Temperature Distribution and Heat Trasfer in Container Glass during Forming Operations

By

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A method for calculating the temperature distribution and rate of heat transfer in glass during glass container machine-forming operations is presented. An attempt at calculating the temperature in glass during a blow-and-blow forming process was carried out. It was shown that radiation plays a small but important part in comparison with that of conduction in the extraction of heat from glass.

Introduction

Forming technology has developed empirically and it would not be possible to eliminate the trial and error approach. However, in order to minimize uncertainty and attain greater sureness in forming operations, fundamental studies have been carried out by various authors[1~6]. The purpose of this paper to also gain a knowledge of the temperature distribution in glass during forming, which is of fundamental importance to a better understanding of forming operations.

Calculation of Temperature in Glass

In this paper, the attempt at calculating the temperature distribution in glass was restricted to the blow-and-blow forming process. Fig. 1 shows schematically the blow-and-blow container forming sequence. The forming sequence begins at the feeder with the shaping of the gob.

Fig. 1 (a)—Fig. 1 (e) represent the characteristic forming stages, i. e., (a) settle blow, (b) counter blow (parison formed), (c) transfer stage from blank mold, (d) finishing mold closed, and (e) finish blow. The stages (c) and (d) correspond to the reheating time.

The mold equipment acts as a controlled environment and is maintained

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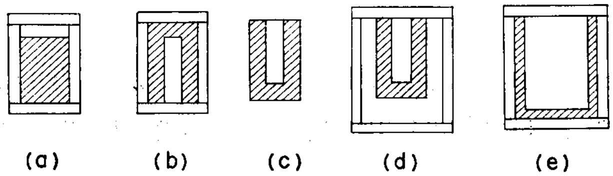

Fig. 1. Blow-and-blow container forming sequence.
(a) settle blow, (b) counter blow,
(c) transfer stage, (d) finishing mold closed,
(e) finish blow.

at operating temperature by a balance between the heat absorbed from the glass and the heat removed by radiation, conduction, and convection.

In discussing radiant effects, one must bear in mind that even transparent materials are practically opaque to radiation of some wave lengths. For the temperatures involved in forming processes the radiation of wavelengths less than 1.0 μ is completely neglible. As will be seen from Fig. 2[4], a good approximation to the remainder of the spectrum is given by a step function with constant absorption coefficients $\gamma=0.3$, 3.0, and ∞ for the bands 1.0-2.8 μ, 2.8-4.5 μ, and beyond 4.5 μ, respectively. In the region beyond 4.5 μ the glass is, for all practical purposes, opaque to radiation. This procedure is accurate enough for calculations of the temperature in forming processes and reduces the detail of the computational routine.

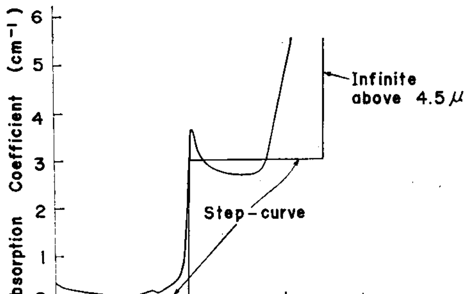

Fig. 2. Absorption coefficient of flint bottle glass.

For calculating the temperature of glass it was assumed that the glass and mold walls could be considered as infinite plane slabs of finite thickness. It is expected that the errors due to this substitution are not greater than about 5 % for the temperature of glass during the forming operation in the case where the thickness of glass is less than 10 mm. On the model as shown in Fig. 1 a heat balance was performed in each of the following stages:

(1) from gob in to counter blow.

(2) from counter blow to blank mold open.
(3) reheating.
(4) finish blow.

A mathematical treatment of the model leads to a set of equations for calculating the temperature distribution in glass. This treatment is presented in the Appendix.

Results and Conclusions

For Japanese wine bottles (1800 ml bottles) on a New-10 machine (Lynch Corp., Anderson) gob temperature, the blank mold temperature, operation time, etc., are shown in Table 1.

Table 1. Gob temperature, blank mold temperature, operation time, operation condition, etc. for 1800 ml bottle.

Gob temperature, °C	1050	Heat transfer coefficient, Kcal/ $m^2 \cdot hr \cdot °C$	
Temp. of internal surface of blank mold, °C	380	from blank mold open to finishing mold closed	70
Temp. of internal surface of finishing mold, °C	520	from finishing mold closed to finishing blow	20
Temp. of ambient atmosphere, °C	20	Inner diameter of blank mold, mm	40
Operation times, sec.		Thickness of parison, mm	10
beginning time	0	Thickness of bottle, mm	4
counter blow	2.5	Refractive index of glass	1.50
blank mold open	4.5	Specific heat of glass, cal/g·°C	0.357
finishing mold open	8.5	Density of glass, g/cm^3	2.402
finishing blow	12.5	Emissivity of mold	1.0
internal cooling	15.5–19.0		
finishing mold open	19.5		

The calculation of the temperature distribution through the glass during forming was performed by the use of a numerical method. The results obtained are shown in Fig. 3. Three curves show the temperature distributions through the glass during forming, i. e., in the stages of operation times, 4.5, 12.5, and 19.5 sec. after beginning.

The calculated temperature of the glass surface with its temperature measured by a pyrometer of the Thermdot type were compared, and the agreement between these values was regarded as satisfactory.

Fig. 4 shows the rates of heat transfer by conduction, radiation, and convection during bottle forming. It is seen that in every stage the radiation heat transfer plays a small but important part in contrast to the conduction heat transfer under the conditions considered here. It is hoped that such an

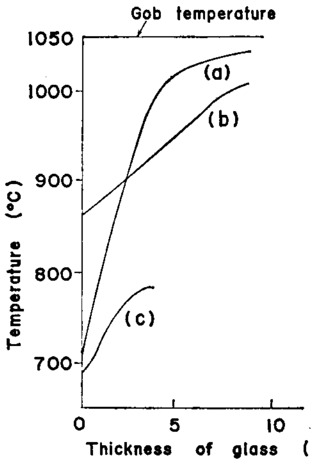

Fig. 3. Temperature distribution in glass during forming.
(a) Blank mold open (4.5 sec after beginning of loading)
(b) finish blow beginning (12.5 sec)
(c) finishing mold open (19.5 sec).

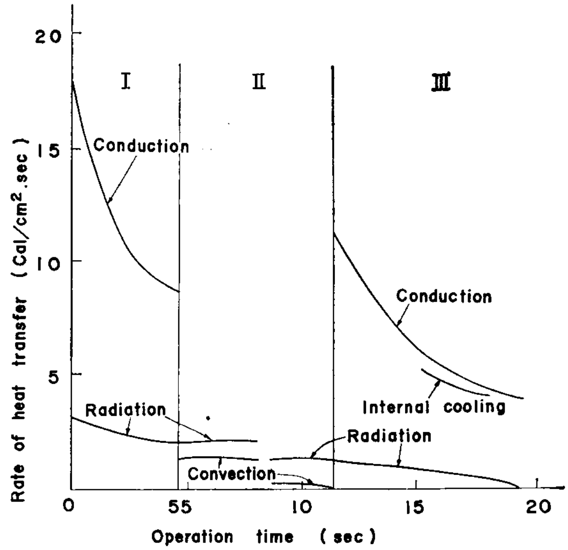

Fig. 4. Rates of head transfer during forming.
I stage of settle blow and counter blow,
II reheating,
III finish blow.

analysis has afforded some suggestions concerning the technical problems of automatic bottle blowing.

Appendix

For understanding the method of calculating the temperature distribution in the glass during forming, a mathematical treatment for heat transfer in the stage of gob in-counter blow is presented here comprehensively.

(1) Temperature distribution within the glass

The glass plate, which has a total thickness, L, is divided into an even number of slices, each having a thickness $\Delta x = L/N$. Temperatures are then considered at the places distant $x = r \cdot \Delta x$ from one surface, r taking on the valus 0, 1, 2, 3,$\cdots$. Corresponding to this stepwise variation of position, $T_{i+1}(r)$ is given by

$$T_{i+1}(r) = T_i(r) + \Delta t \frac{\partial T_i(r)}{\partial t} \quad (1)$$

where $T_i(r)$ is the temperature at position r and at time $i \cdot \Delta t$. The values of $\partial T_i(r)/\partial t$ are calculated by the following equation:

$$\frac{\partial T_i(r)}{\partial t} = \frac{1}{C_p \rho \Delta x}\left[Q_C(x) + Q_A(x) - Q_E(x) + Q_R(x)\right] \quad (2)$$

In this equation the various Q's denote the rates of absorption (or dissipation) of energy per unit volume of slice, where

Q_C=rate of absorption of energy by the slice of Δx thickness from the conductive flux of heat within the glass,

Q_A=rate of absorption by the slice of radiation from outside the glass,

Q_E=rate of emission of radiation by the slice itself,

Q_R=rate of reabsorption by the slice of radiation emitted in other parts of the glass.

The conductive flux of heat Q_C replaces the following term:

$$Q_C=\frac{k}{C_p\rho}\,\frac{T_t(r-1)-2T_t(r)+T_t(r+1)}{(\Delta x)^2} \tag{3}$$

Thus equation (2) takes the form

$$\frac{\partial T_t(r)}{\partial t}=\frac{1}{C_p\rho}\Big[Q_A(x)-Q_E(x)+Q_R(x)\Big]+\frac{k}{C_p\rho}\cdot\frac{T_t(r-1)-2T_t(r)+T_t(r+1)}{(\Delta x)^2} \tag{4}$$

(2) Radiation within the glass.

The rate of emission of radiation by the slice itself is given by:

$$Q_E=4\gamma n^2 W_B \Delta x \tag{5}$$

where W_B is the radiant flux of a black-body radiator.

(3) Rate of reabsorption by the slice of radiation emitted in other parts of the glass.

Reabsorption of internally emitted radiation from Δx between x_i and x_{i+1} is given by

$$Q_E(x)=2\gamma n^2 W_B\{K_1(-\gamma x_i)-K_1(-\gamma x_{i+1})\}\Delta x \tag{6}$$

where $K_1(-\gamma x)=e^{-\gamma x}+(\alpha x)E_i(-kx)$ and $E_i(-kx)=-\int_0^\infty \frac{e^{-\gamma x}}{\gamma x}dx$.

(4) Absorption of energy reflected at the interface between the glass and the mold.

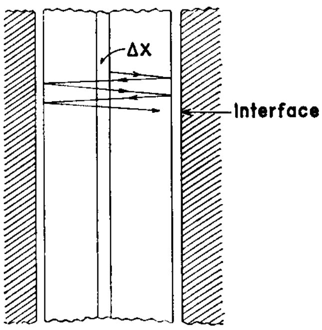

Fig. 5. Reflection of radiation at the interface between glass and mold.

As shown in Fig. 5, there are one or more reflections of internally emitted radiation from the slice Δx at the interface. The radiation energy reflected is given by

$$\int_0^{\pi/2} 2\gamma\pi^2 W_B dx \cdot \rho e^{-\gamma(x+y)/\cos\alpha} \cdot \frac{\sin\alpha d\alpha}{1-\rho e^{-\gamma L/\cos\alpha}} \tag{7}$$

where ρ is the internal directional reflectivity.

(5) Radiation from the interior of the glass to the mold.

The radiation energy from the interior of the glass to the mold is

$$W_B \int_0^{\alpha T} n^2 \tau \sin 2\alpha d\alpha \tag{8}$$

where τ is the directional transmissivity and α_T the total reflective angle.

(6) Radiation from the mold to the interior of the glass.

This is given by

$$2\int_0^{\alpha T} n^2 W_H \frac{\tau e^{-\gamma x/\cos\alpha}}{1-\rho e^{-\gamma L/\cos\alpha}} \cdot \cos\alpha \cdot \sin\alpha d\alpha \tag{9}$$

where W_H is the radiant flux from the mold.

(7) Heat transfer on the surface layer of the mold in contact with the glass.

At the glass surface the heat balance is expressed by

$$k_g \frac{\partial T}{\partial x} = \left\{hc + h_{r(4.5\mu)}\right\} \Delta T \tag{10}$$

where k_g is the conductivity of the glass, hc is the convective heat transfer coefficient, and $h_{r(4.5\mu)}$ is the radiation heat transfer coefficient for wavelengths over 4.5 μ.

At the mold surface, this is given by

$$k_m \frac{\partial T}{\partial x} = (hc + h_r) \Delta T \tag{11}$$

where h_r is the radiation heat transfer coefficient.

(8) Heat balances on slices in the interior of the mold and for the outer surface layer of the mold.

In the interior of the mold the usual process of heat conduction alone takes part in the heat transfer.

The rate of heat transfer for the outer surface layer of the mold is given by

$$(hc + h_r)(T_m - T_a) \tag{12}$$

where T_m and T_a are the temperatures of the surface of the mold and of the ambient atmosphere, respectively.

List of Symbols

C_p	Specific heat, cal/g·°C	T	Temperature, °C
d	Density of glass, g/cm^3	W	Emissive power or radiant flux
h_C	Convective heat-transfer coefficient, Kcal/m^2·hr·°C	x	Position coordinate (distance from surface)
i	Time parameter ($i=t/\Delta t$)	y	Auxiliary position coordinate (distance from surface)
k	Thermal conductivity, Kcal/m·hr·°C	α	Angle between direction of beam and normal to plate, in degrees
L	Thickness of glass, mm	α_T	Total angle of reflection, in degrees
n	Refractive index	ε	Emissivity
Q	Rate of absorption of energy per unit volume	λ	Wave length, μ
r	Position parameter ($r=x/\Delta x$)	ρ	Internal directional reflectivity
t	Time, sec.	τ	Directional transmissivity

Subscripts

a	of ambient atmosphere	H	Refers to radiation from environment
B	of black-body radiator	i	Refers to conditions at the end of the ith time interval
C	conductive	R	Refers to the reabsorbed part of internally emitted radiation
E	Refers to radiation internally emitted		

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