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A model for foam formation, stability, and breakdown in glass-melting furnaces

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Abstract

A dynamic model for describing the build-up and breakdown of a glass-melt foam is presented. The foam height is determined by the gas flux to the glass-melt surface and the drainage rate of the liquid lamellae between the gas bubbles. The drainage rate is determined by the average gas bubble radius and the physical properties of the glass melt: density, viscosity, surface tension, and interfacial mobility. Neither the assumption of a fully mobile nor the assumption of a fully immobile glass-melt interface describe the observed foam formation on glass melts adequately. The glass-melt interface appears partially mobile due to the presence of surface active species, e.g., sodium sulfate and silanol groups. The partial mobility can be represented by a single, glass-melt composition specific parameter ψ. The value of ψ can be estimated from gas bubble lifetime experiments under furnace conditions. With this parameter, laboratory experiments of foam build-up and breakdown in a glass melt are adequately described, qualitatively and quantitatively by a set of ordinary differential equations. An approximate explicit relationship for the prediction of the steady-state foam height is derived from the fundamental model.

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1. Introduction

1.1. Foam formation in glass-melting furnaces

In a glass-melting furnace, a foam layer can be formed on top of the batch blanket of raw material (primary foam) or on top of the liquid glass melt (secondary foam). Primary foam is formed by gas-forming reactions in the various melting stages of the raw material, e.g., carbonate decomposition leads to the evolution of CO_2 gas and oxidation reactions of carbon containing contaminants with sulfates lead to the evolution of CO_2 and possibly SO_2 gas.

After the raw material has melted, initially, the fresh glass melt will always contain small gas bubbles, so-called seeds, originating from the melting of the raw materials in the batch blanket (air inclusions, small CO_2 bubbles from carbonate decomposition). Furthermore, the glass melt becomes supersaturated with dissolved gases for two reasons. Firstly, the solubility of gases decreases as the temperature increases in the glass melt. Secondly, the glass melt around undissolved sand particles contains more SiO_2, which decreases the gas solubility. Thus, fresh seeds will be formed predominantly near sand particles.

The glass product will be rejected if too many of these small gas bubbles are present in the final product, thus leading to production and energy losses. The problem with these small gas bubbles is that they have a very low rise velocity in the highly viscous glass melt. With these low rise velocities, the majority of the gas bubbles will not reach the glass-melt surface in the time available to them in the glass-melting furnace. This problem is commonly solved by adding so-called fining agents to the glass melt. These fining agents decompose at higher temperatures, forming at least one gaseous component. The gaseous component(s) will diffuse into the gas bubbles, and the gas

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bubbles will grow in size. The rise velocity of gas bubbles is proportional to the radius squared. Thus, the gas bubbles rise faster to the glass-melt surface, eventually resulting in a bubble-free glass melt.

The amount of fining agent that can be added to the glass melt is limited. When the gas flux from the glass melt to the glass-melt surface exceeds a specific value, a layer of foam will be formed. This foam layer reflects the heat radiation from the combustion space above the glass melt. Heat transfer is severely restricted toward the glass melt; the transmission of radiation heat decreases by approximately 50% for each bubble layer [1,2]. The reflection of the radiation increases crown temperatures (increased refractory-attack hazard) and reduces glass-melt temperatures. Maintaining glass-melt temperatures at specified values by burner fuel input becomes increasingly difficult with increasing foam-layer thickness. Thus, for an optimal design and control of a glass-melting furnace, an accurate foam height model is required. Moreover, the model can indicate which measures can be taken to reduce the foam formation.

2. Theory

2.1. Foam structure

An extensive treaty on foam types and structure has been given by Bikerman [3], to which one is referred for more background. The major conclusions relevant for glass-melt foams and the development of the model are discussed shortly.

Generally, two types of foam are distinguished: spherical foam and polyhedral foam. In spherical foam generally all bubbles maintain a more or less spherical shape throughout their lifetime. In this case, the liquid boundaries or lamellae are curved at all positions, though the radius of curvature may change along the perimeter of a single gas bubble. Polyhedral foam is formed from a highly drained spherical foam. The visually flat lamellae between nonspherical bubbles are stabilized by surface-active components. These lamellae are interconnected through triangular bridges, so-called Plateau borders. The difference in curvature between the flat lamellae and the strongly curved borders induces a pressure difference between the bridges and the lamella centers, which causes the lamellae to drain faster. Polyhedral foams are metastable foams, consisting of flat lamellae with a reported thickness of approximately 100 nm and lower. The drainage process is virtually stopped; an equilibrium between gravity forces and capillary forces prevents further drainage. The lamellae break down due to an external disturbance, e.g., gas turbulence, chemical reactions, or temperature/pressure shock.

There are some experimental observations that polyhedral foam can be formed in a glass melt, with Na_2O as surface-active component [4]. Also, silanol groups (Si–OH) are known to be surface-active [5]; they can be formed at the glass-melt surface by reaction with water vapor. Kucuk et al. [6] investigated how the surface tension is influenced by changes in the bulk concentration of some common glass-melt components in a soda–lime–silica glass, see Table 1.

Table 1
The influence of some common glass components on the surface tension of a soda–lime–silica glass at 1400 °C according to Kucuk et al. [6]

Component	σ_A ($\mathrm{N\,m^{-1}}$)	Component	σ_A ($\mathrm{N\,m^{-1}}$)	Component	σ_A ($\mathrm{N\,m^{-1}}$)
Al_2O_3	0.347	MoO_3	−2.45	Na_2O	≈0
CaO	0.334	B_2O_3	−0.286	ZnO	≈0
SrO	0.332	K_2O	−0.222	SiO_2	≈0
MnO	0.292	PbO	−0.138	Fe_2O_3	≈0
FeO	0.268				
MgO	0.196				
Li_2O	0.148				
BaO	0.128				

A value of ≈0 indicates that the contribution to the bulk value ($\sigma_0 = 0.271\ \mathrm{N\,m^{-1}}$) is insignificant. The surface tension is given by $\sigma = \sigma_0 + x_A\sigma_A$, with x_A the mole fraction of component A.

In this paper only a spherical geometry of the bubbles in the foam is considered. The spherical shape is assumed to be approximately valid for polyhedral foams. In the next section, existing models for the prediction of foam height are discussed. Based on these models, a new foam-height model is derived in the consecutive sections.

2.2. Foam height models

For both spherical and polyhedral foams, the steady-state foam-layer height, H_F, is given by [3,7]

$$H_F = j_{\mathrm{in}}\tau_{\mathrm{bf}}, \tag{1}$$

with τ_{bf} the average lifetime of a gas bubble in the top of the foam (also referred to as unit of foaminess) and j_{in} the gas flux of bubbles rising to the gas–liquid interface.[1] A dynamic model for the formation of a foam is given by [8]

$$\frac{\mathrm{d}h_F(t)}{\mathrm{d}t} = j_{\mathrm{in}}(t) - j_{\mathrm{in}}(t-\tau_{\mathrm{bf}}), \tag{2}$$

where $h_F(t)$ equals the foam height at time t. For an initially foam-free surface and a constant gas bubble flux, Eq. (2) reduces to

$$h_F(t) = \begin{cases} j_{\mathrm{in}}t & \text{for } t \leqslant \tau_{\mathrm{bf}}, \\ j_{\mathrm{in}}\tau_{\mathrm{bf}} & \text{for } t > \tau_{\mathrm{bf}}. \end{cases} \tag{3}$$

Thus, according to this equation, a foam layer of height H_F is built up linearly with a slope j_{in} in time τ_{bf}. This τ_{bf} is generally considered to be a function of liquid properties, e.g., viscosity, density, surface tension, and of the gas flux.

Several authors use a different approach, based on a pseudo-continuous representation of foam, with liquid flow primarily through the Plateau borders, as though the foam resembles a packed bed of solid spheres. A detailed recent overview of these models is given by Pilon et al. [1]. All these models require some initial foam height and initial liquid distribution in the

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[1] The foam height in Eq. (1) represents the height of the gas phase only. For the total foam height, H_F should be divided by the gas hold-up. In this paper a discrete model is developed, which describes the foam build-up in layers of bubbles rather than in units of length; the gas hold-up is in that case irrelevant.

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