Analysis of Energetic Performance of Glass Melting Processes as a Basis for Advanced Glass Production

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The experimental and theoretical knowledge of the industrial glass melting process, acquired during two last decades, opens a way to new melting concepts, characterized by smaller size, high performance and flexibility, low energy consumption and by producing high quality glasses. This work presents a method to evaluate the effect of temperature, process time, flow conditions and insulation in a model melting space (simulating melting tanks) on energy consumption, melting performance and flexibility of the process in terms of sand dissolution and bubble removal (fining). The condition of complete accomplishment of both homogenization processes just prior to the glass leaving the space was kept in all calculations. The calculations applying the laboratory sand dissolution times and fining times aimed at finding theoretical optimum conditions of dissolution and bubble fining processes during glass melting. The results obtained under isothermal conditions provide a way to improve fundamentally both processes; particularly by process separation, application of controlled glass melt flows and special conditions for bubble removal. Several examples show the increase in performance of the model melting space when applying the suggested intensification factors.

Introduction
The glass producers face frequently problems of glass quality, energy consumption, investments into technology and environmental damages. The complete analyses of single processes became necessary, leading to theoretically best conditions, this knowledge being subsequently accompanied by searching for new technical means of realization, including non-traditional means and arrangements. This work resumes some author’s ideas about the topic, supported by laboratory results of sand dissolution and bubble removal and by calculations of specific energy consumption and space pull out [1].

Theory
The general ambition of future glass melting processes is obvious: to produce cheaply and flexibly high quality glass. The mentioned task calls for the set of criteria and quantities being associated with the process: the technological criteria expressing the process efficiency, as are the specific energy consumption, the melting performance (pull out of the space), the process flexibility to convert from one glass type to another glass type and glass quality characterized by the zero level of defects in leaving glass, and fundamental quantities influencing the values of criteria, as are temperature, process kinetics (homogenization times), flow conditions (utilization of the space for homogenization processes) and space insulation.

It is desirable to define the technological criteria in a simple way. Thus, only fundamental process features should be involved:
a) The specific energy consumption, $H_M^0$, makes it possible to compare energy efficiency of different facilities. The specific energy consumption in the steady process operation may be composed from two terms. The first term expresses the specific energy consumption of chemical reactions and phase transitions, as well as energy to heat the mixture to melting temperature (the theoretical heat of melting) and the second term expresses the specific energy, lost by the heat flux through boundaries during melt residence time in the space. The second term introduces two important process quantities into the energy balance: homogenization times of the appropriate process (dissolution, refining) and the utilization of the melting space for the process accomplishment.

The detailed history of glass flow, temperature development and coupled melting kinetics resulting from numerical models provides a distribution of melting histories and abilities [2-7]. However, it appears difficult to compare different cases obtained at varying initial and boundary conditions and characterized consequently by a spectrum of results. That is why the simple melting space and simple conditions have to be applied to get qualitative knowledge about the effect of temperature, other processes enhancing factors (melt stirring and bubble growth as a consequence of fining conditions are considered), space utilization and space insulation on the specific energy consumption and pull out of the melting space. The condition of zero particle or bubble level in resulting melt was accepted. The applied cubic model melting space having volume $1\, \text{m}^3$ and being enclosed by two layers of refractory materials is described in detail in [8]. The choice of wall thickness and typical refractory materials simulate approximately heat losses through boundaries typical for the industrial glass melting as is demonstrated by the dependence between the specific heat flux through boundaries and temperature in Fig.1 of Ref. [8].

The laboratory data involving sand particle dissolution times or bubble removing times are used in presented criteria to calculate tendencies in specific energy consumption or pull out of the melting space. The appropriate data were obtained under history of rapid heating to the constant melting temperature and the impact of the melting history on results is therefore very restricted The laboratory values of sand dissolution times and bubble removing times (refining times) were applied to get the standard homogenization times, $\tau_{D0}$, (sand dissolution time) and $\tau_{R0}$ (bubble refining time). Details are present in [1].

Besides the times needed to accomplish the process, the utilization of the melting space was defined. The quantity $m$ defines the fraction of the sc. dead space (the space where the melt does not neither flow nor circulate) and the dimensionless constant $K^Q$ expresses integrally the differences between homogenization pathways in the melting space. The greater is the value of $K^Q$, the lower is the space utilization for the given process. The minimum value of $K^Q=1$ designates the case characterized by equivalent pathways (the sand dissolution in the isothermal channel with plug flow, e.g.). The entire space utilization may be then defined by the quantity $(1-m)/K^Q$. The greater is the mentioned quantity, the higher space utilization sets in the space. The more details to the definition of $K^Q$ for the sand dissolution and bubble removal is in [1].

b) The pull out (performance), $P$, of the space is defined as the mass of glass leaving the space per unit of time $[\text{t/(m}^3\times 24\, \text{hrs})]$. 
c) In addition, the flexibility function was defined as the quantity expressing the ability of the space to convert completely its content. Thus, the flexibility function, \( F \), is the fraction of the space changed with environment per unit of time [1/s].

In the following part of this work, the calculations of the specific energy consumption and the performance (pull out) of the glass melting process in the model melting space will be presented as a function of temperature, laboratory sand dissolution and bubble removal times, utilization of the model melting space and its insulation. The impact of the melting history in calculations will be restricted to the case of rapid heating of material and glass to the constant melting temperature, corresponding to the time-temperature history under which the applied laboratory data were obtained. The calculations were performed with the aim to define optimum conditions of both homogenization processes, i.e. particle dissolution and bubble removal, under mentioned simplifications.

**Results and discussion of calculations of melting criteria in a simplified space**

The published study gives picture of potential glass melting improvements in the following case with assumptions:
- No detailed information is given about glass flow inside the melting space. Only space utilization, \((1-m)/K^0\), is defined by its numerical value chosen between 1 and zero.
- Only homogenization times of particle dissolution or bubble removing, \( \tau_D \) and \( \tau_R \), are used, obtained by laboratory measurements and the average residence time of glass \( \bar{\tau} \) is in relation to the sand dissolution time or to the bubble removing time [1].
- The melting space is a cube having volume \(1m^3\), surrounded by two layers of refractory materials [8].
- No detailed information is given about the energy source. Material is instantly heated to the mixture of melt and particles, no energy recuperation is considered (the energy source is not defined).

The following independent variables are present in the presented results:
- Temperature. The temperature variations influence both terms of the specific energy consumption, i.e. the theoretical heat of melting (through the melting temperature) and the heat losses (through variations in heat flux across boundaries and variations of homogenization times).
- The degree of processes homogenization by other means than temperature (stirring of glass to enhance the dissolution process, the application of refining agents to accelerate refining). The quantity \( \tau_D/\tau_{D0} \) or \( \tau_R/\tau_{R0} \) is the fraction of the standard process time attained by assumed process intensification.
- The degree of reduction of heat losses, \( \hat{H}_A/H_{A0} \), attained by better space insulation (application of thicker space walls or refractory materials with very low heat conductivity, e.g.). Here, \( \hat{H}_A \) is the specific heat flux related to the unit of boundary surface.
- The reciprocal value of the space utilization, \( K^0/(1-m) \). The ideal value is 1 (\( K^0=1, m=0 \)). The reciprocal value increases with decreasing space utilization for the process.

The values of \( H_M^0 \) and \( P \), calculated for the sand dissolution process and different heat losses, as well as reciprocal values of the space utilization, are plotted as a
function of temperature in Fig. 1. The single curves represent the cases when the standard heat loss term (curve 1.0, (5)) decreased to 60% and 20% of its original value (curves 0.6, (3) and 0.2, (1) in Fig 1). The obvious reduction of heat losses may be attained by the corresponding decrease in homogenization times, heat flux through boundaries, or by the decrease in the reciprocal value of the space utilization (here $K^O / (1-m) = 3$ corresponds to the case of 60% and $(1-m) / K^O = 1$ to 20% of the original heat loss term). The corresponding situation for the bubble removal process is presented in Fig. 2.

The results presented in Figs 1-2 show energy consumption minima for the dependence $H^O_M$ on $t$ (temperature in °C) and the steep pull out increase for sand dissolution and refining with increasing melting temperature. As already mentioned, the parameters 5, 3 and 1 designate three levels of values of $K^O / (1-m)$ in Fig 1 and 1.0, 0.6 and 0.2 are the ratios $\tau_D / \tau_{D0}$, $\tau_R / \tau_{R0}$ or $\dot{H}_A^L / \dot{H}_A^{LO}$ in both Figures where the 0-index means the standard state. As is obvious from Figures 1-2, the values of $H^O_M$ and $P$ may be influenced:

1. By the decrease in $\dot{H}_A^L$ (the specific heat flow through walls) as the term of heat losses decreases (curves 1.0, 0.6 and 0.2 in Figs. 1-2). The value of $\dot{H}_A^L$ may be suppressed by thick or composed walls and by the use of materials with low heat conductivity. The quantity $\dot{H}_A^L$ is however not involved in the relation for the space output, consequently, no output increase may be attained by better space insulation.

2. By the temperature increase. The steep decrease in $H^O_M$ and increase in $P$ due to exponential decrease in dissolution and bubble removal times, $\tau_D$ and $\tau_R$, is obvious. The specific energy consumption function, $H^O_M$, shows a minimum because both the specific theoretical heat and $\dot{H}_A^L$ are growing with rising temperature.

3. By the relative decrease in $\tau_D$, i.e. reduction of $\tau_D / \tau_{D0}$, or by the decrease in $\tau_R$, i.e. reduction of $\tau_R / \tau_{R0}$, by other factors than temperature (curves 1.0, 0.6 and 0.2 in Figs. 1-2). The heat losses are reduced.

4. By the increase in the utilization of the melting space, i.e. by the decrease in its reciprocal value, $K^O / (1-m)$ (curves (5), (3) and (1) in Fig. 1). The heat losses are as well reduced.
Fig. 1: The specific energy consumption (—) and space performance (-----) for the dissolution process as a function of temperature and degree of intensification. (1), (3), (5): the values of $K^Q/(1-m)$; 1.0, 0.6, 0.2: the values of $\tau_D/\tau_D^0$ or $H_A^L/H_A^{L0}$. $H_M^0$ is heat needed to melt the unit mass of glass and is without the heat content of flue gases as the heat source is not explicitly defined (see eq. (1)).

Fig. 2: The specific energy consumption (—) and space performance (-----) for the bubble removal process (fining as a function of temperature and degree of intensification). The same significance of parameters of curves is as in Fig. 1. $\tau_R/\tau_R^0$ is instead of $\tau_D/\tau_D^0$. The influence of the utilization of the melting space is not involved ($(1-m)/K^Q = 1$).
The values of optimum temperatures, \( t_{opt} \), may be calculated from the derivation \( \frac{\partial H^0_{\mu}}{\partial T} = 0 \). The values of optimum temperatures, \( t_{opt} \), for both processes, sand dissolution and bubble removal, are plotted in Fig. 3. As is obvious from the figure, the values of \( t_{opt} \) decrease when \( \tau_D / \tau_D^0, \tau_R / \tau_R^0 \) and \( K^0 / (1 - m) \) decrease too, i.e. the process time decrease and the utilization of the space increases. The decrease in optimum temperatures could be favorable for the process since the very high melting temperatures enhance wall corrosion and losses of volatile glass components from the level.

![Graph showing the optimum temperature of sand dissolution and bubble removal processes as a function of degree of intensification](image)

**Fig. 3:** The optimum temperature of the sand dissolution and the bubble removal process as a function of degree of intensification: the reciprocal value of utilization of the space, \( K^0 / (1 - m) \), the relative decrease in process time, \( \tau_D / \tau_D^0, \tau_R / \tau_R^0 \), and the relative decrease in heat losses through walls, \( H_A^L / H_A^{L0} \). The influence of utilization of the fining space is not involved \( ((1 - m) / K^0 = 1) \).

The following Figures 4 and 5 show that the glass pullout at optimum temperature, \( P_{opt} \), may be kept on almost constant value, despite the relatively low optimum melting temperatures are applied. However, the value of \( P \) may be kept almost constant only when decreasing \( \tau_D / \tau_D^0, \tau_R / \tau_R^0 \) or \( K^0 / (1 - m) \). The decrease in heat losses through boundaries, \( H_A^L / H_A^{L0} \), leads to the simultaneous decrease in \( P_{insulation} \) when applying the decreasing optimum temperature. Consequently, better insulation is not a proper intensification factor of the space performance (see decreasing lines in Figures 4-5).
Fig. 4: The specific energy consumption and space performance for the dissolution process at optimum temperature as a function of degree of intensification, $K^0/(1-m)$, $\tau_D/\tau_{D_0}$ and $\bar{H}_A^L/\bar{H}_A^{L0}$.

Fig. 5: The specific energy consumption and space performance for the bubble removal process at the optimum temperature as a function of intensification factors, $\tau_D/\tau_{D_0}$ and $\bar{H}_A^L/\bar{H}_A^{L0}$.

The overall pictures of $H_M^0$ and $P$ dependences on temperature and on increasing level of intensification of the dissolution process (decrease in $\tau_D/\tau_{D_0}$ or in $K^0/(1-m)$) are represented by Figs. 6 and 7. The values of $H_M^0$ and $P$ at optimum temperatures are represented by squares in both Figures.
Fig. 6: The 3D representation of specific energy consumption of the dissolution process as a function of degree of intensification: $t$, $K^0 / (1 - m)$, $\tau_D / \tau_{D0}$ and $\dot{H}_A^L / \dot{H}_A^{L0}$. The specific energy consumption at optimum temperature is marked by the square points.

Fig. 7: The 3D representation of space pull out (performance) for the dissolution process as a function of degree of intensification: $t$, $K^0 / (1 - m)$ and $\tau_D / \tau_{D0}$. The value of $\dot{H}_A^L / \dot{H}_A^{L0}$ does not influence the space output (see eq. (7) and is not involved in the Figure. The pull out at optimum temperature is marked by the square points.
The flexibility function $F$ is proportional to $P$ and therefore is also plotted in Fig. 7. When evaluating its information ability, the flexibility attributes should be reminded:

a) The rapid glass exchange in the space, characterized by a high value of $F$. The property is significant for rapid and economic product type change to meet market demands. The possible ways of the flexibility increase are:
- To decrease $K^Q/(1-m)$, i.e. to increase the space utilization, $(1-m)/K^Q$. This step is especially important for the dissolution process. The low value of $K^Q$ means equal particle dissolution history for all paths. Small values of $m$ require the elimination of still sections or rotating melts. The installation of regime of high space utilization assumes setting up the controlled glass melt flow in the entire space.
- To increase the melt throughput velocity, i.e. to accelerate the processes. The factors accelerating particle dissolution or bubble separation process (temperature, pressure, composition, glass convection etc.) should be applied. If the value of space length (throughput size) will be preserved, the space pull out will grow.
- To decrease the space length, i.e. to reduce the space volume. The space volume reducing, however, should be accompanied by the increase in space utilization or process rate in order to maintain the glass quality.

b) The substantial change of the space pull out, i. e. the reaching the high value of $\Delta F$. The high value of $\Delta F$ is attainable for the small melting space with high utilization of its volume for given process. In order to reach high $\Delta F$, the change of temperature, of the process rate (the variation of values of $\tau_D/\tau_{D0}$ or $\tau_R/\tau_{R0}$), utilization of the space (the variation of the value of $(1-m)/K^Q$), the change of the space volume and the increase or decrease in melting reserve (if at disposal) may be applied. The question of the impact of the mentioned different options on the specific energy consumption is solved in [1]. Generally, any increase in the space output (and $F$) at lower and medium temperatures decreases distinctly the specific energy consumption whereas the same impact is reduced at high process temperatures. This fact is obvious from Fig. 8, where the specific energy consumption of the standard case is plotted as a function of the space output.
Fig. 8: The dependence between the specific energy consumption, $H_M^0$, and space performance, $P$, for the sand dissolution process.

The presented results of application of technological functions provide the preliminary instruction how to suggest factors of advanced glass melting. The extreme melting temperatures are debatable as mentioned defect processes (corrosion, evaporation) damage glass quality and the environment, and shorten furnace life. However, approaches leading to decrease in melting times (dissolution times, bubble removal times) by other factors than temperature and promoting higher utilization of the melting space exhibit low energy consumption and high output as well at medium temperatures. The efficient factors of both processes, based on results of laboratory measurements, were already stated in [1] and may be summarized as:

Efficient factors of the dissolution process:
- melt stirring
- controlled granulometry of solid particles
- optimum temperature as for $H_M^0$

Efficient factors to enhance bubble removal:
- temperature ensuring activity of the refining agent
- glass composition (refining agent concentration, redox state of glass)
- reduced pressure
- additional forces (ultrasonic, microwave, centrifugal)

Space utilization:
- controlled glass flow

The optimum conditions for advanced dissolution and bubble removal are not completely equivalent (melt stirring, reduced pressure, e.g.) which fact asks for local separation of both processes. The question arises how to realize melting spaces and conditions inside to set up favorable conditions of both processes. Some examples of assumed increase in the performance of the melting space (leading to decrease in the specific energy consumption, see Fig. 8) will be now presented in the following text.
The stirring of the glass melt in a series of mixers

The result of the process analysis leads to application of optimal temperatures from the point of view of energy consumption. The value of $t_{opt}$ decreases with increasing utilization of the dissolution space and with acceleration of the dissolution process by other factors than temperature. The way of application of last two favourable factors simultaneously may be connected with setting up the controlled convection in the dissolution space. In contrast to the bubble separation process, the vigorous mixing of glass appears efficient as the dissolution is accelerated and the dead or great circulation spaces are reduced or removed. The completing the dissolution process asks nevertheless for necessary residence time of melt inside the space. That is why no perfect mixing of the entire space is required but the combination of the plug flow and vigorous mixing in the direction perpendicular to the main stream of the melt may be imagined. The case may be realized by the series of stirred spaces or glass domains [How to melt glass tomorrow]. The following Fig. 9 shows the decrease in concentration of undissolved sand in a series of mixers which leads to increase in the dissolution performance and consequently to the decrease in the specific energy consumption of the space as an example. The stirred domains do not have to be the separated spaces and their number to dissolve completely particles is calculated by using the appropriate calculation procedure and experimental sand dissolution data under given conditions [9]. The experimental data about influence of glass convection on the rate of sand dissolution are needed to determine the optimum conditions of dissolution.

![Fig. 9](image-url)

Fig. 9: The decrease in concentration of undissolved sand in a series of ten stirred spaces.

The application of reduced pressure for bubble removal in a refining channel

The decrease in external pressure increases substantially the bubble growth rate and consequently, the rate of the bubble removal process. The following Fig. 10 presents the influence of pressure decrease on the refining performance of the horizontal refining channel [10]. The decrease in refining temperature is alternatively feasible leading to the decrease in the specific energy consumption.
Fig. 10: The refining performance of the orthogonal horizontal channel (the length 1m, the width 0.5m, the layer of glass melt 0.5m) as a function of external pressure [11]. 1: TV glass refined by Sb$_2$O$_3$, 1300°C, 2: Lead-silicate glass refined by As$_2$O$_3$ at 1300°C, 3: Lead-silicate glass refined by As$_2$O$_3$ at 1400°C, 4: Lead-silicate glass without any refining agent at 1400°C.

The application of centrifugal force for bubble removal in a rotating cylinder

Bubbles in the rotating cylinder with melt are efficiently separated to the cylinder center due to their low density. Under high rotation velocities, however, the pressure inside of bubbles considerably increases and the bubble shrink due to both gas compressibility and their dissolution in the melt. This fact hinders the bubble separation but some bubbles may be completely dissolved in the melt. The optimum conditions for rapid bubble removal process involve therefore appropriate choice of temperature, rotation velocity and initial bubble composition. The following Fig. 11 brings the dependence between the bubble removing time by both separation and complete dissolution as a function of the cylinder rotation velocity [11].

Fig. 11: The dependence between the maximum bubble removal time from the model TV glass (regardless of temperature and initial bubble radius) and the cylinder rotation velocity [11]. O$_2$ and CO$_2$ bubbles, V/V$_0$=0.5, where V$_0$ is the cylinder and V the melt volume. The radius of the cylinder is 0.25m and its height 0.5m.
The application of suitable glass convection in the horizontal refining channel

The glass flow patterns in the refining spaces influence the bubble trajectories and consequently the refining performance of the channel. The application of suitable boundary conditions is therefore significant for the process. The following Fig. 12 shows the dependence between the refining performance of the horizontal refining channel and the fraction of the dead space in the channel [12]. The increasing longitudinal temperature gradient evokes longitudinal circulation regions which reduce the efficient refining space and consequently the refining performance. The efficient refining requires therefore the melt with minimum temperature differences between the glass input and output.

![Graph showing the relation between the critical refining performance of the horizontal channel and the value of the fraction of dead space. The full lines express the theoretical course [12]. 1 – The channel with one circulation circle 2 – The channels with two or even number of circulation circles ■, ▲ – the values obtained by mathematical simulation of the channel.]

**Fig. 12:** The relation between the critical refining performance of the horizontal channel and the value of the fraction of dead space. The full lines express the theoretical course [12].
1 – The channel with one circulation circle
2 – The channels with two or even number of circulation circles
■, ▲ – the values obtained by mathematical simulation of the channel

**Conclusion**

The chemical engineering approach appears useful when searching for the glass melting process exhibiting low energy consumption and high performance. The significant homogenization processes are investigated under simplified conditions in order to find and evaluate the main intensification factors as are temperature, the degree of process acceleration and the utilization of the homogenization space for the given process. The examples presented in this work are aimed at increase in the rate of process and space utilization, attained by application of controlled glass convection, reduced pressure and centrifugal force. This leads to increase in space performance and consequently to the decrease in the energy consumption of melting.

In order to find and verify the optimum melting and design conditions for particle dissolution and bubble removal from this theoretical approach, and to find more details about optimum process conditions to be applied, laboratory studies are recommended. Such experimental simulation studies on particle dissolution and bubble behavior in glass melts will provide additional data to be used in theoretical
models or relations. For instance, simple melting experiments in confined spaces such as crucible melts can be carried out. The optimum glass melt flows in a tank should be investigated to obtain a high utilization (low $K^0$ value and low $m$ value) by the use of basic flow models (plug flow and perfect mixing) and CFD modeling.

Parameter studies will help to find the optimum process and design parameters. The process parameters of major importance are temperature, temperature gradients, glass and batch chemistry, pressure, convection of the melt, particle sizes and space design. Complete modeling of the melting process, including heat transfer, mass transfer, convection and tracing of bubbles and particles (reference), using results of previous parameter studies and simulating the real glass melting furnace operation, is the last step to find the final design and process set up. The results of these approaches may lead to new melter designs for commodity glass as well as special glass production.

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