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Numerical study of glass fining in a pot melting space with different melt-flow patterns

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ABSTRACT

A numerical model of glass-melt flow and bubble removal was applied in a pot melting space with a different character of melt flow. The linear-temperature gradients with a higher temperature either near the space wall or in the center of the melt level were put on the melt level to simulate the melt circulations, corresponding to melt heating through the pot wall and from the top, respectively. The removal times of the small bubbles have been calculated at different intensities of evoked melt circulations and compared with the values attained in the quiescent glass melt. The results have shown that the melt circulations increased the rising time of bubbles and consequently led to higher energy consumption and lower melting performance. The impact of melt circulations became stronger with the increasing intensity of the circulations and weakened with the increasing bubble growth rate. The removal times of critical bubbles were generally lower in the case of heating from the top and the relevant values obtained in the space at very low bubble growth rates and relatively high melt circulation velocities attained even lower values than in the quiescent melt. The low values of the bubble fining times were described by the characteristic shapes of the critical bubble trajectories. The case may be utilized for the fining of special glasses without addition of fining agents.

1. Introduction

Discontinuous glass melting in pot-melting furnaces is characterised by a considerably high energy consumption caused mostly by the fact that both the melt and melting furnace undergo the heating and working cycles at apparently different temperatures. The main portion of the energy is nevertheless consumed during the heating and melting period and consequently an improvement of the melting processes would beneficially impact the total energy usage. One of the energy-determining melting processes is fining, which is slow owing to the considerably low bubble-rise velocity in the viscous melt, thick melt layers and the existence of melt-flow patterns in the space. In the past, the rate of the fining process has been extensively examined through laboratory experiments, with the important role of the fining agents, as well as the temperature, pressure and glass composition being defined [1–7]. The mathematical models of bubble behaviour in a quiescent glass melt were constituted [8–11] and subsequently applied in continual glass melting furnaces [12–15]. However, the quantitative expression of the impact of the melt flow character on the rate of the bubble removal (fining) process was realised neither in continuous nor discontinuous (pot melting) spaces. In their recent works [16–21], the authors and colleagues have dealt with the impact of glass flow character on bubble removal in a continuous glass melting channel and found both advantageous and disadvantageous types of natural melt flows in terms of the bubble removal process. In a discontinuous pot furnace, the glass-melt flow is determined by the radial temperature gradients between the pot wall and the inside. The arising vertical circulations of the glass melt resemble the transversal melt circulations set in a horizontal continuous channel, where the bubble should pass a part of its trajectory against the downward melt flow, and its rising to the level is thus hindered [21]. In a previous work [22], the authors derived a simplified model of bubble behaviour in a rotating glass melt with the aim of revealing the fundamental features of mutual interactions between bubbles and vertically rotating melt. The conception of the space utilisation applied in [17–21] was also utilisable to describe the problem of bubble removal.

The heating of the melt through the space wall or from the top was simulated by means of temperature gradients put on the melt level. The modelling results have shown that the bubble fining times under isothermal conditions and in a vertically rotating glass melt are higher than those in a quiescent melt. The bubble removal was retarded by an increasing intensity of melt circulations, whereas the increasing bubble growth rate enhanced the fining process. At higher bubble growth rates, the melt rotation intensity barely influenced the rate of the fining process. The results generally provided evidence of a more intensive fining process under conditions simulating the heating of the glass from the top. This work is at first focused on the qualitative comparison

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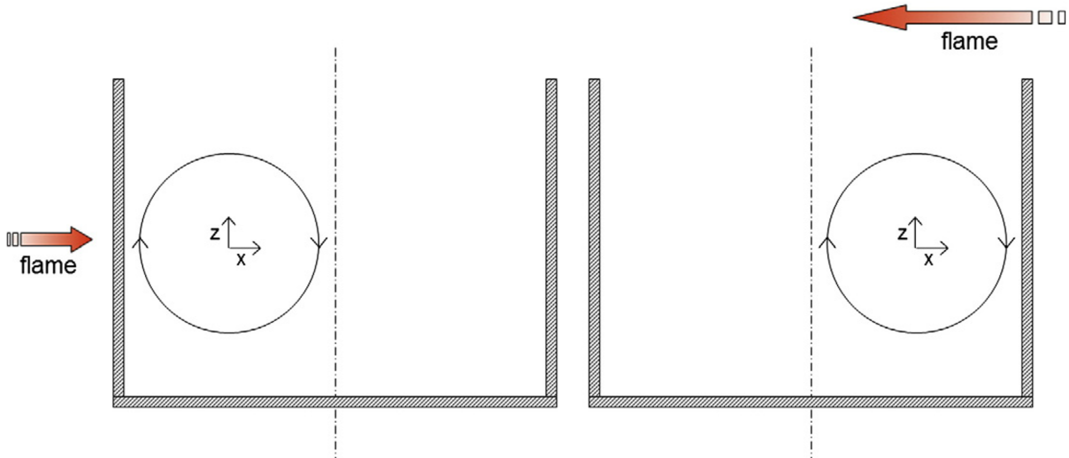

Fig. 1. a, b. The schematic picture of two simulated cases of glass melting in the pot. Left: the melt is heated through the wall. Right: the melt is heated from the top.

of the simplified mathematical model with a numerical one, which works under non-isothermal conditions and applies linear temperature gradients between the space wall and melt to evoke melt circulations. The qualitative agreement or difference between both models would provide a reliable chance to use the available simplified model for assessing fining efficiency should there be interest. However, the principal goal of the work is the calculation of more precise quantitative relations between the fining efficiency, melt circulation intensity, and bubble growth rate.

2. Theoretical

For an isothermal or almost isothermal process without energy recycling, the melting performance and specific energy consumption of the fining process can be described by the following equations [17–21]:

$$\dot{V} = \frac{V}{\tau_G} = \frac{V}{\tau_{Fref}} u_F \tag{1}$$

$$H_M^0 = H_M^T + \frac{\dot{H}^L \tau_G}{\rho V} = H_M^T + \frac{\dot{H}^L \tau_{Fref}}{\rho V} \frac{1}{u_F}, \tag{2}$$

where $\dot{V}$ [m^3/s] is the melting performance of the volume of the melting space V [m^3], τ_G is the mean residence time of the glass melt in the space, $\tau_G = V/\dot{V}$, τ_{Fref} [s] is the bubble removal time for the bubble of the critical size in a quiescent molten glass which started from the space bottom, H_M^0 [J/kg] is the specific energy consumption, H_M^T [J/kg] is the specific theoretical heat necessary for the chemical reactions, phase transitions and heating of both the batch and melt to the melting temperature T [K], $\dot{H}^L$ [J/s] is the total heat flux across the space boundaries, ρ [kg/m^3] is the glass density. In analogy with the space utilisation in a continuous space, the space utilisation in the pot furnace expresses the virtual dead space and the ratio between the fining time of the critical bubble in the quiescent and circulating melts:

$$u_F = (1 - m_{virt}) \frac{\tau_{Fref}}{\tau_{Fcrit}}; u \geq 0. \tag{3}$$

In the pot furnace, τ_{Fcrit} is the fining time of the critical bubble with flow patterns. The melting performance of the pot, given by Eq. (1), is then described by the effective melting performance. The value of the fraction of dead space, m_{virt}, defined in [17–21] has a zero value for the discontinuous melting space, because $m_{virt} = 1 - \tau_{Fcrit}/\tau_G$, but τ_G is equivalent to τ_{Fcrit} if the process is discontinuous. The space utilisation is then simply given by the ratio:

$$u_F = \frac{\tau_{Fref}}{\tau_{Fcrit}} \tag{4}$$

The value of τ_{Fref} can implicitly be calculated from the following equation [17,20,21]:

$$h_0 = \frac{2g\rho}{9\eta}\left(a_0^2 \tau_{Fref} + a_0 \dot{a} \tau_{Fref}^2 + \frac{\dot{a}^2 \tau_{Fref}^3}{3}\right). \tag{5}$$

When η [Pa·s] and ρ are the glass melt viscosity and density, h_0 is the height of the glass melt layer in the pot, a_0 is the initial bubble radius and $\dot{a}$ is the growth rate of bubble radius. Possibly, the simplified Eq. (5a) could be used for calculation of τ_{Fref} when $a_0 \to 0$:

$$\tau_{Fref} = \left(\frac{27 h_0 \eta}{2g\rho \dot{a}^2}\right)^{1/3}. \tag{5a}$$

If the value of τ_{Fcrit} is expressed in analogy with Eq. (5a) and by using the average values of glass density and viscosity, we have:

$$\tau_{Fcrit} = \left(\frac{27 h_{virt} \eta}{2g\rho \dot{a}^2}\right)^{1/3}, \tag{6}$$

where h_{virt} is the virtual height, which is the vertical distance passed by the critical bubble with respect to the flowing glass melt in time τ_{Fcrit}.

Table 1
The composition of the TV-glass used for modelling, in wt.%.

SiO_2	60.6	BaO	11.2	CeO_2	0.3
Al_2O_3	2.0	PbO	2.2	TiO_2	0.2
MgO	0.5	ZrO_2	1.35	Sb_2O_3	0.6
CaO	1.0	Na_2O	7.6	Fe_2O_3	0.05
SrO	5.0	K_2O	7.4		

Table 2
The temperature dependences of the most important quantities of the TV glass melt, i.e. viscosity, density and thermal conductivity. T in K.

Kinematic viscosity ν (m^2/s)	$\nu = \exp(-11.50 + 6144.57/(T - 710.64))$
Density ρ (kg/m^3)	$\rho = 2790 - 0.2378 \cdot T$
Thermal conductivity λ (W/(m·K))	$\lambda = 2 + 1.5 \cdot 10^{-8} \cdot T^3$