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Heat transfer at the glass-mold interface

Von Delford Armstrong McGraw, Toledo, Ohio (USA)

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The nature of the glass-to-mold-metal interface and its influence upon the interfacial heat transfer is discussed. Initially the glass-to-mold separation is approximately $2{,}5 \cdot 10^{-5}$ cm, increasing to approximately 0,004 cm after more than one second of dwell time. The initial heat transfer is ascribed to free-molecule conduction in the air gap, and undergoes a transition to ordinary bulk conduction as the gap widens. Both the magnitude and time dependent nature of the heat transfer coefficient are explained.

The same general considerations should apply in any process involving the forming of a hot deformable material in a solid mold.

Transfert de chaleur à l'interface verre–moule

On discute de la nature de l'interface verre-moule métallique et de son influence sur le transfert de chaleur à cet interface. Initialement, l'espace verre-moule est approximativement de $2{,}5 \cdot 10^{-5}$ cm et augmente pour atteindre 0,004 cm environ après un temps de séjour supérieur à une seconde. Le transfert de chaleur initial est attribué à la conduction par les molécules libres dans le vide d'air et passe à une conduction de masse ordinaire lorsque le vide s'élargit. On explique l'importance du coefficient de transfert de chaleur et sa dépendance vis-à-vis du temps.

Les mêmes considérations générales doivent s'appliquer à tout processus impliquant le formage d'un matériau déformable à chaud dans un moule solide.

Wärmeübergang in der Grenzzone Glas–Form

Die Art der Grenzzone Glas–Form und ihr Einfluß auf den Wärmetransport in dieser Grenzzone werden diskutiert. Die Ablösung des Glases von der Form beträgt anfänglich $2{,}5 \cdot 10^{-5}$ cm und erhöht sich nach einer Sekunde Berührungszeit auf 0,004 cm. Der anfängliche Wärmetransport läßt sich durch eine freie Bewegung der Moleküle im Luftspalt beschreiben. Mit sich aufweitendem Spalt geht er in eine normale Wärmeleitung über. Sowohl die Intensität als auch die zeitliche Änderung des Übergangskoeffizienten werden erklärt.

Die gleichen grundsätzlichen Betrachtungen gelten bei der Formgebung eines heißen deformierbaren Materials in einer festen Form.

When heat is transferred between two solids whose surfaces are in close proximity, a temperature discontinuity exists at their interface. The quantity of heat that moves across the interface is described by a parameter called the heat transfer coefficient, or the interface coefficient. This coefficient characterizes the heat flux per degree of temperature difference between the surfaces and is usually expressed in $kW/m^2 \cdot K$ (kilowatts per square meter-degree Kelvin) or $cal/cm^2 \cdot s \cdot °C$ (calories per square centimeter-second-degrees Centigrade). It is thus exactly analogous to the parameter that characterizes convective heat transfer between a solid and a moving fluid.

The interfacial heat transfer coefficient between hot glass and the mold surface against which it is formed is a case of considerable practical significance. This coefficient was first evaluated for glass pressing and blowing operations by a combination of experimental and simulation techniques [1 and 2]. The time average value of the coefficient and its time dependent behavior described in [1] are widely utilized in the glass industry. Further definitive research on the interface coefficient has been reported by the British Glass Industry Research Association [3].

The heat transfer coefficient is, of course, an empirical parameter; it defines the rate of heat movement but does not describe the mechanism by which energy is transferred across the interfacial distance. It is the purpose of this paper to offer a possible description of the phenomenon, in the expectation that it may stimulate further experimentation and understanding leading to improvements in glass molding operations.

1. Description of the interface

When fresh hot glass is initially pressed or blown toward a metal mold surface, it has a viscosity on the order of 10^3 to 10^5 Poises. In this condition it conforms readily to the contour of the mold and comes to close proximity with it. It is unlikely, however, that the glass ever makes direct and intimate physical contact with the metal surface except at a few points comprising not more than two or three percent of the total surface area. From purely practical observation of forming operations, one can infer that if direct contact were achieved over extensive areas for any measurable time interval, the glass and metal would cohere so strongly that removal of the mold would be nearly impossible. This is readily apparent to anyone who has seen "stuck glass" in a forming line. Further, the replication of glass to container mold contours has been reported by Merchant [4]. His work shows that the glass surface is always more smooth than the mold surface, and one can conclude from his data that, at nearest proximity, there is an average separation of about $2{,}5 \cdot 10^{-5}$ cm between the surfaces.

At this initial time the heat transfer coefficient is known to be greater than 11 $kW/m^2 \cdot K$. Early cooling of the glass is extremely rapid, and within milliseconds its surface hardens to a viscosity on the order of 10^8 Poises. The cooling also causes volume contraction of the glass and expansion of the mold to begin, and the interfacial

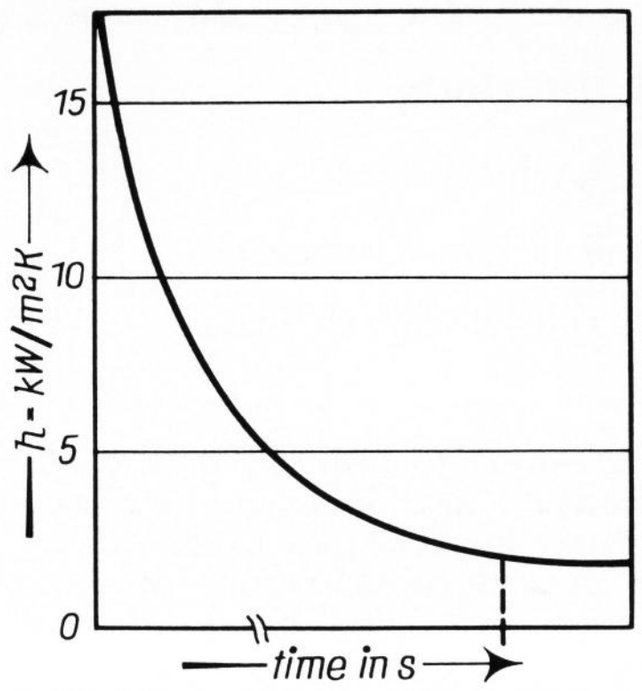

Figure 1. Heat transfer coefficient, as observed experimentally.

separation starts to increase. Concurrent extraneous motions or vibrations of the machine and mold parts serve only to further increase the separation since the glass surface is too solid to reconform to the mold contour, and the rate of heat removal is at all times too rapid to permit surface reheating. As the separation increases, the heat transfer coefficient decreases. At the end of dwell periods typical of glass container forming operations, the heat transfer coefficient is about 2,0 to 2,5 $kW/m^2 \cdot K$. From consideration of average glass and mold temperatures, the separation between the two due to volume changes is approximately 0,004 cm in a typical case.

2. Heat transfer across the interfacial gap

It is the writer's thesis that the observed magnitude and time dependence of the interface coefficient can be entirely explained as gaseous conduction in the air gap between the surfaces. To recapitulate the observations cited above, the coefficient during glass-to-mold contact behaves approximately as shown in figure 1 [1 and 3]. Variations in forming parameters such as temperature and pressure affect the shape of the descent, but the general course is as depicted in the figure.

Two cases, representing the extremes of the curve, will be discussed:

Case I: Contact time longer than 1 s; the interface coefficient, $h \simeq 2\ kW/m^2 \cdot K$; the gap separation, $d \simeq 0{,}004$ cm.

In this case, demonstration that heat transfer is by conduction is simple and straightforward; the heat transfer coefficient will be given by

$$h = k/d$$

where k is the bulk conductivity of air in the gap, and d is the gap width. At T = 870 °C, k = (approx.) $1{,}8 \cdot 10^{-4}$ $cal/cm \cdot s \cdot °C$;

$$h = 1{,}8 \cdot 10^{-4}/0{,}004 = 0{,}045\ cal/cm^2 \cdot s \cdot °C \simeq 2\ kW/m^2 \cdot K.$$

Thus the heat transfer after 1 s or more of dwell is adequately explained by the bulk conductivity and the gap dimension.

Case II: The beginning of dwell (time zero); $h > 11\ kW/m^2 \cdot K$; $d \simeq 2{,}5 \cdot 10^{-5}$ cm.

Here the assumption of bulk conductivity is not adequate; for, taking k the same as case I,

$$h = 1{,}8 \cdot 10^{-4}/2{,}5 \cdot 10^{-5} = 7{,}2\ cal/cm^2 \cdot s \cdot °C \simeq 300\ kW/m^2 \cdot K$$

which would appear to be at least an order of magnitude too large.

The fact that now becomes important, however, is that gaseous conduction in a sufficiently small gap is a different kind of phenomenon than conduction in bulk. The extreme case is that in which the mean free path of the gas molecules is of the same order of magnitude as the gap spacing. The means of calculating the mean free path L can be found in any textbook on Kinetic Theory of Gases, e.g., Loeb [5]. Under the conditions that obtain for the interface at time zero, the mean free path of air is approximately

$$L \simeq 10^{-5}\ cm;$$

whereas, the initial gap spacing between the glass and the mold is

$$d \simeq 2{,}5 \cdot 10^{-5}\ cm = 2{,}5\ L.$$

Molecule-to-molecule collisions are infrequent when the total separation distance is less than about 5 L, and the predominant mode of heat transfer is known as free-molecule conduction. This is analogous to certain classical experiments in which plates are separated by relatively great distances, but the gas between them is at sufficiently low pressure that molecular collisions are improbable. The theory for such cases is well known and a moderate amount of experimental work has been done in the area. Both are documented by Kennard [6].

For the quantity of heat Q transferred by free-molecular conduction between two surfaces 1 and 2, Kennard derives the following:

$$Q = \frac{a_1 a_2}{a_1 + a_2 - a_1 a_2} \cdot \frac{1}{2}(\gamma + 1) \cdot \frac{cp}{\sqrt{2\pi RT}} \cdot (T_1 - T_2).$$

Here a_1 and a_2 are accommodation coefficients determined experimentally. When a free gas molecule strikes a solid surface, it may give up all or part of its translational energy; the accommodation coefficient is a measure of the fraction of energy lost. The values given in Kennard are mainly for simple gases in contact with metal surfaces, with limited data for one gas contacting glass. By inference from these data, the best estimate is that $a_1 = a_2 = 0{,}6$, for air against glass and against mold-metal surfaces. The remaining terms in the expression for Q are described below.

Note that the Kennard expression contains the term $(T_1 - T_2)$, the difference between the surface temperatures. It follows then that the balance of the expression is the heat conductance, i.e., the heat transfer coefficient h. Therefore, one may write:

$$h = \frac{a}{2 - a} \cdot \frac{1}{2}(\gamma + 1) \cdot \frac{cp}{\sqrt{2\pi RT}}$$

where

h = the interface coefficient, to be calculated;
a = accommodation coefficient as above = 0,6;
γ = ratio of specific heats = 1,4 for air;
c = specific heat (at constant volume) = 0,172 $cal/g \cdot °C$, under these conditions;
p = pressure of the gas = 1 atmosphere (the gas is unconfined) = $1{,}0 \cdot 10^6\ g/cm \cdot s^2$;

R = the gas constant = $2{,}87 \cdot 10^6$ cm²/s² · degree (assuming "molecular weight" of air = 29);

T = gas temperature = 1150 K (assumed to be the average between the initial glass and mold surface temperatures).

Substituting in the above equation, one obtains

$$h = 0{,}60 \text{ cal/cm}^2 \cdot \text{s} \cdot °\text{C} = 25 \text{ kW/m}^2 \cdot \text{K}.$$

This is in rather good agreement with the experimentally observed $h > 11$, particularly in view of the fact that bulk conduction would require that the coefficient be more than tenfold larger.

3. Conclusion

The author has, then, explained the initial heat transfer across the interface as free-molecular conduction and the transfer at times relatively late in the dwell period as ordinary bulk conduction. The behavior between these extremes is now readily visualized and is postulated to be as shown in figure 2. True free-molecular conduction is not a function of the gap separation; hence the heat transfer coefficient should be nearly constant until the effect of molecule-to-molecule collisions begins to be a factor. This should start to occur when the total gap separation is approximately five times the mean free path (L), or in this case at about $5 \cdot 10^{-5}$ cm. Since the time required to reach a 5 L separation is very short, the initial plateau is not observed experimentally. Beyond this point in time, there will continue to be a free-molecule effect within a "jump distance" of about 2,5 L

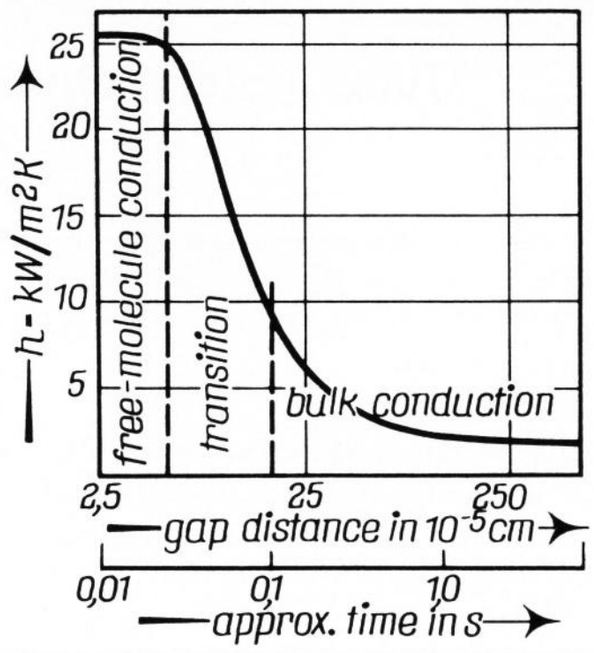

Figure 2. Postulated behavior of h, as interfacial gap increases.

from each surface, but in the remaining gap separation the transfer will be by bulk conduction, i.e., the energy interchange will be by molecular collisions. As the gap size increases, the bulk conduction effect increases in importance until finally the jump distances are a negligible part of the whole gap size.

A similar interfacial behavior should be expected in other forming processes involving rapid rates of heat removal as, for example, in metals casting, and the various methods of plastics forming.

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