A method of calculating the melting rate of glass batch and its use to predict effects of changes in the batch

Summary

Equations are derived which predict the melting times of glass batch fed by screw and blanket chargers to a tank furnace. They are used to predict the effect on melting time of preheating the batch and of substituting NaOH for Na₂CO₃, and Ca(OH)₂ or CaO for CaCO₃, as batch ingredients.

These equations rely on Kröger's finding, that the thermal conductivity of batch is very small until it reaches a temperature at which liquid phases appear. For many batches this coincides with the beginning of reaction in the batch. For such batches it can be shown that heat transfer takes place effectively between fixed temperatures: the surface temperature and the temperature at which reactions begin, the heat absorbed at the lower temperature being that required to raise the temperature of the batch ingredients from room temperature to the reaction temperature, plus the heat of reaction. Knowledge of the thermal conductivity and thickness of the fused layer and the thickness of heat needed to convert batch at room temperature into glass at the reaction temperature enables the melting rate to be calculated.

Introduction

The work described below arose out of our interest in a new material for the glass industry. We realized that materials which require less heat to make glass would be advantageous in saving fuel, but it soon became clear that much greater savings in the cost of glass manufacture could be obtained by increasing the output of any given glass furnace. In this way the standing heat losses from the furnace would be spread over a larger tonnage of glass as would also the capital, maintenance and some of the operating charges of the furnace. We therefore thought it necessary to be able to predict the output of a tank furnace fed with various batches. We soon found that the problem is one of appalling complexity, since even if one could accurately predict the melting rate, the refining rate has also to be considered.

The treatment of melting rates of various batches given below therefore concerns itself only the melting stage of glass manufacture and does not attempt to predict overall changes in furnace output. The treatment attempts to calculate the "melting time" by which is meant the time needed to convert all the batch fed to the furnace at any instant to the partly molten but unrefined condition, in which the batch reactions are complete but the residual sand grains are not completely dissolved in the primary silicates. The melting time thus corresponds to the interval between feeding and the conversion of the last portion of a blanket or batch pile to the molten condition — the time taken by a portion of batch to move from the dog house to the foam line.

During the melting stage of glass manufacture, the rate of conversion of the unreacted batch ingredients to the molten state is governed by the rate at which heat can flow into the batch. Before reaching the unreacted batch, heat must first of all pass through the molten layer which covers it and

*) (Imperial Chemical Industries Limited, Mond Division, Runcorn Heath, Cheshire). Efter föredrag vid NGF:s värme 1968.
so the rate of melting of batch is determined by the thickness and thermal conductivity of this molten layer and the temperature gradient across it. During the melting of a level blanket of batch, the thickness of the molten layer will increase steadily as more and more batch is melted. In the melting of ridges of batch formed by the use of screw feeders, molten glass streams continually down the sides of the ridge, and the thickness of the molten layer covering the batch increases to a constant value at which the rate of formation of melt from batch is exactly balanced by the rate at which fluid melt runs down the side of the ridge. The two types of melting process are thus different and will be considered separately.

**Melting of a blanket of batch**

The melting of a horizontal layer of batch formed by a blanket feeder is similar to many processes in which the resistance to the flow of heat or matter changes as the process continues because the thickness of one phase, through which heat or matter must pass, increases at the expense of the second phase which is undergoing transformation. Such problems as the freezing of lakes and water-bearing soil, solidification of castings, and corrosion fall into this class which, because of its technical importance and mathematical interest, has received much attention. Reviews of this class of problem, generally known as Stefan’s problem, have appeared recently (1–3).

The problem of freezing or melting was solved analytically by Neumann (4) but only for the case in which the thermal diffusivity of the transformed layer (e.g. ice during the freezing of a lake) does not vary with temperature. For glass this condition is very far from being fulfilled; as a further complication, the transformation from batch to melt involves a series of reactions with finite reaction velocities which are also temperature dependent. The problem could probably be solved numerically by computer using finite difference techniques, but such an approach must inevitably give particular solutions to specific examples. The following treatment enables the importance of certain factors in the melting rate of glass to be estimated and semi-quantitative predictions of melting rate for conditions other than those generally encountered, to be obtained.

Part of the complexity of the problem of melting with a moving boundary between phases lies in the fact that heat is flowing into the unmolten material and raising its temperature so that the conditions in the unmolten layer are changing with time; thus the temperature of the unmolten layer could be very much hotter at the end of the melting period than at the beginning. This difficulty is avoided if the unmolten material — batch in our case — is a perfect insulator since heat flow into the interior of the unmolten layer is then impossible. Fortunately, as discussed below, the thermal conductivity of unreacted batch is so small that it can be considered to be a perfect insulator, and this is the basis of the simplified treatment of glass melting rates given here.

As stated above, the rate of melting of batch is governed by the rate of heat transfer through the molten layer covering it. The thermal conductivity of batch was measured by Kröger & Eilgehausen (5) over the temperature range 100°C to 1250°C. Their results are given in Fig. 1. They show that the thermal conductivity of batch remains virtually constant until the batch reactions begin and the first molten phases appear, when there is a sudden rapid increase in thermal conductivity. The results can be fitted very closely over the range 750°C to 1250°C by the expression.

$$K_\Theta = 7.43 \times 10^{-10} \Theta^{3.2} \text{kcal/m.h.}°\text{C} \ldots \ldots 1$$

where $K_\Theta$ is the thermal conductivity at temperature $\Theta$ °C.

Consider a blanket of batch of uniform thickness across the width of the furnace (Fig. 2) made up of sodium carbonate, calcium carbonate and silica in the proportions used for a normal container glass. Suppose that the batch is already partly molten. The molten layer rests on the unmolten layer and accor-
Fig. 2. Section through a melting blanket of batch.

ding to Ito et al (6) does not percolate through to the underlying layers. We shall assume a constant surface temperature of the molten glass, or in other words, that heat transfer from the flame to the surface is rapid compared with the rate of heat transfer through the melt. In the case of a container glass, the first major liquid phases appear at about 850° C. The reaction between sodium carbonate, calcium carbonate and silica also starts to occur rapidly at about this temperature. The bottom of the fusing layer, resting on the unreacted batch will therefore be at about 850° C.

Heat flowing through the molten layer is thus flowing across a constant temperature interval from the surface temperature to the reaction temperature, and a knowledge of the mean thermal conductivity of the melt would enable the rate of heat transfer through it to be calculated.

Referring to Fig. 2, consider any horizontal zone of thickness δL and area A in the partially molten layer of thickness L. Let the temperature of the zone be θ and the temperature differences across it be δθ. The thermal conductivity of the material in the molten layer is a function of temperature; let the thermal conductivity of the material at temperature θ be Kθ. The rate of heat transfer (Q) through this zone is then

\[ Q = -K \frac{\partial \theta}{\partial L} \]

or in the limit

\[ Q = -K \frac{d\theta}{dL} \]

This equation can be integrated if Q is assumed constant

\[ \int_{\theta_2}^{\theta_1} Q dL = -A \int_{\theta_2}^{\theta_1} K \theta d\theta \]

where \( \theta_1 \) and \( \theta_2 \) are temperatures of the upper and lower surfaces respectively of the partially molten layer of thickness L. \( \theta_2 \) is 850° C in our example.

\[ Q = \frac{A}{L} \int_{\theta_2}^{\theta_1} K \theta d\theta \]

The integration of equation (4) can be carried out analytically using equation (1) or graphically by measuring the area under the curve given in Fig. 1 between the ordinates \( \theta_1 \) and \( \theta_2 \). This is the area cross-hatched in Fig. 1.

The heat flowing through the molten layer passes into the unreacted batch. If we assume that batch is a very poor conductor, the heat entering it will be totally absorbed by a very thin layer adjacent to the lower surface of the melt. The heat absorbed will raise this very thin layer to the reaction temperature, further heat will then be absorbed by the batch reactions and the thin layer of batch will be converted to the partially molten state, so increasing the thickness of the partially molten layer. The time needed to convert the entire layer of batch to the molten condition can be calculated as follows.

In time \( \theta T \), the quantity of heat flowing through an area A of the molten layer of thickness L is.

\[ Q \theta T \]

substituting the value of Q from equation (4) gives for this quantity

\[ \left( \frac{A}{L} \int_{\theta_2}^{\theta_1} K \theta d\theta \right) \theta T \]

This quantity of heat will be totally absorbed by a thin layer of batch which will be converted to the molten condition so increasing the thickness of the molten layer by an amount \( \theta L \). The relationship between \( \theta L \) and \( \theta T \) is given by the equation

\[ \frac{A}{L} \int_{\theta_2}^{\theta_1} K \theta d\theta = AH_f \]

where \( AH_f \) is the heat required to raise a quantity of batch to the reaction temperature and convert it to unit weight of melt at the reaction temperature, and \( \rho \) is the density of the melt.

In the limit, this equation can be integrated

\[ \int_{t}^{0} dt = \frac{\rho AH_f}{L} \]

\[ t = \frac{\rho AH_f}{L^2} \]

where \( t \) is the time in hours.
The time needed to form a layer of glass increases therefore as the square of the thickness of the layer. This time corresponds to the period between the charging of a portion of batch and its total disappearance: the time taken for a portion of batch to travel from the batch charger to the foam line.

The validity of the assumptions made in deriving this expression will be considered later. Let us first of all examine some of the implications of the equation.

In order to reduce the melting time of a layer of batch of a given thickness two terms can be changed: \( \Delta H_f \) must be reduced and \( \int_{\theta_1}^{\theta_2} K_0 \ d\theta \) increased.

\( \Delta H_f \) consists in reality of two terms: the “sensible heat” (\( \Delta H_s \)) required to raise the batch to the reaction temperature, and the “heat of reaction” (\( \Delta H_r \)) needed to carry out the batch reactions and produce melt from batch at the reaction temperature.

\[
\Delta H_f = \Delta H_s + \Delta H_r \quad \ldots \ldots \quad (10)
\]

It is possible to vary either or both of the quantities on the right of this equation. To reduce the sensible heat (\( \Delta H_s \)) it is necessary only to preheat the batch — an idea which has often been studied and which has been widely discussed. The chemical heat of reaction (\( \Delta H_r \)) can only be changed by changing the batch ingredients. Unfortunately, of fortunately, depending on your point of view, the raw materials for glass are already so astonishingly cheap that the range of raw materials one might consider using is very small; the effect of using NaOH, Ca(OH)\(_2\) and CaO instead of the usual Na\(_2\)CO\(_3\) and CaCO\(_3\), and of preheating a conventional batch to various temperatures, are examined below.

The values of \( \Delta H_f \) for a preheated carbonate batch were calculated according to the scheme given in Fig. 3. \( \Delta H_f \) is given by the expression.

![Fig. 4. Calculation of \( \Delta H_f \) for batches at 25°C.](image)

**Table 1. Values of \( \Delta H_f \) for various batches**

<table>
<thead>
<tr>
<th>Batch Number</th>
<th>Batch Ingredients</th>
<th>Batch Temp. °C</th>
<th>( \Delta H_f ) (k,cal/g glass)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( \text{Na}_2\text{CO}_3 ) (c) + ( \text{CaCO}_3 ) (c) + ( \text{SiO}_2 ) (q)</td>
<td>25</td>
<td>0.352</td>
</tr>
<tr>
<td>2</td>
<td>ditto</td>
<td>330</td>
<td>0.314</td>
</tr>
<tr>
<td>3</td>
<td>ditto</td>
<td>630</td>
<td>0.227</td>
</tr>
<tr>
<td>4</td>
<td>( \text{NaOH} ) (c) + ( \text{CaCO}_3 ) (c) + ( \text{SiO}_2 ) (q)</td>
<td>25</td>
<td>0.301</td>
</tr>
<tr>
<td>5</td>
<td>( \text{Na}_2\text{CO}_3 ) (c) + ( \text{CaO} ) (c) + ( \text{SiO}_2 ) (q)</td>
<td>25</td>
<td>0.280</td>
</tr>
<tr>
<td>6</td>
<td>( \text{NaOH} ) (c) + ( \text{Ca(OH)}_2 ) (c) + ( \text{SiO}_2 ) (q)</td>
<td>25</td>
<td>0.263</td>
</tr>
</tbody>
</table>

\[
\Delta H_f = \Delta H_1 + \Delta H_2 + \Delta H_3 + \Delta H_4 - H \Delta s - \Delta H_5 - \Delta H_6 - \Delta H_7 - \Delta H_8 \quad \ldots \ldots \quad (11)
\]

\( \Delta H_1 \) was calculated from data in Ref. 7. There is no data on the standard heat of formation of \( \text{CaSiO}_3 \) glass, so by analogy with \( \text{Na}_2\text{SiO}_3 \) and \( \text{SiO}_2 \) it was assumed to be 3.0 kcal/mole less than crystalline \( \text{CaSiO}_3 \). The other terms were calculated from Kelley’s data (8). He gives no data on the heat content of vitreous \( \text{Na}_2\text{SiO}_3 \) and is assumed to be equal to that of crystalline material. Any error so introduced will be very small.

The value of \( \Delta H_f \) for batches of a chemical composition other than the conventional mixture of sand, soda ash and limestone were calculated according to the scheme given Fig. 4.

Table 1 gives the calculated values of \( \Delta H_f \) for various batches which would yield glass of the composition 15% \( \text{Na}_2\text{O} \), 10% \( \text{CaO} \), 75% \( \text{SiO}_2 \).
the limits 1300°C and 850°C using Krögers data gives a value for this expression of 22.5 k.cal/cm² h.
Insertion of this value, a value of 2.5 g/cm³ for the
density of the melt and an appropriate value of ΔHf
from Table 1 into equation (9) enables the melting
times of batches of various thicknesses, compositions
and temperatures to be calculated. The results of
such calculations are given in Fig. 5 where the mel-
ting times is plotted as a function of the thickness of
melt formed. The numbers of the curves refer to the
batch numbers in Table 1. The density of batch is
very close to half that of the melt so that the thick-
ness of the melt will be half that of the layer of
batch from which it was formed.

The curve shows that for a conventional container
batch fed to the furnace at 25°C, a blanket of batch
10 cm thick will need 32 minutes to be converted to
the molten state and the a blanket 20 cm thick will
need 127 minutes. These figures are in the range
quoted by Jack & Jaquest (5) from observations on
actual glass tanks. Using this batch, a layer of melt
8.9 cm thick can be formed in 100 mins. The times

needed to form the same thickness of melt using the
other batches given in Table 1 are given in Table 2.

It would appear therefore that there are substan-
tial improvements in melting time to be obtained
from changes in the batch. It would seem best to
preheat the batch since this could be done cheaply
using waste heat from the furnace gases, although of
course, capital expenditure would be necessary. Of
the remaining variants, the new batch ingredients
are certain to be more expensive than soda ash and
limestone; caustic soda is hygroscopic and demands
special care in handling. Probably the cheapest and
least objectionable change in chemical would be to
substitute quicklime for calcium carbonate.

In studying the effect of changes in batch compo-
sition, only cold batch has been considered. If the
batch containing the more reactive ingredients were
heated, it would be possible to reduce the value of
ΔHf to very small values with correspondingly
large reductions in melting time according to equa-
tion (9), but this is probably stretching the validity
of this equation beyond even the semi-quantitative
range. It is even possible to find a batch for which
ΔHf is zero: if the surface of a batch made up with
NaOH, CaO and SiO2 preheated to 740°C were
suddenly exposed to a temperature of 850°C to
initiate the reaction of CaO + SiO2, sufficient heat
would be evolved to sustain the reaction.

Having considered the ways in which the ΔHf
term in equation (9) can be varied to increase the
melting rate, let us consider the other variable in

the equation, \[ K_\theta \int_{\theta_2}^{\theta_1} \alpha d\theta, \]

which is the area under

the curve of thermal conductivity vs. temperature
(Fig. 1). To decrease the melting time, this term
must be increased. The most obvious way of doing
so is by increasing the surface temperature of the
molten layer, and this is the way in which furnace
outputs have been increased in recent years, furnace
temperatures pressing hard on the heels of each new
generation of refractories. Because of the very
strong temperature dependence of thermal conduc-
tivity, a modest increase in temperature can bring
about an enormous increase in the area under the
K_\theta vs. temperature graph and hence a large
increase in melting rate. For example, by increasing
the surface temperature of the melt from 1300°C
to 1400°C the area under the curve is increased by
60%. The two areas are shown hatched differently
in Fig. 1. Thus according to equation (9) the time

needed to melt a blanket of conventional composi-

Table 2.
Comparison of melting time for Various Batches
(Carbonate batch at 25°C : 100 minutes.)

<table>
<thead>
<tr>
<th>Batch Number (see Table 1)</th>
<th>Melting time (t) (mins)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>82</td>
</tr>
<tr>
<td>3</td>
<td>59</td>
</tr>
<tr>
<td>4</td>
<td>79</td>
</tr>
<tr>
<td>5</td>
<td>73</td>
</tr>
<tr>
<td>6</td>
<td>60</td>
</tr>
</tbody>
</table>
tion, of any given thickness, using a surface temperature of 1400° C is only 60% of that required to melt the same blanket with a surface temperature of 1300° C.

The other way to increase the area under this curve is to obtain batches which fuse at a low temperature so that the curve starts its steep upward climb at lower temperatures than with the conventional batch. This can be accomplished by the use of melt accelerators such as sodium nitrate which promote the reaction of sodium carbonate with silica at low temperatures. Unfortunately, because the other reactions, in particular the reaction of calcium carbonate with silica, take place at very much higher temperatures, the situation is too complicated to be dealt with using the simple treatment described above. In L.C.I. we were interested particularly in an intimate mixture of sodium hydroxide and calcium hydroxide which we called "soda lime". Thermogravimetric measurements showed that this material starts to react rapidly with silica at about 550° C when the calcium hydroxide decomposes and releases the caustic soda which up to this point has been imprisoned in the pores of the calcium hydroxide. Without repeating Krögers work it was only possible to guess at the area under the curve of thermal conductivity against temperature. From our thermogravimetric measurements we estimated that the area under this curve was about 20% greater than that for the conventional carbonate batch assuming a surface temperature of 1300° C in each case. In the previous section we showed that ΔH_r for a batch made up with sodium and calcium hydroxides in only 70% of that for a conventional carbonate batch. Combining the two factors of low melting temperature and low heat of reaction, it seems that the melting time of a hydroxide batch would be only 60% of that for a carbonate batch.

Having dealt with some illustrations of the use of equation (9), it is necessary to consider the validity of the assumptions made in deriving it.

The first of these is that the batch reactions are complete at 850° C and that solution of the residual silica in the primary silicates requires little heat. Very satisfactory agreement with Krögers experimental data on heats of reaction to form glass is obtained assuming that glass in a mixture of sodium metasilicate glass calcium silicate glass, and vitreous silica. It follows therefore that the heat of solution of residual silica in the primary melts will be the heat of devitrification of silica. This is only about 5% of the total heat of formation of glass and we can ignore it.

The rate of the primary batch reactions must also be considered since these must be completed rapidly compared with the overall reaction time if we are to assume that the heat of reactions is absorbed at a particular temperature. Reaction rates at particular temperatures have been measured by Kröger (11) for simple batches and for batches containing accelerators. From his results for a simple batch it seems that at 850° C, reaction is 90% about 13 minutes, whereas at 875° C reaction is 90% complete in about 3 minutes. There is considerable discussion in the literature about the exact course of these reactions and whether or not calcium carbonate forms a double carbonate with soda. The differential thermal analysis results of Oldfield (10) show a peak at 895° C indicating that at least some of the calcium carbonate is being decomposed at this temperature; on the other hand Kröger (11) maintains that the rate of reaction in the presence of silica is 100 times faster than the simple decomposition reaction in the absence of silica. Wilburn and coworkers (12), admittedly in the presence of dolomite, find that calcium carbonate reacts with silica below 898° C as the double carbonate. On balance, it seems that the CO_2-releasing reactions are sufficiently rapid between 850 and 900° C to give complete reaction in a time much shorter than the total melting time of the blanket for normal blanket thicknesses.

It was also assumed that the unreacted batch is a perfect insulator and hence that heat entering the
batch is totally absorbed in a thin layer adjacent to the fusing layer. This of course is not true and a plot of temperature of the batch against distance from the molten layer would have approximately the form shown in Fig. 6. The "thin layer" absorbing the heat thus has an effective thickness $\gamma$ which is the thickness of the layer of batch at a temperature above the temperature at which the batch was charged. As long as this distance $\gamma$ is small compared with the total thickness of batch still unmelted we can think in terms of a thin layer of batch absorbing heat transmitted through the molten layer. When $\gamma$ becomes comparable to the thickness of batch still unmelted, the assumption is no longer valid.

Calculation of the exact shape of the temperature profile in the batch (the shape of the curve in Fig. 6) would be very complex, but it is easy to put limits on the value of $\gamma$. The slope $\left(\frac{d\theta}{dl}\right)_{l=0}$ of the curve where it touches the temperature axis (point A) is defined by the equation

$$Q' = K_b \left(\frac{d\theta}{dl}\right)_{l=0} \quad \ldots \ldots \ldots (12)$$

where $Q'$ is the rate of flow of heat into unit area of the batch at the interface between the molten and unmolten layers, $K_b$ is the thermal conductivity of unmolten batch and $l$ is distance in the batch from the interface. The heat $(Q)$ flowing into the unreacted batch represents the "sensible heat" fraction of the total heat flowing through the molten layer, since this is the heat needed to raise the batch to the reaction temperature (equation 10).

Hence

$$Q' = Q \cdot \frac{\Delta H_s}{\Delta H_f} \quad \ldots \ldots (13)$$

Thus, for any thickness of the molten layer, it is possible to calculate the temperature gradient in the batch at the interface. The intersection of this gradient with the distance axis (point C, Fig. 6) gives a lower limit $(y)$ for the value of $\gamma$. Some calculated values of $y$ for several values of the thickness of the molten layer $(L)$ are given in Table 3.

As a first approximation to finding the true shape of the curve $AB$ one could postulate that it will have the form of one of the family of curves obtained by considering that the batch is a body initially at room temperature whose upper surface is suddenly raised to $850^\circ$C for various periods of time. If no melting takes place and the surface remains stationary it is an easy matter to find the temperature profile corresponding to a particular period of time which has elapsed since the surface temperature was changed. Each of these curves can be related, according to its temperature gradient at the point A (Fig. 7), to a particular thickness of the molten layer.

This family of curves can be used to find a value for the velocity at which a point on the low temperature end of the curve (point D, Fig. 7) advances through the batch, as a function of the temperature gradient at that point. We know that this velocity cannot be less than the velocity with which the thickness $(l)$ of unreacted batch decreases as its

<table>
<thead>
<tr>
<th>Thickness of Molten layer $(L)$ (cm)</th>
<th>Effective thickness of fusing layer $(y)$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.2</td>
</tr>
<tr>
<td>2</td>
<td>0.3</td>
</tr>
<tr>
<td>4</td>
<td>0.5</td>
</tr>
<tr>
<td>6</td>
<td>0.7</td>
</tr>
<tr>
<td>8</td>
<td>1.0</td>
</tr>
<tr>
<td>10</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Fig. 7. Section through a melting ridge of batch.
surface is converted to the molten condition. The latter can be calculated by differentiating equation (9) and applying a factor to account for the fact that we are considering the velocity through the unreacted batch rather than the rate of change of thickness of the molten layer.

\[ \frac{dl}{dt} = \int \frac{K \theta}{\Delta H_f L} d\theta \]

where \( q \) is the density of the unmelted batch. We can thus find the slope of the curve at the point D for any given thickness of the molten layer.

Comparison of the temperature gradients at points A and D shows that temperature profiles calculated assuming a stationary boundary between melt and batch give an erroneously high value for \( \chi \), so that if the values of \( \chi \) so calculated turn out to be small compared with the thickness of the batch layer, then the assumption made when deriving equation 9, that the fusing layer is very thin, is valid. Figure 7 shows three such temperature profiles for the situation where the batch is overlain by 5 cm, 10 cm and 15 cm of melt respectively. When the thickness of melt is 5 cm, the effective thickness of the melting layer (\( \chi \)) is about 1.5 cm; so that as long as the total thickness of batch remaining unmelted is several times this thickness the approximation we have used is valid. Similarly when the thickness of the melt is 10 cm, \( \chi \) becomes about 3 cm. For a 15 cm thickness of melt, the effective thickness \( \chi \) of the melting layer has increased to more than 4 cm. However, we should remember that 15 cm of melt corresponds to about 30 cm of original batch so that even for a blanket of batch of this thickness, it is only towards the end of the melting period that the thickness of the melting layer is becoming too great for the approximation to be valid.

Heat transfer to the underside of the blanket, through the hot glass on which it is floating, has so far been ignored. It is likely to be small compared with direct heat transfer from the flames since the dependence of heat transfer rate on the surface temperature is so enormous. If the temperature of the glass under the batch were 1150°C, the melting rate of the underside of the batch would be less than half that of the top surface at 1300°C. The few measurements available on the temperature under the batch \(^{(12)}\) seem to indicate a value 150°C lower than the maximum temperature of the surface.

The most important assumption made in deriving equation (9) was that heat flow through all the layers of melt is equal. This is untrue since any element of melt below the surface increases in temperature with time, and the heat flowing through the upper layers must necessarily be greater than that flowing through the lower layers. Therefore the temperature gradients are steeper at the surface and shallower at the boundary between melt and batch than has been assumed. The actual rates of melting will be lower, therefore, than those predicted by equation (9).

This assumption is commonly made \(^{(11)}\) in dealing with problems of this type since it leads to an analytical solution. It would nevertheless be desirable to know the extent of the error introduced in the present case and an indication of the size of the error can be obtained as follows. Equation (9) gives too low a value for the melting time of a batch blanket. The value would be increased by increasing the value of \( \Delta H_f \) and reflection shows that the value of \( \Delta H_f \) is actually too low since the treatment has assumed, effectively, that the melt is all at 850°C, whereas its mean temperature is about 1150°C. A not unreasonable second approximation might therefore be to increase the value of \( \Delta H_f \) to include the sensible heat necessary to raise the melt to 1150°C instead of 850°C. This has the effect of increasing the calculated melting time of a conventional carbonate batch fed to the furnace at room temperature by about 20%, and slightly reduces the calculated beneficial effects of preheating the batch or changing its composition.

### The melting of batch piles

To calculate the melting rates of batch piles is very much more difficult than for the preceding case of a blanket of batch, and no attempt will be made to calculate actual melting rates; nevertheless it is possible by making simplifying assumptions, to estimate the effects of changes in the temperature and composition of batch on the melting rate.

When batch is fed to the furnace through a screw feeder, it floats on the surface of the glass as a ridge-shaped body. The molten layer on the surface of the ridge increases in thickness until the rate of formation of melt is balanced by the rate at which melt runs down the side of the batch pile. This case thus differs from the preceding one for a blanket of batch in that the thickness of melt limiting the rate of heat transfer to the batch is constant as long as the angle of slope of the side of the batch pile remains constant. The melting rate is thus determined
by the hydrodynamics of molten glass. If, once the steady state has been reached in which the rates of streaming and melt formation are equal, the heat required to convert the batch to the molten condition were suddenly reduced, the rate of glass formation would increase suddenly. The thickness of the streaming layer would then have to increase in order to balance this increased rate of glass production. In order to be able to assess the effects of changes in batch composition, it is thus necessary to be able to relate the streaming rate to the thickness of the streaming layer. This is attempted below.

In the steady state we can write

\[
\dot{V} = \frac{Q}{\varrho \Delta H_f} \tag{15}
\]

Where \( \dot{V} \) is the volumetric flow rate of glass running down the side of unit length of the ridge of batch, \( Q \) is the rate of heat transfer to the surface of the batch in this unit length of batch ridge and other symbols have the meanings defined formerly.

Fig. 7 shows a portion of a section through the surface of a batch ridge. We can distinguish three layers. Layer 1 consists of very hot fluid glass streaming down from the higher parts of the ridge. We shall assume this will have a constant temperature \( \theta_1 \) of say 1400°C and its thickness will vary from the top of the ridge to the bottom. Layer 2 is a layer of melt of thickness \( L \) formed from the batch beneath it. Part of this layer is fluid, and it is the volumetric flow rate of this fluid part which determines the melting rate according to equation (15). Layer 3 is unreacted batch. The boundary between layers 2 and 3 will be at a constant temperature \( \theta_2 \) just as for the melting blanket of batch discussed above. For a normal carbonate batch \( \theta_2 \) will be about 850°C.

Heat is thus transferred across layer 2 between constant temperature limits and we can write

\[
Q = \frac{b \bar{K} (\theta_1 - \theta_2)}{L} \tag{16}
\]

where \( b \) is the length of the sloping side of the batch pile.

\( \bar{K} \) is the mean thermal conductivity of the melt in layer 2, whence from equation (15)

\[
\text{melting rate} = \frac{b \bar{K} (\theta_1 - \theta_2)}{L \varrho \Delta H_f} \tag{17}
\]

The temperature distribution through layer 2 will be of the form given in Fig. 8. On the same axes is plotted the viscosity of glass as a function of thickness based on the temperature distribution. We can thus divide layer 2 arbitrarily into two layers, a stationary layer with a viscosity greater than say 1000 poise and a fluid layer with a viscosity less than 1000 poise.

The volumetric flow rate \( \dot{V} \) of this mobile layer for unit length of the ridge of batch is given by the expression

\[
\dot{V} = \frac{g (\varrho L)^3}{3 \bar{v}} \sin \varnothing \tag{18}
\]

where \( \varnothing \) is the angle of slope of the batch.

\( \bar{v} \) is mean viscosity

\( \varrho L \) is the thickness of the mobile portion of layer 2.

From equations (15), (17), (18)

\[
K b (\theta_1 - \theta_2) \frac{g \varrho^2 L^2}{L p \Delta H_f} = \frac{g \varrho^2 L^2}{3 \bar{v}} \sin \varnothing \tag{19}
\]

Assuming constant furnace operating conditions, the only variables are \( L \) and \( \Delta H_f \)

\[
L = C \left( \frac{1}{\Delta H_f} \right)^{1/4} \tag{20}
\]

where \( C \) is a constant.
Table 4.
Comparison of Melting Times for Various Batches
(carbonate batch at 25° C : 100 mins)

<table>
<thead>
<tr>
<th>Batch No.</th>
<th>Melting Time (mins)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>86</td>
</tr>
<tr>
<td>3</td>
<td>68</td>
</tr>
<tr>
<td>4</td>
<td>84</td>
</tr>
<tr>
<td>5</td>
<td>79</td>
</tr>
<tr>
<td>6</td>
<td>76</td>
</tr>
</tbody>
</table>

Substituting for L in equation (17)
\[
\text{melting rate} = \frac{1}{\Delta H_f} \quad \frac{C'}{C''} \quad \frac{3}{4}
\]

This treatment shows that the thickness of the fusing layer is insensitive to the heat of fusion of the batch and hence that the melting time is, to a close approximation, directly proportional to the heat required to convert batch to melt (\(\Delta H_f\)).

\[
t = \frac{C''}{C'} \Delta H_f \quad \frac{3}{4} \quad \text{......... (21)}
\]

where \(C''\) is a constant.

Using equation (21) and the data in Table 1 gives the following melting times for the batches in Table 1, assuming that a conventional carbonate batch fed to the furnace at 25° C, melts in 100 minutes.

Comparison of the figures in Tables 2 and 4 shows that the benefits of changing the batch composition or temperature are slightly less marked when batch is fed to the furnace as piles rather than as a level blanket.

As in the preceding case, the treatment has neglected the heat required to raise the melt above reaction temperature, and in the present case too, a more accurate result will be obtained by increasing the value of \(\Delta H_f\) to take account of the fact that the mean temperature of the melt will be about 1200° C rather than 850° C as implied in the treatment. Applying this correction will slightly reduce the calculated benefits of changing batch composition or temperature.

The proportional increase in melting rate resulting from increasing the furnace temperature will be greater for the melting of batch piles than for the blanket, since in addition to the increase in heat transfer rate at constant melt thickness (the area under the \(K_b\) vs. \(\Theta\) graph) already discussed when considering the melting of a batch blanket, the increased temperature will reduce the viscosity and hence the thickness, of the mobile part of layer 2, leading to a further increase in the heat transfer rate to the batch.

Conclusions

It would be technically feasible to preheat batch to a temperature below that at which the first molten phases appear. It would also be technically feasible to substitute other batch ingredients in place of the soda ash and ground limestone normally used for container glass; in fact some furnace operators already use burnt lime. The treatment given in this paper enables the melting rate of these non-standard batches to be calculated. The data given show that preheating the batch can increase melting rates by 40%, and that substitution of more reactive but still relatively inexpensive batch ingredients in place of those normally used can increase melting rates by 20–30%.

These predictions apply only to the melting phase of glass production; whether or not the full potential gain in output resulting from changes can be realised in practice will depend on the ability of any given furnace to refine the extra glass produced.

References: