Experimental methodology for the determination of the heat transfer coefficient at the glass/mould interface

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A new laboratory testing for the analysis of the glass/mould contact is proposed. The various components of the installation and their kinematics, the choice of the measuring instruments and their accurate location are described. From the temperature evolution in the contact area, coupling inverse method and thermal computations by finite difference method leads to the transient estimation of the heat exchange coefficient at the glass/mould interface.

Introduction

In glass forming, the optimization of the process using numerical modeling requires the accurate knowledge of the heat exchange between the glass and the forming tools. The determination of the heat transfer coefficient between the two materials is complex: it results from a thin gap of air and combustion product from the lubrication between the glass and the forming tools. The thermal properties of the thin gap depend especially on the thermal properties of materials, the initial temperatures before contact, the contact pressures, the presence of lubricants and oxide coatings. These parameters limit or not the heat transfer at the glass/tool interface and then settle the value of the heat transfer coefficient.

Several experimental investigations have been developed to get a better understanding of the heat exchange. Thus, specific measurements of the heat transfer were realized using thermocouples inside the forming moulds during laboratory[1,2] and industrial testing[3,4]. In the first ones, initial conditions before contact are better controlled and measurements of the temperature evolution, in different forming situations, are easier. In second ones, real conditions of forming are present but measurements are relatively difficult. In Fellows and Shaw works[1], the glass hold by a graphite crucible is blown with a gas mixture in hot mould material. From the measured glass surface evolution, the heat transfer coefficient is determined for several initial glass and mould temperatures and pressures. In Loulou and al. works[2], a small glass patch and a metallic substrate are put into contact and the measurements are carried out inside the metallic substrate. The authors give here the evolution of the heat transfer coefficient taking into account the semi-transparent character of glass. The previous studies in industrial testing[3,4] concern the measurement of the temperature evolution in the mould during the production of bottle by blow-and-blow. The non-homogeneous temperature map of the glass gob is not correctly known and consequently, the determination of the heat transfer coefficient is then difficult.

In all these experimental studies, the authors clearly precise the importance of the accurate choice and location of thermocouples to get relevant temperatures. The thermocouple must have a short response time (several measurements below 1s) in order to correctly measure the rapid increase in the temperature (a maximum rise of 150°C). In this way, in place of commercial thermocouples, some of the authors manufacture their own thin thermocouples with diameter reaching 25μm. In each case, the thermocouples have nor to be placed close to the interface (the risk of damage would be important) neither too distant from the contact[5] (the sensitive of measurements would be small, and the transient evolution of the heat transfer would be difficult to be determined).

From experimental measurements, thermal models taking into account or not the radiative part have been developed to determine the heat transfer coefficient. Mac Graw[6] firstly deduces that the heat transfer is mainly carried out by conduction. He defines the heat transfer coefficient as the ratio of the heat exchange during the time t by the product of the surface of exchange, the time of contact and the difference of mean temperatures of surfaces. In the same way, based on pure conduction, Pchelyakov and al. [7] give an original expression of the heat transfer coefficient as the ratio between the conductivity of the air by the thickness of the gap. The thermal compression and the plunger pressure are taken into account in the computation of this thickness. Recently, using previous studies, Stork[8] affirms again that the influence of the radiative heat flux is negligible compared to the conductive heat flux. However, others authors[2,4] think that the semi-transparent character of the glass has to be taken into account to determine precisely the heat transfer coefficient. They introduce in the computation of the glass/mould heat transfer the radiative part. In these approaches, few significant experimental results are given to confirm the radiative effect.

In this paper, we present a new laboratory testing for the analysis of the glass/mould contact. From the measured temperature evolution in mould specimen, coupling inverse method and thermal computations by finite difference method leads to the transient estimation of the heat exchange coefficient at the glass/ mould interface. As Mac Graw, Pchelyakov and Stork approaches[6,7,8], we do not take into account the radiative part in the thermal model for the determination of the heat transfer.

Description of the laboratory testing

The principle of our laboratory testing (Figure 1) is to put hot glass into contact with a hot mould specimen (height: 30mm, diameter: 60mm). Glass, contained in a steel crucible (height: 45mm, diameter: 50mm), is initially heated at a homogeneous temperature about 1100°C inside an electric furnace. The inside of the furnace is under argon atmosphere to avoid the oxidation of the crucible and then the pollution of the glass specimen by oxide coating. After uniform heating, the crucible is rapidly carried and placed in the center of the measurement installation; an infrared radiation pyrometer measures then the initial temperature at the glass surface. A first jack immediately pushes the glass into contact with the hot mould specimen; a second jack makes it possible to reach the required contact pressure, under control of a pressure valve. According to the tests, the mould specimen is heated by an inductor at a homogeneous temperature between 20°C and 600°C. Three thermocouples record the temperatures in the mould specimen during the four first seconds of the contact. The thermocouples are commercial standard ones : butt-welded wire thermocouples of 250 μm diameter, 200ms response time. The thermocouples are placed to 3mm, 6mm and 9mm from the mould surface specimen, parallel to isotherms to avoid thermal troubles. An acquisition system completes the equipment and temperatures are recorded with a 5Hz frequency.

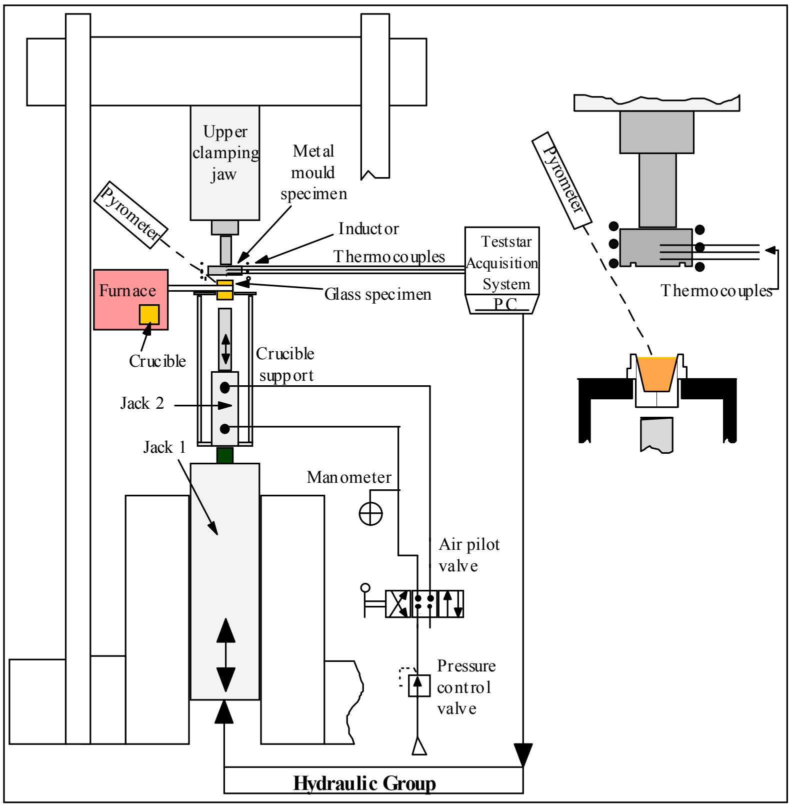

Figure 1: Description of the laboratory testing.

Finite Difference Formulation and Inverse Method

To find the transient evolution of the heat transfer coefficient, we use a one-dimensional thermal modeling by the finite difference method with an explicit scheme[9]. The heat flux in the axial directions of the equipment is large compared to the flux in the radial directions and justifies the choice of a one-dimensional model. The glass and mould regions are discretized by 600 nodes, the distance between each node is 0.1mm. Using transient evolution of h(t) given by Pchelyakov[7] (Figure 2), temperature evolutions at our three thermocouples obtained by the finite difference model are given in Figure 2.

We have developed an inverse method using the previous finite difference model and our experimental temperatures at the three thermocouples during the 4s contact time. The transient evolution of the heat transfer h(t) is modeled by couples (h_i,t_i) with h_i the heat transfer coefficients at time t_i. The choice of a sufficient number of time t_i in the 4s of contact will give a correct idea of the real transient heat tranfer. The purpose of the inverse method is to determine, iteratively, the transient evolution of the heat transfer h(t) : h_1, h_2, h_3, h_4, h_5… by the minimization of an error $E(h_1, h_2, h_3, h_4, h_5…)$, defined as the difference, between the temperature evolutions computed by finite difference method T* and the experimental temperature Te measured by the three thermocouples.

$$E(h_1, h_2, h_3, h_4, h_5 \ldots) = \frac{1}{2}\sum_{i=1}^{m}(T^*(h_1, h_2, h_3, h_4, h_5 \ldots) - T_e)^2 \quad (1)$$

m represent the number of measurements for the three thermocouples for the 4s contact time. The algorithm of Schnur and Zabaras[10] is used to minimize the function E(h_1, h_2, h_3, h_4, h_5…). After an initial choice of the evolution of the heat transfer coefficient $h(t)^{(0)}$=(h_1, h_2, h_3, h_4, h_5…$)^{(0)}$, an iterative sequence is performed to find the best adapted corrections dh(t)=(dh_1, dh_2, dh_3, dh_4, dh_5…) and to reduce the error E(h_1, h_2, h_3, h_4, h_5…). At the iteration k, the correction dh(t)=)=(dh_1, dh_2, dh_3, dh_4, dh_5…) is obtained by:

$$\left[(J^{(k)})^T J^{(k)} + \lambda^{(k)} I\right] dh(t)^{(k)} = -\left(J^{(k)}\right)^T r^{(k)} \quad (2)$$

where, at the iteration k, $J^{(k)}$ is the jacobian matrix of E(h_1, h_2, h_3, h_4, h_5…), $r^{(k)}$ is the residual vector ($T^{*(k)}$ -Te), λ, the non-negative scalar defined by Levenberg-Marquardt[11] for the convergence of the iterative scheme, I is the identity matrix.

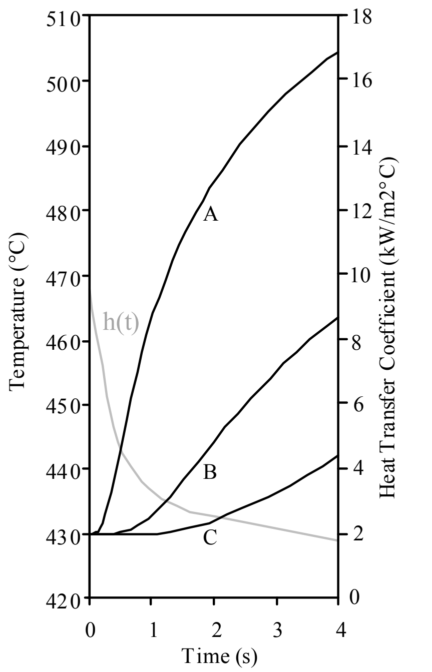

Figure 2: Temperature evolution at 3 mm, 6mm and 9 mm (respectively A, B and C) with initial temperature of the glass Tg=1100°C, the mould Tm=430°C and h(t) [7].

Validation and results

Before identification, a first sensitivity analysis[11] is realized on the thermal parameters of the finite difference model : h_1, h_2, h_3, h_4, h_5…, the thermal heat coefficients, (k_m, k_g) the conductivities of the mould and the glass, (C_m, C_g) the specific heats of the mould and the glass (in our case, the glass is a soda-lime-silica one and the mould is made of AISI310). The error function (1) is now function of h_1, h_2, h_3, h_4, h_5…, k_m, k_g , C_m, C_g . With the sensitivity analysis, we have estimated the influence of each previous parameter on the temperature evolution for the three thermocouples and also for the glass surface. For example, a variation of 20% of the specific heat produces an increase of the glass surface temperature of 100°C at 4s (in this case of initial temperature of the glass Tg=1100°C and an initial temperature of the mould Tm=430°C) .

The second step is the validation of the experimental devices. After the calibrating of thermocouples, first trials have been carried out and will be presented, with the sensitivity analysis, the day of the 6th ESG Conference.

Conclusions

A new laboratory testing is developed to analyze the heat transfer between glass and mould in contact. Using jacks, a perfect control of the contact pressure is obtained and with the help of thermocouples inside the mould specimen, the temperature evolution at three locations are recorded. The identification of the transient evolution of the heat transfer coefficient at glass/mould interface is made by coupling finite difference modeling and inverse method. Next step of the job will be to use this test to quantify more precisely the importance of lubricant in the heat transfer during glass forming.

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