Journal of Non-Crystalline Solids 456 (2017) 101–113

Contents lists available at ScienceDirect

Journal of Non-Crystalline Solids

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

Bubble removal and sand dissolution in an electrically heated glass melting channel with defined melt flow examined by mathematical modelling

Lukáš Hrbek *, Petra Kocourková, Marcela Jebavá, Petra Cincibusova, Lubomír Němec

Laboratory of Inorganic Materials, Joint Workplace of the University of Chemistry and Technology Prague, Technická 5, 166 28 Prague 6, Czech Republic
The Institute of Rock Structure and Mechanics of the ASCR, v.v.i., V Holešovičkách 41, 182 09 Prague 8, Czech Republic

ARTICLE INFO

Article history:
Received 16 March 2016
Received in revised form 31 October 2016
Accepted 11 November 2016
Available online 16 November 2016

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

ABSTRACT

The electrically heated glass melting channel as a part of the segmented melting furnace was examined by mathematical modelling. Different melt flow characters were set up by proper configurations of the heating electrodes in the channel with either level or close-to-bottom melt input. The sand particle dissolution and bubble removal of defined sizes were followed up to the achievement of the critical state. This was characterized by the termination of the less effective melting phenomenon just before the output from the channel. The utilization of the melting space, the melting performance, and the specific heat losses in the critical state were evaluated. The effect of the melt input character and melt input temperature, electrode length, and energy distribution were investigated. The results have shown that the best results were attained when the energy distribution in the channel was balanced or when it was near the balanced state. Hence, no or only weak longitudinal circulations of the melt arose in the space and the helical-like melt flow could be set. This state was achieved when the melt input temperature was equivalent or not far from the average temperature of the melt in the space. Such as state can be set up by an energy shift to the regions with lower temperature and by enhancement of the transversal melt circulations.

1. Introduction

The melt flow character plays a significant role in the continual glass melting process owing to its considerable impact on the history of the homogenization phenomena accomplished in the melt – quartz dissolution, bubble removal, and chemical homogenization. In the industrial melting process, the batch conversion in the batch blanket and phenomena in the melt are practically serially ordered. Besides the batch conversion rate, the slow homogenization of the melt may also limit the melting performance of the entire melting process. The naturally set melt flow in the horizontal glass melting spaces is characterized by powerful longitudinal circulations which are indicated by the broad residence time distribution function of the melt, and consequently by the short critical trajectories along which the homogenization phenomena occur. Due to this effect, glass producers are forced to build large glass melting furnaces with low specific performance and with high specific heat losses. The way to ensure better cooperation of the melt flow with the melting process leads to either uniform melt flow or to efficient transversal melt circulations resulting in a helical-like flow, both characterized by lower dead spaces and a narrower residence time distribution function. The strengthening of the transversal circulation appears easier to implement under industrial melting conditions; several patents describe the use of different mechanical or heating means to fulfil the task to set the helical-like melt flow [1–5]. In fact, the superposition of the evoked transversal circulations on the already existing longitudinal ones leads to the desired helical-like flow only when the ratio between the transversal and longitudinal velocity component of the melt is sufficiently high. The character of the helical-like melt flow and its relation to the running homogenization phenomena was studied in [6–10]. The relative quantity called utilization of the space has been introduced. The quantity indicates which part of the melting space is used for either the dissolution of quartz relicts or bubble removal under a given character of the melt flow. Applying space utilization, the temperature conditions of efficient helical-like flow were determined in the model channel by mathematical modelling. The results have shown that melt flow structures were attained – advantageous simultaneously for both phenomena – at relatively high ratios between the transversal and longitudinal temperature gradients. The ratios of temperature gradients corresponding to highest utilization values of 0.6–0.8 move mostly between 5 and 10 [6,8–10]. However, it would be difficult to realize the corresponding melt velocity ratios in the classic

* Corresponding author.
E-mail address: Lukas.Hrbek@vscht.cz (L. Hrbek).

http://dx.doi.org/10.1016/j.jnoncrysol.2016.11.013
0022-3093/

melting space with the batch blanket owing to the existing strong longitudinal melt circulations; therefore, the published patented solutions appear less probable.

The results of mathematical modelling may nevertheless assist in the construction of special melting spaces without a batch blanket if the previous batch conversion to glass was ensured in a separated space or region. Several ways of rapid batch conversion have been published in the literature: the examples include submerged combustion [11–12], mechanical stirring of the converting batch [13–14], or in flight melting [15–16]. In the subsequent melting module, the desired helical flow may be set up relatively easily with the currently used heating elements such as the application of Joule heat and electrodes. Such a module manifests a very high homogenization ability up to 10 tons/(m^3 day) and correspondingly low heat losses [17]. However, the detailed conditions of the module application are not known yet whereas the following are: convenient average temperature in the module, the acceptable difference between the input and average temperature of the melt, and the efficient energy distribution inside the module. The detailed investigation of the mentioned factors in the glass melting module heated by electrodes is the subject of this work.

2. Theoretical

The quantity “utilization of the melting space u” has been used for the evaluation of the character of the melt flow with respect to sand dissolution and bubble removal [6–10]. The utilization of the continual space for bubble removal (fining) u_F expresses the relation between the reference fining time in a quiescent melt τ_{Fref} and the theoretical mean residence time of the melt in the space under critical conditions τ_G. Similarly, the utilization for sand dissolution u_D expresses the relation between the average sand dissolution time in the space, τ_{Dave} and τ_G [6]. The critical state then describes the situation when the bubble of the initially minimal radius attains the melt level just at the output from the space, or the initially maximal sand particle dissolves right there.

$$u_{F,D} = \frac{\tau_{Href}}{\tau_G}, \tau_G = \frac{V}{\dot{V}}, u \in \langle 0; 1 \rangle \tag{1}$$

where τ_{Href} is either τ_{Fref} or τ_{Dave}, 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). For the plug flow, $\tau_{Href} = \tau_G$ is valid, so $u_{F,D} = 1$ [8].

Both values of the space utilization may be involved in the expressions for the heat losses of the process and for the melting performance. In the critical state, the values of the melting performance and specific heat losses represent the maximum and minimum values, respectively. If both homogenization phenomena are considered as parallel, then the less efficient phenomenon is the controlling one. The specific heat losses of the space through boundaries decrease, and the performance of the melting process increases with space utilization according to:

$$H_M^L = \frac{\dot{H}^L \tau_{Dave}}{\rho V} \frac{1}{u_D} \text{ or } H_M^L = \frac{\dot{H}^L \tau_{Fref}}{\rho V} \frac{1}{u_F} \tag{2a, b}$$

$$\dot{V} = \frac{V u_D}{\tau_{Dave}} \text{ or } \dot{V} = \frac{V u_F}{\tau_{Fref}} \tag{3a, b}$$

where H_M^L are the specific heat losses (J/kg), $\dot{H}_L$ is the total heat flux across the space boundaries (J/s) and ρ is the glass density (kg/m^3). The quantity τ_{Fref} is the fining time which the critical bubble needs to ascend the distance h_0 in a quiescent liquid at average temperature in the space; the details of τ_{Fref} calculation are given in [7]. The former expressions in Eqs. (2a, ba, b) and (3a, ba, b) are valid for the case of sand dissolution as the controlling phenomenon, and the latter ones for the controlling phenomenon being bubble removal.

The space utilization for the sand dissolution u_D may be expressed with the assistance of two fractions of dead spaces – the fraction of dead space for the melt flow m_G and the fraction of space of the sand dissolution as the overprocessing m_D. Similarly, the space utilization for the bubble removal u_F can be expressed through the fraction of virtual dead space for bubble removal m_{virt} and virtual bubble rising distance h_{virt} [9]. The mentioned quantities provide a more detailed view of the character of the melt flow. Only the values of the space utilization as a final quantity will be applied in this work.

If bubble nucleation on the sand particles does not occur, both phenomena run simultaneously, so the less efficient phenomenon becomes the controlling one. When the melting conditions are varied and sand dissolution is the controlling phenomenon, the effect of melt flow changes – described by the utilization value u_D may be separated from the effect of different time-temperature histories described by the value of τ_{Dave}. If bubble removal controls the melting, both effects are separable only when the average temperature in the space varies – at a constant average temperature, the value of τ_{Fref} is constant.

The quantities defined by Eqs. (1)–(3a, b) may be acquired by modelling the critical state of bubble removal (in the critical state, the initial minimal bubble is removed just at the space exit) or the critical state of sand dissolution (the maximal particle is dissolved just at the output) in the melting space with adjusted flow patterns. Here, the demanded flow patterns have been set by proper energy distribution in the model melting space.

The set up of the controlled flow in glass melting spaces substantially depends on the distribution of energy delivered to the melting space in the case when no other tool is used to affect the melt flow. The specific energy consumption of a melting space with electric or other inner heating is given by:

$$H_M^0 = H_M^T + H_M^L \tag{4}$$

where H_M^T is the theoretical energy to convert the inputting batch and to heat the arising melt to the space exit temperature.

The crucial condition of the control of the favorable melt flow is the balanced distribution of delivered energy between the input (batch) region and subsequent region where the melting phenomena are completed. If the distribution is balanced, the necessary energetic condition for the uniform or efficient helical flow [19] is fulfilled; otherwise, clockwise longitudinal circulations occur with energy being in excess in the input region, and counterclockwise when the energy supplied here is lower than a balanced one. Most of energy should regularly be delivered to the input region in order to convert the batch, to heat the arising melt, and to cover the heat losses of the region while the needed energy in the subsequent part of the space includes only the heat losses. If the fraction of the input region is designated by ξ, Eq. (4) can be written as [19]:

$$H_M^0 = H_M^T + \xi H_M^L + (1-\xi) H_M^L \tag{5}$$

The energetic equilibrium in the melting space is attained if the specific energy given by the term $H_M^T + \xi H_M^L$ is delivered to the input region H_{glass1}, and the energy provided for the subsequent region H_{glass2} is equivalent to $(1-\xi)H_M^L$. Usually, the inequality $H_{glass1} < H_M^T + \xi H_M^L$ is valid in horizontal industrial melting furnaces, so intensive counterclockwise longitudinal circulations set up and restrict the melt flow control. In addition, the vertical and other detailed distribution of energy in each region play the role, and local convection currents can be expected even though an energetic balance exists. This work tries to reveal the best conditions to achieve high space utilization in the common modulus for sand dissolution and fining when the type of the melt input is varied, as well as the average and input temperatures, and the energy distribution inside the modulus.