Original Paper

Energy efficiency benchmarking of glass furnaces

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A method for a comparison of data on the specific energy consumption of a large set of glass melting furnaces is presented. This benchmarking of the energy efficiency levels takes the effect of the cullet fraction in the batch into account. The investigated energy consumption data, including electric boosting and oxygen consumption, are normalized to the primary energy equivalent (primary energy consumption of electricity and oxygen generation). A ranking of the energy efficiency of about 130 container glass furnaces has been derived. The difference in the specific energy consumption of the most energy efficient container glass furnaces and the furnace ranking the position 50 % is only about 20 to 25 %. The effect of furnace age, specific pull, total pull rate, type of furnace, cullet fraction and glass colour on energy consumption levels of container glass furnaces has been derived from a set of energy consumption data of more than 130 furnaces. From these data, the most energy efficient container glass furnace has been identified and a typical energy balance for such a furnace is given. Based on primary energy equivalent and 50 % cullet in the glass forming batch, the most energy efficient container glass furnaces show energy consumption levels close to 3.8 MJ/kg of molten glass. Results of a benchmarking analysis of the specific energy consumption of float glass furnaces are also presented. The energy consumption levels of these furnaces depend strongly on the size of the furnace, pull rate and furnace age, correlations for these factors have been derived.

1. Introduction

The consumption of energy for the production of glass articles is predominantly determined by the energy efficiency of the glass melting process. On average (Dutch data 1999) about 65 % of the total primary energy demand of the glass industry is used for melting (taking into account the fossil energy required to produce and transport electricity). The CO_2 emission is mainly related to the fossil fuel consumption of glass production installations, but CO_2 is also released from carbonate raw materials or organic contamination. The total mass of emitted components, such as CO_2 and NO_x, depends on the fuel consumption and resulting flue gas volume flows. Therefore, energy efficiency improvement often will not only lead to lower energy costs, but will also lower release of pollutants to the atmosphere. There is an urgent need for energy efficient melting processes, in order to meet the CO_2 emission targets set by the Kyoto protocol and to limit the depletion of fossil fuel resources in the world. CO_2 emission trading or trading of permits for emissions of other greenhouse gases offers an extra driving force for the glass industry to limit the use of energy, especially energy derived from the limited resources of fossil fuels.

Today, the glass industry is investigating several methods to identify the most energy efficient glass melting operation:

- best-practice methods and application of energy balance models to find the most efficient energy saving technologies [1 to 3];
- determination of the theoretical energy or enthalpy demand [4 and 5] and the practically lowest possible level of energy consumption [6];
- benchmarking of specific energy consumption of industrial glass furnaces [7 to 9];
- development of new melting and fining techniques [10 and 11].

In this document, the option of benchmarking of the energy efficiency of glass melting furnaces will be discussed and results of such benchmark studies, carried out for container and float glass furnaces in the period 1999 to 2002, will be shown.

The collection of all relevant process and energy consumption data of glass furnaces and the processing of these data to inter-compare specific energy consumption levels of all participating furnaces in a specific sector of the glass industry requires the preparation of questionnaires and methods to normalize the obtained data. Since 1999, data of about 250 industrial glass furnaces have been collected for the purpose of benchmarking the glass furnace energy efficiency in different glass industry sectors. The annual averaged production and energy consumption data have been obtained (most data from 1999). For the float glass and the container glass sector, these data are used to identify the most energy efficient glass melting processes in operation today.

Data have been obtained from different areas in the world: Europe, Japan, USA, Canada and Turkey.

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Important correlations between the energy consumption per unit mass of molten glass (specific energy consumption) and process operation have been found and a few examples of such correlations will be presented here.

One aspect is to identify the most energy efficient installations or to compare the energy consumption of a specific furnace to that of the most energy efficient furnace. The other objective is to derive the most important process and furnace design parameters which determine the energy efficiency of a glass melting process in a specific glass industry sector.

2. Objective of energy efficiency benchmarking of glass furnaces

The main objective of energy efficiency benchmarking is the ranking of the energy efficiency of a glass furnace in a list of energy efficiency values of other glass furnaces representative for the same glass industry sector. The sectors investigated in the 1999 benchmark study are the container glass industry, the flat glass industry and the fibreglass (continuous fibre) sector. The set of investigated furnace data should represent the relevant energy efficiency ranges in the specific sector. This means the ranking of a furnace should give a representative impression of the energy efficiency of this glass furnace, compared to a representative sample of furnaces in the sector worldwide.

Unfortunately, the collection of a complete and reliable set of data from all furnaces within a sector worldwide appears to be not feasible. Therefore, data are mainly collected from glass production in Europe and North America.

The objective for the energy efficiency level of a glass furnace is, for instance, to become part of the top 10 % with respect to energy efficiency within the sector. This means that the difference in energy consumption between this glass furnace and the furnace in the position 10 % in the energy efficiency ranking will represent the minimum energy savings to be achieved. This difference is called the distance to the world top[1]. Thus, from the benchmarking study and ranking of energy efficiencies the energy efficiency improvement target can be derived. It is important that the inventory of data allows the determination of the process and furnace design factors or parameters which govern the energy efficiency in order to select the most promising energy saving measures.

3. Benchmarking methods

Different methods of benchmarking or ranking of energy efficiency can be applied. From these different methods, the target energy efficiency can be derived.

For instance, the energy efficiency of all participating furnaces in a sector (for instance the container glass or the float glass sector) can be ranked from the furnace with the lowest specific energy consumption to that with the highest energy consumption. A target may be to achieve specific energy consumption levels which are lower than the energy consumption of the furnace ranking in the position of 10 % of the number of furnaces investigated — as previously explained.

Another method is the so-called best region method. In this case, the benchmark target is the average energy consumption determined for of all the furnaces in a country or an area (state or group of countries) in the world with the expected highest energy efficiency level within a glass industry sector.

The third method is to find the best practice: the lowest achievable energy consumption of a glass furnace applying all best available techniques. The target may be to achieve an energy consumption level with less than 10 % more energy consumption than expected for the very best practice. Best available techniques can be derived from literature, suppliers and the IPPC BREF document prepared for the glass industry [12].

4. Parameters determining energy efficiency

The energy demand of a glass-melting furnace — as constructed — depends on its design, type, and insulation. The energy consumption also depends on the operating conditions, such as the applied excess air in the combustion process, the composition of the glass forming batch, application of batch wetting and recycled cullet level in the batch. The presence of a sophisticated waste glass collection system and waste glass processing installations offer the opportunity to melt batches with large cullet fractions [13]. The production of coloured container glass, especially green glass often allows the use of large amounts of cullet, up to more than 80 to 90 %, depending on cullet quality and colour purity of the cullet. For clear glasses, the recycling level of waste glass cullet may be limited because of the colour constraints and organic contaminants in the cullet, which may lead to glass colour deviations. Other factors, which may depend on external conditions or from outside imposed regulations (such as local or European legislation), are the needs to apply air pollution control measures in order to meet the emission limits. These measures can influence the energy efficiency of glass furnaces.

Conradt [6] showed that the theoretical energy demand for heating and fusion of the batch, determined by thermodynamics, depends on the selected raw materials and the glass melt exit temperature (average temperature in the throat or channel of the melt tank). This theoretical energy demand includes the tangible heat of the melt (relative to a standard temperature 273.15 or 298.15 K) and the enthalpy required for the endothermic reactions; mainly the decomposition of the carbonates, during the fusion process. Thermodynamic models exist today [4 and 6] to determine these values. However, the thermodynamically determined energy demand does not represent the lowest achievable energy consumption.

Due to limitations in heat transfer rates and required driving forces for heat exchange in the furnace, the lowest achievable energy consumption is above the theoretically derived value estimated from thermodynamic models. The cullet fraction in the batch has a large influence on this minimum energy demand.

The inventory of glass furnace energy consumption data plus other relevant process data, and glass furnace energy

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[1] Selection of 10 % most energy efficient furnaces in an industrial sector.

balance models show that the factors given in the next sections are relevant for the energy consumption of the melting process.

4.1 Glass cullet fraction in batch

The chemical energy for fusion of normal raw materials is determined by the endothermic batch reactions involved. For soda-lime-silica glasses, such as most container glass types and float glass types, the release of CO_2 from the carbonates: limestone, dolomite, soda ash or potash takes place between 700 and 950 °C. The carbonate decomposition / calcination processes are endothermic and determine most of the chemical energy demand of the batch melting processes. Replacing normal batch with cullet will lower the energy consumption, because the fusion of glass cullet will not require enthalpy for chemical reactions.

The theoretical energy demand to form a glass melt at a temperature level of 1400 °C from a typical soda-lime-silica batch (dolomite, limestone, soda ash, sand, feldspars, sulphate) is about 0.52 MJ/kg of glass for the chemical reactions, and 1.75 MJ/kg for heating the glass melt. The released batch gases (CO_2, H_2O, fining gases) are heated up in the furnace atmosphere and cooled down in the flue gas heat recovery system. Depending on the flue gas temperature, the energy loss by batch gases is 0.15 MJ/kg of glass at about 750 °C and only about 0.10 MJ/kg at a flue temperature of 500 °C (typical temperature level of flue gases from regenerators). The replacement of a part of normal batch with cullet will decrease the chemical energy demand and the heat contents of the exhausted batch gases. This will decrease the total fuel consumption, resulting in a lower flue gas volume flow and lower flue gas energy losses. Furnace energy balance models show that 10 % raw material in the batch replaced with cullet leads to 2 to 3.5 % energy savings compared to 100 % normal batch. However, these energy savings depend on the batch composition, level of cullet percentage and the final flue gas temperatures. Increasing cullet fractions in the batch often allow an increased melting load; the reduction in the specific energy consumption is generally larger when a cullet increase is accompanied by a load increase. At constant melting load, an increase of 10 % cullet in the batch will lead to about 2 to 2.2 % less energy consumption compared to the energy consumption of a normal batch per unit mass of glass melt. But at constant energy input and increased pull, the investigated data and the energy balance models show that the specific energy consumption will decrease by about 0.29 % of the energy consumption of a normal batch for an end-port fired regenerative furnace, per 1 % more cullet.

The total collection of the benchmarking results show that in general, 10 % replacement of batch with cullet leads to slightly more energy savings in a batch with a low cullet recycling level compared to a batch with more cullet recycling. Thus a little bit more energy will be saved, going from 0 to 10 % cullet compared to an increase from 80 to 90 % cullet.

4.2 Raw material selection

The chemical energy required for melting of a batch can also be reduced by the application of oxides in the batch, instead of carbonates, for instance using CaO or MgO instead of limestone or dolomite. This, however, may lead to increased batch costs and a changing melting behaviour of the batch. Magnesium oxide or calcium oxide may show different melting kinetics compared to limestone, dolomite or magnesium carbonate [14].

The batch compositions with larger amounts of gas forming components, such as sulphates, may lead to foam formation on top of the molten glass. Foam can block the heat radiation from the combustion chamber into the molten glass. This will decrease the heat transfer from the combustion space to the melt; extra energy has to be added to the furnace and consequently the flue gas temperatures and flue gas volume flows will increase. Foaming may lead to decreasing pull rates or increased energy consumption levels in the order of several percents.

Other batch parameters influencing the energy consumption are the batch humidity: a water content above 2 to 3 % leads to extra energy requirements for evaporating the water. Some batch wetting however is preferred in most cases to suppress batch segregation. Energy balance models show that the energy consumption of a glass furnace increases by roughly 0.5 % for 1 % extra water content of the batch.

4.3 Type of furnace

The flue gas heat recovery system is an important factor for the energy consumption of a glass furnace. Furnaces equipped with compact well-insulated regenerators with air preheating up to more than 1250 °C appear to be the most energy efficient furnace types. Recuperative furnaces, showing a much lower air preheat temperature (400 to 750 °C), and a higher final temperature of the flue gases, generally need a much higher specific energy supply. However, some recuperative furnaces (such as the $LoNO_x^{®}$ melter) apply batch or cullet preheaters and a special furnace design [15], in order to meet the energy consumption levels comparable with very efficient end-port fired regenerative furnaces.

The average cross-fired regenerative furnaces appear to be less energy efficient than the average end-port fired regenerative glass furnace types. Probably, this is caused by the structural heat losses of the burner ports and relatively large outside regenerator surface area of cross-fired regenerative furnaces. Oxygen-fossil fuel fired furnaces, without flue gas heat recovery, generally show improved energy efficiency compared to recuperative furnaces. However, taking into account the energy consumption for oxygen separation from air by cryogenic distillation or by vapour swing adsorption systems, the average efficiency of end-port air-fossil fuel fired furnaces appears to be ahead of the overall energy efficiency of average oxygen-fired container glass furnaces. The application of oxygen instead of preheated air is to be considered as a measure to control NO_x emissions and the extra energy consumption for oxygen separation has to be taken into account in the benchmarking.

4.4 Specific pull and total pull rate of glass furnaces

The specific energy consumption decreases when increasing the pull of a glass furnace up to a certain level. However, at very high pull levels or excessive specific pull rates, the glass quality may become worse due to limited time available for melting or fining. At very high specific pull rates, the specific energy consumption may even increase again, because of the limited available surface area for the increased demand of heat exchange in the furnace and in the regenerators. The regenerators may become too small for the increased gas volume flows at high glass melt pull. In general, data show that the energy consumption per unit mass of glass decreases with the melt pull or with the specific pull, up to 3 to 3.5 t of glass per m^2 glass tank surface area per day.

The specific energy consumption for float glass furnaces increases drastically when decreasing the size or pull of the furnace [8].

High-quality glass products, which require a high residence time, show a higher energy demand than products with a lower quality requirement. The larger residence time leads to lower specific pull rates and higher specific energy consumption levels. Therefore, one should be aware that the energy efficiency of the same furnace types producing different types of glasses cannot be directly compared without taking into account the glass quality differences.

4.5 Furnace age

The benchmark studies show that the most energy efficient furnaces are the newer furnaces. Monitoring of the energy consumption shows that besides a seasonal effect, the energy consumption will increase steadily with time due to ageing of the furnace structure: insulation values will be affected, extra metal line cooling may be desired and the heat exchanging efficiency of the regenerators will decrease in the course of time, because of fouling of the surfaces of the checkers. Leaks and open joints may appear and hot gases will escape from the furnace.

According to Trier [1], the energy consumption of regenerative furnaces may increase by 1.5 to 4 % per year and in wintertime energy consumption is generally higher compared to summertime.

4.6 Electric boosting

Electric energy is efficiently converted to sensible heat of the glass melt mass by the application of electrodes in the melt basin. The alternating current, I, in the melt with electric resistance, R, generates heat by the Joule principle: energy input = $I^2 \cdot R$. The efficiency of converting electricity supplied by electrodes to heat input into the molten glass is very high. However, the production of electricity in a fossil fuel fired power plant and transport of electricity to the factory is less efficient. For the generation of 1 kWh about 9 MJ of fossil energy is required in a fossil fuel fired power plant (in the Netherlands, the energy efficiency benchmarking studies assume on average a 40 % efficiency of fossil fuel conversion into electric power). Electric boosting is often applied in tanks, producing coloured glasses in order to compensate for the limited radiation of heat from the combustion space through the coloured melt. All-electric melting is applied in countries with cheap electricity and for glass types which could lead to high emissions or release of toxic vapours in fossil fuel fired furnaces.

In most cases and in most countries, the total energy consumption of a glass furnace is determined from the fuel consumption and the low (net) calorific combustion value and the net energy content of electricity (1 kWh = 3.6 MJ). However, in the case of energy benchmarking, this is not the correct method and the energy losses in the power plant should be taken into account. Therefore, the overall energy consumption of the glass melting processes is expressed in primary energy equivalent, taking into account the average efficiency of the fossil fuelled power plant and energy losses during electricity transport.

4.7 Batch preheating by flue gases

A few different systems are available for glass industries, especially applied in the container glass sector, for the preheating of recycled cullet or a cullet-rich batch. Flue gases from regenerators (400 to 550 °C) or recuperators (650 to 90 °C) can be used to preheat the cullet or batch [16 to 20], typically up to 275 to 375 °C. Flue gases from directly oxygen fossil-fuel fired glass furnaces can be quenched by water or preferably are diluted by ambient air to cool down the flue gas temperature typically below 600 °C, before entering a cullet or cullet and batch pre-heater [16]. Application of the batch pre-heater systems will considerably lower flue gas temperatures and will lead to 8 to 15 % energy savings. Even larger energy efficiency improvements can be achieved when increasing the pull in combination with batch and/or cullet preheating.

4.8 Other parameters determining energy efficiency of a glass furnace

The furnace design (outside surface area versus tank volume), the thickness of the insulation layers and the sealing of the furnace superstructure will have an important impact on the energy consumption. Compact unit melters or furnaces with only a few burner ports will show smaller structural heat losses compared to large furnaces with relatively large outside surface areas or burner ports.

An excess of air required to avoid reducing conditions above the glass melt surface will lead to increased NO_x formation and extra flue gas volume flows. This will cause an increase in the energy consumption. However, there is a lower limit for the excess air, since the combustion should be completed in the furnace, as reducing conditions may lead to increased emissions of glass components (sulphur, metals, dust) and to glass quality problems (for instance in the case of lead crystal glass).

The type of burner and fuel oil or natural gas and air velocity will determine the flame shape and the emission coefficient of the flame. Since radiation is the main heat transfer process in a glass furnace, most of the energy is transferred, from flames and superstructure to the batch or melt, by radiation. The flame characteristics will have an important effect on the energy consumption. Combustion modelling studies for glass furnaces show that radiation heat transfer contributes to 95 to 98 % of the total heat flux from the combustion chamber to the melt in an air or oxygen fired container glass furnace [21]. Energy balance modelling calculations show that an increase in an emission coefficient of the flames from 0.15 to 0.25 will decrease the energy consumption of a regenerative furnace by about 4 to 5%.

5. Inventory of production and energy consumption data based on a questionnaire

Process and energy consumption data of glass furnaces mainly from Europe, the USA, Japan and Canada are investigated. Annual energy consumption (natural gas, fuel, oil, electricity, oxygen) and annual glass pull data for mainly the year 1999 have been collected for 131 container glass and 24 float glass furnaces. Also information on the type of furnace, furnace size, glass colour, type of fuel, net calorific value of the fuel, electric energy consumption, oxygen consumption, cullet ratio in the batch, average residence time of the melt or average annual pull and hours of operation have been collected for most furnaces investigated.

Only the energy consumption data of the melting tank, excluding the fuel and electricity consumption for feeders, forehearths and working end, have been compared for container glass furnaces. For float glass furnaces, the energy consumption of the complete melting tank plus working end section is included. The energy consumption of the flue gas fans or for cooling air or combustion air is excluded.

Data from other sectors: fibreglass (E-glass) and tableware have been collected as well, but the results are not reported here.

It is important to prepare an inventory of the detailed process data in order to derive the primary energy consumption, taking into account the primary energy demand for the electricity used and oxygen consumption, and optionally to normalize the energy consumption data to a fixed cullet percentage in the batch or to a fixed furnace age.

Information on additional process data is also helpful to understand the differences in the energy efficiency values of the furnaces investigated and to find methods for improving energy efficiency. All the data are treated confidentially and the results are presented in an anonymous way.

6. Inventory of process data and normalization of energy consumption

The rough process data, such as annual fuel consumption, electricity consumption and glass melt pull, obtained from the completed questionnaires for each individual furnace cannot directly be compared, because of differences in the net fuel combustion enthalpy of the fuels and differences in the ratio between fossil fuel and electricity use.

6.1 Electricity and oxygen consumption for the melting process

In general, the energy from electricity applied via electrodes is more efficiently transferred to the glass melt compared to the energy released to the glass from the combustion space. However, the production of electricity and also oxygen, separated from air, requires primary energy. Based on an average energy efficiency of a power plant plus the transport losses of electricity, only about 40 % of the fossil fuel energy contents is effectively converted into electrical energy. The electricity consumption levels of an oxygen separation plant are between 0.32 and more than 0.5 kWh/m^3 of pure oxygen[2)], dependent on the size of the oxygen separation plant and the oxygen production capacity used. The average value is estimated at an average of 0.4 kWh/m^3 of oxygen production. This estimation is based on experiences in the Dutch glass industry in the period from 1994 to 1999, using on-site produced oxygen. Thus, the primary energy equivalent of 1 kWh is 9 MJ, and to generate 1 m^3 of pure oxygen, the primary energy consumption is set at about 3.6 MJ.

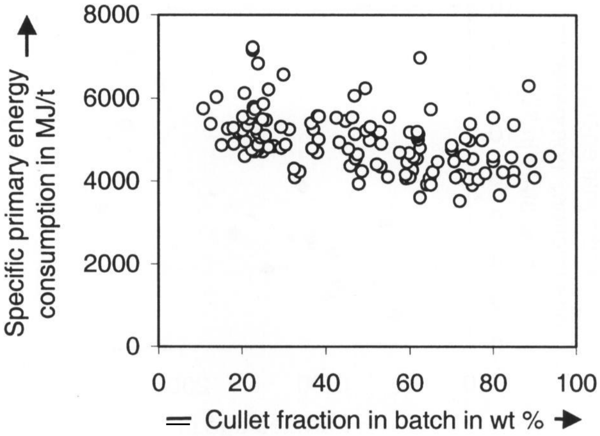

Figure 1. Specific energy consumption (based on primary energy and molten glass), dependent on cullet fraction in batch for 126 container glass furnaces; 1 kWh = 9 MJ primary energy equivalent.

In some countries, the reported energy consumption data of glass furnaces are not based on the primary energy equivalent. In that case, furnaces using large amounts of oxygen and with a high level of electric boosting apparently show relatively low energy consumption levels. Depending on the way of electricity production, this will often lead to an incorrect figure for the total primary energy consumption of the glass production process.

In this study all results presented are given as primary energy equivalent.

6.2 Cullet level

The energy consumption of glass furnaces with high levels of waste glass cullet in the batch show much lower specific energy consumption levels, compared to furnaces with a low cullet ratio. Based on the benchmarking data, the specific primary energy consumption figures are correlated with the annual averaged cullet ratios in the batch. Figure 1 shows the specific energy consumption levels obtained for a set of 126 container glass furnaces. The data are presented against

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[2)] Here and in the following referred to a state at 1013 mbar and 273 K.

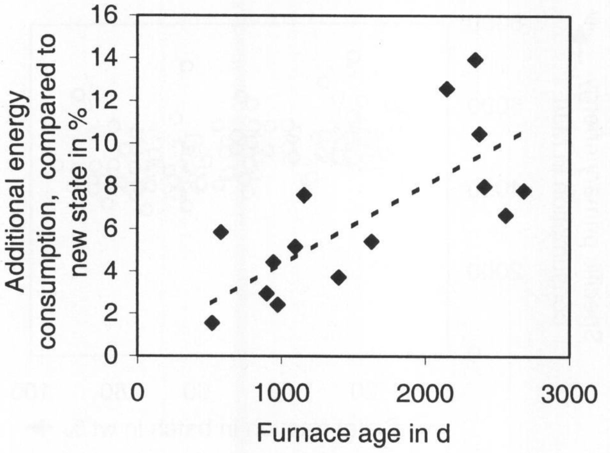


Figure 2. Impact of furnace age on specific energy consumption for melting container glass, based on data from 15 container glass furnaces.

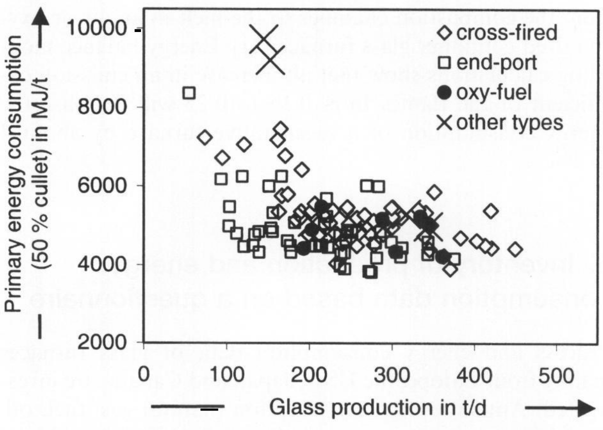


Figure 3. Specific energy consumption, based on primary energy and dependent on furnace type and pull (tons of molten glass per day).

the cullet fraction in the batch. The spread is very large, because of the large differences in pull, furnace sizes, age, type of glass, application of different air-preheat systems and sometimes batch preheating within the set of all investigated furnaces.

A normalization to 50 % cullet in the batch has been applied to all energy consumption data of container glass furnaces, using the linear correlation between the energy consumption and cullet fraction. Here it is assumed (based on data of 131 furnaces) that on average the specific energy consumption decreases by about 0.28 to 0.3 % of the specific energy consumption of a normal batch (without cullet) for a 1 % increase in cullet in the batch.

This linear relation (equation (1)) is derived from energy balance models applied to all container glass furnaces investigated. This normalization is important since the applied cullet ratio depends very much on the type of glass, glass colour and region in the world. For clear flint glass production, the use of recycled post-consumer glass is limited, but for green and amber glass compositions, cullet levels in the complete batch may exceed the 80 mass% level.

The normalization ($E_{\text{norm, 50\%cullet}}$) of the actual specific primary energy consumption (E_{act}) from an actual cullet percentage (C_{act}) in the batch to a fixed level of 50 % for container glass furnaces is given by equation (1):

$$E_{\text{norm, 50\%cullet}} = E_{\text{act}}/(1.174-0.00348\,C_{\text{act}})\,. \qquad (1)$$

This equation has been derived from energy balances of 131 container glass furnaces investigated. This means an average reduction in energy consumption of 0.296 % compared to the energy consumption of normal batch per 1 % increased cullet level. This 0.296 % based on the energy consumption of the normal batch is equal to 0.348 % compared to the energy consumption of a batch with 50 % cullet, since a batch with 50 % cullet consumes on average about 14.8 % less energy compared to a normal batch.

For float glass furnaces, the annual average cullet ratio is between 25 to 35 % for most furnaces, here the normalization is carried out on a fixed level of 25 % cullet in the complete batch.

One may discuss the normalization of the specific energy consumption data in order to take into account:

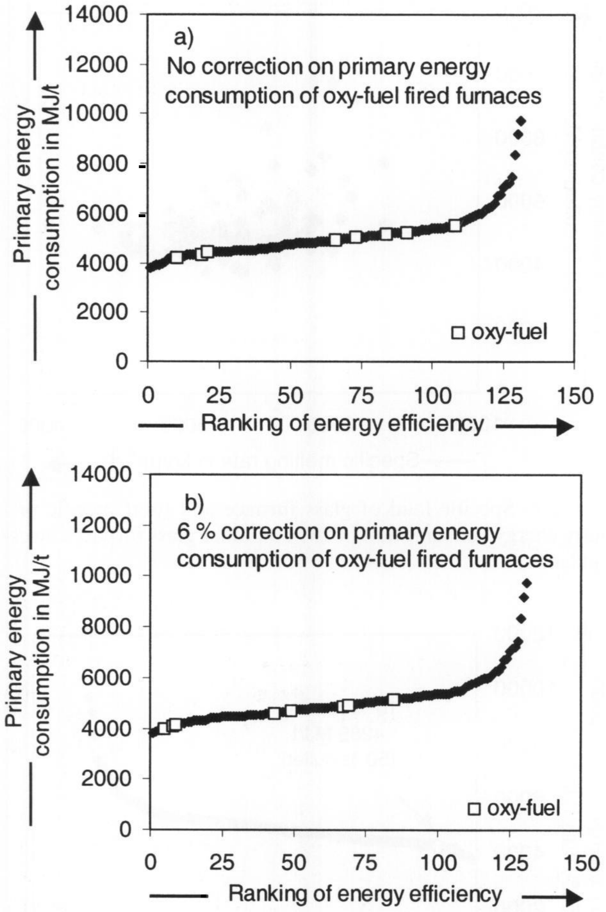
a) The age of the furnace, by normalizing the energy consumption to the new state. Figure 2 shows for 15 container glass furnaces the specific energy consumption development over the lifetime of the furnace. Clearly, the energy consumption increases, due to increased cooling of the sidewalls, increasing open joints and leakage, fouling of the regenerator checkers and deterioration of the insulation.

However, in this study the data are not normalized for ageing. The information from the inventory of all furnace data appeared to be insufficient to make this normalization to all furnaces investigated. The total age of the furnace is not the only important factor which influences energy consumption, also repairs during the furnace campaign will influence the effect of ageing on energy consumption. Normalization to a standard furnace age is hardly possible without a good definition of the age of a glass furnace.

b) The additional energy consumption of air pollution control measures. The energy consumed by the fans, electrostatic filters or scrubbing devices is not taken into account. All-oxygen firing of the glass furnaces is considered to be an efficient way of reducing the formation of nitrogen oxides. Therefore, it can be considered as an emission controlling measure. The benchmarking results show that the total primary energy consumption equivalent of oxygen fired furnaces (taking into account the primary energy consumption equivalent of the electricity required for the separation of oxygen from air) is about 6 % higher compared to the most energy efficient container glass furnace types: the end-port regenerative furnaces.

It is a point of discussion whether or not a correction of 6 % on the energy consumption should be made for oxygen fired furnaces, to take into account the extra energy of these furnace types to achieve a reduction in specific NO_x emissions.

c) The specific pull rate or total average pull rate of a furnace appears to be an important process parameter influencing the specific energy consumption. Figure 3 shows the specific primary energy consumption, depending on the total average pull rate (average for a complete year) for the investigated end-port, cross-fired regenerative, recuperative and oxygen-fired glass furnaces. Up to about 250 to 300 t of molten glass per day, the energy efficiency improves by increasing the pull. The furnaces showing a low average pull



Figures 4 a and b. Ranking of energy efficiency of eight oxygen fired container glass furnaces among 131 furnaces. Normalization of energy consumption to 50 % cullet and based on total primary energy consumption (including electricity and oxygen generation). Figure a): Case 1, ranking without 6 % reduction in energy consumption, figure b): Case 2, ranking with 6% correction on energy consumption.

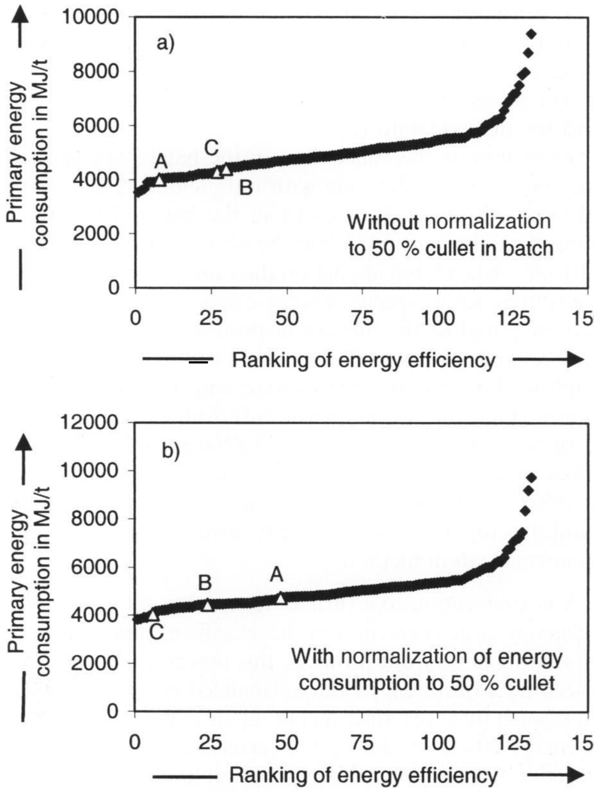
rate are mostly furnaces producing high-quality container glass types for perfume bottles or flacons for pharmaceutical applications. Normalization for a fixed pull rate (average) is point of discussion.

The average pull rate (P_{av} = average pull of molten glass per day averaged over a whole year) in the series of investigated container glass furnaces with more than 150 t of molten glass per day is ±250 t/d.

A normalization of the actual specific energy consumption (E_{act} in MJ/t) at an actual pull P_{act} (in t/d) to a fixed pull level (P_{av} in t/d = 250 t/d) for glass furnaces with more than 200 t of molten container glass per day is derived from the correlation found between the average specific energy consumption and the average pull of the 131 glass furnaces investigated. This relation is presented by equation (2):

$$E_{norm,pull} = \frac{E_{act}}{(35.12/P_{act} + 0.860)} . \tag{2}$$

External factors which may have an effect on the energy consumption of a glass furnace are among others, the average annual ambient temperature, the fuel types which are supplied in a certain region or supply of different types of raw materials. For instance, energy balance models show that an increase in the average annual ambient temperature by 10 K will lead to about 0.8 % energy savings for regenerative container glass furnaces.



Figures 5a and b. Ranking of all furnaces investigated, a) without and b) with a normalization to fixed cullet level in the batch. Furnace A with about 85 % cullet in the batch, furnace B with 52 % cullet and furnace C with 32.6 % cullet.

In the benchmark study for container glass furnaces only normalization to a fixed cullet fraction in the glass forming batch has been applied unless indicated else. For float glass furnaces, the influence of furnace size or pull also has been taken into account.

7. Impact of normalization method on benchmarking results

It is essential for a benchmarking analysis that the results are not too much dependent on the way of normalization. However, it is shown here by some examples that the ranking of the energy efficiency may strongly depend on normalization to a fixed age, fixed cullet percentage in the batch and/or a fixed pull rate. For all-oxygen fired furnaces a 6 % subtraction from the energy consumption of the furnace, including the energy related to the oxygen production, has an important effect on the ranking of such furnaces. In this benchmark study, eight all-oxygen fired furnaces have been included. Figures 4a and b show the positions of the eight oxygen-fired container furnaces in% in the ranking list of 131 container glass furnaces with and without the 6 % subtraction.

A normalization to 50 % cullet in the batch will result in lower normalized specific energy consumption figures for furnaces with an average cullet fraction below this level. Figures 5a and b show the ranking positions for three furnaces for the case with (figure 5a) and without (figure 5b) normalization of the cullet ratio in the batch; one furnace with about 85 % cullet, one with only about 32.6 % cullet and one with about 52 % cullet in the batch. From these figures it can be concluded that the normalization to a fixed cullet ratio has a large impact on the ranking and the difference (difference in specific energy consumption of the furnace compared to the furnace in position 10 % of the furnaces ranked as most efficient) to the target energy consumption. For example, the furnace with an average cullet fraction of 85 % in the batch will shift from a ranking within the 10 % most efficient furnaces to a lower rank when normalizing the specific energy consumption to 50 % cullet. On the other hand, the example with 32.6 % cullet will be among the top 10 % most efficient furnaces when applying this normalization method.

A normalization to a furnace age of 0 years will lead to a relatively large correction in the specific energy consumption figures of very old furnaces, this however may result in misleading adjustment of the normalized energy consumption of such furnaces, since a cold repair may have improved the energy efficiency during the furnace campaign and the correction to lower energy consumption levels would be too large. In the glass industry, different levels of furnace overhauls (with or without renovation of the regenerators) or cold repairs can be distinguished. Information on the kind of repairs within the running furnace campaign is necessary to apply proper age normalization rules. In the present study no normalization has been applied for furnace age.

8. Correlation between process parameters and (normalized) energy consumption figures

In this benchmark study on the energy efficiency of glass melting furnaces, the parameters:

- cullet percentage,
- pull rate,
- furnace age,
- type of furnace,
- glass colour,
- oxygen firing,
- specific load based on surface area ($t/m^2 \cdot d$)

have been investigated. Figure 1 shows the effect of cullet fraction on the reported specific energy consumption of container glass furnaces. Figure 2 illustrates the impact of the furnace age. In figure 3, the effect of pull rate and furnace type is given. After normalizing to standard (50 %) cullet fraction in the raw material batch, it appears that the average specific energy consumption (given as primary energy equivalent) of flint glass furnaces, 5107 MJ/t of molten glass, and container glass furnaces producing coloured glasses, 5110 MJ/t of molten glass, are hardly different. Probably, the increased absorption of heat radiation by the top layers of the coloured glass composition melt and free convection heat transfer is compensated by the increased radiation heat transfer to the flint glass melt.

The current generation of oxygen-fired furnaces for container glass production appears to be less energy efficient (taking the primary energy equivalent of the oxygen into account) compared to the modern end port-fired container glass furnaces. But further developments in these relatively new furnace types may improve their future energy efficiency level. In other sectors, such as the special glass, TV glass or glass fibre sector, all oxygen-fired furnaces appear to be the most energy efficient ones and rank among the best 10 to 20 % in the respective benchmarking inventories.

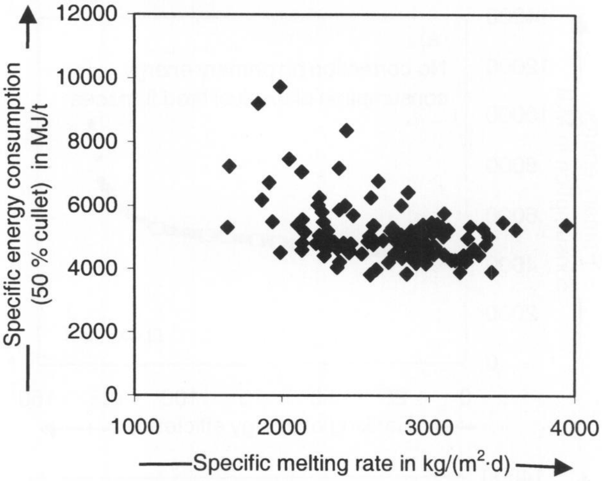


Figure 6. Specific load of glass furnace and total specific primary energy consumption of 131 container glass furnaces investigated.

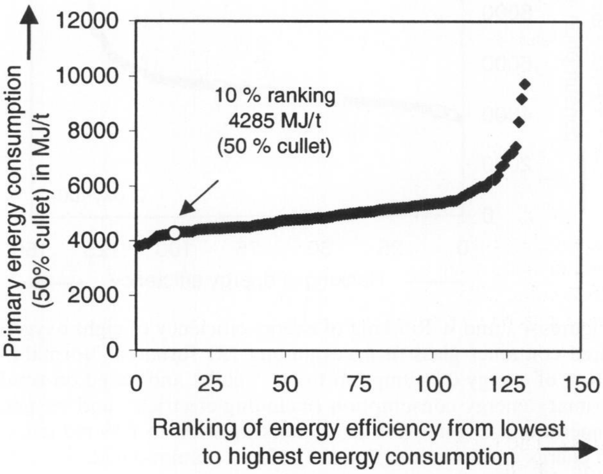
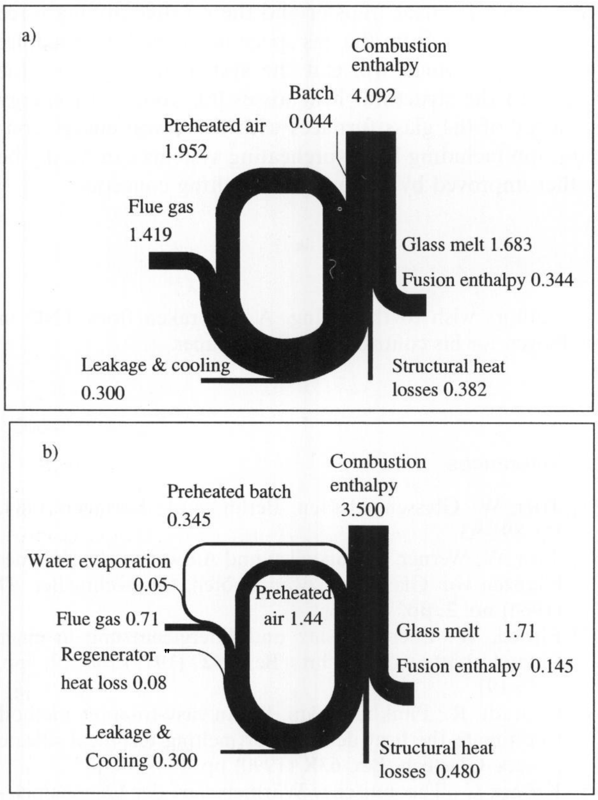


Figure 7. Ranking of energy efficiency of 131 container glass furnaces investigated (data 1999), normalization to 50 % cullet, total primary energy consumption (including electricity and oxygen generation).

The specific load and specific energy consumption data of the container glass furnaces investigated are presented in figure 6. Above a specific melting load of 3 t/m^2 per day the energy consumption will hardly decrease anymore. The glass quality may even become worse at high melting loads.

9. Container glass furnace benchmarking 1999

Figure 7 shows the ranking of the 131 investigated furnaces from the lowest to the highest value of specific primary energy consumption. The 10 % level is at 4285 MJ/t of molten



Figures 8a and b. Sankey diagrams for most energy efficient container glass furnaces (> 250 t/d). Numbers in MJ energy per kg of molten glass. Figure a): end-port fired regenerative furnace with 35 % cullet (275 t glass/d), figure b): cross fired regenerative furnace with batch pre-heater and 70 to 75 % cullet.

glass. The difference between the specific energy consumption of the most energy efficient furnace and the energy consumption of the furnace ranking in the middle (50 %) is only about 25 %. Among the 10 % most energy efficient furnaces, the most dominant types are the end-port fired regenerative furnaces with a relatively high pull rate (> 200 t/d). A few of these furnaces apply batch and cullet preheating. The furnace with the highest energy efficiency shows a specific (annual averaged) primary energy consumption of 3800 MJ/t of molten glass at a level of 50 % cullet in the batch. Compared to other values reported in the literature [8, 15 and 16], this seems to be rather high, but in this case the energy consumption through electricity is calculated as primary energy equivalent (1 kWh = 9 MJ) instead of the net value (1 kWh = 3.6 MJ) and the data are normalized to a level of 50 % cullet in the batch.

The best practice for an energy efficient production of container glass is using an end-port fired furnace, with regenerator designs and structures resulting in > 60 % heat transfer efficiency from the exhaust gas to the combustion air and with cullet/batch preheating up to temperatures of 275 to 325 °C, only moderate electric boosting, insulation of the crown, and optimum sealing of all joints. The furnace typically operates at a pull above 250 to 300 t/d with a specific pull around 3 t/m^2 per day. The burners and combustion control should lead to luminescent flames with a moderate excess of air (0.8 to 1.2 vol.% of oxygen in the exhaust gases).

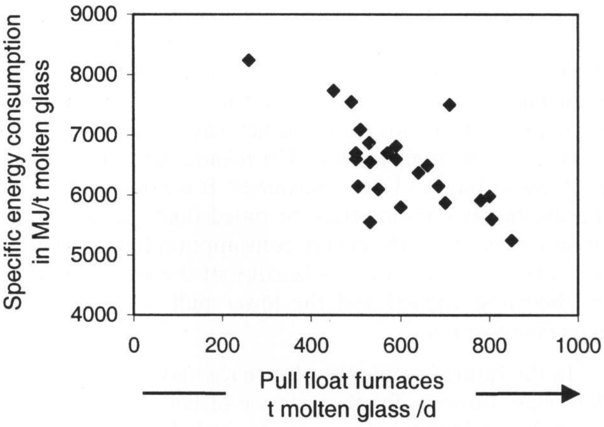


Figure 9. Impact of average pull on energy efficiency of 24 float glass melting furnaces (data 1992 to 1999), normalized to 25 % cullet in the batch.

A typical energy balance, for one of the most energy efficient glass furnaces, is given by a Sankey diagram, presented in figures 8a and b.

Conradt [6] shows that, taking into account the driving force required for heat transfer and limited time available for heat transfer and the laws of thermodynamics, the minimum practically possible energy consumption calculated for a fossil-fuel fired container glass furnace with very large regenerator and optimally insulated is about 790 kcal/t of glass melt (3300 MJ/t) for 70 % cullet in the batch (without batch preheating). Normalized to 50 % cullet, this minimum practically achievable energy consumption will be about 3500 MJ/t.

Thus the difference between the energy consumption of the most efficient container glass furnaces today (3600 to 4200 MJ/t of molten glass from batch with 50 % cullet) and the minimum possible energy consumption is already very small.

The furnace with the lowest energy consumption, not taking into account the primary energy required for oxygen production and electricity production (1 kWh = 3.6 MJ) and not normalizing to 50 % cullet, was an oxygen fired furnace, with 60 % cullet in the batch, using on average 3380 MJ of energy per ton of molten glass. However, normalization to 50 % cullet and conversion to primary energy equivalent will result in a much higher value for this case: about 4200 MJ/t. This example shows the importance of the normalization rules, having a large impact on the ranking of the energy efficiencies. The most energy efficient end-port fired furnaces with very high cullet percentage (80 to 90 %) show energy consumptions of 3400 to 3600 MJ/t of glass, before normalization to 50 % cullet and to primary energy equivalent.

Note that in the benchmark study the annual average production and energy consumption data have been used to derive the average specific energy consumption. Temporarily some furnaces may use more energy or less energy, for instance depending on melting load.

10. Float glass furnace benchmarking 1999

Figure 9 shows the annual averaged specific energy consumption (primary energy equivalent) of 24 float glass furnaces. The process and furnace data of all these furnaces were not complete and some figures are estimated. The specific energy consumption data are normalized to a situation with 25 % cullet in the batch. The average pull appears to be one of the major factors which have an impact on the specific energy consumption. Up to now the effect of the glass colour has not been determined. It is expected that the specific energy consumption for tinted float glasses will be larger compared to the energy consumption figures of clear float glass melting processes because of the increasing electric boosting applied and the lower pull rates for tinted glass compositions.

In the future inventories of furnace and process data of float glass furnaces for the purpose of benchmarkings, the age, pull, total fired surface area, type of glass, type of fuels, electric boosting capacity used, oxygen consumption, annual melting production, fuel consumption and cullet fraction in batch are all required. The largest float glass furnaces generally show the lowest specific energy consumption. Values down to 5250 MJ/t of float glass have been found, based on 25 % cullet in the float glass forming batch.

11. Conclusions

Although the number of furnaces investigated on their energy consumption levels is still limited and represents only a small part of the container glass and the float glass sector worldwide, the results probably enable a sufficient analysis of the best practice and most energy efficient furnaces in these sectors. Comparison of energy consumption data is a tedious procedure and should be carefully undertaken. Only the comparison of the primary energy equivalent consumption of glass furnaces appears to be correct. Without converting electricity and oxygen consumption to their primary energy equivalent for their generation, furnaces using only electric energy or a high level of electric boosting and oxygen-fired furnaces would show the lowest specific energy consumption figures. This however does not reflect the impact on the overall energy demand, since oxygen separation from air and electricity generation are energy intensive processes. The normalization of the collected data to a fixed cullet ratio in the batch or a fixed furnace age and pull rate will have a significant effect on the ranking of the furnace energy consumption levels of all investigated furnaces, therefore it is recommended to define internationally accepted rules for benchmarking and for the way of normalization of the specific energy consumption data per glass industry sector.

Today the most energy efficient furnaces based on primary energy consumption equivalent are end-port fired furnaces with batch and cullet preheating. The most energy efficient float glass furnaces are the larger furnaces with more than 800 t of glass production per day. The size of the regenerators, cullet percentage in batch and pull rate or specific pull and age of the furnace are important factors determining the energy consumption of glass furnaces.

The best practice energy consumption target cannot directly be derived from the theoretical energy demand determined from the heat capacity of the glass melt and batch gases plus the reaction enthalpy for conversion of a glass forming batch into a glass. The required residence times, the time needed for heat transfer and the positive driving force for heat transfer from the gas space to the melt will require extra energy, which will exit the system through the flue gases and the structural heat losses [6]. Today, the energy efficiency of the glass furnaces with the lowest energy consumption including batch-preheating systems can hardly be further improved by current glass melting concepts.

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