# Foam formation, stability, and breakdown in glass-melting furnaces

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#### Abstract

A transient foam model for glass-melts is derived here, based on the average life time of a single gas bubble. This average life time is derived from the equation of continuity and the momentum balances. The model compares well to laboratory experiments of glass-melt foaming.

# Introduction

In the glass-melting furnace, undesired foam formation on the glass-melt surface can sometimes be observed. The foam effectively insulates the underlying glass-melt from the heat radiation generated in the combustion space above the glass-melt. Heat transfer is severely restricted towards the glass-melt and a large amount of heat is reflected, thus increasing crown temperatures (increased refractory attack hazard) and reducing glass-melt temperatures. Consequently, maintaining glass-melt temperatures at specified values by burner-control becomes increasingly difficult with increasing foam-layer thickness.

The foam can either be formed from the raw batch materials (primary foaming), or from the fining process (secondary foaming). This paper will focus on the modelling of secondary foaming. The physical mechanisms involved in foam-layer build-up are inventoried. Based on (modified) available models a new model is developed, which is verified by experiments.

#### **Fining process**

Initially, the glass-melt will always contain small gas bubbles, originating from the melting of the raw materials in the batch-blanket, e.g., air inclusions,  $CO_2$  from carbonate decomposition.

These gas bubbles are undesired in the final product; it will be rejected, leading to production and energy losses. Unfortunately, small gas bubbles 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.

This problem is generally solved by adding 'fining-agents' to the glass-melt, which will decompose at higher temperatures into at least one gaseous component. The gaseous component(s) will diffuse into the gas bubble, causing the gas bubble to grow. Because larger gas bubbles have a higher rise velocity, they will rise to the glass-melt surface more readily, and the glass-melt will be rendered bubble-free.

#### Foam

In literature, generally two types of foam are distinguished: spherical foam and polyhedral foam [1]. 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 differ. Polyhedral foam is formed from spherical foam, when the lamellae between non-spherical bubbles are stabilized by surface-active components. When spherical foam is drained and the liquid flows from between the bubbles, flat, non-curved, lamellae are formed between gas bubbles, which 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.

In principle, polyhedral foams are metastable foams, consisting of flat lamellae with a thickness of 100 nm and lower, which 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 silanol-groups (Si-OH) or Na<sub>2</sub>O as surface-active component [5]. When the gas flux to the glass-melt surface exceeds a specific value, a layer of foam will be formed.

#### Foam height models

For both spherical and polyhedral foams, the steady-state foam-layer height,  $H_F$ , is given by [1], [4]:

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

with  $\tau_{bf}$  the average lifetime of a gas bubble in the foam-layer (also referred to as unit of foaminess,  $\Omega$ ,  $\Sigma$ ) and  $j_{in}$  the gas flux of bubbles rising to the gas-liquid interface. The transient foam layer height,  $h_F(t)$ , is given by:

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

For an initially foam-free surface and a constant gas bubble flux, equation (2) reduces to:

$$h_F(t) = \begin{cases} j_{in}t & \text{for } t \le \tau_{bf}, \\ j_{in}\tau_{bf} = H_F & \text{for } t > \tau_{bf}, \end{cases}$$
(3)

The gas-bubble flux to the gas-liquid interface is generally known or can be easily calculated, whereas the average lifetime of a gas-bubble in a foam is unknown and needs to be determined experimentally. Recently, Pilon et al. [7] reported a general relationship for this average foam-bubble lifetime, based on a vast amount of literature data. The relationship found from these data is:

$$\tau_{bf} = 213.77 \frac{\sigma(\mu (j_{in} - j_m)^{0.77})}{j_{in} R^{2.54}}$$
(4)

with  $\sigma$  and  $\mu$  the glass-melt surface tension and viscosity,  $j_m$  the onset of foaming gas flux, and R the gas-bubble radius. Unfortunately, a relationship or value for  $j_m$  is not given, which makes application of equation (??) difficult. Also, the influence of surface-active species on foaming behavior cannot be modelled.

Concluding, in literature, an adequate transient foam height model is not available. Therefore, in this paper, an improved transient foam height model is derived. The derivation is based on the average lifetime of a single gas bubble at a gas-liquid interface, derived from the momentum balances and the equation of continuity. The foam height dynamics predicted by the model are compared to experimental foam height dynamics in a viscous glass-melt.

## Derivation transient foam height model

In this section, first, the average survival time of a single gas-bubble at the glass-melt interface is derived. Subsequently, this average survival time is used for the derivation of the average survival time of a gas-bubble in a foam.

### Derivation average single gas bubble lifetime

As was clear from the previous section, the gas bubble lifetime in a foam is an important parameter for predicting the foam laver height. In this section, the equation of continuity and the momentum balances [2] are solved for a single gas bubble at the gas-liquid interface. The geometry for which the equations are solved is given in figure ??. Using spherical coordinates, the following assumptions are made:

▶ Axisymmetrical flow, <sup>∂</sup>/<sub>∂φ</sub> = 0,
 ▶ Constant density and viscosity of gas and liquid,

▶ The momentum balance in  $\theta$ -direction determines the flow, the momentum balance for the r-direction is ignored,

▶ Pseudo steady-state,  $\frac{\partial}{\partial t} = 0$ . The decrease in lamella thickness  $\delta$  is calculated from the pseudo steady-state solution for the radial velocity at  $r = R + \delta$ ,  $v_{R+\delta}(\theta, \delta)$ , with:  $\frac{d\delta(\theta)}{dt} = v_{R+\delta}(\theta, \delta(\theta))$ . ▶ The gas bubble will burst when the critical thickness  $\delta_c$  is reached. This critical value has been

estimated by de Vries [3] as a function of liquid surface tension,  $\sigma$ , and disturbance intensity,  $E_d$ :

 $\delta_c = \sqrt{\frac{E_d}{\sigma}}$ . Here we will assume  $\delta_c = 100 \ \mu \text{m}$  and an initial thickness  $\delta_0 = 1 \ \text{mm}$ .  $\blacktriangleright$  The gas-bubble lamellae drain due to gravity and Plateau border suction, i.e., the driving force for drainage equals  $\rho g + \frac{\sigma}{r_{PB}}$ , with  $r_{PB}$  the curvature at the Plateau-border. The curvature in the center of the lamella is assumed infinite. Plateau-border suction and gravity become of equal order when  $r_{PB} = \frac{\sigma}{\rho g} (\approx 10^{-5} \ \text{m}$  for a typical glass-melt).

► General boundary conditions :  $\frac{\partial v_{\theta}}{\partial \theta}\Big|_{\theta=0} = 0$  and  $v_r|_{r=R} = 0$ ► Partially mobile interface; the force due to concentration gradients of surface active species x at the surface, is equal to the force due to viscous shear stress  $\mu \frac{\partial v_{\theta}}{\partial r}\Big|_{\substack{r=R\\r=R+\delta}} = \frac{1}{r} \frac{\partial \Gamma}{\partial \theta}\Big|_{\substack{r=R\\r=R+\delta}}$ , ► Surface concentration,  $\Gamma$ , is a function of  $v_{\theta}$ . Levich [6] showed for flow around a sphere, that, in

case of a diffusion limited process and in case of an adsorption-desorption limited process, the surface concentration profile equals:  $\Gamma^* - \Gamma = \psi \frac{g(r)}{r} \cos \theta$ , where  $\Gamma^*$  is the surface concentration in equilibrium with bulk concentration, c, and  $\psi = \frac{2\Gamma^*}{\alpha}$  (sorption) or  $\psi = \frac{\delta_L}{D} \frac{2\Gamma^*}{\left(\frac{\partial c}{\partial \Gamma}\right)}$  (diffusion).

With these assumptions the equations to be solved are:

$$\frac{1}{r^2} \frac{\partial}{\partial r} (r^2 v_r) + \frac{1}{r \sin \theta} \frac{\partial}{\partial \theta} (v_\theta \sin \theta) = 0 \text{ (continuity)},$$
  
$$\frac{\partial}{\partial r} \left( r^2 \frac{\partial v_\theta}{\partial r} \right) + \frac{\partial}{\partial \theta} \left( \frac{1}{\sin \theta} \frac{\partial}{\partial \theta} v_\theta \sin \theta \right) + 2 \frac{\partial v_r}{\partial \theta} + \frac{\rho g + \frac{\sigma}{r_{PB}}}{\mu} r^2 \sin \theta = 0 \text{ (momentum)}.$$
(5)

A general solution for the velocity profiles has the form:  $v_r = f(r) \cos \theta$ ,  $v_\theta = g(r) \sin \theta$ , with  $f(r) = \frac{a}{r^3} + \frac{b}{r} + c + dr^2$  and  $g(r) = \frac{a}{2r^3} - \frac{b}{2r} - c - 2dr^2$  [2]. The constants a, b, c, and d are determined from equation 3 and the boundary conditions. The resulting relationships are:

$$b = \frac{2dR^3 \left(\frac{\psi R-4}{3+3\psi R} \left(3-\psi R-\psi \delta + (3+\psi R) \left(\frac{R+\delta}{R}\right)^4\right) + \dots\right)}{2\left(\frac{(R+\delta)}{R}\right)^4 \left(\psi R-2 - \left(\frac{R+\delta}{R}\right) (\psi R+\psi \delta + 2)\right)}{\left(\left(1-\psi R-\psi \delta\right) \left(\frac{R+\delta}{R}\right)^2 + (1+\psi R) \left(\frac{R+\delta}{R}\right)^4 + \dots\right)}{\left(\frac{1-\psi R}{3+3\psi R} \left(3-\psi R-\psi \delta + (3+\psi R) \left(\frac{R+\delta}{R}\right)^4\right)\right)}\right)}$$
(6)  
$$a = \frac{bR^2(1-\psi R) + 2dR^5(\psi R-4)}{3+3\psi R}, \quad c = -\frac{a}{R^3} - \frac{b}{R} - dR^2, \text{ and } d = (\rho g + \frac{\sigma}{r_{PB}})/10\mu.$$

### Average gas bubble lifetime in foam

The average gas bubble lifetime will be higher in a foam layer when compared to the single gas bubble lifetime. The lamella will drain more slowly because of the in-flow of fresh liquid, originating from



Figure 1: The geometry of a gas bubble at the gas-liquid interface,

the drainage of gas bubbles higher in the foam layer. The inflow of fresh liquid can be accounted for by taking the decrease of lamella thickness as the difference between inflow and outflow of liquid at  $\theta = 0$ .

The inflow of liquid is modelled by assuming that the increase in thickness of bubbles residing in the  $n^{\text{th}}$  layer in a foam is equal to the decrease of thickness of a bubble in the  $(n - 1)^{\text{th}}$  layer directly on top of the layer. Thus,  $\frac{d\delta_n}{dt} = v_{R+\delta_n}(\delta_n) - v_{R+\delta_{n-1}}(\delta_{n-1})$ . The following *n* equations then need to be solved, when *n* bubble layers are present in the foam:  $\frac{d\delta_i}{dt} = v_R(\delta_i) - v_R(\delta_{i-1})$ , i = 1..n. Substitution of  $v_R$ 

Figure 2: The average gas bubble lifetime  $\tau_{bf}$  normalized with the single gas bubble survival time  $\tau_c$ , versus the number of layers present in the foam, n, calculated for different bubble layer formation times  $\tau_f$ , according to equation (??).

 $v_R(\delta_i) - v_R(\delta_{i-1})$ , i = 1..n. Substitution of  $v_R(\delta)$  and solving these equations, finally results in the following relationship for the average gas bubble lifetime in a *n*-layer foam:

$$\frac{\delta_c}{\delta_0} = e^{-\frac{\tau_{bf}}{\tau}} \sum_{i=1}^n \left[ \frac{\tau_{bf} + (i-1)\tau_f}{\tau} e^{-\frac{\tau_f}{\tau}} \right]^{(i-1)} \tag{7}$$

where  $\tau = \frac{\mu}{3(\rho g + \frac{\sigma}{r_{PB}})R} \left(1 + \frac{6\psi R^2}{\delta_c \ln(\delta_0/\delta_c)}\right)$  and  $\tau_f = \frac{N\frac{4}{3}\pi R^3}{j_{in}S}$  with N/S the number of bubbles per foam layer area.

# **Results and discussion**

### Experiments

The average bubble lifetime is determined as follows. A float glass of known composition is melted in a quartz glass crucible placed in an oven at specified temperature. The glass-melt properties are:  $\mu=22(1300^{\circ}\text{C})$  and  $15(1400^{\circ}\text{C})$  [Pas],  $\sigma=0.320$  Nm,  $\rho_s=2.3$  10<sup>3</sup> kg/m<sup>3</sup>.

With a mass flow controller a gas flow is introduced in the glassmelt through a platinum capillary, resulting in a uniform bubble flow. At some critical gas flow a surface-covering foam layer will be formed, depending on the glass-melt properties and other experimental conditions. Below this gas flow the surface is only partly covered. The gas flow is stopped after 300 s, or when the foam height reaches 100 mm, the crucible height. All measurements are done with a digital camera system, which takes a digital photograph of the experiment every 5 s, after the gas bubble flow has been started. The transient foam height curve and the gas bubble radius are determined from these photographs. The average gas-bubble radius is given in table 1 for all experiments. In figures 1 and 2 the transient foam height is shown for

gas flux	Т	radius, R
(m/s)	$(^{\circ}C)$	(mm)
0.75	1400	$6.7\pm0.3$
0.38		$5.5\pm0.5$
0.19		$5.0{\pm}~0.4$
0.70	1300	$8.3\pm0.5$
0.35		$7.0\pm0.4$
0.18		$6.1\pm0.4$

Table 1: The average gasbubble radius for all experiments.

glass-melt temperatures of 1300°C and 1400°C. At each temperature the transient foam height was measured for three different gas fluxes, for each setting a duplicate experiment was performed, which is also displayed in figures 1 and 2. An good reproducibility is observed for the foam build-up, the foam breakdown becomes more erratic for the higher gas fluxes.

### $\mathbf{Model}$

With equations (??) and (2) the transient foam height can be calculated. This is done for the conditions at which the experiments were performed. In figures 3 and 4 the resulting curves are displayed. The foam formation curve compares very well to the experimental curve for  $j_{in} = 0.18$  and 0.19 m/s for both temperatures. The foam build-up for the higher gas fluxes is also reasonably predicted,

but, especially for the experiments at 1300  $^{\circ}$ C, the foam breakdown is not. More experiments are required to investigate this unexpected breakdown. Future research will focus on the influence of gas atmosphere and surface active species in glass-melts on the foaming behavior. Also, a comparison with experiments from literature will be made.

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Figure 3: Foam height as a function of time.  $T = 1300^{\circ}C$  gas fluxes 0.70, 0.35, and 0.18 m/s



Figure 5: Predicted foam height as a function of time.  $T = 1300^{\circ}C$  gas fluxes 0.70, 0.35, and 0.18 m/s



Figure 4: Foam height as a function of time. T =  $1400^{\circ}$ C gas fluxes 0.75, 0.38, and 0.19 m/s



Figure 6: Predicted foam height as a function of time.  $T = 1400^{\circ}C$  gas fluxes 0.75, 0.38, and 0.19 m/s