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Modeling of drawing thin glass sheet from a preform

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A one-dimensional model of thin glass sheet drawing has been developed. This model includes momentum, heat and mass balance equations. The density, viscosity and specific heat of the glass were calculated as functions of temperature, and the glass emissivity was defined and calculated as a function of both temperature and glass thickness. After allowed simplifications, two ordinary differential equations were obtained and solved using the Runge Kutte method. The model was used to investigate the influence of different process parameters (the velocity of lowering the preform into the furnace, the axial temperature profile of the furnace, the drawing force and its direction, *etc.*) on the change in the shape of the drawn glass sheet for different glass compositions and various geometrical characteristics of the preform. A laboratory device for drawing thin glass sheets from rectangular preforms enabled full control of the process parameters, their measurement, as well as data acquisition. The results of the numerical simulation were compared with the experimental data and good agreement between them was found.

Key words: glass, glass sheet drawing, modeling.

Glass sheets of uniform thickness, thinner than 1 mm, are commonly used, for example, in microelectronics, as small parts of electronic devices, and components in light microscopy, *etc.* Drawing glass from rectangular preforms into thin sheets is one of the manufacturing possibilities. An attempt has been made to develop a simple method for calculating the distribution of temperature in the glass, as well as its thickness whilst being drawn from a rectangular preform.

MODEL OVERVIEW

Several processes are simultaneously involved when a thin glass sheet is drawn from a preform. The cold glass block is moved into the furnace at an appropriate velocity. The glass block is heated in the furnace until it softens and becomes drawable and stretchable. The drawn glass is cooled so that it hardens into a thin glass sheet. Considering all these processes as engineering phenomena, momentum, heat and mass balance equations were established. The process was regarded as a steady state one.

The glass properties were considered with most care, none of them was considered as a constant. The glass density, viscosity and specific heat were considered to be temperature dependent, and the glass emissivity to be temperature and glass thickness dependent.

A schematic presentation of the changes in the glass geometry during the drawing process is given in Fig. 1. The drawing direction, geometric dimensions and some process variables which change during the drawing process are marked in Fig. 1.

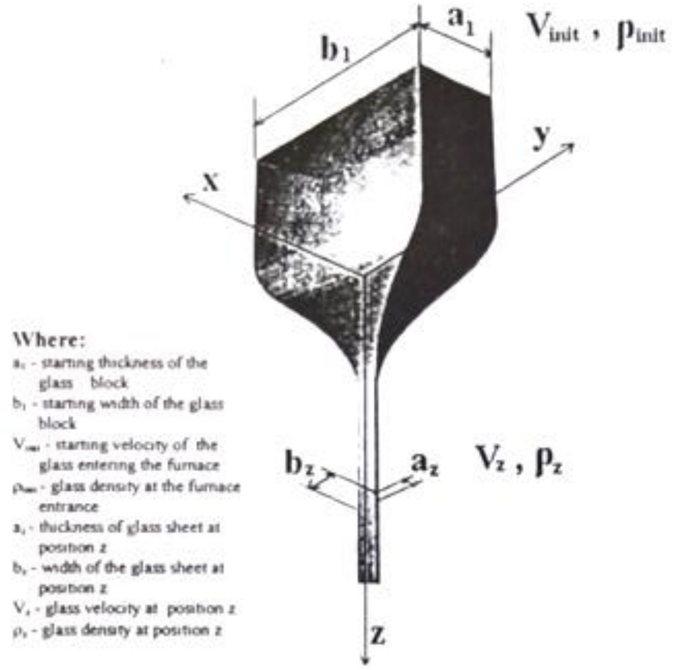

Fig. 1. Schematic presentation of the changes in the shape of glass during the drawing process.

Mass balance

The quantity of glass entering the furnace must equal the quantity of glass leaving the furnace, so the continuity equation is given by:

$$\rho_z a_z b_z \upsilon_z = \rho_1 a_1 b_1 \upsilon_{init} \tag{1}$$

where is glass velocity at the indicated position. while ρ, a and b have the meaning indicated in Fig. 1.

Force analysis

As the process was regarded as a steady state one, the forces involved in the glass drawing must be in balance and no time dependent term was considered. Analogous to the force balancing commonly used in modeling the drawing of glass fibers,[1-3] it can be stated that the drawing force F_{dr} in the z-direction is balanced with the algebraic sum of all other forces effecting the glass in the z direction, *i.e.*,

$$F_{dr}(z) = F_{rheo}(z)+F_{iner}(z)+F_g(z)+F_S(z)+F_s(z) \tag{2}$$

where F_{dr} is the drawing force; F_{rheo} the rheological force; F_{iner} the inertial force; F_s the surface tension; F_g the gravitational force and F_a the aerodynamical force.

The rheological force is the most important one in the drawing process. Most mathematical models neglect all forces except this one, which is not always correct. When the sheet is formed the tension[4] is calculated according to:

$$\sigma_z = 3\eta_T \frac{\partial \upsilon_z}{\partial z} \tag{3}$$

where σ_z is the tension in the z- direction; η_T the glass viscosity at temperature T and z-the drawing direction.

The glass viscosity depends on the chemical composition of the glass, as well as on the glass temperature. Here, the Vogel-Fulcher-Tammann's (VFT) equation was used:[5]

$$\log \eta_T = A_v \frac{B_v}{T - T_v} \tag{4}$$

where A_V, B_V and T_V are VFT coefficients depending on the chemical composition of the glass, and T is the temperature of the glass in K.

The intertial and aerodynamic forces are, under the used experimental conditions,[6] more than 10000 times smaller than the other forces and so can be neglected to enable simplification of the equation without introducing any serious error.

The gravitational force at a distance z from the entrance of the furnace, is given by:[6]

$$F_g(z) = \rho_T g \int_z^L ab(z)\mathrm{d}z \tag{5}$$

where g is the gravitational constant (9.81 m/s^2); L the total length of the sheet; $ab(z)$ the area of the glass at z position (cross-section of a glass ribbon); ρ_T the glass density as a function of glass temperature.

The surface tension is important in the region when the glass viscosity is less than 10^7 Pa s.[5] The surface tension depends on the glass composition, the temperature and the shape of the surface. After certain simplifications,[1,7] the components of the surface tension in the z direction can be expressed in the form:

$$F_s(z) = K_{st}(a_z + b_z) \tag{6}$$

The constant K_{st} is a surface tension constant obtained from the product of the surface tension and sur face curvature.

Using Eqs. (2-6), the equation for the rheological force kan be presented as:

$$\frac{\mathrm{d}\upsilon}{\mathrm{d}z} = \frac{F\,\mathrm{d}r - F_s + F_g}{3a_z b_z \eta_T} \tag{7}$$

Heat transfer analysis

Considering the drawing process, three different temperature regions can be recognized. First, from the furnace entrance to the point where the glass viscosity is low enough for the glass to be shaped ,second, where the glass viscosity is in the range 10^5-10^7 Pa s where shape changes occur, and third where the glass is cooling.[7]

Three heat transfer mechanisms are present in glass. Conduction and convection are considered in the same way as for all other materials, but radiative heat transfers are much more complicated in glass as a semi-transparent material and all emissivity or absorption coefficients must be regarded as bulk coefficients.[7,8]

The general heat transfer equation is given by.[8]

$$\rho c\left[\frac{\partial T}{\partial \tau}+\upsilon_x\frac{\partial T}{\partial x}+\upsilon_y\frac{\partial T}{\partial y}+\upsilon_z\frac{\partial T}{\partial z}\right]-\left[\frac{\partial}{\partial x}k_x\frac{\partial T}{\partial x}+\frac{\partial}{\partial y}k_y\frac{\partial T}{\partial y}+\frac{\partial}{\partial z}k_z\frac{\partial T}{\partial z}\right]+\dot{q}_{\mathrm{rad}}+\dot{q}_{\mathrm{conv}} \quad (8)$$

where x, y and z are directions; k_x, k_y and k_z are the thermal conductivities in the x, y and z direction, respectively; υ_x, υ_y and υ_z are glass velocities in the x, y and z direction, respectively, while $\dot{q}_{\mathrm{rad}}$ and $\dot{q}_{\mathrm{con}}$ are radiative and convective fluxes, respectively.

Heat accumulation is neglected since the process is considered to be in steady state. Analysis of Eq. (8) would be a very difficult task, so some assumptions to simplify the model have to be made:

- the drawing process is continuese and so the time dependent term can be eliminated, *i.e.*, $\partial T/\partial\tau = 0$;

- the glass velocities in the direction normal to the drawing direction are smaller than the velocity in the drawing direction (the z - direction), and the direction and the change in temperature in directions normal to the drawing direction are significantly lower than in the z-directions, *i.e.*, $\upsilon_x\, \partial T/\partial x << \upsilon_z\, \partial T/\partial z$ and $\upsilon y\, \partial T/\partial y << \upsilon_z\, \partial T/\partial z$. Thus, it is possible to neglect the terms in the equation that are partial derivatives of temperature with either the x- or the y-direction;

- heat conduction in the direction of sheet drawing can be neglected compared to convection according to the Peclet number (Pe).[9] Under the conditions of the process, Pe>800, meaning that convection is more than 800 times more intensive than conduction in the glass drawing direction. Hence, neglecting conduction introduces an error of less than 0.12%.

To be most exact, it must be admitted that the one-dimensional model is acceptable for the process of drawing a glass sheet from a preform for all parts of the glass ribbon except for its edges where thickening occurs. The three-dimensional aspect must be taken into consideration for an appropriate analysis of this part of the glass ribbon.

Natural convection can be calculated as:[10]

$$q_{\mathrm{con}} = A_{\mathrm{con}}(T_{\mathrm{s}} - T_{\mathrm{env}})^{5/4} \quad (9)$$

where T_s, is the glass temperature at the sheet surface which was taken to be equal to the glass temperature, T, T_{env} is the environmental temperature and A_{con} is the natural convection constant.

Heat transfer by radiation can be calculated according to:[11]

$$q_{rad} = \varepsilon_T{}^a \sigma_B (T^4 - T_{env}^4) \tag{10}$$

where σ_B is the Stefan-Boltzman constant and $\varepsilon_T{}^a$ is the glass emissivity as a function of temperature T in K and glass thicknes a in mm.

Gardon gave a set of curves showing the dependence of $\varepsilon_T{}^a$ on temperature for different thickness of window glass.[12] In present model five curves were fitted giving polynomial equation of the glass emissivity as a function of temperature for different glass thickness: 10 cm, 1 cm, 5 mm, 2 mm and 1 mm. The $\varepsilon_T{}^a$ values for glasses of intermediate thicknesses were calculated by interpolation, while for glasses thinner than 1 mm the emmisivity was calculated according to the equation given for 1 mm thick glass.

The relationship between the emmisivity and temperature (T in K), for constant glass thickness, is a regression having the following general form:

$$\varepsilon_T{}^a = k_1 T^3 + k_2 T^2 + k_3 T + k_4 \tag{11}$$

where the regression coefficients k_1, k_2, k_3 and k_4 have different values for each glass thickness.

Equation (8), after simplifications, has the form:

$$\frac{dT}{dz} = \frac{q_{conv} + q_{rad}}{\rho_T c_T \upsilon_z \sqrt{a_z b_z}} \tag{12}$$

where c_T the heat capacity, is regarded as a temperature dependent variable.

Three balance equations: the continuity equation, Eq. (1), the heat transfer equation, Eq. (12), and the force balance equation, Eq. (7), are part of the model of the glass drawing process. The model includes three equations giving the temperature dependence of the glass density,[13] the glass viscosity, Eq. (4), and the heat capacity[14] of the glass and a set of five equations for the dependence of the glass emissivity on temperature and glass thickness, Eq. (11).

The model allows three options for the type of glass used for the preform: window glass, glass of known composition or glass with known characteristics. These characteristics include: density at room temperature (293 K - ρ_{293}); heat capacity at 273 K (c_{273}), and VFT coefficients. All these values depend on the glass composition, and can either be measured or given by the glass producer, and than directly inputted in computer code. For common window glass, the values given in the literature[7] were used.

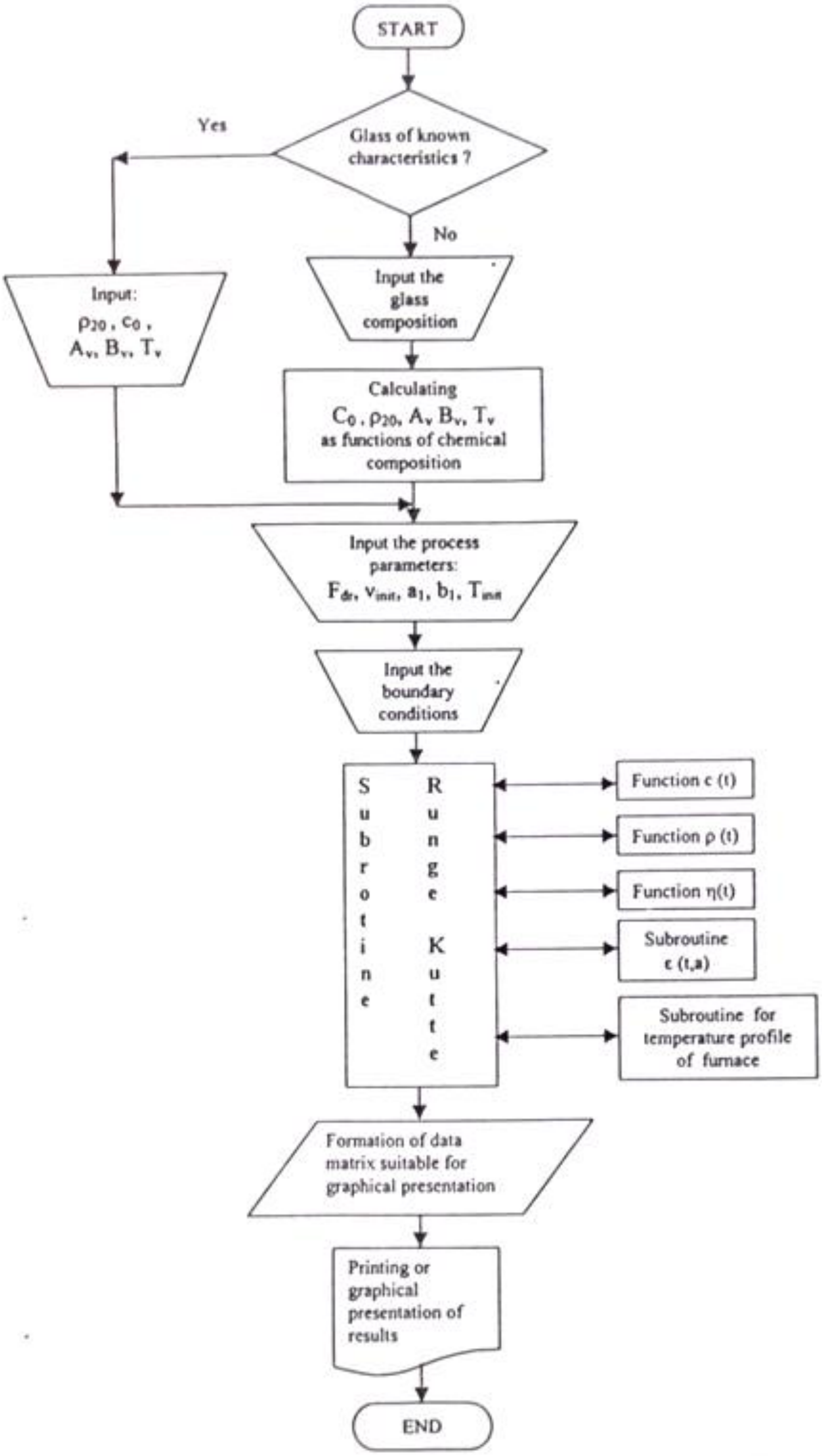

Fig. 2. Program algorithm.

For glasses of given composition these values were calculated dependent on the chemical composition. The heat capacity was calculated according to Sharp and Ginther,[14] the density using the additive factors given by Baillie[13] and the VFT coefficients according to the formula given by Lakatos.[15]

Due to the explained simplifications, Eqs. (7) and (12) were obtained in the form of two simple differential equations, so they were solvable by the Runge Kutte algorithm.[16] All other constituent equations of the model were treated as appropriate submodules.

The computer program includes three different parts. The first part involves setting the initial and boundary conditions and the glass properties, the second part calculating the temperature, viscosity and dimensional changes during changes in the z-direction and the third part presenting the calculated data graphically. The algorithm used in this model is given in Fig. 2.

RESULTS OF MATHEMATICAL SIMULATION

The computer program was written and numerical results of glass sheet drawing were obtained for various supposed experimental conditions. The results are presented as changes of the glass thickness with axial distance from the entrance into the furnace. The changes of temperature and viscosity of the glass during drawing, together with the axial temperature profile of the furnace are presented graphicaly. In this way it is possible to compare different supposed experimental conditions, and also to make a comparison between the simulation results and the actual experimental results.

Using the numerical simulation of the influence of various drawing conditions on the change in the shape of the drawn glass ribbon, the phenomena of the drawing process were investigated. The simulated conditions were within real, potential experimental conditions with the additional condition that the final thickness of the drawn glass must be in the range 0.1-1.0 mm.

The influence of the following variables on the shape of the glass sheet were investigated:

- the velocity of lowering the preform into the furnace;
- the axial temperature profile of the furnace;
- the temperature of the glass before entering the furnace (how much the glass preform was preheated);
- the length of the furnace;
- the drawing force and its direction (upward and downward);
- the type of glass (window glass or glass of known composition);
- the dimensions of the glass preform (different width and thickness at a constant length of 1 m).

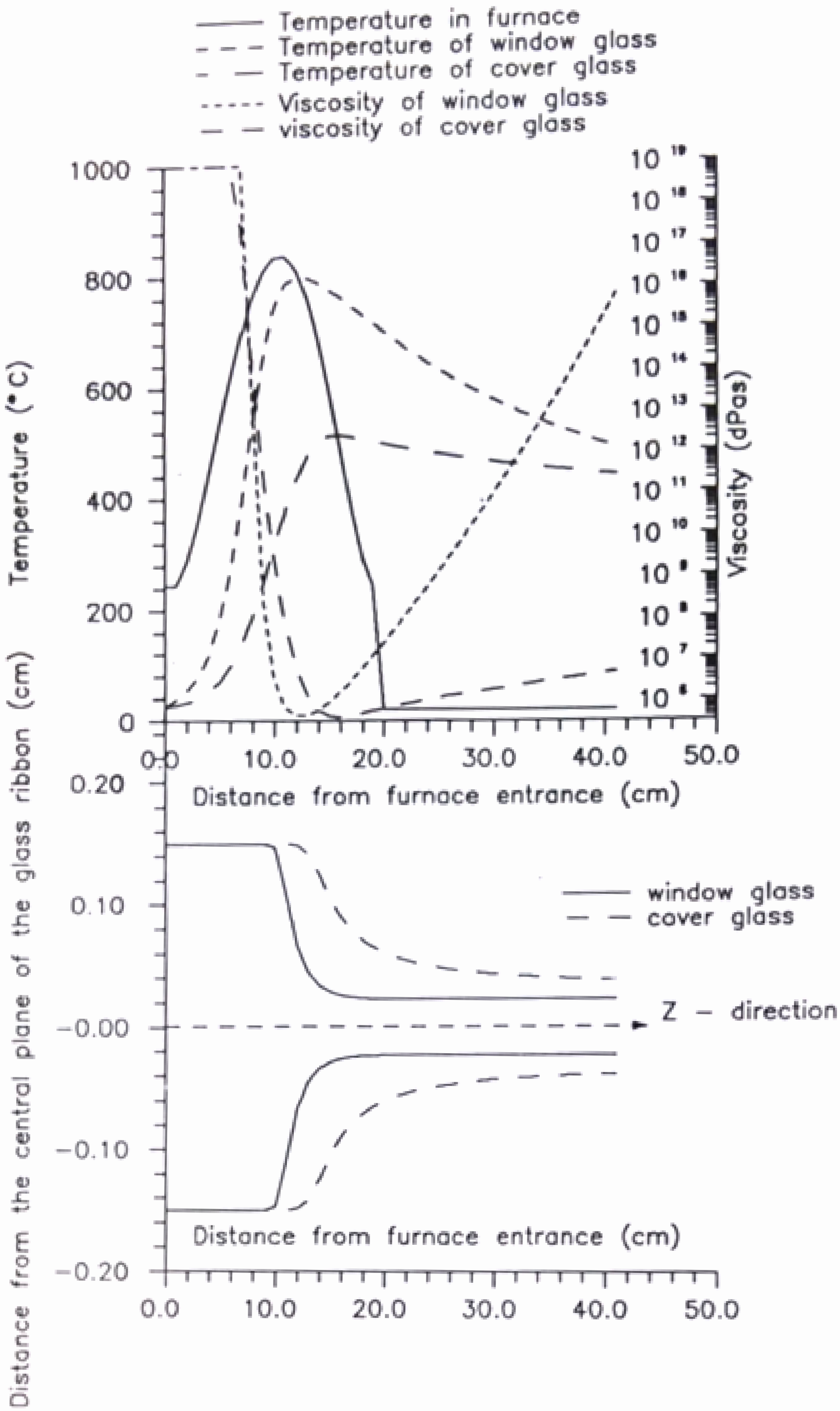

Fig. 3. The change of dimensions, temperature and viscosity within a glass block in the z-direction for common window glass and microscope cover glass.[17]

Only part of these investigations is presented in this paper. The influence of the chemical composition of the glass on the drawing process is illustrated in Fig. 3. The change of dimensions, temperature and viscosity within the glass block in the z-direction for two different types of glass preforms are presented in Fig. 3.

To enable a comparison of the data all other process variables were kept constant, except for the type of the glass. The simulation was performed for common window glass and for glass envisaged for microscope cover glass.[17] The composition of this glass is given in Table I.

TABLE I. Chemical composition of the microscope cover glass[17]

Oxide	Mass %
SiO_2	65.0
Na_2O	8.7
K_2O	4.2
Al_2O_3	4.2
MgO	1.0
CaO	2.3
B_2O_3	6.8
BaO	1.4
ZnO	2.2
TiO_2	2.2
ZrO_2	1.4
Sb_2O_3	0.6

Both preform block had dimensions 3 mm × 150 mm × 100 mm. The furnace was 200 mm long with the axial temperature profile in the z-direction as presented in Fig. 3. The glass ribbon was drawn with a force of 2 N pulling the glass downwards. The preform was lowered into the furnace with a velocity $\upsilon_{init} = 5 \times 10^{-5}$ m/s.

The heat capacity, density and VFT coefficients were calculated for the cover glass first as chemical composition dependent functions in the manner explained earlier. If the same process parameters were hold for cover glass as for window glass, the glass would shrink ending up as a glass fiber instead of a glass ribbon. To enable the drawing of cover glass some process parameters had to be altered. In the case presented in Fig. 3, the lowering velocity was increased to $\upsilon_{init} = 2.2 \times 10^{-4}$ m/s.

In the same way, the influence of all other process parameters was investigated. Special attention was focused on the influence of the temperature profile of the furnace and the length of the heating zone.

COMPARISON OF RESULTS OF MATHEMATICAL SIMULATION WITH EXPERIMENTAL

A laboratory device for drawing thin glass sheets from rectangular preforms enabled the verification of the mathematical model. The first step was to establish the temperature profile of the furnace. The drawing process was fully controlled.[18] An appropriate mechanism allowed the glass block to be lowered into the furnace with a controlled velocity. The temperatures in the furnace at different positions and drawing velocities were controlled. All the controlled process parameters were measured and the values collected using a data acquisition system HP 3497A connected to a HP 9386 computer.

Direct measurement of the dimensions of the glass block inside the furnace is very difficult. To enable the measurement of the changes in the dimensions of the glass block during drawing, the process was "frozen". Abrupt lowering of the temperature in the furnace resulted in the glass cooling rapidly and so be "frozen" in the shape it had inside the furnace. The so-called "frozen cone" was used to measure the changes in the dimensions of the glass block during the drawing process.

Figure 4 shows one of many comparisons of experimentally obtained data (from the "frozen cone" and the data acquisition system) with the results of numerical simulation. The change in the width of the glass ribbon in the z-direction from the point where shrinkage of the glass begins is presented for the same experimental conditions. The window glass preform, with dimensions: 8 × 50 × 1000 mm, was drawn with a drawing force of 1.92 N. The drawing velocity was $\upsilon_{dr} = 6.125 \times 10^{-2}$ m/s while the velocity of lowering the preform into the furnace was $\upsilon_{init} = 1.92 \times 10^{-4}$ m/s.

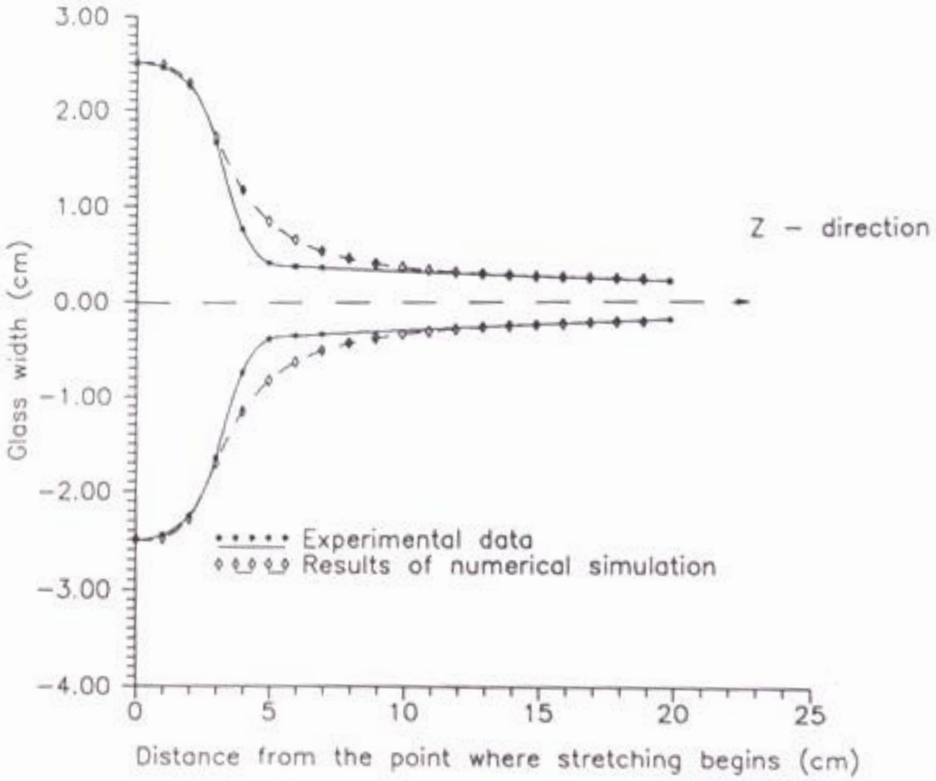

Fig. 4. Comparison of the experimental data with the results of numerical simulation.

There are certain deviations between the two data, but the agreement is good enough to plan experiments and so reduce the number of required experiments. Certain assumptions made in the model (one-dimensionality, neglection of conduction) are probably the reasons why the agreement model-experiment is not even better.

CONCLUSION

A one-dimensional mathematical model of drawing glass from rectangular preforms has been developed. The model includes momentum, heat and mass balance equations. The glass density, viscosity and specific heat were calculated as functions of temperature, and the glass emissivity was calculated as functions of both temperature and glass thickness. Two ordinary differential equations were obtained and solved using the Runge Kutta method.

The presented model takes into consideration various forces affecting the glass during the drawing process, not only the rheological force. In addition to this improvement, the fact that all glass properties are considered as functions of temperature distinguish this model from previous ones, where all glass properties were treated as constants. The disadvantage of the model is that, due to its one-dimensionality, the effect of surface tension on the edges of the drawn thin glass, which makes the edges more round and thick, is neglected.

Using the established model, it is possible to investigate the influence of different process parameters on the characteristics of drawn glass ribbon. It provides useful data for the construction of the furnace and enables the process to be optimized with a reduced number of experiments.

The validity of the numerical simulation was confirmed by experiments. Comparison of the results of the numerical simulation and the experimental data established that good agreement between them exists.

ИЗВОД

МОДЕЛ ИЗВЛАЧЕЊА ТАНКИХ СТАКЛЕНИХ ТРАКА ИЗ ПРЕДОБЛИКА

АЛЕКСАНДРА МИЛУТИНОВИЋ-НИКОЛИЋ,[1] РАДМИЛА ЈАНЧИЋ[2] и РАДОСЛАВ АЛЕКСИЋ[2]

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Развијен је једнодимензиони математички модел процеса извлачења танких стаклених трака. Модел обухвата билансе количине кретања, масе и енергије. Густина, топлотни капацитет и вискозитет стакла израчунати су као функције температуре, док је емисивност стакла дефинисана и израчуната као функција и температуре и дебљине стакла. Након увођења дозвољених поједностављења добијене су две обичне диференцијалне једначине, које су решаване коришћењем методе Runge Kutte-a. Модел је коришћен за испитивање утицаја различитих параметара процеса (брзине спуштања предоблика у пећ, аксијалног температурног профила пећи, силе извлачења и њеног смера и др.) на промену облика извучене стаклене траке за различите хемијске саставе стакла, као и геометријске карактеристике предоблика. Лабораторијски уређај за извлачење танких стаклених трака из призматичног предоблика обезбедио је потпуну контролу процесних параметара, њихово мерење и прикупљање података. Резултати нумеричке симулације упоређени су са експерименталним резултатима и констатована је задовољавајућа сагласност између ових резултата.

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REFERENCES

1. R. Aleksić, *Ph. D. Dissertation*, Faculty of Technology and Metallurgy, Belgrade, 1985
2. R. Aleksić, R. Jančić, *Mater. Sci. Forum* **214** (1996) 73
3. R. Jančić, R. Aleksić, *J. Serb. Chem. Soc.* **59** (1994) 587
4. V. N. Vasiljev, N. Dulnev, V. D. Naumchic, *Glass Technol.* **30** (1989) 283
5. W. Vogel, *Kemija stakla*, SKTH/Kemija u industriji, Zagreb, 1985
6. A. Milutinović-Nikolić, *MSc Thesis*, Faculty of Technology and Metallurgy, Belgrade, 1992
7. F. G. Salinov, *Proizvodstvo listovoga stekla*, Stroiizdat, Moskva, 1976
8. R. Viskanta, *AIChE Symposium Series-Heat Transfer* **245** (1985) 63
9. S. Cvijović, D. Simonović, D. Vuković, S. Končar-Đorđević, *Tehnološke operacije II-toplotne*, TMF, Beograd, 1980
10. F. Booth, D. E. Bourne, M. C. Harrison, *Glass Technol.* **13** (1972) 22
11. R. H. Perry, C. H. Chilton, *Chemical Engineer's Handbook*, Fifth McGraw-Hill, London, 1973
12. R. Gardon, *J. Amer. Ceram. Soc.* **44** (1961) 305-12
13. M. B. Volf, *Mathematical Approach to Glass - Glass Science and Technology 9*, Elsevier Amsterdam, p. 221, 1988
14. *Ibid*, p. 258
15. *Ibid*, p. 198
16. V. Simonović, *Numeričke metode*, Mašinski fakultet, Beograd, 1983, pp. 101-7
17. R. C. Andrews, A. H. Bedford, US Patent No. 3.420.648, Jan. 1969
18. S. Milinković, R. Aleksić, D. Mitraković, A. Sadibašić, *Glass Technol.* **34** (1993) 148.