



Numerical simulation of vitrification processes: glass homogeneity by gas bubbling study

E. Sauvage

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Numerical simulation of vitrification processes: glass homogeneity by gas bubbling study

Workshop on gases and bubbles in molten glasses | E. Sauvage

CEA-Marcoule, BP 17171, 30207 Bagnols sur Cèze, France

13 MAY 2016

Summary

1- Vitrification technology presentation

2- Semi empirical approach

2-a Model

2-b Interaction with mechanical stirring

3- VOF simulation



CEA / AREVA Joint Vitrification Laboratory (LCV)



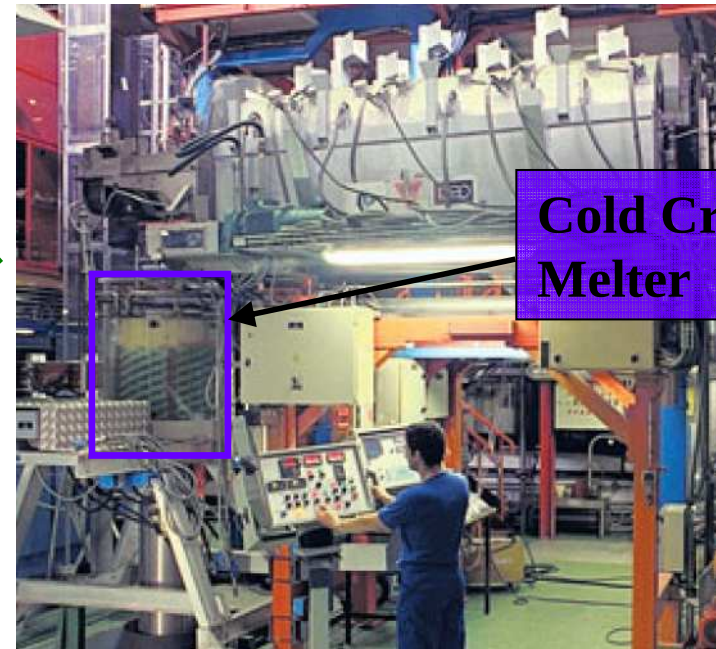
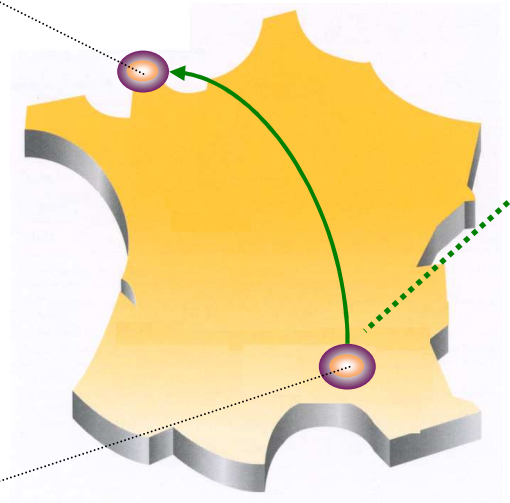
**La Hague
(AREVA)
Industrial plant**



**Marcoule
(CEA)
Research center**

Areva

- Commercial and industrial operator of 3 vitrification plants



**Cold Crucible
Melter**

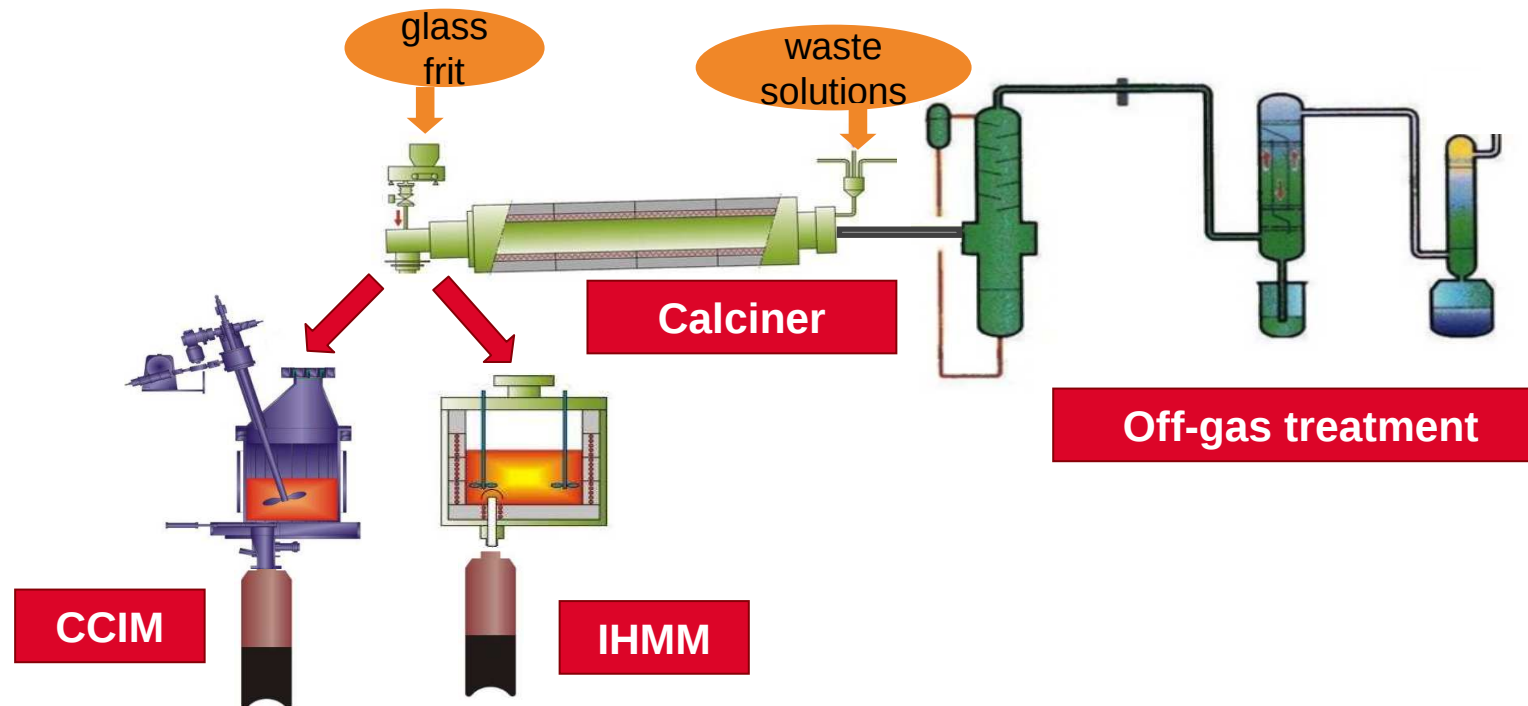
Current pilot of vitrification process
CEA Marcoule (inactive cell)

French Atomic Energy Commission (CEA)

- Confinement Research Engineering Department
Waste Confinement and Vitrification Service

VITRIFICATION PROCESS OPERATED IN THE LA HAGUE PLANT

➔ Industrial French Vitrification Design / A two-step vitrification process

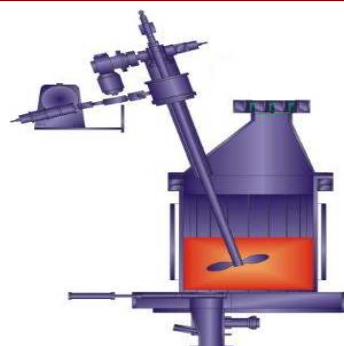


- ➔ Solution fed to a rotary calciner (evaporating, drying and calcining functions)
- ➔ Glass frit fed separately
- ➔ Melter fed continuously / poured batchwise
- ➔ Off-gas treatment unit (recycling of particulate material and purification of the gas streams)

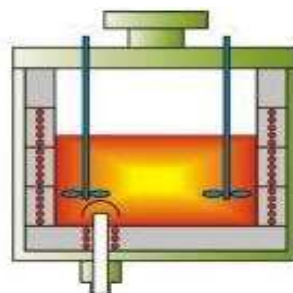
VITRIFICATION PROCESS OPERATED IN THE LA HAGUE PLANT

Furnaces technology

Cold Crucible Inductive Melter



Inductive Hot Metallic Melter

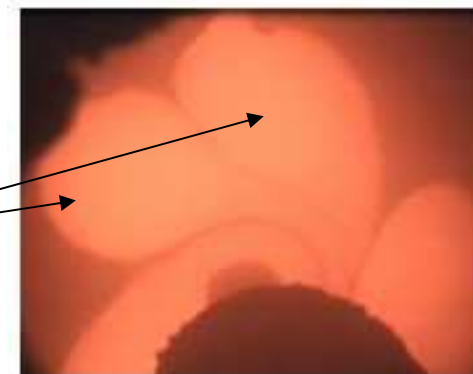


Characteristics:

- Molten glass mass	400 kg	270 kg
- Max throughput	36 kg/h	25 kg/h
- Max temperature	>1400°C	1100°C
- Mechanical stirring	yes	yes
- Gas bubbling	yes	yes
- Approx. life time	>2 years	0.5 year
- Number in LH plant	1	5

Average chemical compositions for R7T7 glass produced in the industrial facilities at La Hague	
Oxides	Average composition of industrial glass (w %)
SiO ₂	45,6
B ₂ O ₃	14,1
Al ₂ O ₃	4,7
Na ₂ O	9,9
CaO	4
Fe ₂ O ₃	1,1
NiO	0,1
Cr ₂ O ₃	0,1
P ₂ O ₅	0,2
Li ₂ O	2
ZnO	2,5
Oxides (PF+Zr+actinides) + Suspension of fines Actinide oxides	17
SiO ₂ +B ₂ O ₃ +Al ₂ O ₃	64,4

Inside view in CCIM

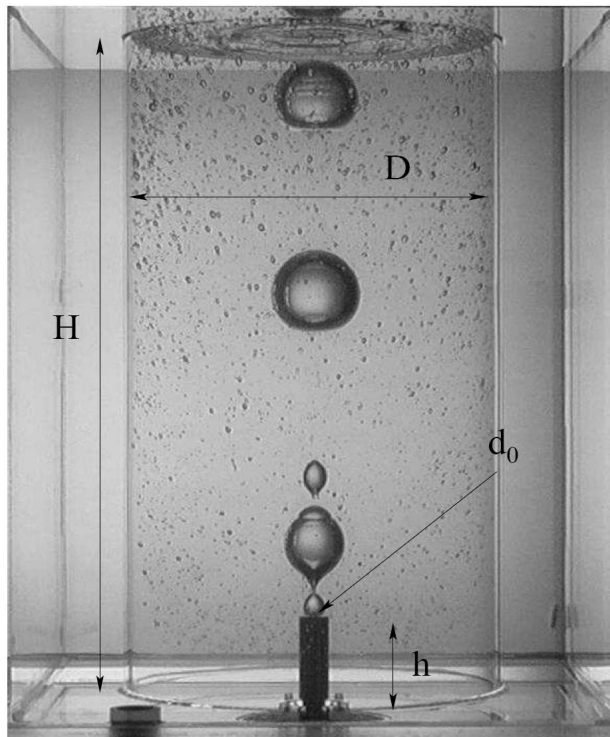


2 Bubbling characterization and modelisation

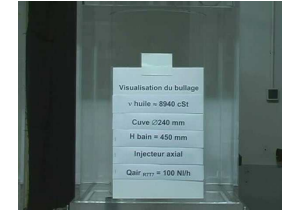
Air bubbling overview

Experiment in hydraulic similarity with silicon oil

R. RIVA (CEA / Grenoble)



30 to 60 cm



Visualisations
rapides 250 im/s

1 bullage

Q_{air} = 50 NI/h
à Q_{air} = 1000 NI/h

Viscosité = 3890 cSt

- Oil with the same kinematic viscosity as glass (at a given temperature)
- Explored parameters: liquid viscosity, air flow rate, hole diameter of the injector...

Adimensionnals numbers for similarity

		Hot glass	Oil
Mo	$g\mu_L^4/\rho_L\sigma^3$	1321	170616
$\log_{10}(Mo)$		3,12	5,23
Ga	$\rho_L^2 g d_0^3 / \mu_L^2$	0,0475	0,0475
Re	$\rho_L V_g d_0 / \mu_L$	63,2	63,2
ρ^*	ρ_G / ρ_L	$8,55 \cdot 10^{-5}$	$1,23 \cdot 10^{-3}$
μ^*	μ_G / μ_L	$5,26 \cdot 10^{-6}$	$5,12 \cdot 10^{-6}$

2-a « One mesh » model

Nomenclature :

Q Gas flow rate (L/h)

g Gravity (m/s^2)

d_0 Orifice diameter (m)

V_g Gas velocity (m/s)

V_B Bubble rising velocity (m/s)

d_e Equivalent diameter of bubble (m)

f_z Body force imposed in the fluid (N/m^3)

C_d Drag coefficient (-)

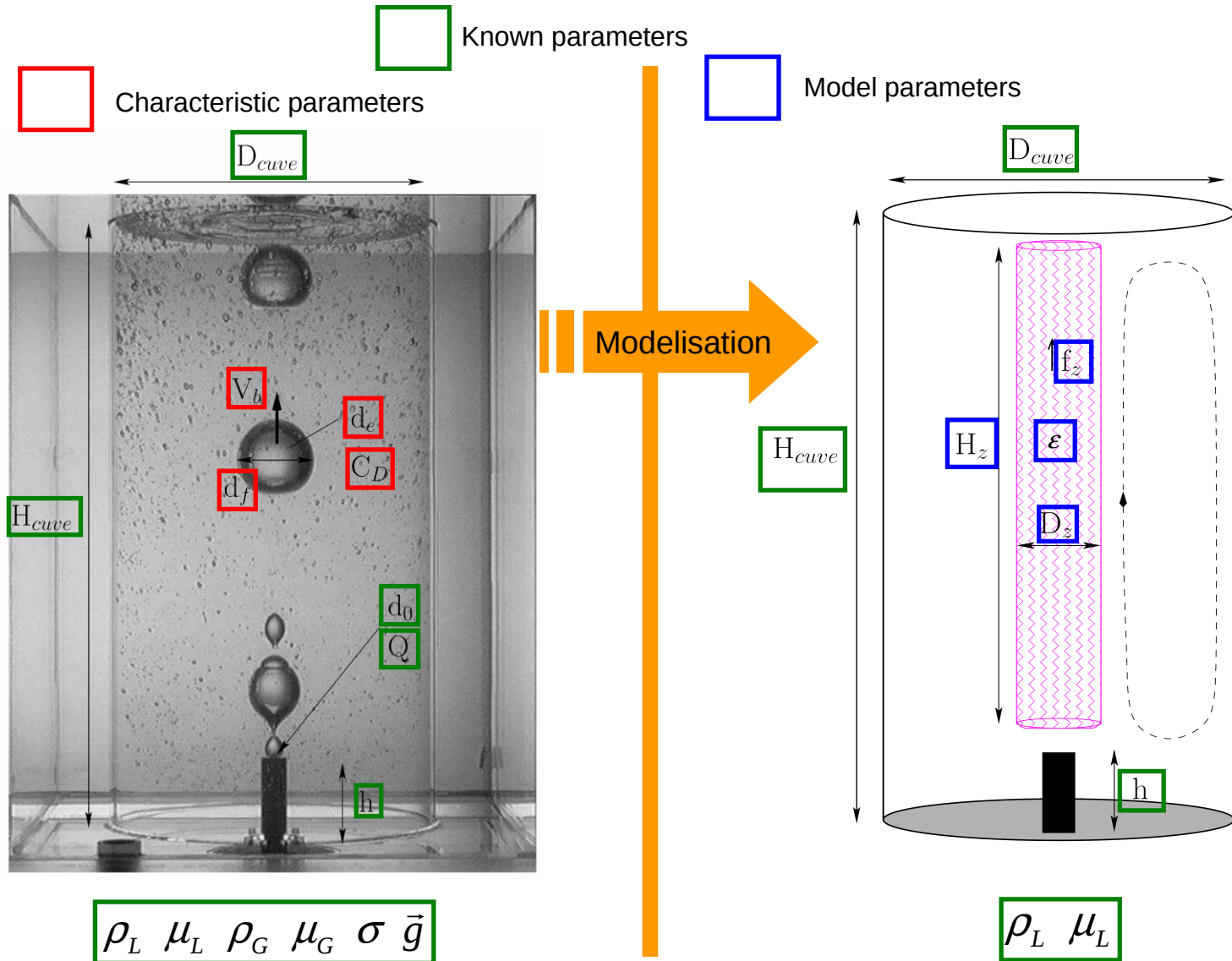
V_{ol} Volume of a bubble (m^3)

p Liquid pressure (Pa)

ρ_L Liquid density (kg/m^3)

μ_L Liquid viscosity (m^2/s)

ε_G Volume fraction of gas



Diapositive 7

es1

The liquid is driven by the rising bubbles

This driving is modelise by a constant vertical body force in the liquid

es210797; 22/08/2012

2-a « One mesh » model

 = f() = experimental correlation

Jamialahmadi, M. et al, Study of Bubble Formation Under Constant Flow Conditions, *Chemical Engineering Research and Design*, **2001**, 79, 523 - 532

$$d_e = d_0 \left(\frac{5}{Bd^{1,08}} + 9,261 \frac{Fr^{0,36}}{Ga^{0,39}} + 2,147 Fr^{0,51} \right)^{\frac{1}{3}}$$

$\rho_L g d_0^2 / \sigma$

$\rho_L^2 g d_0^3 / \mu_L^2$

$V_g^2 / g d_0$

$$d_f = 1,23 d_e$$

 = f(,) = choice of model

Snabre, P. & Magnifotcham, F. Recirculation flow induced by a bubble stream rising in a viscous liquid
The European Physical Journal B, **1998**, 4, 379-38

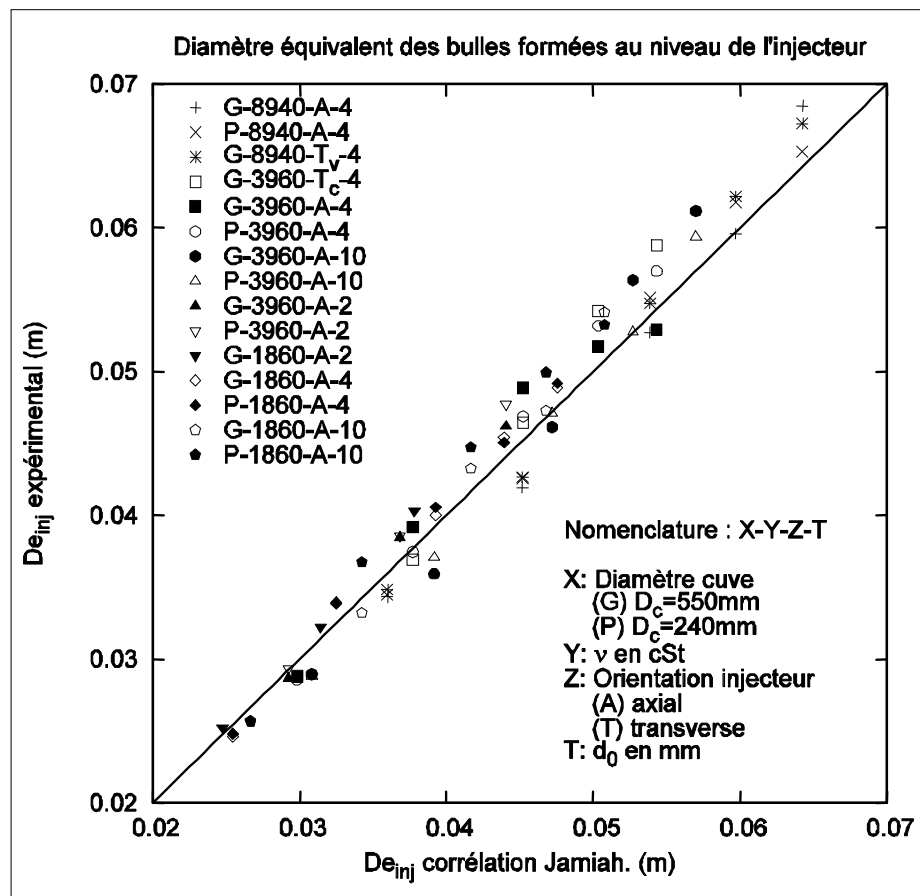
$$H_z \approx H_{cuve} - h_{inj}$$

$$D_z \approx d_f$$

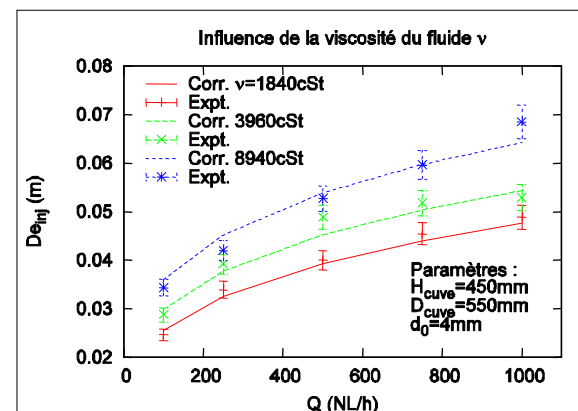
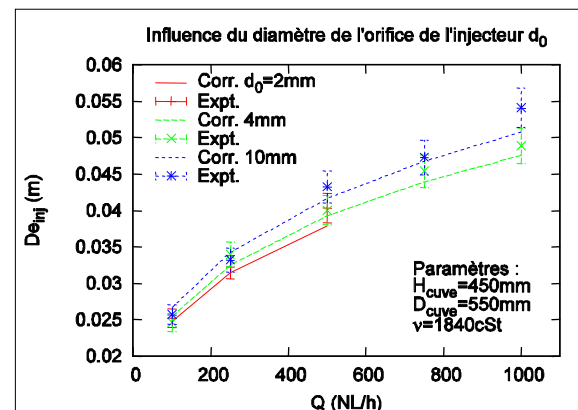
$$f_z \approx \rho g \varepsilon \quad [N m^{-3}]$$

$$\varepsilon = \frac{2 \boxed{Q} \boxed{d_e}}{3 \boxed{V_B} V} \quad V_B^2 = \frac{4 d_e g (1 + \varepsilon)}{3 C_d}$$

Correlation for bubbles diameter

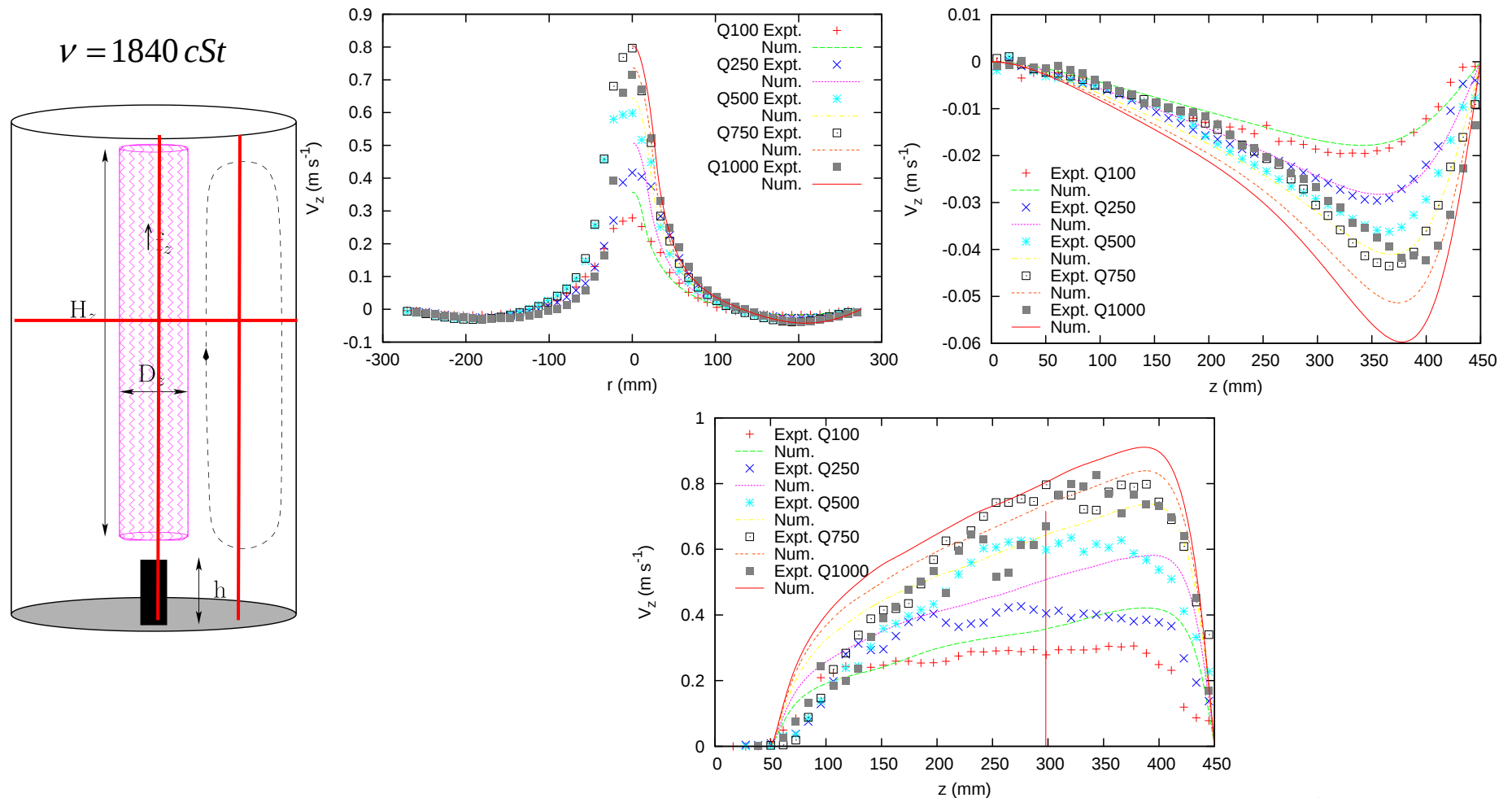


Jamialahmadi, M. et al, Study of Bubble Formation Under Constant Flow Conditions, *Chemical Engineering Research and Design*, 2001, 79, 523 - 532



2-a « One mesh » model

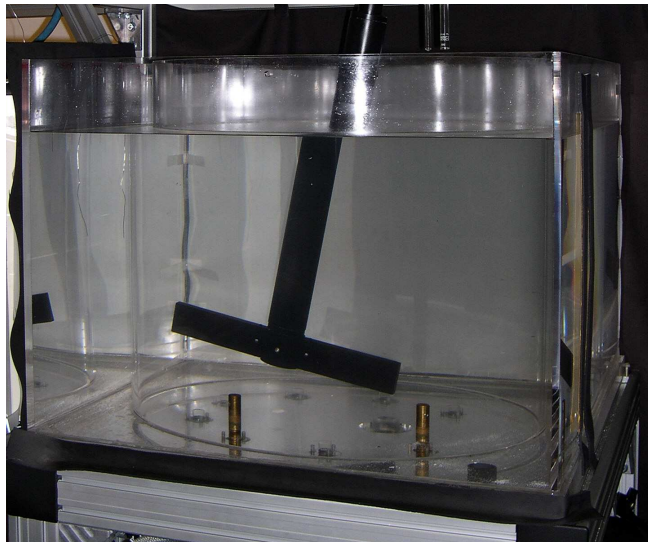
PIV measurement vs numerical simulation



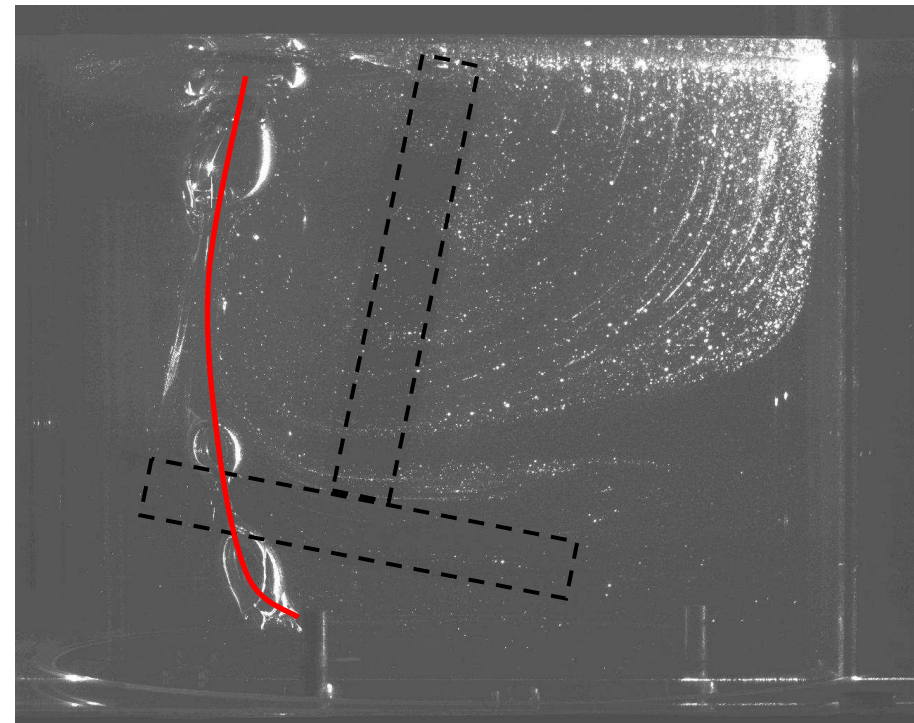
2-b Interaction with mechanical stirring

Effect of external flow induced by the mechanical stirring

Experimental set-up



PIV measurement



Deviation of the bubble train trajectory

No influence of the rotating speed on the size of bubble

Trajectory of bubble train

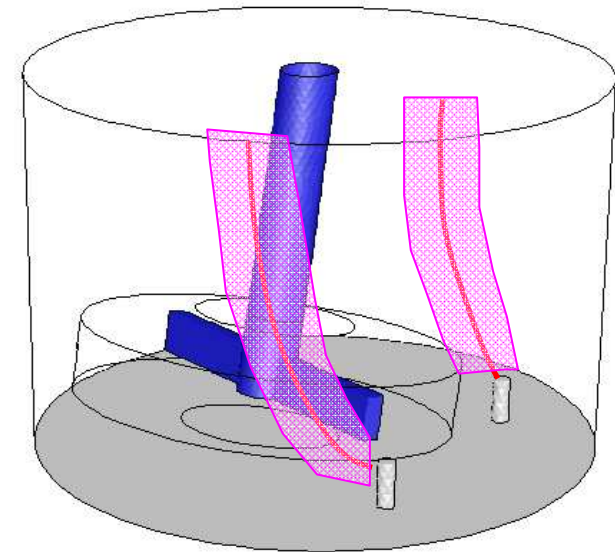
Lagrangian equation for the trajectory :

$$\frac{d\vec{u}_p}{dt} = F_D (\vec{u} - \vec{u}_p) + \frac{\vec{g}(\rho_p - \rho)}{\rho_p} + \vec{F}_{\text{sup}}$$

Drag force $F_D = \frac{18\mu}{\rho_p d_p^2} \frac{C_D \text{Re}}{24}$

$$\vec{F}_{\text{sup}} = \frac{1}{2} \frac{\rho}{\rho_p} \frac{d}{dt} (\vec{u} - \vec{u}_p) + \frac{\rho}{\rho_p} \vec{u}_p \frac{\partial u}{\partial x_i}$$

Added mass



Specific drag coefficient :

$$Cd = 1 + \frac{16}{\text{Re}}$$

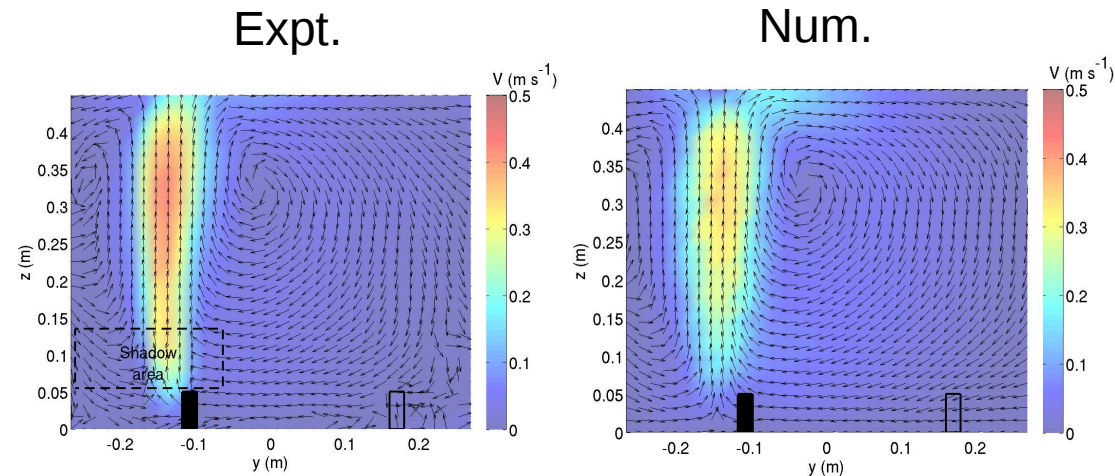
with $\text{Re} = \frac{\rho d_p |u_p - u|}{\mu}$

2-b Interaction with mechanical stirring

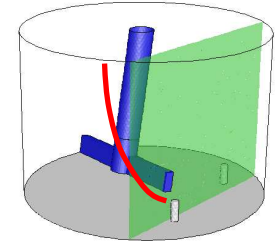
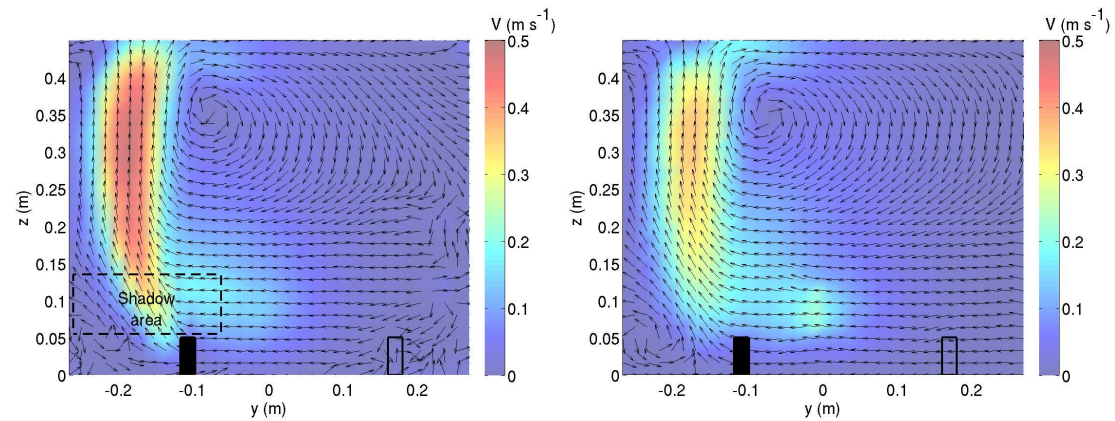
With one Air Bubler

Stirring speed

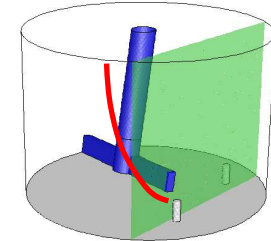
0 rpm



20 rpm

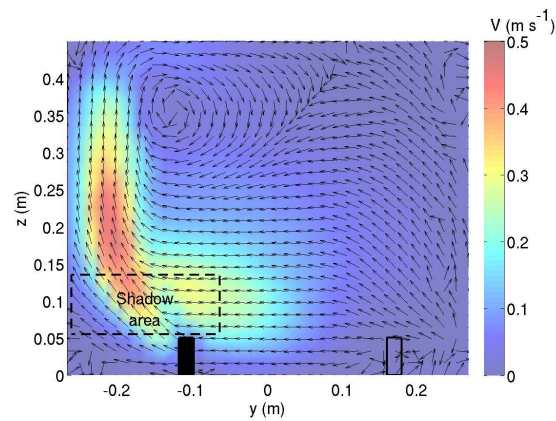


2-b Interaction with mechanical stirring

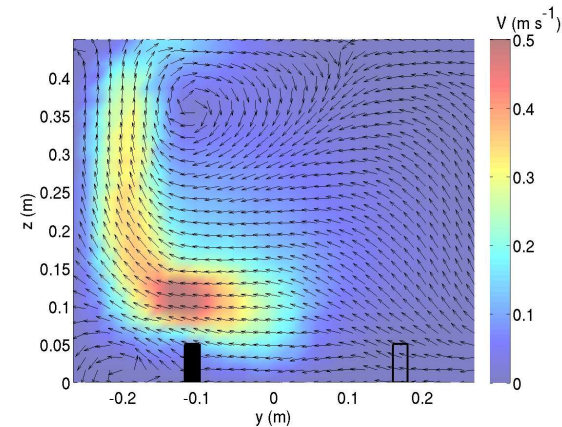


Stirring speed
40 rpm

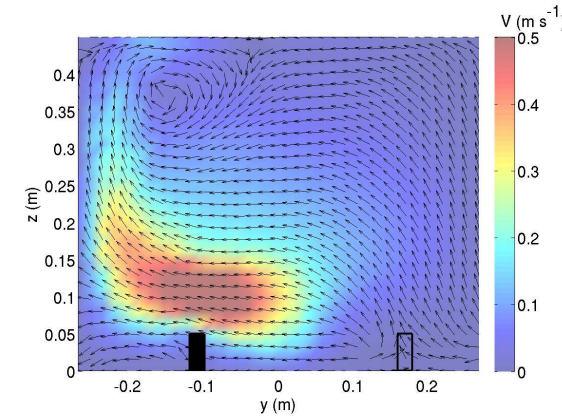
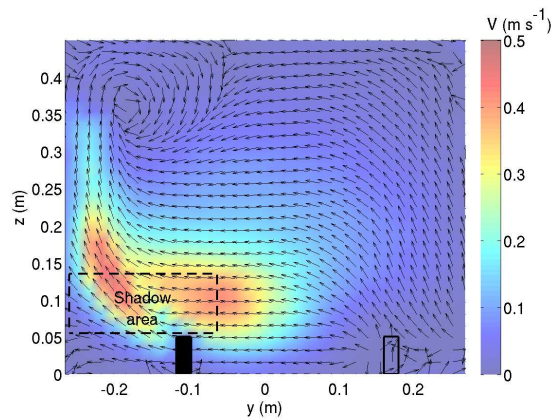
Expt.



Num.



60 rpm



Results

- A **Semi empirical model, simple, validated in a specific range of bubbling, easy to set up in global calculation of the process.**
- The interaction of mechanical stirrer is taken into account
 - **Drawback : not predictive outside the range of validation.**
- This model is used in our project of optimisation or conception of new vitrification furnace
- But some specifics cases can't be simulated with this model

Visualisations
rapides 250 im/s

Coalescence de
2 trains de bulles

$Q_{air} = 2 \times 100 \text{ NI/h}$
à $2 \times 500 \text{ NI/h}$

Ecartement = 60 mm

Viscosité = 3890 cSt

Modeling the gas-liquid interface

Volume Of Fluid (VOF) model equations

- Volume fraction of one phase

$$\frac{1}{\rho_L} \left[\frac{\partial}{\partial t} (\varepsilon_L \rho_L) + \nabla \cdot (\varepsilon_L \rho_L \vec{v}_L) \right] = 0 \quad \varepsilon_L + \varepsilon_G = 1$$

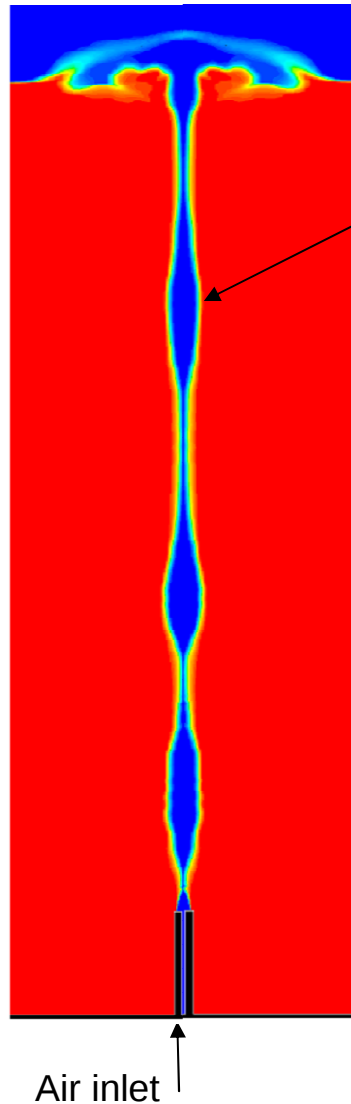
- Momentum equation

$$\frac{\partial}{\partial t} (\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot [\mu (\nabla \vec{v} + \nabla \vec{v}^T)] + \rho \vec{g}$$

$$\rho = \varepsilon_L \rho_L + \varepsilon_G \rho_G \quad \mu = \varepsilon_L \mu_L + \varepsilon_G \mu_G$$

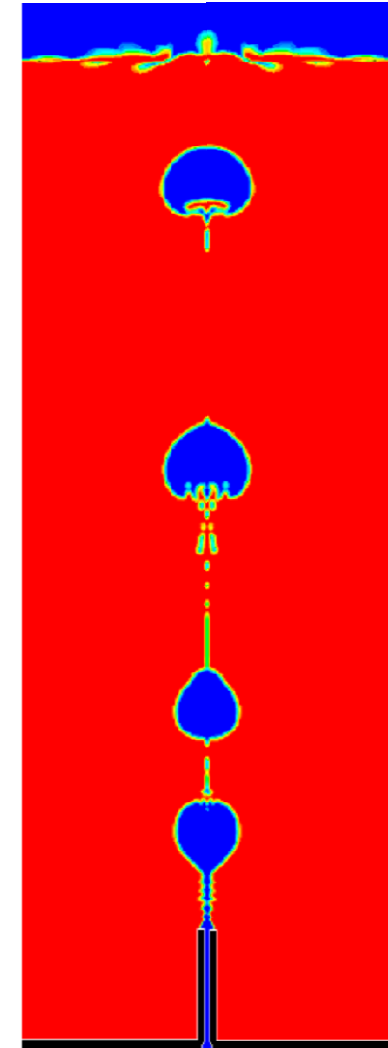
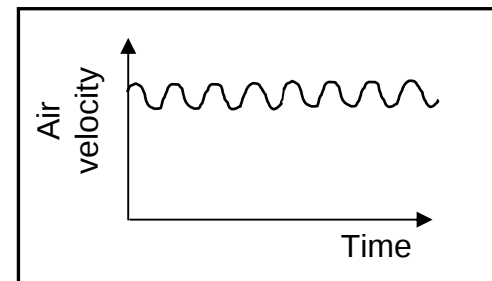
2-b Multiphase model

Problem :
No bubbles
are formed

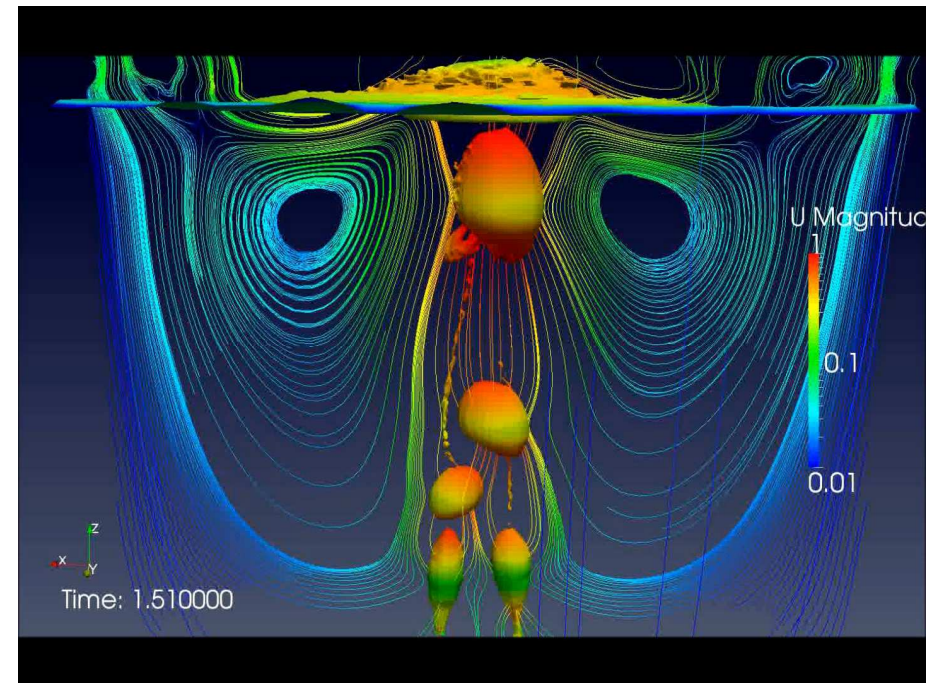
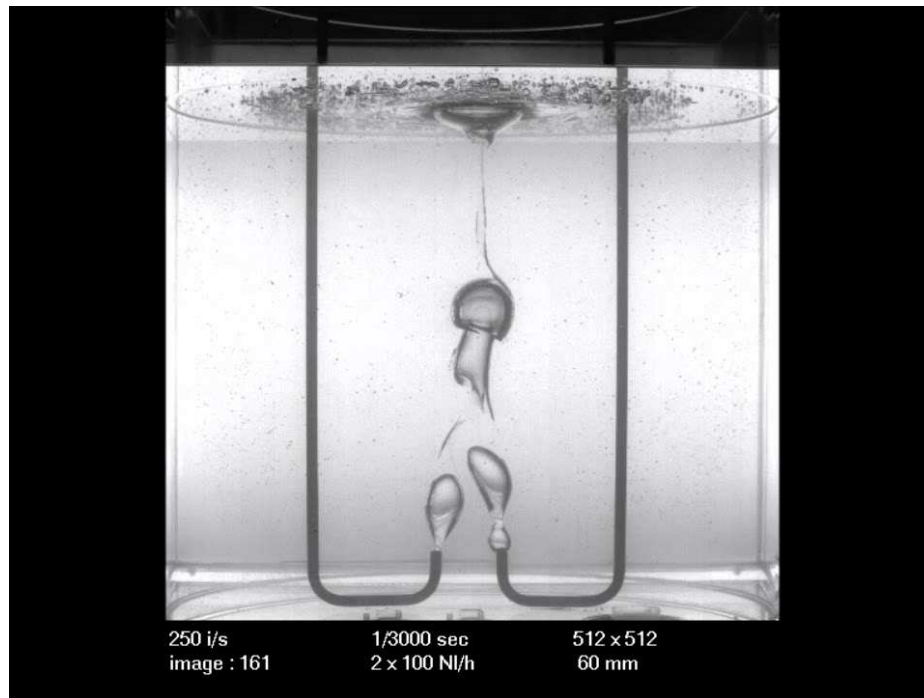


Air jet is a Rayleigh-Plateau instability. This instability should be numerically excited.

With high
frequency
modulation of
the inlet air flow
(300 Hz and 4%
magnitude)



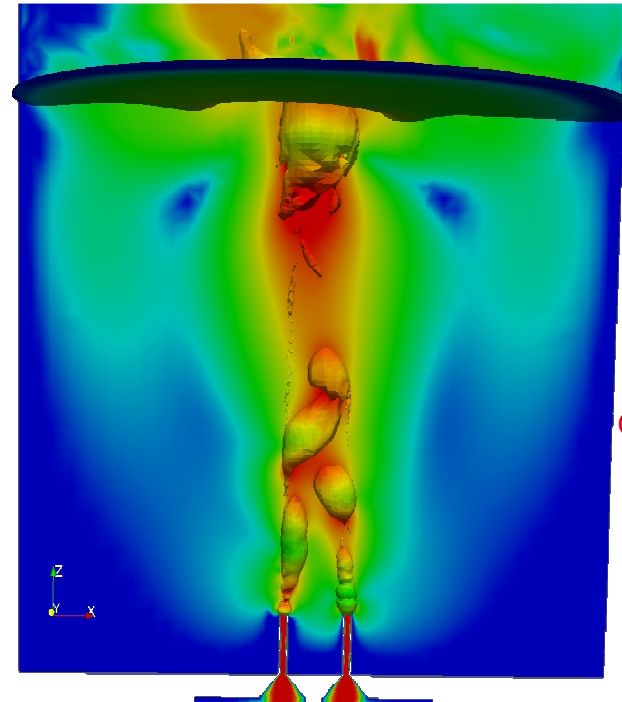
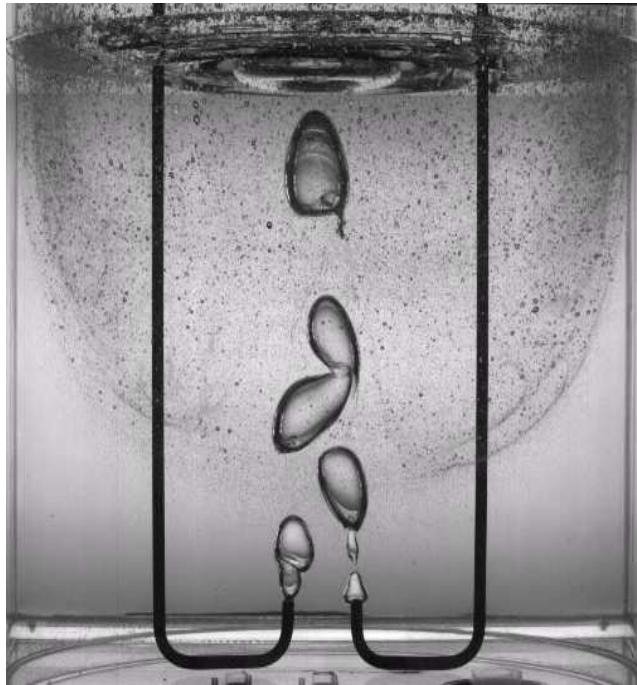
Complex diphasics flows have been successfully simulated.



Slow motion
(real time / 10)

Prospects : Multiphase model

VOF model, very accurate and allowing to simulate complex configuration.
Tool extremely useful to understand phenomena



Openfoam software
~2 millions mesh
elements

Good qualitative agreement – No more experimental-based correlations

Drawback : Highly time consuming (1 week of calculation for 1 second simulated)

Conclusion and prospects



Numerical Simulation of mixing molten glass with air bubbling is well advanced :

1 - A Semi empirical model, simple, validated in a specific range of bubbling, easy to set up in global calculation of the process.

- The interaction of mechanical stirrer is taken into account
 - **Drawback : not predictive outside the range of validation.**

This model is used in our project of optimisation or conception of new vitrification furnace

2 – A multiphase flow direct simulation (with VOF model) is used for specifics studies involving very complex interface interaction

Prospects :

Include redox aspect

Thank you for your attention

Any questions ?

Commissariat à l'énergie atomique et aux énergies alternatives
Centre de Marcoule | 30207 Bagnols-sur-Cèze cedex
T. +33 (0)4 66 79 XX XX | F. +33 (0)4 66 79 XX XX

Etablissement public à caractère industriel et commercial | RCS Paris B 775 685 019

Direction de l'Energie Nucléaire
DTCD
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