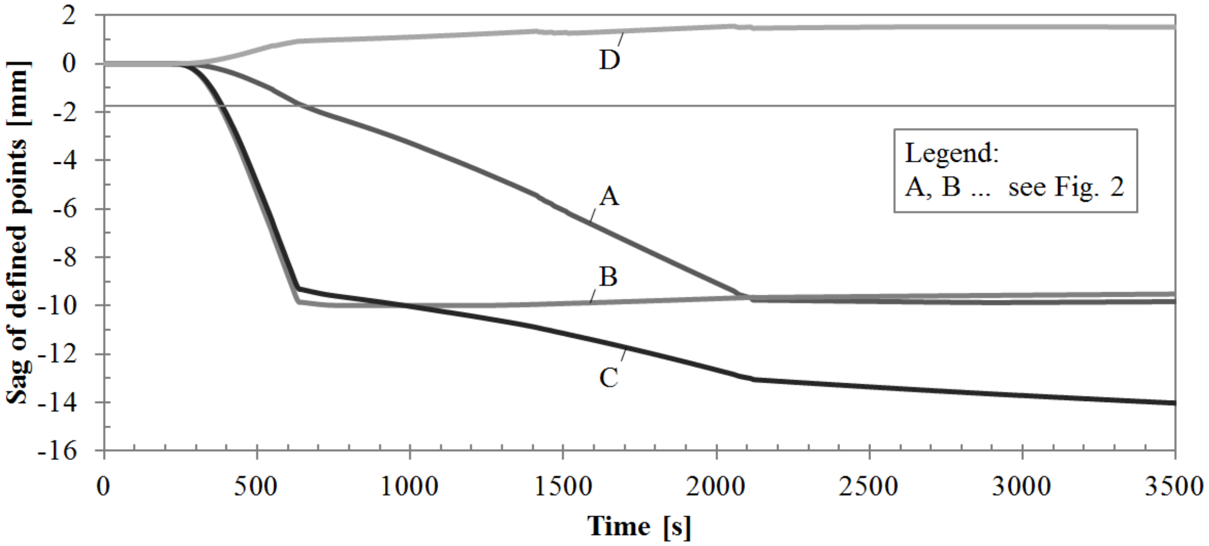

Fig. 8: Development of maximum displacement during sagging for defined points and sample thickness 2,1mm

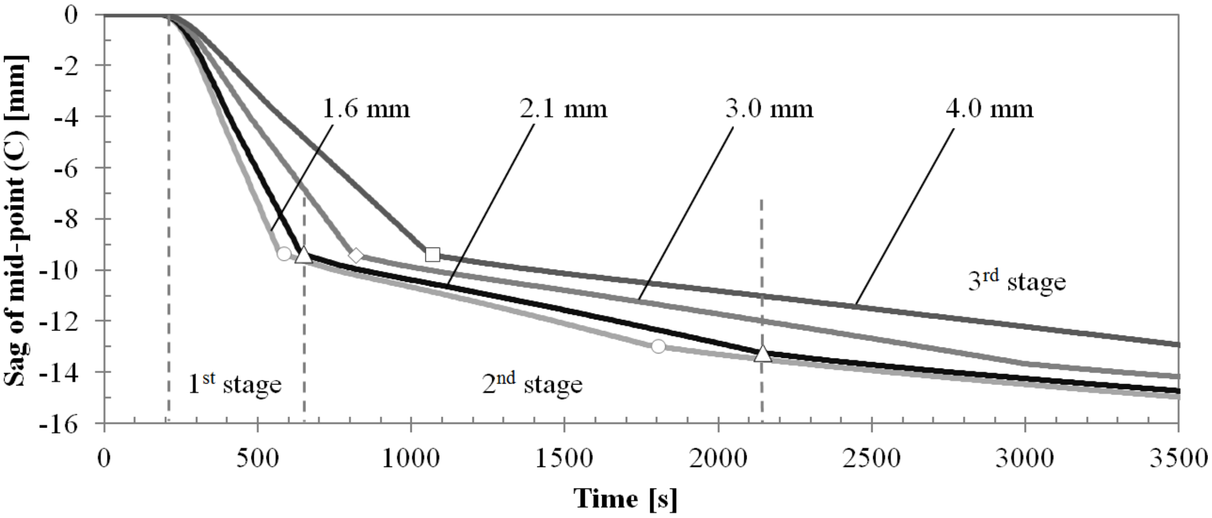

Fig. 9: Development of maximum displacement during sagging for various sample thicknesses

After warming through the cross section to the temperature above the temperature of deformation point glass sheet starts to deform (approx. 220 s from the moment of the sample feeding to the furnace for working temperature 618 °C and thickness 2.1 mm) - primarily along the longitudinal (longer) side. During the first stage samples deforms in similar way that is characteristic for the free bending between two supports. In the moment when sample comes to the contact with ring along longitudinal sides (Fig. 6 - for the sample thickness 2.1 mm, ca. 650 s after feeding glass sample into the furnace) the geometric conditions are modified, sample stiffness is changed that results in reduction of sagging velocity and the first stage is transformed to the second one. Sagging process continues with deformations along shorter side mainly. When the shorter sides come to the contact with the ring, velocity of sagging further decreases starts final stage (see Fig. 9).

The thermal field distribution in a shaped sheet was necessary to modify to obtain the equality of virtual model and experimental measurement. Laboratory furnace experiments were done by set control temperature of 630 °C. The stabile temperature on the upper surface of the sheet was 621 °C and on the bottom surface it was 613 °C due to these experiments. By this temperature distribution the maximal bend curve is moved to lower times, that means that sag bending runs faster then it corresponds to the experimental measurement. For this reason thermal flow intensity had to lowered down. The temperature of upper and bottom surface was decreased to 619 °C, respectively 612 °C.

According to these conditions there was in the time of 2400 s registered the distribution of displacements among curves showed on Fig. 10. The displacement behaviour along curves (for appointed range) is in really high equality with realized experiments, maximal deviation is under 1 %.

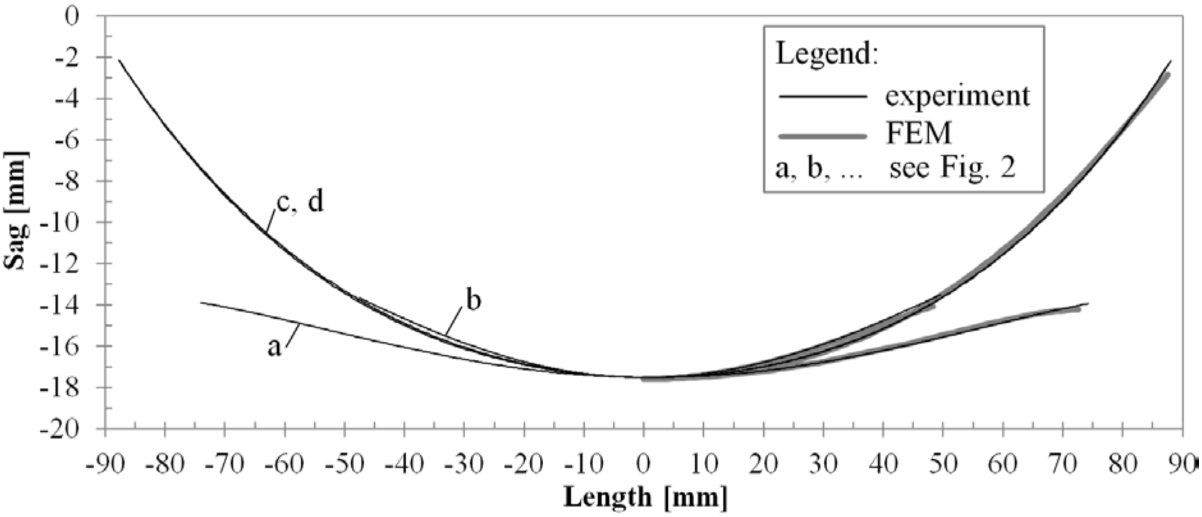

Fig. 10: Sample deflection along basic curves at time 2400 s and sample thickness of 2.1 mm

The numerical model verification allowed analyzing the influence of chosen parameters of sagging process. The sagging speed changes linearly with the viscosity change, the important characteristic is in this case except temperature also the quality of viscosity curve temperature dependency. The various thickness influence for simplified boundary conditions (the sample temperature is described by reference temperature) for the interval of 1.6 to 4.0 mm is shown on Fig. 9. The sagging speed in the first stage (and approximately in the second stage as well) of two blanks with various thickness is set by the square ratio of their thickness.

The sagging rate change in the gravity center due to the change in the thickness of glass sheet can be described by equation (5), generally, whereas for the 1st stage of the sagging process coefficient $c(l_l,l_t)$ is equal to 1.

$$v_2(z) = c(l_l, l_t)\frac{h_1^2}{h_2^2} v_1(z) \,, \tag{5}$$

where: $v_i(z)$ - sagging speed of the sample gravity center in vertical direction, h_i - sample thickness, $c(l_l, l_t)$ - geometrical coefficient, l - support distance along longitudinal (l_l) and transversal (l_t) axis.

5. Conclusions

In the paper a computer analysis of sagging process is presented. Comparison of numerical results with experiment validated the reliability of the numerical model. The sagging process on 3D support rings itself proceeds in three different stages and sagging rate decreases relatively markedly with the stiffness increase due to change of boundary conditions. Maximum sagging rate (at the sample gravity centre) changes linearly with the viscosity and with the square ratio of sample thickness.

Acknowledgement

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