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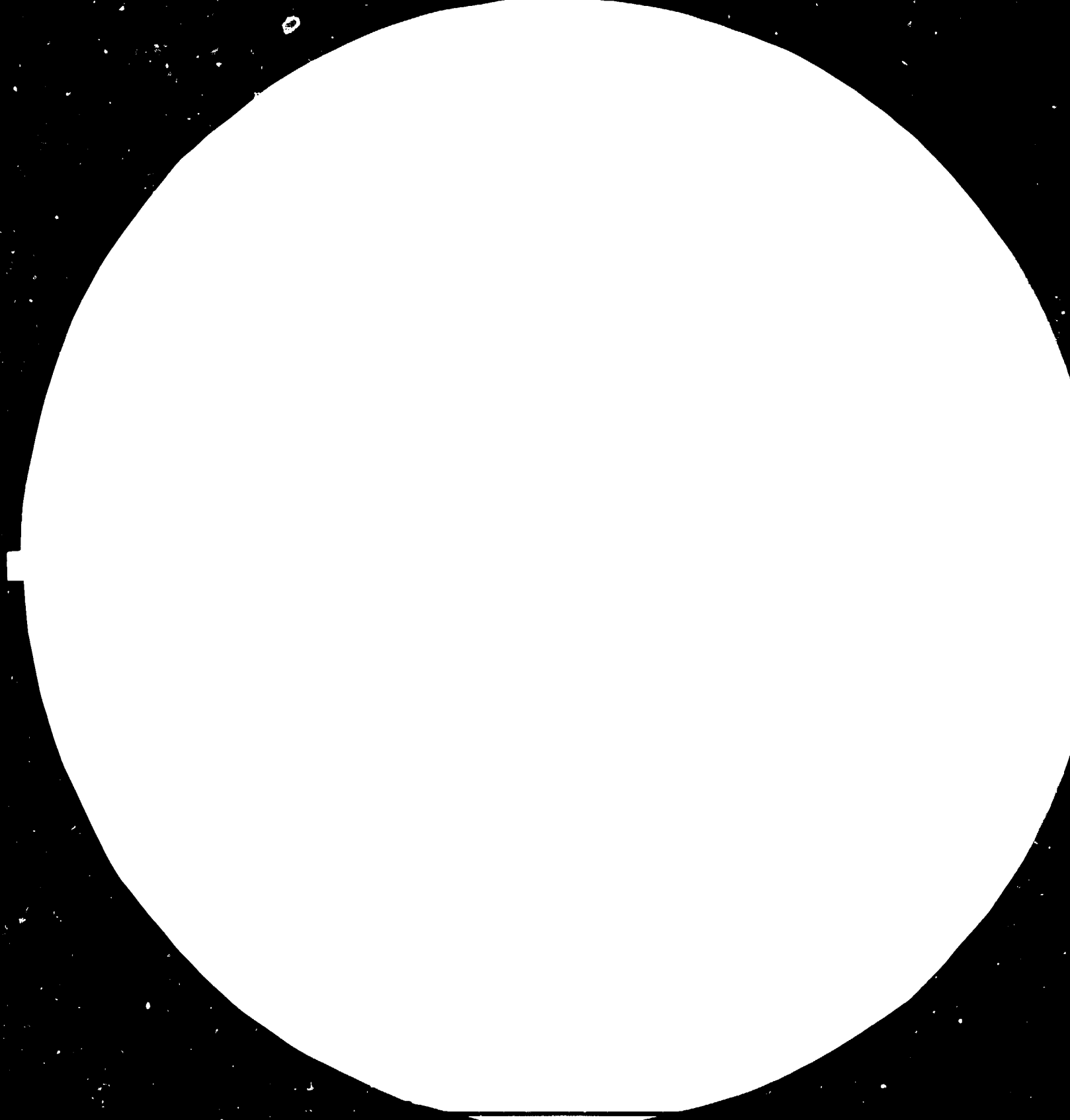
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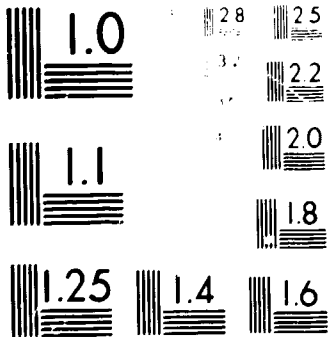
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HEAT CONSUMING UNITS IN GLASS INDUSTRY

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Heat Consuming Units in Glass Industry
/Possibilities of energy savings by melting of glass/

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One of the most frequently quoted definitions of the term "glass" is that proposed in 1945 by the American Society for Testing Materials: "Glass is an inorganic product of fusion which has cooled to a rigid condition without crystallizing"/1/.

Most commercially important glasses are oxide glasses and silica is almost always a major component. A number of commercial compositions are given in Table 1.

Table 1
Some commercial glass compositions

Application	Weight per cent										
	SiO ₂	Al ₂ O ₃	B ₂ O ₃	MgO	CaO	BaO	ZnO	PbO	Na ₂ O	K ₂ O	Li ₂ O
Containers	72,2	1,9		1,5	9,6				14,6		
Window glass	72,0	1,3		3,5	8,2				14,3		
Float glass	72,9	1,3		3,8	8,4				13,0	0,5	
Lamp bulbs	71,5	2,0		2,8	6,6				15,5	1,0	
Television bulbs B-W	67,0	5,0				11,7			7,0	8,3	0,6
Lead crystal	56,0							29,0	2,0	13,0	
boro-silicate Pyrex	80,8	2,2	12,8						3,2	1	
Sodium vapour resistant	5,5	17,5	16,0		9,51	52,0					
Solder glass	5,0		17,0				14,0	64,0			

Most of the glasses contain many components. These composition have usually been arrived at after many years of development, partly by systematic experiment, but more commonly by ad hoc adjustment.

The development of the technology which has resulted in the mass production of a wide range of glass products has also necessitated the use of a large quantity of energy mostly in the form of direct fossil fuels to effect the melting of the glass itself./2/

This situation is not confined only to the glass industry, in fact it can justly be stated that modern society has developed through the expenditure of the earth's reserves of energy. However it is now increasingly being recognised that these reserves are finite, and at the rate of consumption that attained immediately prior to 1974, the suggestion was seriously put forward that finite meant 20 to 30 years for the supply of oil and natural gas, although somewhat longer for coal.

The ultimate recognition of that has become known as the energy crisis.

Whatever the future, the time is ripe for an examination of the glass melting process with a view to establishing routes along which technical progress can be made towards drastically reducing the amount of energy required to melt glass.

It would be a major omission if no mention were made of the fact that over the past thirty years there has been considerable improvement in energy utilisation, in some cases there has been a reduction of 75% in fuel expended per glass item produced. This is a combined effect of furnace design and machine technology, which illustrates the fact that energy utilisation efficiency can be brought about by improved techniques which are the province of any number of skills.

However, it ought to be expected that any dramatic downward step change in energy consumption could be achieved largely in the high temperature area and to this end the first place to look is in the furnace function. In a glass plant about 80% of

the energy supplied to the plant is utilised in the furnace and whilst the proportioning 80% / 20% itself is not important /in fact, only to be expected/ it does point to where the greatest effort in energy savings ought to be made where energy is a high cost factor.

When considering the melting of glass it is necessary to deal with the melting process in general beginning with the raw materials and ending with the particular homogeneous glass of the required properties/3/.

We have to consider the properties and the quality of the raw materials, their refining, the handling of the batch, its charging and the charging equipment, the melting and refining of glass, the flow of the glass-melt in furnaces, the means of intensification of the melting process as e.g. the bubbling and electric boosting.

The melting process has to be considered namely from the point of view of the consumption of fuel and energies needed for the melting. The shape and the design of the furnace play here a significant role.

Raw materials

In well managed plants the regular and exact control of raw materials by chemical as well as by granulometric analyses are today commonly used. The use of modern analytical methods especially the X-ray fluorescence analysis makes it possible to have the results of the tests available in shorter time, and consequently increase the number of the tests performed in the same time /4,5/.

The recommended tolerances of impurity contents as well as of particle-size distribution of different raw materials used in manufacturing of sheet glass are given in Table II.

Table II

Raw materials for melting glass	Recommendations of quality criteria				
	Chemical composition			Grain size distribution	
	Oxide	Boundary value/%/	Tolerance/%/	Grain Size /mm/	Share/%/
Sand	SiO ₂	>99,5	± 0,2	> 0,6 > 0,5	0 < 2
	Al ₂ O ₃	< 0,3	± 0,05	> 0,3 0,1-0,3	20 Main part
	Fe ₂ O ₃	< 0,05	± 0,01	< 0,1	< 5
	Other minerals: chromite, corundum, disthen < 0,2g/100kg Sand < 0,3 mm				
Dolomite	Rock minerals	< 0,5	± 0,5	> 1,5	0
	Al ₂ O ₃	< 0,3	± 0,1	> 1,0 > 0,5 0,1-0,5	< 5 < 15 Main part
	Fe Fe ₂ O ₃	< 0,2	± 0,05	< 0,1	< 30
	Other minerals: chromite, corundum < 0,3mm				
Limestone	Rock minerals	< 1	± 0,2	1,5 1,0	0 5
	Al ₂ O ₃	< 0,3	± 0,1	0,5 0,1-0,5	15 Main part
	Fe ₂ O ₃	< 0,2	± 0,05	0,1	30
Feldspar	Al ₂ O ₃	≈ 14,5	± 0,5	> 0,4	0
	Fe ₂ O ₃	< 0,2	± 0,1	> 0,3	< 5
	Na ₂ O+K ₂ O ≈ 10		± 0,5	> 0,1	< 20
	Other minerals: chromite, corundum			< 0,1	> 75
< 0,3mm					

It is a general tendency to replace the natural raw materials by chemically manufactured substances, whose composition is more stable than that of natural minerals. It is another tendency to replace the soda ash by caustic soda, in order to

intensify the melting of glass. When using the soda ash the humidity /3 to 5%/ and the temperature of the batch are of great importance. The temperature has to be at least 32°C in order to stabilise the hydratation grade of the alkali raw materials, e.i. soda ash and sodium sulphate which are usually used as monohydrate or anhydride. The caustic soda /NaOH/, when used in batch, stabilizes the higher hydratation grade of soda ash and sodium sulphate also at lower temperatures.

Processing of the batch

The term "processing of the batch" means a special pretreatment which is carried out between the completion of batch mixing and the charging of the batch into the melting furnace/ 6/. It may be carried out either mechanically by compacting e.g. by briquetting or pelletizing or thermally by pre-heating or sintering right up to pre-melting. Combinations of these processing techniques have also proved practicable in operation.

By means of batch processing it is possible

- to consolidate the thorough mixing of the batch and to eliminate its segregation
- to prevent the dusting in the melting furnace and its adverse effect on its lifetime
- to avoid the inhomogeneities of the melt
- to increase the melting speed due to the higher thermal conductivity of the briquets or pellets.

Loose batch possesses a thermal conductivity
 $\lambda_1 = 0,2726 \text{ Wm}^{-1}\text{K}^{-1}$, compressed batch $\lambda_2 = 0,43 \text{ Wm}^{-1}\text{K}^{-1}$

The solidification of glass batch increases the melting process by 20% to 30% without any additional energy input, such as electric energy, comparing with the melting rate of the normal loose batch. Yamamoto /7/ specifies the conditions under which e.g. the pellets have to be prepared. when pelletizing the batch, the caustic soda has to be used and it acts as a binding agent and at the same time

as a good melting accelerator. Partial substitution of NaOH for soda ash is therefore a specific feature of pelletizing technology. Granular soda ash cannot be used for pelletizing but powder soda ash should be used /7,8,9/.

In the case of silica sand the grain-size distribution is of major importance, similarly as in melting from a loose batch. Yamamoto recommends that the amount of coarse grains, i.e. from 0,3 to 0,42 mm, should not exceed 3%, the intermediate-size group /0,15 to 0,3 mm/ should be under 30% and the major part of the sand should be of finer grain sizes e.i. from 0,07 to 0,15 mm.

Limestone and dolomite must have finer grain than those normally used, and powder under 180 μ m is recommended.

All kinds of refining agents can be used, such as sodium nitrate and diarsenic trioxide /NaNO₃-As₂O₃/, sulphate etc. In the case of sulphate fining much smaller additions than those added to loose batches are recommended.

Cullet can be added to the pellets in any ratio. The amount of NaOH to be added must be controlled continuously in exact proportion to the flow rate of mixed powder. For pelletizing, a pan-type pelletizer is commonly used. It is necessary to dry the pellets either in a rotary or in a band type drier. After drying, the pellets are screened and the dust and under size pellets are treated with a view to reusing.

There is a possibility of preheating pellets before charging into the furnace, which will provide a good basis for the future progress of glass melting. Waste gases may be used for preheating.

The melting process itself may be divided into several stages/10/. First of all it is necessary to heat the batch until reactions begin. After that the major melting, mainly chemical reactions take place, then follows the dissolution of residual silica grains, then the refining and ultimately

the homogenizing of the glass-melt. According to the differential thermal analysis work of Wilburn /11/ the thermogravimetric studies of Kröger/12/ the reaction of silica with other materials reaches sufficiently high rates to be of interest around 700°C. Heating of the batch from room temperature to around 600°C can be regarded as the first stage at which the heat transfer is the main problem. The pelletizing and the possibility of preheating the batch is therefore very important at this stage.

The complex melting reactions reach very high rates when the temperature has reached 1000 to 1100°C. From this point of view higher temperatures than these are not required. The viscosities of molten sodium carbonate and other liquids are very low and too rapid heating could therefore easily cause melting segregation. At the end of the vigorous gas evolution large proportion of the silica has reacted and has dissolved. The rest of the grains dissolves quite slowly and this process is controlled by diffusion in the melt/13,14/. This is the stage at which a temperature of around 1500°C is desirable.

Refining

The raising of the temperature also accelerates the refining process and here again the temperatures in the range between 1500 and 1600°C are desirable even though the fuel consumption increases enormously. Refining involves both chemical and physical processes some of which are not well understood yet. Many authors are dealing with this problem. Cable /15,16,17/ states that appropriate additions of refining agents have greater effects on the refining than any other single parameter. Understanding the refining process therefore ought to make greater contribution to increasing the efficiency of the refining process than any other factor. Such knowledge would be particularly valuable nowadays when the known effective refining agents are disapproved of for various reasons.

Firstly, arsenic and antimony are known to be poisons, secondly it has been shown by many authors/Hulínský, Staněk/18/, Ooka/19/, Pieslinger /20/ that they corrode heavily the molybdenum electrodes when used as refining agents in electric melting or boosting.

Sodium sulphate, used generally for refining may be an important source of atmospheric pollution. It also increases the corrosion of the molybdenum electrodes. From this point of view it is necessary that the amount of refining agents should be as small as possible.

Increases in temperature accelerate refining but should only be resorted to after the minimum necessary amount of the refining agent has been established.

Careful design and use of electrode systems can produce correctly localized hot zones, which might be useful here.

The laboratory observation method introduced by Němec /21/ is a very good instrument for establishing the proper rate of the refining agents for the batch concerned, to observe the influence of these agents on the corrosion of the electrodes, of the refractory materials, to observe the developing of the bubbles on grains of sand, on refractory materials etc.

On the basis of visual and photographic observations of the glass melt containing bubbles and of the derived theoretical equations, the bubble removal from the glass melt has been quantitatively described and the role of individual gases during diffusion has been evaluated. The existence of heterogeneous bubble nucleation at refining temperatures makes it possible to divide the melting process into the period of SiO_2 dissolution and the period of bubble ascension.

It is practicable to accelerate the refining by bubbling with appropriate gases at suitable stages. This method has been studied by Goetz and Staněk /22/. It is well known that

the chemical reactivity of the atmosphere/waste gases/ above the glass-melt has a great influence on the refining process. The reducing atmosphere above the melting area of the furnace where the temperature curve is rising supports the degassing of the glass-melt. The oxidizing atmosphere above the refining and above the non-heated areas of the furnace, e.i. where there are maximum temperature and the sinking part of the temperature curve, supports the ability of the glass-melt to dissolve gases which are contained in the melt as a residue left after the refining.

It is possible to create the reducing and the oxidizing zones in the glass-melt itself by means of bubbling of the reducing or the oxidizing gases through the melt. There are nozzles in the bottom of the furnace by means of which the reducing gas is introduced into the melt held in the melting zone and the oxidizing gas into the melt which is held in the refining zone. The refining process is thus intensified by means of this kind of bubbling.

The time to dissolve the residual grains is directly proportional to the square of the grain size and inversely proportional to diffusivity. Small grains and high temperatures are favourable to the process of dissolution. Fine sand would generally help, but excessively fine sand might lead to refining difficulties.

When batch preparation and melting reactions have been optimized, only high temperature remains as a major factor to aid the dissolution of residual grains. High temperatures are also justified at this stage.

Homogenizing

The freshly produced melt contains regions differing in composition. Homogenizing calls for reduction of the size as well as of composition differences by diffusion and flow. The time needed for achieving sufficient homogeneity can be reduced by minimizing the size of the

inhomogeneities, which is the problem of raw materials, of the batch and its loading; by raising the temperature to increase diffusivity; by attenuating and redistributing inhomogeneities by flow or by stirring. These are problems which may be solved by a proper design of the furnace and its equipment.

Raising temperature can improve homogeneity by increasing effective diffusivity. But it may also entail disadvantages. Volatilisation and corrosion of refractory materials are increasing and this may deteriorate homogeneity. The cost of fuel which rises enormously is not a negligible item either. Stirring is the most attractive method of improving homogeneity. As may be deduced from Cooper's/13/ treatment of the problem a reduction in thickness by a factor of ten, reducing diffusion time by a factor of 100, is easy to achieve.

The stirring is commonly used for optical glasses, is nearly always used in the troughs of feeder forehearths; the lead crystal is stirred in the working area of the furnace. Stirring is also applied when manufacturing sheet and plate glass of special properties/colour or mirror glass/. A very interesting combination of stirrers, weirs and floaters has been used by Ishiyama et alii /23/ when conducting the research of manufacturing coloured flat glass.

Heat requirements

We have to consider the manufacturing of glass not only from the point of view of the quality and homogeneity of the glass but also from the point of view of the possibility to reduce the heat consumption to the minimum.

Most of the chemical reactions involved in glass-making, are endothermic and a certain amount of heat must be supplied to bring them about. The minimum heat required may reasonably be defined as that needed to accomplish the

melting reactions and heat the melt to about 1200°C. Higher temperatures are used only for kinetic reasons, i.e. to complete the processes more quickly.

Kröger /12/ has measured the amount of heat required for only melting the glass, then the heat required to melt the glass and heat it up to 1200°C, and finally alternatively to 1500°C. The data this researcher has obtained are given in Table III. As can be seen from this table the heat consumed in the chemical reactions is only 18 to 24% of the total heat needed to raise the temperature of the melts to 1500°C.

Table III

Kröger's data for minimum heat requirement /12/

Type of glass	Heat of reaction			Total heat to 1200°C			Total heat to 1500°C		
	$\frac{\text{kcal}}{\text{kg}}$	$\frac{\text{kWh}}{\text{kg}}$	$\frac{\text{MJ}}{\text{kg}}$	$\frac{\text{kcal}}{\text{kg}}$	$\frac{\text{kWh}}{\text{kg}}$	$\frac{\text{MJ}}{\text{kg}}$	$\frac{\text{kcal}}{\text{kg}}$	$\frac{\text{kWh}}{\text{kg}}$	$\frac{\text{MJ}}{\text{kg}}$
Container	113	0,1314	0,473	507	0,5896	2,123	624	0,7257	2,613
Flat	168	0,1954	0,703	576	0,6699	2,412	701	0,8153	2,935
Borosilicate laboratory ware	98	0,1139	0,410	436	0,5071	1,825	537	0,6245	2,248
Lead glass 62% SiO ₂ , 19% PbO	96	0,1117	0,402	437	0,5082	1,830	538	0,6257	2,252

In the conventional fuel fired furnace, the heat requirement can best be illustrated in the following way/2/:

1. batch materials at ambient temperature are mixed together and allowed to react chemically. This can be considered as taking place at ambient temperature. In this reaction, heat is absorbed and the value of this absorbed heat is 0,155 kWh/kg or 0,560 MJ/kg or 133,56 kcal/kg of glass produced.
This is really the true heat required to make glass as the raw material and finished product start and end at the same temperature level.
2. during the reaction, gases /mostly CO₂/ are evolved and leave the system at temperature. In the case of fuel fired furnaces the gases must exit from the furnace at the same temperature as the other furnace gases which is of the order of 1650-1700°C. It is important that this temperature be defined.; viz. sensible heat in the cases evolved /1700°C/ 0,111 kWh/kg or 0,401 MJ/kg or 95,77 kcal/kg of glass produced.
3. the glass produced must be heated to working temperature, 1100-1200°C varying with the type of ware being produced. The glass leaves the melting end at a temperature higher than the working temperature; of the order of 1300°C. It is important that the temperature of the glass at the point of the process which is being investigated be defined; viz. sensible heat in the glass/leaving the furnace at 1300°C/ 0,440 kWh/kg or 1,584 MJ/kg or 378 kcal/kg of glass produced. This last figure is important as it represents the requirement for melting cullet. The requirement for melting glass from raw materials is the sum of 1,2, and 3 with the appropriate temperature values./The values given above are approximately those found in practice/ The heat for melting glass from batch is therefore 0,706kWh/kg or 2,54 MJ/kg or 607 kcal/kg.
Cullet ratio in the batch is important in that the correct heat requirement will be between 0,440 and 0,706 kWh/kg or 1,584 and 2,54 MJ/kg or 378 and 607 kcal/kg.
It goes without saying that the less the heat requirement the greater the potential for lower energy

consumption in melting glass, but with the basic composition fixed and the working exit temperature more or less fixed there is little that can be done to affect dramatically this figure except by utilising more cullet; and thus "bottle bank" and other returns are likely to be of increasing importance.

However, in seeking a guide as to what the ultimate energy requirement must be, the figure of 0,706 kWh/kg is a good target to aim for on the conventional furnace. Once this value is being approached, then precise refinement of the requirement will become necessary, but as the nearest values at the moment are in the region of 1,1723 kWh/kg/for melting only/ then a more qualitative approach is appropriate.

It must be pointed out that this target figure of 0,706 kWh/kg includes the working end and forehearths as, theoretically at least, these sections of the furnaces are cooling sections and should not require the expenditure of energy. In reality, energy is expended in cooling the glass and it is important to appreciate that between the exit point from the melting end to the point of working the present system must lose about 0,06 kWh of energy from every kg of glass made. All energy expended in working end and forehearths is therefore "wasted" on cooling imbalances in these zones.

The second case which illustrates the need to modify the target value is that of all electric melting. Here the basic requirement of 0,155 kWh/kg of glass is the same, but the heat carried away by the evolved gases can be greatly reduced as, for example, in the "Gell" furnace with the cold top batch blanket. Here the gases must leave the system at a temperature of 100-200°C and the loss of 0,1114 kWh/kg is almost eliminated. The exit temperature could still be of the order of 1300°C but the target consumption figure is reduced from 0,706 to

0,576 kWh/kg a reduction of 16%. For the conventional furnace however, let 0,706 kWh/kg be the target figure.

How the energy is utilised

Having expressed a value for a "target heat consumption" of about 0,706 kWh/kg and noting the actual values that are attained in practice, the discrepancy ought to be accounted for by an assessment of the heat flows in the system. A full and proper investigation into heat flows in any furnace is a highly technical operation, but at the end of such a study the results can /in the first instance/ be illustrated pictorially in a simplified Sankey diagram. Figure 1 illustrates the heat flows in an oil-fired/cross-fired/ furnace melting 90 ton/day of container glass and consuming 1,846 kWh/kg/1586 kcal/kg/ for melting and 0,276 kWh/kg /236,6 kcal/kg/ for working end and forehearths. The heat flows at the melting end are /see Fig.1/

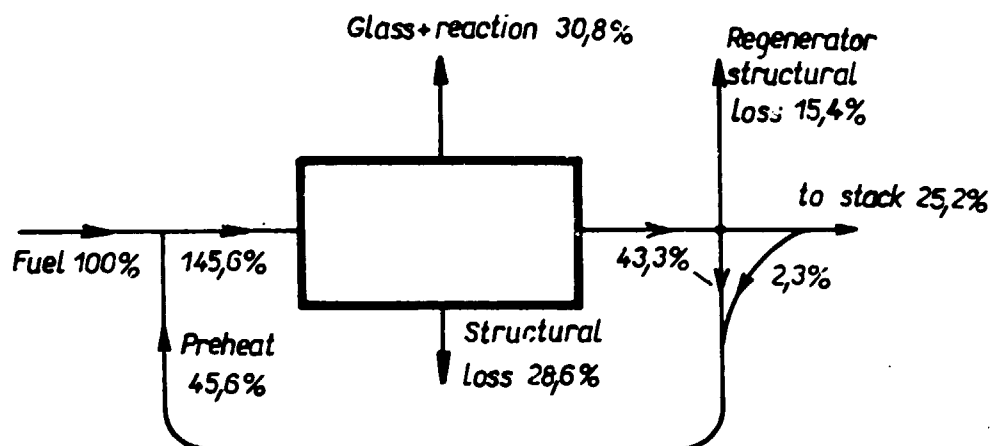


Fig.1

Inputs

fuel 100%
air preheat 45.6%

Outputs

Chemical reaction 6.8%
sensible heat in the glass leaving the melting chamber at 1300°C, 24.0%
structural losses/superstructure and glass containing refractories/, 28.6%
heat entering the regenerator, 58.7% of which 43.3% is returned as preheat
regenerator structural loss 15.4%
chimney loss 27.5% of which 2.3% is returned in the incoming combustion air.

In the context of these figures the efficiency is expressed as

$$\frac{\text{Reaction heat+Sensible heat in the glass leaving the melting end}}{\text{Total heat input/from fuel/}} =$$

$$= \frac{6.8+24.0}{100} = 30.8\%$$

In practice, the heat flows are much more complicated than this, in particular this simple type of diagram does not consider the differences in firing a regenerative furnace where the regenerated heat is not returned directly to the furnace but is stored for return to a different set of conditions on the next cycle. However, the combined diagram serves to illustrate certain ideas, although it is worthwhile pointing out that there is invariably a difference between the firing of one side and the other, which can mean in some instances that the thermal history of the melting batch is not uniform within the same furnace. For most purposes this is not a problem, but in respect of special

quality requirements it is a factor worth bearing in mind.

Ways for maximum heat utilisation

The heat requirement in the furnace may be reduced in different ways. Finding ways and means of lowering the maximum melting temperature would save considerable amounts of heat. The maximum temperature and the furnace load are determined by the dissolving of residual grains, by refining and homogenizing of the glass-melt. Changes in batch materials and melting reactions have to be considered in order to save fuel. It has been shown by Pugh/24/ that the replacement of Na_2CO_3 by NaOH or CaCO_3 by CaO or Ca(OH)_2 ought to be advantageous from this point of view.

To preheat the batch is another way of cutting down the heat requirements. Using smaller batch clumps would accelerate heating effectively even if no other changes are made.

From this point of view the charging of the batch into the furnace is also very important. The charging into the tank-furnaces is nowadays nearly always done by mechanical devices. The batch is loaded into the furnace in a shape of a coherent thin blanket. The heat transfer by radiation into the batch is maximal in this case, as has been proved by Trier/25/.

The cullet is either laid under the batch - in a furnace for melting sheet or plate glass - or mixed with the batch - in a furnace for melting container glass. Eloy/26/ has shown that preheating of the batch to 700°C may save 6,5% of the total amount of fuel required for melting. It is necessary to use granules or pellets in this case. The vertical tower counter-flow preheater used on the Brichard /27/ furnace and similar devices may be of interest here.

Other ways to reduce the heat requirement are to

reduce losses from the furnace structure, and to decrease the heat carried away by gases by means of improved regeneration or recuperation. For a given glass these are the only possibilities which may be taken into consideration when melting this glass in a furnace heated by gas or oil.

Heat insulation

The simple answer is to insulate the structure as much as possible, but in the past this has not always met with the success that had been anticipated. In particular, crown failure was attributable to two major causes:

1. the penetration of fine batch alkali dust through cracks in the insulating brickwork to the hot interface of insulation and silica where chemical attack from the outside of the silica brick inward would commence, and gradually "drill" a hole through the structure which would rapidly widen
2. the effect of insulation would also reduce the temperature gradient through the mass silica structure bricks and then most if not all of this brick would be at an elevated temperature; thus penetrative attack from the alkali vapours in the flame gases would be accelerated and holes drilled from the inside, outwards.

Clearly any cracks in the structure, inside or out, were the focal points of any resultant damage, and consequently great care was necessary in constructing a crown to ensure tight joints both inside and outside and ensuring that gaps which developed on warm-up were sealed before insulation was applied. Once the insulation was applied, this was also sealed over.

In spite of the above mentioned difficulties it has to be kept in mind that the thermal conductance of a properly insulated crown may be as 4 times lower than a conductance of an unisolated crown.

Very important is the insulation of the melting basin, since the heat energy which the glass-melt contains has been introduced into it by a heating process of a low efficiency. The cost of the heat losses from the basin is therefore very high. When the walls of a basin are built up of palisades it is possible to insulate them as high as the glass level. In the case of furnaces for melting of sheet glass due to their greater depth it is recommended to do the insulation step by step.

The insulation of the bottom of the basin is also very important from the point of view of heat economy. However in this case we have to consider a greater possibility of corrosion of the bottom, and it is therefore necessary to cover the bottom by a paving of corrosion-resistant refractory material. The insulation of the bottom is used especially when melting coloured glasses.

The heat flow through these structures is the product of the conductance and the temperature difference of the inside and outside surfaces. Clearly the objective is to construct a furnace with walls having as low a thermal conductance value as possible, but at the same time minimizing the refractory wear by selection of a suitable hot face material.

The conditioning zone of a sheet glass furnace and the working end of a bottle glass furnace are not insulated. The reason is that it is necessary to remove the heat from the glass in these zones and cool it to a suitable temperature. The depth of the basin depends on the insulation of its bottom.

It is now a general tendency to build deeper basins. The furnaces for melting coloured glasses are usually 1 to 1,2 m deep, for melting clear glasses the depth is up to 1,5 m. In spite of the great depth of the basin the temperature of the bottom is high enough, due to its insulation. It is necessary to keep the temperature at high levels, for otherwise there is a risk of a shift of crystallized and toughened glass at the bottom.

Optimising the combustion

There are several aspects of the combustion which embrace the whole of the furnace operation; all are important, and the optimum utilisation can only be attained if all these aspects are considered and applied together. The first consideration is the design of the heat release with the development of a high heat flux. The type of flame that predominated in the days of producer gas firing was of the diffusion type where streams of fuel and air diffused together in the initial stages and the combustion reactions caused turbulence and high heat release only in the latter part of the combustion length. With the introduction of oil firing, oil droplets mixed easily with the stream of air and the bulk of the heat release was then in the early part of the flame length. More recently, natural gas has been introduced and a problem of mixing fuel and air again presented itself. This problem has been overcome by developments in port and burner design. In practice the burner comprises the port and burner and their relative dispositions.

The principles governing the requirements of a port/burner arrangement are illustrated in Figure 2. Here the port is inclined downwards to introduce hot air into the furnace chamber adjacent to the glass surface. At some position before this air stream becomes heavily diluted with recirculating waste gases, a jet of fuel is introduced with such momentum that the stream of air and jet of fuel mix rapidly and combustion takes place immediately in front of the port mouth.

The importance of the rapid mixing of the fuel and air, and the development of intense and early combustion is to be found when attempts are made to minimise the exhaust gas temperature as it leaves the melting chamber. The exhaust gas temperature cannot be less than the general furnace temperature at the point of exit, but delayed

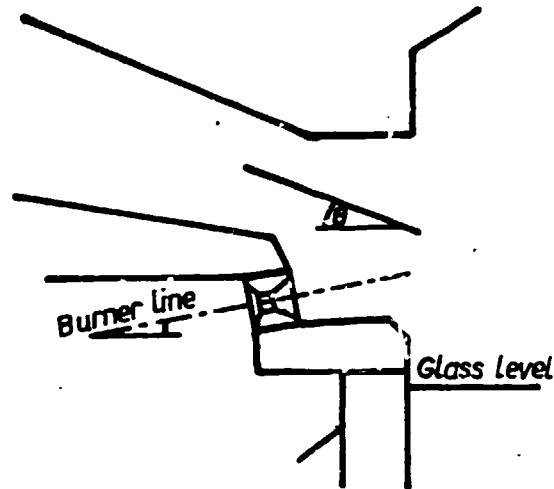


Fig.2

combustion minimises the opportunity of dissipating the heat before the gases leave. Invariably, in a great number of cases, the gases are still reacting as they pass through the exhaust port, and the assumption namely that combustion is complete, need not be valid. Maximum flame temperature is attained at slightly fuel rich mixtures, but this may not be desirable from a gas/glass reaction point of view or other practical consideration.

The mixing of the fuel and air is brought about by the turbulence created by the difference in the energy contained in the streams of air and jet of fuel.

The use of air through the burners, although very necessary for flame length control, has the unfortunate effect of reducing the heat intensity that can theoretically be attained, and after the attainment of rapid and intense combustion, the next important requirement of the flame is the production of the highest heat flux that

can be obtained in practical application/i.e. maximum heat content per unit volume of gases, which is equivalent to the highest gas temperature/. In practice the greatest heat intensity is attained by using the optimum amount of combustion air preheated to as high a temperature as possible and excluding as much as possible of the cold air which, deliberately or otherwise, enters the system. In addition, entrainment of furnace waste gases must be minimised, although the view is held by some that this recirculation is necessary to hold the heat flux to an acceptable level.

Heat transfer is determined by temperature differences, thus the higher the flame temperature, the greater the transfer rate and quantity transferred.

Thus it can be seen that several aspects of the combustion problem are all inter-related and interdependent:

1. optimising the combustion by achieving rapid mixing of fuel and air to give intense combustion, and flame positioning immediately in front of the port, thus minimising the exit gas temperature
2. optimising the heat available by achieving as high a flame temperature as possible, excluding cold air, optimising the fuel/air ratio, and maximising the air preheat.

Once these conditions have been met, two additional by-products may be forthcoming. First the flame will be away from the refractory and second, the revised port design may in some cases shield the regenerator top from the direct radiation loss from the flame.

Thus to improve the heat utilisation overall, several main courses of action are possible; most, if not all, are inter-related, the greatest benefit being derived from the combinations of the improved techniques:

1. use of heavy insulation in all parts of the structure and regenerators

2. the development of early rapid and intense combustion within the furnace chamber by precise attention to the detail of port and burner design
3. the development of the greatest practical heat flux in the flame, which requires attention to the exclusion of all parasitic cold air both in the furnace regenerator and flues
4. the development of the greatest heat release adjacent to the greatest heat sink
5. the development of the highest preheat temperature possible within certain practical limitations.

The effect of the technical improvements

Table IV shows the heat flows in the furnace already illustrated compared with those which are predicted by modifying the furnace design in accordance with the above principles, and Figure 3 illustrates the improved design graphically.

Table IV

Comparison of heat flows/%/ in the original and improved designs

	Original design	Improved design
Heat from fuel	100/6887 kW/	100/4437 kW/
Heat from preheat	45.6	43.8
Heat for chemical reaction	6.8	10.5
Sensible heat in glass	24.0	37.1 47.6
Heat to structural losses	28.9	15.6
/Heat to waste gases entering regenerator/	/85.9/	/80.4/
Regenerator structural losses	15.4	11.8
Heat stored in regenerator	45.6	43.8
Stack losses	24.95	24.6
kWh/kg of glass	1.817 kWh/kg	1.181 kWh/kg

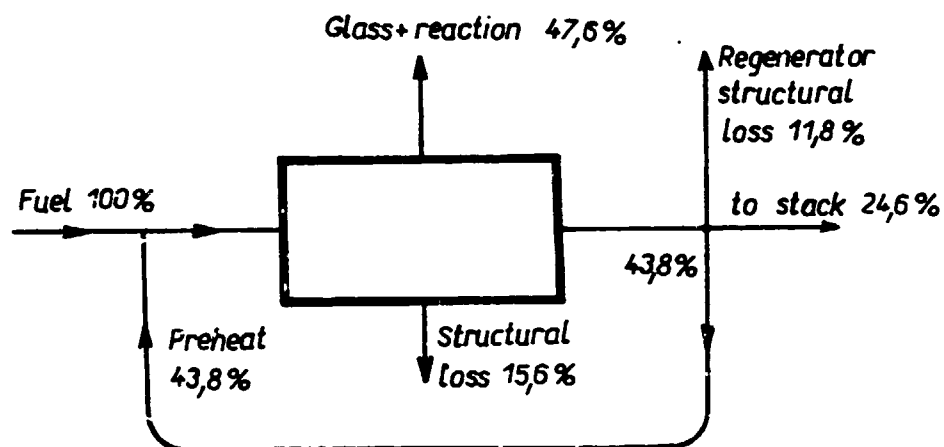


Fig.3

There can be little doubt that the major reduction in heat consumption is due to the application of heavy insulation. It must be however stressed that success lies in the combined approach, and once this has been developed then stability of operation is necessary to obtain the best in overall fuel consumption and optimum glass quality.

Maintaining the optimum performance

In any glass melting equipment, the onus still falls on the operator to achieve the required output in the most efficient manner possible. The key to this aspects is the maintenance of stability within the glass bath itself with minimisation of the periods of overheating and the control of "load changes" within the complete system.

The glass bath and its flow system, however, is the main concern and in recent times much theoretical work has been carried out into this problem with the aid of computer programmes which have enabled a long-established interest to proceed forward once again.

The flow of the glass-melt influences substantially the heat economy of the melting furnace. It has a double function. It transports the heat energy from one place of the furnace to another, and at the same time it mixes the melt and makes it more homogeneous.

Many authors have dealt with this problem mainly on the basis of model observations. Trier/28/ dealt with the flow of glass in the furnace as a whole, Safaieh/29/ with currents under the batch blanket, Lennertz/30/ described the influence of different barriers, and Karkosza/31/ the influence of floaters on streaming of the glass-melt. Goerk/32/ reported about the experiments he had made on a tank-furnace in operation. Sokolov/33/ contributed substantially to the knowledge of the glass-melt flows in a furnace in general. Staněk /34/ and Tober/35/ described the convection currents in furnaces heated by electricity.

The regime which fitted the observation is as follows: /see Fig.4/ Batch is fed on to the hot glass surface adjacent to the back wall; from this point it floats forward in the direction of the shadow wall receiving heat from the flames being developed above it, and heat from the hot molten glass beneath it; from the bottom of the batch piles molten glass falls into the lower layers of the tank and flows at these levels towards the throat.

As the batch moves forward it thins out due to melting and becomes warmer, although it is still rapidly absorbing heat, and finally a distinct batch line is reached where a surface flow of hot glass moving from the hot spot to oppose the batch flow, prevents further forward movement/see Fig.5/.

The zone of higher temperatures across the furnace, which can be obtained by suitable design of the ports and the operating conditions, will form a thermal barrier, which plays an important role in the melting and flow of the glass. Near the doghouse the melt is continually cooled by charging the cold batch, and the convection current coming

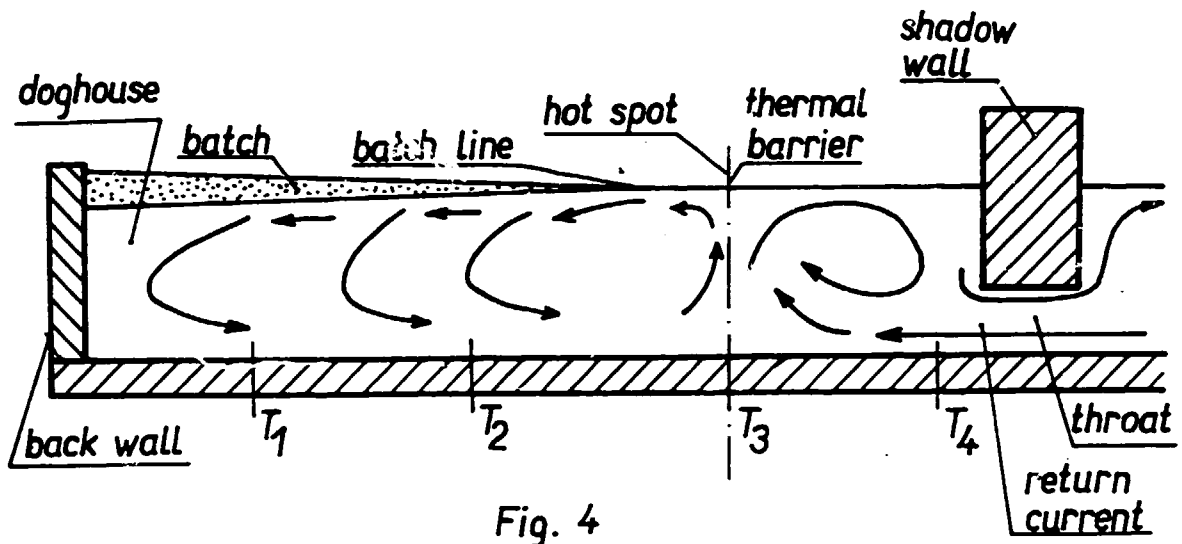


Fig. 4

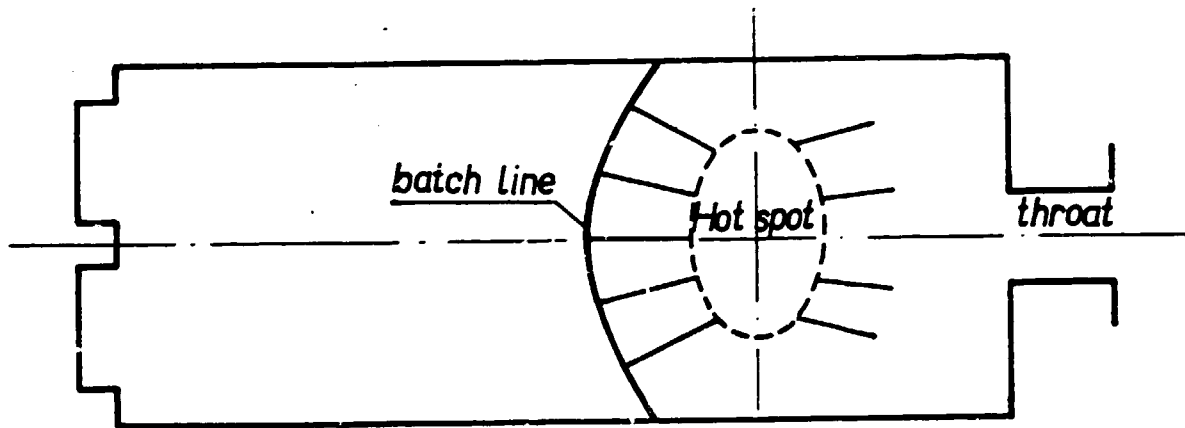


Fig. 5

from the thermal barrier containing appr. 10 to 25% of the total melting energy which is then used for the melting of the batch. As the convection current travels against the pull current it retains the insufficiently melted glass in the melting zone at the "batch line"/see Fig.5/

At this "batch line" the hotter glass flow passes beneath the batch and heat is supplied to the underside of the batch in this way. Glass that is formed beneath the hotter batch will fall to the lower regions but will be at a higher temperature than the glass formed nearer the back wall, and this effect will be progressive beneath the batch down the longitudinal line of the tank. Thus the temperature at the bottom of the tank will gradually increase from T1 to T3. At about T3 beneath the hot spot there is an upward force due to the heating effect on the glass where some of the bottom flow is drawn upwards whilst some continues towards the throat. This effect is also observed in the horizontal dimension and the hot stream from the hot spot radiates towards the batch line and beneath it, turning again to the lower strata near or adjacent to the sidewalls/Figure 5/.

Thus there are two mutually compatible heating zones in a furnace of this nature, the flames above the batch and the flames heating the glass at the hot spot which in turn will supply heat beneath the batch. The hot spot heat will also continue to heat the glass between T3 and T4 but the value of T4/the exit temperature/ will be determined by the other bottom glass temperatures.

From the point of view of thermodynamics the above-described convection current is not very advantageous because the mass is first brought to a very high temperature and melted in the hot zone and then used for the heating of the cold batch. But this convection current is indispensable to the melting process.

There is another important flow, the so-called return current which - travelling from the working zone of the furnace along its bottom into the warmer zone of the furnace is gradually heated and decreases its thickness, since it merges with the cold currents coming from the lateral walls, and rises slowly toward the surface.

The return current increases the heat losses in the furnace, as the already molten glass from the furnace working chamber is returned to the melting end and reheated unnecessarily.

From the point of view of heat economy of the furnace the return current is therefore undesirable. Between the melting and the working ends of the furnaces for the melting of bottle glass, or between the melting and the conditioning zones in furnaces for melting sheet glass, various kinds of barrages may be set up: floaters, bridges, weirs, lateral constrictions or throats. Their purpose is to divert the direction of the stream of molten glass, extend the time of residence of the glass in the melting zone, prevent the penetration of the surface currents directly from the melting end into the working end, to control the cooling of the molten glass and last but not least, assuming a correct design in this respect, to prevent or at least reduce the return current.

The correct operation of the thermal barrier is extremely important for stabilizing the flow pattern of the melt in the furnace.

The location of the maximum temperature in the combustion space does not always coincide with the hot spot in the melt. The location of the maximum temperature varies with the pull. As the pull increases the maximum temperature shifts toward the working end. Moreover, with the increasing load on the furnace, the temperature maximum is flattened and eventually the thermal barrier ceases to fulfil its

function; it does not hold the inadequately melted glass back near to the doghouse, but allows it to pass into the working end, and this results in inferior quality of the glass. It also allows the return current to penetrate too far into the melting zone. When the load of the furnace changes then also the bottom glass moves and enters the working end through throat and may lower the general quality of the final product.

An important method of maintaining and strengthening the thermal barrier consists in bubbling or in electric boosting.

In practice a stabilization of the temperature maximum in the molten glass despite the fluctuations of the furnace load can only be achieved by a proper location of the electric boosting electrodes in the tank. In such cases the electrodes stabilize and strengthen the thermal barrier, thus stabilizing the flow pattern of the melt in the furnace.

Electric melting and boosting

It is well known that the efficiency of the heat transfer in a gas-or oil-heated furnace is very low and reaches no more than appr. 30%. It is due to that fact that the glass-melt is heated from above and the heat penetration therefore is generally very poor, especially when a coloured glass is melted. In order to improve the heat transfer substantially at a sweeping rate it would be necessary to change basically the way of heating and heat the glass-melt from inside. This idea may be realized either by using the deep immersion burners or by using the electricity for melting the glass.

To solve the problem of melting the glass by immersed burners and bring this melting method to an acceptable technical solution will be probably very difficult if not impossible.

On the other hand the heating and melting of the glass by passage of electrical current through the melt has been solved and is used nowadays on a large scale/36/. This method has a high thermal efficiency, is easy to control, yields homogeneous glass possessing the required properties and is therefore economically attractive. The construction of electric melting furnaces is simpler than that of the flame-fired furnaces. A greater amount of glass is produced by a unit volume in electric furnaces and consequently the dimensions of electric furnaces are smaller than those of the flame-fired furnaces for the same output.

The running cost of a thermal unit /kWh/ obtained by a direct combustion of fuel in the furnace is today still lower than the cost of a thermal unit obtained by the passage of electric current through the glass. Other factors must however also be taken into consideration. Those are e.g. the initial costs of an electric furnace, the shorter time in which it can be rebuilt compared with a combustion furnace.

There are also good reasons why some glasses should be melted by electric current, especially those from which some components volatilize rapidly from an uncovered melt surface. These include borosilicate glasses as well as glasses containing fluorine. In all-electric melting, where the surface is covered by the batch, losses due to volatilization are substantially smaller and the cost of the melting is therefore cut down. Besides, we may have to deal with pollutants detrimental to health, such as fluorine, and all-electric melting is consequently desirable in minimizing the atmospheric pollution. This factor may be of decisive importance for the choice of the melting technology, in the case of glass melts from which substances harmful to human health volatilize.

The electric boosting is most advantageous thermally, technically and economically. This is because the furnace output is always substantially augmented with electric boosting, while the dimensions of the furnace are not

increased. The whole of the batch is heated more thoroughly and as a result the melting of the batch is improved. As is has been stated before, the electric boosting stabilizes the thermal barrier, and consequently also the flow in the furnace. In furnaces heated by a primary fuel with fluctuating calorific value it is advisable to use electric boosting as a stabilizing instrument.

By introducing electric boosting the efficiency of combustion of primary fuel is usually also improved, and the output of the furnace as well as the efficiency of its operation as a whole will thereby again be increased.

The thermal, technological and economic advantages of using electric boosting are considerable, and electric boosting is therefore regarded as the most efficient means of accelerating melting. This is why electric boosting is currently used with most continuous glass-making tank furnaces.

There are other factors which are making the electric energy into the main source of energy for melting glass in the future.

If we eliminate producer gas as unsuited for the heating of glass-making furnaces, we are left with oil, natural gas and electric current as possible fuels for in industrial glass furnaces. Taking into consideration that it is preferable to use oil or natural gas as raw materials for chemical industries and that the electric energy will be produced from the nuclear sources in an ever-growing proportion then electric current remains as a major energy source available for glass-melting furnaces in the future.

The developments and practical experience gained up to the present has shown that all kinds of glass can be melted electrically, and therefore it is only relatively minor problems of economy left which we anticipate are most likely to be solved in the near future.

Then the electric power will have truly become the dominating energy for the melting of glass.

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