Multifield CFD calculations of industrial geometries

Stéphane MIMOUNI

EDF R&D, Fluid Dynamics Power Generation and Environment

« Multiscale Modeling and Simulation » (MSME) - UMR 8208 CNRS

Laboratoire de Modélisation
et Simulation Multi Echelle

Stephane.Mimouni@edf.fr

NEPTUNE_CFD CODE : BASE MODEL

- NEPTUNE_CFD is a three dimensional two-fluid code developed more especially for nuclear reactor applications.
- The code deals with compressible, unsteady, turbulent 3D two-phase or multi-phase flow.
- The numerical approach is based on a finite volume co-located cell-centered approach.
- Equations of the two-phase flow model (so-called 6 equation model): mass, momentum and energy balance for both liquid and gas are solved.
- Turbulence for the liquid phase is modelled by a RSM (SSG)
- IATE + fragmentation, coalescence, condensation
- Forces exerted on bubbles : lift, drag, added mass and turbulent dispersion force.
- Wall transfer model for nucleate boiling

TWO-FLUID MODEL IN THE CODE NEPTUNE_CFD

Ishii [1975]

- **Mass balance equation:**

$$\partial_t(\alpha_k\,\rho_k) + \nabla.(\alpha_k\,\rho_k\boldsymbol{u}_k) = \Gamma_k \ \text{ with } \ \textstyle\sum_k \alpha_k \ = 1$$

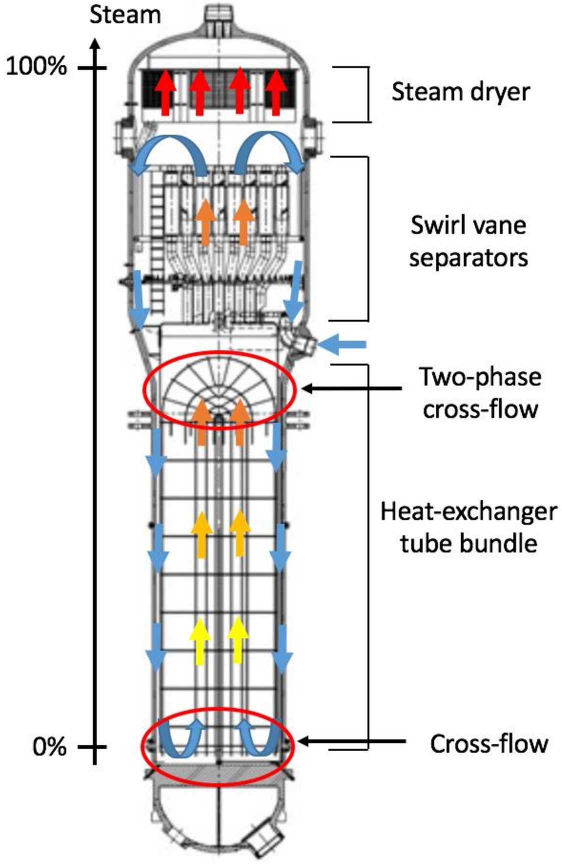
- **Momentum balance equation:**

$$\partial_t(\alpha_k\,\rho_k\boldsymbol{u}_k) + \nabla.(\alpha_k\,\rho_k\boldsymbol{u}_k\otimes\boldsymbol{u}_k) = \nabla.\left(\alpha_k\,\mu_k\underline{\underline{S_k}}\right) - \ \alpha_k\,\nabla P + \alpha_k\,\rho_k\boldsymbol{g} \\ + \boldsymbol{F}^{spe}$$

- **Energy balance equation:**

$$\partial_t(\alpha_k\,\rho_k H_k) + \nabla.(\alpha_k\,\rho_k H_k\boldsymbol{u}_k) = -\,\nabla.(\alpha_k\,Q_k) + \nabla.\left(\alpha_k\,\mu_k\underline{\underline{S_k}}\boldsymbol{u}_k\right) \\ +\alpha_k\,\partial_t P + \alpha_k\,\rho_k\boldsymbol{g}.\boldsymbol{u}_k + E_k^{Int}$$

[Ishii, M., 1975, Thermo-fluid dynamic, theory of two-phase, Eyrolles, University of Michigan]

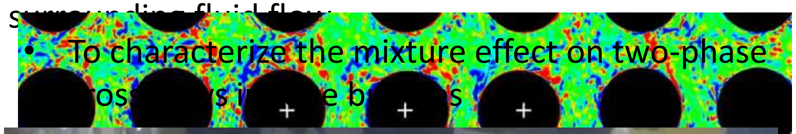


Objectives:

- To develop a numerical method able to perform two-phaseflow induced vibration

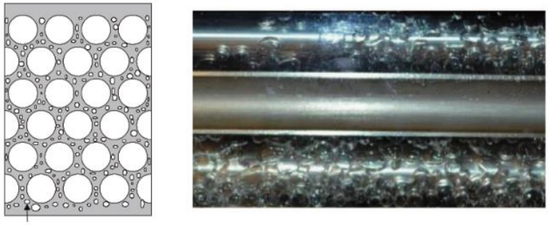
Fluid–structure interaction (FSI): interaction of some movable or deformable structure with an internal or surrounding fluid flow.

- To characterize the mixture effect on two-phase ross ys i e bu s

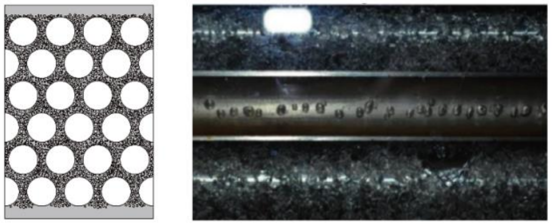


Source: Orano Youtube

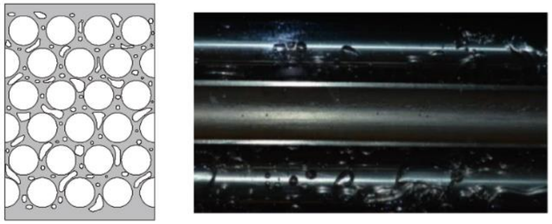
Two-phase flow patterns in tube bundles



Bubbles

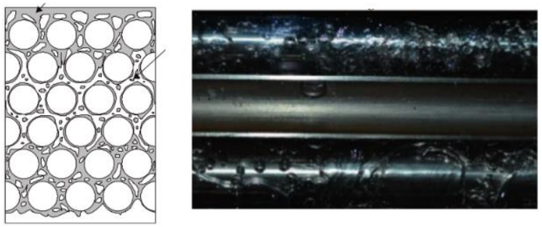


Dispersed bubbles

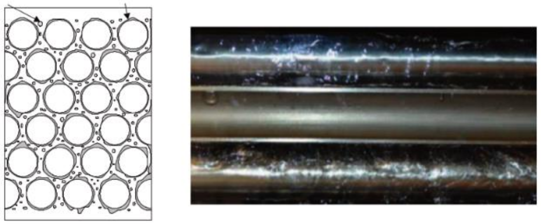


Large Bubbles

Churn



Intermittent



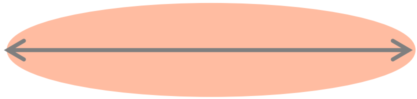
Annular

Kanizawa & RIbatski IJMF (2016)

CONTEXT

- **Safety issues involved complex flows**

Large range of bubbles diameters



Ex : Lift force coef $4 \le Eo_H \le 10 \quad C_L = 0.00105 Eo_H^3 - 0.0159 Eo_H^2 - 0.0204 Eo_H + 0.474$

$$Eo_H = \frac{g(\rho_g - \rho_l) d_H^2}{\sigma}$$

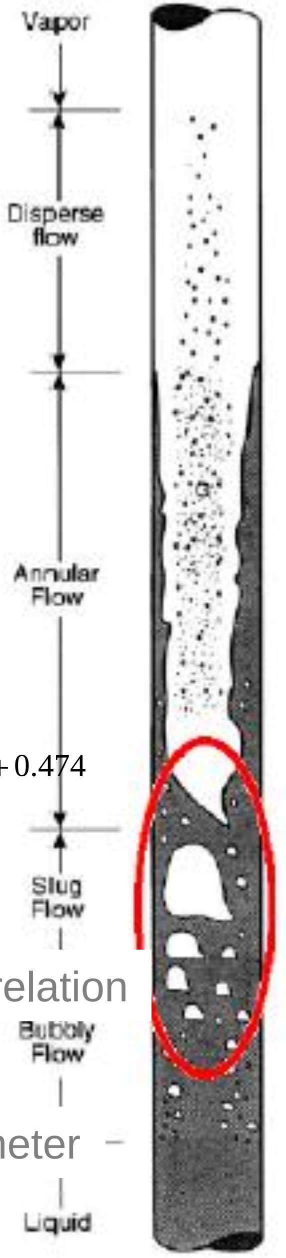
$$d_H = \mathrm{D_b} \sqrt[3]{1 + 0.163 Eo^{0.757}}$$

Wellek's correlation

$$Eo_H = \frac{g(\rho_g - \rho_l) D_b^2}{\sigma}$$

Db= mean Sauter Diameter

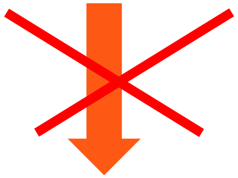
→ Large discrepancies for distorted bubbles



Stephane.Mimouni@edf.fr

CONTEXT

- **Large bubbles, considered as too distorted to be accurately described by correlations, are simulated through an interface locating method.**



> 1 billion of cells for the simulation of a whole reactor vessel containing small bubbles of 1mm

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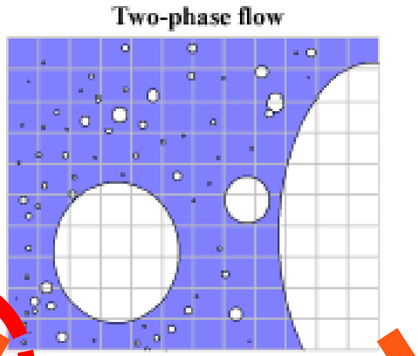
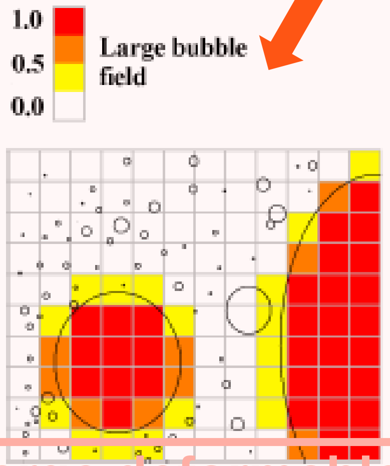
MODELLING STRATEGY: MULTIFIELD APPROACH



Surface tension, drag force model, interface sharpening equation

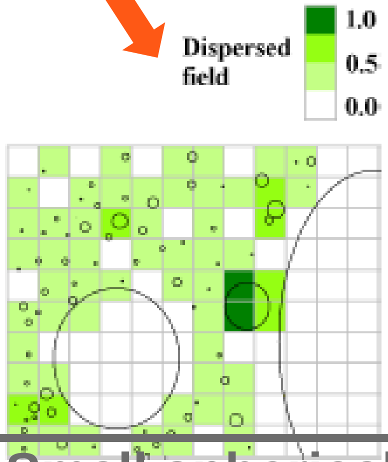
Interfacial momentum closure laws (drag, lift, added mass,…)

Large Bubble Model



Mass transfers

Coalescence and breakup



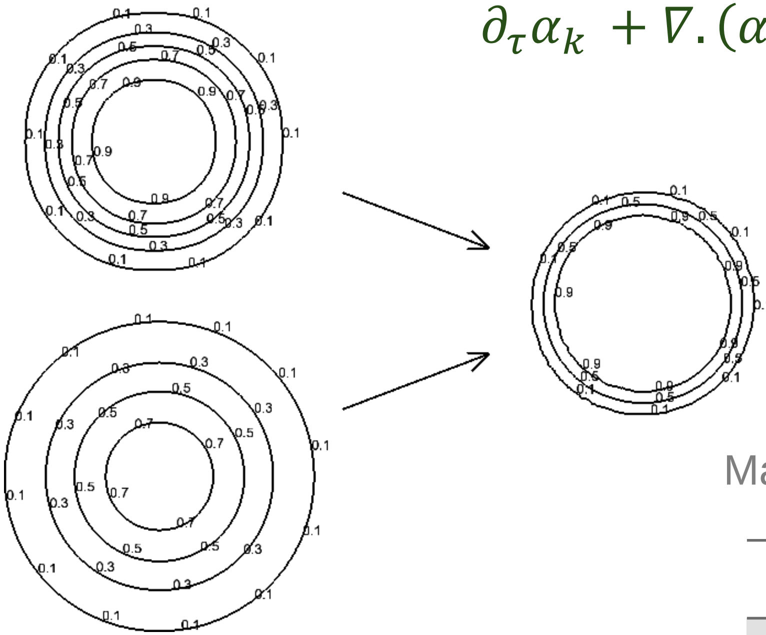
Large deformable bubbles

Small spherical bubbles

LIQUID / VAPOR INTERFACE

- **Interface sharpening equation,** *Olsson and Kreiss [2005]*:
  - To control the interface thickness

$$\partial_\tau \alpha_k + \nabla.(\alpha_k (1-\alpha_k) n) = \epsilon \Delta \alpha_k$$



Final interface thickness = 5 cells

$$\Delta\tau = \frac{\Delta x}{32} \quad \text{and} \quad \epsilon = \frac{\Delta x}{2}$$

Mass balance error by time step in the whole domain:

Non conservative implementation	10^{-11} %
Conservative implementation	10^{-17} %

$$\partial_t(\alpha_k \rho_k) + \nabla.(\alpha_k \rho_k \boldsymbol{u}_k) = \Gamma_k$$

Total mass flux = mass flux (mass balance) + mass flux (interface sharpening)

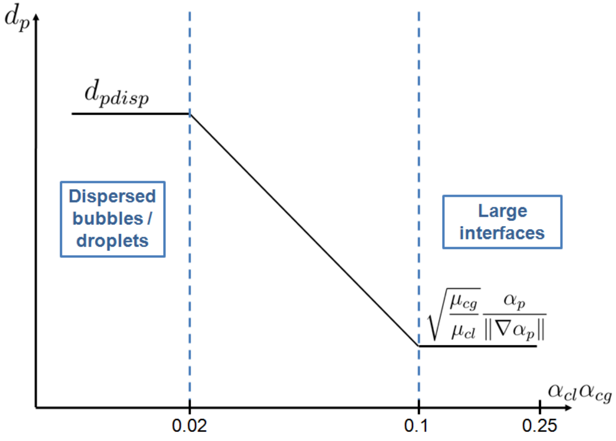
[Olsson, E., and Kreiss, G., 2005, A conservative level set method for two phase flow, *J. Comput. Phys.*, Vol. 210, pp. 225–246]

LIQUID / VAPOR INTERFACE

- **Surface tension force,** *Brackbill et al. [1992]*:
  - For deformable interfaces with a finite thickness

$$F_{CSF} = \alpha_k \, \sigma \kappa \nabla \alpha_k \quad \text{with } \kappa = -\nabla . \left(\frac{\nabla \alpha_k}{||\nabla \alpha_k||} \right)$$

- **Drag force law:**
  - To couple the velocity of each field at the interface



Bubbly flow

$$\alpha_{cg} < 0.3 : \qquad \mathbf{F}_{bubble} = \alpha_{cl}\alpha_{cg} \frac{18\mu_{cl}}{\alpha_{cl} d_p^2} (\mathbf{u}_{cl} - \mathbf{u}_{cg})$$

Droplet flow

$$\alpha_{cg} > 0.7 : \qquad \mathbf{F}_{droplet} = \alpha_{cl}\alpha_{cg} \frac{18\mu_{cg}}{\alpha_{cg} d_p^2} (\mathbf{u}_{cl} - \mathbf{u}_{cg})$$

Complex flow

$$0.3 \leq \alpha_{cg} \leq 0.7 : \quad \mathbf{F}_{mix} = \frac{0.7 - \alpha_{cg}}{0.7 - 0.3} \mathbf{F}_{bubble} + \frac{\alpha_{cg} - 0.3}{0.7 - 0.3} \mathbf{F}_{droplet}$$

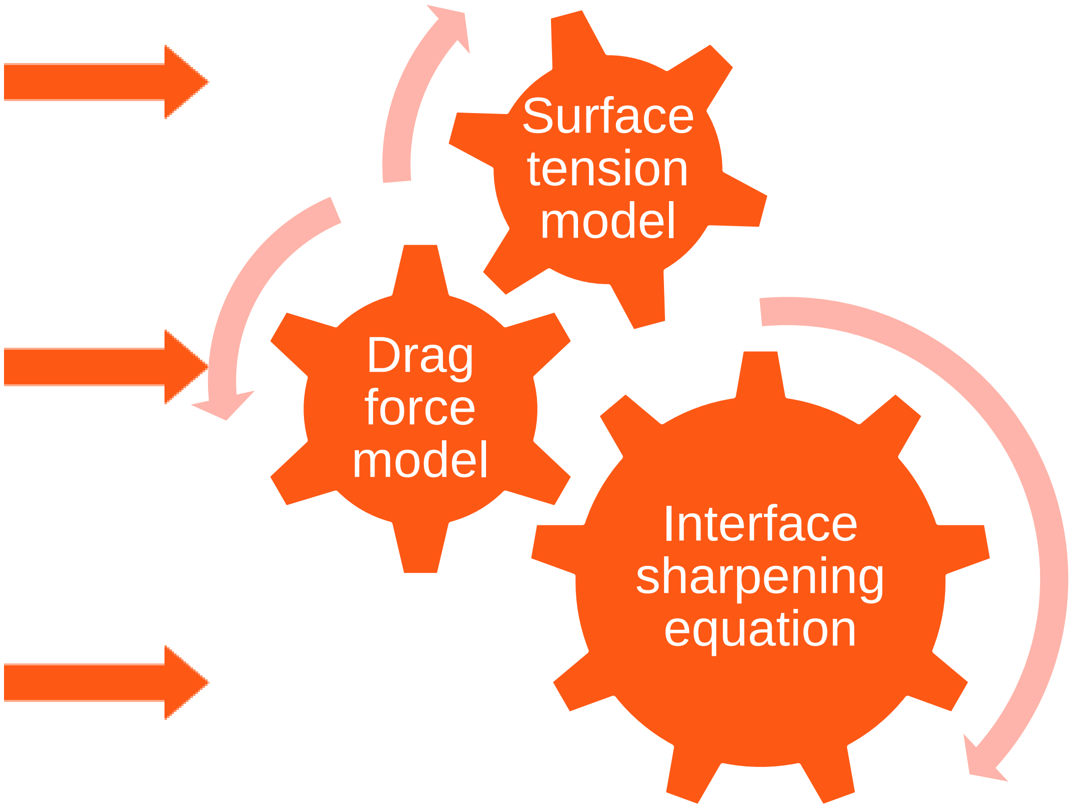
[Brackbill, J.U. *et al.*, 1992, A continuum method for modeling surface tension, *J. Comput. Phys.*, Vol. 100, pp. 335-354]

LIQUID / VAPOR INTERFACE

Large Bubble Model

- **Large deformable interfaces**
- **Two different velocity fields are defined at the interface**
- **Interface smearing caused by the two-fluid approach**

Control the interface thickness



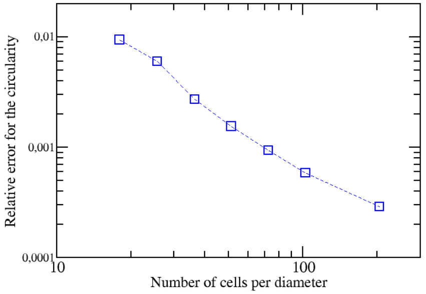
Surface tension model

Drag force model

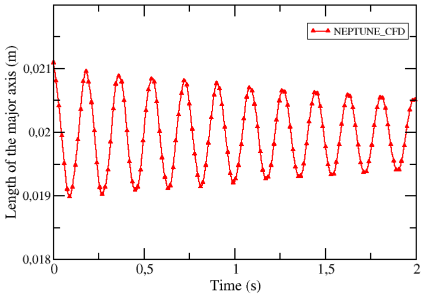
Interface sharpening equation

VALIDATION ON ISOTHERMAL FLOWS

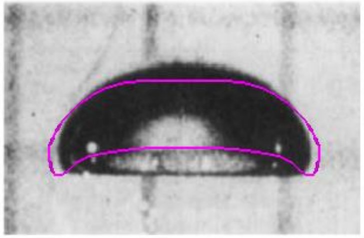
- Bubbly flows:
  - Stationary bubble



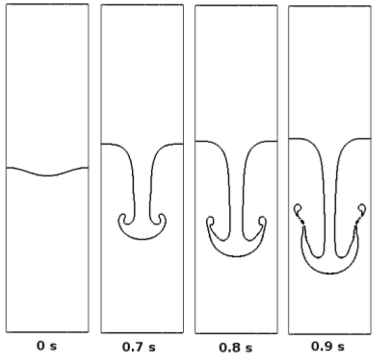
  - Oscillating bubble



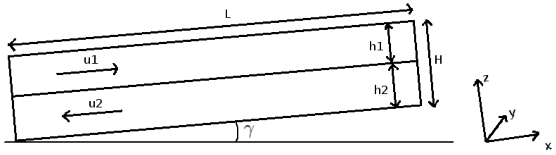
  - Bhaga's rising bubble

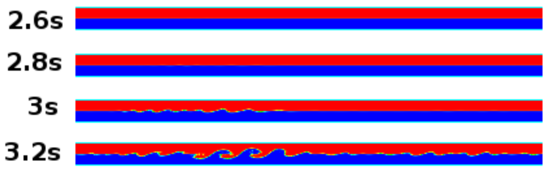


- Interfacial liquid / liquid flows:
  - Rayleigh-Taylor instability

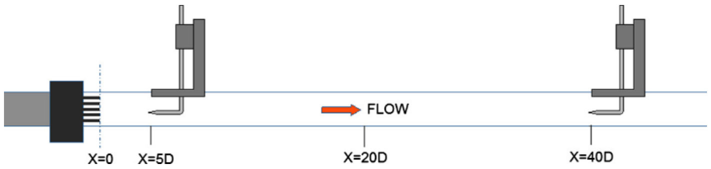


  - Kelvin-Helmholtz instability

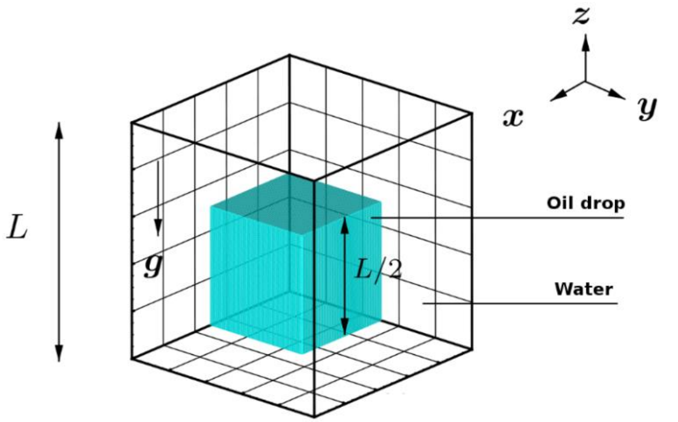




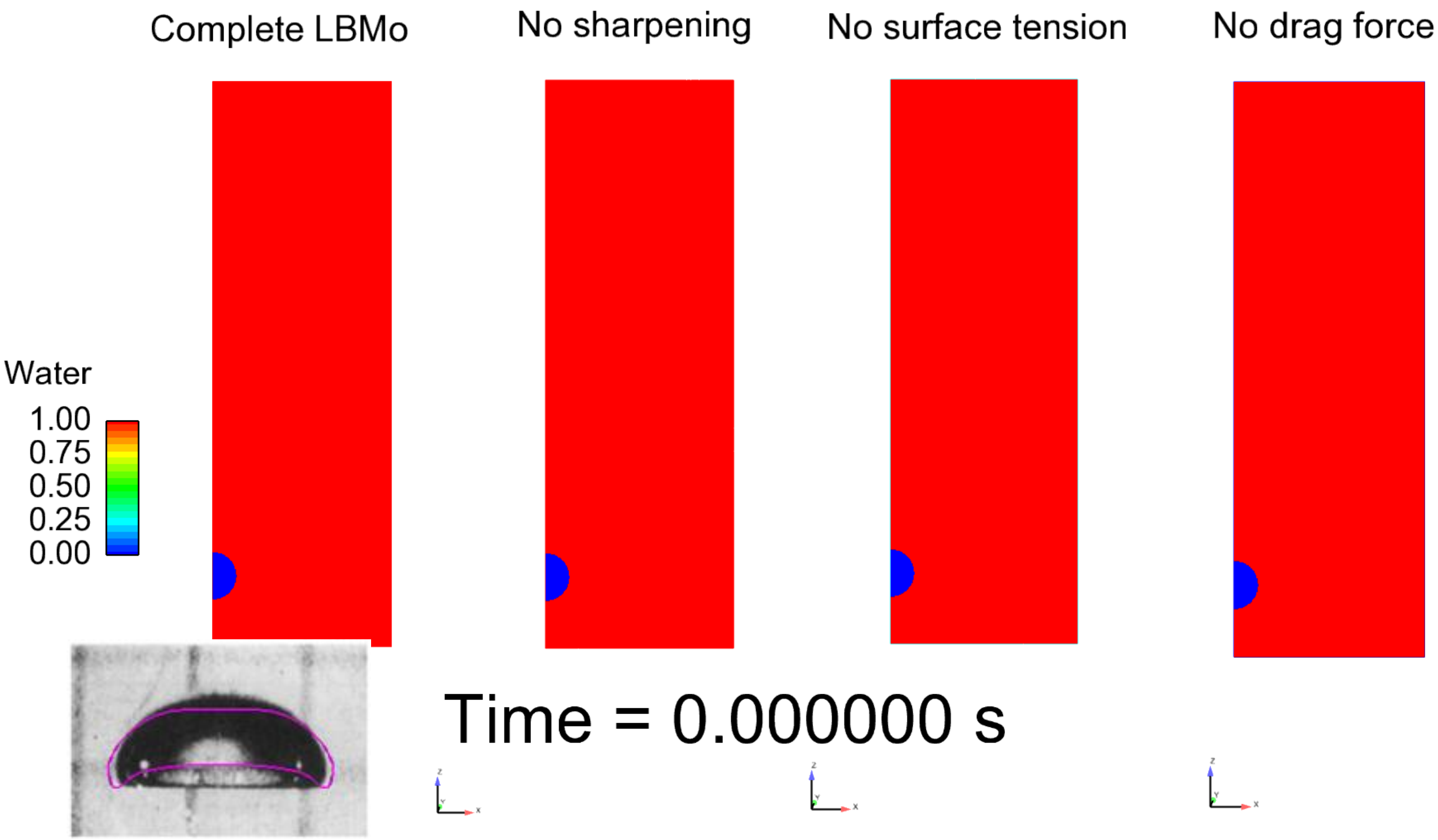
- **Multi-phenomena flows:**
  - METERO experiment



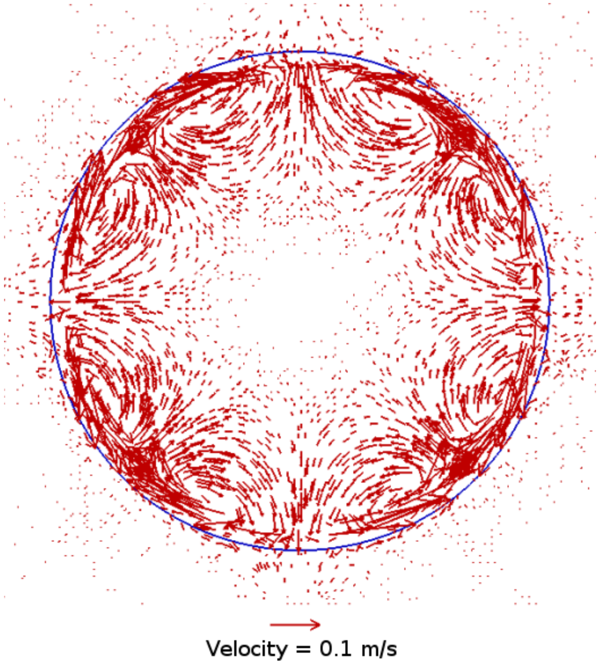
  - Phase inversion benchmark



NEED OF THE INTERFACE LIQUID/VAPOR MODELS : CASE OF A RISING BUBBLE



STATIONARY BUBBLE

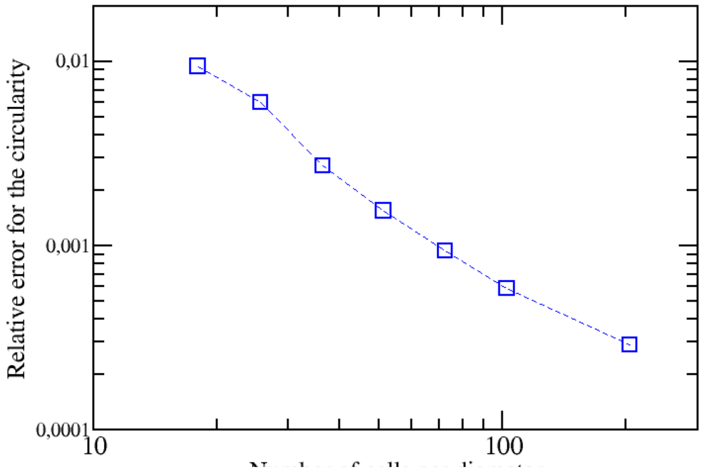


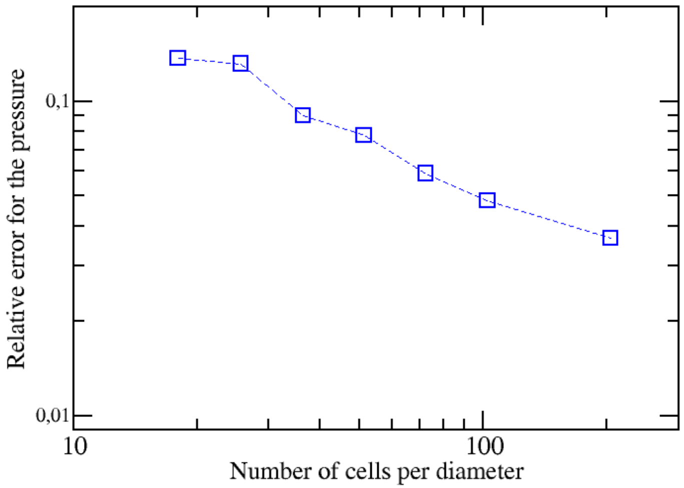
- 2D test case: square, 5 cm
- Mesh convergence study: 45^2, 64^2, 91^2, 128^2, 181^2, 256^2 and 512^2 cells
- Constant time step: 0,1 ms
- Physical properties:

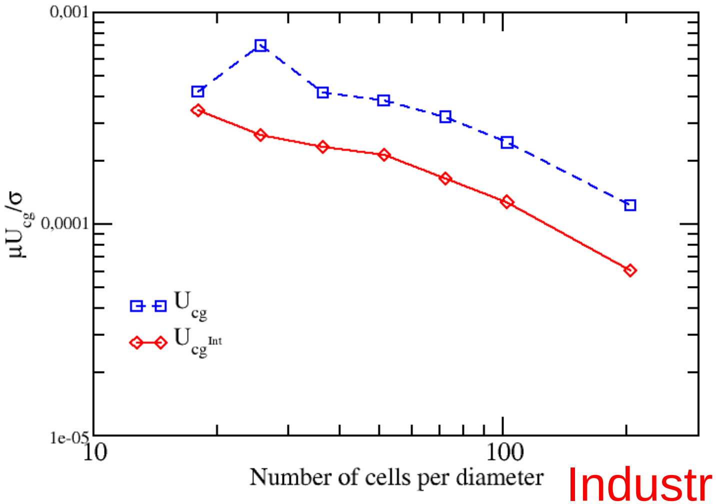
	Density	Viscosity	Surface tension
Air	1,29 kg.m^{-3}	1,5.10^{-5} Pa.s	0,08 N.m^{-1}
Water	1000 kg.m^{-3}	1.10^{-3} Pa.s	

- Circularity: $C = \frac{2\pi R}{L}$
- Laplace equation in 2D: $P_{in} - P_{out} = \frac{\sigma}{R}$
- Capillary number: $Ca = \frac{\mu_{cl} U_{cg}}{\sigma}$, $U_{cg} = \frac{\sum_{\alpha_{cg}>1.10^{-3}} \alpha_{cg}\rho_{cg}U_{cg}}{\sum_{\alpha_{cg}>1.10^{-3}} \alpha_{cg}\rho_{cg}}$ and $U_{cg}^{Int} = \frac{\sum_{\alpha_{cl}\alpha_{cg}>0,1} \alpha_{cg}\rho_{cg}U_{cg}}{\sum_{\alpha_{cl}\alpha_{cg}>0,1} \alpha_{cg}\rho_{cg}}$

STATIONARY BUBBLE







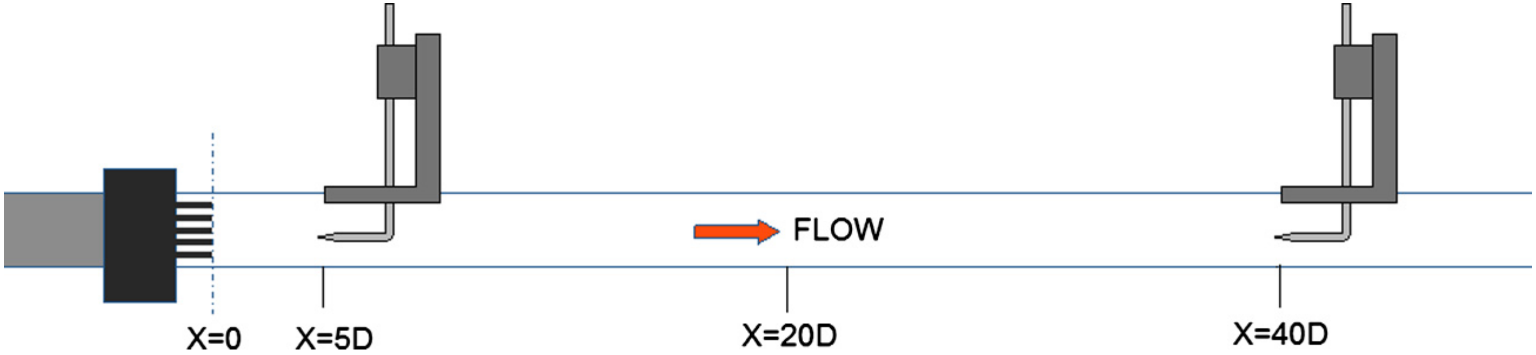
- ✓ **Convergence order:**
  - ✓ Circularity: 1,7
  - ✓ Pressure: 1,4
  - ✓ Velocity within the interface thickness : 0,35
- ✓ **Critical capilary number:** 0,001

Industrial study + cell size → Ca > Critical capillary number given in the same T/H conditions

METERO EXPERIMENT (CEA)

- M. Bottin, J.P. Berlandis, E. Hervieu, M. Lance, M. Marchand, O.C. Öztürk, G. Serre, “Experimental investigation of a developing two-phase bubbly flow in horizontal pipe”.

- This experiment has been developed in the frame of the NEPTUNE project, jointly developed by CEA, EDF, AREVA and IRSN.

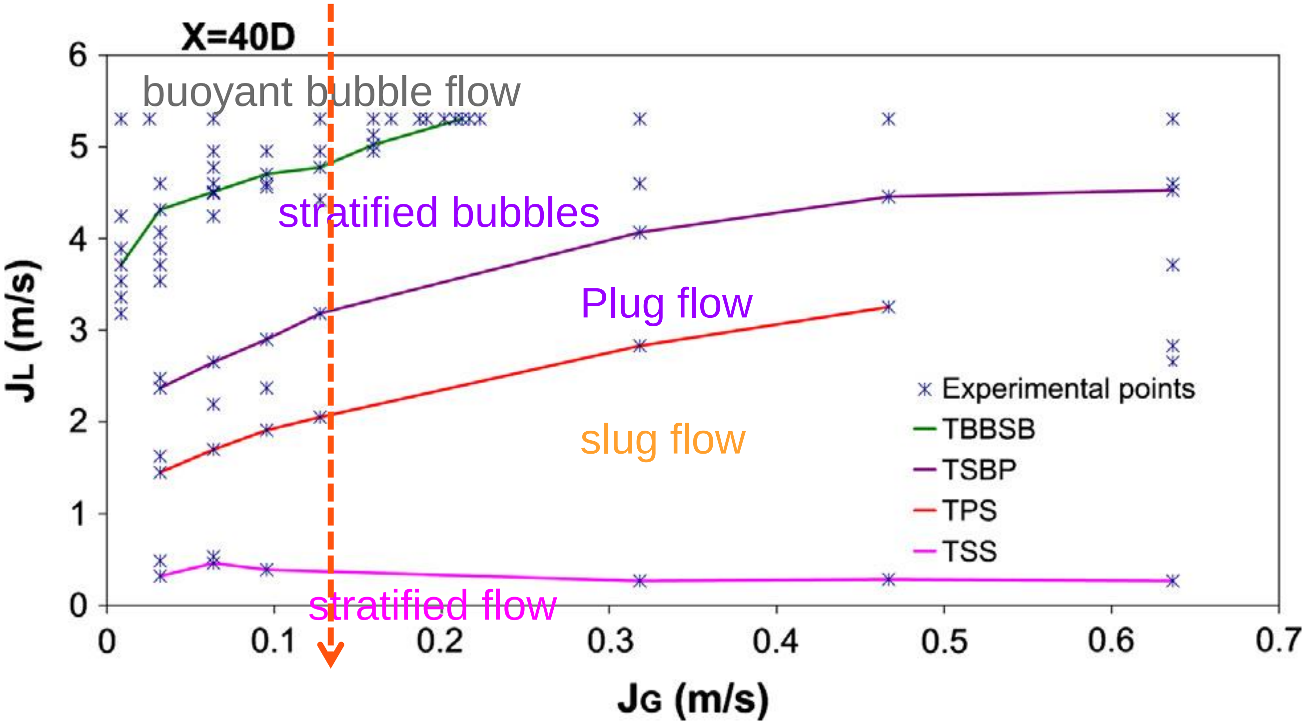


- The test section, 5.40 m long, has an inner diameter D = 0.1 m
- air injection tubes have been set to ensure uniform bubble injection in the inlet section.
- Inlet : water (0–5 m/s)+ air bubble (0–0.7 m/s).

→ provide a flow pattern map.

METERO: FLOW PATTERN MAP FOR X/D = 40

Calculations : Jg is fixed and Jl increases



Transition from slug to stratified flow (TSS)

transition from plug to slug flow (TPS)

transition from buoyant bubble flow to stratified bubble flow (TBBSB)

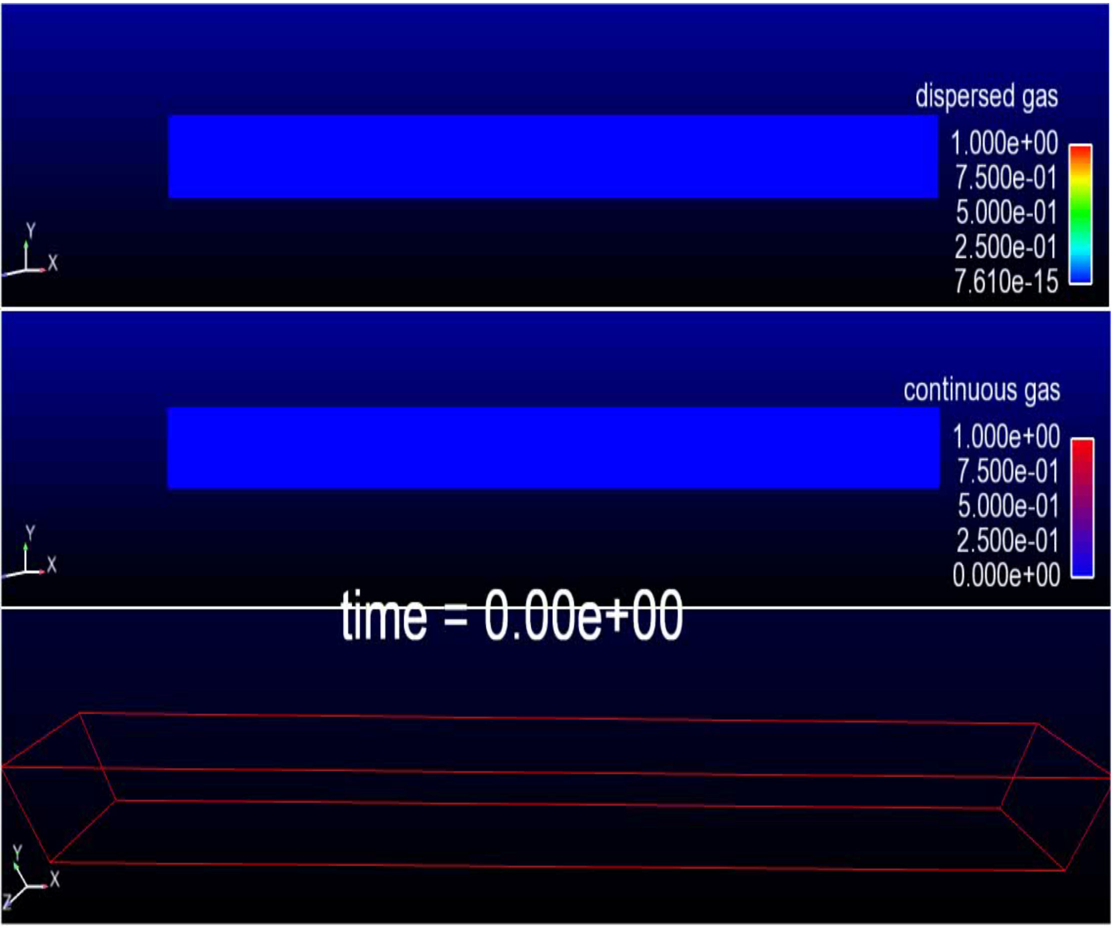
transition from stratified bubbles regime to plug (TSBP)

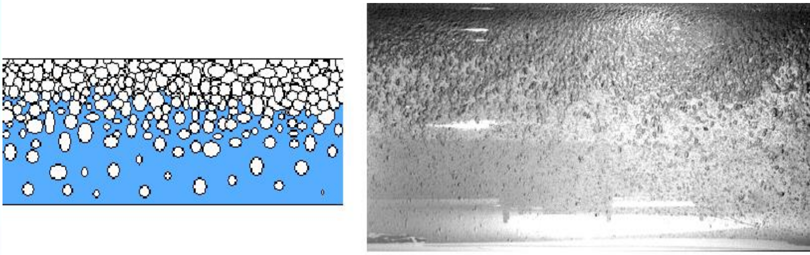
STRATIFIED BUBBLES FLOW REGIME: HIGH VALUE OF LIQUID MASS FLOWRATE

600 000 cells
Dx ~ 0.8 mm

JL = 4.42 m/s; **JG = 0.1273 m/s is fixed**

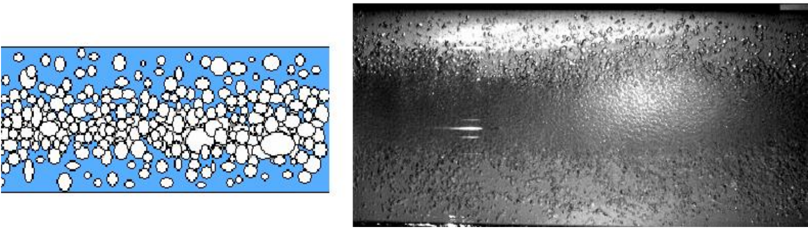
JL = 4.55 m/s; JG = 0.094 m/s

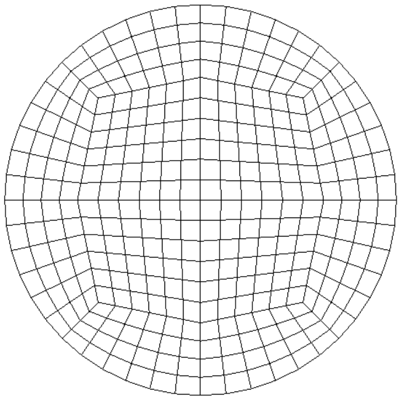




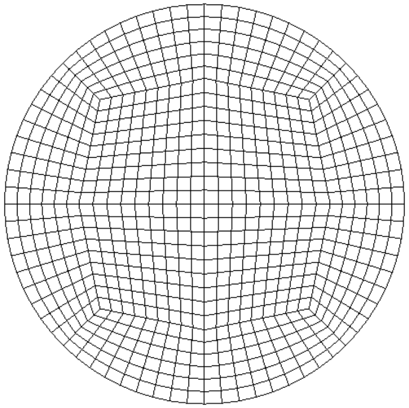
Side view

Top view

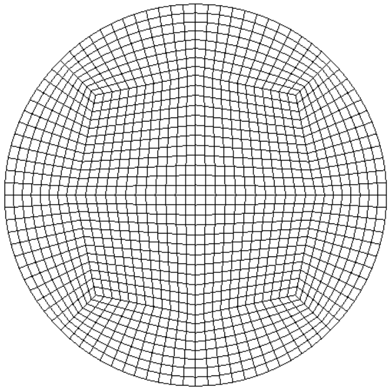




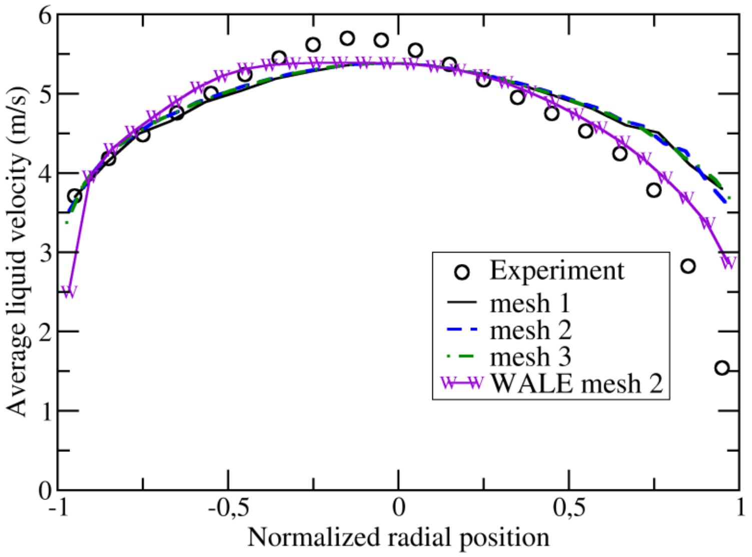
mesh 1 = 271000 cells



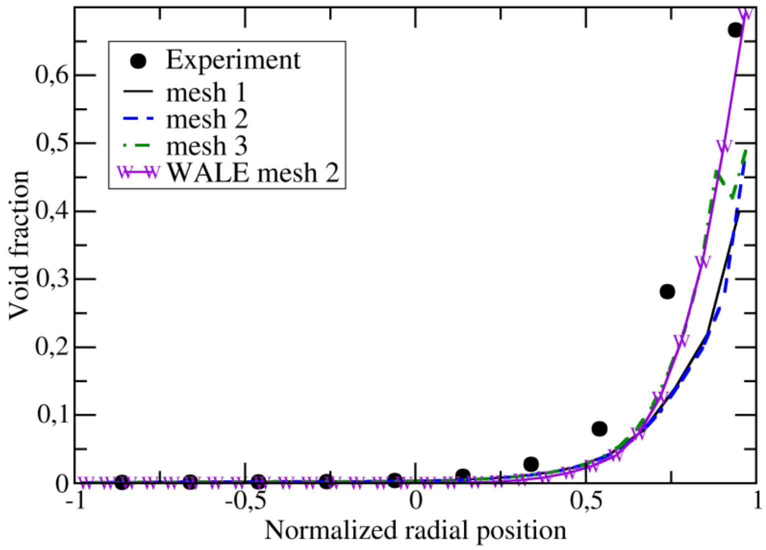
mesh 2 = 966000 cells



mesh 3= 2 327000 cells



Bubble velocity at 40D (stratified bubbly flow).

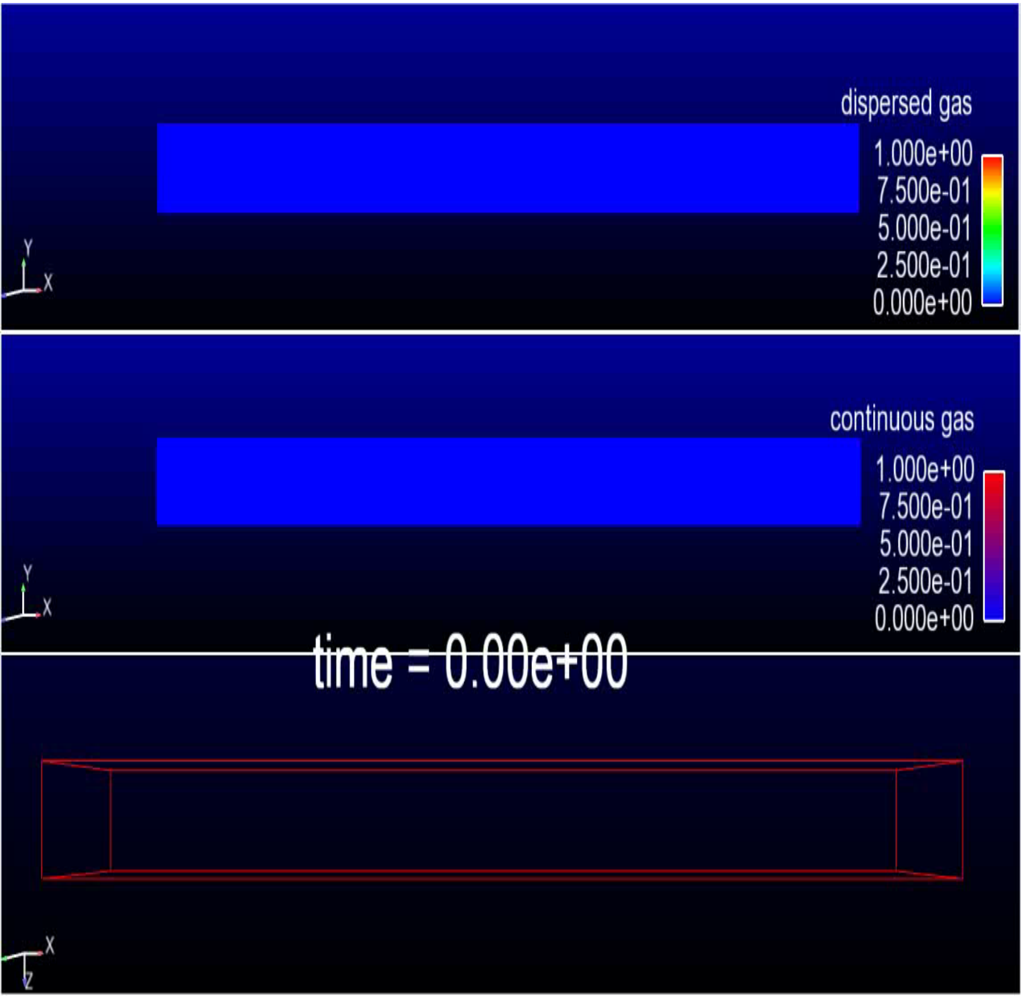


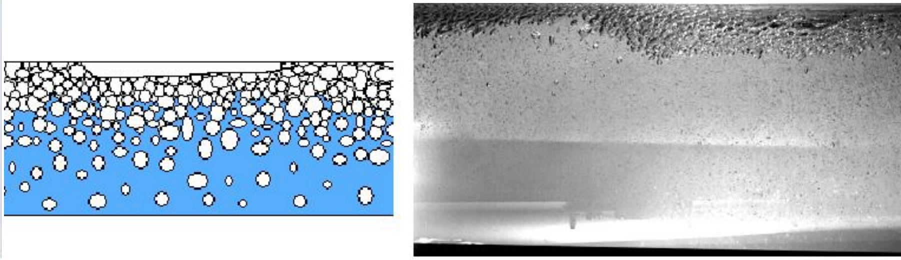
Void fraction at 40D (stratified bubbly flow).

PLUG FLOW REGIME: MEDIUM VALUE OF LIQUID MASS FLOWRATE

JL = 2.12 m/s; JG = 0.1273 m/s

JL = 2.4 m/s; JG = 0.03m/s

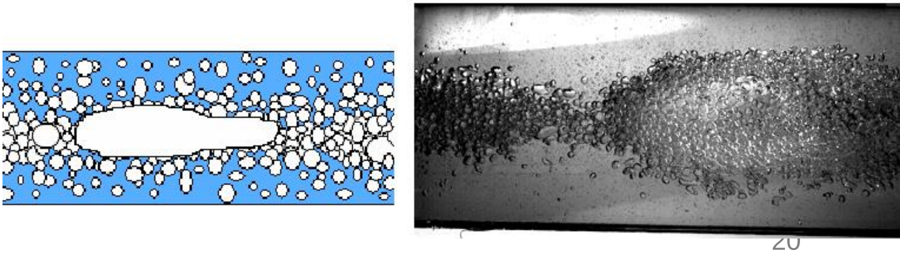




Side view

top bubbles coalesce to form plugs→ intermittent regime

Top view



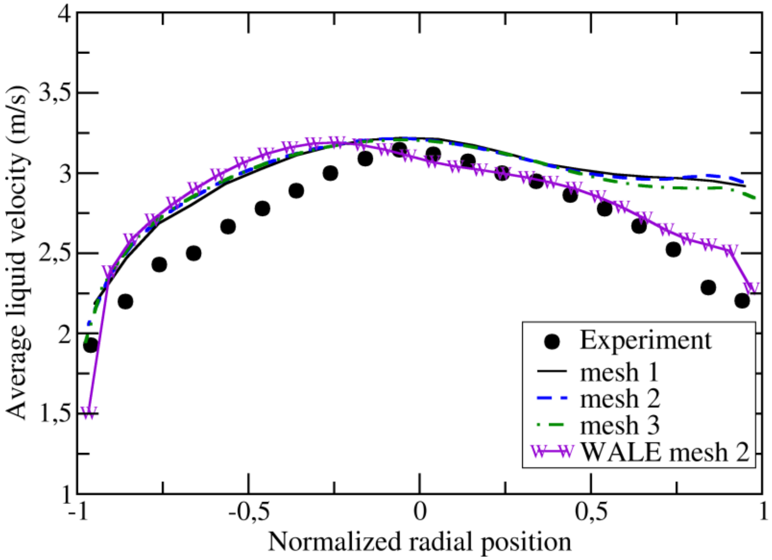


Figure 9c: Bubble velocity at 40D (plug flow).

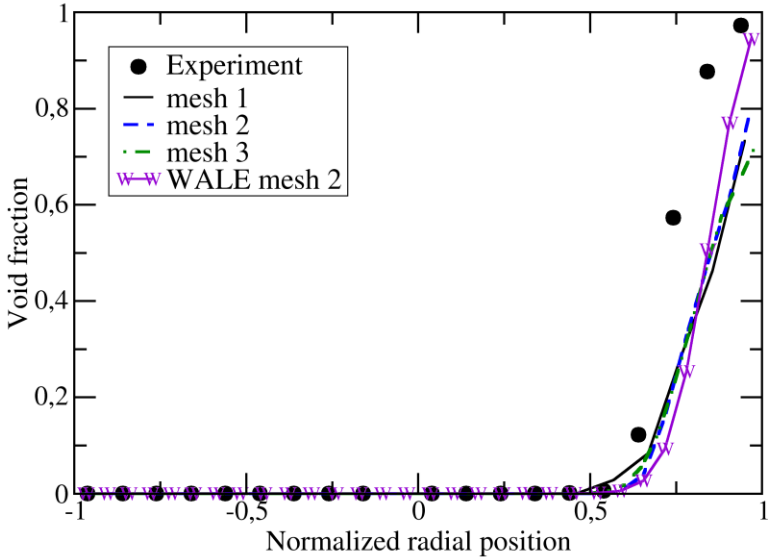
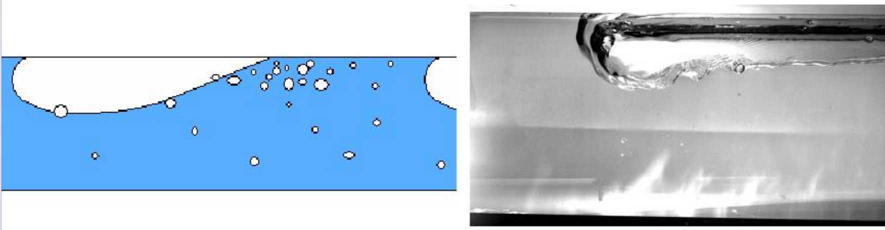


Figure 9d: Void fraction at 40D (plug flow).

SLUG FLOW REGIME : LOW VALUE OF LIQUID MASS FLOWRATE

JL = 1.06 m/s; JG = 0.1273 m/s

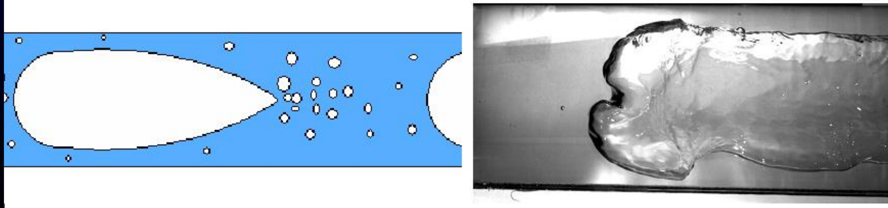
JL = 0.53 m/s; JG = 0.062 m/s

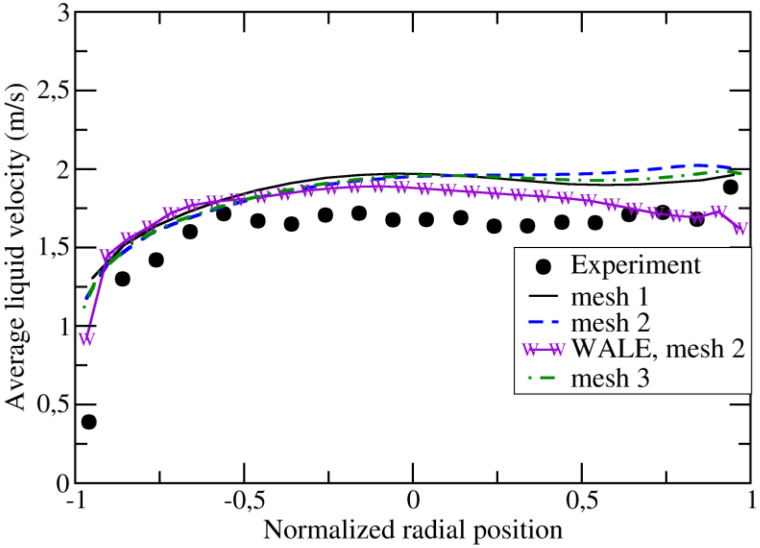


Side view

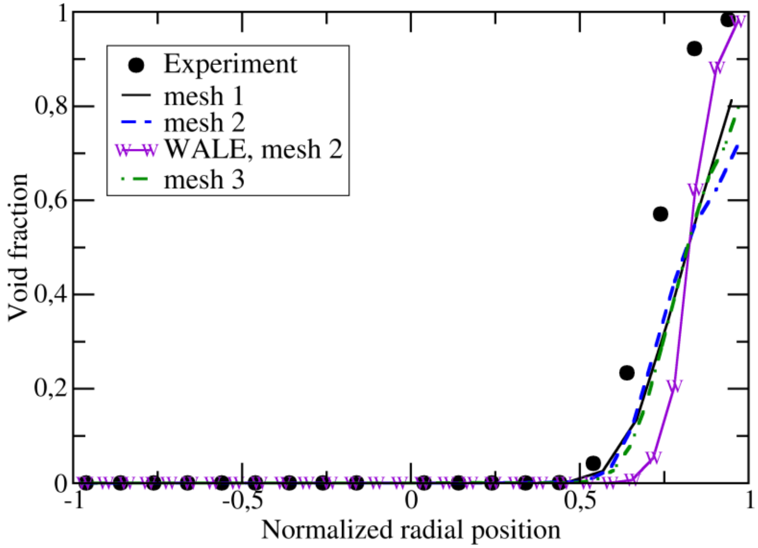
Kelvin–Helmoltz instabilities →
liquid reaches periodically the upper wall →
high velocity slug

Top view





Bubble velocity at 40D (slug flow).

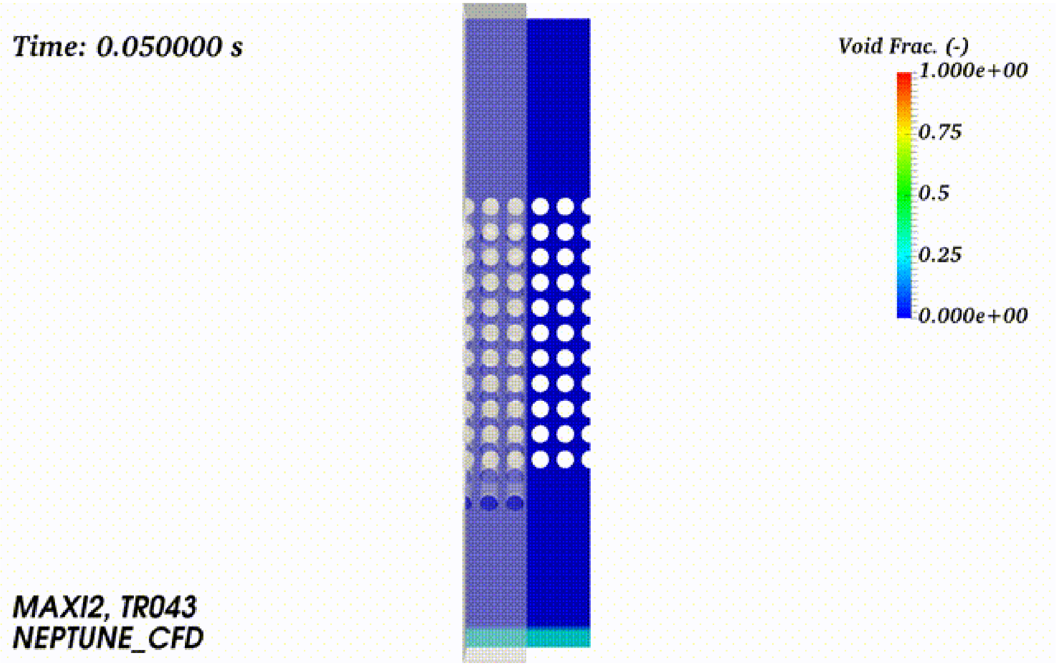


Void fraction at 40D (slug flow).

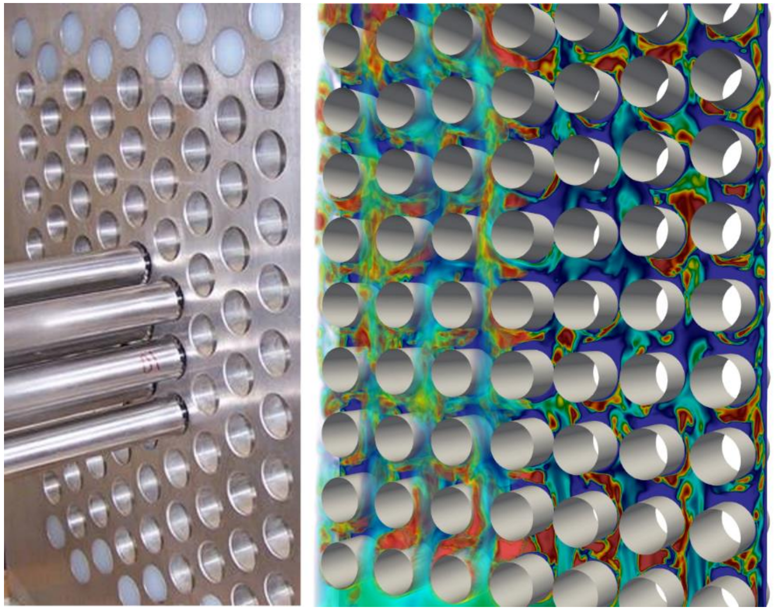
Stephane Mimouni , *CFD calculations of flow pattern maps and LES of multiphase flows*, Nuclear Eng and Des.

Zoom sur la vibration des tubes GV

Validation of the two-phase numerical model
MAXI2 Experiment Freon/Freon

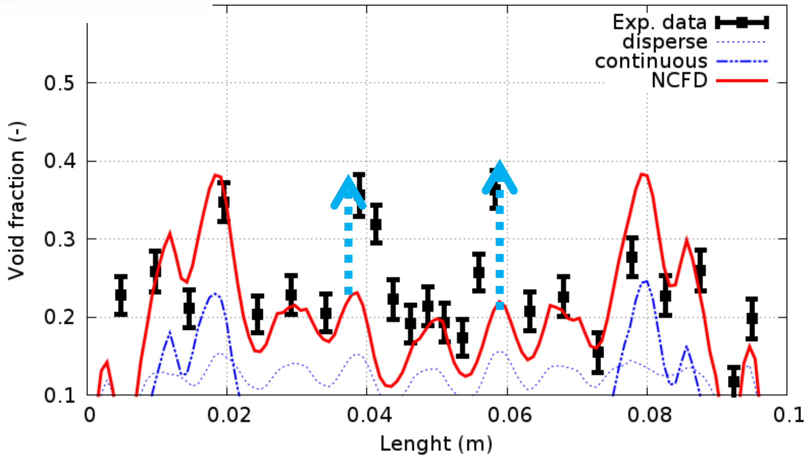


Water freon two-phase flow
VISCACHE Experiment

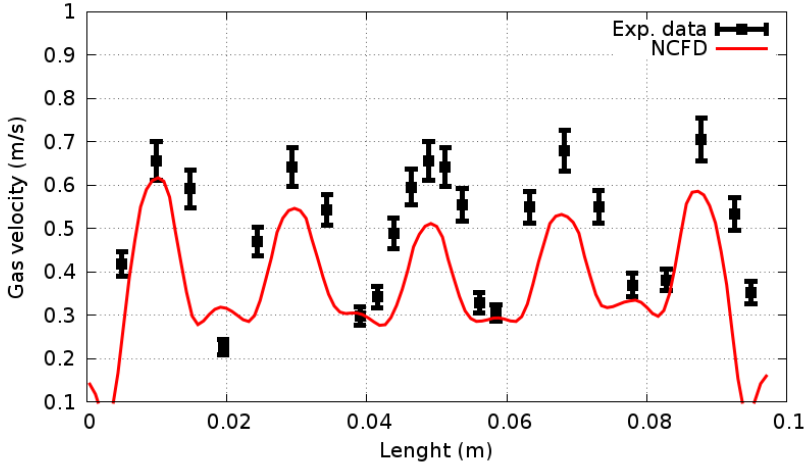


MAXI : 3 FIELDS → QUITE ENCOURAGING

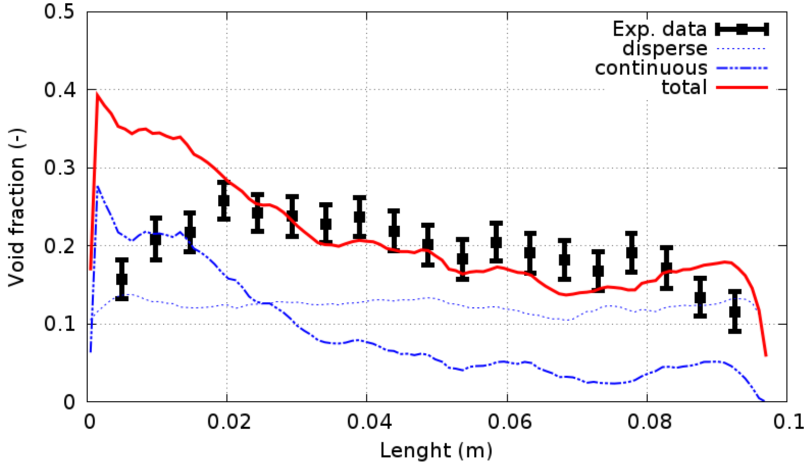
North/South line



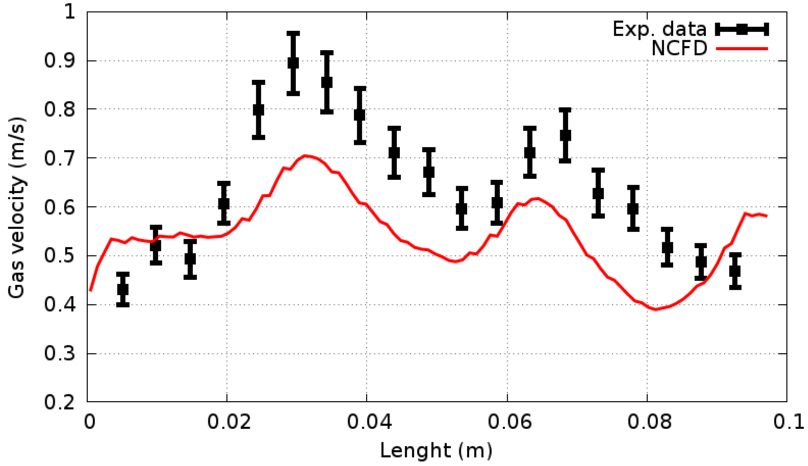
North/South line



West/East line



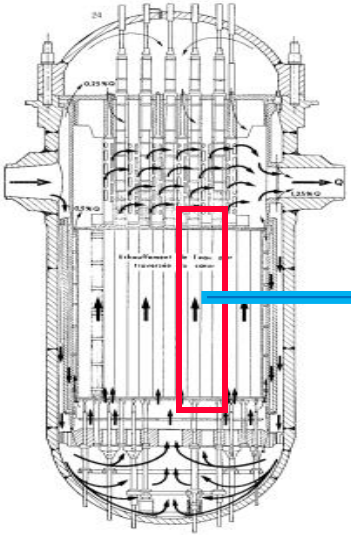
West/East line

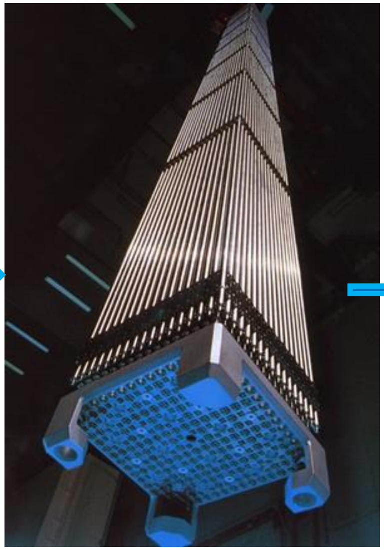


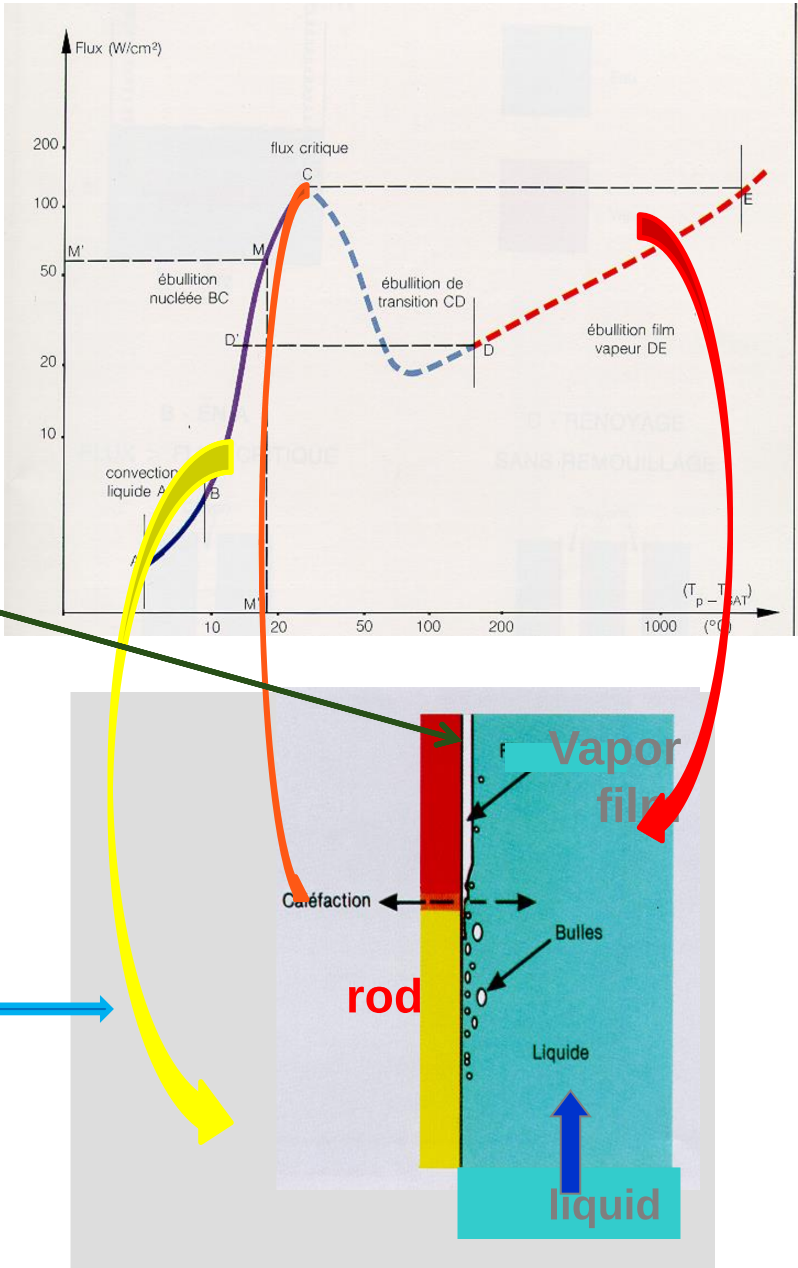
DNB : INDUSTRIAL CONTEXT

- **In nucleate boiling, heat flux increases and reaches a maximum value with increasing wall temperature.**
- **→ severe damage or meltdown of the surface.**

A vapour film isolates the fuel from the water: the fuel heats up sharply and suddenly





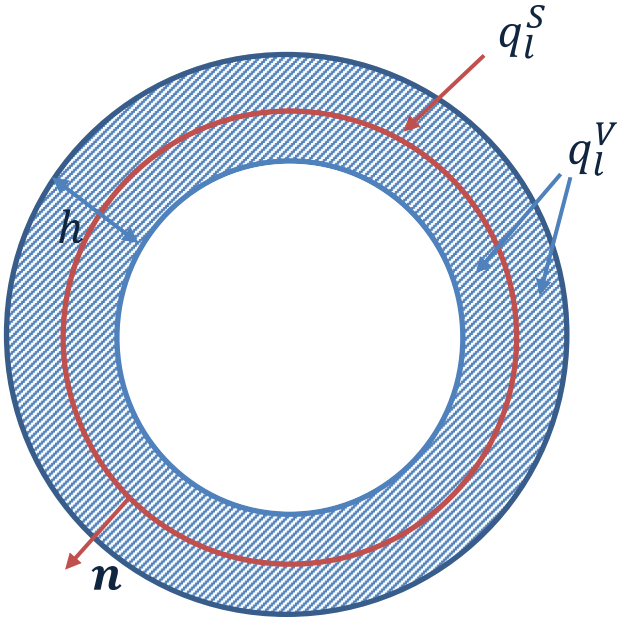


NEW PHASE CHANGE TERM

- **Zero thickness interface** **(W.m^{-2}):** $q_l^S = \lambda_l \nabla T_l . \boldsymbol{n}$ **: accross the liquid-vapor interface**
- **Non-zero thickness interface** **(W.m^{-3}):** $\lim_{h\to 0}\left(\int_{V^{Int}} q_l^V(x)dx^3\right) = \int_{A^{Int}} q_l^S(x^{Int})dA$
- **Brackbill's methodology:**

$$\int_{A^{Int}} q_l^S(x^{Int})dA = \int_{V^{Int}} q_l^S(x)\delta(\boldsymbol{n}(x^{Int}).(x - x^{Int}))dx^3$$

$$= \int_{V^{Int}} \lambda_l \nabla T_l . \boldsymbol{n}(x)\ \delta(\boldsymbol{n}(x^{Int}).(x - x^{Int}))dx^3$$



$$\lim_{h\to 0} \nabla c(x) = \boldsymbol{n}(x)\ \delta(\boldsymbol{n}(x^{Int}).(x - x^{Int}))\ [c]$$

$$\int_{A^{Int}} q_l^S(x^{Int})dA = \lim_{h\to 0}\left(\int_{V^{Int}} \lambda_l \nabla T_l . \frac{\nabla c(x)}{[c]} dx^3\right)$$

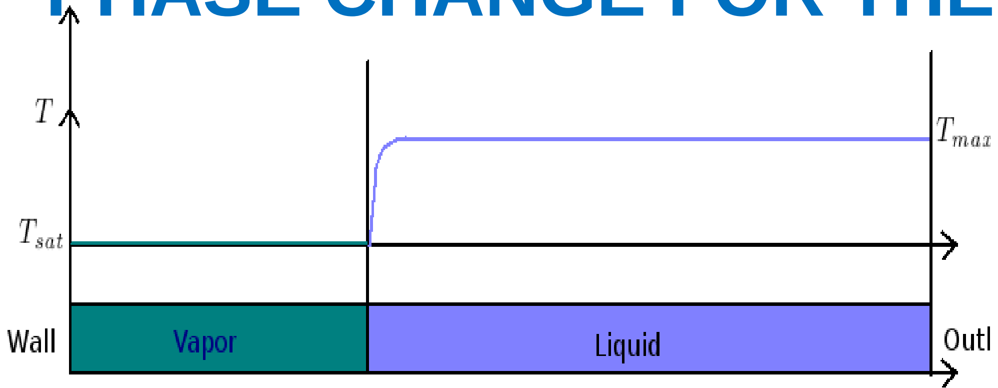
➡

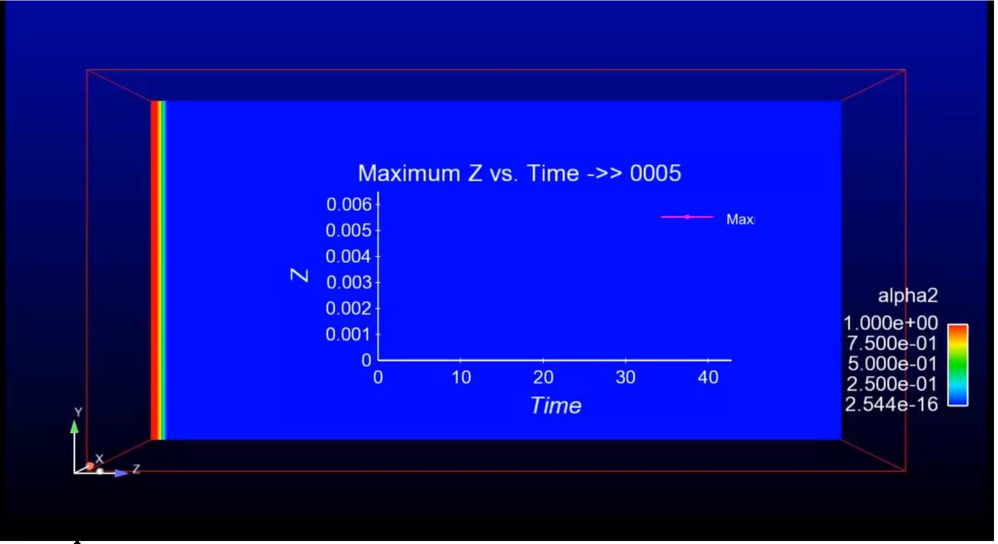
$$q_l^V(x) = \lambda_l \nabla T_l . \frac{\nabla c(x)}{[c]}$$

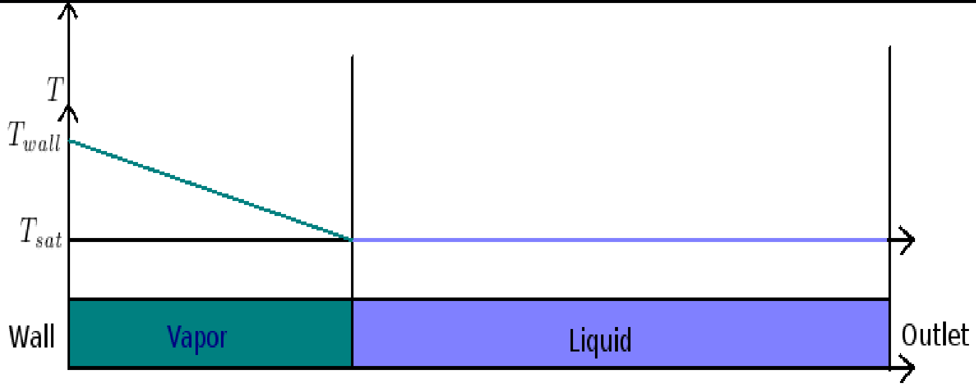
✓ Extension to the two-fluid model:
$q_k^V = \alpha_k \lambda_{\boldsymbol{k}} \nabla T_{\boldsymbol{k}} . \nabla \alpha_k$: *implemented in the CFD code*

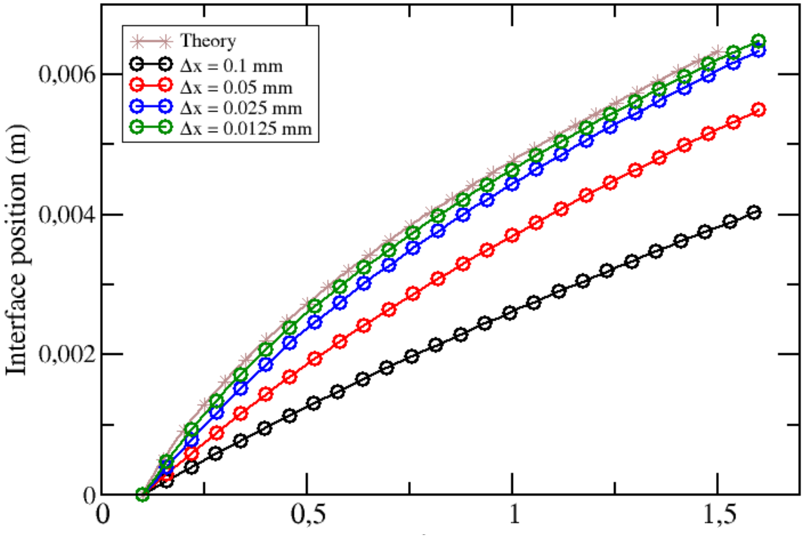
[Brackbill, J.U., *et al.*, 1992, A continuum method for modeling surface tension, *J. Comput. Phy.*, Vol. 100, pp. 335-354]

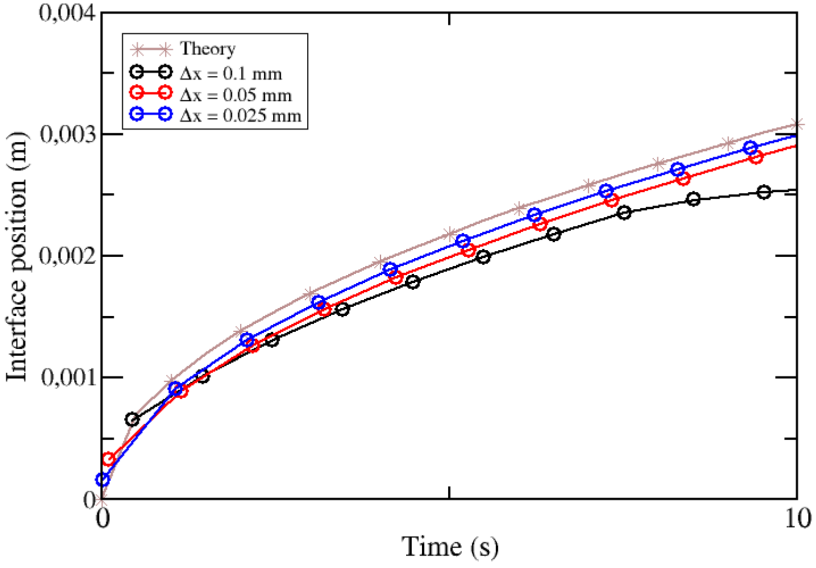
PHASE CHANGE FOR THE CONTINUOUS PHASES



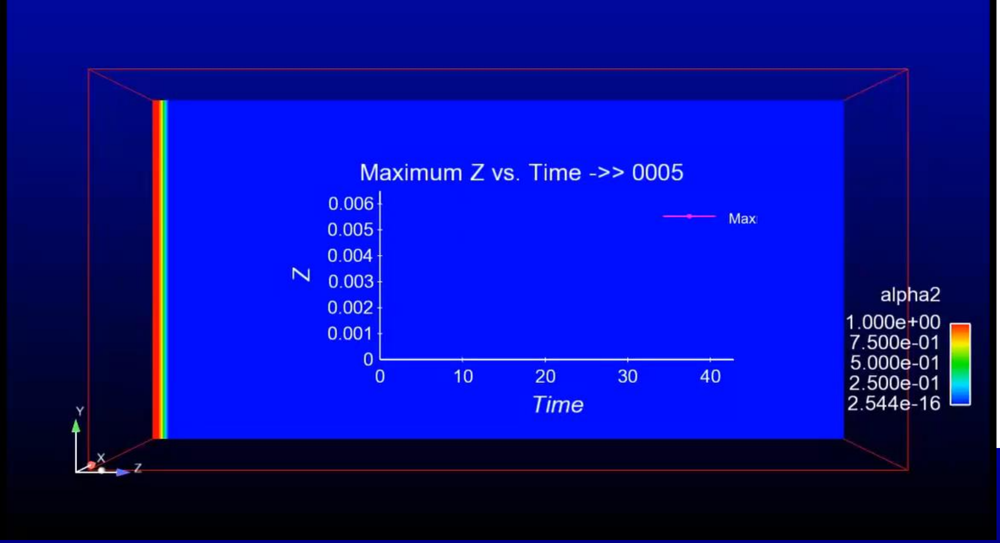


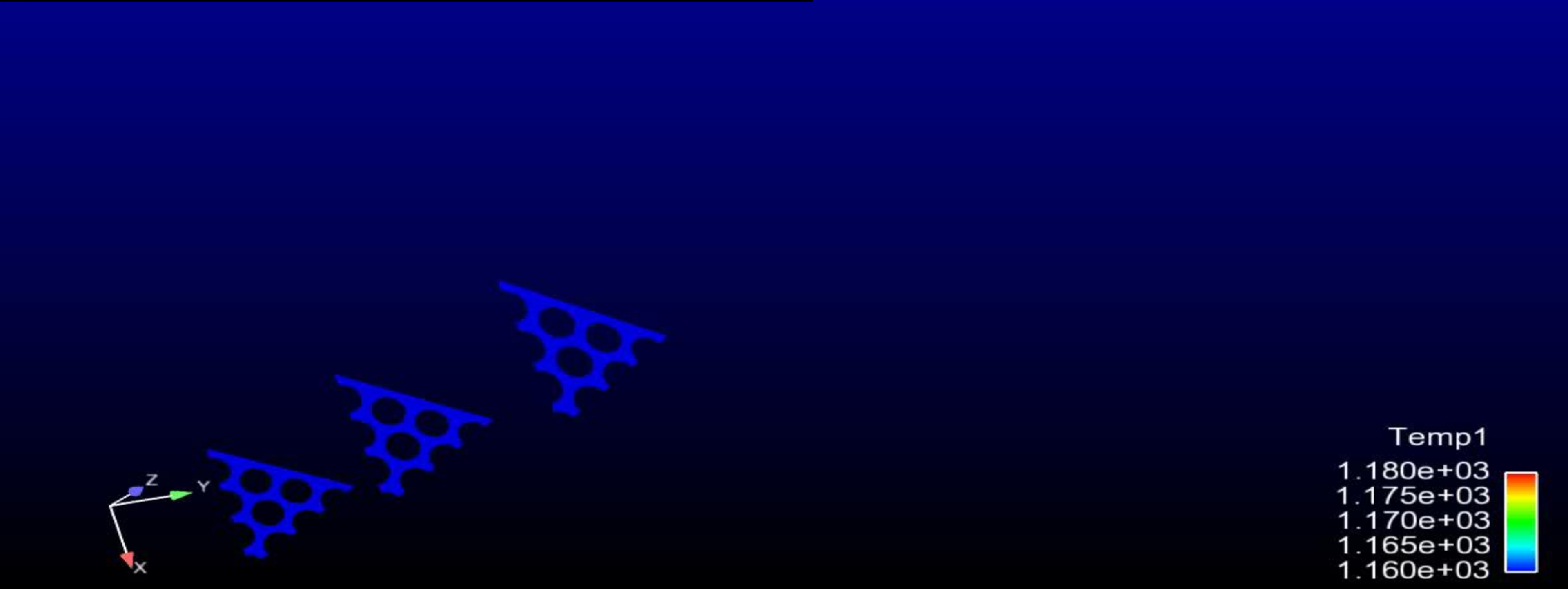






Phase change





Conclusions – Phase change

- New phase change model for large interfaces:
  - Brackbill's methodology

- Validation on various academic test cases:
  - Convergence studies
  - Pressure conditions occurring in nuclear power plants

- Industrial application (OK not shown here):
  - Non-isothermal turbulent two-phase flow
  - Industrial geometry
- Some issues remain :
  - Results sensitive to the time step and mesh refinement → calibration on verification test cases.
  - → Improve the numerical robustness of the mass and energy source terms !!

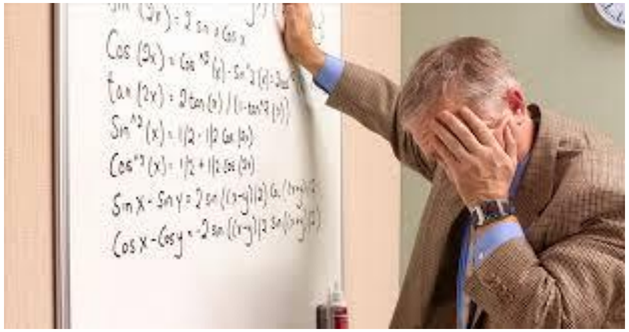
Stephane.Mimouni@edf.fr

INTERFACE LOCATING METHODS
→ LES

EQUATION FILTERING

- **LES filter G:** $\overline{\varphi}(x,t) = G \circ \varphi = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} G(x-y, t-t')\varphi(y,t')\,dy\,dt'$
- **Filtered mass balance equation:**

$$\rho_k \partial_t \overline{\alpha_k} + \rho_k \nabla.\left(\overline{\alpha_k}\ \overline{\boldsymbol{u}_k}\right) + \boxed{\tau_{interf}} = 0$$



- **Filtered momentum balance equation:**

$$\rho_k \partial_t\left(\overline{\alpha_k}\ \overline{\boldsymbol{u}_k}\right) + \boxed{\tau_{time}} + \rho_k \nabla.\left(\overline{\alpha_k}\ \overline{\boldsymbol{u}_k} \otimes \overline{\boldsymbol{u}_k}\right) + \boxed{\tau_{conv}} = \mu_k \nabla.\left(\overline{\alpha_k}\,\overline{\underline{\underline{S_k}}}\right) + \boxed{\tau_{diff}}$$

$$-\overline{\alpha_k}\nabla\overline{P} - \boxed{\tau_{pressure}}$$

$$+ \overline{\alpha_k}\rho_k \boldsymbol{g} + \widehat{\boldsymbol{F}_{CSF}} + \boxed{\tau_{superf}} + \widehat{\boldsymbol{F}_{Drag}} + \boxed{\tau_{drag}}$$

[Vincent, S., Tavares, M., Fleau, S. *et al.*, 2016, *A priori* filtering and LES modeling of turbulent two-phase flows Application to phase separation, *Comput. Fluids*]

SUBGRID TERMS

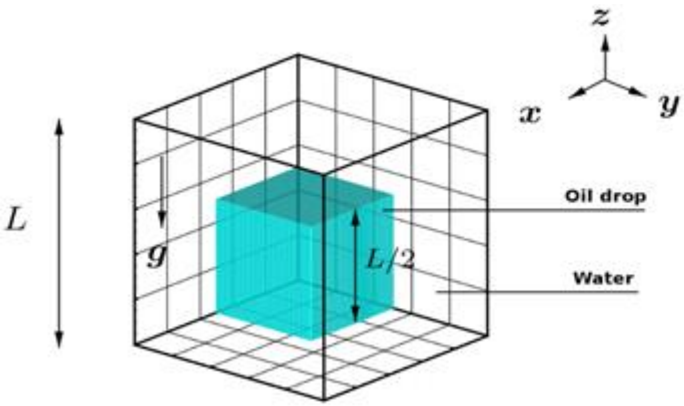
- **Filtered curvature:** $\hat{\kappa} = -\nabla.\left(\frac{\nabla\overline{\alpha_k}}{\left|\left|\nabla\overline{\alpha_k}\right|\right|}\right)$

Subgrid terms	Expression
τ_{interf}	$\rho_k\left(\nabla.\left(\overline{\alpha_k\,\boldsymbol{u}_k}\right) - \nabla.\left(\overline{\alpha_k}\;\overline{\boldsymbol{u}_k}\right)\right)$
τ_{time}	$\rho_k\left(\partial_t\left(\overline{\alpha_k\,\boldsymbol{u}_k}\right) - \partial_t\left(\overline{\alpha_k}\;\overline{\boldsymbol{u}_k}\right)\right)$
τ_{conv}	$\rho_k\left(\nabla.\left(\overline{\alpha_k\,\boldsymbol{u}_k\otimes\boldsymbol{u}_k}\right) - \nabla.\left(\overline{\alpha_k}\;\overline{\boldsymbol{u}_k}\otimes\overline{\boldsymbol{u}_k}\right)\right)$
τ_{diff}	$\mu_k\left(\nabla.\left(\overline{\alpha_k\,\underline{\underline{S_k}}}\right) - \nabla.\left(\overline{\alpha_k}\,\overline{\underline{\underline{S_k}}}\right)\right)$
$\tau_{pressure}$	$\overline{\alpha_k\,\nabla P} - \overline{\alpha_k}\,\nabla\overline{P}$
τ_{superf}	$\sigma\left(\overline{\alpha_k\,\kappa\,\nabla\alpha_k} - \overline{\alpha_k}\,\hat{\kappa}\,\nabla\overline{\alpha_k}\right)$

$+\ \tau_{drag}$

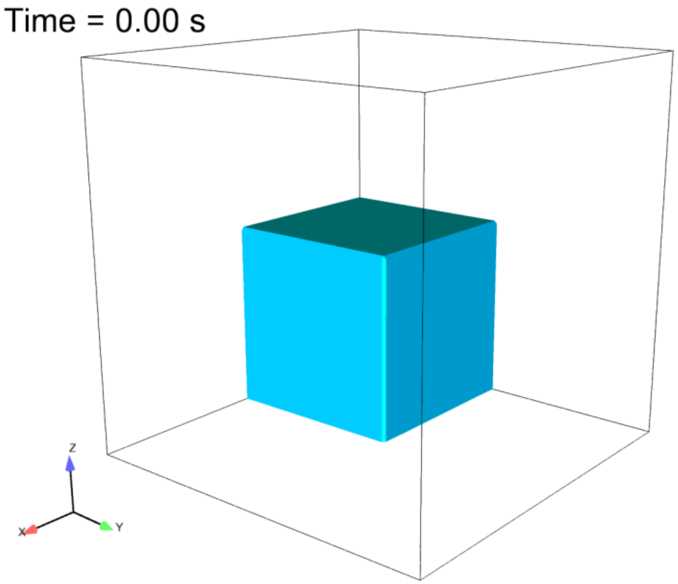
- ✓ **New subgrid terms:** $\tau_{pressure}$ and τ_{drag}
- ✓ **LES filter:** 7 subgrid terms

PHASE INVERSION BENCHMARK *Vincent et al. [2008]*



	Density	Viscosity
Oil	900 kg.m^{-3}	0,1 Pa.s
Water	1000 kg.m^{-3}	0,001 Pa.s

Mesh	128^3 cells	256^3 cells	512^3 cells
Time step	0,8 ms	0,2 ms	0,05 ms
Cores	144	1152	1152
Duration	7 hours	47 hours	2 months

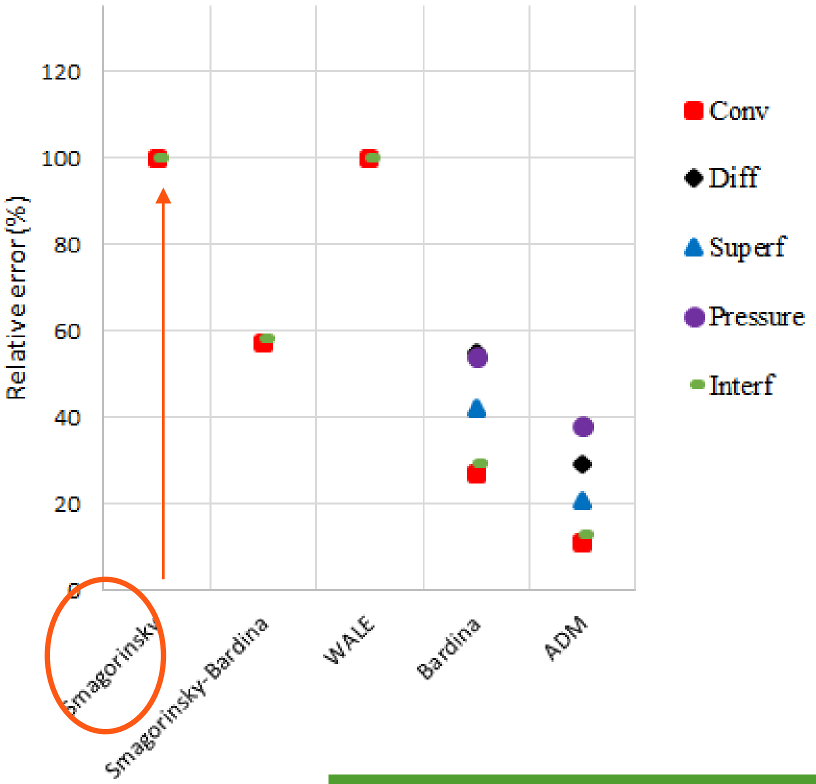


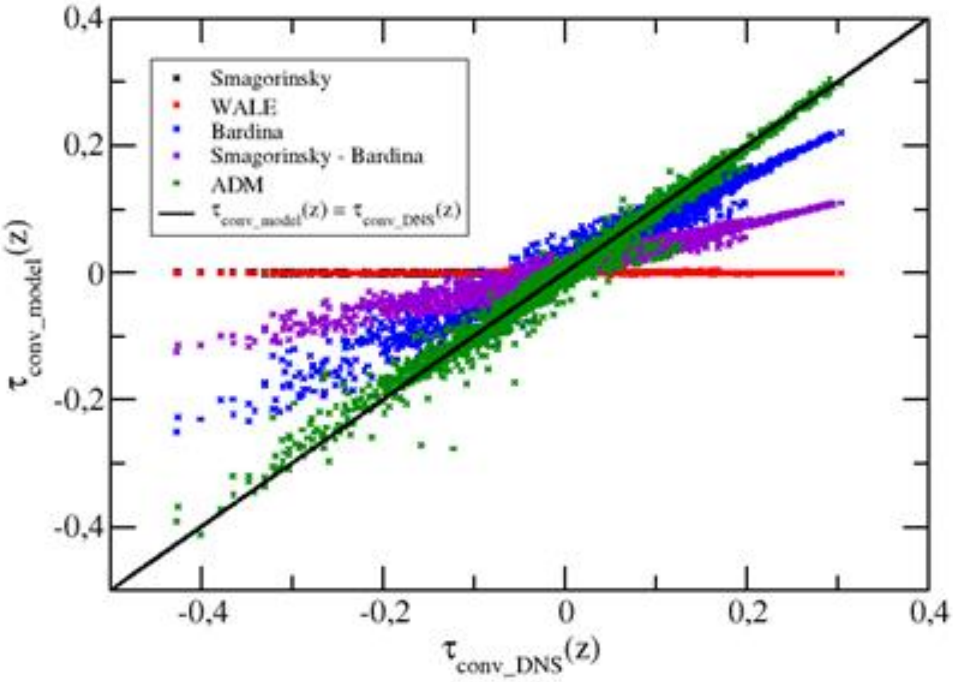
- ✓ Results consistent with DNS obtained with one-fluid models: *Vincent, Tavares, Fleau et al. [2016]*

[Vincent, S., Tavares, M., Fleau, S. *et al.*, 2016, *A priori* filtering and LES modeling of turbulent two-phase flows Application to phase separation, *accepted in Comput. Fluids*]

TURBULENCE MODELS COMPARISON

Convective subgrid term → Reynolds stress tensor in single phase flow





- ✓ Smaller errors with structural models especially ADM, consistent with one-fluid results: *Vincent, Tavares, Fleau et al. [2016]*

[Vincent, S., Tavares, M., Fleau, S. *et al.*, 2016, *A priori* filtering and LES modeling of turbulent two-phase flows Application to phase separation, *accepted in Comput. Fluids*]

CONCLUSIONS – LARGE EDDY SIMULATION

- **Equation filtering:**
  - 1st time for a two-fluid model applied to large interfaces
  - New Specific subgrid terms

- **Turbulence models:**
  - Limited modeling errors with structural models especially ADM

- **ADM implementation:**
  - Exploratory results encouraging
  - Multiple implementation choices that have to be deeply investigated

Time and space order should be increased

numerical scheme → diffusion → interacts LES filter ?

numerical effects vs turbulence modelling ?

CONCLUSION

- **Large interface model needs its own closure laws : a surface tension model, a drag force law necessary to couple the velocity of the two continuous fields at the interface + interface <u>sharpening</u> equation in order to control the interface thickness.**

- **validation of the multifield approach : Verification cases, Validation cases, Integral validation cases**

- **Sensitivity to mesh refinement**

- **LES vs Rans for large interfaces**

- **Phase changes : dispersed gas phase and continuous gas phase → SFR … DNB, Steam Generator, …**

- **Dynamics of capillary bridges in a crack (capillarity, wetting effects)**

- **HPC : Recently steam generator 1.5 Billion cells in two-phase flow !!**

- **Meet the requirements for industrial needs BUT:**

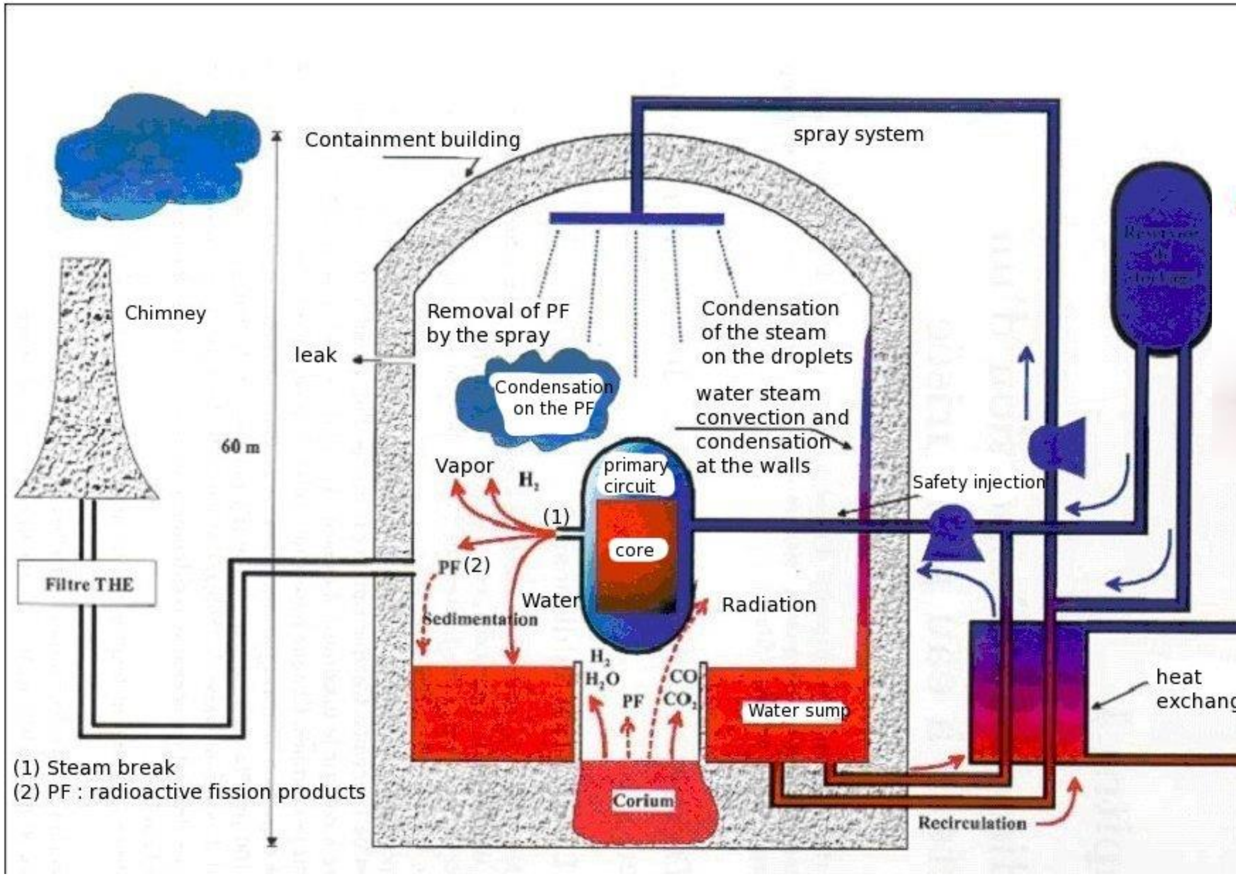
- **Pb of Spurious currents should be addressed**

- **LES calculations for large interfaces in industrial applications**

- **Transition regimes flow**

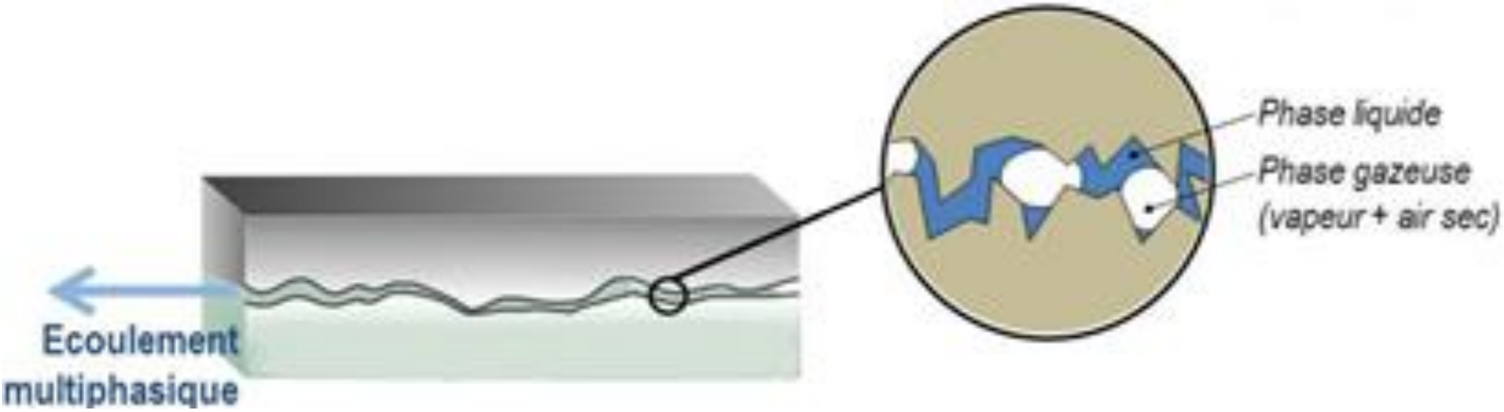
Background

During the course of hypothetical accidents in a PWR which lead to large mass and energy releases into the containment (Steam Line Break, Loss of Coolant Accident, etc.), spray systems are used in the containment in order to limit overpressure, to enhance the gas mixing in case of the presence of hydrogen and to drive down the fission products. Thus, spray modeling and wall condensation play an important part in thermal-hydraulic containment codes.

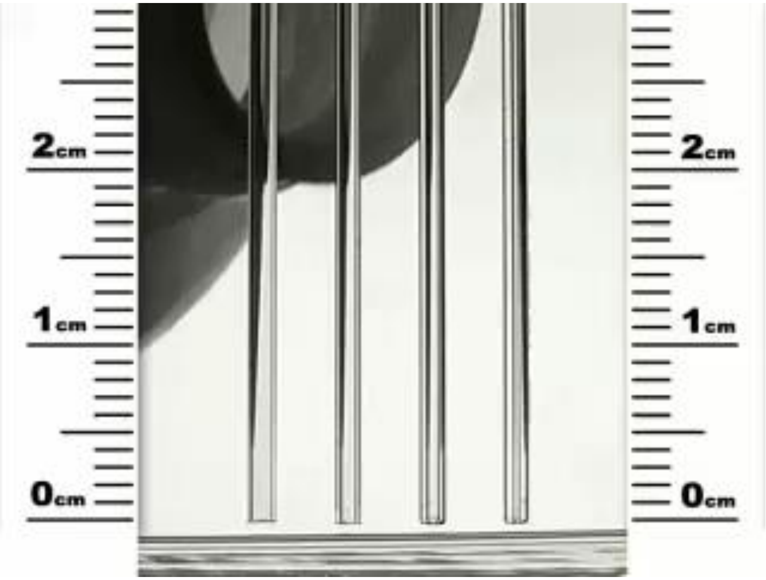


WETTING, CAPILLARITY AND DYNAMIC OF THE TRIPLE LINE

Enceinte sous pression : quel débit de vapeur à travers les fissures du béton?



CAPILLARITY EFFECTS



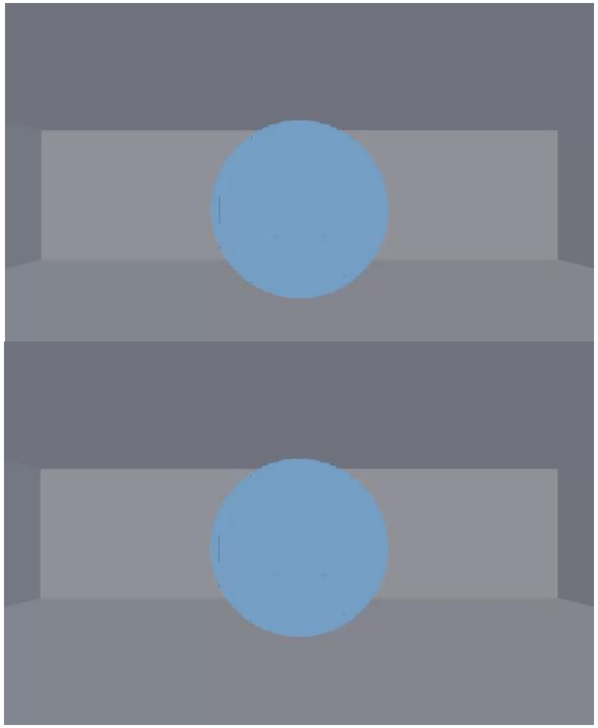
Source: P-G. de Gennes

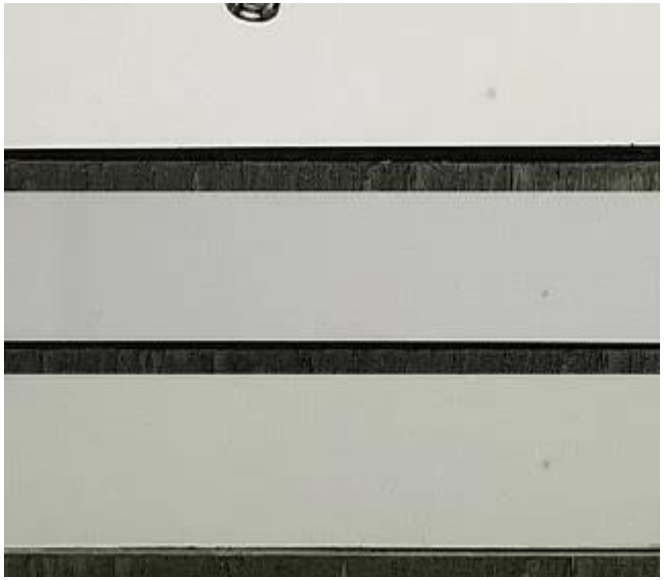
Surface tension force: $F_{CSF} = \alpha_k \, \sigma \kappa \nabla \alpha_k$ with $\kappa = -\nabla . \left(\frac{\nabla \alpha_k}{||\nabla \alpha_k||} \right)$

In order to compute more precisely the interface curvature, we diffuse the interface:

$$\frac{\Delta \alpha_k}{\Delta \tau} - \nabla . D \nabla \alpha_k = 0 \longrightarrow \kappa = -\nabla . \left(\frac{\nabla \alpha_{k,diff}}{||\nabla \alpha_{k,diff}||} \right)$$

WETTING EFFECTS



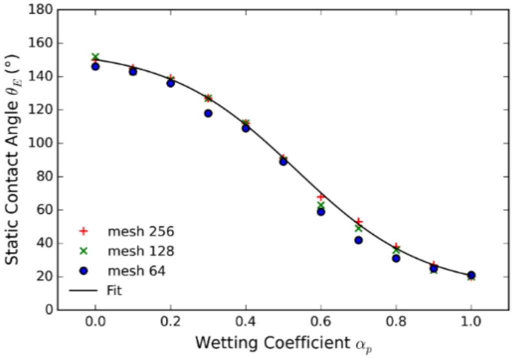


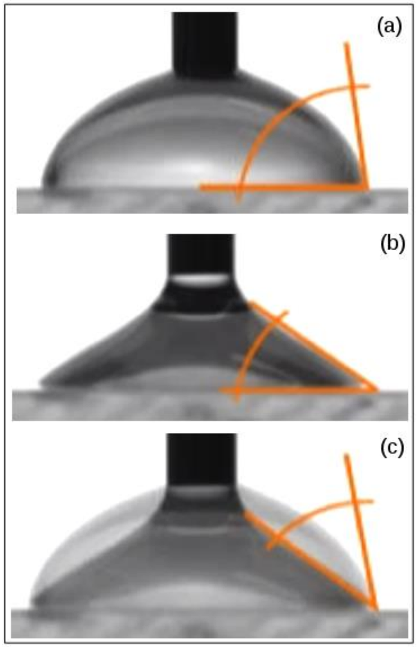
Source: P-G. de Gennes

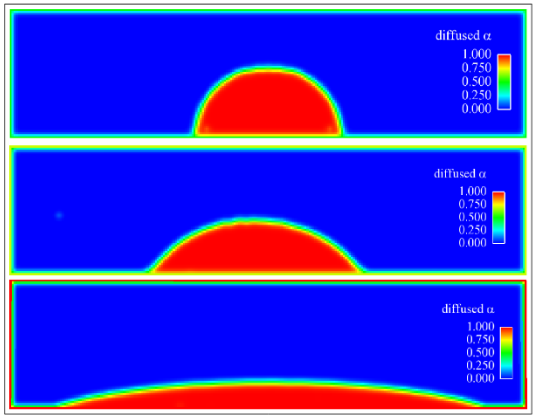
Diffusion equation generalized : $\frac{\Delta\alpha_k}{\Delta\tau} - \nabla.D\nabla\alpha_k + B^S(\alpha_k^{n+1} - \alpha_p) = 0$

At the wall : B → ∞ → $\alpha_{k;diff} \rightarrow \alpha_p$ at the wall.
Penalty term

WETTING ANGLE : CALIBRATION OF THE MODEL

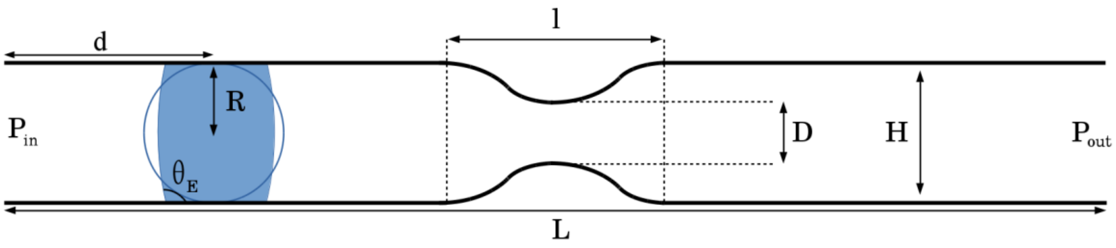


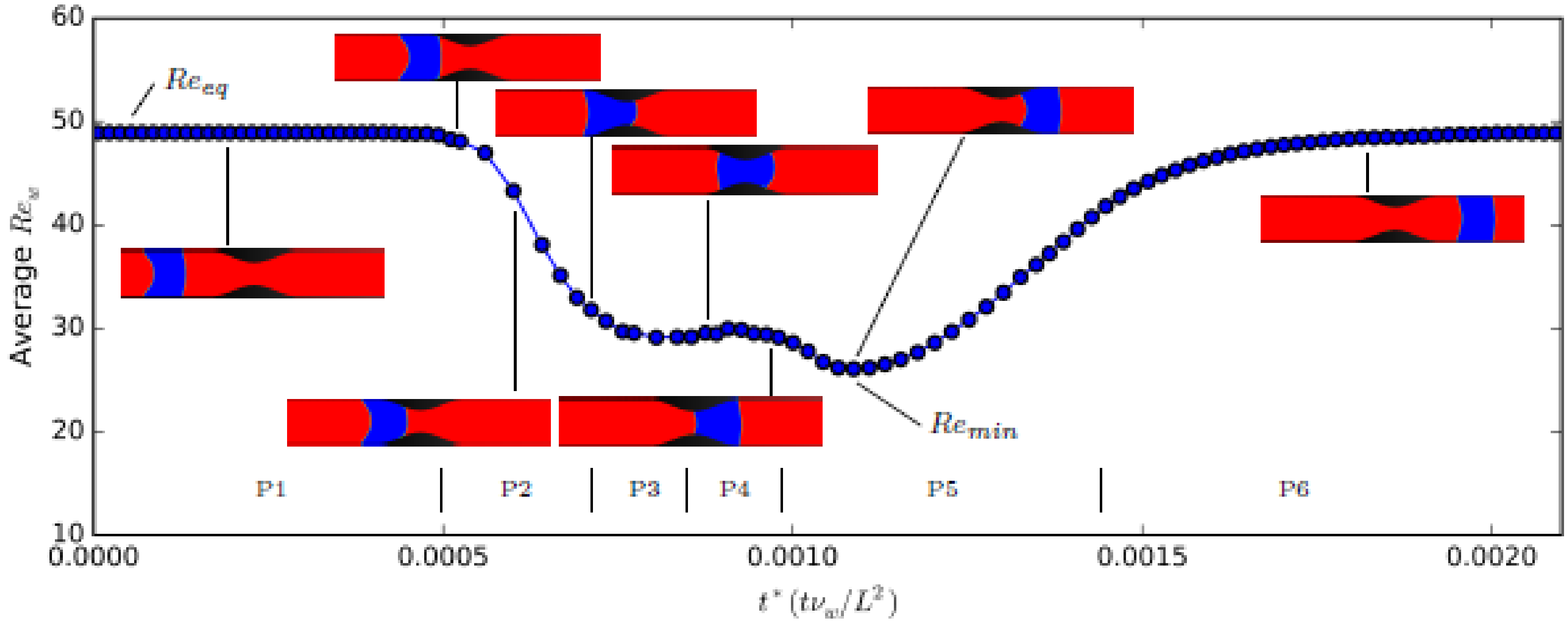




DYNAMICS OF CAPILLARY BRIDGES

Dynamics of a capillary bridge accross a narrowing in a crack

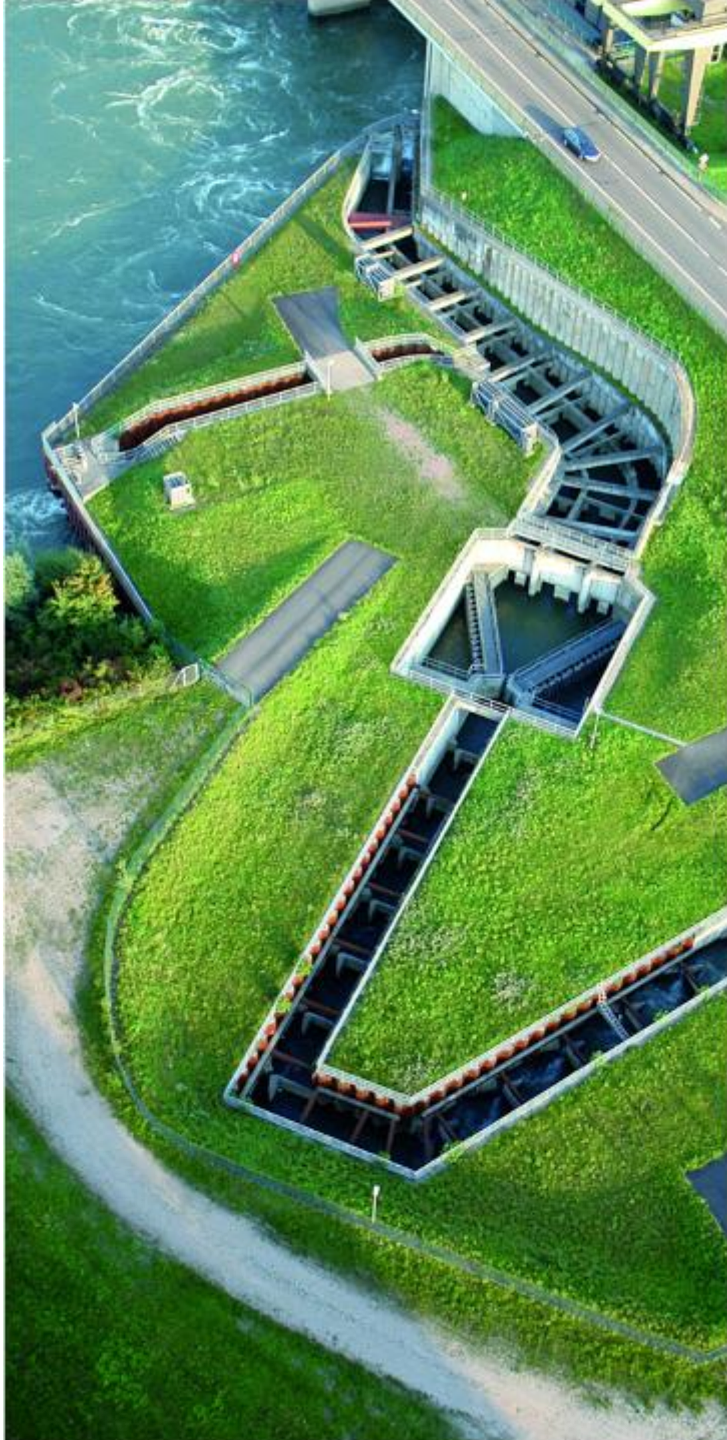




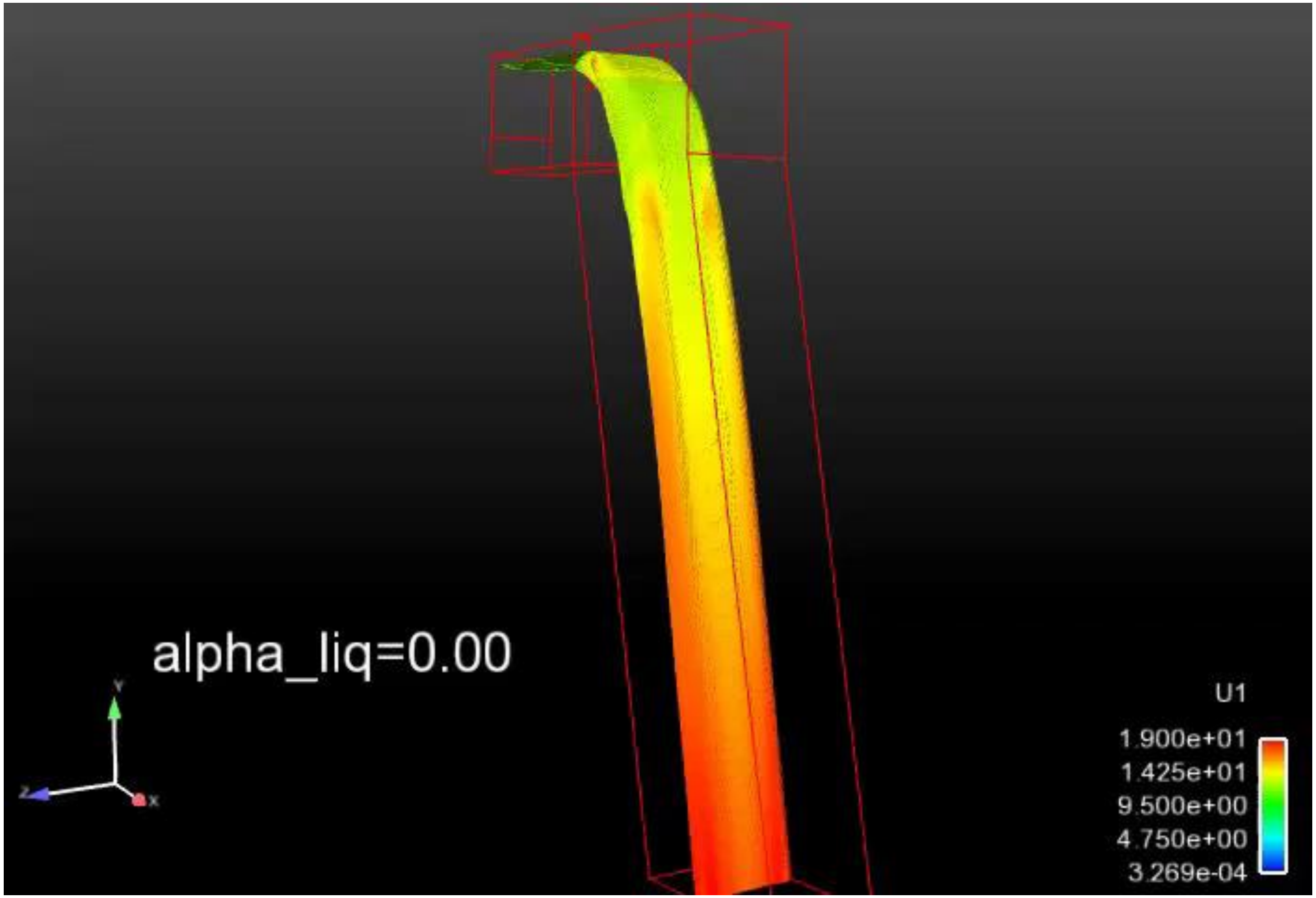
Débordement de barrage:

3 champs

(liquide et gaz continus, gouttes dispersées)

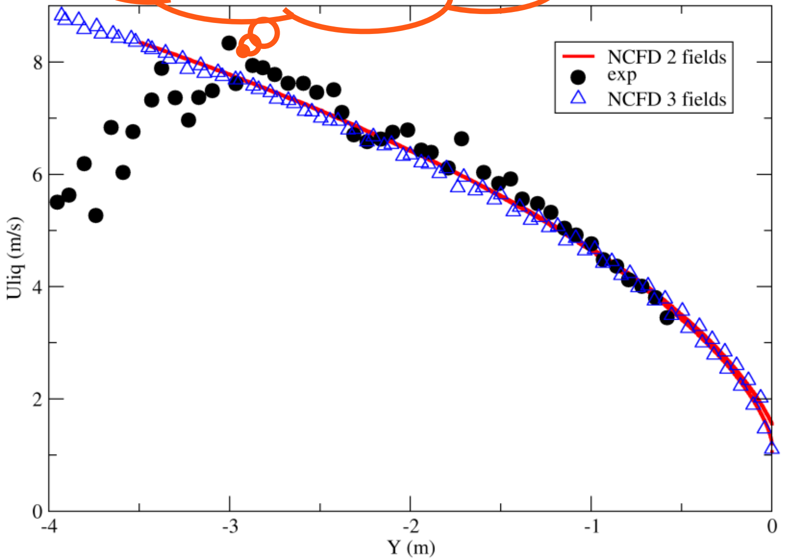


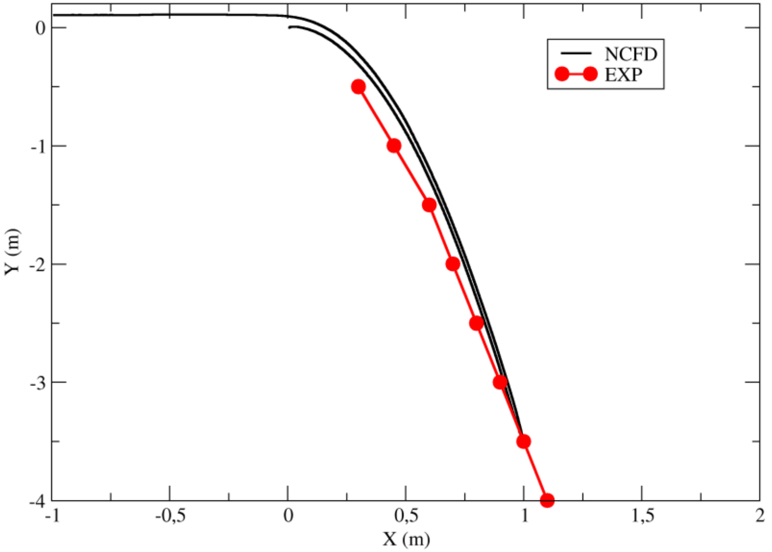
SAUT DE L’ANGE: 22,5M DE CELLULES

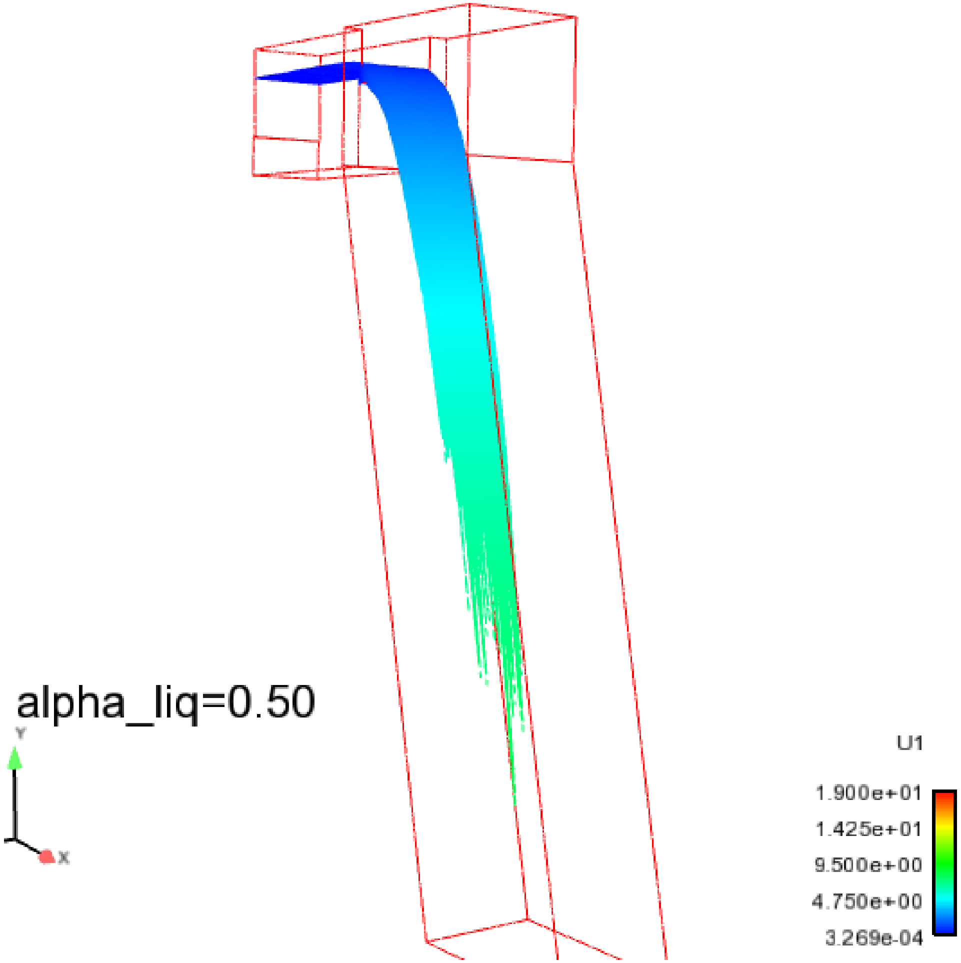


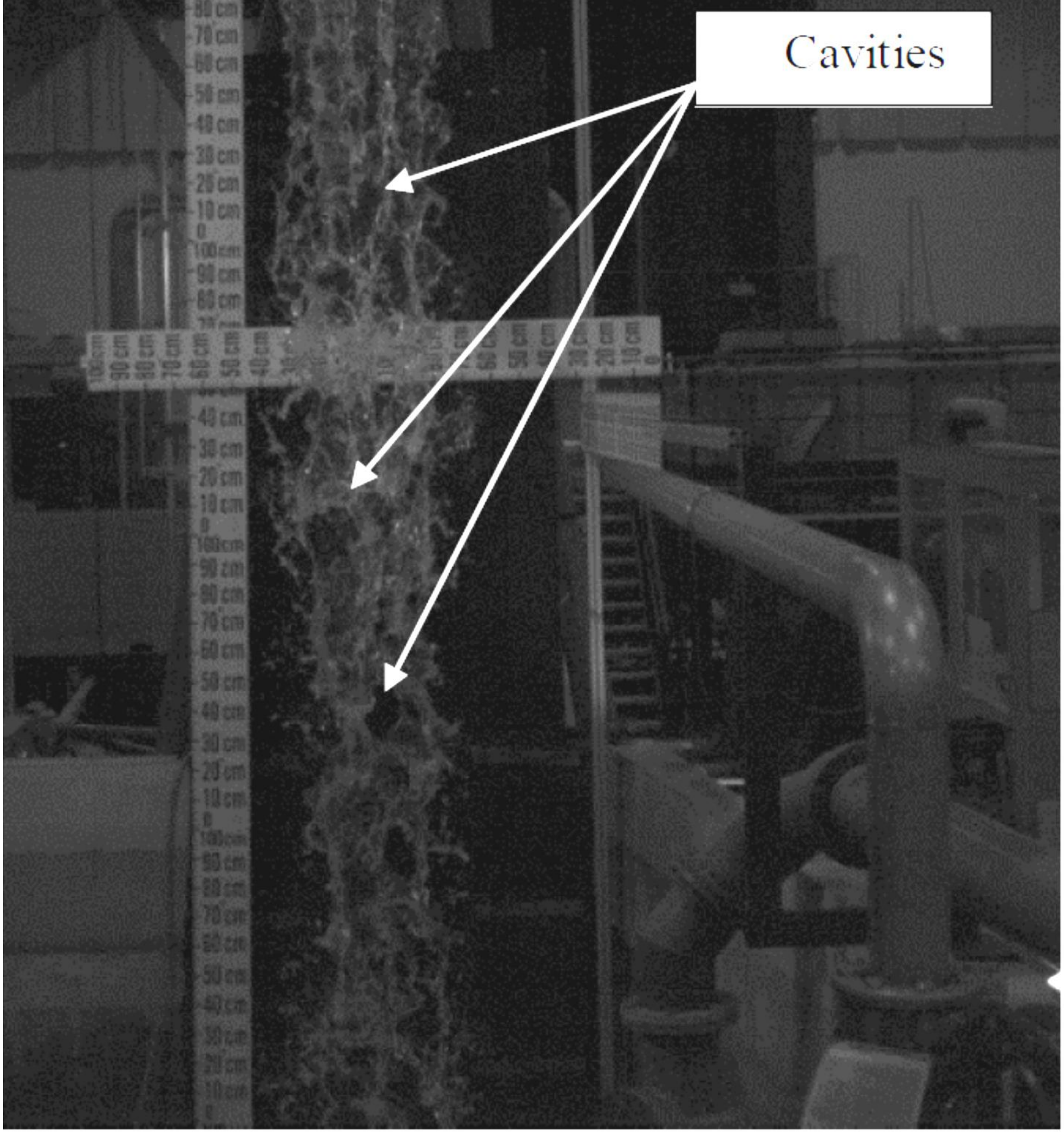
Au boulot !

SAUT DE L’ANGE









Cavities

SAUT DE L’ANGE

Premiers calculs: position du jet, vitesse.

Fragmentation du jet : turbulence, …

Maillage ~ 5mm , 1 mm → trop grossier?

Calculer d’autres essais