INDUSTRIAL OPPORTUNITIES OF CONTROLLED MELT FLOW DURING GLASS MELTING PART 2: POTENTIAL APPLICATIONS

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A review of the recent results and applications of controlled melt flow in the glass melting spaces [1] leads to the idea of helical flow as the most efficient way of melt flow through the continuous glass melting space. The results of mathematical modelling provide conditions under which the character of the melt flow can be set up and quantity space utilization is used for the quantitative evaluation. We designed a melting device (module) without a batch blanket and with a controlled melt flow that performs both homogenization processes in parallel, substantially increases the melting performance and reduces the total energy consumption. We also delivered an overview of non-traditional melting techniques and discussed possibilities for implementing the module in real technology. The concept of the implementation of the controlled melt flow into spaces with a batch blanket and the preliminary results of the mathematical modelling are presented as well.

INTRODUCTION

The first part of this work [1] provided the definition of the quantity space utilization which can be applied to an evaluation of the melt flow character in the continuous glass melting space.

The principal results of the mathematical modelling in the simple rectangular melting space showed that the optimum flow conditions approximately corresponded to the helical character of the melt flow [2-7] as had also been referred to in the patent literature [8-12]. Nevertheless, the helical-like character of the melt flow may be attained only for the specific energy distribution in the melting space, i.e. at a precisely defined ratio between the average transversal and longitudinal temperature gradients in the space. The optimal values of the gradients can be determined by the mathematical modelling of the processes of sand dissolution and bubble removal in the melt which flows through the given horizontal space [3-5]. High values of the space utilization between 0.6-0.8 were obtained for both processes. When considering sand dissolution and bubble removal as parallel processes in a common space, both processes should run at equivalent conditions, i.e. the more effective process should be adjusted to the less effective [7]. Consequently, knowledge of the tendencies between the space utilisation and the values of the temperature gradients should be known in a broad interval of temperature gradients.

The opportunities of application of the melt flow control in glass melting spaces

The opportunities of the application of the controlled flow may be classified into the categories of melting spaces without and with a batch blanket.

The opportunities in melting spaces without a batch blanket

The results of mathematical modelling show that a helical flow can be relatively easily set up under conditions that the above-mentioned ratio between the gradients is at least equivalent but rather greater than 1 but better results are acquired at higher ratios. The horizontal distribution of temperatures can be easily set up without a longitudinal temperature gradient or with a small positive longitudinal temperature gradient which hinders the forward velocity component at and near the glass level. The sufficiently high value of the ratio between the transversal and longitudinal temperature gradients can be particularly attained by the longitudinal thermal barrier created by a central row of electrodes and by natural heat losses through the side walls. Figure 1 shows the critical trajectories of the dissolving sand particles in the float type of glass at an average temperature of 1400°C in a melting channel 2 m long, 1 m wide and with the layer of glass 0.5 m thick. The melting space is provided by the central longitudinal row of six electrodes [13]. The temperature of the glass being inputted was equivalent to the average temperature in the space. The shape of the trajectories proved that the helical flow was set up in the entire melting space.

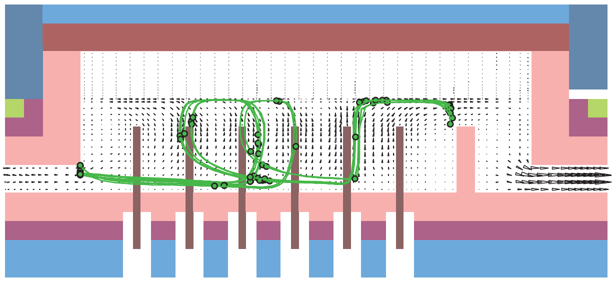

Figure 1. The projection of the critical sand particle trajectory into the central vertical longitudinal plane of the melting space.

The average ratio between the transversal to longitudinal temperature gradient amounted to 5.6, the space utilization was 0.656, and the critical specific performance for sand dissolution as a controlling process was 52.6 t/(m^3day). The dissolution performance increased and the structural heat losses decreased several times regarding the space with the longitudinal circulations simulating the melt flow in a classical melting space [13]. Similar results were obtained for the removal of bubbles as a controlling process in a larger melting space that was 6.74 m long, 2 m wide and with the layer of glass 1 m thick, where the space utilization also exceeded 0.6 [13]. What is important is the already mentioned and generally found similarity of the optimum conditions for both melting phenomena. This fact offers a chance to operate dissolution with bubble removal in a common melting space and under mutually beneficial melt flow conditions [6]. Nevertheless, some work still has to be performed involving the study of the effects of the relevant parameters: the average temperature of the melt in the space and its difference from the melt input temperature, the optimal distribution energy in the space and the way of melt input into the space (input by the bridge-wall or across the level).

The very promising results should, however, be confronted with the fact that the high specific melting performances in the melt should be accompanied by a high batch conversion capacity, being serially preordered to the homogenization processes in the melt. The batch conversion should be either substantially enhanced or the batch area enlarged. An interesting alternative is represented by different non-traditional ways of glass melting, working mostly with the separated batch conversion space and indicating a very high rate of batch conversion to glass. Some of them will be mentioned now with respect to the application of the successive melt flow control in a second space.

Three aspects should be taken into account when assessing the application of the given melting method for synthesis with a controlled melt flow:

1. The way the melt from the batch conversion space enters the space with a controlled flow (inlet by a bridge wall below the melt level, inlet across the level).
2. The temperature of melt entering the space with a controlled flow.
3. The character of the entering melt (glass with bubbles and sand, foam with a non-reacted batch).

The relevant ways of glass melting will be now classified according to point 1 and with respect to points 2 and 3.

The inlet to the space with a controlled melt flow is accomplished through an input below the melt level

The Submerged combustion [14]

The typical equipment is presented in Figure 2. In this case, oxy-gas burners are placed on the bottom of a furnace. A feeder places the batch on the glass level. Flames from the submerged burners directly heat and mix the batch with the melt. The melted glass contains many sand seeds and bubbles after the melting process and is even foamy. The placement of the output near the bottom appears to be the most convenient due to the high content of gas phase in the glass [15]. The need of a high output temperature from the melting space is attainable due to effective heating by powerful burners. The equipment is suitable for the application of the controlled melt flow in the second space where sand dissolution and fining completing is completed.

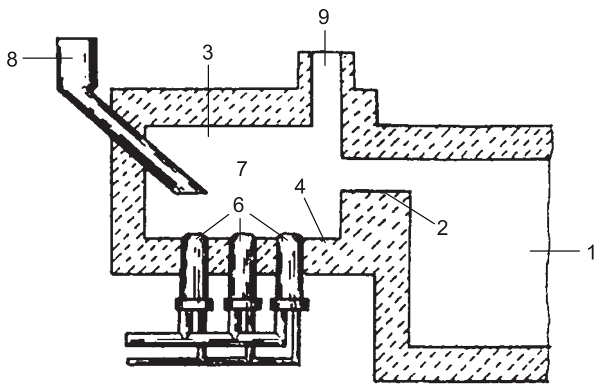

Figure 2. The furnace with submerged burners [22]; 1 - fining area, 2 – flow, 3 – melting area, 4 – bottom, 6 – burners, 7, 8 – batch input.

The Submerged batch charging [16]

The furnace can most probably work as a one- or two-space equipment. The batch charging occurs at a level below the surface of the molten glass. The batch is pushed into the molten glass by a screw charger mounted in the furnace wall. The batch reactions are fast due to the instant contact of the charged batch with molten glass but the glass can contain relicts of unreacted batch and foam on that level. The boosting of the melt in the charging region should be necessary in order to attain a fining temperature downstream of the process. If the batch conversion proceeds in a separate space, the outlet should be placed at the bottom of the furnace, because this type of melting produces glass with a very high amount of bubbles. The procedure of submerged batch charging is suitable for combination with the melt flow control downstream of the process. It is expected that boosting would provide a sufficiently high fining temperature of the arising melt.

The inlet to the space with a controlled melt flow is accomplished across the melt level

The FAR Melter

The Saint Gobain Glass Company suggested segmented melting [17, 18]. Figure 3 shows this technology. Firstly, a compacted batch is preheated by the furnace gases in a recuperator. The batch comes on the top of the melt surface in an inclined hearth where is then melted by gas-air burners. After the melting, the mixture flows into the next foaming section heated by electrodes and then is fined in the subsequent clearing zone. At the end, the melt flows out at the bottom of the melter. The preheater guarantees energy utilization from flue gases. The electric alternative of the FAR melter is the FARE melter [18]. In that case, the inclined hearth melter has been replaced by a horizontal stirred electric melter, followed by the clearing and stirred homogenizing zones. The melt flow controlled in both cases appears realizable when merging the foaming, clearing and homogenization zones into a common one. The high input temperature in the arisen space is attainable owing to intensive heating of the preceding primary melter or by heating at the beginning of the following common space with a controlled melt flow. However, the barrier from above should be positioned at the beginning of the merged space to avoid foam leaking.

The Mixmelter

This possibility is a part of RAMAR glass melting (Figure 4). Richards proposed the Mixmelter with its interior constructed from a refractory metal [18-20]. Inside the vessel, there is a very strong metallic impeller which serves along with the metallic walls of the melter as electrodes. The batch is charged from the top on the melt level. The combination of stirring and electrical heating causes the melt to have a temperature high enough for fining in the next step. The glass melt flows out through the bridge-wall of the melter and the melt flow control can be easily realized through the level input in the following space. A high temperature at the output from the Mixmelter can be expected.

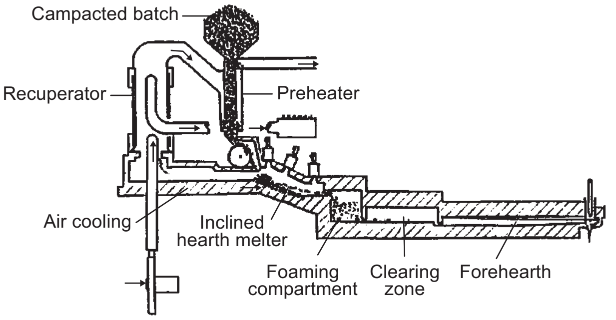

Figure 3. The FAR melter [19].

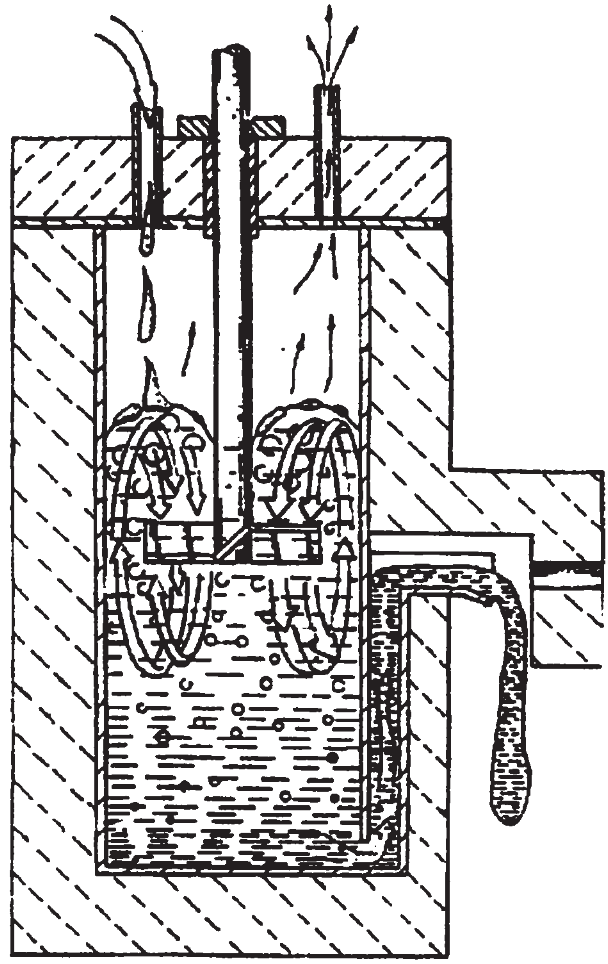

Figure 4. The scheme of the Mixmelter [19, 20].

The VORTEC melter

Raw materials are injected with fuel and air into a cyclone vortex melter. The first part of the cyclone is the preheater (top of the cyclone) and the second is the melter (lower part on the cyclone). The batch melts and flows down the cyclone along its walls [21]. At the bottom of the cyclone, there is a melt tank which collects the liquefied melt. The air is pre-heated in a recuperator. Most likely, no solid particles leave the cyclone and the melt flow control would involve only fining and chemical homogenization. The efficient application of the melt flow control is restricted to bubble removal.

The RAMAR glass melting [22]

A silo delivers the batch on the melt level in the first cell (Figure 5). The batch is heated electrically by the molybdenum electrodes and simultaneously stirred (200 rev/min), thus the melting process is fast. The working temperature is 1340ºC in this cell and the energy input is 350 kW. The cell can produce 12 t/day and the specific energy consumption is 2.5 GJ/t. Then, the melted batch flows into the next cell with stirring (a molybdenum cylinder with 40 rev/min) where the majority of the bubbles are removed without using any refining agents. The last cell called RAMAR has intensive stirring (1100 rev/min) and can produce 12-16 t/day with a working temperature of approximately 1325ºC [18, 19]. From the last RAMAR cell, the glass flows out at the bottom. The chance for setting up a controlled flow exists if three departments following the macro mix melter would be allied in one horizontal space with a controlled melt flow. A barrier against foam leaking at the space input and heating of the entering melt to fining temperature would probably be necessary.

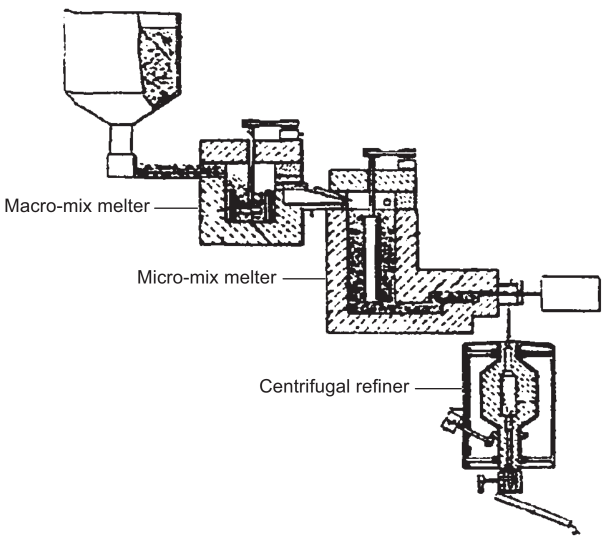

Figure 5. The RAMAR melting process [19].

The P10 Process

PPG Glass Company developed a process where the batch was pre-heated in two rotary kilns: soda ash and sand in the first one and the other raw materials and coal in the second one. Subsequently, the batch from both kilns is mixed and melted in the next conical furnace (Figure 6) and flows along the walls of the rotating furnace modulus. There is an eccentric burner which melts the rotating batch on the walls. A similar procedure with separate preheating and premelting raw materials was presented by Battele (Pyroflux [18, 26]). The melting modulus is followed by the sand dissolution and (sub atmospheric [23, 24]) fining modules. The initial melting modulus appears to be suitable as a melting system with a controlled melt flow. The melt from the melting modulus would therefore flow on the level of the modulus with the controlled melt flow. Because the temperature of the melt at the output of melting modulus is only about 1200-1320°C, an initial heating of the melt entering the second modulus would be necessary.

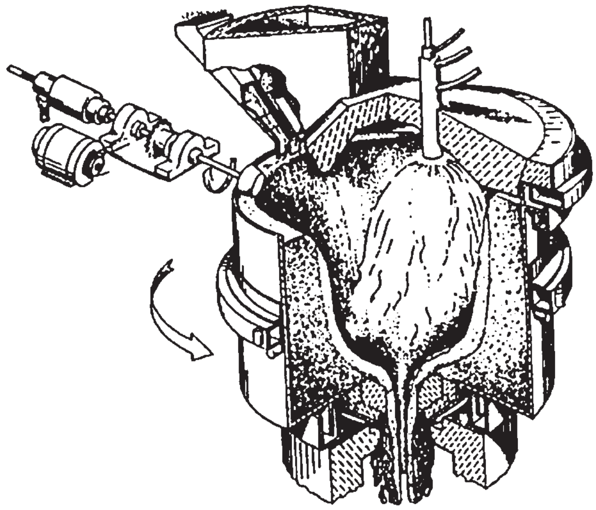

Figure 6. P10 melting module only [18]. The batch is loaded from the top into the rotating module. An eccentric burner melts the batch which flows down along the conical walls to the outlet.

The stair and talus furnaces

Typically, the batch is loaded into a furnace by several pushers which form the batch into a talus as is obvious from the example in Figure 7. The surface of the talus is continuously glazed by the flames and the arisen melt flows on the talus down to the melt level in the basin. It is an efficient type of melting because there is no back flow of the melted glass [18, 25]. Several types of melting facilities have been invented based on this principle. Pilkington proposed a pre-melter in a way that burners were placed on the top of the melter [27]. Gelnar presents another furnace type consisting of a staircase and electrically heated channel [28]. Since both undissolved particles and bubbles can be expected in the melt leaving the talus, the following basin is suitable for the application of the controlled melt flow. The initial heating of the melt in the second module to reach an acceptable fining temperature would probably be needed.

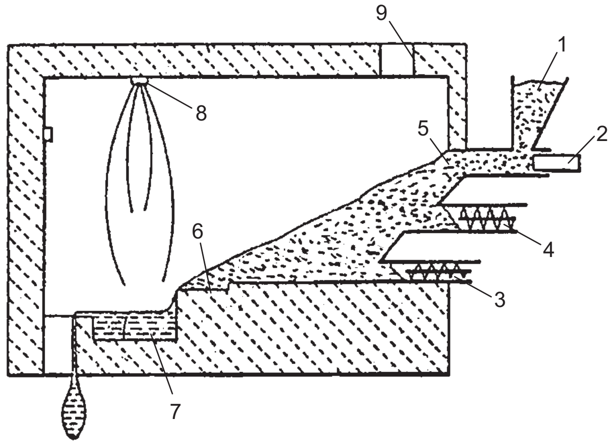

Figure 7. NIXON Melter proposed by Pilkington [27]; 1 – batch, 2, 3, 4 – hoppers and interpolators, 5 – melting batch, 6 – melted glass, 7 – fining area, 8 – burner, 9 – gas outlet.

area heated by electrodes or microwaves. Every module is linked to the next one so that no back flow could occur. According to Beerkens, the glass melt needs 6.25-7.25 h to flow through the whole arrangement. Theoretically, the space with a controlled melt flow accomplishing the simultaneous dissolution and bubble removal can be included behind the first melting modulus. However, the high melting temperature 1400-1450°C should be attained only in the initial part of the space with a controlled melt flow.

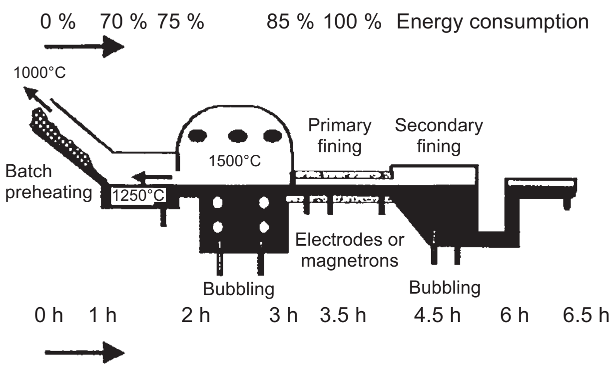

Figure 8. The application of Beerkens' sequenced melter [25, 30].

The application of rotating kiln furnaces [29]

Glass melting can be realized also in rotary kilns. The kilns have an almost horizontal axis and are rotating, so the glass batch is melted in a thin layer. The required amount of heat is delivered by oxygen-natural gas heaters. There is a temperature gradient inside the rotary kiln. At the beginning of the kiln, the batch is preheated by exhaust. As it proceeds through the kiln, the temperature of the batch rises. The energy consumption of the method is around 4.2 GJ/t [19]. The glass melt flows to the next area at the end of the kiln. The next area can be proposed as the module with a controlled melt flow. The output temperature of the melt is expected to be high owing to melting in a thin layer with good heat transfer.

The Modular melting

Figure 8 shows Beerkens' conception of glass melting [30]. There is a short mean residence time and relatively long minimal residence time in this type of furnace [22]. The batch is preheated by exhaust gases from the first module up to 1250°C. The next module heats the melt up to 1500°C mainly by electrodes. Primary fining then proceeds in a thin layer of the melt in the next

The In-flight melting

This very specific type of melting is based on the principle that the glass batch is injected together with fuel into a combustor. Melting occurs directly in the flames. The Gas Research Institute developed the advanced glass melter in Chicago [31]. There is a gas-air burner which forms little droplets of melt bunting to a cooled metal cone in the next area. The melt then flows over the cone into the basin and contains many seeds. Another in-flight method using plasma was proposed in Japan [32]. The batch needs to be ground very fine at first. Then the powder is pelletized (about 0.1 mm) and consequently charged into the flames. The energy consumption of oxygen-fired burners is 3.6-4 GJ/t [19]. The chance for the application of a controlled melt flow behind the in-flight melting is low because only bubbles should be removed from the melt.

SUMMARY

The majority of the patented and presented melting procedures separate the single melting stages in separate spaces and present relatively complicated melting equipment with the anticipated problems during implementation. The size and melting performance mostly do not meet the needs of large industrial production and low specific energy consumption is not guaranteed. Despite that, interesting ideas appear as preheating systems, intensive mixing and heating of the initial melt mixtures, melting in rotating kilns or in the talus and physical fining procedures. The main problem results from the fact that the single melting phenomena frequently need different melting conditions and different characters of the melt flow. When following the phenomena ordering presented in Figure 1 [1], the causes of the main problems of the non-traditional melting procedures arise. The batch conversion process is substantially in series with other homogenization phenomena, its capacity is mostly determined by the necessary huge heat supply in the batch and the melting performance of the entire melting process is thus limited. In the melt bath, the melting efficiency considerably depends on the character of the melt flow but the phenomena occurring along the melt trajectories (particle dissolution, chemical homo-genization) and across them (bubble removal) apparently need different flow conditions. A detailed study of melt flow with respect to melting phenomena showed [2-7] that the principal problem - common for all the melting phenomena - consists in the existence of longitudinal melt circulations with a huge back flow of the melt near the melt level. Consequently, its restriction or abolition helps any homogenization phenomenon. The separation of the entire melting process into two spaces then has its justification; the space for batch conversion and the space with controlled convection for dissolution (both particles and chemical inhomogeneities) and bubble removal. In light of this arrangement, particularly the procedures assuming the fast conversion of the batch into melt presented in this chapter become significant. The spaces with submerged batch charging [16] and submerged combustion [14-15], with intensive stirring [17-22, 26, 30], rotating kilns [29] and melting in talus [27-28] should be remembered. That is why a detailed modelling of the melting module with a controlled melt flow at the conditions of melt input through the bridge and on the glass level has to be realized.

The opportunities of the flow control in melting spaces with a batch blanket

The batch blanket covering the molten glass level in the charging part of the melting furnace significantly affects the melt flow. The simple sketch of situation is provided in Figure 9.

A distinct temperature difference arises between the hot spot temperature on the free level, T_{max}, and the relatively cold melt with temperature T_i at the interface between the glass and batch blanket. Consequently, a huge backward melt flow aimed from the hot spot at the batch blanket sets up owing to the temperature gradient, *grad* T_{horiz}, which brings a part of energy flux below the batch blanket but causes voluminous longitudinal circulation of the melt as well. It is probable the condition of a high ratio between the transversal and longitudinal temperature gradient could be generally realized to evoke a transversal movement of the melt in the space. Therefore, if the gradient ratio were low, dead rotation spaces could emerge in the space (see Figure 1), as well as long circulating trajectories, which would broaden the residence time distribution of the melt in the space. In addition, the cold forward (working) flow would move near the space bottom with a temperature not too far from the bottom temperature. The arising vertical temperature gradient *grad* T_{vert} would prevent the needed vertical mixing of the glass and maintain the slow speed of the homogenization reactions. Thus, two temperature gradients show obstacles of the controlled flow in spaces with the batch blanket, the horizontal temperature gradient between the hot spot and melt under the batch blanket, *grad* T_{horiz}, and the vertical temperature gradient between the free melt level and space bottom, *grad* T_{vert}.

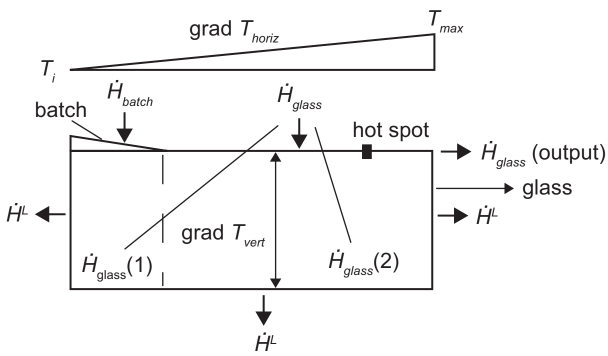

Figure 9. The schematic representation of the thermal situation in the glass melting furnace.

Future effort should be therefore focused on the overall energy distribution in the space. The decrease in heat flux reduces both *grad* T_{horiz} and *grad* T_{vert}, however, the subtracted part of should be returned to the batch blanket as see Figure 9. In this case, the application of Joulean heat in the region of the batch blanket seems to be a realizable procedure. It is expected that the mentioned energy transfer will decrease the intensity of the longitudinal circulations, i.e. reduce the dead spaces, and will facilitate the transversal circulations in the region below the free level. However, a lower level temperature will be the price for it. The targeted transfer of a part of as (see Figure 9) is an alternative to support the transversal circulations.

The location of the bridge-wall between the batch region and the region with the free melt level (see the dashed line in Figure 9) is already a part of the most conservative arrangement of the process presented in the previous chapter 2.1. A detailed modelling of the cases outlined by Figure 9 and by the previous text is therefore needed.

The following two examples indicate the effect of energy redistribution on the character of the melt flow and, consequently, on the value of the space utilization relevant to the controlling process. The same active melting space for the case with the controlled melt flow was chosen as in 2.1., being 6.74 m long, 2 m wide, with the layer of the melt as 1 m thick. The layer of the batch was simulated by the glass melt input through the melt level near the space front wall. The glass input temperature 950°C was chosen so that the energy supply into the batch was simulated. The heat supply into the melt was simulated by the direct heat development in the defined region of glass. The energy development was concentrated in the central vertical longitudinal layer of the melt having its base at the space bottom and being 0.6 m high and 0.05 m thick (simulating the effect of the central longitudinal row of electrodes). 50% of energy here was developed in the region below the melt input and 50% below the free level. The average temperature in the space was kept at 1420°C. Figure 10 shows the transversal section through the space in the half of the space length with the projections of the segments of the melt trajectories. It proves the existence of transversal circulations of the melt leading to a helical-like melt flow. However, it was not possible to model credibly the

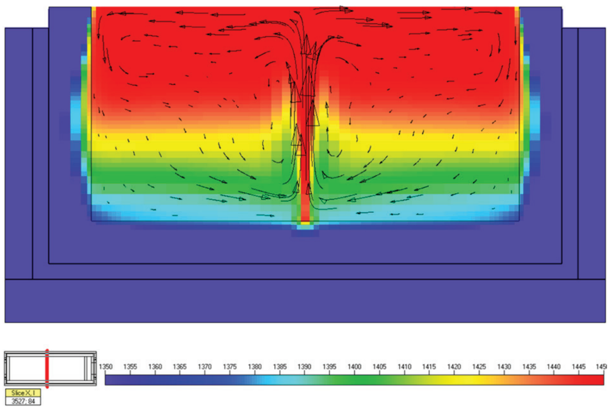

Figure 10. The transversal section through the melting space in the middle of the space length with the projections of the segments of the melt trajectories. The case with heat development in the central longitudinal layer below the melt level. 50 % of the energy is developed in the region below the glass melt input and 50 % below the free level. The average temperature is 1420°C, u_F = 0.180, and the specific melting performance is 13.8 t/(m^3 day).

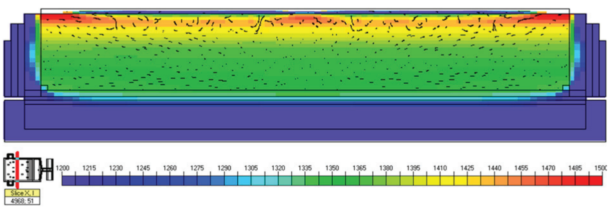

Figure 11. The transversal section through the melting space in the middle of the space length with the projections of the segments of the melt trajectories. The reference case with heat development near the melt level. The average temperature is 1387°C, u_D = 0.073 and the specific melting performance is 2.4 t/(m^3 day).

situation relevant to the classical heating of glass through the free level for the same melting space arrangement as in Figure 10. That is why the industrial container gas-fired furnace working at an average temperature of 1387°C was chosen as the representative reference space. The values of the space utilization reflecting the character of the melt flow are acceptably comparable for both cases. As is apparent from Figure 11, almost no transversal melt flow is apparent in the same transversal section as in Figure 10 where the longitudinal circulations dominate. Whereas the corresponding values for the case with a controlled melt flow (Figure 10) amounted to a utilization value of 0.180 for bubble removal as the controlling process and to the specific melting performance of 13.8 t/(m^{3}day), the space utilization in the reference case (Figure 11) simulating the classical type of the melt flow, i.e. without transversal circulations, was only 0.073 for the sand dissolution as the controlling process and the relevant specific melting performance amounted to 2.4 t/(m^{3}day), The energy redistribution below the level and near the glass input in Figure 10 led to an increase of the space utilization and substantial growth of the specific melting performance. A more detailed examination should continue in order to gain optimal results for practical applications.

CONCLUSION

The modelling of melting spaces with real heating means shows that there exists a real chance to control the melt flow and intensify thus the melting process in special spaces without the batch conversion to glass. However, the batch conversion should be then accomplished in a separate pre-set space. There are several non-traditional technologies of glass melting described in literature or patents and mentioned in this article which could be used for the batch conversion in the separate space. If some of them are applied, both homogenization phenomena occurring in the melt (bubbles removal, sand dissolution) can be simultaneously operated in the subsequent space with controlled melt flow. This two space technology is simpler than other modular glass technologies proposed in literature. Consequently, the detailed modelling of flow conditions and phenomena courses in modules with controlled melt flow will be in the center of our attention.

The spaces involving the batch conversion raise serious obstacles to the controlled melt flow owing to naturally arising large longitudinal and vertical temperature gradients and resulting longitudinal circulations of the melt. The presented examples of preliminary calculations show that the substantial redistribution of delivered energy in the melting space appears necessary which leads to conditions of the controlled melt flow, to higher space utilization and beneficial melting characteristics. The substantial part of modelling effort should be therefore devoted to this problem.

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