Original Paper

Centrifugal casting of glass plates: a finite-element analysis of process parameter influence

Dominique Lochegnies, Charles Thibaud and Jérôme Oudin

Laboratoire de Génie Mécanique, URA CNRS D1775, Université de Valenciennes, Valenciennes (France)

For the first time, glass centrifugal casting is analyzed by finite-element viscoplastic models. First of all, the sensitivity of the process parameters is analyzed on the radius lengthening of a glass gob during casting using central processing unit time-saving models. The suitability of glass for centrifuging is evaluated, taking its temperature, viscosity, mould rotation speed and time dependency, casting time and initial gob shape into account. A refined finite-element analysis of an NBS-710 plate production is then achieved. The results are used in decision-aid process design curves which allow the manufacturer to efficiently adjust process parameters with regard to the desired final shape.

Schleudergießen von Glasscheiben: Finite-Element-Analyse des Einflusses der Prozeßparameter

Zum ersten Mal wird das Schleudergießen von Glas mit Hilfe von viskoplastischen Finite-Element-Modellen untersucht. Vor allem wird die Einflußnahme der Prozeßparameter auf die Veränderung des Glastropfenradius während des Gießvorganges mit zeitsparenden Zentraleinheitsmodellen analysiert. Die Eignung von Glas für das Schleuderverfahren wird abgeschätzt, wobei Temperatur, Viskosität, Rotationsgeschwindigkeit der Form und Zeitabhängigkeit, Schleuderzeit und ursprüngliche Tropfenform berücksichtigt werden. Sodann wird die Finite-Element-Analyse für die Herstellung einer Platte aus NBS-710-Glas weiterentwickelt. Die Ergebnisse werden in Kurven umgesetzt, die die Form beschreiben und es so dem Glasproduzenten ermöglichen, die Prozeßparameter sehr effektiv auf die gewünschte endgültige Form des Erzeugnisses auszurichten.

1. Introduction

Centrifugal casting is an automated mass-production glass-shaping process for forming axisymmetric items as simple as dishes or bowls, or as complex as television picture tubes or missile nose cones. The essential manufacturing steps are the generation of a gob, equivalent in volume to the final item to be cast, which is then dropped into the mould to get the initial gob shape, and the final shape is obtained after the mould rotation.

Unlike pressing, this process involves a minimum amount of energy consumption, but requires a maximum amount of practical knowledge because manufacturers have no direct control over thickness and shape of the product during its formation. Moreover, the centrifugal casting speed (the daily rate of plate production can exceed 9500 units per machine) as well as the high glass temperature (800 °C or more) do not allow the manufacturer to stop production in order to get an accurate picture of the gob deformation.

General studies dealt with the properties of glass: e.g., mathematical modelling of the temperature dependence of the glass viscosity has been achieved in the range of 500 to 1400 °C [1]. According to the Newtonian behaviour of glass, assumption limits have been shown especially at high strain rates, where the viscous flow of glass becomes nonlinear, which can drastically affect its workability in some cases [2 and 3]. Other papers have dealt with glass homogenizing at the furnace exit [4] and the heat-transfer phenomena at the molten glass/metal mould interface [5 and 6], depending on temperature, metal surface smoothness and chemical composition.

As a result of these previous studies on the properties of glass, numerical approaches using finite-element analysis have more recently been developed for models of pressing and blowing operations [7 to 9]. For centrifuging, available data is rather rare and only concerns the general purpose of the two processes, i.e., first, centrifugal forming with mould rotation round a vertical or horizontal axis [10], where glass is driven in the prescribed direction with a distribution finger; and second, centrifugal casting on a mould revolving around a horizontal axis without direct control over the molten glass distribution [11].

In this paper, the authors put forward a new numerical approach to centrifugal casting using finite-element models to optimize the process. First of all, a sensitivity analysis of the main centrifuging parameters (glass temperature and associated NBS-710 glass viscosity, mould rotation speed and time dependency, casting time, initial gob shape) is achieved with Central Processing Unit (C.P.U.) time-saving models for the finite-element analysis. Then, the previous results are confirmed with a refined finite-element analysis relating to the industrial production of NBS-710 glass plates. Finally, manufacturing decision-aid process design curves are provided in

Received May 18, 1994, revised manuscript August 8, 1994.

Table 1. Significant viscosity and equivalent strain rate of the NBS-710 glass

temperature in °C	viscosity in MPa s	critical strain rate for onset of non-Newtonian flow in s^{-1}
860	$3 \cdot 10^{-2}$	17
900	$1 \cdot 10^{-2}$	36
936	$5 \cdot 10^{-3}$	67
960	$3 \cdot 10^{-3}$	100
1015	$1 \cdot 10^{-3}$	223

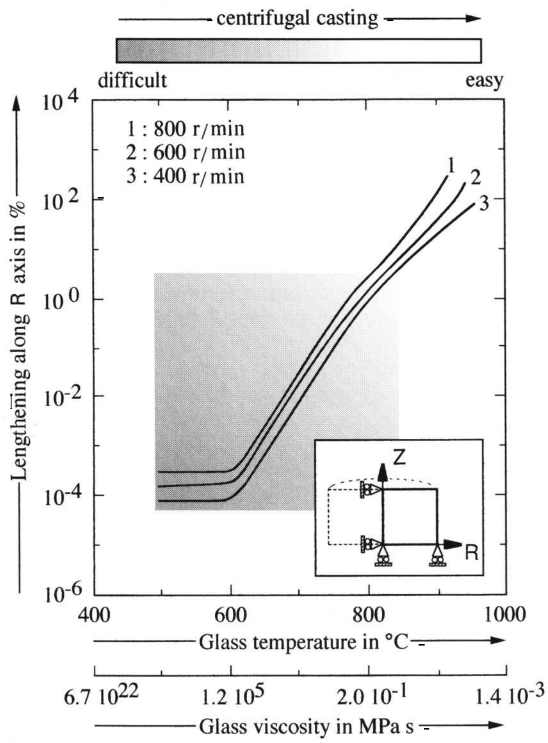


Figure 1. Effect of mould rotation speed, temperature and viscosity on radius lengthening after 1 s centrifuging.

order to establish the most efficient centrifuging parameters (mould rotation speed, initial gob temperature and time) with regard to the desired final product shape.

2. Centrifugal casting data base

In this study, the final industrial product of reference is an NBS-710 standard soda–lime–silica plate glass (chemical composition (in wt%): 70.5 SiO_2, 8.7 Na_2O, 7.7 K_2O, 11.6 CaO, 1.1 Sb_2O_3, 0.2 Al_2O_3 and 0.2 SO_3) modelled initially by a disc 260 mm in diameter and 4 mm thick (the dimensions usually observed for commercial items).

The following description is of interest considering standard manufacturing situations where the parison – an unshaped mass of molten glass before it is moulded into final form – is supposed to fall into the centre of an AISI 316 steel mould. In this case (representing 95 % of the production, with 5 % waste products or special non-axisymmetric items) centrifuging resembles an axisymmetric casting process, accomplished in industry via a mould rotation speed of 400 to 800 r/min and at temperatures from 800 to 1100 °C.

Centrifuging modelling is applied to NBS-710 soda–lime–silica glass properties. The glass is considered as a homogeneous body at high temperatures (above 800 °C), thanks to the elimination of bubbles by natural movements due to convection effects at the furnace exit. It is macroscopically isotropic because of its amorphous state. The NBS-710 molten glass stress/strain-rate relationship is represented by the Newtonian incompressible viscoplastic law in terms of the equivalent Von Mises stress $\bar{\sigma}$ and the equivalent strain rate $\dot{\bar{\varepsilon}}$ as follows

$$\bar{\sigma} = 3\,\eta(\theta)\,\dot{\bar{\varepsilon}} \tag{1}$$

where $\eta(\theta)$ is the viscosity of the NBS-710 soda–lime–silica glass. It is expressed in MPa s, from the Fulcher model [1], in the temperature range of 500 to 1400 °C, by

$$\lg(\eta(\theta)) = -8.655 + \frac{4266}{(\theta - 264.5\,°C)}\,. \tag{2}$$

For a given temperature, the model is valid if the glass strain rate does not exceed the critical strain-rate value (table 1): This condition is observed for mould rotation speeds and glass temperatures used in standard industrial centrifuging. Other characteristics are the density ($\varrho = 2.5 \cdot 10^{-6}\,kg\,mm^{-3}$) of the NBS-710 glass and the acceleration due to gravity (9.81 m s^{-2}).

3. Suitability of glass for centrifugal casting according to central processing unit time-saving finite-element models

In order to produce the industrial reference glass plate by centrifuging a gob in a rotating mould, the following centrifuging parameters need to be adjusted: initial gob shape before rotation, gob temperature, rotation speed level and time.

3.1. Analyses of main centrifuging parameters

Given that the initial gob shape is a cylinder 80 mm in diameter and 40 mm thick (this is an estimate of standard industrial gobs), the industrial purpose for centrifuging a plate 260 mm in diameter and 4 mm thick (section 2.) is to reach a lengthening of 225 % of the radius of the initial gob. Taking industrial practices into account, the sensitivity of the casting parameters is analyzed within the temperature range from 400 to 1000 °C (corresponding to the viscosity range of $6.7 \cdot 10^{22}$ to $1.4 \cdot 10^{-3}$ MPa s after equation (2)) of the NBS-710 glass), the mould rotation speed range from 400 to 800 r/min and the centrifuging time range from 1 to 3 s. A first finite-element mesh of the gob is made of 15 nodes and 10 Q4 reduced integration elements (figure 1): The achieved displacement values are stable

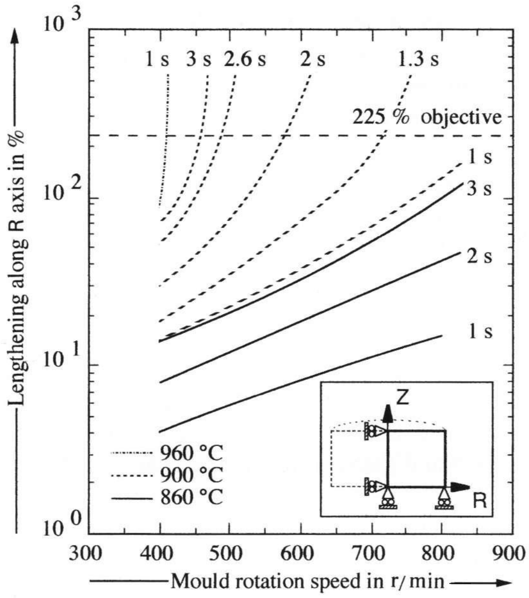


Figure 2. Effect of mould rotation speed, temperature and processing time on radius lengthening of a NBS-710 soda–lime–silica glass gob (2 R = 80 mm, Z = 40 mm).

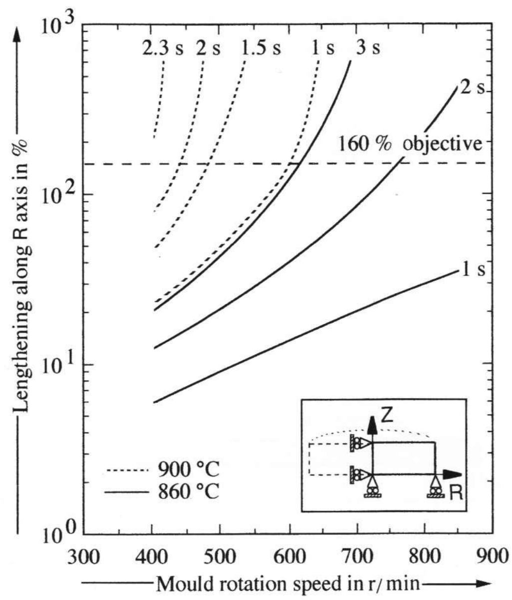


Figure 3. Effect of mould rotation speed, temperature and processing time on radius lengthening of a NBS-710 soda–lime–silica glass gob (2 R = 100 mm, Z = 27 mm).

at 9 or more meshes. The prescribed displacements are related to the axisymmetry $u_R = 0$ and to the glass/mould interface $u_Z = 0$; the contact is first considered as slippery to preserve the mesh during centrifuging; consequently, there is no need to remesh to reach the 225 % radius lengthening.

The first finite-element analysis concerns the influence of temperature on lengthening of the radius according to different rotation speeds (figure 1).

For NBS-710 glass, the minimum temperature necessary to reach a significant lengthening of the radius (greater than 3 % during the first second of centrifuging, in order to obtain a centrifuging total time of between 1 and 3 s) is established in this way: The NBS-710 glass temperature must be greater than 860 °C (i.e., the NBS-710 viscosity must be lower than $3 \cdot 10^{-2}$ MPa s (after equation (2)) to allow industrial centrifuging of the initial cylindrical gob, which is 80 mm in diameter and 40 mm thick.

The second step of the finite-element approach is a sensitivity analysis of the main casting parameters for three cylindrical gobs. With this aim, given the gob size usually used in plate manufacturing (100 mm in diameter and 27 mm thick; i.e., a gob which is three times as wide as high), two similar sizes of gob are defined: one 80 mm in diameter and 40 mm thick (section 2.) and another one 120 mm in diameter and 18.8 mm thick, both with the same NBS-710 glass volume of $212 \cdot 10^3$ mm^3. In fact, it is not technologically possible to produce a flatter gob, and centrifugal forces are also essential to spread the molten glass correctly onto mould-prints. The results are presented via process design curves (figures 2 to 4).

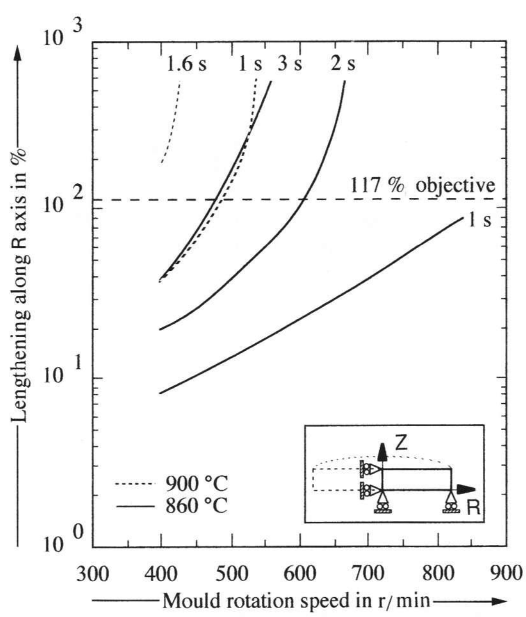


Figure 4. Effect of mould rotation speed, temperature and processing time on radius lengthening of a NBS-710 soda–lime–silica glass gob (2 R = 120 mm, Z = 18.8 mm).

First, in comparison to the three process design curves, the initial gob radius affects centrifuging in terms of radius lengthening: A greater initial radius will decrease the centrifuging time and make the radius lengthening easier. According to figures 2 to 4, it appears that spreading the initial gob is equivalent to translating the curves towards the top left corner.

Table 2. Influence of initial glass gob shape on radius lengthening after 1 and 2 s processing time with a mould rotation speed of 600 r/min at a temperature of 860 °C

lengthening for the 860 °C reference gob shape in %	lengthening of other 860 °C gob axisymmetric shapes in %	relative difference in %
2 *R* = 100 mm *Z* = 27 mm 1 s → 13.69 2 s → 37.71	2 *R* = 100 mm *Z* = 43.2 mm 1 s → 13.13 2 s → 28.63	4.09 24.08
	2 *R* = 100 mm *Z* = 31.2 mm 1 s → 13.54 2 s → 29.35	1.09 22.17
	2 *R* = 100 mm *Z* = 30.8 mm 1 s → 13.49 2 s → 30.58	1.46 18.91

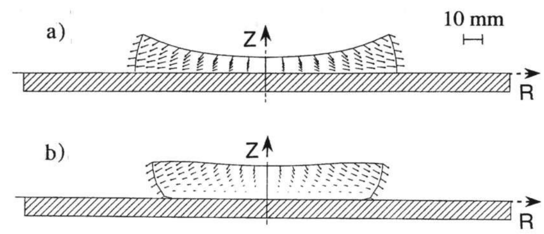
Secondly, for all gob radii, centrifugal casting of NBS-710 glass plates is also industrially impossible (the centrifuging time is too long) at a temperature below 860 °C (i.e., a viscosity greater than $3 \cdot 10^{-2}$ MPa s (after equation (2)).

Finally, these process design curves are the first step in the decision-aid: Each curve allows the manufacturer to know, according to a desired lengthening, the rotation speed and temperature values (e.g., with a gob 100 mm in diameter and 27 mm thick, the plate is cast in 2 s at a temperature of 860 °C and a mould rotation speed of 700 r/min).

3.2. New results on glass centrifugal casting

Previous results have to be corrected in line with influences on initial gob shapes, conditions of AISI 316 steel mould/NBS-710 molten glass contact and rise time on the normal mould rotation speed. This is illustrated with a gob 100 mm in diameter and 27 mm thick with a temperature of 860 °C (i.e., an NBS-710 glass viscosity of $3 \cdot 10^{-2}$ MPa s (after equation (2)) and a mould rotation speed of 600 r/min.

According to various kinds of feeders, different initial gob shapes are then defined with the volume constraint of a final plate, 260 mm in diameter and 4 mm thick, and related lengthenings after 1 and 2 s of processing are presented in table 2. According to the relative variations of lengthening, compared to the lengthening of the radius of the reference shape, i.e., a cylindrical gob 100 mm in diameter and 27 mm thick, the influence of the initial gob shape can be important, giving more than 18 % relative variation (table 2).



Figures 5a and b. Contact incidence on glass flow of a cylindrical NBS-710 glass gob (2 *R* = 100 mm, *Z* = 27 mm) at 860 °C after 2 s processing time for a mould rotation speed of 600 r/min with 40 % decrease in radius lengthening. Contact NBS-710 glass/AISI 316 steel mould a) modelled by $u_Z = 0$, b) considered as perfectly sticky.

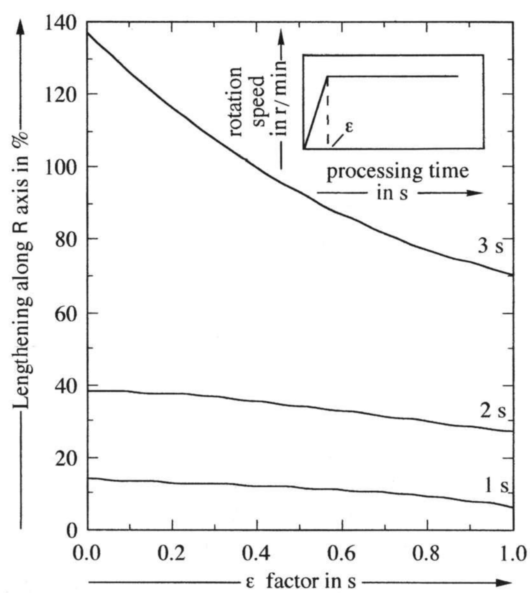


Figure 6. Influence of mould rise time on normal mould rotation speed (ε) on radius lengthening of a glass gob at 860 °C centrifuging with a speed of 600 r/min after a processing time of 1, 2 and 3 s.

Further, if the contact conditions between the steel mould and molten glass are considered as perfectly sticky, the glass flow is modified and consequently, the influence of the centrifugal force on radius lengthening is reduced (figures 5a and b).

The last sensitivity factor to take into consideration is the rise time on the normal mould rotation speed (figure 6): Indeed, industrial application of the process requires the gob to be dropped into a stopping mould. The rise time on the normal mould rotation speed (expressed by ε in figure 6), which depends essentially on the choice of motor, and which is all the more important because it can not be technologically neglected, appears as a significant parameter in the centrifugal casting process. For example, for a 0.6 s rise time, the new estimated

Table 3. Adjustment of decision-aid process design curves with a glass gob at 860 °C and a mould rotation speed of 600 r/min after 2 s of centrifugal casting (the rise time on normal mould rotation speed (ε) is taken to be 0.6 s)

initial gob shape	reference gob lengthening in %	correction ratio in %	new lengthening estimation in %
2 R = 100 mm, Z = 43.2 mm	37.7	− 24.1[1] − 40.0[2] − 14.7[3]	14.4
2 R = 100 mm, Z = 31.2 mm	37.7	− 22.2[1] − 40.0[2] − 14.7[3]	14.8
2 R = 100 mm, Z = 30.8 mm	37.7	− 18.0[1] − 40.0[2] − 14.7[3]	15.4

[1]) Initial gob shape influence (table 2).
[2]) Sticky contact modulation (figure 5b).
[3]) Rise time on normal running effects (figure 6).

radius is about 22.2 compared to 37.7, leading to a 14.7 % relative decrease.

Previous complements, which have been found for NBS-710 glass at a temperature of 860 °C and a mould rotation speed of 600 r/min, using finite-element models, show that modification of the initial gob shape, sticky conditions between molten NBS-710 glass and AISI 316 mould and rise time on the normal mould rotation speed are three main negative factors with regard to radius lengthening.

Thus, previous decision-aid process design curves for NBS-710 glass manufacture by centrifugal casting give relevant information on general NBS-710 suitability for centrifuging, which have to be corrected according to decision-aid complements because of overestimated radius lengthening. Table 3 shows the radius lengthening adjustments on a gob 100 mm in diameter and 27 mm thick at 860 °C and 600 r/min, taking initial gob shapes, contact conditions and a 0.6 s rise time on the normal mould rotation speed into account.

4. Refined finite-element analysis and decision-aid process design curves for plate manufacture

Previous analyses give general information about the suitability of centrifuging the NBS-710 glass. It now requires a more careful study of the manufacture of the plate 260 mm in diameter and 4 mm thick according to glass flow, thickness and temperature evolutions. Experiments have shown that the initial gob shape, a result of

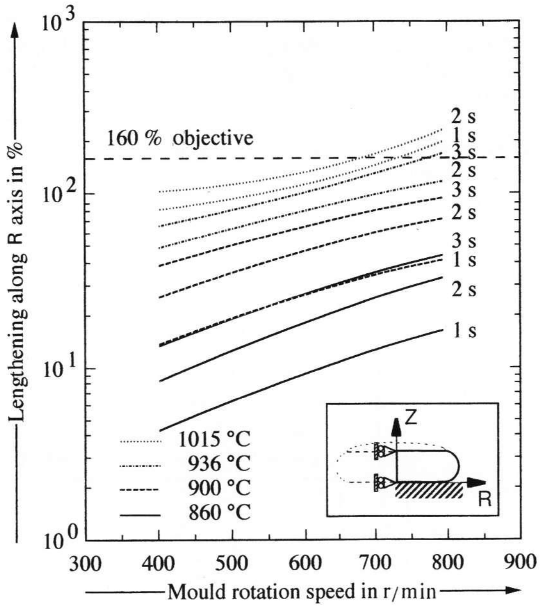


Figure 7. Refined decision-aid design curve concerning the effects of mould rotation speed, temperature and processing time on radius lengthening of a toric NBS-710 glass gob.

dropping a gob into the mould, is modelled with more precision when it is a full torus shape (a "pancake" shape) with a width three times its height (figure 7).

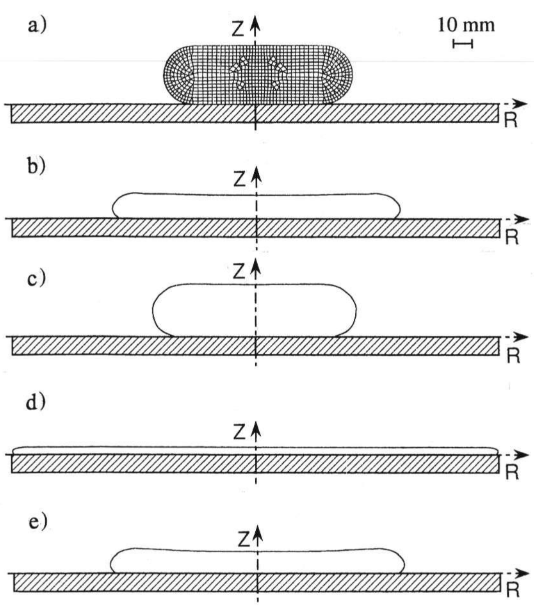
4.1. Glass flow and decision-aid process design curves for plate manufacture

425 4-node and 3-node axisymmetric isoparametric elements and 443 nodal points are used for the initial mesh; remeshing takes place during computation when elements are too distorted. The full torus 100 mm in diameter and 30.94 mm thick is now laid down on the mould and adheres perfectly (in fact, the mould must impart the rotation speed to the molten glass. Through experiments, this condition, corresponding to a temperature of about 650 °C at contact between the NBS-710 glass and the AISI 316 steel mould, is achieved by water cooling in the latter).

For the temperature range from 860 to 1015 °C and the rotation speed range from 400 to 800 r/min, the decision-aid process design curve (figure 3) is modified in figure 7. This process design curve shows that to achieve the centrifugal casting of the full torus (to get a centrifuging time of less than 3 s), a minimal NBS-710 glass temperature of 936 °C is necessary, i.e., an NBS-710 glass viscosity of $5 \cdot 10^{-3}$ MPa s. For a 160 % desired lengthening and a technically feasible centrifuging time, the manufacturer will also find information on the glass temperature and the associated mould rotation speed. Some typical manufacturers' decisions, taken as a result of the refined process design curve (figure 7) are summarized in table 4.

Table 4. Possible manufacturer decisions according to refined decision-aid process design curves

temperature in °C	necessary production time in s	mould rotation speed in r/min
936	3	800
1015	1	700
1015	2	600



Figures 8a to e. Glass gob deformation during the centrifugal casting process, a) initial gob shape and finite-element mesh, b) computed deformed 1015 °C gob after 0.2 s of centrifugal casting, c) computed deformed 936 °C gob after 0.2 s of centrifugal casting, d) computed deformed 1015 °C gob after 2 s of centrifugal casting (it corresponds to the final shape), e) computed deformed 936 °C gob after 2 s of centrifugal casting.

4.2. Glass thickness homogeneity along plate radius

In the end, industrial success in centrifuging relies on the final length reached and also on homogeneous thickness at the end of the process (the purpose, for the reference product, is fixed to 4 mm). According to two reference NBS-710 glass temperatures and mould rotation speeds (1015 °C, 700 r/min and 936 °C, 400 r/min), figures 8a to e show, with different deformation stages, that radius lengthening depends on both glass temperature and mould rotation speed.

If, at the start of the process, the inner curvature of the glass surface becomes parabolic, deviations from the parabola are achieved by a reduction in thickness. (The maximum strain rates, during deformation, are much lower than the critical values (table 1).) In order to have a more precise view of the distribution of thickness, average thickness evolution and relative thickness variation between maximal and minimal thicknesses along the radius of the plate, during centrifugal casting (until

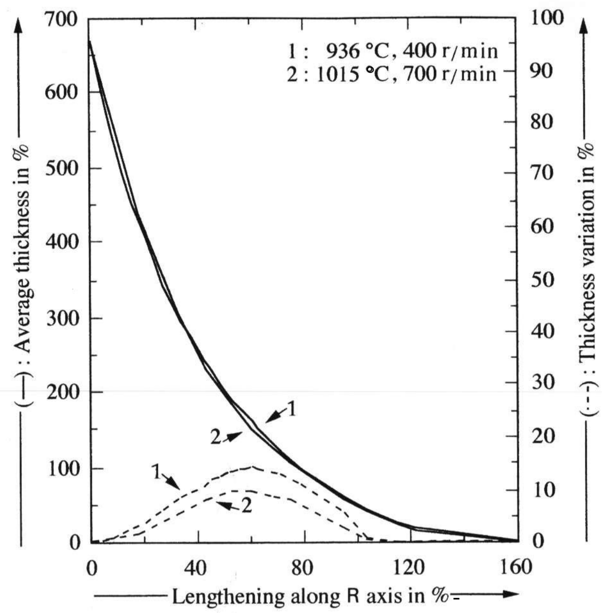


Figure 9. Comparison of thickness distribution of glass gob versus radius lenthening.

the objective of a radius lengthening of 160 %) are presented in figure 9.

The distribution of thickness is only dependent on the lengthening of the radius; if, at the start of the process, the gob (936 °C, 400 r/min) has a less homogeneous distribution of thickness (equivalent to an upper thickness variation), the average thickness evolution versus radius lengthening is similar for the two gobs. The only difference is the amount of time needed to produce the product changes: 2 s with a gob (1015 °C, 700 r/min) compared to 8 s for the other one. The role of the initial glass temperature is simply to give enough flexibility to reach the final shape in the first 3 s.

4.3. Glass temperature evolution during the process

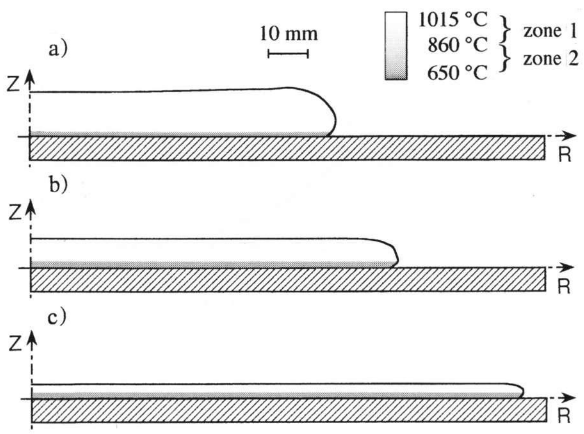
Finally, the temperature evolution takes place in order to adjust previous conclusions. The AISI 316 mould has a constant temperature of 650 °C to maintain adhesion with the initial glass melted at 1015 °C; the ambient air (room) temperature during casting is 600 °C, with a $3 \cdot 10^{-5}$ W/(mm^2 K) convective heat-transfer coefficient (including the radiation participation). Other thermophysical properties are specified in table 5.

Temperature maps, obtained during the centrifuging of the 1015 °C gob, are given in figures 10a to c: When glass is chilled against the mould wall, a relatively thin surface layer cools, and its viscosity increases. At the start, the thickness of the layer will be approximately proportional to the square root of the time of contact.

Thermal analysis distinguishes two distinct zones. The first one (zone 1 in figures 10a to c) is close to the

Table 5. Thermophysical properties and heat-transfer coefficients of glass and mould

material	density in kg mm^{-3}	specific heat capacity in J kg^{-1} K^{-1}	thermal conductivity in W mm^{-1} K^{-1}	contact heat-transfer coefficient in W mm^{-2} K^{-1}
glass NBS-710	$2.5 \cdot 10^{-6}$	1250	$1.7 \cdot 10^{-3}$	$8 \cdot 10^{-3}$
mould AISI 316	$7.8 \cdot 10^{-6}$	500	$1.6 \cdot 10^{-2}$	



Figures 10a to c. Thermal study of a NBS-710 glass gob with an initial temperature of 1015 °C; thermal diffusion shown after a) 0.25 s, b) 0.55 s, c) 2 s.

contact surface between molten glass and steel, with temperatures below 860 °C; it resists inner centrifugal forces. The second one (zone 2 in figures 10a to c) is necessary to the success of the process because it spreads across the mould surface.

If thermal diffusion between the mould and the glass is instantaneous in the first 0.8 mm of the glass, it does not really increase during the process. It is concluded that:

- near the mould (0.8 mm distance), the glass is quasi-fixed (the NBS-710 viscosity is greater than $3 \cdot 10^{-2}$ MPa s), because of the related temperature dependence of the viscosity (table 1);
- the glass has a quasi-homogeneous temperature throughout the process, depending on the initial gob temperature.

This justifies analyses of the centrifugal casting under adiabatic hypothesis and sticky mould/NBS-710 glass contact conditions.

5. Conclusions

Finite-element viscoplastic models have been developed for the first time to optimize centrifugal casting.

a) With central processing unit time-saving finite-element models, the suitability for centrifuging the glass is analyzed via sensitivity analysis of the casting parameters on radius lengthening of the gob. New principal results are obtained from:

- the minimum NBS-710 glass temperature to form the gob during the process,
- the relationship between NBS-710 glass temperature and AISI 316 steel mould rotation speed,
- the correction of the two previous parameters, according to the initial gob geometry, the mould rise time on the normal mould rotation speed and the NBS-710 glass/AISI 316 steel mould contact.

b) For a production of plates from NBS-710 glass, finite-element analysis is carried out; decision-aid process design curves are proposed to the manufacturer to establish casting parameters according to the final product shape.

6. References

[1] Fulcher, G. S.: Analysis of recent measurements of the viscosity of glasses. J. Am. Ceram. Soc. **8** (1925) no. 6, p. 339–355.

[2] Simmons, J. H.; Ochoa, R.; Simmons, K. D. et al.: Non-Newtonian viscous flow in soda–lime–silica glass at forming and annealing temperatures. J. Non-Cryst. Solids **105** (1988) p. 313–322.

[3] Simmons, J. H.; Simmons, C. J.: Nonlinear viscous flow in glass forming. Am. Ceram. Soc. Bull. **68** (1989) no. 11, p. 1949–1955.

[4] Cable, M.: The principles of homogenizing of glass melts. Glastech. Ber. **63K** (1990) p. 308–322.

[5] Fellows, C. J.; Shaw, F.: A laboratory investigation of glass to mould heat transfer during pressing. Glass Technol. **19** (1978) no. 1, p. 4–9.

[6] Lukisher, E. H. M.; Flow, Z. C.: Résistance thermique à l'interface verre–métal et échange thermique lors du formage du verre. (Orig. Russ.) Fiz. Khim. Stekla **10** (1984) no. 5, p. 630–634.

[7] Cormeau, A.; Cormeau, I.; Roose, J.: Numerical simulation of glass-blowing. In: Pittman, J. F. T.; Zienkiewicz, O. C.; Wood, R. D. et al. (eds.): Numerical analysis of forming processes. New York (et al.): Wiley 1984. p. 219–237.

[8] Lochegnies, D.: Oudin, J.: Simulations numériques par éléments finis des écoulements newtoniens: Application au formage isotherme du verre. In: 11ème Congrès Français de Mécanique, Lille-Villeneuve d'Ascq (France) 1993. No. 2, p. 29–31.

[9] Williams, J. H.; Owen, D. R. J.; Sa, J. M. A. C.: The numerical modelling of glass forming processes. In: XIV International Congress on Glass, New Delhi (India) 1986. Coll. papers. Vol. 3. Calcutta: Central Glass & Ceram. Res. Inst. 1986. p. 138–145.

[10] Trier, W.: Forming processes of hot glass. In: Mazurin, O. V. (ed.): Glass '89. XVth International Congress on Glass, Leningrad 1989. Survey papers. Leningrad: Nauka 1988. p. 494–515.

[11] McLellan, G. W.: Corning Glass Works. In: DeLeuxe Library Edition (ed.): Encyclopedia Americana. Vol. 12. Danbury, CT: Grolier 1991. p. 784–792.

0195P003