Original Paper

Analysis of heat transfer during glass forming

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A thermal model is described which is intended to simulate internal heat transfer in glass being cooled by the mold and plunger after pressing. The heat transfer analysis in glass accounts for the spectral nature of radiation, the dependence of the thermophysical properties of glass on temperature and the contact heat transfer between mold and glass as well as plunger and glass during and after pressing. Heat exchange between glass and mold as well as plunger across a very small gap by contact conduction and thermal radiation are also accounted for. To assess the utility of the Rosseland diffusion approximation for radiative transfer, the results are compared with those based on rigorous formulation of radiative transfer. Numerical solutions have been obtained for typical conditions simulating symmetric and asymmetric cooling as well as cyclic operation, and the results are presented and discussed. During the dwell time thermal contact conduction between the glass and the mold as well as plunger is the dominant heat extraction mechanism from the glass. Results show that radiation from the surface of the glass plays a relatively small part in the heat extraction process, but radiation from the interior of the glass is much more significant but less important than thermal contact conduction.

Untersuchung der Wärmeübertragung bei der Glasformgebung

Es wird ein thermisches Modell zur Simulierung der Wärmeübertragung im Inneren von Glas beschrieben, das nach dem Preßvorgang durch die Form und den Plunger gekühlt wird. Die Wärmeübertragungsanalyse trägt der spektralen Natur der Strahlung, den thermophysikalischen Eigenschaften des Glases in Abhängigkeit von der Temperatur und dem Wärmeübergang beim Kontakt zwischen Form und Glas sowie Plunger und Glas während und nach dem Preßvorgang Rechnung. Ebenso wird der Wärmeaustausch zwischen Glas, Form und Plunger durch einen sehr kleinen Spalt über Wärmeleitung und thermische Strahlung berücksichtigt. Die Ergebnisse werden mit solchen, die auf exakten mathematischen Formulierungen der Strahlungsübertragung basieren, verglichen, um die Gültigkeit der Rosseland-Diffusionsnäherung für die Strahlungsübertragung zu beurteilen. Es sind numerische Lösungen für typische Bedingungen erhalten worden, die symmetrisches und nichtsymmetrisches Kühlen sowie einen periodischen Verlauf simulieren. Die Resultate werden vorgestellt und diskutiert. Während der Dauer des Kontakts ist die Wärmeübertragung durch Wärmeleitung zwischen Glas, Form und Plunger der dominierende Mechanismus der Wärmeabfuhr aus dem Glas. Die Ergebnisse zeigen, daß die Oberflächenstrahlung des Glases eine relativ geringe Rolle beim Wärmeabfuhrvorgang spielt. Die Strahlung aus dem Glasinneren ist viel maßgebender, jedoch weniger wichtig als die Wärmeübertragung durch Wärmeleitung.

1. Introduction

Cooling of glass under different forming conditions is an important step in glass manufacture, and understanding of the process is critical towards improving this vital stage of operation. Understanding of glass cooling is essential in order to reduce thermal or forming stresses and defects. For example, Tatsukoshi et al. [1] have shown that the depth of a sink mark observed on the product is strongly affected by the initial temperature of the plunger and mold, pressing duration and pressure. The quality of glass products such as lenses, TV panels and others which are manufactured by pressing can be affected by so-called sink marks, which are slight dents on the surface of the product.

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Heat transfer in high-temperature glass is by combined conduction and internal thermal radiation [2], and these processes are well understood [3 and 4]. Computational difficulties arise under glass forming and cooling conditions owing to the complex shapes of glass objects being formed. Heat transfer from the hot glass being pressed to the mold and/or the plunger is very complex, has received much less research attention and is not fully understood.

The experimental and theoretical/computational studies of heat transfer during glass forming have been reviewed by Fellows and Shaw [5] and more recently by Tatsukoshi et al. [1 and 6]. However, understanding and modeling of heat transfer during forming of glass and subsequent cooling is still not satisfactory. For example, Fellows and Shaw [5] neglected internal radiation in glass. They assumed that heat transfer is only by conduction. They determined the time-dependent effective heat-transfer coefficient (thermal contact conductance) by measuring the mold temperature and heat flux across the interface. The thermal contact conductance $h_c(t)$ was defined by

$$h_c(t) = q(t)/[T_g(0,t) - T_m(0,t)] \quad (1)$$

where $q(t)$ is the instantaneous heat flux at the interface, and $T_g(0,t)$ and $T_m(0,t)$ are the glass surface and mold surface temperatures, respectively. The conductance was found to depend on the initial glass and mold temperatures as well as the pressure acting across the interface.

Very recently, Storck et al. [7] studied theoretically heat transfer during parison forming of glass. The spectral nature of radiative transfer in glass was neglected. They found that the influence of internal radiation in glass is negligible in comparison to conduction during parison forming and determined the temperature distribution in glass to be symmetrical.

The first purpose of this paper is to set up a physical model of internal heat transfer in the glass and of heat exchange across the glass-mold boundary for gaining understanding of cooling behavior of glass after forming. The second purpose of the paper is to assess the utility of the Rosseland diffusion approximation for radiative transfer, because rigorous formulation of radiative transfer in intricate-geometry glass objects being pressed is very complex. The intent is not to simulate the geometry and process details during a complete cycle, but only during the forming and cooling phases when the heat extraction from the glass formed is most intense. The problem is formulated for a one-dimensional cooling of a glass panel (sheet) and is based on fundamental principles of heat transfer in glass by combined conduction and radiation and on current understanding of contact heat transfer across a small gap (i.e., between glass and mold).

2. Analysis

We consider the cooling (during and after pressing) of an infinite plane sheet of glass between infinite molds (mold and a plunger). Heat transfer between glass gob before the glass fills the space between plunger and mold is not considered. A schematic of the model is shown in figure 1. Although the system is idealized, the model should still enable the effects of changes in the various parameters controlling the cooling processes to be examined and would not involve complications inherent in cylindrical or other even more complex geometries. Except for the corners, the geometry would approximate well, for example, the cooling of a TV panel or the screen of a computer monitor. The outside surfaces of the mold have cooling air or water applied continuously or at a desired time cycle.

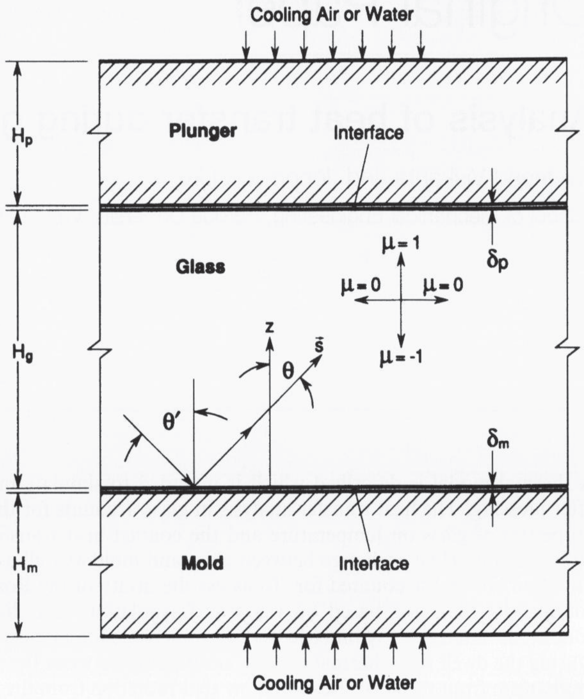


Figure 1. Schematic model of the mold with glass.

The following assumptions are made in the analysis:

a) Heat transfer in the glass, mold and plunger is transient and one-dimensional. The mass of the gas in the gap between the glass and the mold is negligible in comparison to the mass of glass and is neglected.

b) Heat transfer in the glass sheet is by combined conduction and radiation with thermophysical properties dependent on temperature.

c) The glass is taken to be semitransparent to radiation for wavelengths λ smaller than the cutoff wavelength λ_c and opaque (surface radiation) for $\lambda > \lambda_c$.

d) Heat transfer in the glass mold and plunger is by conduction only.

e) The plunger and the mold are not perfectly smooth, and there is a finite gap between the plunger and glass (δ_p) as well as the mold and glass (δ_m). These gaps are controlled by the rms roughness of the mold construction materials and the pressure imposed by the plunger. The gaps are assumed to be filled with air. The presence of residues from repeated mold lubrication is ignored, and the thermophysical properties of the gas filling the gaps are assumed to be those of air.

f) Hot glass is semitransparent to radiation, i.e., capable of absorbing and emitting but not of scattering radiation. The glass is at local thermodynamic equilibrium for which Planck's and Kirchhoff's laws are valid [8], and the spatial dimensions of the glass sheet are much larger than the wavelength of radiation in the semitransparent band, i.e., the coherence effects are negligible.

g) The mold and plunger surfaces are assumed to be diffuse emitters and reflectors of radiation.

h) During cooling glass shrinks and its thickness decreases, and the shrinkage during the process is accounted for using the thermal expansion coefficient of the glass.

Based on the assumptions made, the energy conservation equations in the three components of the system are:

– for the plunger:

$$\varrho_p c_p \frac{\partial T_p}{\partial t} = \frac{\partial}{\partial z}\left(k_p \frac{\partial T_p}{\partial z}\right) \tag{2}$$

– for the glass:

$$\varrho_g c_g \frac{\partial T_g}{\partial t} = \frac{\partial}{\partial z}\left(k_g \frac{\partial T_g}{\partial z}\right) - \frac{\partial F}{\partial z} \tag{3}$$

– for the mold:

$$\varrho_m c_m \frac{\partial T_m}{\partial t} = \frac{\partial}{\partial z}\left(k_m \frac{\partial T_m}{\partial z}\right) \tag{4}$$

where the subscripts p, g and m stand for plunger, glass and mold, respectively. In equation (3) F denotes the local radiative flux in the part of the spectrum where the glass is semitransparent to radiation. Analysis for predicting this flux is presented in the following subsection.

The thermal boundary conditions at the outer surfaces, i.e., plunger on the top and mold on the bottom, are expressed in a form of a heat transfer coefficient,

$$-k_i \frac{\partial T_i}{\partial z} = h_i (T_i - T_{amb,i}) \tag{5}$$

where i denotes either the plunger or the mold, and h_i is an appropriate convective heat transfer coefficient which depends on the fluid used and flow/thermal conditions. The coolant can be water or air. If the coolant is air, radiation from the surface may be significant and may have to be considered.

At the glass/mold and glass/plunger interfaces glass is being cooled by contact conduction and radiation during pressing. Thermal energy balances at the bottom and top surfaces of the glass layer yield the requisite conditions. For example, at the bottom surface ($z = 0$) the boundary condition is

$$-k_g \frac{\partial T_g}{\partial z}\bigg|_{z=0} = h_c (T_g - T_m) + \pi \int_{\lambda_c}^{\infty} \left[\frac{I_{b,\lambda}(T_g) - I_{b,\lambda}(T_m)}{(1/\varepsilon_{g,\lambda}) + (1/\varepsilon_{m,\lambda}) - 1}\right] d\lambda \tag{6}$$

where the first term on the right-hand-side of this equation accounts for the gap thermal conductance and the second for the radiation in the part of the spectrum where glass is considered to be opaque to thermal radiation. The thermal contact conductance of the gap h_c between the metal mold and glass was calculated using accepted methodology by accounting for the mold roughness, contact pressure, gas in the gap and other factors such as the temperature jump [9]. The gap conductance h_c was expressed as

$$h_c = k_{gap}/(\delta_m + 2g) \tag{7}$$

where k_{gap} is the thermal conductivity of the gas in the gap, and δ_m is the mean physical gap which depends on the mean roughness and contact pressure. The temperature jump distance g depends on the accommodation coefficient and the thermophysical properties of the gas filling the gap. The interference and radiation tunneling effects caused by the very small (δ_m is of the order of 1 µm) gap filled with a dielectric medium (gas) have been neglected in writing the second term in equation (6). Cravalho et al. [10] and Boehm and Tien [11] have shown that tunneling and interference effects can be appreciable if $\delta_m/\lambda < 1$, and the predictions of radiation heat exchange can differ significantly from those calculated using the second term on the right-hand-side of equation (6). Unfortunately, precise calculations for materials and gap height δ_m changing with time (because of the contraction) have not been analyzed and are not available.

The thermal boundary condition at the glass/plunger interface ($z = H$) can be written in a similar manner as equation (6) and need not be repeated here. The only difference is that the temperature and radiation properties of the mold must be replaced with those of the plunger.

The initial temperatures of the mold and plunger of a pressing system operating in a cyclic manner are difficult to specify. These temperatures can be measured or established computationally by performing a large number of pressing cycles. In this analysis the initial mold and plunger temperatures are chosen on the basis of observations in typical forming operations. The initial temperature of the glass is taken to be uniform

$$T_g(z,0) = T_{g,0}(t=0). \tag{8}$$

2.1 Radiative transfer in glass – rigorous formulation

In the rigorous formulation, the glass is considered to be semitransparent to radiation. That is, for $0 < \lambda < \lambda_c$, where λ_c is the cutoff wavelength, the glass is considered to be semitransparent to radiation, and the spectral absorption coefficient is taken to be a function of both temperature and wavelength. For $\lambda_c < \lambda < \infty$ glass is assumed to be opaque, and radiation is treated as a surface phenomenon. In view of the deficiencies of the diffusion approximation for radiative transfer in thin glass layers [12], radiation transfer is formulated rigorously. The radiative flux divergence, $\partial F/\partial z$, in the total energy conservation equation (3) can be expressed as [3]

$$\frac{\partial F}{\partial z} = \int_0^\infty \frac{\partial F_\lambda}{\partial z}\,\mathrm{d}\lambda = \int_0^\infty \kappa_\lambda\,[4\pi\, n_\lambda^2\, I_{\mathrm{b},\lambda}(T) - G_\lambda(z)]\,\mathrm{d}\lambda\,. \qquad (9)$$

The local spectral radiative flux $F_\lambda(z)$ and the spectral irradiance $G_\lambda(z)$ are defined as

$$F_\lambda(z) = 2\pi \int_{-1}^{1} I_\lambda(z,\mu)\,\mu\,\mathrm{d}\mu \qquad (10)$$

and

$$G_\lambda(z) = 2\pi \int_{-1}^{1} I_\lambda(z,\mu)\,\mathrm{d}\mu \qquad (11)$$

respectively. In these equations $I_\lambda(z,\mu)$ denotes the spectral radiation intensity which at any position z is a function of direction $\mu (= \cos\theta)$ (see figure 1). This intensity is obtained by solving the radiative transfer equation (RTE) within the layer of glass [3 and 8],

$$\mu\,\frac{\mathrm{d}I_\lambda}{\mathrm{d}z} = \kappa_\lambda\,[n_\lambda^2\, I_{\mathrm{b},\lambda}(T) - I_\lambda(z,\mu)] \qquad (12)$$

where $I_\lambda(z,\mu)$ is the spectral intensity of radiation and is a function of position, direction and wavelength, and $I_{\mathrm{b},\lambda}(T)$ is the spectral intensity of blackbody radiation given by Planck's function. The boundary condition for equation (12) at an optically smooth free surface at $z = 0$ from the interface conditions between the glass and the mold is written as

$$I_\lambda(0,\mu) = \tau_\lambda(\mu^{\mathrm{o}})\, I_{\mathrm{m},\lambda} + \varrho_\lambda(\mu)\, I_\lambda(0,-\mu) \qquad (13)$$

where $I_{\mathrm{m},\lambda}$ is the spectral intensity leaving the mold surface; $\tau_\lambda(\mu^{\mathrm{o}})$ is the directional transmissivity of external radiation for direction μ^{o} ($\theta^{\mathrm{o}} = \cos^{-1}\mu^{\mathrm{o}}$) and $\varrho_\lambda(\mu)$ is the internal reflectivity for direction μ. The angle of incidence of external radiation θ^{o} is related to the refracted angle θ in the glass through Snell's law. The radiation intensity $I_{\mathrm{m},\lambda}$ leaving the mold consists of both emitted and reflected contributions. The interaction of radiation at the smooth interface between two dielectric media (i.e., transmissivity τ_λ and reflectivity ϱ_λ) is governed by Snell's and Fresnel's laws [8]. The boundary conditions at the upper surface of the glass layer facing the plunger ($z = H$) is similarly written as

$$I_\lambda(z,\mu) = \tau_\lambda(\mu^{\mathrm{o}})\, I_{\mathrm{p},\lambda} + \varrho_\lambda(\mu)\, I_\lambda(z,\mu) \qquad (14)$$

where $I_{\mathrm{p},\lambda}$ is the spectral intensity leaving the plunger surface and consists both of emitted and reflected contributions.

The solution of the RTE, equation (12), with the boundary conditions, equations (13) and (14), can be obtained using a number of methods [3 and 4]. Here, we use the discrete ordinates method (DOM) which has been shown to yield accurate results with a rather modest computational effort [12].

2.2 Radiative transfer in glass – Rosseland diffusion approximation

Analysis of radiative transfer in complex-shape glass products being pressed is exceedingly complex. In spite of the fact that Rosseland diffusion approximation (RDA) for radiative transfer is known to perform poorly for thin layers of glass [3, 12 and 13], its simplicity possesses great computational advantages and is attractive. Therefore, it is desirable to assess the utility of the approximation for radiative transfer in pressed glass products being cooled by comparing the results of calculations based on the discrete ordinates method for the solution of the radiative transfer equation.

The RDA is the simplest and the most commonly used approach. It has been known to glass scientists and technologists for a long time [3]. Using this approximation the radiative flux in the z direction can be expressed as

$$F = -k_{\mathrm{R}}\,\frac{\mathrm{d}T}{\mathrm{d}z} \qquad (15)$$

where k_{R} is the radiative conductivity of the material defined as

$$k_{\mathrm{R}} = \frac{4\pi}{3}\int_0^\infty \frac{n_\lambda^2}{\kappa_\lambda}\left(\frac{\mathrm{d}I_{\mathrm{b},\lambda}}{\mathrm{d}T}\right)\mathrm{d}\lambda\,. \qquad (16)$$

In this equation n_λ and κ_λ are the spectral index of refraction and the spectral absorption coefficient of glass, respectively, and $I_{\mathrm{b},\lambda}(T)$ is Planck's blackbody function. This conductivity is known as the Rosseland radiative conductivity. The diffusion approximation is very simple, but it breaks down in the vicinity of the boundary and/or when the opacity of the material is not sufficiently large. The effective thermal conductivity is the sum of the phonon thermal conductivity and Rosseland thermal conductivity given by equation (16) [3 and 12].

For consistent treatment of radiative transfer, the boundary condition, equation (6) needs to be modified to

$$-k_{\mathrm{eff,g}} \frac{\partial T_g}{\partial z}\bigg|_{z=0} = h_c(T_g - T_m) + \pi \int_0^\infty \left[\frac{I_{b,\lambda}(T_g) - I_{b,\lambda}(T_m)}{(1/\varepsilon_{g,\lambda}) + (1/\varepsilon_{m,\lambda}) - 1} \right] d\lambda \,. \quad (17)$$

The thermal conductivity of glass k_g in equation (6) has been replaced by an effective thermal conductivity of glass, $k_{\mathrm{eff,g}}$, which is the sum of the phonon and Rosseland radiative conductivities. Also, since the glass is considered to be opaque to external (mold) radiation, the integration over wavelengths is extended over the entire spectrum.

2.3 Method of solution

The solutions of the model equations, equations (2) to (4), and the requisite boundary conditions were obtained numerically using the control volume formulation [14]. The discretized total energy equation was solved using a fully implicit integration scheme. Thermophysical property variation with temperature of glass and mold materials was accounted for. The radiative flux divergence, $\partial F/\partial z$, in the glass energy equation, equation (2), appears as a local source/sink term. In spite of the fact that the integral (exact) solution of the radiative transfer equation is available [3 and 4], the discrete ordinates method [12] was used to solve the equation, because it requires much less computer resources than the exact, integral formulation for the radiative flux. Very accurate solutions can be obtained using the S_8 level symmetric quadrature due to Fiveland [12]. Dependence of the absorption coefficient of glass on wavelength and temperature has been accounted for. Numerical calculations were performed using six and ten bands in the semitransparent spectral range between 0 and 4.7 µm. But, the solutions were practically identical, and the numerical results reported in the paper have been obtained using six spectral bands.

The Rosseland radiative conductivity of glass given by equation (16) was evaluated numerically from the knowledge of the absorption coefficient dependence on wavelength and temperature for the specific glass considered as an example.

A grid sensitivity study has been conducted, and it was concluded that for a glass layer 1 cm thick, from 50 to 100 nonuniformly spaced interior gridpoints were considered. It was found that 70 gridpoints were sufficient to obtain grid-independent solutions. Time step sensitivity study was also conducted, with time steps ranging from 0.01 to 1.0 s. Time step independent solutions were obtained with a time increment of 0.01 s.

In order to validate the mathematical/numerical model, the predictions need to be compared with experimental data. For this purpose two sets of data are

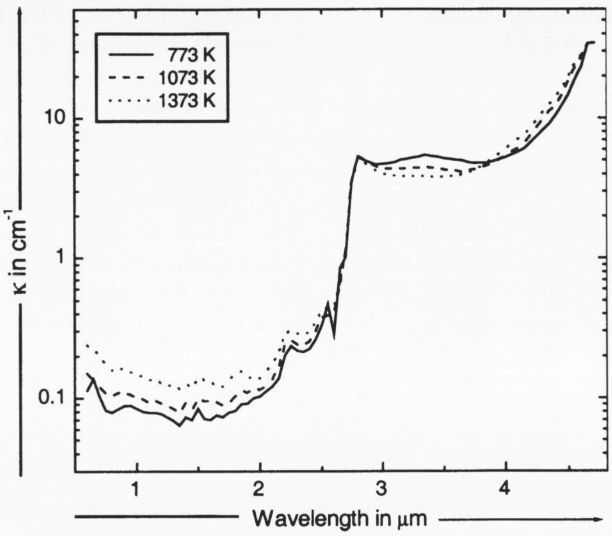


Figure 2. Spectral absorption coefficient of TV glass used in the calculations.

known to the authors. The extensive experimental data of Fellows and Shaw [5] could not be used, because the glass employed was not specified and the spectral absorption coefficient and index of refraction of the glass were not known. Other parameters such as mold roughness etc. were also not provided. Qualitatively, the mold surface heat fluxes, glass surface temperatures and the thermal contact conductances predicted agreed with the experimental data for the conditions tested, but a quantitative comparison could not be made for the reasons stated. The other glass pressing/cooling data [1 and 6] are for a very small (50 to 70 g) glass gob being pressed in a three-dimensional mold. The geometry was not planar and a direct comparison could not be made.

3. Results and discussion

There is a large number of parameters required to describe the problem. Some of the parameters cannot be well characterized and approximations are necessary. We examine here two physical situations. First, we consider the cooling to be symmetrical in order to reduce the number of model parameters. Second, we consider asymmetric cooling of the glass product after it has been pressed. In both situations, TV glass is used as an example, and available thermophysical and radiative property data are used in the calculations. Since the focus of the work is on understanding of heat extraction and of the dynamic temperature distribution in the glass, no attempt is made to truly mimic the cooling cycle.

The thermophysical properties of glass used in the calculations were approximated by the following: density, $\varrho = 2779 - 0.1367\,(T - 298.15)$ in kg/m³; specific heat, $c = 558.2 + 0.3306\,T$ in J/(kg K); thermal (phonon) conductivity, $k = 1.5 + 0.000114\,(T - 273.15)$ in W/(m K). The radiative (Rosseland) component of the effective conductivity was calculated from equation (16) with the knowledge of the spectral absorption coefficient κ_λ and the spectral refractive index of glass. The index of refraction index of the glass was approximated to be 1.55, and the spectral absorption coefficient used in the analysis is given in figure 2. For clarity, the values of κ_λ are provided only for a few selected temperatures. In the calculations more extensive data were available, and additional values needed were obtained by interpolation.

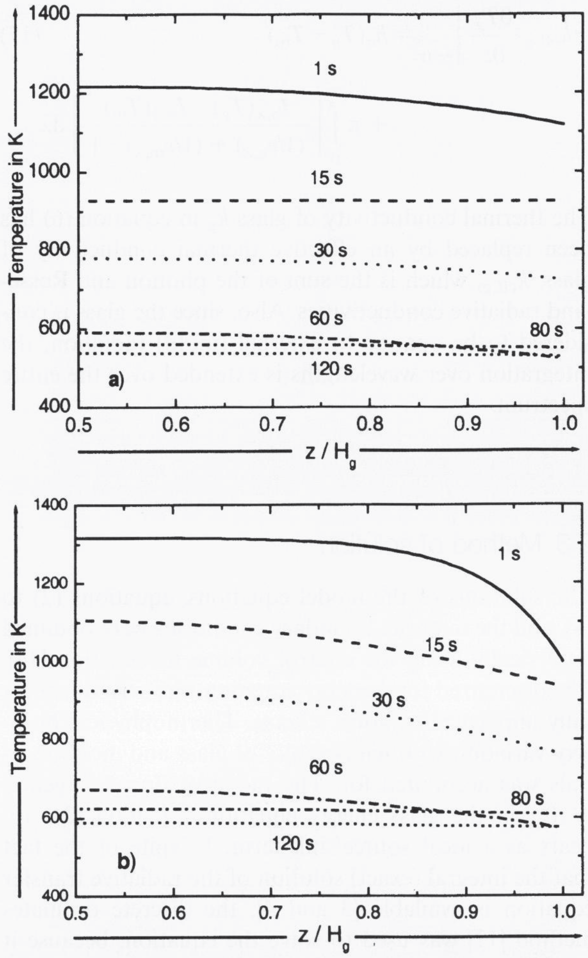
3.1 Symmetric cooling

To start, an idealized pressing/cooling situation is considered in which the pressing/cooling is assumed to be symmetric about the center-plane of the glass panel (layer). The mold/plunger physical parameters and cooling conditions are assumed to be such to produce symmetric cooling. In particular, the physical parameters and conditions imposed for the simulations are the following:

- initial glass temperature, 1050 °C;
- constant plunger/mold temperature, 650 °C;
- glass thickness, 10 mm;
- black plunger and mold, $\varepsilon_p = \varepsilon_m = 1.0$;
- mean root square roughness of plunger and mold, 2 µm;
- pressing/cooling time from 0 to 120 s (for 0 < t < 15 s pressing; for 15 < t < 60 s forced convection cooling; for 60 < t < 120 s natural convection cooling);
- forced convection heat transfer coefficient, 200 W/(m^2 K).

To establish a baseline for comparison, two different radiation heat transfer models in glass are considered: 1) the Rosseland diffusion approximation (RDA) and 2) the discrete ordinate method (DOM). The material (TV glass) is semitransparent to radiation, and the internal radiation transfer is treated as a diffusion process using the RDA. Internal radiative transfer is treated rigorously, and the radiative transfer equation is solved using the DOM [12]. The natural and forced convection heat-transfer coefficients were predicted using established correlations reported in the literature [15]. For comparison purposes, results were also obtained by treating the TV glass to be opaque to radiation (i.e., radiation is considered as a surface phenomenon only).

As expected, the results reveal that the glass cools much more slowly when internal radiation is not considered (not presented in the paper) in the total energy model. Comparison of the results with those in which radiative transfer is correctly modeled (figures 3a and 3b) reveals that diffusion is a slow process and that neglect of radiation is inadequate for predicting the transient cooling of glass during and after pressing. Use of the RDA for radiative transfer is also inadequate, and both



Figures 3a and b. Transient temperature distributions in the TV glass layer for symmetric cooling: a) RDA and b) DOM.

magnitude and trends of the temperature distribution in the glass layer are not predicted correctly. Comparison of figures 3a and 3b reveals that the RDA for radiative transfer in glass predicts much lower temperature gradients near the interface than does the DOM. For example, at t = 15 s the RDA (in figure 3a) predicts only about a 5 K lower surface temperature than at the mid-plane. This is a consequence of the highly nonlinear nature of radiation transfer, interaction between phonon conduction and radiation diffusion and imposed thermal (cooling) boundary conditions. Comparison of the temperature distributions in figures 3a and 3b at t = 30 s reveals that the surface layers of glass lose heat more readily by contact conduction and opaque radiation, because here the temperature gradient is decreasing more rapidly with distance during the dwell time (figure 3b). The results are in concert with those reported elsewhere [12]. In spite of the fact that fraction of the radiation emitted in the interior of the glass layer (near the mid-plane) is absorbed near the surface, these layers of the glass radiate heat away to the plunger. The interaction between conduction and radiation is substantial and contributes to the sharp temperature decrease of the

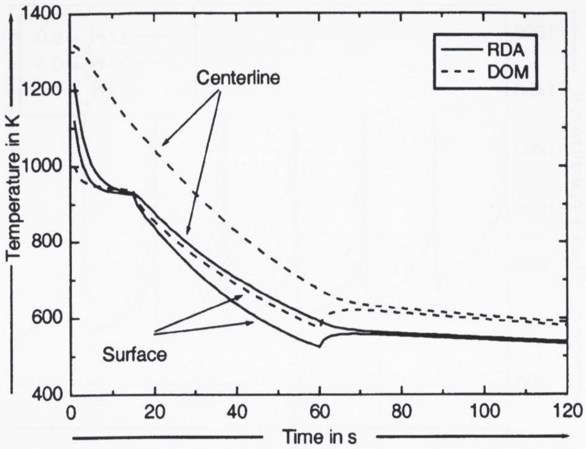
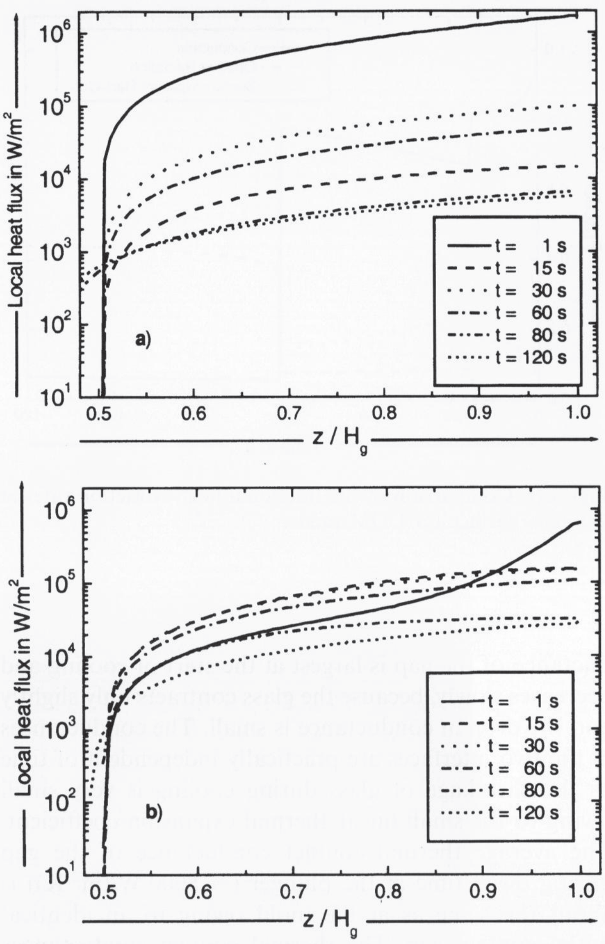


Figure 4. Variation of center-plane and surface temperatures predicted by RDA and DOM models during symmetric cooling.



Figures 5a and b. Local heat flux distributions in the glass layer during symmetric cooling: a) RDA and b) DOM.

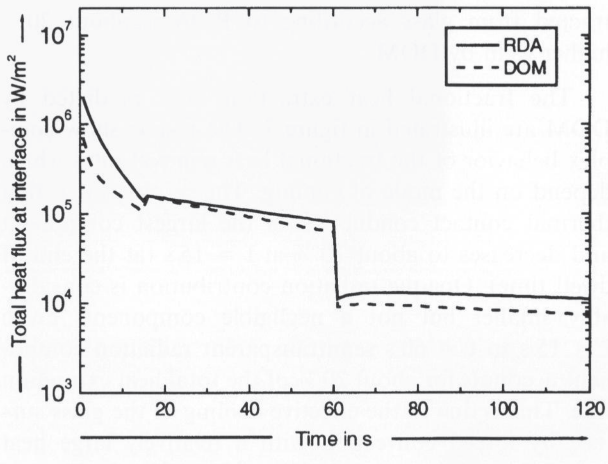


Figure 6. Comparison of total heat flux variations with time at the surface in the glass layer during symmetric cooling for RDA and DOM models.

glass during the cooling period. During this period conductive heat transfer is confined to the surface layers ($0.85 < z/H_g < 1.0$), and the interior of the glass cools rather uniformly.

The variation of the surface and center-plane temperatures with time is illustrated in figure 4. The temperatures at the quarter-plane are between those of the surface and center-planes (but closer to those at the center) and are not shown for the sake of clarity. It is clearly shown that, as the plunger is removed (at $t = 15$ s), the surface temperatures flatten out (i.e., only about a 5 K recovery in temperature) owing to reheating caused by heat conduction from within the interior of the glass. But this rise cannot be clearly indicated in the figure. The recovery in temperature at $t > 60$ s is greater because convective heat transfer for natural convection conditions is much smaller than 200 W/(m^2 K) used for forced convection from $t = 15$ s to $t = 60$ s. As shown by Tatsukoshi et al. [1], the reheating characteristics are strongly influenced by the initial temperature of the plunger, pressure and the pressing duration. It is also expected to depend on the spectral absorption characteristics of the glass. The findings concerning reheat are consistent with the results reported by Rawson [16] and Merkwitz et al. [17].

The instantaneous local (conductive and radiative) fluxes predicted by RDA and DOM models are shown in figures 5a and 5b, respectively. Except for the very early time ($t \leq 1$ s) the fluxes predicted by the two models exhibit the same trends with time. The heat fluxes calculated by RDA are higher than those calculated by DOM. This finding is consistent with results for the temperature distributions (figure 3) calculated by the two models and is a consequence of the complex interactions between conduction and internal thermal radiation.

The heat flux variation with time at the glass surface during the pressing/cooling time is illustrated in figure 6. The results obtained (not shown) reveal that thermal contact conduction predominates over the opaque and semitransparent radiation components. The contact con-

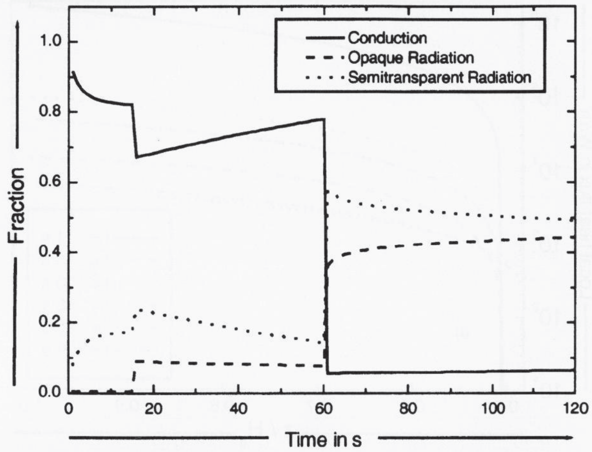


Figure 7. Comparison of the fractional heat extraction rates at the glass surface for DOM model.

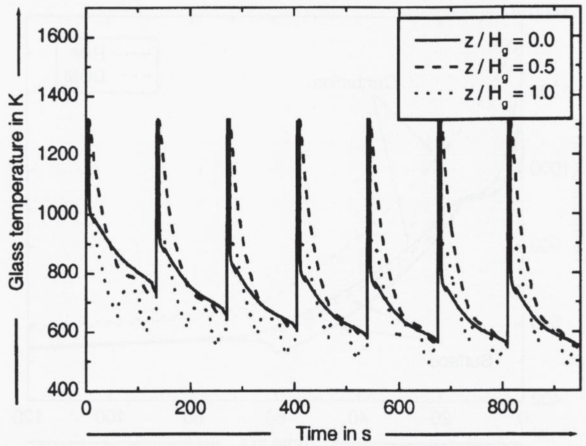


Figure 8. Comparison of the centerline and glass surface temperatures during cyclic, asymmetric cooling of TV glass layer for DOM model.

ductance of the gap is largest at the start of cooling and decreases slowly, because the glass contracts only slightly and the drop in conductance is small. The conductances at the two interfaces are practically independent of time as the shrinkage of glass during cooling is very small owing to the small linear thermal expansion coefficient. The average thermal contact conductance of the gap during dwell time at the plunger ($\approx$ 8000 W/(m^2 K)) is about the same as at the mold owing to an identical initial contact gap. The thermal contact conductances agree qualitatively with the experimental results reported in the literature [5]. The cumulative heat extraction rates (i.e., integrated over time) have been calculated for RDA and DOM models, but are not shown for the sake of brevity. The results reveal that at t = 120 s the heat extracted from glass according to RDA is about 20 % higher than by DOM.

The fractional heat extraction rates predicted by DOM are illustrated in figure 7. The results show complex behavior of the fractional heat removal rates which depend on the mode of cooling. The results reveal that thermal contact conduction is the largest component and decreases to about 70 % at t = 15 s (at the end of dwell time). Opaque radiation contribution is considerably smaller but not a negligible component. From t = 15 s to t = 60 s semitransparent radiation component accounts for about 20 % of the total heat extraction rate. This is due to the effective cooling of the glass surface by forced convection with a relatively large heat transfer coefficient [= 200 W/(m^2 K)]. The fraction of heat extracted from the glass layer in the semitransparent band would be larger if a smaller convective heat transfer coefficient had been selected for the sample calculations. For the period of 60 s < t < 120 s when the glass panel is cooled by natural convection, semitransparent radiation accounts for about 50 % of the total heat extraction rate; opaque radiation contribution accounts for about 40 % and natural convection for only 10 %. It should be noted that the above results are process parameters specific. The heat extraction fractions from the glass depend on the glass layer thickness, pressing and cooling conditions, type of glass, mold and plunger roughness, etc.

The effect of the glass layer thickness on the cumulative heat extraction from the product defined has been examined. The calculations have been performed for glass layer thicknesses of 2.5, 5.0 and 10.0 mm using DOM. The results show that heat extraction is greatest for the 10 mm thick layer and smallest for the 2.5 mm. During the 15 s dwell time the differences are relatively small. The thermal contact conduction accounts for the largest fraction (i.e., of cumulative total) of the heat extraction and opaque radiation for the smallest. The trends in the heat extraction fractions for the three thicknesses are the same, and, as expected, the differences for opaque radiation contributions are the smallest.

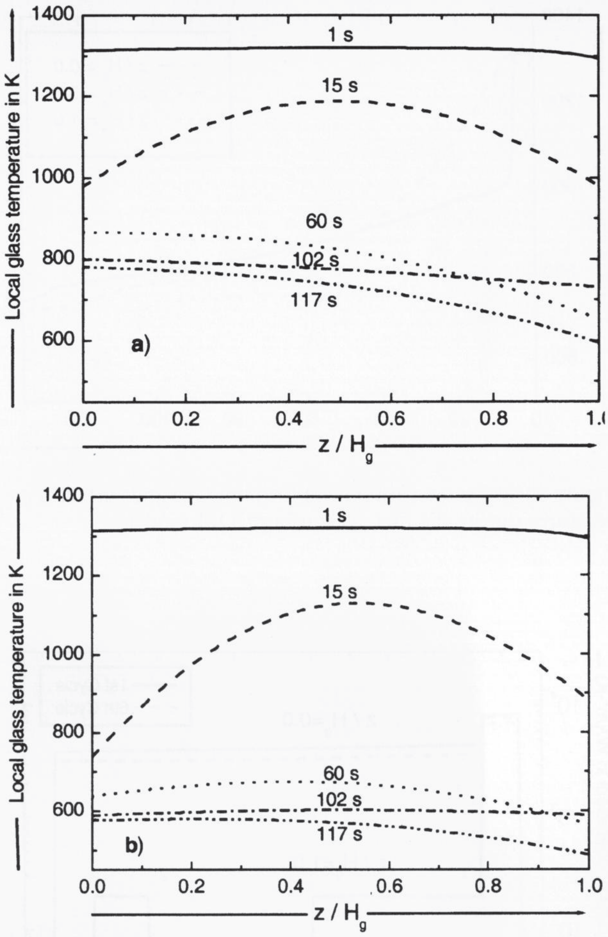
3.2 Nonsymmetric cooling

Heat transfer processes mimicking glass forming have been simulated for the typical situation when heat extraction through the plunger and the mold differ, and this results in an asymmetric temperature profile in the glass. The purpose here is to mimic heat extraction from the glass during the complete revolution (cycle) of the carousel (forming machine). As a specific example, TV panel glass is considered, and the system is described by the following parameters:

- initial glass temperature, 950 °C;
- glass thickness, 10 mm;
- initial plunger and mold temperatures, 550 °C/550 °C;
- plunger/mold thicknesses, 30 mm/30 mm;
- initial gap distance between plunger and glass, 2 μm;
- initial gap distance between mold and glass, 4 μm;

– emittance of plunger/mold, 1.0/1.0;
– convective heat transfer coefficient between cooling air and plunger, 200 W/(m² K);
– convective heat transfer coefficient between cooling air and mold, 300 W/(m² K);
– total cycle time, 135 s (from 0 < t < 5 s open; from 5 < t < 15 s pressing; from 15 < t < 60 s forced convection cooling after plunger has been removed but glass stays on the mold; from 60 < t < 102 s natural convection cooling but glass stays on the mold; from 102 < t < 135 s forced convection cooling but glass stays on the mold.

To determine if truly cyclically steady pressing/cooling operation has been reached, five, six and seven cycles were simulated using DOM. This was necessary because the initial plunger and mold temperatures assumed may not have been consistent with cyclically steady pressing/cooling operation. The glass centerline and surface (glass/mold and glass/plunger) temperatures are illustrated in figure 8. After the sixth cycle, for example, the glass comes out slightly colder than after the first cycle. This indicates that the initial mold and plunger temperatures assumed for calculations were inconsistent with the cyclically steady operation. Comparison of the glass temperatures during the fifth and seventh cycles are practically the same, and this indicates that cyclically steady pressing/cooling conditions have been reached on the carousel. The mold and plunger surface temperatures show similar trends, but it has taken the mold the longest to reach cyclically steady temperatures. This is because of the different thermal contact and convective cooling conditions at the glass/plunger and glass/mold interfaces. The results are not shown for the sake of brevity.



Figures 9a and b. Local glass temperature distributions during cyclic cooling for DOM model: a) first cycle and b) sixth cycle.

The local temperature distributions during the first and sixth pressing/cooling cycles are illustrated in figures 9a and 9b, respectively, and clearly reveal that the temperatures are not symmetrical about the midplane of the glass layer. This can also be clearly seen from figure 8 for the seven cycles. The asymmetrical cooling is due to greater heat extraction rate at the plunger/glass interface than at the mold/glass interface because of the differences in the external thermal conditions imposed on the mold and plunger as well as removal of the plunger at t = 15 s. At early times in the first cycle (i.e., t = 15 s in figure 3a) the temperature distribution in the glass layer is nearly symmetrical about the midplane. At this time there is only about 5 K difference between the glass/mold and glass/plunger interface temperatures. The main reason for this result is the fact that the initial mold and plunger temperatures were assumed to be the same (550 °C) and that there was insufficient time for the imposed external cooling conditions at the mold and plunger to influence heat extraction from the glass during the 15 s of the process time. The temperature distributions in the glass illustrated in figures 9a and 9b for the first and the sixth cycles, respectively, clearly show the impact of the assumed initial temperatures in the plunger and the mold. This is due to the fact that the plunger and mold are more massive and, therefore, have higher heat capacities than the glass panel, and their outer boundaries have different imposed cooling conditions. The local radiative flux divergence ($-\partial F/\partial z$) in the energy equation (2) is also not symmetrical about the midplane, but is not shown because of the need for brevity.

The variation of glass temperatures with time at the center and the two interfaces for the first cycle are illustrated in figure 10 and clearly reveal asymmetric cooling. At t = 135 s there is only about a 50 K temperature difference across the glass. The trends in the mold/glass and plunger/glass interface temperatures with time are not the same because of the differences in the cooling conditions. The glass product is in continuous contact with the mold, whereas the contact of the plunger and glass has been terminated at t = 15 s, and the upper glass surface is first being cooled by forced and later by natural convection.

A comparison of the instantaneous heat transfer coefficients (thermal contact conductances) and of the total heat fluxes during the first and sixth cycles predicted

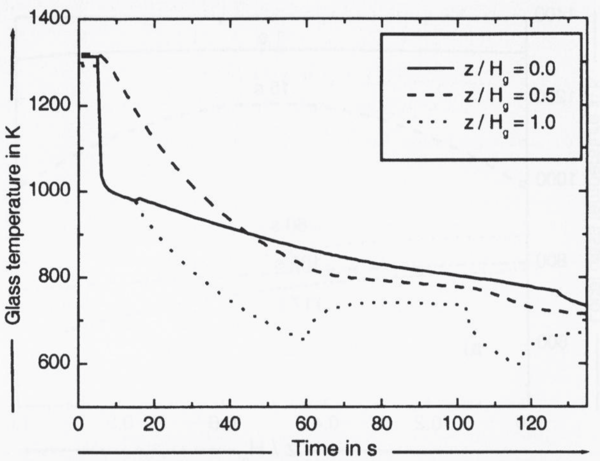


Figure 10. Variation with time of the midplane and surface temperatures during the first cycle using DOM model.

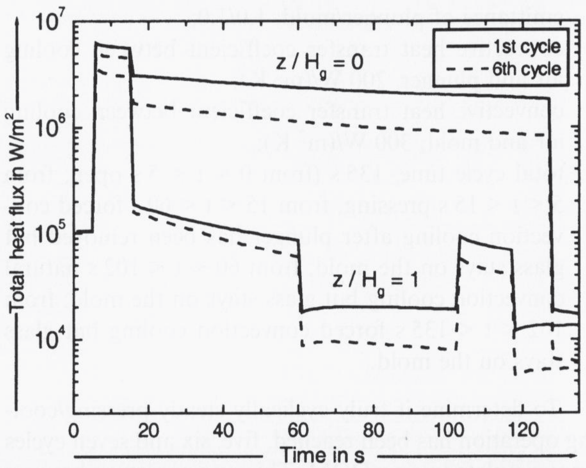


Figure 12. Comparison of total heat flux variations with time at the mold/glass and plunger/glass interfaces during the first and sixth cycles using DOM model.

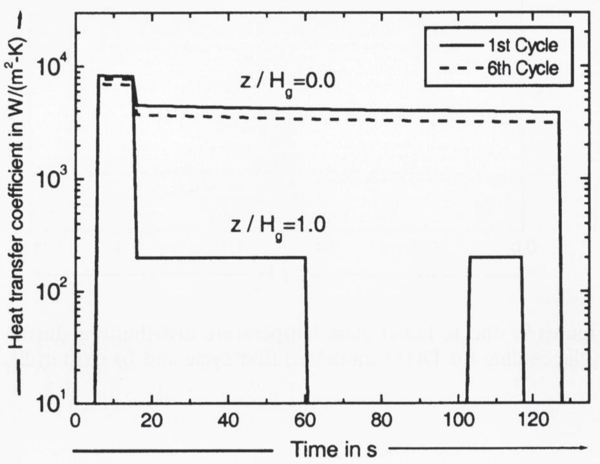


Figure 11. Comparison of thermal contact conductances at the mold/glass and plunger/glass interfaces during the first and sixth cycles using DOM model.

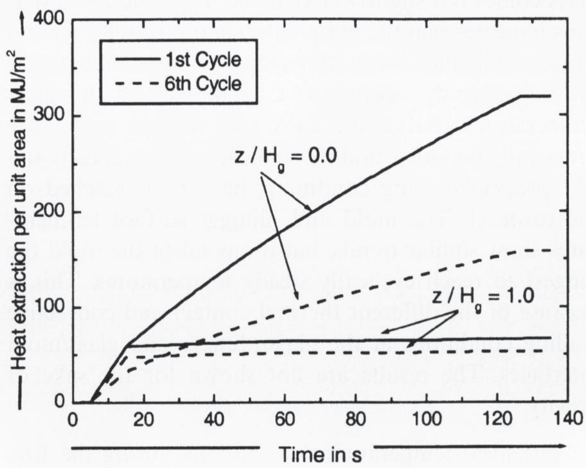


Figure 13. Comparison of cumulative heat extraction rates at mold/glass and plunger/glass interfaces during the first and sixth cycles using DOM model.

by DOM model are illustrated in figures 11 and 12, respectively. The results reveal complex trends which are consistent with the modes of heat transfer during the cycle. Note that the contact conductance at the mold/glass interface ($z/H_g = 0$) is practically constant for $t > 15$ s (figure 11). During this time period the glass is situated on top of the mold, and the contact pressure is considered to be due to the weight of the glass. The total heat flux (figure 12) during this time period decreases slowly, because the temperature of the glass decreases as the heat is extracted. The cumulative heat extraction rates from top and bottom interfaces of the panel during the first and sixth cycles are compared in figure 13. The results, as expected, show that more heat is extracted from the bottom than the top and that after six cycles steady (cyclically) thermal conditions have not yet been reached.

In a paper which has become available to the authors (after this manuscript has been submitted for publication), Merkwitz et al. [17] have demonstrated the importance of radiation heat transfer during glass forming processes when there exists a strong contact between mold and glass. The major findings reported in their paper are completely consistent with the results of this work.

4. Concluding remarks

Temperature distributions in glass pressing/cooling have been calculated for a TV glass panel having wavelength- and temperature-dependent spectral absorption coefficient. The temperature distributions for symmetric and asymmetric cyclic pressing/cooling situations have been analyzed to show the local rates of heat loss by conduction and radiation in the glass. Based on the results obtained, the following conclusions can be drawn:

a) For the conditions considered, radiation from the surface in the opaque part of the spectrum and from the interior of the glass in the semitransparent part of the spectrum plays a small but important part in the extraction of heat from the glass. In the center of the glass the loss of heat by radiation at the start of the cooling process is virtually the only cooling process.

b) Use of the Rosseland diffusion approximation for radiative transfer in glass during pressing/ cooling is not recommended and is discouraged. The approximation overpredicts the cooling rates in the central regions of the panel and underpredicts the glass temperatures in the surface regions.

c) The results of calculations for both symmetric and asymmetric cooling conditions show that the thermal contact conduction is the dominant mechanism for heat extraction from the glass to the plunger and the mold during the dwell time. The gap distances (rms roughness) between the glass and the plunger and the glass and the mold are important parameters which control cooling of the glass during the dwell time.

d) The interaction between conduction and radiation within the glass is such that change in thermal contact conduction affects radiative transfer to compensate for this change particularly in the surface layers.

e) The results clearly show that computer codes which do not account for internal radiation transfer in the glass or use the Rosseland diffusion approximation will be incapable of predicting correctly the temperature distribution and residual stresses in a glass product.

We have shown that it is possible to study theoretically the effects of different plunger and mold materials, as well as of thermal conditions on heat extraction from glass being formed/cooled. It is also possible to couple the thermal problem for predicting glass temperature distributions to that for calculating thermal and form stresses resulting from forming/cooling of the glass.

5. Nomenclature

5.1 Symbols

c	specific heat in Js/(kg K)
F	local total radiative flux in W/m^2
F_λ	local spectral radiative flux defined by equation (11) in W/(m^2 µm)
G_λ	spectral irradiance defined by equation (12) in W/(m^2 µm)
g	temperature jump distance in m
H	thickness in m
h	convective heat transfer coefficient in W/(m^2 K)
h_c	gap conductance defined by equation (1) in W/(m^2 K)
I_λ	spectral radiation intensity in W/(m^2 µm sr)
$I_{b,\lambda}$	spectral black body intensities of radiation given by Planck's law in W/(m^2 µm sr)
k	thermal conductivity in W/(m K)
k_R	Rosseland radiative conductivity defined by equation (16) in W/(m K)
n	index of refraction
q	instantaneous heat flux at the interface
s	unit vector, see figure 1
T	temperature in K
t	time in s
z	depth in µm
α	thermal expansion coefficient in 1/K
ε	emissivity
δ	gap distance in m
θ	reflection angle, see figure 1
κ	absorption coefficient in 1/m
λ	wavelength in µm
μ	direction cosine, cos θ
μ^o	directon cosine, cos θ^o
ϱ	density in kg/m^3 or reflectivity (dimensionless)
$\tau_\lambda(\mu^o)$	transmissivity of external radiation for direction μ^o

5.2 Subscripts

amb	refers to ambient or conductance
b	refers to a black body
c	refers to cutoff wavelength
g	refers to glass
gap	refers to gap
i	index refers to either plunger or mold
m	refers to mold
p	refers to plunger
R	refers to Rosseland radiative conductivity
λ	refers to wavelength

5.3 Superscripts

o	refers to the direction of external radiation
'	refers to angle of incidence, see figure 1

*

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