



June, 13th 2019, Boston

X-ray imaging of high temperature furnace applied to glass melting

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Figure 1: Motion of bubbles in a mixing of a dark and clear glass former liquids.





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Agenda

1. Materials and methods

- 1.1 Materials
- 1.2 Experimental set-up
- 1.3 Image analysis
- 1.4 Optical flow

2. Results

- 2.1 Overall dynamics
- 2.2 Bubble size distributions
- 2.3 Velocity field with the optical flow technique
- 2.4 Bubble rising velocity

3. Conclusions and perspectives



1.1 Materials

SiO ₂	Na ₂ O	CaO	Al_2O_3	K ₂ O	SO ₂	Fe ₂ O ₃	FeO
73.10	12.75	11.40	1.77	0.74	0.15	0.02	0.0054



Figure 2: μ (Pa·s) vs. T (°C).

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1.2 Experimental set-up



Figure 3: Experimental set-up with the X-ray source, the furnace with crucible and the flat panel (LGC).

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1.2 Experimental set-up

- > YXLON power generator (2500 W); radiation rate $2.2 \cdot 10^{10} \mu$ Sv/h \gg 80 μ Sv/h.
- Flat panel: 20×20 cm² with 1024×1024 px², space resolution of 80 μm/px.

- Image acquisition: every 4 s with integration of signal over 130 ms (~ 30 images) and recording time of 50 ms.
- Circular crucible in alumina; $r_{\text{int.}} = 9.5 \text{ mm}$, $r_{\text{ext.}} = 11 \text{ mm}$.
- Addition of small SnO₂ particles (200 µm) to increase the contraste in the liquid needed for the optical flow technique.



1.3 Image analysis



Figure 4: (a) original image, (b) enhanced contrast image by subtraction of the overall minimum, (c) Subtracting the sliding minimum on a sequence of 10 frames.



1.4 Optical flow

- Light intensity / is associated at each pixel.
- Assuming that this intensity is a continuous function which is conserved over the time, *I* verified the transport equation

$$\frac{\partial I}{\partial t} + \frac{\partial I}{\partial x}U_x + \frac{\partial I}{\partial y}u_y = 0.$$
 (1)

Velocity field of the projected images obtained by minimization of

$$\epsilon_1 = \frac{\partial I}{\partial t} + \boldsymbol{U} \cdot \boldsymbol{\nabla} \boldsymbol{I}, \qquad (2)$$

$$\epsilon_2^2 = (U_x - \bar{U}_x)^2 + (U_y - \bar{U}_y)^2, \tag{3}$$

• \overline{U}_x and \overline{U}_y : averages of velocity components in a neighborhood of the considered point.



1. Materials and methods 1.4 Optical flow



Physical time of movies is 30 minutes [Movies not included in this version]. June, 13th 2019, Boston X-ray imaging

2.1 Overall dynamics



Heating (10K/mn) of glass grain (medium size): Collapse, bubble generation and bubble rising (physical time = 2 h) [Movies not included in this version] June, 13th 2019, Boston X-ray imaging

2. Results 2.2 Bubble size distributions



Figure 5: Snapshots before melting, after T_g and in liquid state.

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2. Results 2.2 Bubble size distributions



Figure 6: Bubble size distributions initially formed after melting for fine grain (0.3-0.8 mm), medium grain (2-3 mm) and large grain (6-8 mm).

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2. Results

2.3 Velocity field with the optical flow technique



Figure 7: Introduction of two glass pucks with an air pocket.

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2. Results2.3 Velocity field with the optical flow technique



Figure 8: Image with recalibration around a bubble, a = 2.25 mm, and velocity field.



2. Results2.4 Bubble rising velocity



Figure 9: Bubble rising in a circular crucible.

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2. Results

2.4 Bubble rising velocity

In Stokes regime with free shear interface, drag force is

$$F = 4\pi\mu aVK(\lambda), \ \lambda = \frac{a}{r},$$
 (4)

According to Haberman and Sayre¹, K:

$$\mathcal{K} = \frac{1 + 1.137855\lambda^5}{1 - 1.4033\lambda + 1.13787\lambda^5 - 0.72603\lambda^6}.$$
 (5)

Terminal velocity is then given by

$$\frac{V}{V_{\rm H-R}} = \frac{1}{K(\lambda)},$$

$$V_{\rm H-R} = \frac{\rho g a^2}{3\mu}.$$
(6)
(7)

¹W. L. Haberman/R. M. Sayre: Motion of rigid and fluid spheres in stationary and moving liquids inside cylindrical tubes, David Taylor Model Basin Report 1143, U.S. Navy Dept., 1958.

2. Results 2.4 Bubble rising velocity



Figure 10: V/V_{H-R} vs. -z/a obtained by bubble tracking.

Figure 11: V/V_{H-R} vs. -z/a obtained by optical flow technique.

3. Conclusions and perspectives

- X-ray imaging measurement applied to the dynamics of glass grain melting.
- The collapse and the bubble trapping and rising are nicely observed.
- Bubble distribution sizes vs. grain size have been determined and match very well with a log-normal distribution in agreement with Reboul et al.².
- More details will be found in the paper³.

²N. Reboul/E. Vincens/B. Cambou: A statistical analysis of void size distribution in a simulated narrowly graded packing of spheres, in: Granular Matter 10.6 (2008), pp. 457–468.

³D. Boloré et al.: X-ray imaging of high temperature furnace applied to glass melting, in: J. Amer. Ceram. soc. 2019, under review.

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- A flow optic technique used to estimate the velocity field in the liquid needing next investigations.
- Use the crucible rotation to have 3d images (computed tomography).
- Study the mixing of the liquid due to the bubble rising.

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Thank you very much for your attention!