INDUSTRIAL OPPORTUNITIES OF CONTROLLED MELT FLOW DURING GLASS MELTING, PART 1: MELT FLOW EVALUATION

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Glass melting is still highly-energy consuming which bothers many technologists dealing with the issue of how to compete with other materials. Glass melting is a complex process consisting of several sub-processes which are ordered in a series or in parallel with their kinetics and ordering determine the effectiveness of the entire melting process. The most important sub-processes during production are sand dissolving and bubble removing (fining), both being performed mostly successively in a commercial melting space and consuming a lot of energy. In the continuous melting process, the route of the melt flow through the melting space is another factor determining the melting efficiency. The new quantity, utilization of the melting space has been introduced recently which quantitatively evaluates the character of the melt flow with respect to both sub-processes. Using space utilization, a simple rectangular melting space with a controlled melt flow was examined which performs both homogenization processes in parallel, substantially increasing the melting performance and reducing the energy consumption. As a theoretical tool, the commercial mathematical model has been applied (Glass Model) which calculates using the experimental data of both processes. The derivation of utilization and some summarizing results are presented in this article. The further current aim resulting from the results in this part will be to deliver an overview of the melting techniques and subsequently discuss possibilities for both implementing the module in real technology and improving the melt flow in the contemporary commercial melting furnace.

INTRODUCTION

Glass melting processes have received attention primarily because of the need to reduce their production costs, which are very high chiefly for large melting facilities and high energy consumption resulting from melting temperatures higher than 1400°C. The contemporary arrangement of melting processes makes it necessary to create extended devices so that the required production capacity could be achieved. These arrangements oppose any reduction of the production cost. Although there are many different melting methods such as Chemical Vapor Deposition (CVD) or sol-gel, these methods are even more expensive when being implemented on an industrial scale. For that reason, attention is now focused on modernizing the melting process. Many glass melting devices have been developed and published or patented.

The glass melting process can be considered basically as a chemical production and melting facilities as chemical reactors. Recently, glass research has been considerably concentrated on reducing the energy costs of the process such as the application of electric melting and boosting, improved furnace insulation, modified combustion spaces, using new types of burners and mainly using oxygen as an oxidizing agent. All of these have resulted in an obvious decrease in energy costs. New methods have been implemented in the process to utilize waste heat for preheating fuel (air, oxygen) and even the glass batch. Combustion and earth gas can be used for a chemical reforming process to provide additional energy in the form of heat [1]. The approach to modify the glass batch from its chemical and granulometric composition is again currently being developed but the effects of these interventions are already based on the physical-chemical processes of glass melting.

By focusing attention on phenomena inside of glass melt, some chances for improvement can be seen. The most important sub-process which occurs during melting is homogenization of the melt. The homogenization consists of two processes: bubble removal (refining) and sand dissolving. Both processes consume a lot of energy during productions. Usually, in technology these processes are carried out separately in two areas or spaces, each of which focusing on only one of the processes. This procedure further increases the price of glass production.

We have simulated a new glass module with a controlled melt flow that can perform both homogenization processes in parallel. The appropriate melt flow is set by transverse and longitudinal temperature gradients in the module, thereby: (i) reducing the total energy consumption needed for the melting process, (ii) increasing the melting performance of the module. Our current aim is to find an appropriate possibility for implementing the module in real technology.

The opportunities for glass melting intensification

The homogenization processes of glass melting lead primarily to the conversion of inorganic and crystalline compounds into a homogeneous melt and, subsequently, to the removal of gas and dissolution of solid and liquid inhomogeneities. Also other processes that occur during the glass melting are either ambivalent for homogenization (bubble nucleation, melt foaming) or just negative (refractory and electrode corrosion). We want to focus primarily on the key homogenization processes: sand dissolving and bubble removal.

The important aspects of the mentioned processes are both their rate and their ordering (serial, parallel). The aim of this study is to accelerate the homogenization or change its order. Figure 1 shows the schema of the principal homogenization processes that occur during glass melting.

Chemical and phase transformations of the raw materials run in the batch blanket flowing on the melt level (I) to form an inhomogeneous melt. Consequently, the batch blanket is the main area for the chemical processes and has a significant effect on the subsequent homogenization processes in the melt. In typical glass furnaces, batch conversion into melt (I) runs almost in series with other processes in the melt (sand dissolving, bubble removal) (II). The conversion process in the batch can be fast if it is bonded with a sufficient energy supply for both batch reactions and heating. This condition often leads to a capacity limitation of the entire melting process.

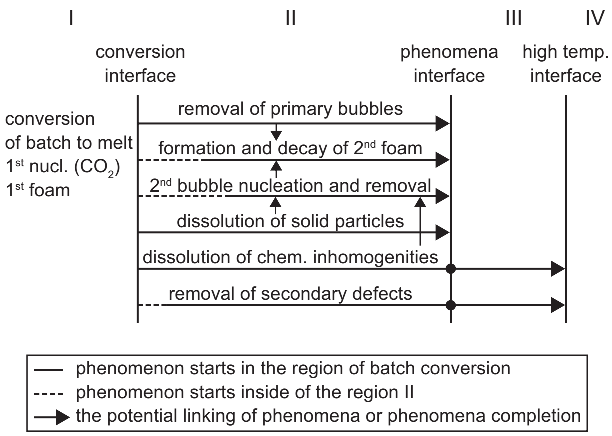


Figure 1. The schema of the principal homogenization processes occurring during glass melting (I - region of batch conversion, II - region of principal melting phenomena, III - region of temperature and chemical stabilization, IV - region of melt processing).

Significant steps making the whole process more effective are batch preheating, improving its thermal properties and enhancement of the batch-conversion kinetics. However, processes such as inhomogeneity dissolution and bubble removal require the majority of time needed for the melting process, as well as very high temperatures. Thus, they also participate in the energy costs and influence the melting capacity. Hence, while modernizing the glass melting process, a lot of attention should be paid to making the batch conversion effective, accelerating the kinetics of inhomogeneity dissolution and supporting bubble removal.

The homogenization processes in the melt are pursued inside of a space across which the viscous melt flows. The complex character of the flow has a great impact on the melting capacity of the furnace and influences the specific energy consumption of the melting. Obviously the heat consumption decreases as the melting capacity increases. We propose the possibility to set up a controlled melt flow in a furnace to reduce the negative effects of the complex melt flow. Figure 2 schematically shows the functional regions in a classical furnace heated by burners and electrodes.

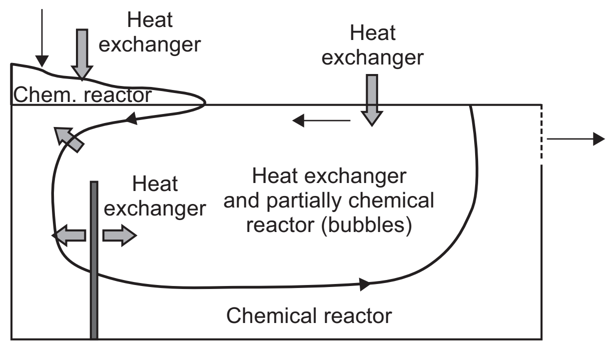


Figure 2. The scheme functions of a classical melting furnace.

According to Figure 2, a glass furnace works simultaneously as a heat exchanger (or heat pump) and a chemical reactor. The required function of the furnace is a chemical reactor. The layer of the batch blanket is the main area for chemical reactions but its interfaces work also as a part of a huge heat exchanger with relatively low efficiency. Further heat exchanging regions are between the combustion area and the melt level, as well as in areas of electrodes anywhere in the melt. Below the batch blanket, the arisen cold and heavier melt flows down along the front part of the device until reaches the bottom. This part of the melt serves as a chemical reactor but works at the lowest temperatures of the entire device. The melt heating across the free level in the region of glass bath then completes the strong and huge natural circulation region along the furnace. The homogenization processes are not terminated until the cold melt is lifted to the free level and heated in the hot spot region before output. Then the backward flow of the hot melt serves only as a heat pump drawing heat under the batch blanket.

Basically this area cannot function as a chemical reactor, except the locality around the temperature maximum. An important function of the circulation is heat transfer under the batch but the massive backward melt stream does not function more for melting. Moreover the large interior part of circulation body does not fulfill any function. Cooper [2] used a simple mathematical model to appreciate the role of natural circulations in the glass melting space and concluded that the transversal circulations prolong and the longitudinal ones shorten the residence time of glass in the melting space. In other words, the classical horizontal furnaces with prevailing longitudinal circulations have low utilization of their space for homogenization. The utilization is low because homogenization phenomena occur in the relatively small volume of the space working as a chemical reactor (see Figure 2). In addition, the processes take part at relatively low temperatures near the space's bottom. The low utilization indicates so-called dead areas (melt with closed circulation) and a very flat character of the residence distribution function of the melt in the space. Consequently, the low melting capacity of the furnace is a result of the low utilization of the otherwise huge furnace melting space. There a question arises of whether is it possible to remove the heat pump function completely or just partially and to utilize the melting space for homogeneous processes as much as possible. And another question is which type of melt flow would be suitable to set up.

When solving the first question, two tasks arise. The first one is to deliver a sufficient amount of energy (at least equal to the theoretical heat consumption) to the batch blanket without mentioning the heat pump. This needs most probably changes of the heating technique and energy distribution over the melting space. The second task is sufficiently fast conversion of the batch into a mixture of melt and inhomogeneities at the same time. Beside the classical conversion of the batch blanket on the melt level, literature and patents describe several procedures of batch conversion into melt by an alternative way. Some of them will be discussed later in connection with controlled melt flow. The interesting thing is especially the separation of the batch conversion space itself as it partially disturbs or abolishes the longitudinal melt circulations.

As regards the second question of beneficial melt flow, firstly, some type of melt flow must be chosen and subsequently evaluated inside the flowing melt. In a viscous melt we consider piston flow to be a very beneficial type of flow because there are no unutilized areas [3]. In addition, the behavior of sand particles and small bubbles is very similar in this type of flow over the most of particle life. Under real conditions, the uniform flow of the melt in a continual space is relevant [3]. However, there exist further types of flow which could increase the furnace performance owing to the homogenization processes. Hence, the potentially beneficial types of flowing can be divided into three categories:

1) Uniform flow of real fluid in an area (without any circulations).
2) Fluid flow with transverse circulations leading to helical flow (with transversal circulations). The precursor of helical flow is the quasi-piston flow which however needs a special type of ideal mixing [4].
3) Fluid flowing over independently mixed cells which are serially linked leading to a vertically circulating and moving flow on the whole.

For a better understanding and description of the flowing, it is essential to determine the ways to evaluate the flowing because of the homogenization processes (sand particle dissolution, bubble removal). Němec et al. [4-15] introduced a new quantity for the quantitative evaluation of the melt flow character owing to the main homogenization phenomena.

Melt flow evaluation by the quantity space utilization

The utilizations of the continual space for particle (sand) dissolution or bubble removal (fining), u_D and u_F, express the relations between the reference sand dissolution or fining time τ_{Dref}, τ_{Fref} and the theoretical mean residence time in the critical case, $\tau_G = V/\dot{V}$, where V is the volume of the space [m^3] and $\dot{V}$ is the volume flow rate (melting performance or pull rate) [m^3/s]. Both quantities, τ_{Dref} and τ_{Fref}, can be obtained by measuring a laboratory melt and calculated as a fining time in a quiescent glass melt. The space utilization is a complex quantity. It involves the dead space m_G and the space of the overprocessing m_D for the sand dissolution phenomenon and the virtual dead space m_{virt}, as well as the virtual height h_{virt}, for bubble removal. The values of dead spaces and virtual height relate to the character of the melt flow. The higher the value they have, the lower the resulting value of the space utilization [7-12].

The critical case is used for the calculation of the space utilization. It describes the situation when the sand particle of the maximal size is dissolved or the bubble of the initially minimal radius attains the melt level just at the output from the space:

$$u_D = \frac{\bar{\tau}_D}{\tau_G};\ u_F = \frac{\tau_{Fref}}{\tau_G};\ u \in \langle 0;\, 1\rangle \qquad (1)$$

where for the plug flow [3], $\overline{\tau_D} = \tau_{Fref} = \tau_G$ and $u_D = u_F = 1$.

The energy consumption decreases and the performance of the glass melting process increases with space utilization:

$$H_M^0 = H_M^T + \frac{\dot{H}^L \tau_G}{\rho V}\frac{1}{u_D} \qquad (2)$$

and:

$$\dot{V} = \frac{V}{\tau_G} = \frac{V_u}{\tau_H} \qquad (3)$$

where H_M^0 is the specific energy consumption [J/kg], H_M^T is the theoretical specific energy necessary for the chemical reactions, phase transitions and heating of both the batch and melt to the melt temperature at the exit [J/kg], $\dot{H}^L$ is the total heat flux across the space boundary [J/s] and ρ is the glass density [kg/m^3]. Equation (2) is valid for an internal source of energy; the electrically heated space for example does not involve heat losses by flue gases in spaces heated by combustion. Both u_D and u_F involve the fraction of dead spaces, thus [7-12]:

$$u_D = (1 - m_G)(1 - m_D);\ u_F = (1 - m_{virt})\,(h_0/h_{virt})^{1/3} \qquad (4a,b)$$

where h_{virt} is the height the critical bubble should rise owing to the buoyancy force to the level and with respect to the flowing melt and h_0 is the height of the glass layer.

Three basic and potentially beneficial melt flows can be then evaluated as follows from examples [9]. Figure 3-5 bring the results of mathematical modelling of the melt flow in an orthogonal horizontal channel (length 1 m, weight 0.5 m, the height of glass melt layer 0.5 m) with the input and output of the glass melt though the entire front walls. The space utilization in the critical state was calculated in all cases. Figure 3 presents the projections of the representative melt trajectories into the longitudinal vertical (axial) plane in the isothermal TV glass melt at 1450°C. The theoretical value of the space utilization for the controlling bubble removal amounts to 0.667 [3] and the relevant value for the case of sand dissolution as the controlling phenomenon is 0.445 [3]. Figure 4 shows the same trajectories in the mentioned space with a typical helical glass flow. The helical flow was set up by linear transversal temperature gradients put on the glass level. The value of the space utilization for bubble removal amounted to 0.705 and the relevant value of u_D was 0.654. The third example in Figure 5 represents the melt trajectories in the model space with two transversal heat barriers created by the relevant longitudinal temperature gradients put on the melt level. The required vertical flow loops are not set up over the entire space. The value of u_F amounted to 0.465 whereas the value of u_D was 0.462. Note that values of space utilization for both phenomena obtained by the simulation of industrial melting spaces were mostly less than 0.1 [14].

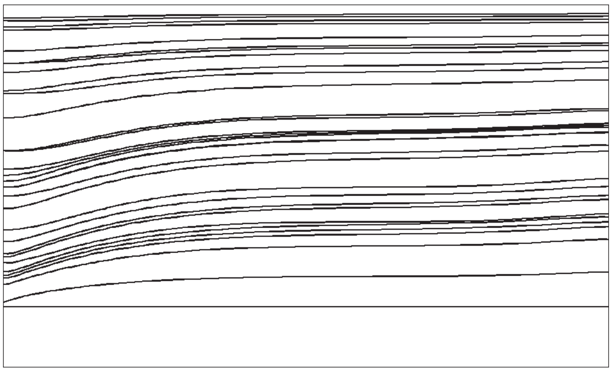


Figure 3. The projections of the representative 25 melt trajectories into the longitudinal vertical (axial) plane in the TV glass melt at a constant temperature of 1450°C, $u_D = 0.445$, $u_F = 0.667$.

Figure 4. The projections of the representative 25 melt trajectories into the longitudinal vertical (axial) plane in the TV glass melt with the helical melt flow. The average temperature was kept at a temperature of 1450°C, the value of the transversal temperature and gradient was 25°C/m and the ratio of the transversal to the positive longitudinal temperature gradient was 5 ($u_D = 0.654$, $u_F = 0.705$).

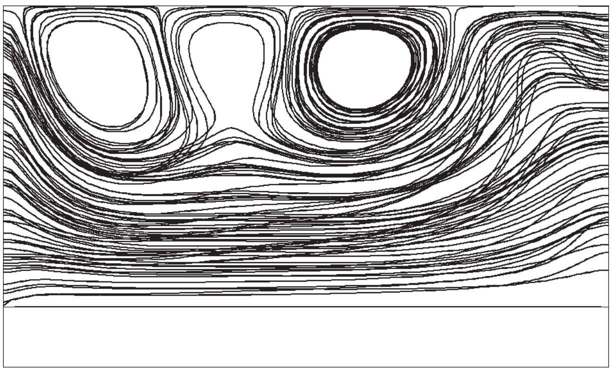


Figure 5. The projections of the representative 25 melt trajectories into the longitudinal vertical (axial) plane in the TV glass melt with two transversal heat barriers created by longitudinal temperature gradients ± 50°C/m. The average temperature was kept at a temperature of 1450°C ($u_D = 0.465$, $u_F = 0.462$).

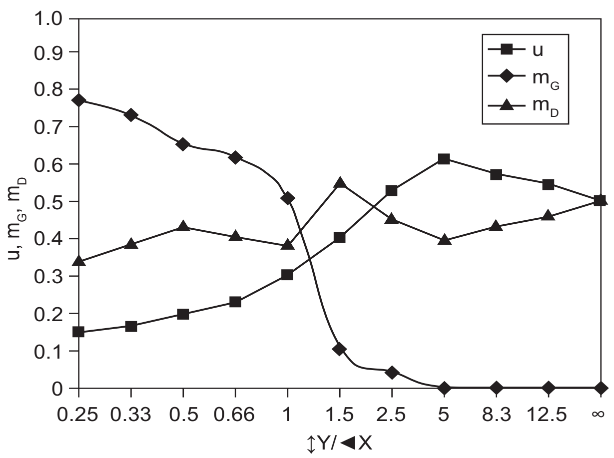
It is obvious from the values of the space utilization that the helical flow generally provides the highest values of space utilization as was also proven by a number of previous modelling experiments [6-15]. The all-around vertical melt flows in the case of transversal heating barriers are hardly attainable. When comparing the helical and uniform melt flow, the helical flow appears generally less sensitive to the existence of small longitudinal gradients which produce dead spaces [9].

The up-to-date practical applications of the controlled melt flow and overall results of modelling

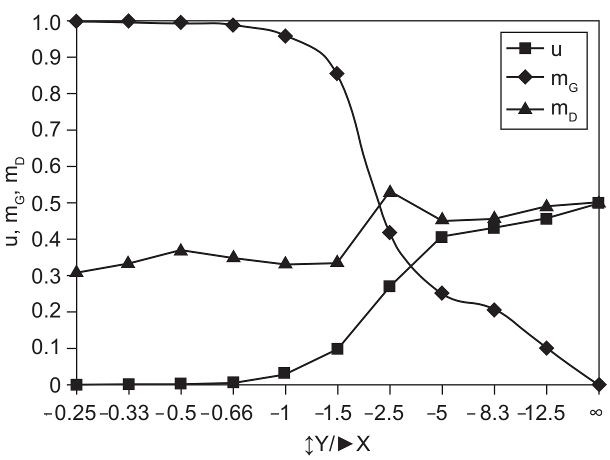
The problem of a natural melt flow and its consequences has been known to glass technologists and attempts have been undertaken to affect the relevant melt flow technology. The support of transversal melt circulations appeared especially hopeful [2]. The transversal circulations assembled with the through-flowing main stream of glass promise formation of helical melt trajectories inside the melting space. As already referred to, the dead spaces diminish and the histories of melt trajectories are equalized. Several patents resolve the matter. Mulholland's patent suggests to separate the batch conversion space from the melting (fining) space by a refractory barrier and to heat the glass in the fining space by burners oriented to the central longitudinal band along the axis of glass level [16]. The expected helical character of melt flow is supported by cooling the side walls. Penberthy applies particularly heating electrodes as localized energy sources which are able to affect the character of the melt flow more specifically [17]. The longitudinal rows of electrodes were applied in the melt bath to stimulate the flow and if need be the transversal row of electrodes was used to heat the melt. Atkeson's patent uses two longitudinal rows of heating electrodes in the vicinity of the furnace side walls which through its special construction makes it possible to bubble gas into the melt [18]. The aim of the construction was to homogenize preferentially the glass melt with corrosion products near the side walls by melt lifting and bringing in spiral mixing. The generation of spiral melt mixing only in the region of the hot spot is proposed in the patent of Takahashi [19]. The company Stein Heurtey presents in its patent [20] a range of means generating transversal circulations, besides the energy sources also different means of mechanical forces (stirrers, bubblers). The expected effects of the flow control were not nevertheless indicated or published. The existence of the helical flow was not possible to prove under conditions of industrial operation and in some cases (existence of batch layer in the melting space) could not be attained without special steps.

The intensity of the transversal circulations plays a very important role here. Since the helical flow velocity involves both transversal and longitudinal components, the ratio between them turned out to be crucial for setting up a helical flow in the continuous melting space. The mathematical modelling of many melting cases has shown that the helical flow in the model space was developed when the ratio between longitudinal and transversal melt velocity component was at least 1 but the optimal results were generally obtained at ratio between 5 and 10 or even more [10, 12-13, 15]. This fact is clearly demonstrated by Figure 6a, where the space utilization u_D and the relevant values m_G and m_D are plotted against the ratio between the transversal and longitudinal temperature gradients [10].

Similar dependences were obtained for the bubble removal phenomenon in Figure 6b but the favorable values of the gradient ratio started at somewhat higher values than 1 [12]. Generally, the maximal values of space utilization are a function of four variables: The ratio between the transversal and longitudinal temperature gradient determining the optimal character of spirals, the



a)



b)

Figure 6. The dependence of the space utilization and the fractions of the dead spaces for sand dissolution on the a) ↕Y/◄X and b) ↕Y/►X ratio (the transversal to the a) positive and b) negative longitudinal temperature gradient).

value of the transversal temperature gradient determining the optimal intensity of the transversal circulations, the kinetics of the relevant process (described by the sand dissolution time and by the average bubble growth rate) and the length of the channel [13]. The absolutely optimal temperature conditions providing the absolutely maximal values of the space utilization for the given process may then be acquired for given process kinetics and space length by mathematical modelling. Figure 7 provides the absolutely maximal values of the space utilization for both processes in a broad interval of sand dissolution times, bubble growth rates and for the length of the model channel 1 m [15].

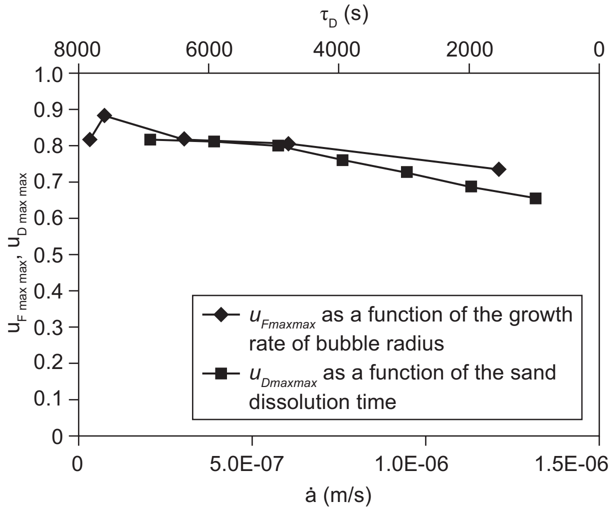


Figure 7. The dependence of the absolutely maximal values of the space utilisation, $u_{Fmaxmax}$ and $u_{Dmaxmax}$, on the relevant growth rates of bubble radius and sand dissolution times, respectively (the length of the channel is 1 m; the lines are merely guides for the eyes but indicate the expected behaviour of the dependences).

The values of the temperature gradients describing the maximal space utilisation in Figure 7 appear realizable with the conventional energy sources used in glass technology. However, another crucial question is whether both important melting phenomena may be realized in a common space at mutually beneficial melt flow conditions. Theoretically, any combination of considered bubble growth rates and sand dissolution times may occur, dependent on the fining agent efficiency and sand particle granulometry at a given temperature and in a given glass. The results of recent works [3, 10, 12-13] have shown that the optimal flow conditions for the sand dissolution process are very similar to these obtained for bubble removal, however, the needed values of the optimal temperature gradients appear to be different. The absolutely optimal values characterizing the sand dissolution process were therefore plotted along with the values characterizing the bubble removal [15]. Generally, the values of $(\updownarrow Y/\blacktriangleleft X)_{optopt}$ and $\updownarrow Y_{optopt}$ for the sand dissolution process were higher than the values valid for the bubble removal, there were nevertheless regions of values that were comparable for both processes. In fact, the absolutely optimal ratio of temperature gradients was almost constant as a function of the bubble growth rates (the bubble removal process) and grew with increasing sand dissolution time (the sand dissolution process). The values for both processes grew with the increasing length of the channel. The relevant optimal values of the transversal temperature gradient, $\updownarrow Y_{optopt,}$ grew with increasing bubble growth rate and decreasing sand dissolution time but the values for the sand dissolution were distinctly higher. The values of $\updownarrow Y_{optopt}$ increased then for both processes considerably with the increasing length of the channel. However, the $\updownarrow Y/\blacktriangleleft X$ ratio is generally the key value when aiming at high utilisation values. If the value of $\updownarrow Y/\blacktriangleleft X$ is greater than about 4, the values of the space utilisation are at least 0.5 for both processes.

When considering an accomplishment of both parallel processes in a common space, the more effective process should be adjusted to the less effective. The flow conditions of the more effective process should be therefore predicted under conditions which are not optimal and the knowledge of tendencies between the space utilisation and the values of the temperature gradients should be known in a broad interval of temperature gradients. In the real case, a couple of the bubble growth rate and sand dissolution time, relevant to the identical average temperature, should be used to model the absolutely optimal cases for both processes. Subsequently, respecting for example the controlling function of the bubble removal process, the more efficient process of sand dissolution should be adjusted to the less efficient process of bubble removal. Should the absolutely maximal values of the dissolution and fining performances differ substantially under the given conditions, the relevant changes of the process kinetics (a change of temperature, the fining agent or its concentration or a change of the sand particle granulometry or even the channel size) are potential ways to adjust the processes to one another. The following example justifies the assumption that the high values of the space utilisation for both processes are attainable in an extended interval of independent variables. The reference case modelled in [13, 15] characterized by the channel length of 1 m, the sand dissolution time of 1970 s and the growth rate of the bubble radius of 3.02×10^{-7} m^3/s, provided the values of $u_{Dmaxmax} = 0.687$, $u_{Fmaxmax} = 0.820$, $\dot{V}_{Dmaxmax} = 8.70\times10^{-5}$ m^3/s, $\dot{V}_{Fmaxmax} = 6.47\times10^{-5}$ m^3/s under temperature gradient conditions of $(\updownarrow Y/\blacktriangleleft X)_{Doptopt} = 6.0$, $(\updownarrow Y/\blacktriangleleft X)_{Foptopt} = 5.45$, $\updownarrow Y_{Doptopt} = 80$ K/m and $\updownarrow Y_{Foptopt} =$ $= 30$ K/m. In order to operate both processes in a common space, the more efficient sand dissolution process should be adjusted to the controlling bubble removal process, characterized by the lower value of the process performance, i.e. the sand dissolution process has to be operated under the temperature conditions of the bubble removal process, (↕Y/◄X)$_{Foptopt}$ = 5.45 and ↕Y$_{Doptopt}$ = = 30 K/m. The modelling case closest to that presented in the previous sentence may be found in Table 1 of the reference [10]: If ↕Y/◄X = 5.5 and ↕Y = 25 K/m, the value of u_D = 0.607 and the value of $\dot{V} = 7.70\times10^{-5}$ m^3/s. Consequently, both processes may be simultaneously operated in a common space under high space utilisation and process performance. The requirement of process adjustment will be confirmed by modelling the melting channel without the batch layer and with real sources of energy – electrodes in the second part of this work.

CONCLUSION

The intensification involves the substantial increase of the specific melting performance and results in a decrease of the structural heat losses. We can evaluate the efficiency of the melt flow character quantitatively using a new quantity: space utilization. The space utilization characterizes the value of the melt flow with respect to either sand dissolution or bubble removal, both being parallel processes. The optimum values of the space utilization at the given space length and process kinetics are realized by the proper distribution of melting energy in the space, reflected by the relevant values of average longitudinal and transversal temperature gradients in the space. Our future work is already focused on analyzing the specific possibilities for application in real melting equipment, and condition adjustment for both examined processes.

Acknowledgement

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