Journal of Non-Crystalline Solids 430 (2015) 52–63

Contents lists available at ScienceDirect

Journal of Non-Crystalline Solids

journal homepage: www.elsevier.com/locate/jnoncrysol

Modelling of the controlled melt flow in a glass melting space — Its melting performance and heat losses

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A R T I C L E I N F O

Article history:
Received 13 July 2015
Received in revised form 20 August 2015
Accepted 22 August 2015
Available online 5 October 2015

Keywords:
Glass melt flow;
Mathematical modelling;
Energy distribution;
Space utilization;
Melting performance

A B S T R A C T

The factors influencing the character of the melt flow were defined and examined in a model glass melting space. The batch blanket was simulated by an inflowing glass melt with sand particles and bubbles and the heating elements by the defined volumes of the melt where heat was evolved. The character of the melt flow was set up by a proper arrangement of the heating elements in the space. The sand dissolution and the bubble removal were modelled in the space; the space utilization, melting performance, and heat losses were calculated. The required character of the melt flow was brought about by the energy evolution in the region of the longitudinal space axis and by the supply of a substantial part of energy to the region beneath the inflowing melt. The results of the modelling have confirmed that the suitable flow character in the space was a helical-like flow, which was attained by the combination of an almost uniform forward flow with imposed transversal melt circulations. High values of the space utilization, several times higher melting performance and proportionally lower specific heat losses were acquired when compared with the values attained under conditions simulating the melt flow in industrial melting furnaces.

1. Introduction

The industrial glass melting space represents a continual reactor in which the homogenization phenomena, namely the dissolution of both solid and liquid inhomogeneities and bubble removal, should be completely and economically accomplished. No wonder so much effort was devoted to the examination of melting kinetics [1–12]. Later, mathematical modelling was an excellent tool for phenomena investigation following also under the condition of the flowing melt [13–16]. Thus, the quality of the melt flow character with respect to the quality of the entire melting process could be assessed as well and the question of the optimal character of the melt flow in the glass melting space arose. Cooper [17] was one of the first who discussed the role of longitudinal and transversal melt circulations present in the horizontal melting space and referred to both positive and negative impacts of natural convection on the course of homogenization melting phenomena. However, the question of the optimal melt flow remained unresolved.

Theoretically, the optimal character of the melt flow may be estimated from the fundamental requirements of the melting process and from the properties of the standard types of liquid flow such as plug flow and ideal mixer. The requirement of homogenization phenomena on the flow character can be briefly summarized as follows: no regions of lazy or longitudinally circulating melt (dead spaces), no regions of overprocessing (regions where the homogenization is already accomplished), adequate time for the homogenization phenomena, and sufficient mixing ability to enhance dissolution phenomena. Both plug flow and mixer fulfil the requirement of zero dead spaces. No regions of overprocessing arise in the plug flow, but no mixing ability is available here. On the contrary, the ideal mixer provides the maximal mixing ability of the melt; nevertheless, its broad residence time distribution curve — starting at the zero residence time — excludes the mixer from the consideration. Regardless of the zero mixing ability, the plug flow is the primitive base for the optimal flow character; its realistic accomplishment is the uniform isothermal flow. When both the dissolution and the bubble removal have an adequate and predictable chance to be realized, no dead spaces exist. However, the practical realization of the flow should encounter problems in glass melting spaces with a slow working flow and heterogeneous temperature distribution. The horizontal temperature gradients as well as heating from the bottom can cause melt circulation and large temperature gradients with higher temperature near the level enlarge the quality differences between melt trajectories and, consequently, the space of overprocessing increases. In spite of that, uniform flow remains a chance for the melting process and should be tested. Another way of efficiently organizing the flow consists in the combination of a forward plug flow with the melt mixing perpendicularly to the main flow which represents a theoretical solution for melting phenomena (quasi-plug flow) [18], but practically does not solve bubble removal. The helical flow resulting from the superposition of slow transversal melt circulations to the uniform longitudinal

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http://dx.doi.org/10.1016/j.jnoncrysol.2015.08.039
0022-3093/

flow appears a realistic variant of the suitable flow character for both phenomena. The helical flow at least partially preserves a good homogenization effect and, in addition, it seems to fulfil also the requirements of efficient bubble removal. To set up the helical character of the melt flow has been the subject of several patents [19–23], but the existence of adequate transversal circulations, as well as the effect of the controlled melt flow on the course of homogenization phenomena, could not be proved under the conditions of industrial operation.

The problem that arose of the quantitative evaluation of the melt flow character was dealt with through the introduction of a new quantity called *utilization of the space* [24–28]. The utilization of the space represents the ratio between the time necessary to accomplish the given homogenization phenomenon under conditions of a quiescent melt and the time consumed in a continual space with a given character of the melt flow. Dead and overprocessing spaces are involved and may be obtained by the mathematical modelling of the relevant homogenization phenomena in the space. The values of the space utilization can be included in the relations for the melting performance and specific energy consumption of the process in the melting space. The values of the space utilization for both phenomena under conditions of the plug flow are 1, for the sand dissolution, they are 0.445, and for the removal of linearly growing bubbles, they are 0.666 in the orthogonal channel with the isothermal uniform flow [27]. The fact of the helical-like character of flow as the optimal variant of flow for both sand dissolution and bubble removal was then proved with the help of the space utilization quantity in the cited modelling studies. The optimal character of the melt flow was determined as a function of the ratio between the preset transversal and longitudinal temperature gradients in the melt; the maximal utilization values were mostly 0.6–0.8 at the gradient ratio between 5 and 10. The results have shown that the melting performance can increase (and the energetic losses decrease) even several times if the helical-like flow were set in the melting space. Now, more realistic conditions are demanded — particularly the sources of energy should be used instead of merely setting temperature gradients to show whether the optimal flow conditions will be realizable in practice. If energy sources are applied to simulate real melting, the resulting character of the melt flow should strongly depend on their local positions in the melting space. This work is focused on the definition of the fundamental factors affecting the establishment of the helical-like melt flow or potentially the uniform flow in a model melting space with a simulated batch blanket and with sources of energy. Further, the work deals with the spatial energy distribution as the main factor determining the character of the flow and, consequently, the utilization of the space, melting performance, and specific heat losses of the model melting space.

2. Theoretical part

The resulting character of the melt flow particularly depends on the horizontal distribution of the supplied energy in the space. Let us consider an orthogonal horizontal space for continual melting. The energy needed for the process primarily involves the theoretical specific heat H_M^T, i.e. the energy for batch reactions, phase and modification transitions and for heating of the contents to the space exit temperature. This part of the energy is dominant and should be delivered just in the batch blanket and its vicinity. The second part of the energy needed represents the heat losses through boundaries, the relevant heat flux $\dot{H}^L$. In a simple space with inner sources of energy, the total heat flux $\dot{H}^{tot}$ is given by:

$$\dot{H}^{tot} = H_M^T \dot{M} + \dot{H}^L \,(\mathrm{kJ/s = kW}), \tag{1}$$

where $\dot{M}$ is the mass melting performance (kg/s).

If the fraction of the space surface corresponding to the region with the batch blanket is ξ, Eq. (1) can be written as:

$$\dot{H}^{tot} = H_M^T \dot{M} + \xi \dot{H}^L + (1-\xi)\dot{H}^L. \tag{2}$$

Thus, the needed heat flux into the input part of the furnace amounts to $H_M^T \dot{M} + \xi \dot{H}^L$ and the heat flux to cover the heat losses in the following part of the space with the free level is $(1-\xi)\dot{H}^L$, If the energy distribution for Eq. (2) is valid, the space occurs in a balanced state from the point of view of energy delivery, no global temperature differences arise between both parts of the space and no natural longitudinal circulations would be expected. In the unbalanced state, however, longitudinal melt circulations develop according to the longitudinal temperature gradient that arises and the adjustment of another type of flow, such as the helical-like flow, would be much more difficult. The situation is schematically presented in Fig. 1.

If Eq. (2) is valid, the actual amount of heat delivered in the region of free level, $\dot{H}_{level}$, is equivalent to $(1-\xi)\dot{H}^L$ and the longitudinal component of the melt velocity will have a parabolic profile as curve 1 shows — a uniform flow will result. On the other hand, if an inequality will hold, longitudinal circulations will develop as curves 2 and 3 demonstrate. The current industrial case is noticeably unbalanced because the actual amount of energy delivered directly in the batch region is lower than the one needed (being currently around $0.5\dot{H}^{tot}$) and a strong longitudinal circulation develops with the backflow near the melt level (curve 2 in Fig. 1) as was observed in practice and proved by mathematical modelling. Consequently, it would be difficult to set up sufficiently intensive transversal circulations in the space leading to a helical-like flow. Particularly, when the amount of energy available for transversal circulations below the free level is low, only a part of heat losses is involved (Eq. (1), the third term). Therefore, it is necessary to examine if all the factors are able to increase the intensity of the transversal circulations merely to attain a helical-like character of flow, especially in spaces with unbalanced energy distribution as well as to modify the helical-like melt flow favourably. The potential factors affecting the process may be defined as follows:

1) The horizontal energy distribution.
2) The vertical energy distribution.
3) The space insulation.
4) The interruption of the symmetry of the imposed transversal circulations.
5) The mechanical support of transversal circulations.

This article deals with the effect of horizontal and vertical energy distributions in the model space on the established character of the melt flow. The values of the relevant quantities — the space utilization, mass melting performance, and specific heat losses — are used. A definition of the space utilization is needed.

The utilization of the continual space, u_H (index H designates the relevant homogenization process, sand dissolution or bubble removal) expresses the relation between the reference homogenization time in a quiescent melt, τ_{Href}, and the mean residence time of the melt in the space under critical conditions, τ_G [25–28]. Thus, τ_G is the time needed for the same process realized in the continuous space with flow patterns, being given by the ratio between the space volume and volume flow rate (see Eq. (3)). The critical state describes the situation when the first particle of the critical size, sand or bubble, coming from the set of the examined particles attains either space output (sand particle) or the melt level (bubble). The slower of the two parallel phenomena is the controlling one. The u_H value is defined as follows:

$$u_H = \frac{\tau_{Href}}{\tau_G}, \quad \tau_G = \frac{V}{\dot{V}}, \quad u \in \langle 0; 1 \rangle, \tag{3}$$