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PSL

DTPF 2018

September, 18th 2018, Toulouse

X-ray imaging of High Temperature furnace applied to glass melting

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Motivations of the present work

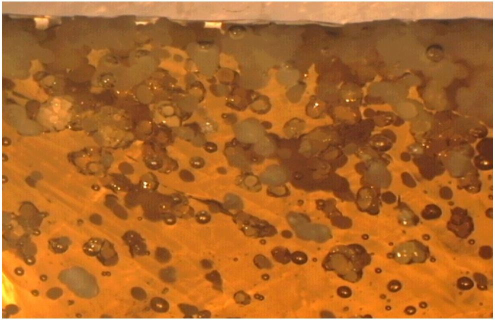

Figure 1: Melting of glass.

$$SiO_2 + xNa_2CO_3 + yCaCO_3 \longrightarrow SiO_2 \cdot xNa_2O \cdot yCaO + (x+y)CO_2. \quad (1)$$

- 1 tonne of glass ➨ **200** kg of CO_2.

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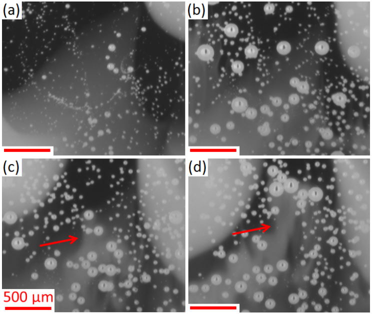

Figure 2: Motion of bubbles in a mixing of a dark and clear glass former liquids.

- What is the effect of bubble motion on the glass mixing?
- What is the bubble size distribution formed during the recycling glass melting?

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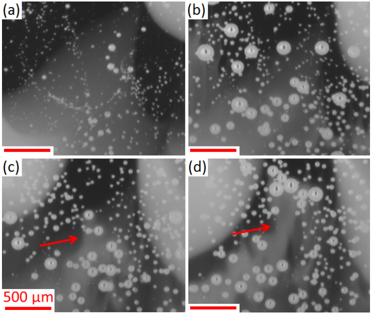

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Development of *in situ* non destructive monitoring set-up using a X-ray imaging

Agenda

1. Materials and methods

1.1 Materials

SiO_2	Na_2O	CaO	Al_2O_3	K_2O	SO_2	Fe_2O_3	FeO
73.10	12.75	11.40	1.77	0.74	0.15	0.02	0.0054

Table 1: Chemical composition (wt %) of the glass used for experiments.

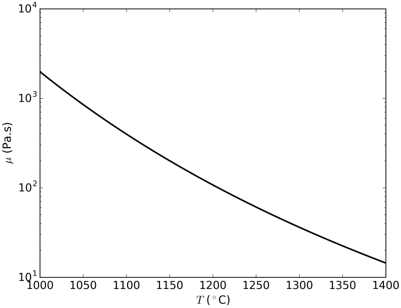


Figure 3: μ (Pa·s) vs. T (°C).

- $\mu =$398.19 Pa·s at $T =$1100°C.
- $\rho =$2383.72 kg/m^3.
- $\gamma =$0.315 N/m.

1. Materials and methods

○ 1.2 Experimental set-up

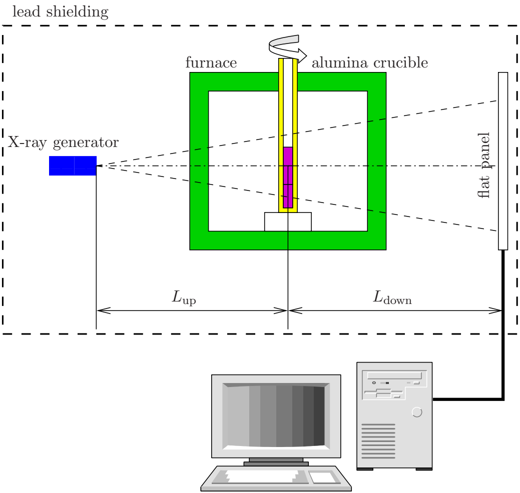


Figure 4: Experimental set-up with the X-ray source, the furnace with crucible and the flat panel (LGC).

1. Materials and methods

○ 1.2 Experimental set-up

- YXLON power generator (2500 W); radiation rate $2.2 \cdot 10^{10}$ μSv/h $\gg$ 80 μSv/h.
- Flat panel: 20$\times$20 cm^2 with 1024$\times$1024 px^2, space resolution of 80 μm/px.
- Image acquisition: every 4 s with integration of signal over 130 ms ($\sim$ 30 images) and recording time of 50 ms.
- Circular crucible in alumina; $r_{\text{int.}} = 9$ mm, $r_{\text{ext.}} = 10$ mm.
- Addition of small SnO_2 particles to increase the contraste in the liquid needed for the optical flow technique.

1. Materials and methods

○ 1.3 Image analysis

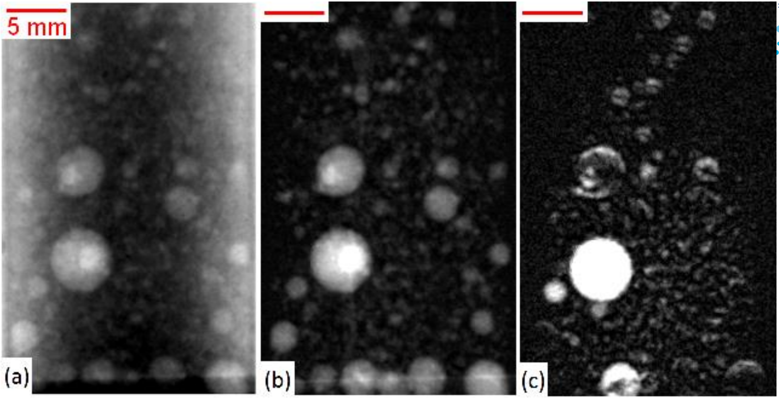


Figure 5: (a) original image, (b) enhanced contrast image by subtraction of the overall minimum, (c) Subtracting the sliding minimum on a sequence of 10 frames.

1. Materials and methods

1.4 Optical flow

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

$$\frac{\partial I}{\partial t} + \frac{\partial I}{\partial x}\frac{d\Phi_x}{dt} + \frac{\partial I}{\partial y}\frac{d\Phi_y}{dt} = 0, \tag{2}$$

$$U_x = \frac{d\Phi_x}{dt}, \; U_y = \frac{d\Phi_y}{dt}. \tag{3}$$

- Velocity field of the projected images obtained by minimization of

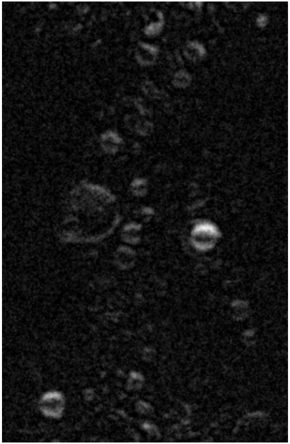
$$\epsilon_1 = \frac{\partial I}{\partial t} + \boldsymbol{U} \cdot \boldsymbol{\nabla} I, \tag{4}$$

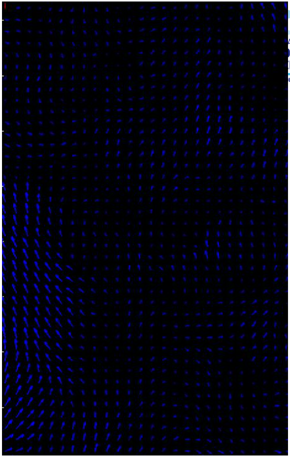
$$\epsilon_2^2 = (U_x - \bar{U}_x)^2 + (U_y - \bar{U}_y)^2, \tag{5}$$

- $\bar{U}_x$ and $\bar{U}_y$: 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.

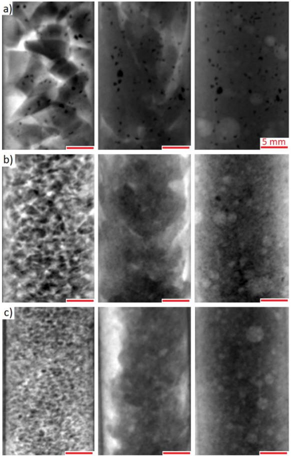
2. Results

○ 2.1 Overall dynamics

Heating (10K/mn) of glass grain (medium size): Collapse, bubble generation and bubble rising (physical time = 2 h)

2. Results

○ 2.2 Bubble size distributions



large grain (6-8 mm)

medium grain (2-3 mm)

fine grain (0.3-0.8 mm)

Figure 6: Snapshots before melting (1st column), after glass transition (2nd column) and in liquid state (3rd column).

2. Results

○ 2.2 Bubble size distributions

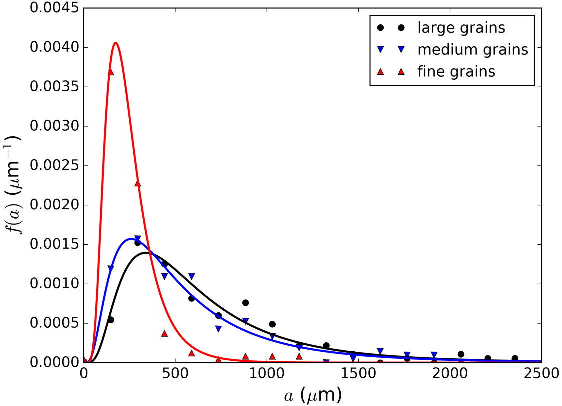


Figure 7: Bubble size distributions initially formed after melting for fine grain (0.3-0.8 mm), medium grain (2-3 mm) and large grain (6-8 mm).

2. Results

○ 2.3 Velocity field with the optical flow technique

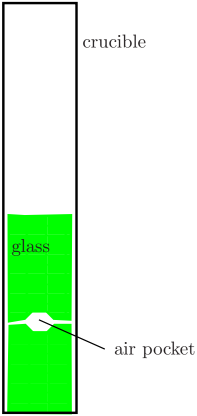


Figure 8: Introduction of two glass pucks with an air pocket.

- Tracking a unique bubble;
- Velocity field determined using the flow optic algorithm;
- Averaging over several bubble positions;
- Recalibration of the bubble position in the center of images.

2. Results

○ 2.3 Velocity field with the optical flow technique

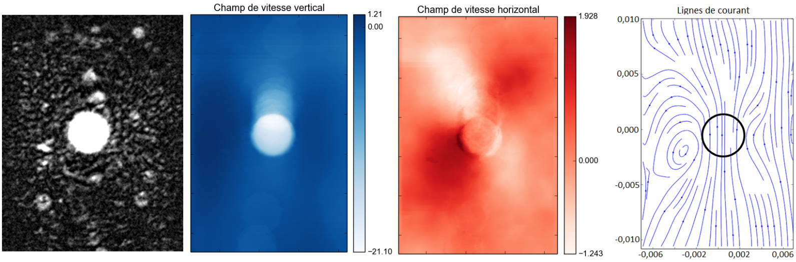


Figure 9: Image with recalibration around a bubble, $a = 2.25$ mm, and velocity field.

2. Results

○ 2.4 Bubble rising velocity

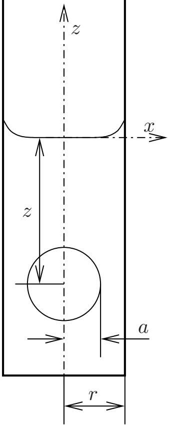


Figure 10: Bubble rising in a circular crucible.

2. Results

○ 2.4 Bubble rising velocity

- In Stokes regime with free shear interface, drag force is

$$F = 4\pi\mu a V K(\lambda),\ \lambda = \frac{a}{r}, \tag{6}$$

- According to Haberman and Sayre[1], K:

$$K = \frac{1 + 1.137855\lambda^5}{1 - 1.4033\lambda + 1.13787\lambda^5 - 0.72603\lambda^6}. \tag{7}$$

- Terminal velocity is then given by

$$\frac{V}{V_{\mathrm{H-R}}} = \frac{1}{K(\lambda)}, \tag{8}$$

$$V_{\mathrm{H-R}} = \frac{\rho g a^2}{3\mu}. \tag{9}$$

[1] Haberman, W. L. & Sayre (1958), U.S. Navy Dept.

2. Results

○ 2.4 Bubble rising velocity

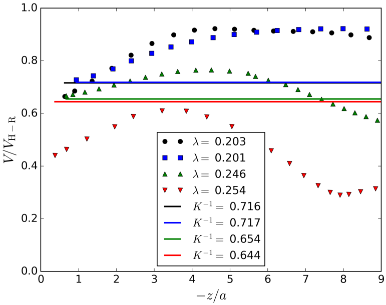


Figure 11: $V/V_{\mathrm{H-R}}$ vs. $-z/a$ obtained by bubble tracking.

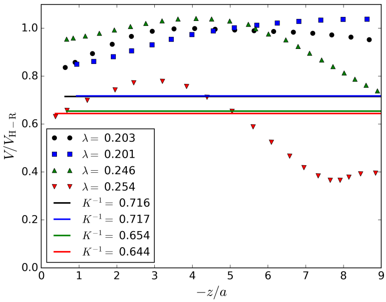


Figure 12: $V/V_{\mathrm{H-R}}$ vs. $-z/a$ obtained by optical flow technique.

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. Yes, but why?
- 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!