DE LA RECHERCHE À L'INDUSTRIE

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Numerical simulation of vitrification processes: Modeling of air bubbling in molten glass

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

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

13 MAY 2016

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Modeling of air bubbling in molten glass

Summary

1- Vitrification technology presentation

2- Semi empirical approach

- 2-a Model presentation
- 2-b Interaction with mechanical stirring
- 2-c Bubbles columns interaction

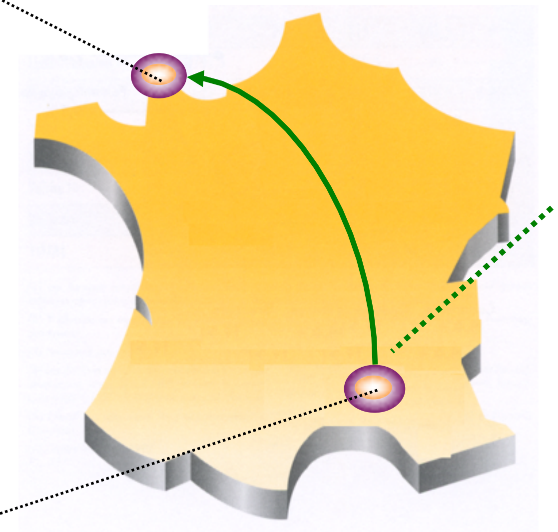
3- VOF simulation

CEA / AREVA Joint Vitrification Laboratory (LCV)

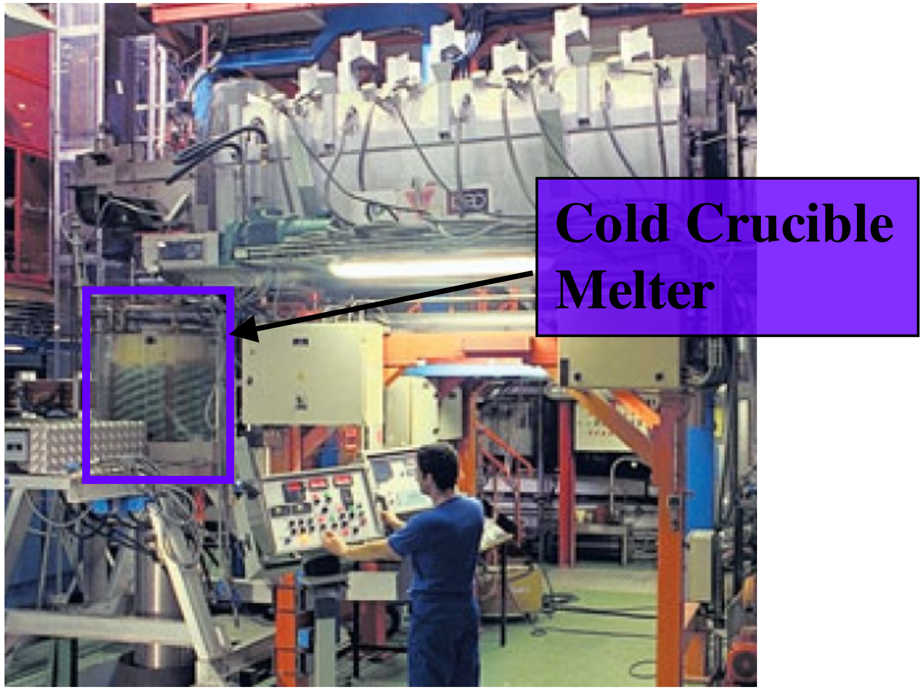
La Hague (AREVA) Industrial plant

Areva

- Commercial and industrial operator of 3 vitrification plants



Marcoule (CEA) Research center



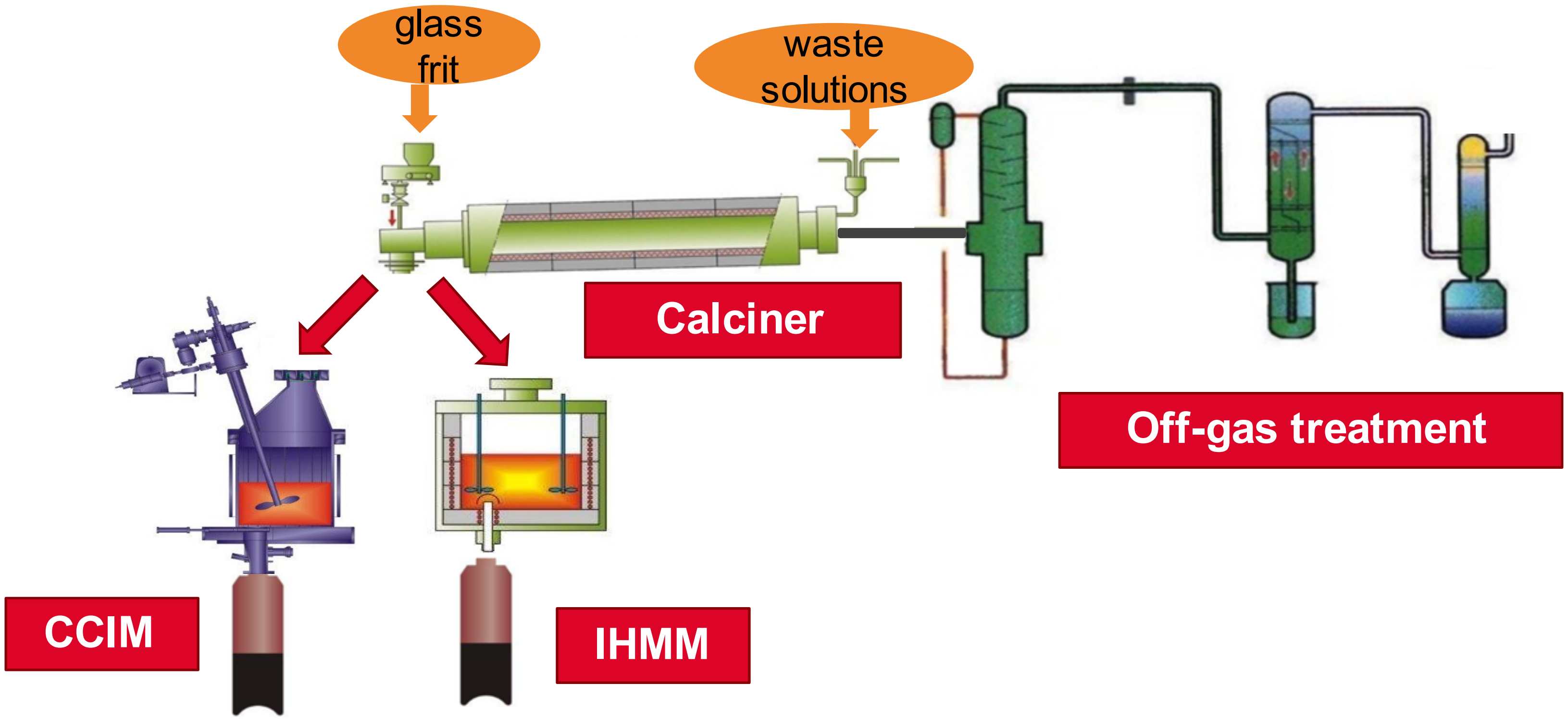
Current pilot of vitrification process
CEA Marcoule (inactive cell)

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

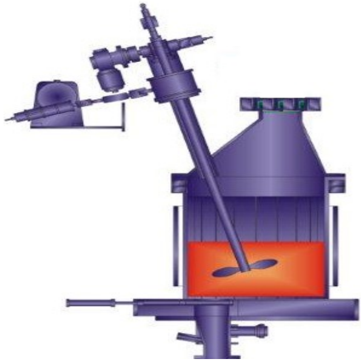


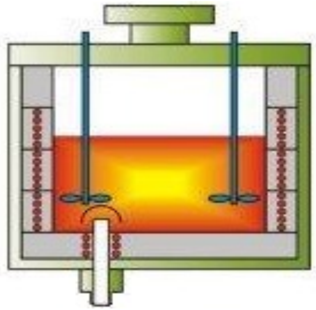
- ➲ Solution fed to a rotary calciner (evaporating, drying and calcining functions)
- ➲ Glass frit fed separately
- ➲ Melter fed continuously / poured batchwise
- ➲ Off-gas treatment unit (recycling of particulate material and purification of the gas streams)

VITRIFICATION PROCESS OPERATED IN THE LA HAGUE PLANT

Furnaces technology

	Cold Crucible Inductive Melter	Inductive Hot Metallic Melter





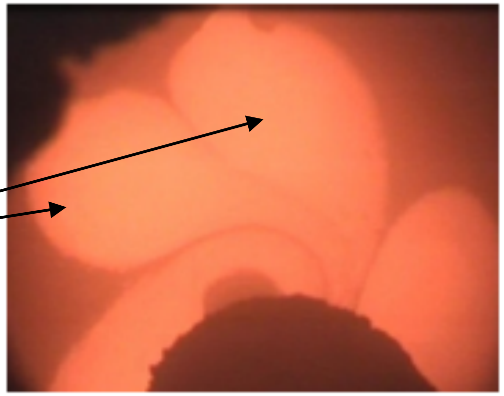
Characteristics:

	Cold Crucible Inductive Melter	Inductive Hot Metallic Melter
- 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 %)
SiO2	45,6
B2O3	14,1
Al2O3	4,7
Na2O	9,9
CaO	4
Fe2O3	1,1
NiO	0,1
Cr2O3	0,1
P2O5	0,2
Li2O	2
ZnO	2,5
Oxides (PF+Zr+actinides) + Suspension of fines Actinide oxides	17
SiO2+B2O3+Al2O3	64,4

Inside view in CCIM

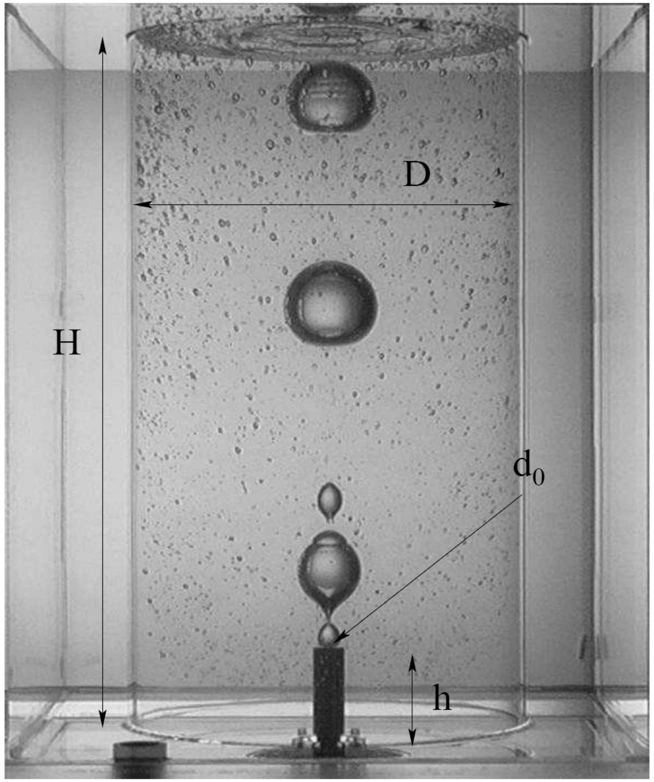


2 Bubbling characterization and modelisation

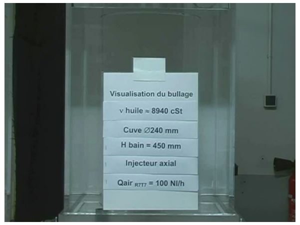
Air bubbling overview

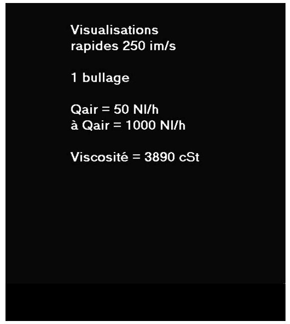
Experiment in hydraulic similirarity with silicon oil

R. RIVA *(CEA / Grenoble)*



30 to 60 cm





- 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 similirarity

		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	$8{,}55.10^{-5}$	$1{,}23.10^{-3}$
μ^*	μ_G/μ_L	$5{,}26.10^{-6}$	$5{,}12.10^{-6}$

2-a « One mesh » model

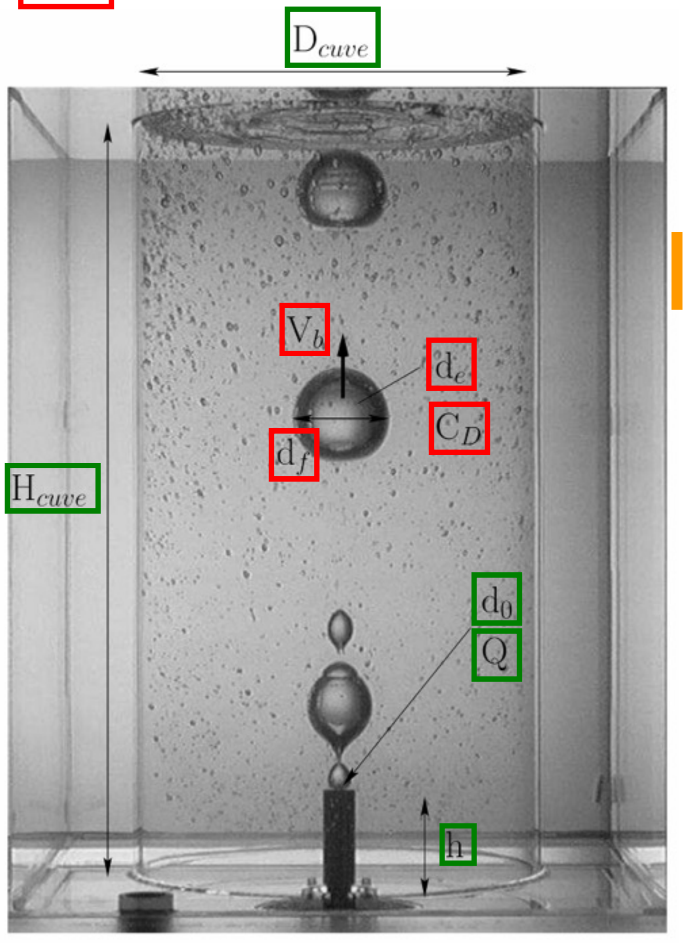
Known parameters

Characteristic parameters

Model parameters

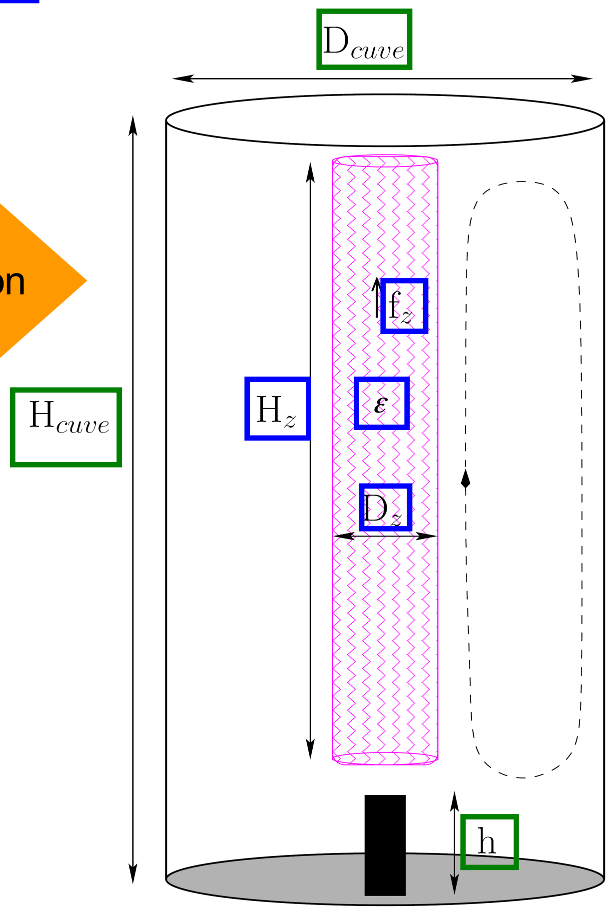
Nomenclature :

- Q Gas flow rate (L/h)
- g Gravity (m/s²)
- 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/m³)
- C_d Drag coefficient (-)
- V_{ol} Volume of a bubble (m³)
- p Liquid pressure (Pa)
- ρ_L Liquid density (kg/m³)
- μ_L Liquid viscosity (m²/s)
- ε_G Volume fraction of gas



$\rho_L \quad \mu_L \quad \rho_G \quad \mu_G \quad \sigma \quad g$

Modelisation



$\rho_L \quad \mu_L$

2-a « One mesh » model

[red box] = f([green box]) = experimental correlation

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

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

$Bd = \rho_L g d_0^2 / \sigma$ $\quad Ga = \rho_L^2 g d_0^3 / \mu_L^2$ $\quad Fr = V_g^2 / g d_0$

$$d_f = 1,23\, d_e$$

[blue box] = f([red box] , [green box]) = 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

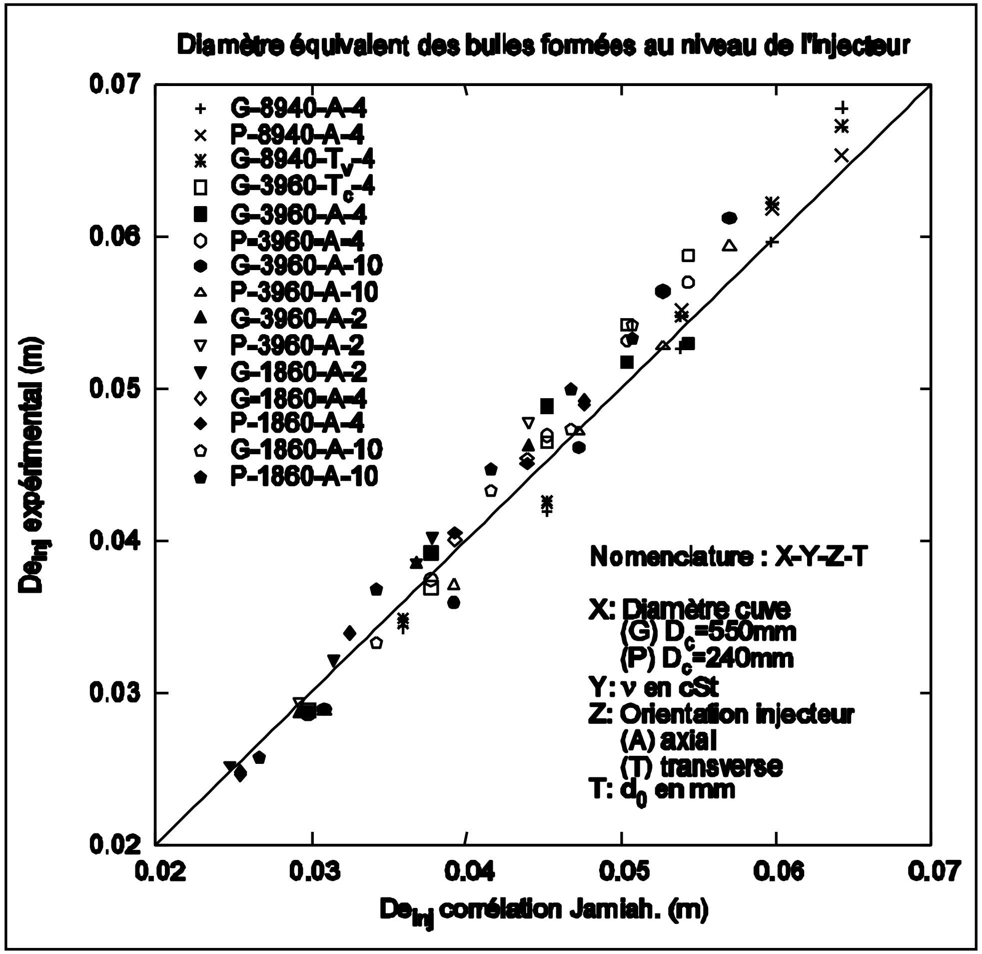
$$H_z \approx H_{cuve} - h_{inj}$$

$$D_z \approx d_f$$

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

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

Correlation for bubbles diameter



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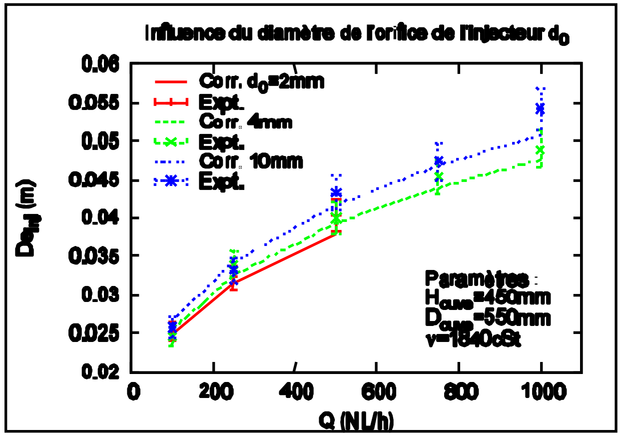
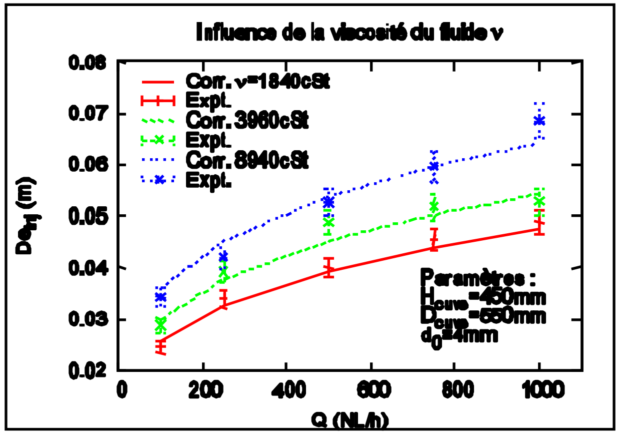
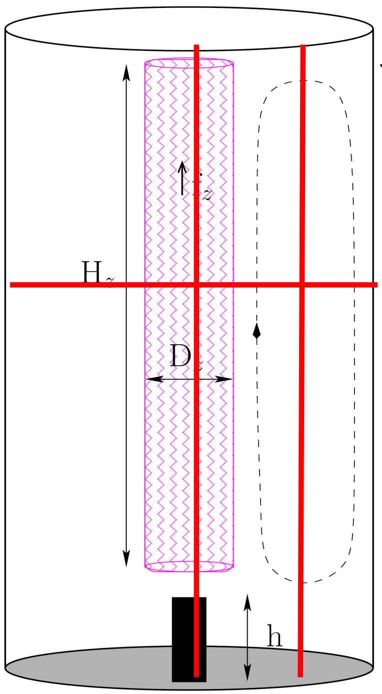
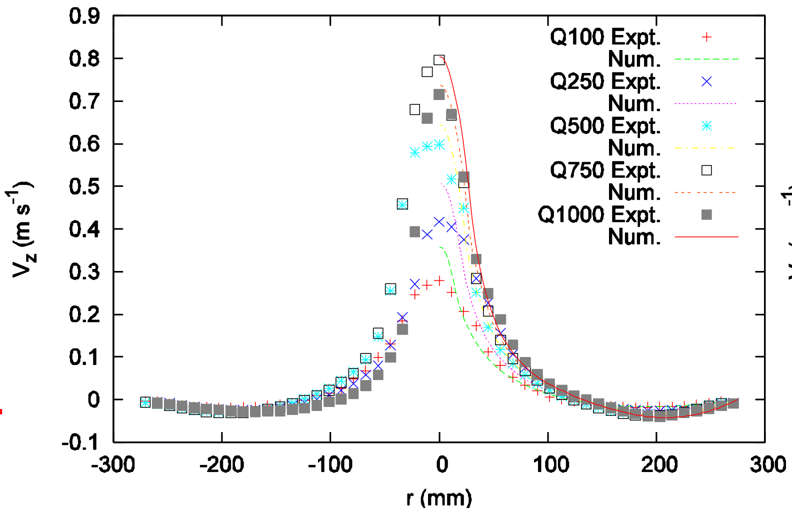


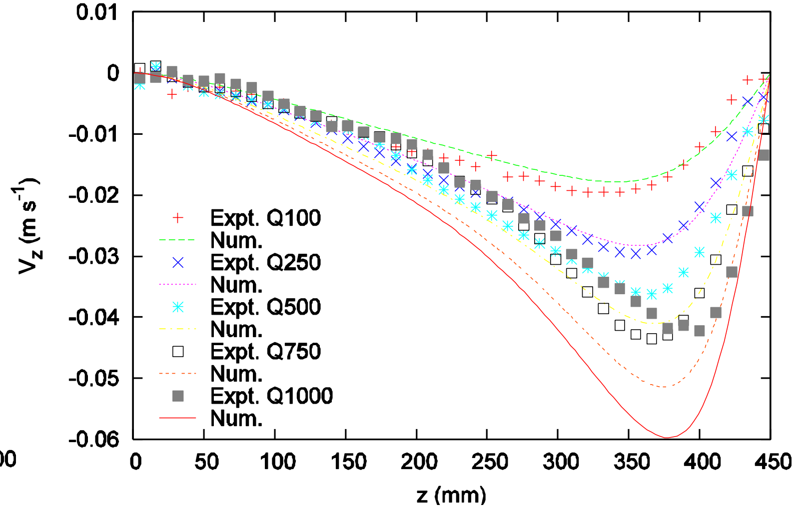


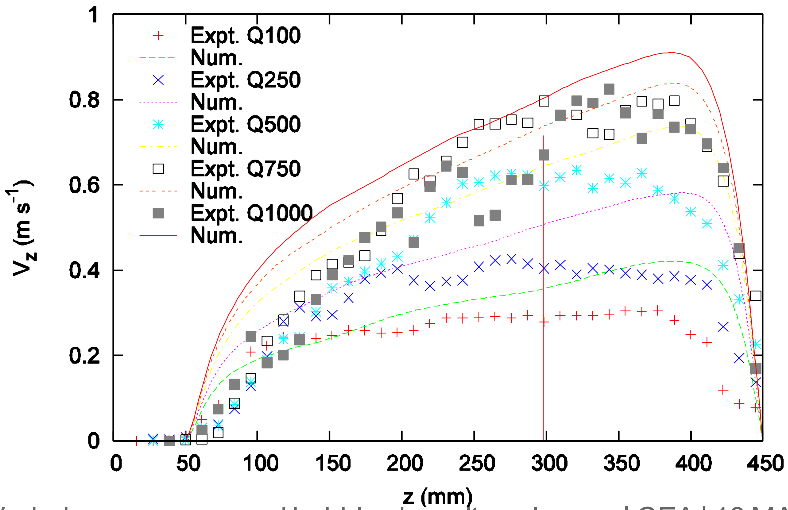
PIV measurement vs numerical simulation

$\nu = 1840\, cSt$





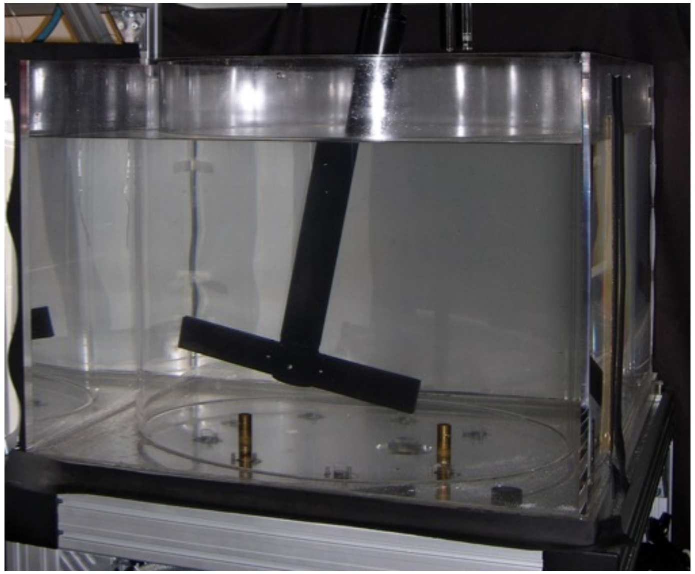




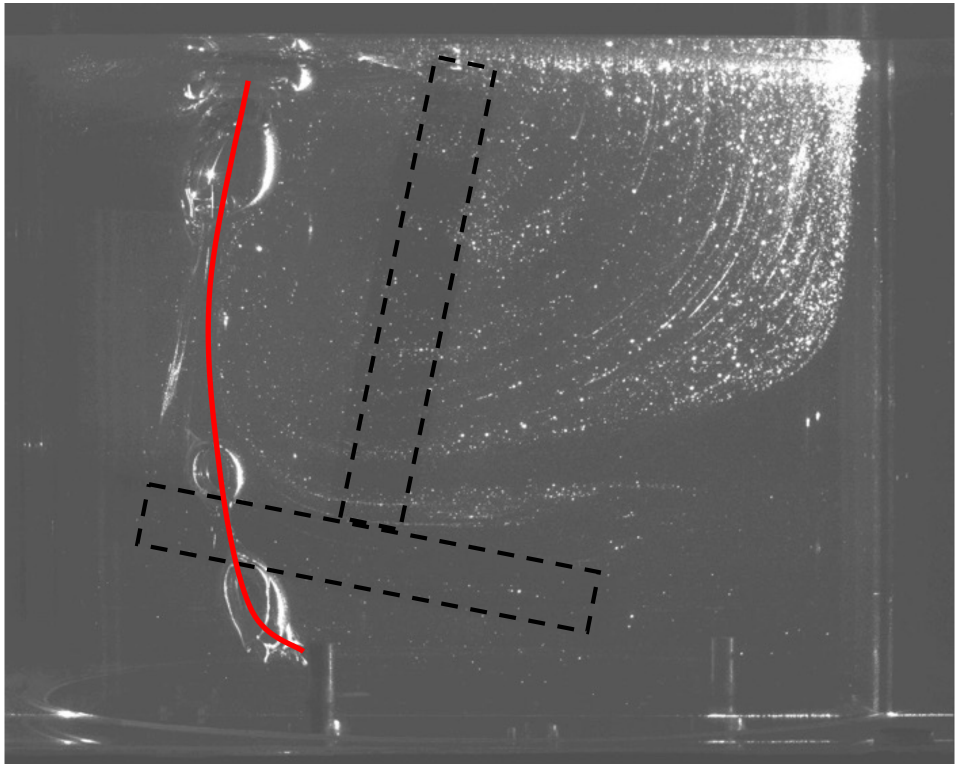
2-b Interaction with mechanical stirring

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 bubbles

2-b Interaction with mechanical stirring

Trajectory of bubble train

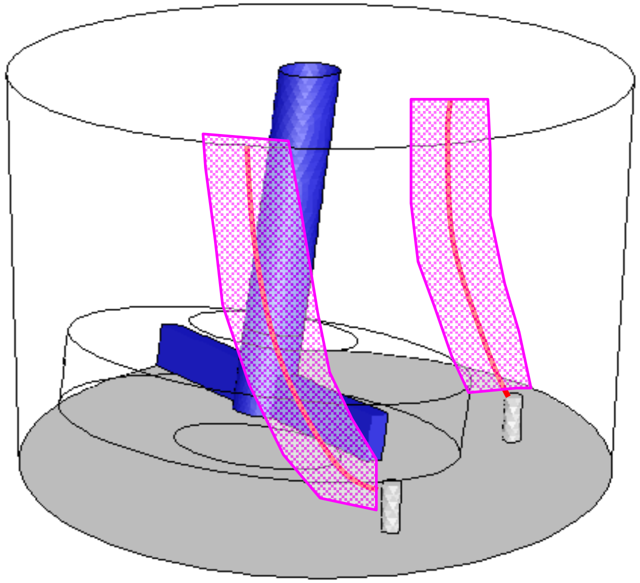
Lagrangian equation for the trajectory :

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

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

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

Added mass

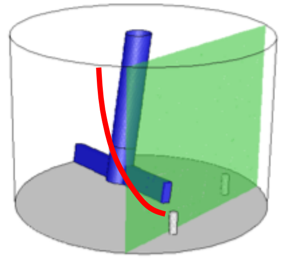


Specific drag coefficient :

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

with $\operatorname{Re} = \frac{\rho d_p \left|u_p - u\right|}{\mu}$

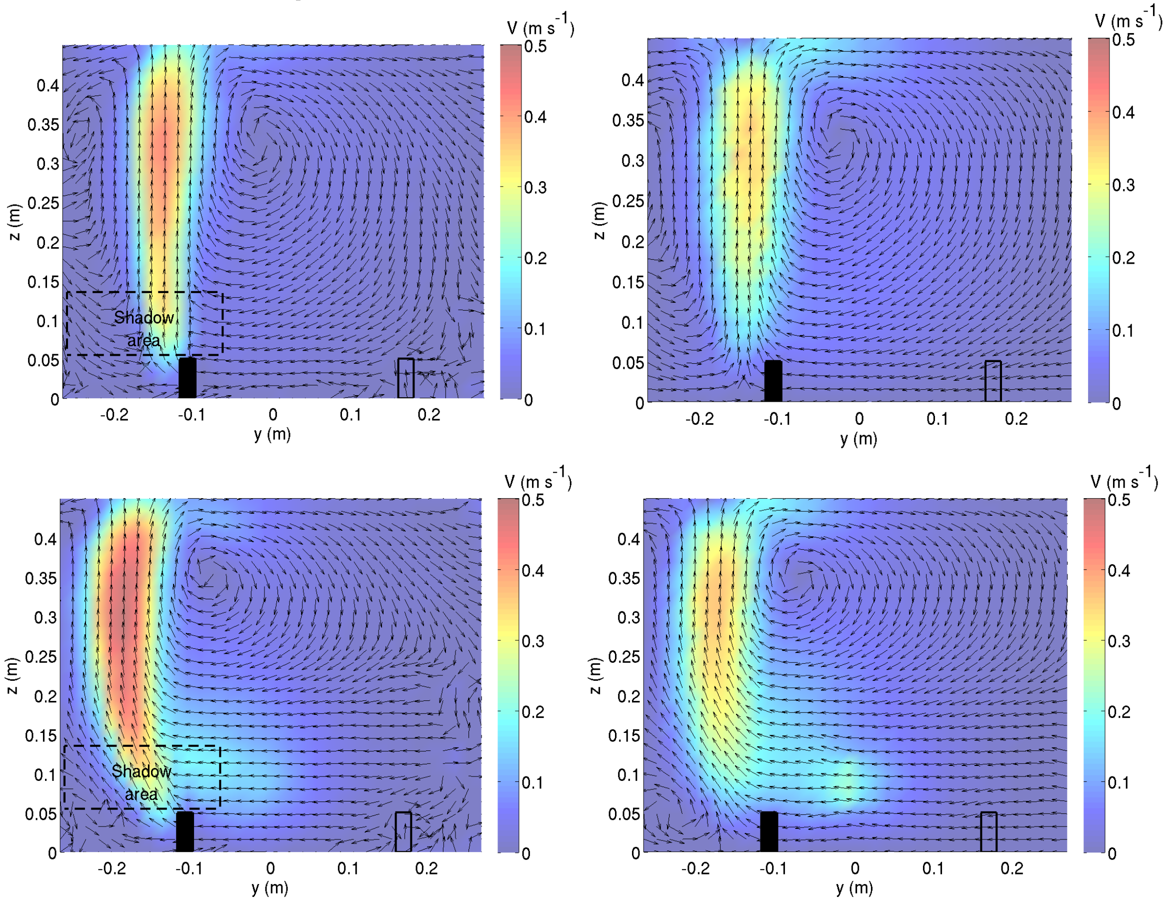
2-b Interaction with mechanical stirring



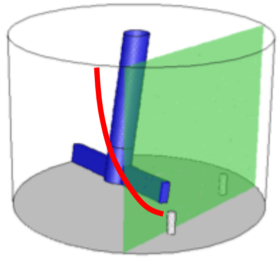
With one Air Bubler

Stirring speed

	Expt.	Num.
0 rpm		
20 rpm		



2-b Interaction with mechanical stirring

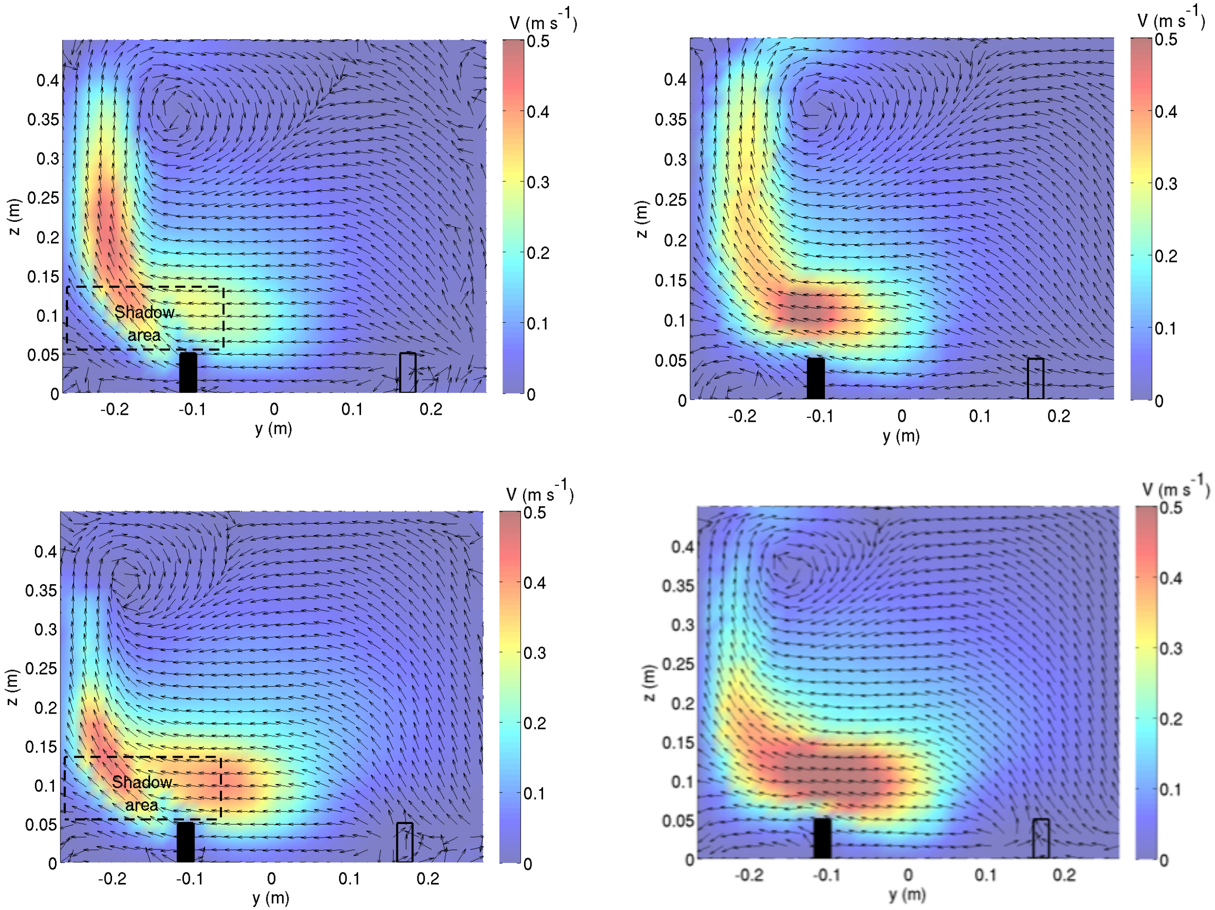


Expt. | Num.

Stirring speed

40 rpm

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.**

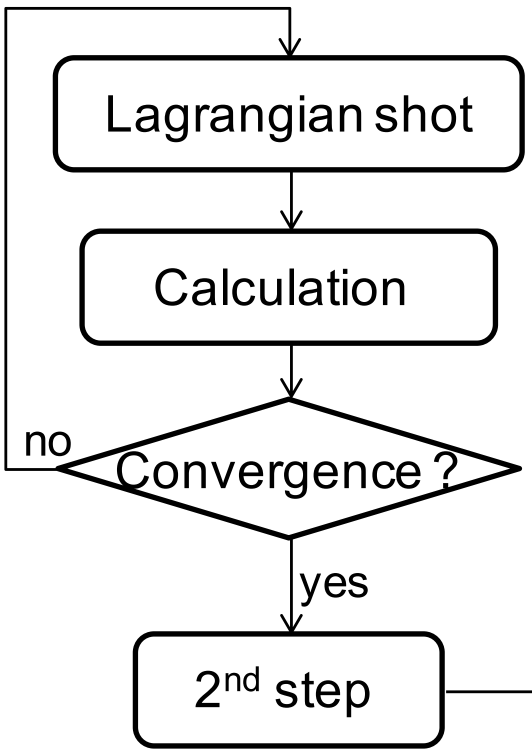
- The interaction of mechanical stirrer is taken into account
  - **Drawback : not predictive outside the range of validation.**

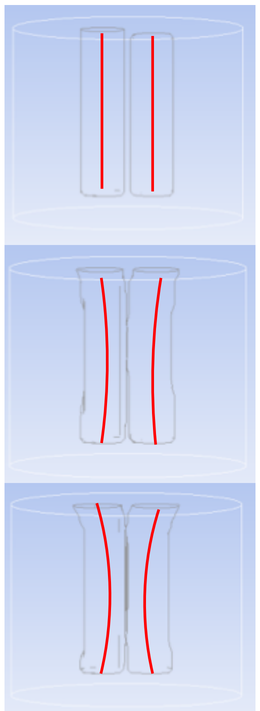
- This model is used in our project of optimisation or conception of new vitrification furnace

- But some specifics cases can't be simulated with this model

Calculation steps with coalescence

1st step





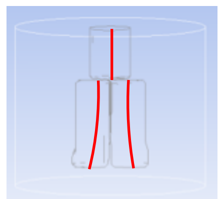
1st shot

2nd shot

6th shot

2nd step

Beginning at the height of coalescence (determined by hydraulic similarity tests), we compute a single path for the new bubble train.



coalescence

D. Gautheron (SymHydro conference 2012)

3 Multiphase model

Modeling the gas-liquid interface

Volume Of Fluid (VOF) model equations

- Volume fraction of one phase

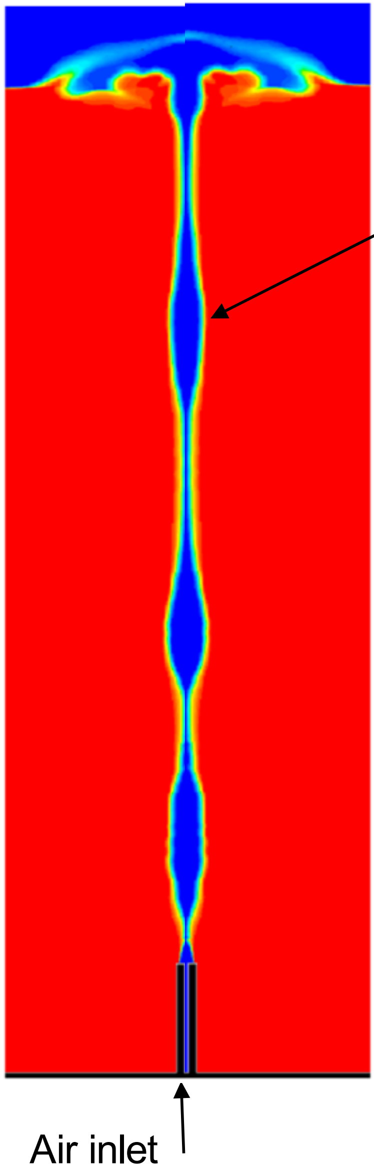
$$\frac{1}{\rho_L}\left[\frac{\partial}{\partial t}(\varepsilon_L \rho_L) + \nabla.(\varepsilon_L \rho_L \vec{v}_L) = 0\right] \qquad \varepsilon_L + \varepsilon_G = 1$$

- Momentum equation

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

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

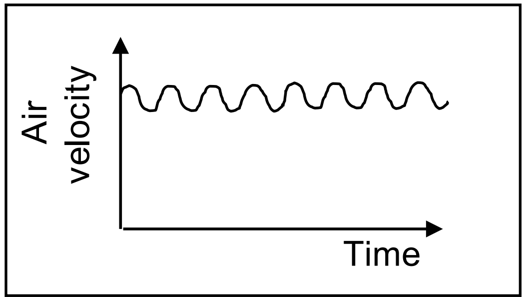
3 - Multiphase model

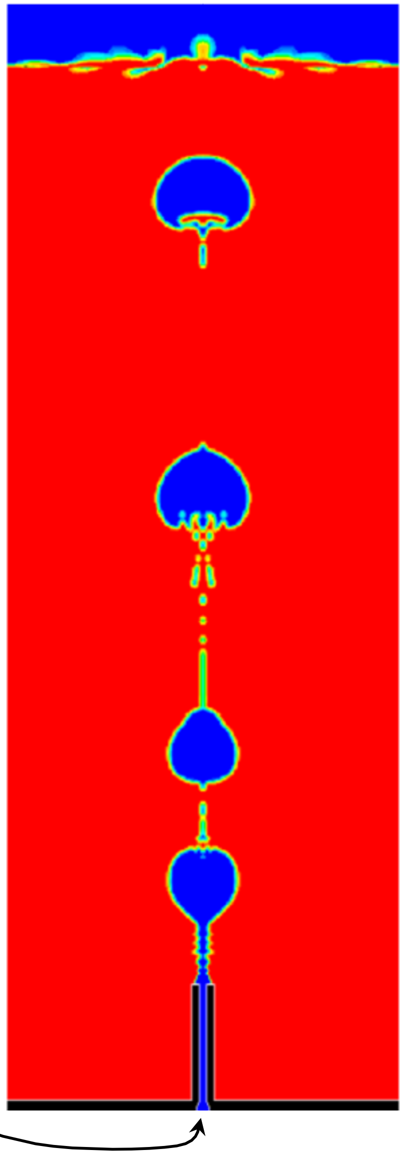


Problem :
No bubbles
are formed

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

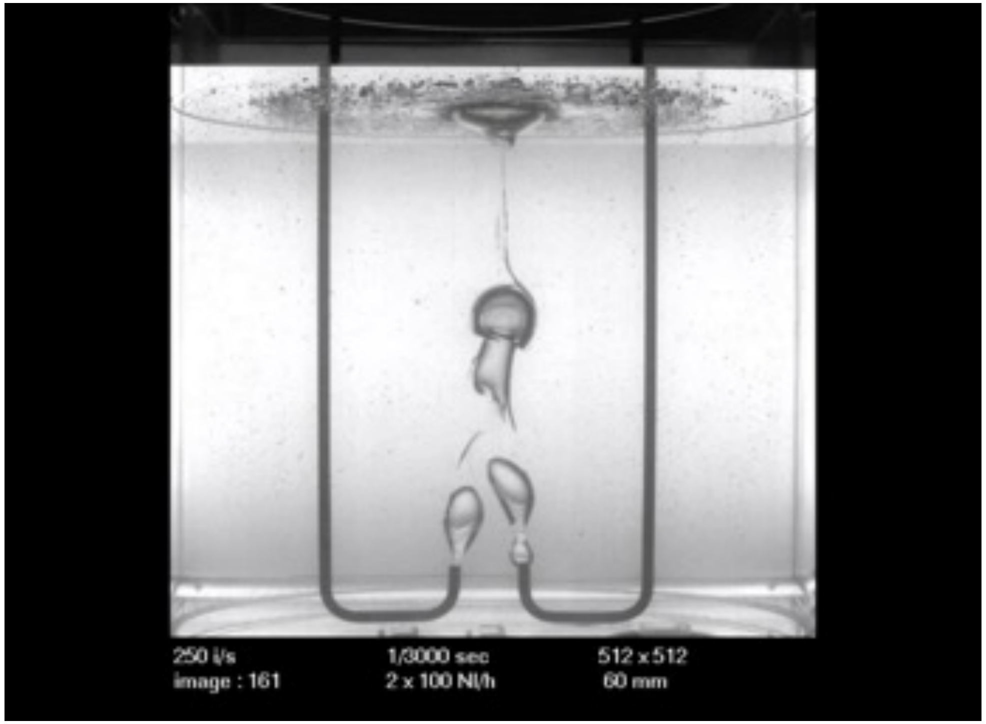
With high frequency modulation of the inlet air flow (300 Hz and 4% magnitude)

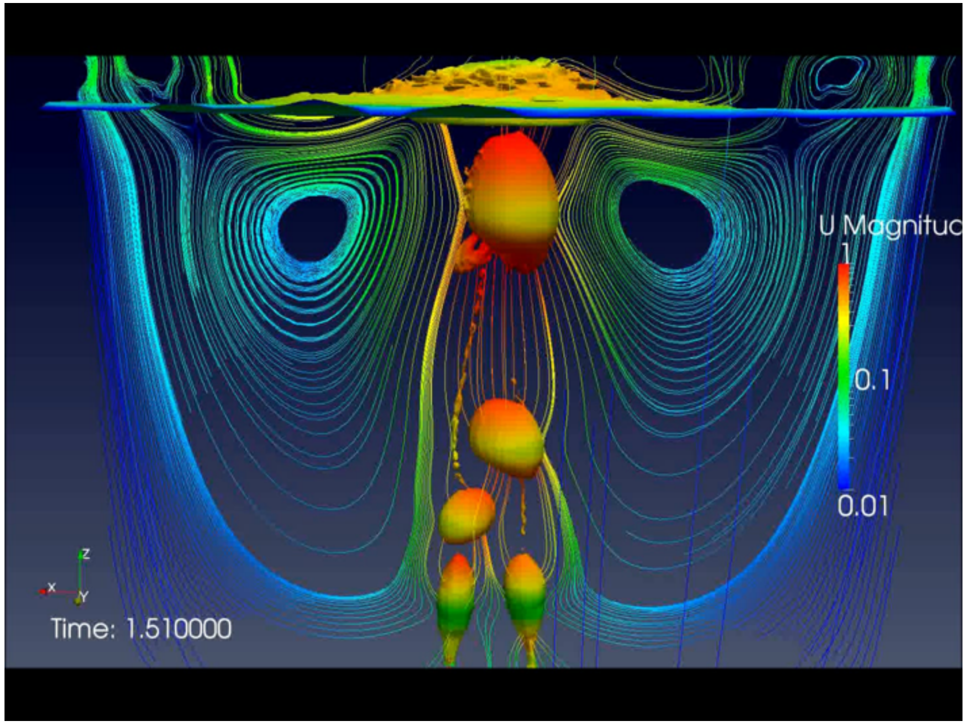




3- VOF Simulation

Complex diphasics flows have been successfully simulated.

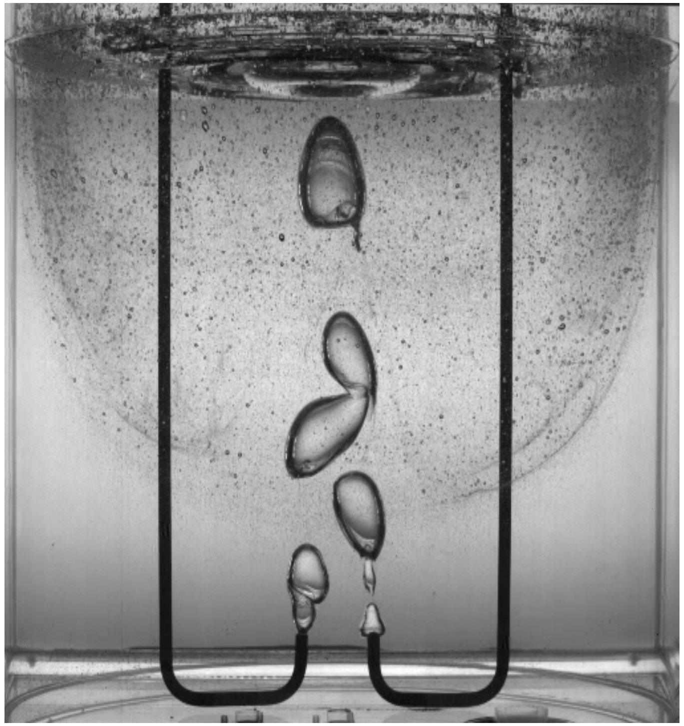


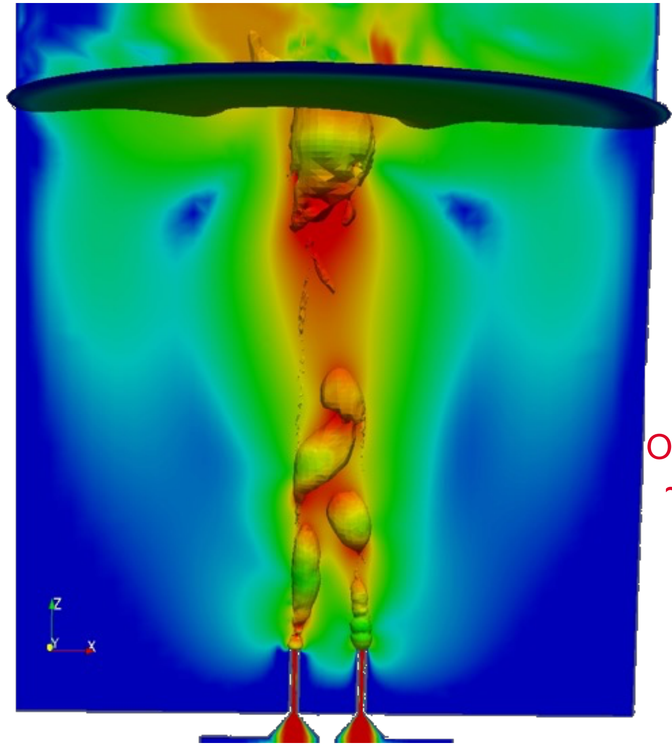


Slow motion
(real time / 10)

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 ?

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