Maillage adaptatif pour des interfaces mobiles gaz-liquide-solide

CFL Research Group
(Computing and FLuids)
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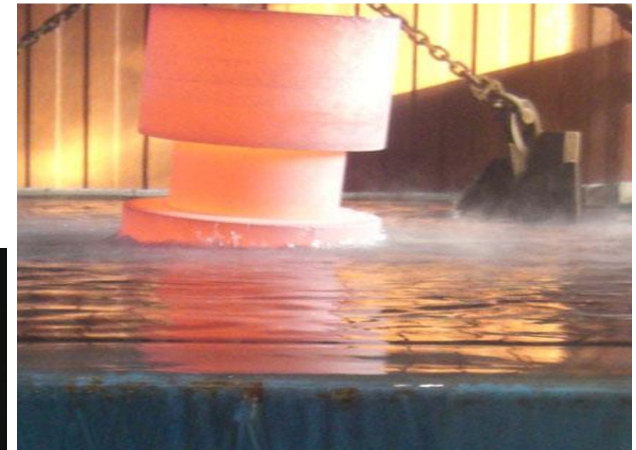
Context: challenges in multiphase flows

...with immersed heated solid



Coupling

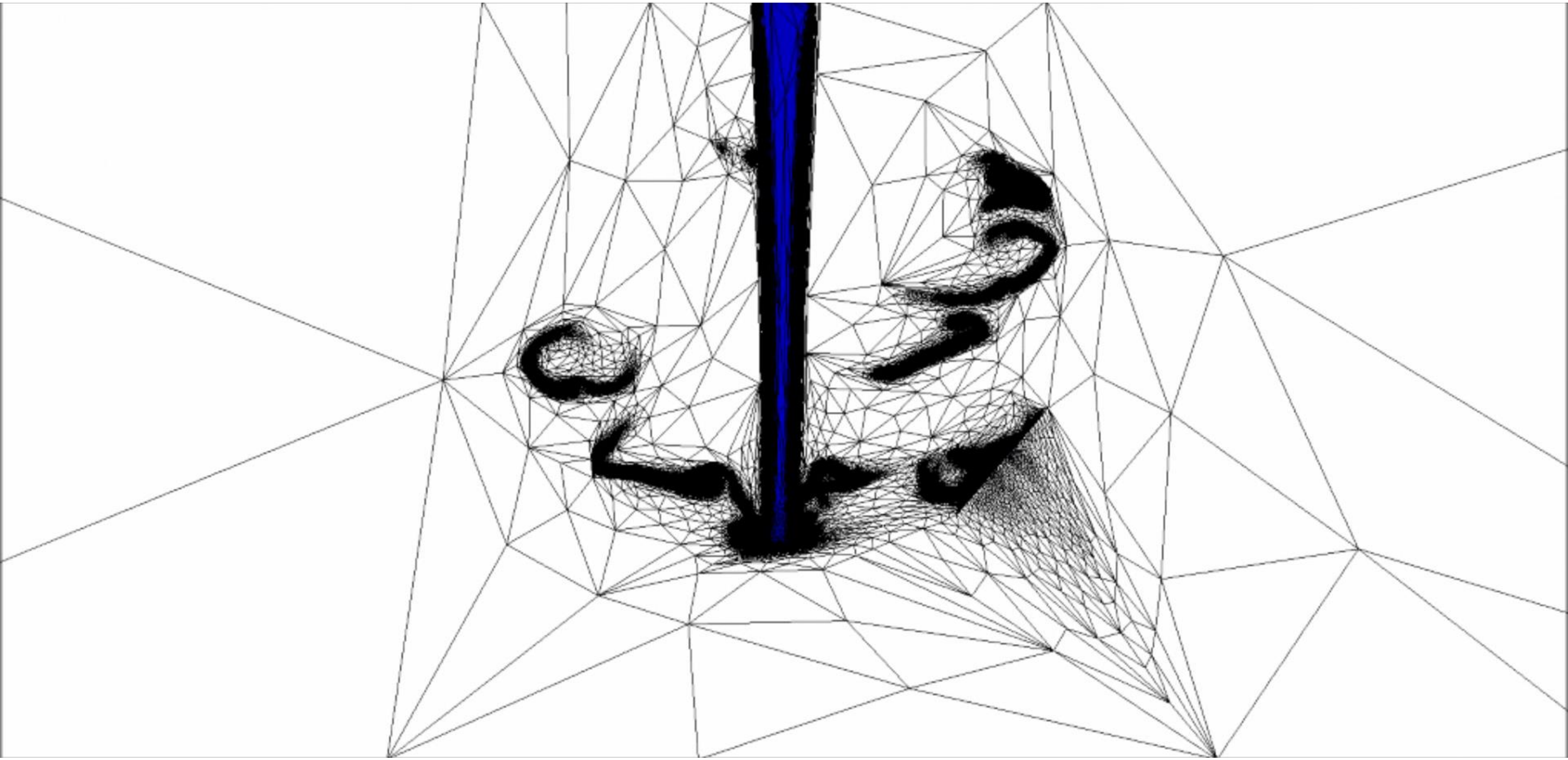
...with phase change

Two phase flows

Number of scales

High fidelity multiphase framework: illustration

Unsteady NS, Anisotropic mesh adaptation, regularisation, parallel computing….

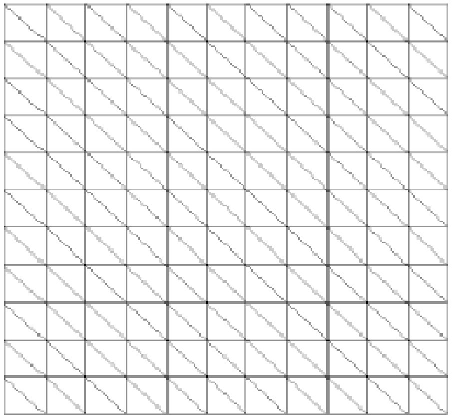


Anisotropic mesh adaptation

Y. Mesri Y., M. Khalloufi, E. Hachem, On optimal simplicial 3D meshes for minimizing the Hessian-based errors, App. Num. Math, 2016, 07

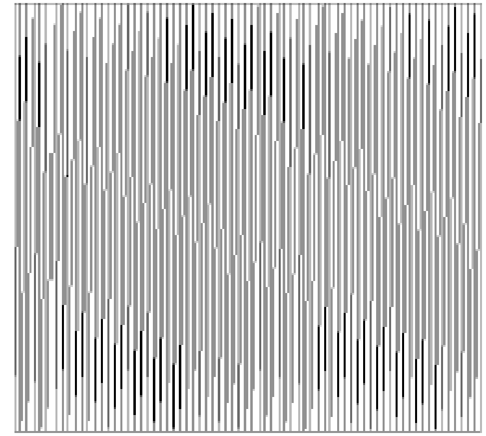
We are concern to capture automatically:

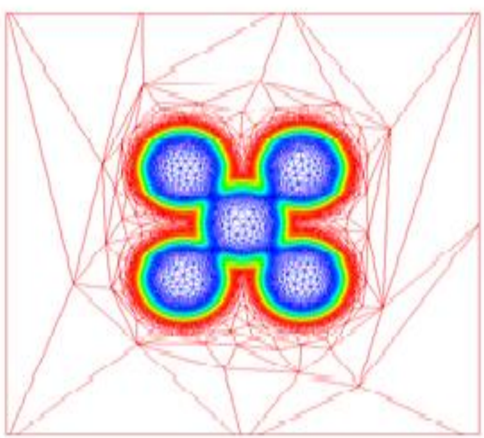
(i) boundary layers (ii) inner layers (iii) flow detachments

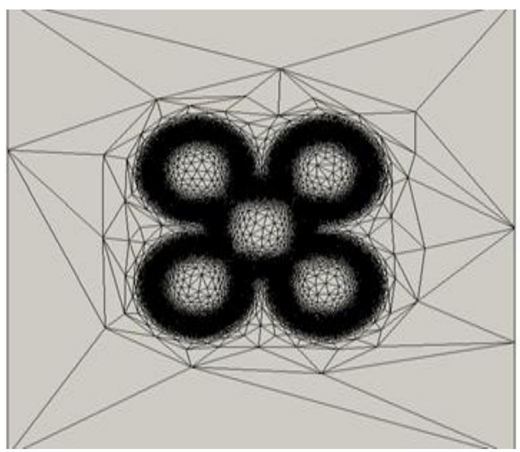


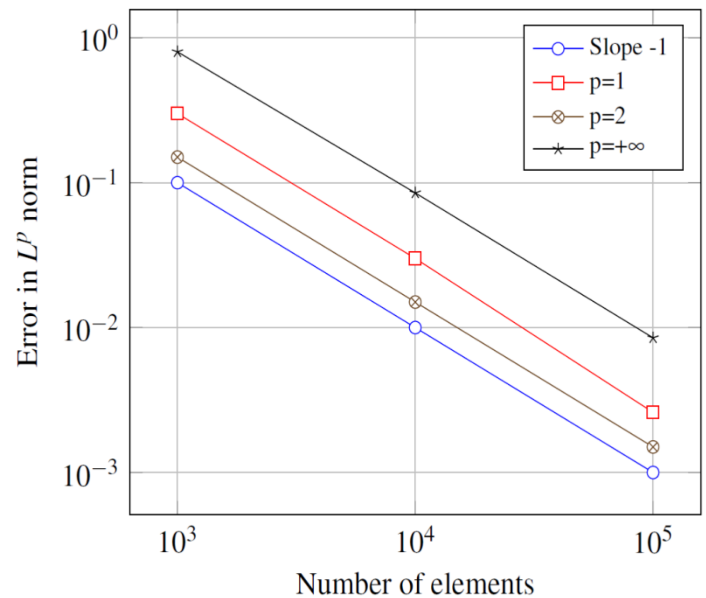
$$+\ M = \begin{pmatrix} \frac{1}{0.01^2} & \\ & \frac{1}{1^2} \end{pmatrix} +$$ improved remesher $=$

Metric (directions, size)





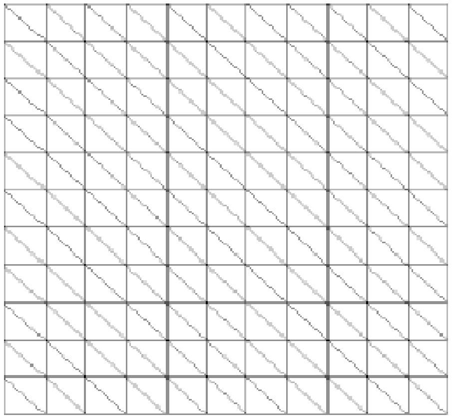




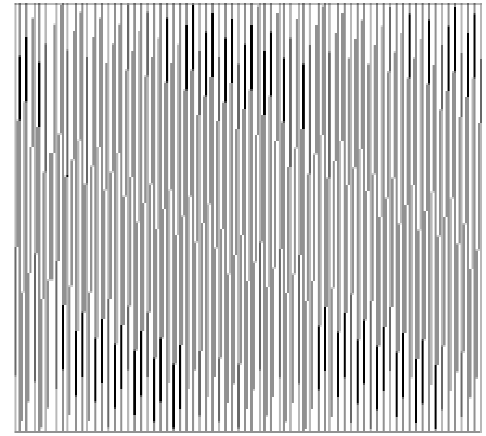
Anisotropic mesh adaptation

We are concern to capture automatically:

(i) boundary layers (ii) inner layers (iii) flow detachments



$$+ \; M = \begin{pmatrix} \frac{1}{0.01^2} & \\ & \frac{1}{1^2} \end{pmatrix} + \text{improved remesher} =$$



Metric (directions, size)

→ We refer to the use of an edge-based metric:

T. Coupez and E. Hachem, Solution of High-Reynolds Incompressible Flow with Stabilized Finite Element and Adaptive Anisotropic Meshing, Computer Methods in Applied Mechanics and Engineering, Vol. 267, pp. 65-85, 2013

$$\widetilde{\mathbb{M}^i} = \frac{|\Gamma(i)|}{d}\left(\widetilde{\mathbb{X}^i}\right)^{-1}$$

With $\widetilde{\mathbf{X}^{ij}} = s_{ij}\mathbf{X}^{ij}$ and $s_{ij} = \left(\frac{e}{e(N)}\right)^{-\frac{1}{2}} = \left(\frac{\sum_i n^i(1)}{N}\right)^{\frac{2}{d}} e_{ij}^{-1/2}$

→ Extended to account accurately for sharp layers using the local wall shear stress:

$$\tau_w \equiv \tau(y=0) = \mu \frac{\partial u}{\partial y}\bigg|_{y=0}$$

L. Billon, Y. Mesri, E. Hachem, Anisotropic boundary layer mesh generation for immersed complex geometries, accepted in Engineering with Computers, 2016 (online)

Illustration 2: Dam breaking (water column with surface tension)

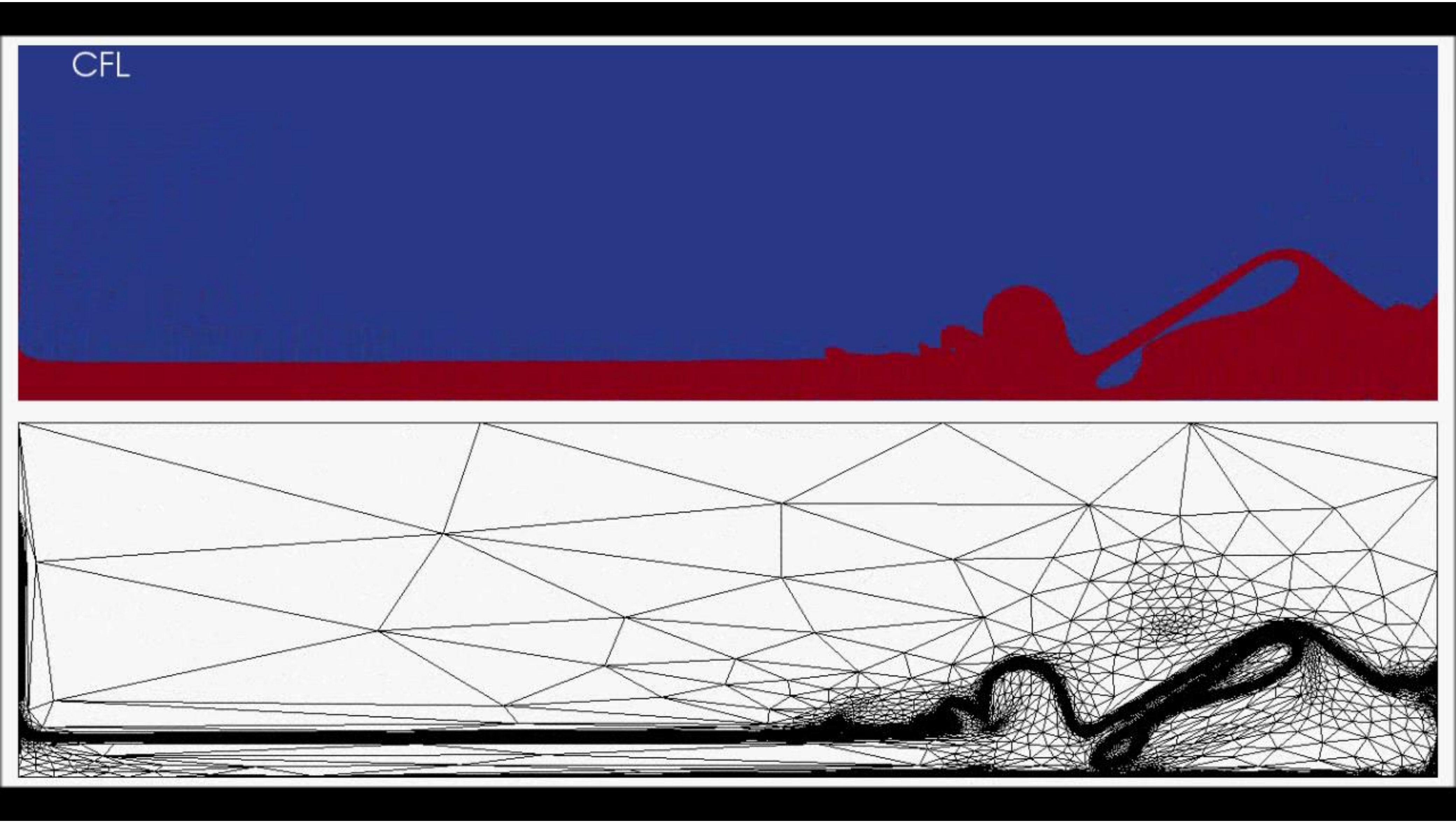
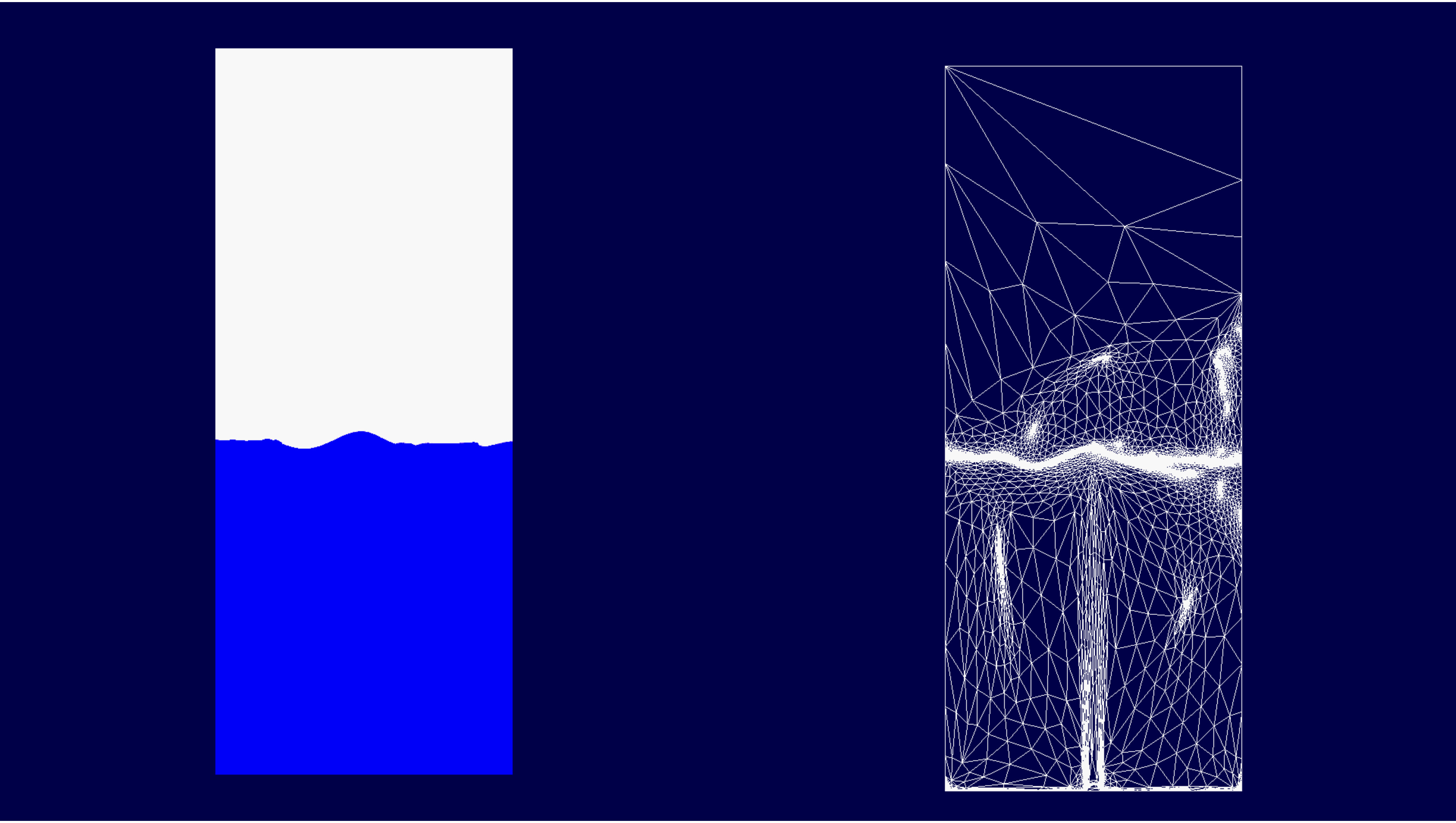
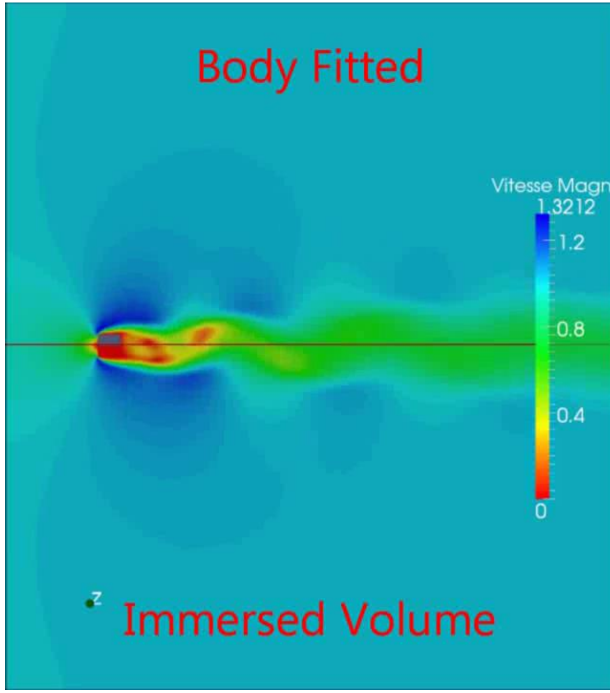


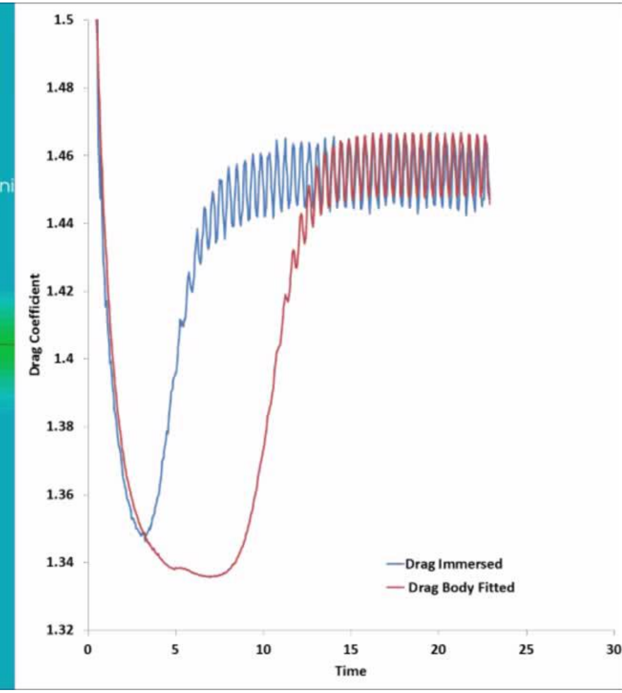
Illustration 3: Filling and dome formation

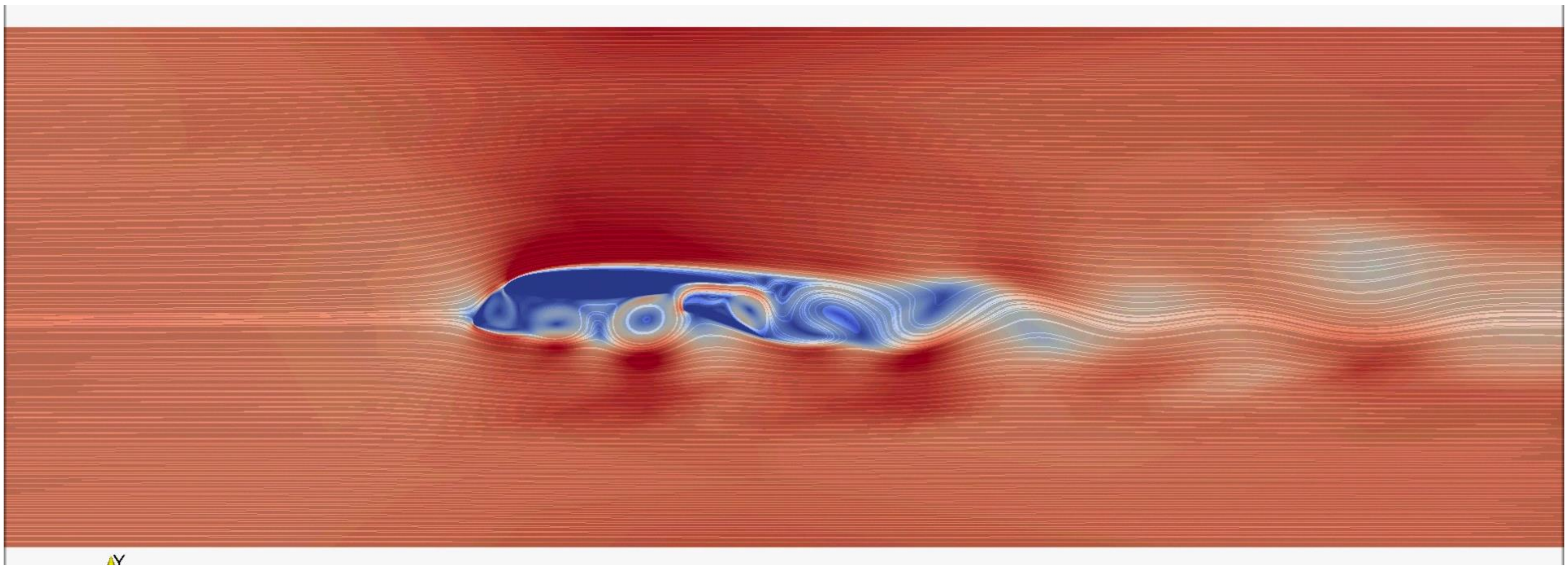


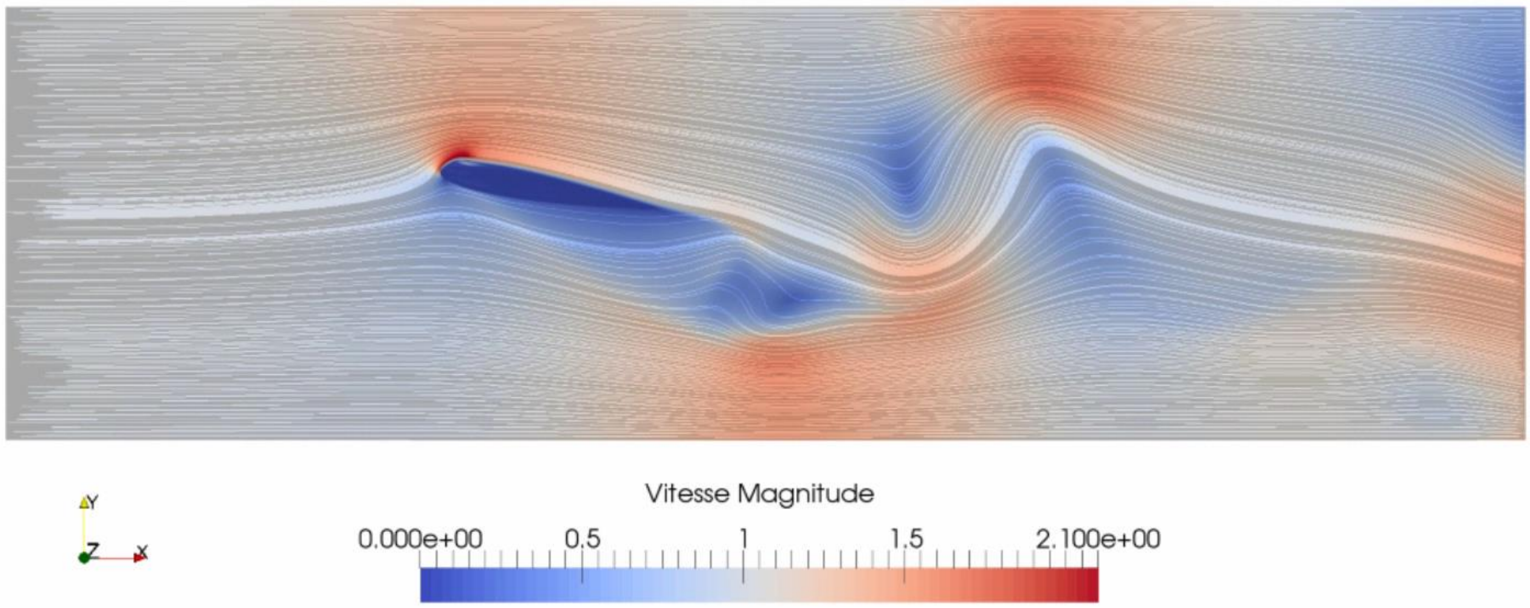
Fluid-Solid flows:

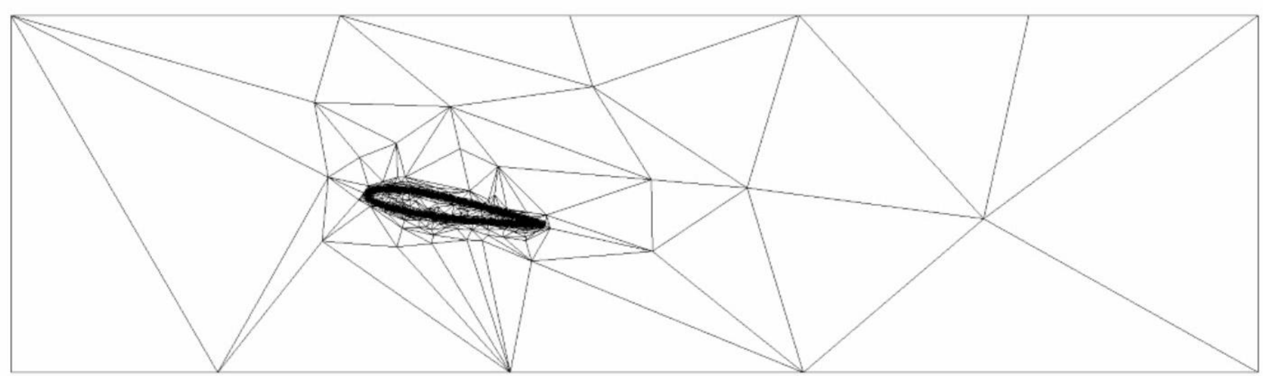
- ❑ Moving solid
- ❑ Implicit representation by a levelset function
- ❑ Penalization by imposing zero rate of deformation
- ❑ Dynamic anisotropic meshing











- ❑ Flapping wing
- ❑ Implicit representation by a levelset function
- ❑ Penalization by imposing zero rate of deformation
- ❑ Dynamic anisotropic meshing

Quenching

Cooling of a hot part from austenization temperature to room temperature

Cooling rate

Mechanical Properties

Residual Stresses

Phase Transformation

Industrial context

THOST Thermal Optimization System:

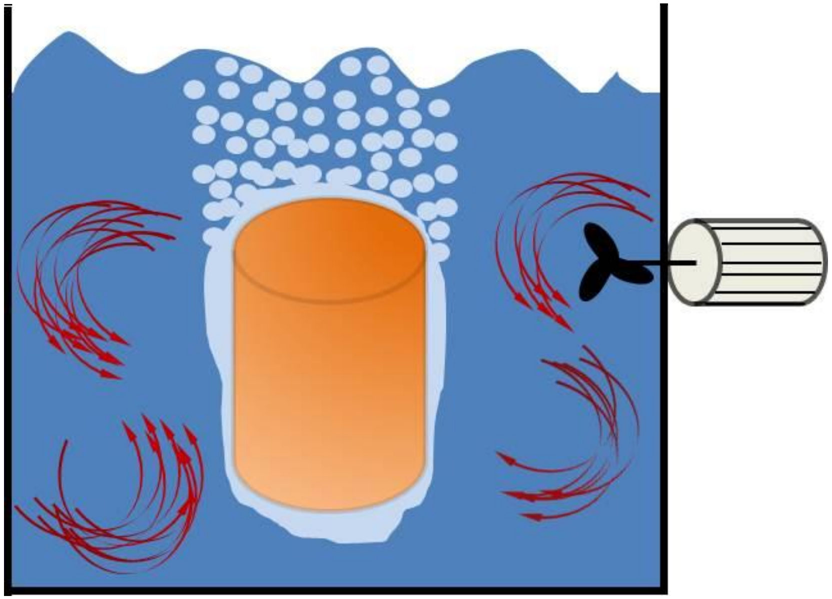
- Several companies
- Different parts
  - Geometries
  - Size (cm to m)
- Different quenchants (water, oil, air, polymer, gas,…)

Hollow cylinder - Areva

Seat flange - Faurecia

Accurate and robust simulation of the quenching processes

Heat transfer



Quenching bath

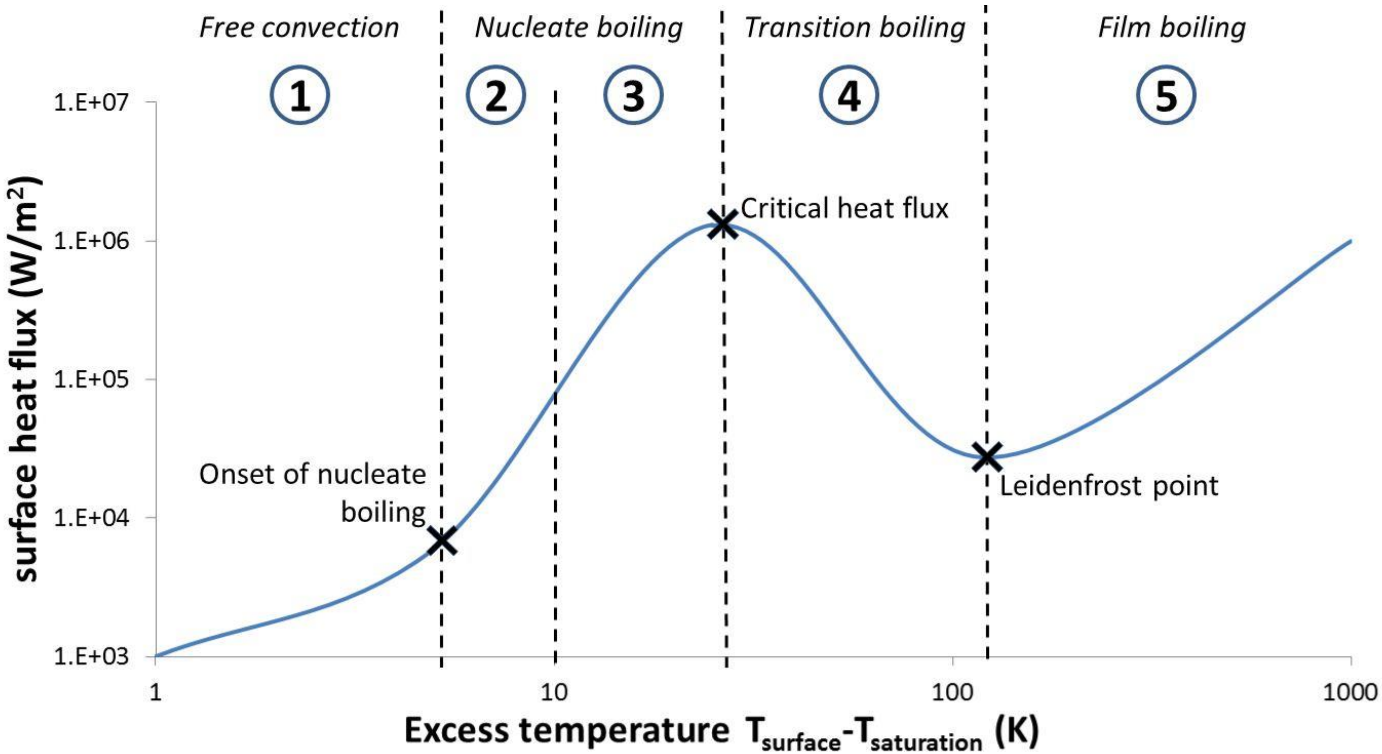
- Multiphase: solid/liquid/gas
- Agitation

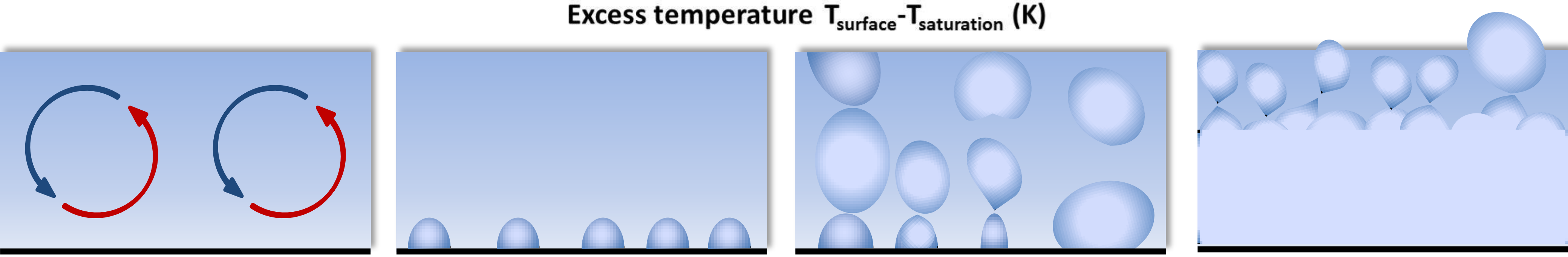
➡ Heat transfer coefficient?

Paradigm:

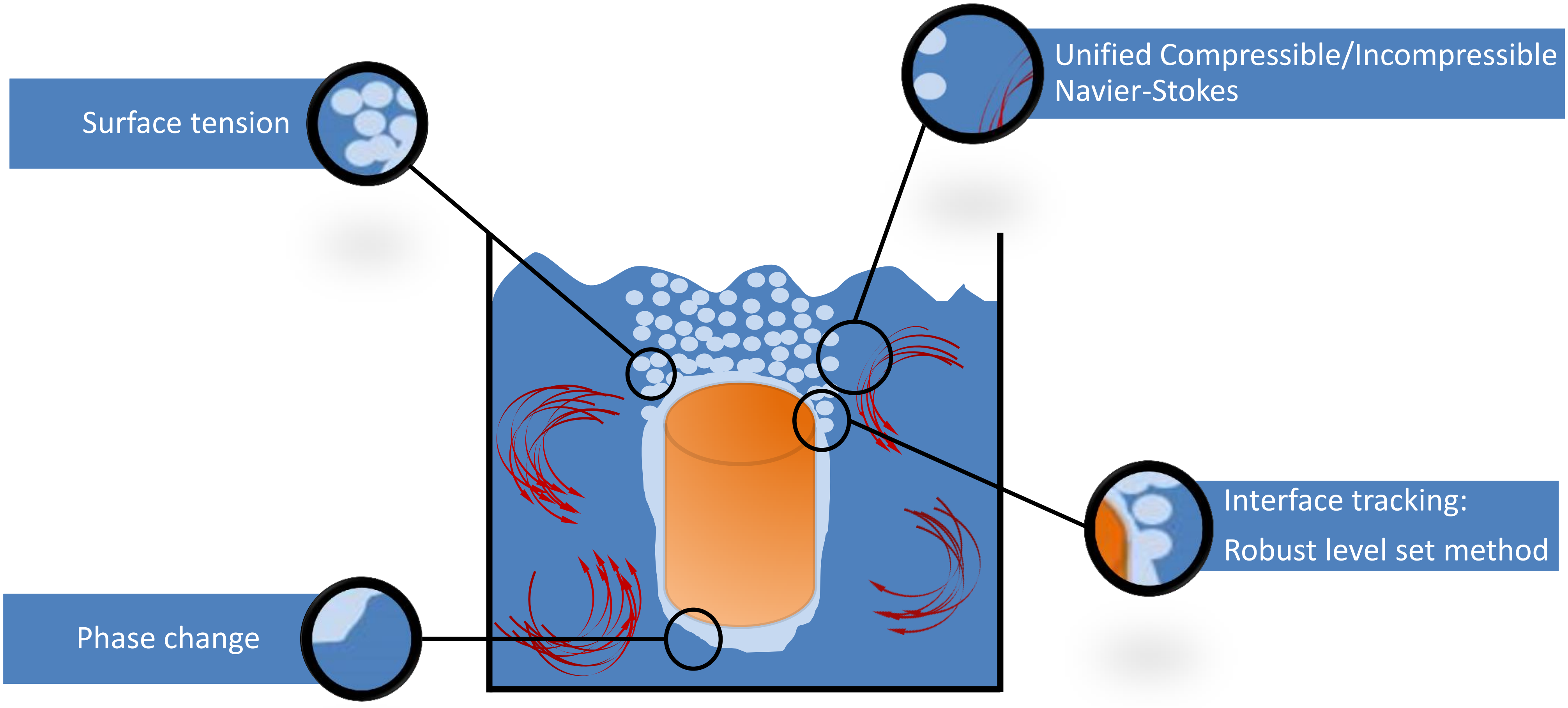
- Immersed volume methods
- Strong coupling solid/fluid/gas
- Natural heat transfer

Heat transfer



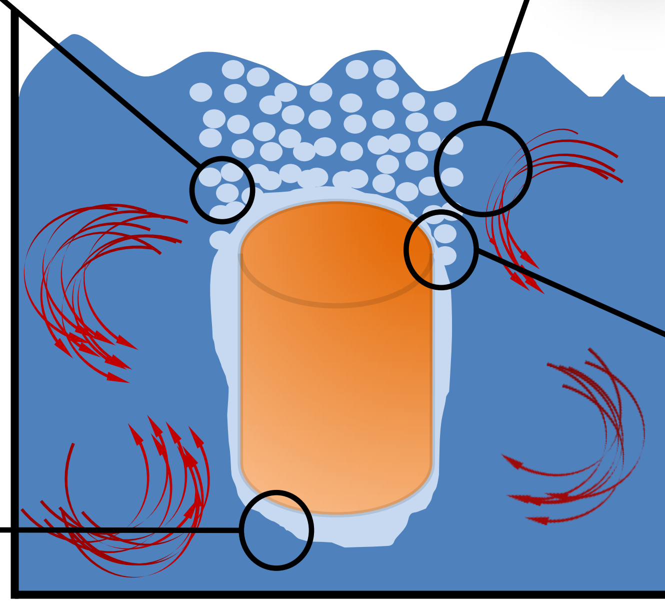


Outline: Looking for a robust multiphase framework…



…dedicated to industrial quenching and heat treatment

Looking for a robust multiphase framework



Surface tension

- Explicit surface tension
- Extremely small time-step
- Divergence otherwise

Unified Compressible/Incompressible Navier-Stokes

- Compressible phase not taken into account

⇩

Wrong physics

Interface tracking:

Robust level set method

- Non conservative
- Different parameters to tune

⇨ Non industrial

- Divergence with high Reynolds

Phase change

- Depends on an ad-hoc coefficient

$$v_\Gamma = C_0 (T - T_{sat}) \cdot \mathrm{n}$$

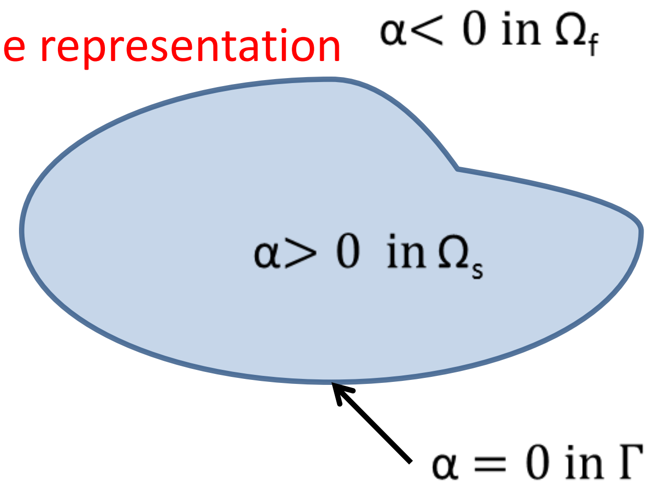
1-Level set

Basic definition

$$\alpha(X) = \begin{cases} -\mathrm{dist}(X,\Gamma) \text{ if } X \in \Omega_f \\ 0 \text{ if } X \in \Gamma \\ \mathrm{dist}(X,\Gamma) \text{ if } X \in \Omega_s \end{cases}$$

$$\|\nabla\alpha\| = 1$$

Phase representation



(1) Transport equation $\dfrac{\partial \alpha}{\partial t} + u \cdot \nabla \alpha = 0$

(2) Hamilton-Jacobi problem $\dfrac{\partial \alpha}{\partial \tau} + \mathrm{s}(\alpha)(\|\nabla\alpha\| - 1) = 0$

Two possibilities:

Solving (1) and (2) separately

Fedkiw 2009, Osher 2000, Sussman 2005

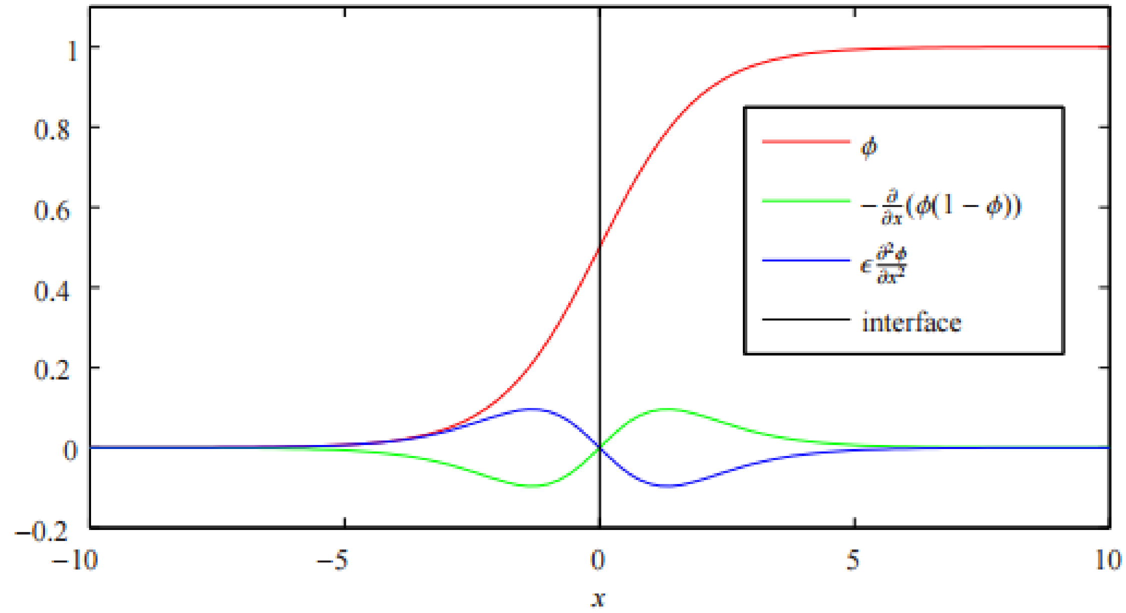
Embedding (2) in (1) : auto reinitialisation

Ville et.al. 2011, Bonito et al 2015

A new Level Set method:

Conservative Level set method:

(1) Filtering $$\phi(\alpha)=\frac{1}{2}\left(1+\tanh\left(\frac{\alpha}{2\varepsilon}\right)\right)$$

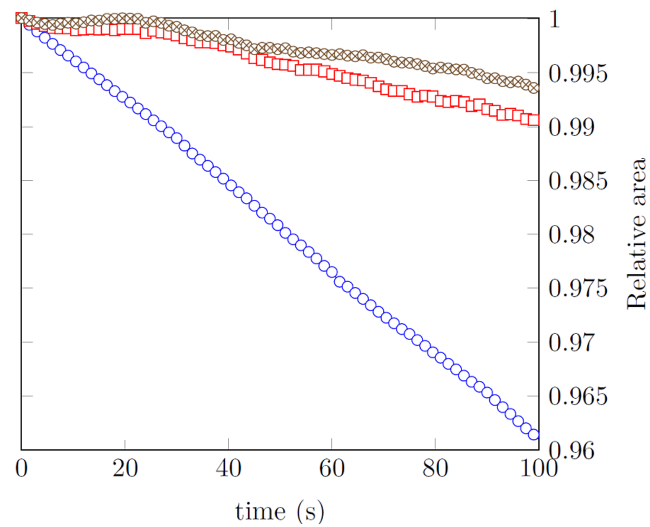


Walker, Müller 2014

(2) Convection $$\frac{\partial\phi}{\partial t}+u\cdot\nabla\phi=0$$

(3) Reinitialization

$$\frac{\partial\phi}{\partial\tau}+\nabla\cdot\Big(\phi(1-\phi)\mathrm{n}-\varepsilon((\nabla\phi\cdot\mathrm{n})\mathrm{n}\Big)=0$$



E. Olsson, G. Kreiss, A conservative level set method for two phase flow, *Journal of Computational Physics*, Volume 210, Issue 1, 2005, Pages 225-246

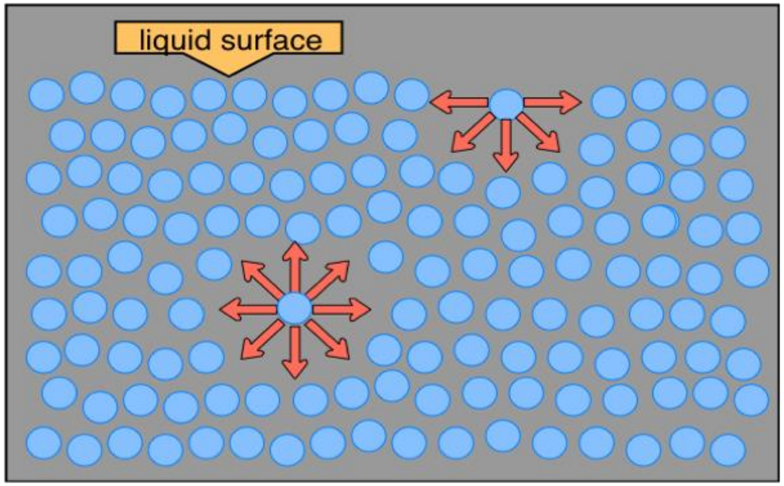
2- Surface tension

Surface tension

$$f_{\mathrm{ST}} = -\gamma\kappa\delta(\Gamma)\mathrm{n}$$

$$\mathrm{n} = \nabla\alpha/|\nabla\alpha| \qquad \kappa = -\nabla\cdot\mathrm{n}$$

γ is the surface tension coefficient



http://butane.chem.uiuc.edu/

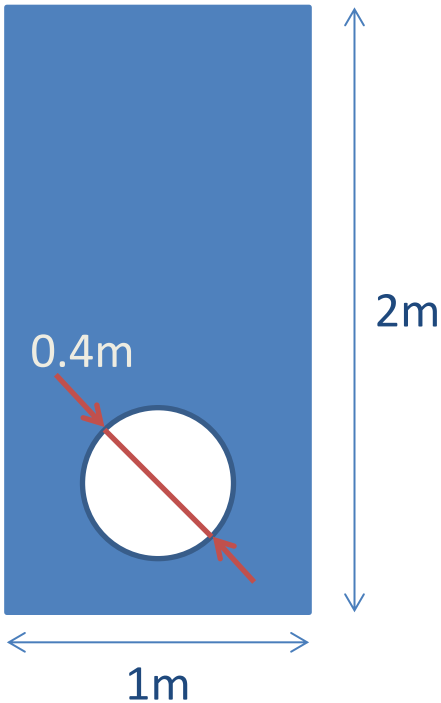
Usually implemented as a source term in NS equations

$$\begin{aligned} \rho(\partial_t u + u\cdot\nabla u) - \nabla\cdot(2\mu\varepsilon(u)) + \nabla p &= f + f_{ST} \\ \nabla\cdot u &= 0 \end{aligned}$$

Numerical analysis shows that: time-step restriction $\Delta t < (\Delta x)^{\frac{3}{2}}\sqrt{\dfrac{\bar{\rho}}{2\pi\gamma}}$

In 3D coupled problems, surface tension is the major bottleneck.

2D and 3D validations



- Liquid
  Density: 10^4 kg/m^3
  Viscosity: 1 kg/(m.s)

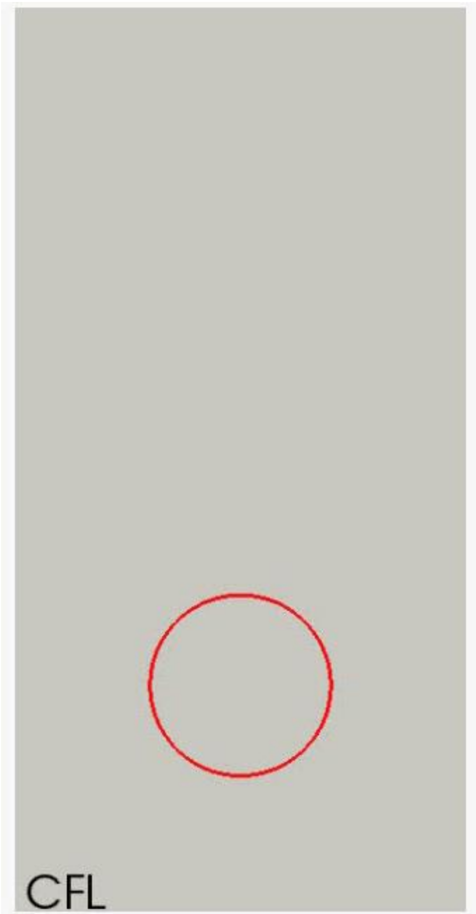
- Vapor
  Density: 10^3kg/m^3
  Viscosity: 1 kg/(m.s)

Surface tension 0,5 kg/s^2
Gravity g=-8x10^{-4}m/s^2

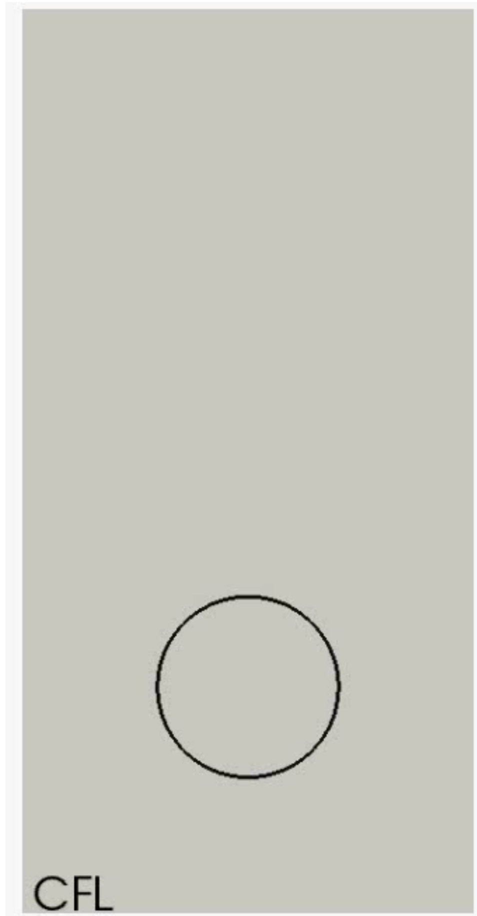
Mesh size h=1/80

Surface tension

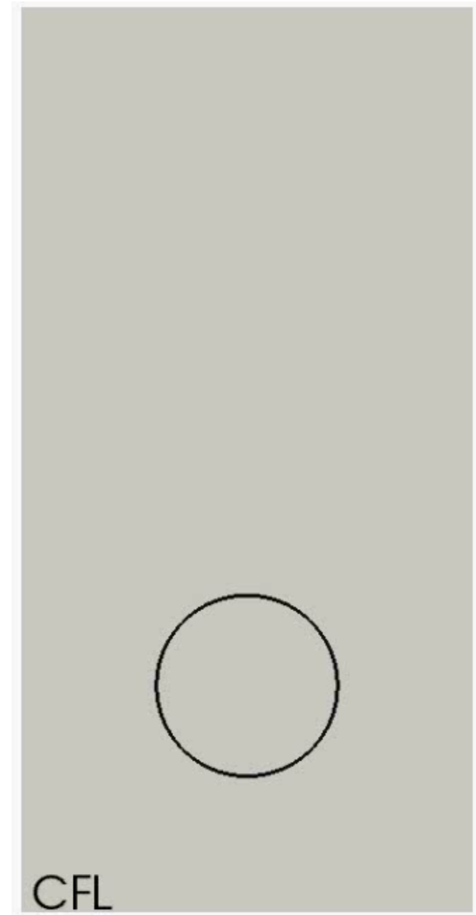
explicit
implicit



dt=0.1s

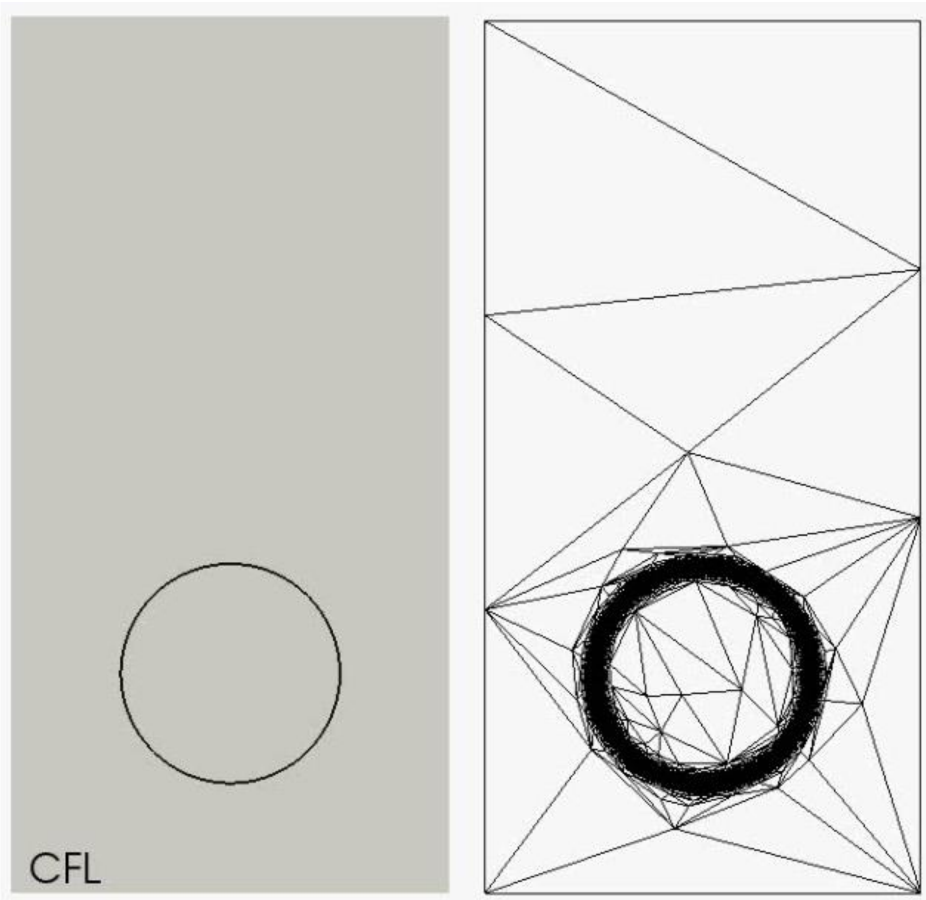


dt=1s

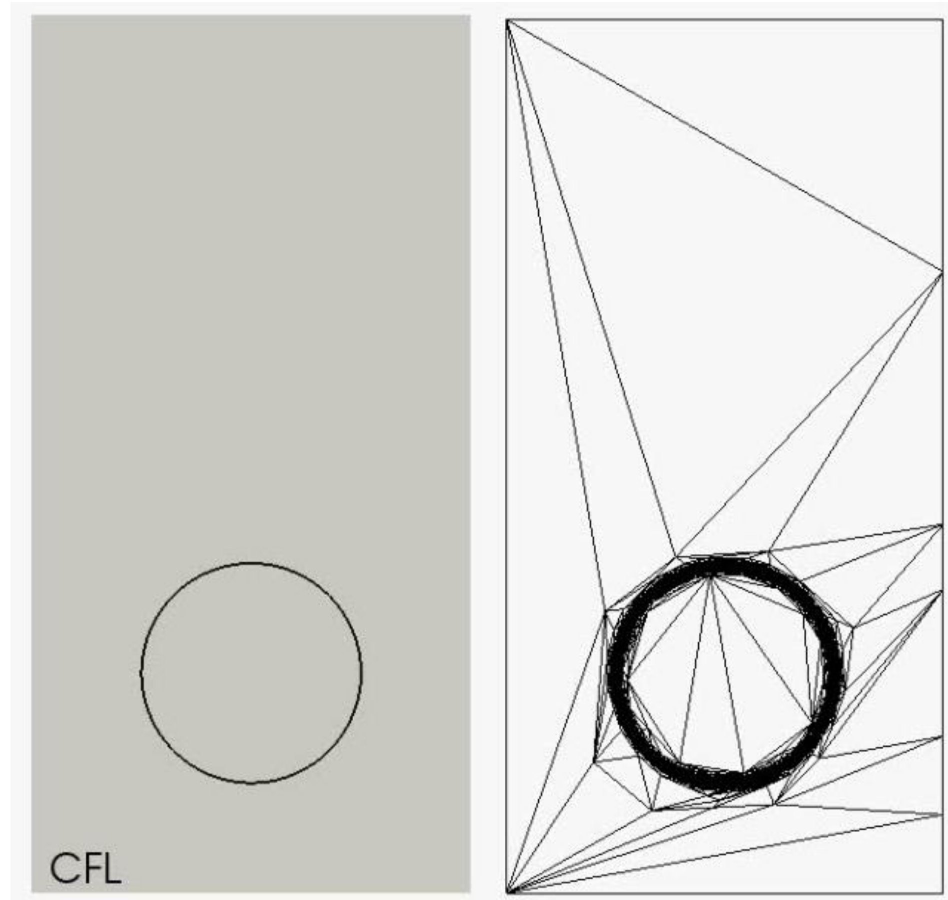


dt=4s

Surface tension



Case 1: High surface tension



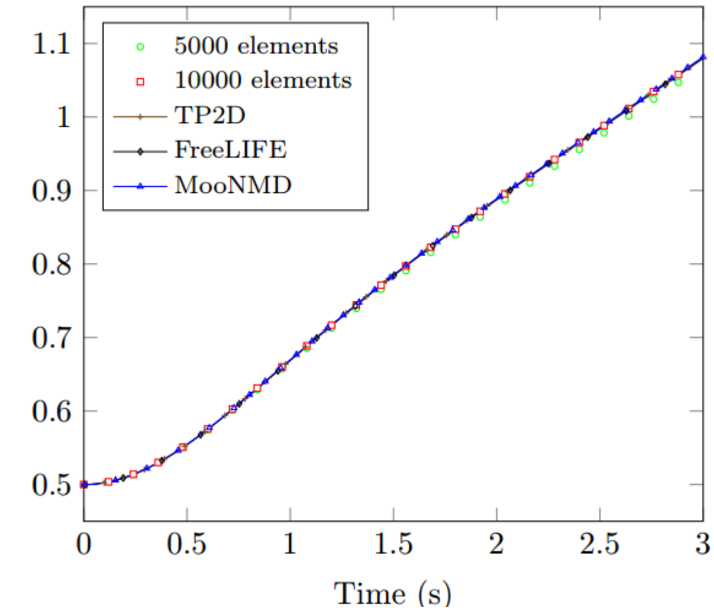
Case 2: Low surface tension

M. Khalloufi, Y. Mesri, R. Valette, E. Hachem, High fidelity anisotropic adaptive variational multiscale method for multiphase flows with surface tension, **Computer Methods in Applied Mechanics and Engineering**, Vol. 307, pp.44-67, **2016**

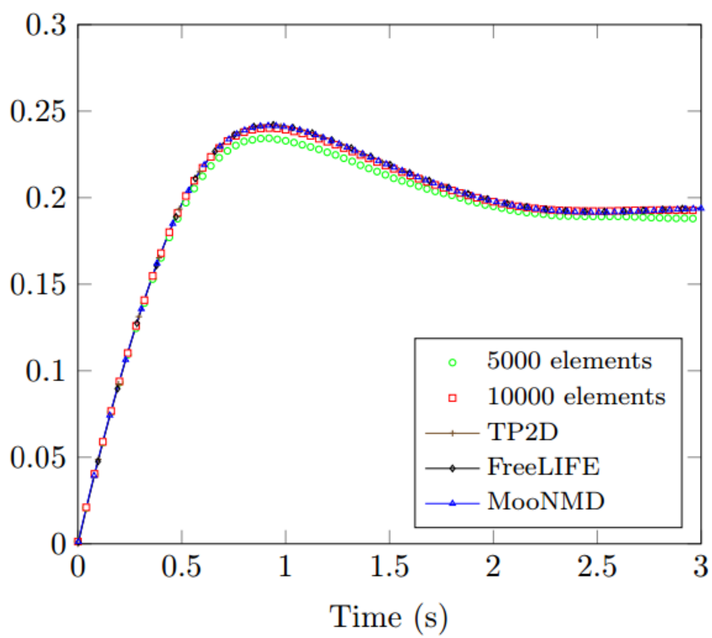
Validation: Rising bubble with mesh adaptation

Case1

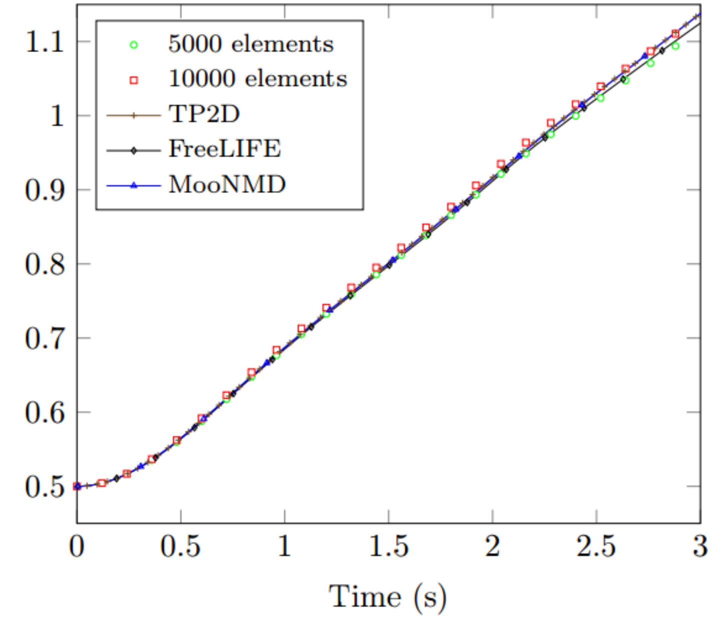
Position of the center of mass

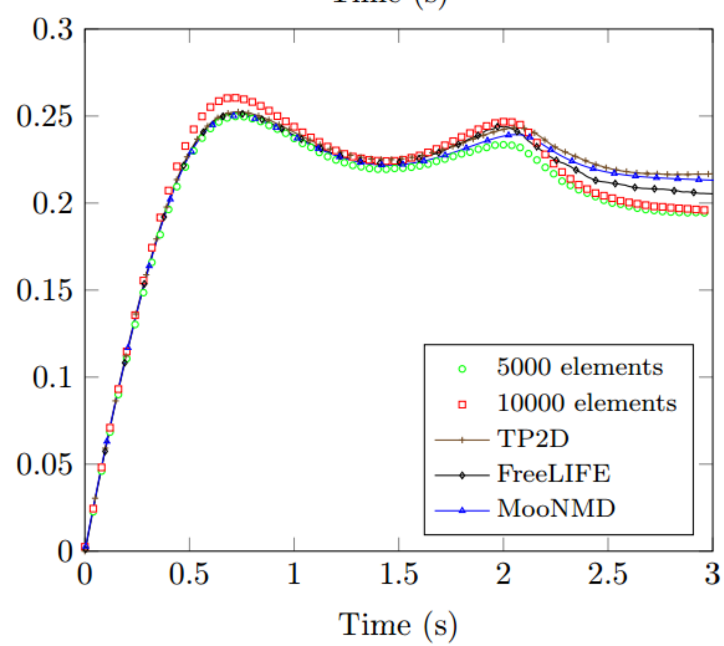


Rising velocity



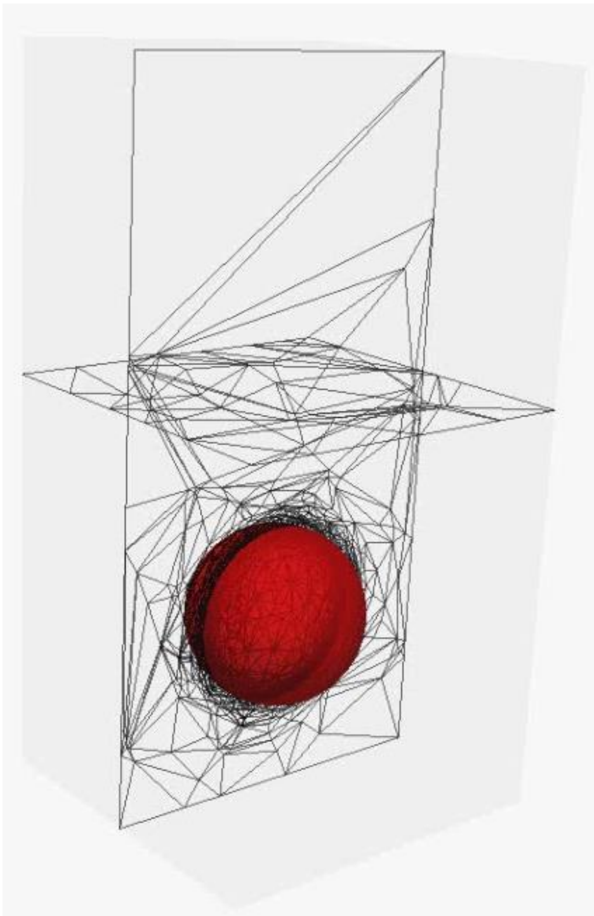
Case2

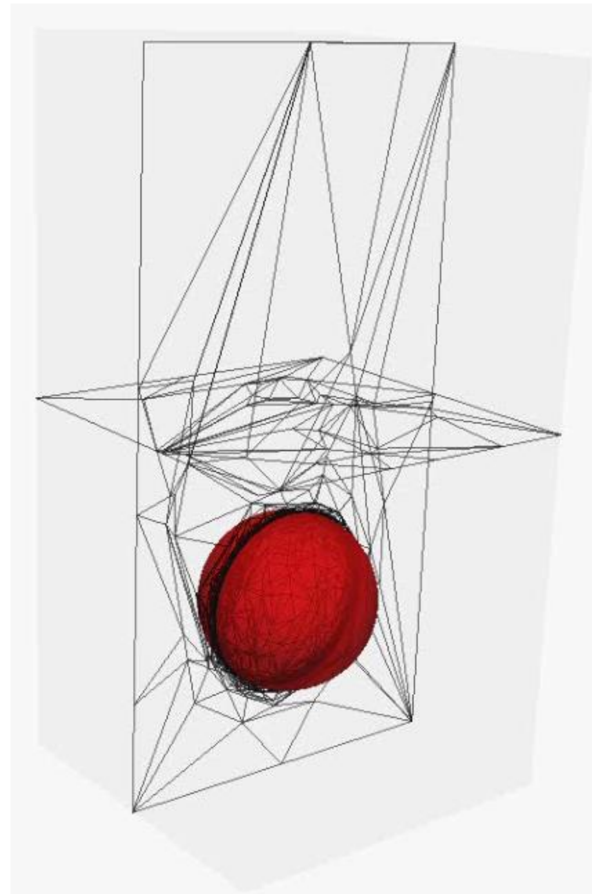




Validation: 3D Rising bubble with mesh adaptation

With
surface
tension





Without
surface
tension

M. Khalloufi, Y. Mesri, R. Valette, E. Hachem, High fidelity anisotropic adaptive variational multiscale method for multiphase flows with surface tension, **Computer Methods in Applied Mechanics and Engineering**, Vol. 307, pp.44-67, **2016**

3-Unified Compressible/Incompressible solver

Navier-Stokes equations

$$\begin{aligned} \rho(\partial_t u + u \cdot \nabla u) - \nabla \cdot \sigma &= f \quad \text{in } \Omega \times [0,T] \\ \nabla \cdot u &= 0 \quad \text{in } \Omega \times [0,T] \end{aligned}$$

$$\frac{d\rho}{dt} = \left(\frac{\partial \rho}{\partial T}\right)_p \frac{dT}{dt} + \left(\frac{\partial \rho}{\partial p}\right)_T \frac{dp}{dt} \quad \Rightarrow \quad \chi_P = \frac{1}{\rho}\left(\frac{\partial \rho}{\partial p}\right)_T \quad \text{and} \quad \chi_T = \frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_p$$

χ_T is the volume expansivity

χ_P is the isothermal compressibility coefficient

Conservation equation

$$\boxed{\nabla \cdot u + \chi_P \frac{\partial p}{\partial t} + \chi_P u \cdot \nabla p = \chi_T \frac{dT}{dt}}$$

M. Billaud, G. Gallice, B. Nkonga, A simple stabilized finite element method for solving two phase compressible–incompressible interface flows, *Computer Methods in Applied Mechanics and Engineering*, Volume 200, Issues 9–12, 2011, pp.1272-1290

3-Unified Compressible/Incompressible solver

$$\rho \frac{\partial u}{\partial t} + \rho u \cdot \nabla u - \nabla \cdot (2\mu\varepsilon(u)) + \nabla p = f_v$$

$$\nabla \cdot u + \chi_P \frac{\partial p}{\partial t} + \chi_P u \cdot \nabla p \quad = f_p$$

By splitting the velocity and the pressure into a coarse scale and a fine scale:

Variaztional Multiscale Stabilized Finite Element Method

$$\left(\frac{\rho\partial(u_h+\tilde{u})}{\partial t}, v_h\right) + \left(\rho(u_h+\tilde{u})\cdot\nabla(u_h+\tilde{u}), v_h\right) - \left(p_h+\tilde{p}, \nabla\cdot v_h\right) + \left(2\eta\varepsilon(u_h):\varepsilon(v_h)\right) = \left(f_v, v_h\right) \quad \forall v_h \in \mathcal{V}_h$$

$$\left(\nabla\cdot(u_h+\tilde{u}), q_h\right) + \chi_P\left(\frac{\partial(p_h+\tilde{p})}{\partial t}, q_h\right) + \chi_P\left((u_h+\tilde{u}).\nabla(p_h+\tilde{p}), q_h\right) = \left(f_p, q_h\right) \quad \forall q_h \in Q_h$$

$$\tilde{u} = \sum_{K\in\mathfrak{I}_h} \tau_u \tilde{P}_u(R_u)$$

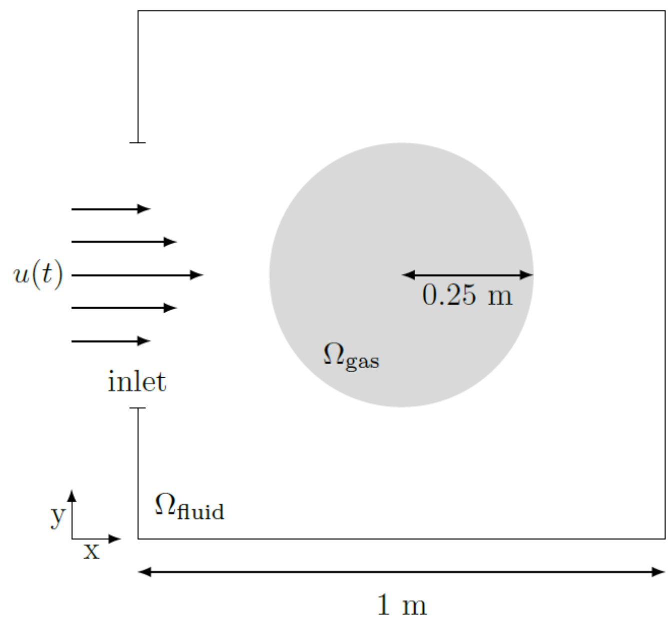
$$\tilde{p} = \sum_{K\in\mathfrak{I}_h} \tau_c \tilde{P}_c(R_c)$$

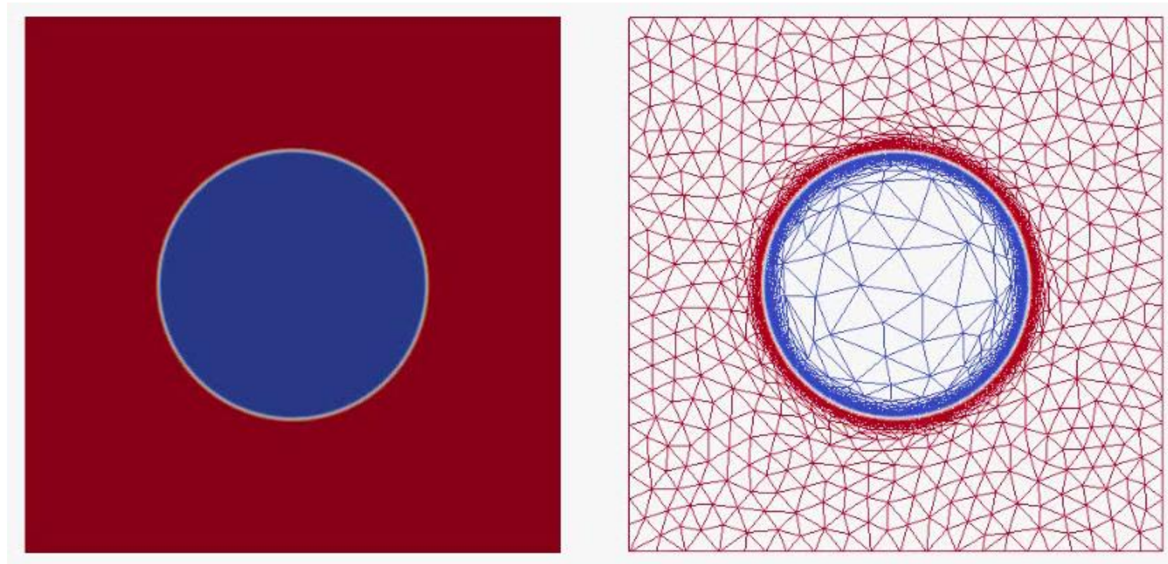
$$R_u = f_v - \rho\frac{\partial u_h}{\partial t} - \rho u_h^c \cdot \nabla u_h + \nabla\cdot(2\mu\varepsilon(u_h)) - \nabla p_h$$

$$R_c = f_p - \nabla\cdot u_h - \chi_P \frac{\partial p_h}{\partial t} - \chi_P u_h^c \cdot \nabla p_h$$

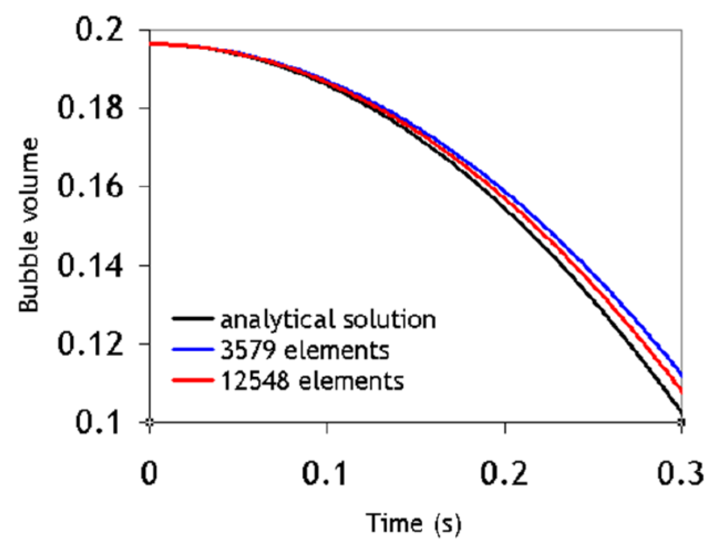
3-Unified Compressible/Incompressible solver

Compression of a bubble – Challenging case

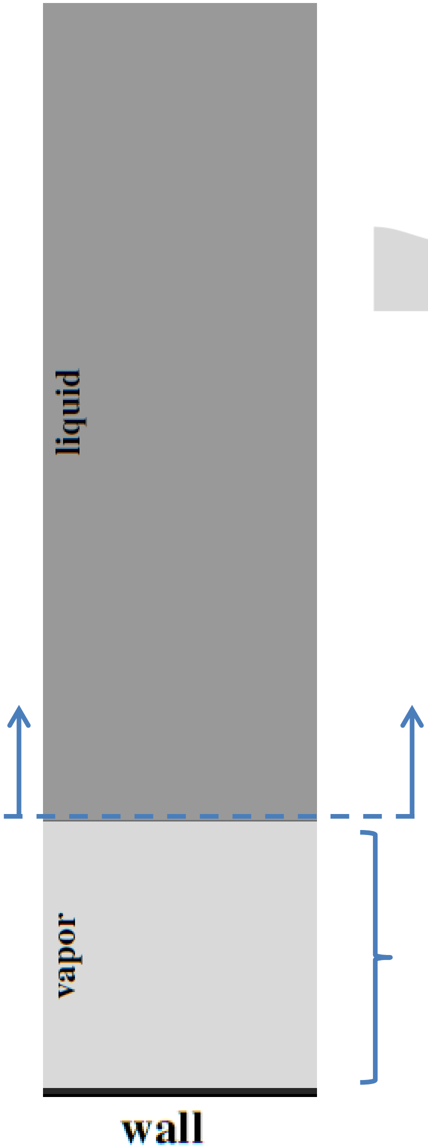




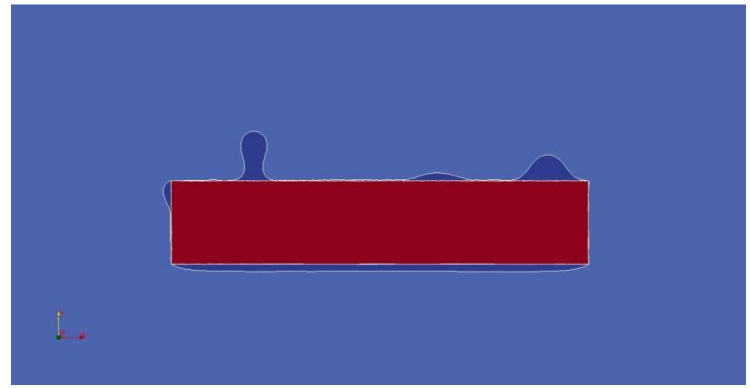
E. Hachem, M. Khalloufi, J. Bruchon, R. Valette, Y. Mesri, Unified adaptive Variational MultiScale method for two phase compressible-incompressible flows, **Computer Methods in Applied Mechanics and Engineering**, Vol. 308, pp. 238-255, **2016**



Phase change



Rayleigh-Taylor instability

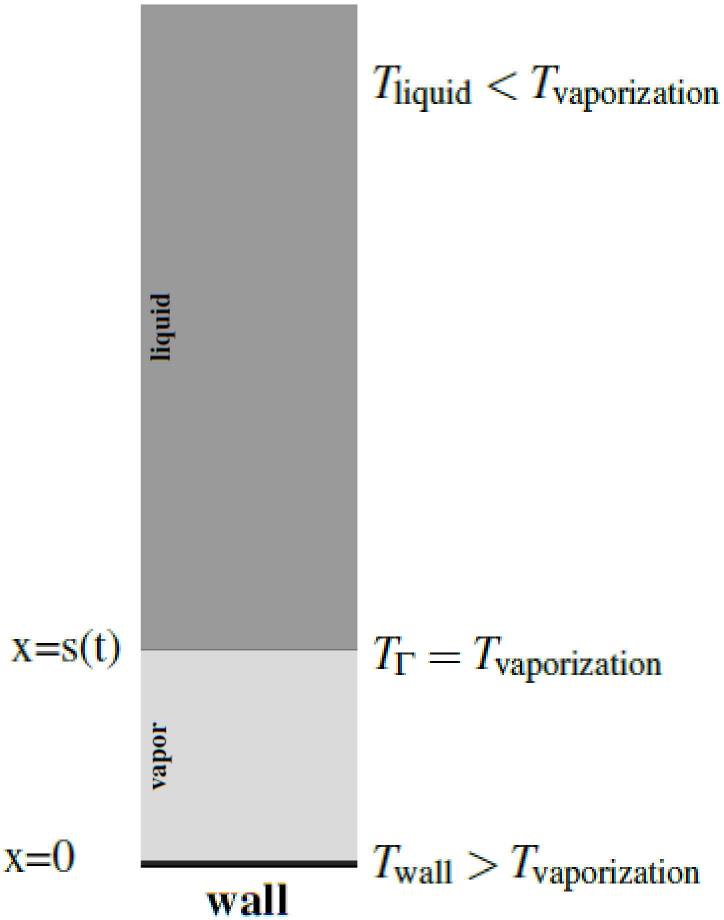


Relaxation

Phase change → Stefan problem

	ρ [kg/m^3]	μ [kg/(s·m)]	c_p [kJ/(kg·K)]	k [W/(m·K)]	L_{vap} [kJ/kg]
Vapor (100°C)	0.6	1.2×10^{-5}	2.027	0.0248	
Water (100°C)	960	2.83×10^{-4}	4.215	0.682	2264.76

Stefan problem



$$\boxed{\rho c_p \frac{\partial T}{\partial t} - k \frac{\partial^2 T}{\partial x^2} = 0}$$

$$T(x,t) = T_{\text{wall}} + \frac{T_{\text{vaporization}} - T_{\text{wall}}}{\operatorname{erf}\left(\frac{s}{2\sqrt{\alpha_v t}}\right)} \operatorname{erf}\left(\frac{x}{2\sqrt{\alpha_v t}}\right)$$

$$\operatorname{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x \exp(-t^2)\,dt$$

Stefan condition with constant density

$$\rho L \frac{ds}{dt} = (-k_v \nabla T_v + k_l \nabla T_l) \cdot \vec{e}_x$$

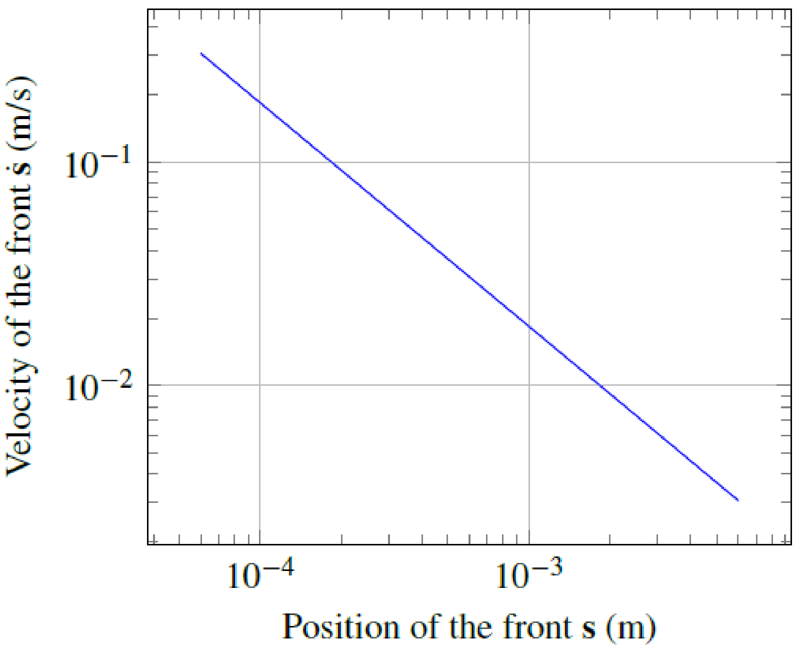
Stefan condition with variable density

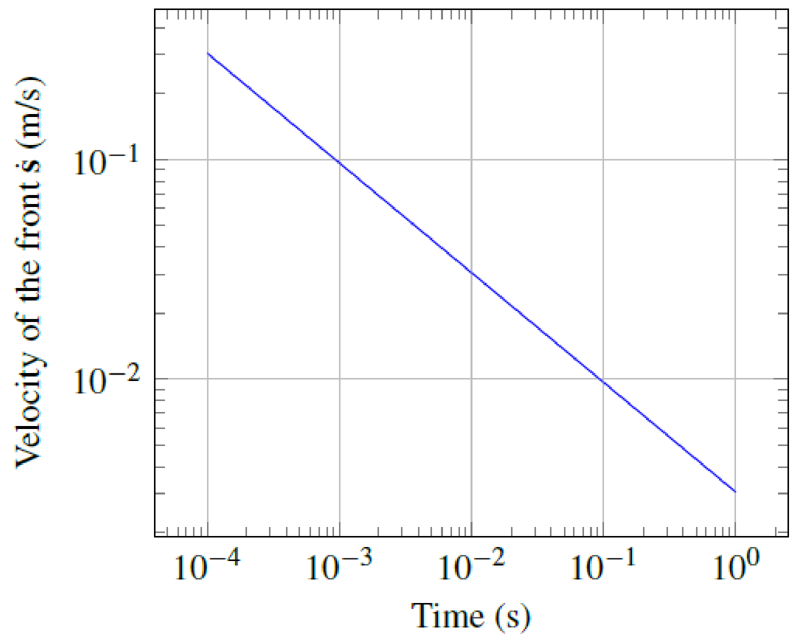
$$-\rho_v L_{\text{vap}} \frac{\mathbf{ds}}{\mathbf{dt}} - \frac{1}{2}\rho_v \left(1 - \frac{\rho_v}{\rho_l}\right)^2 \left(\frac{\mathbf{ds}}{\mathbf{dt}}\right)^{\mathbf{3}} = (-k_l \nabla T_l + k_v \nabla T_v) \cdot \vec{e}_x$$

	ρ [kg/m^3]	μ [kg/(s·m)]	c_p [kJ/(kg·K)]	k [W/(m·K)]	L_{vap} [kJ/kg]
Vapor (100°C)	0.6	1.2×10^{-5}	2.027	0.0248	
Water (100°C)	960	2.83×10^{-4}	4.215	0.682	2264.76

Stefan problem

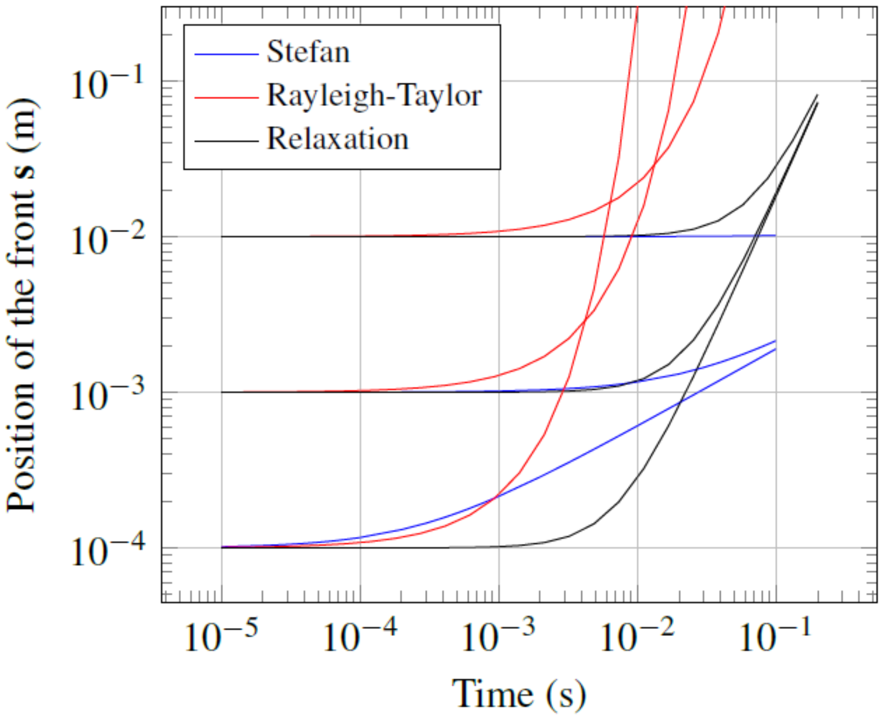
$$\dot{s}(t) = \alpha_v \frac{T_w - T_{\text{vap}}}{T_{\text{ref}}} \frac{1}{s(t)} \approx \frac{1.8 \times 10^{-5}}{s}$$



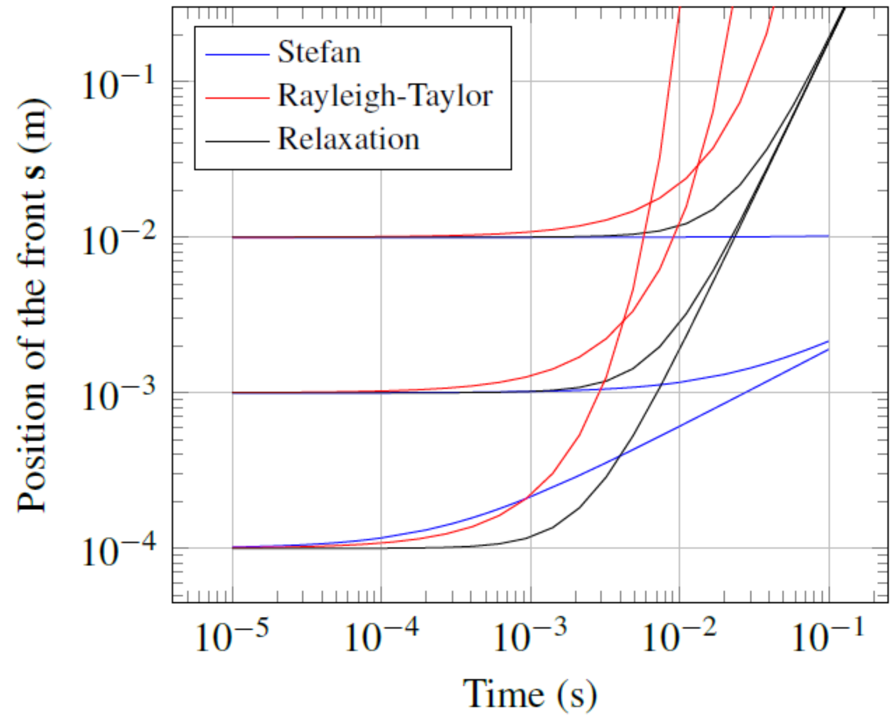


Stefan problem

For a given initial thickness of the film



Grand bain
L=1m P=1.1bar



Petit bain
L=0,1m
P=1bar

Phase change

$$\rho_l c_l \left(\frac{\partial T_l}{\partial t} + u \cdot \nabla T_l \right) - \nabla \cdot (k_l \nabla T_l) = 0 \qquad \text{in } \Omega^l$$

$$\rho_g c_g \left(\frac{\partial T_g}{\partial t} + u \cdot \nabla T_g \right) - \nabla \cdot (k_g \nabla T_g) = 0 \qquad \text{in } \Omega^g$$

Mass rate transfer at the interface

$$\boxed{\dot{m} = -\frac{q_l \cdot n - q_g \cdot n}{L}} \qquad q = -k\nabla T$$

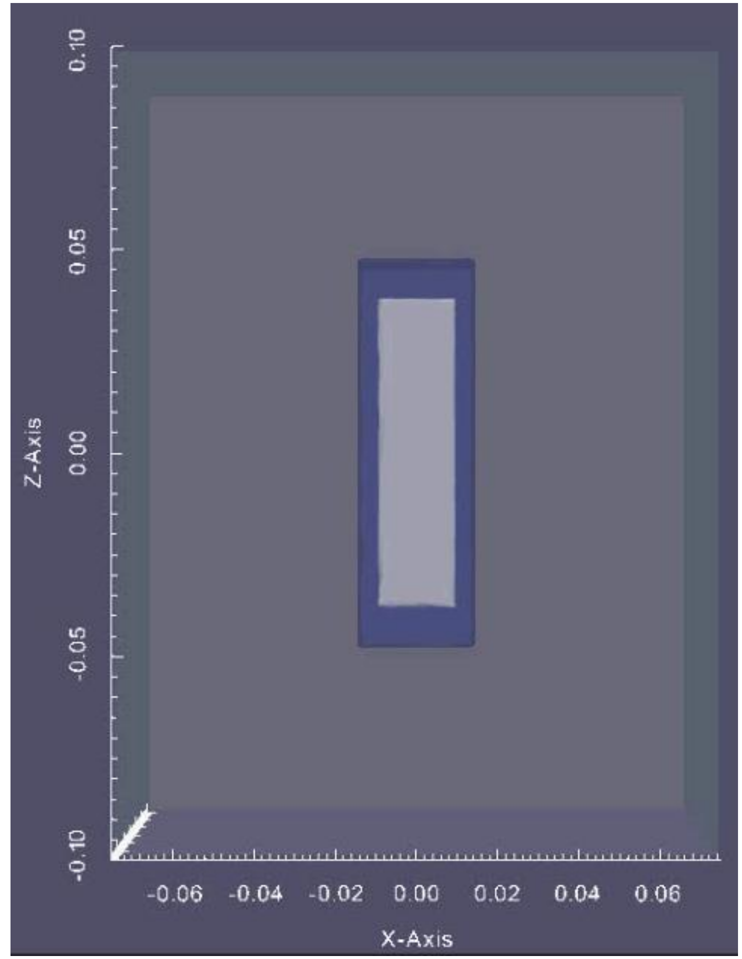
Navier-Stokes equations

$$\rho \left(\frac{\partial u}{\partial t} + u \cdot \nabla u \right) - \nabla \cdot \mu (\nabla u + \nabla^T u) + \nabla p = f_{ST} + \rho g$$

$$\nabla \cdot u = \boxed{\dot{m} \left(\frac{1}{\rho_g} - \frac{1}{\rho_l} \right)}$$

Level Set

$$\frac{\partial \alpha}{\partial t} + u \cdot \nabla \alpha = \boxed{-\frac{\dot{m}}{\rho_l}}$$



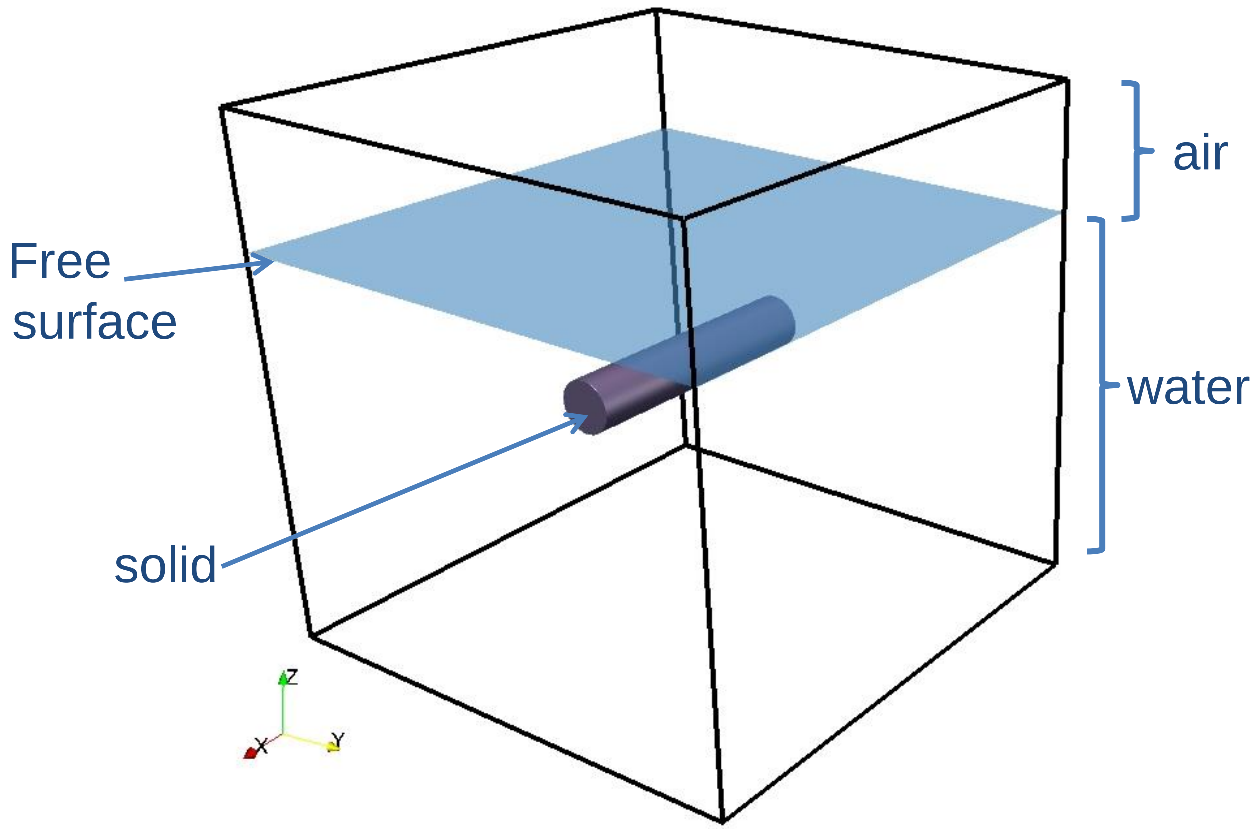
V. Mihalef et al. Physics based boiling simulation. *Proceedings of the 2006 ACM SIGGRAPH/Eurographics Symposium on Computer Animation*, SCA '06, pages 317-324

T. Kim et al. A simple boiling module. *Proceedings of the 2007 ACM SIGGRAPH/Eurographics Symposium on Computer Animation*, SCA '07, pages 27-34

V. Daru et al. Modélisation et simulation numérique du changement de phase liquide-vapeur en cavité. *Comptes Rendus Mécanique*, 334(1):25 - 33, 2006

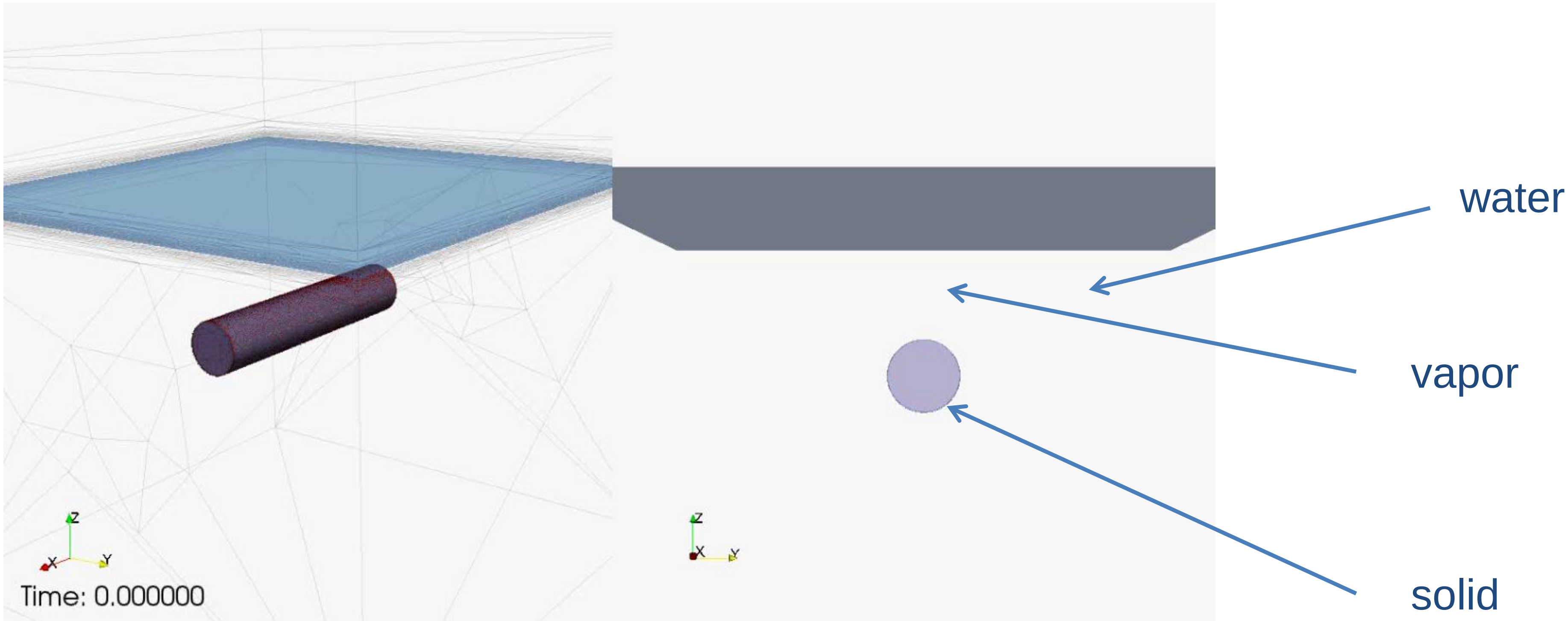
Y. Sato et al. A sharp-interface phase change model for a mass-conservative interface tracking method. *Journal of Computational Physics*, 249(0):127 -- 161, 2013

Phase change



Results in 3D , dt=0.01s, domain: 1m3
Cylinder: length 0,50m , diameter 0,10m

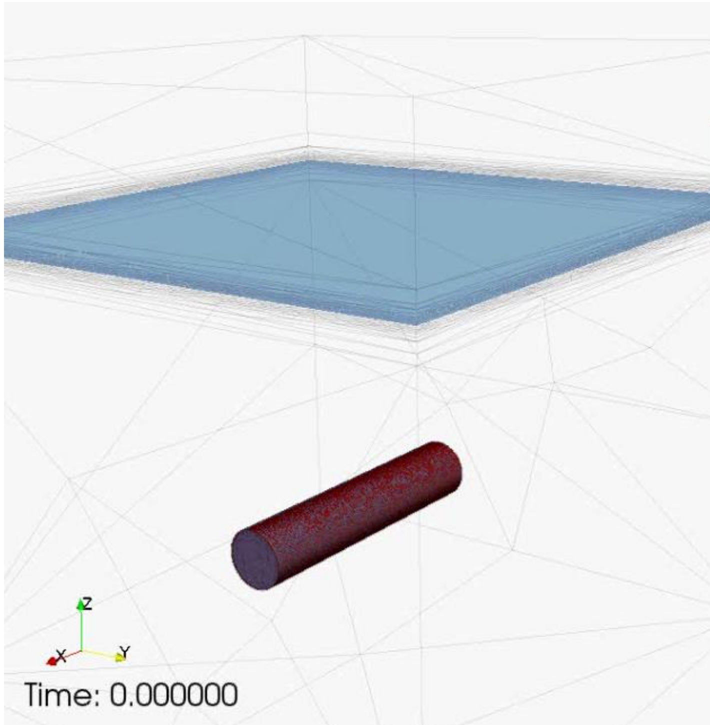
Phase change

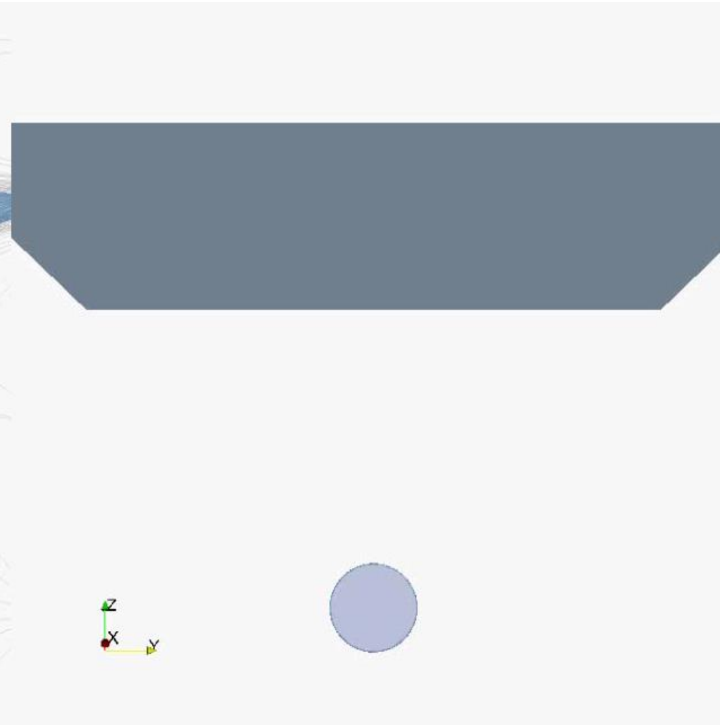


Perspective view

Front view

Results in 3D , dt=0.01s, domain: 1m3
Cylinder: length 0,50m , diameter 0,10m
Position of the cylinder : z=0,50m

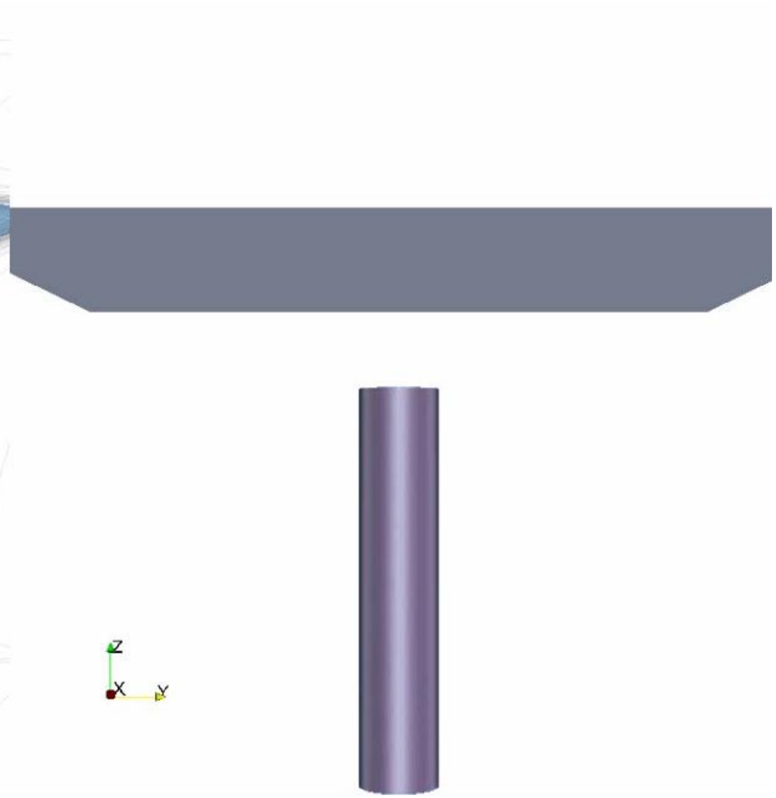




Perspective view *Front view*

Results in 3D , dt=0.01s, domain: 1m3
Cylinder: length 0,50m , diameter 0,10m
Position of the cylinder : z=0,25m

Phase change

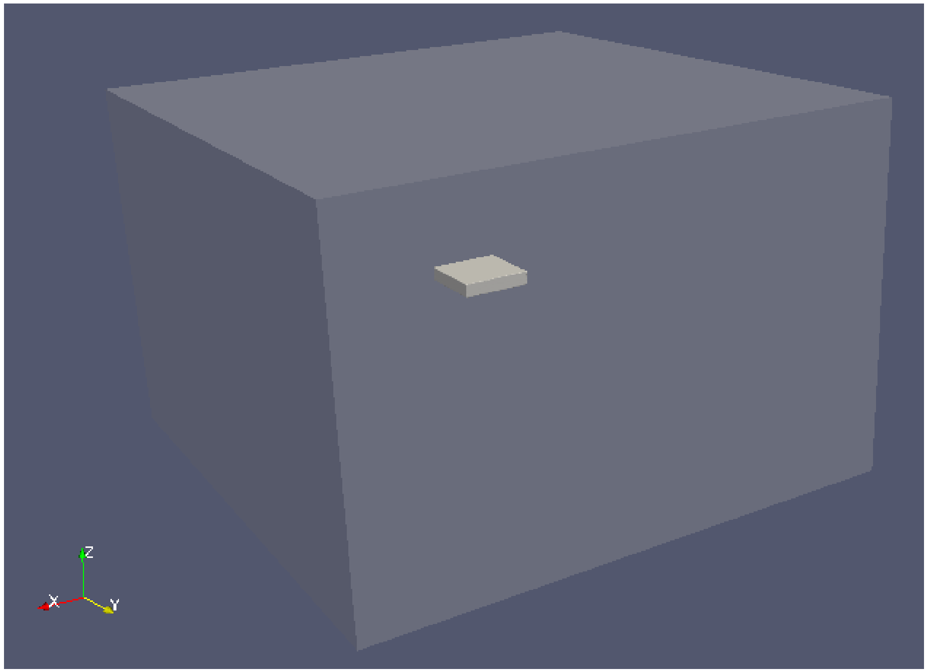


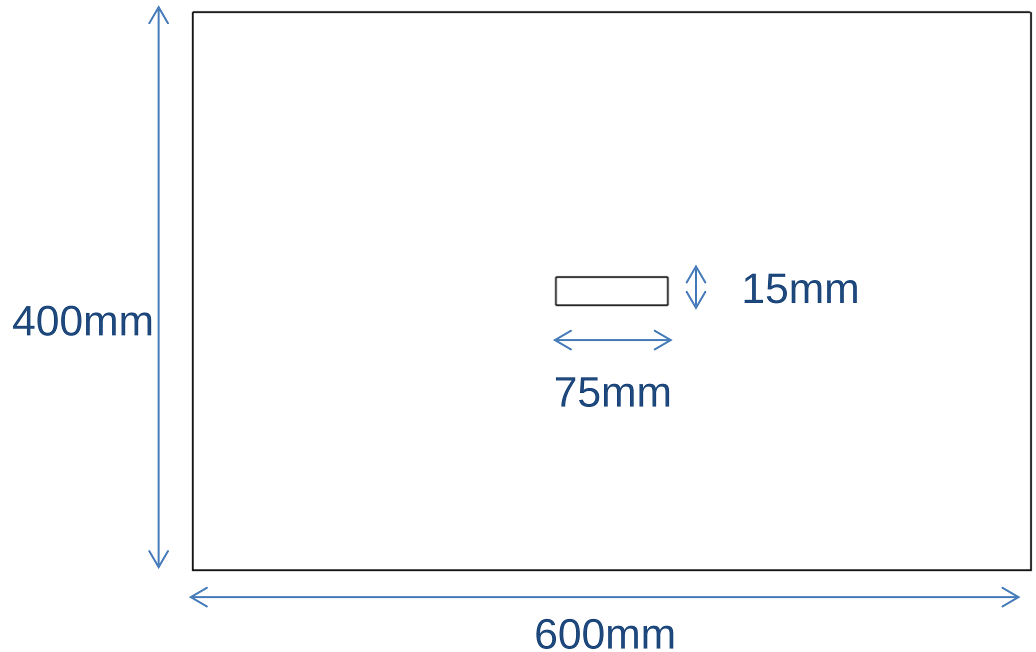
Perspective view *Front view*

Results in 3D , dt=0.01s, domain: 1m3
Cylinder: length 0,50m , diameter 0,10m

Phase change

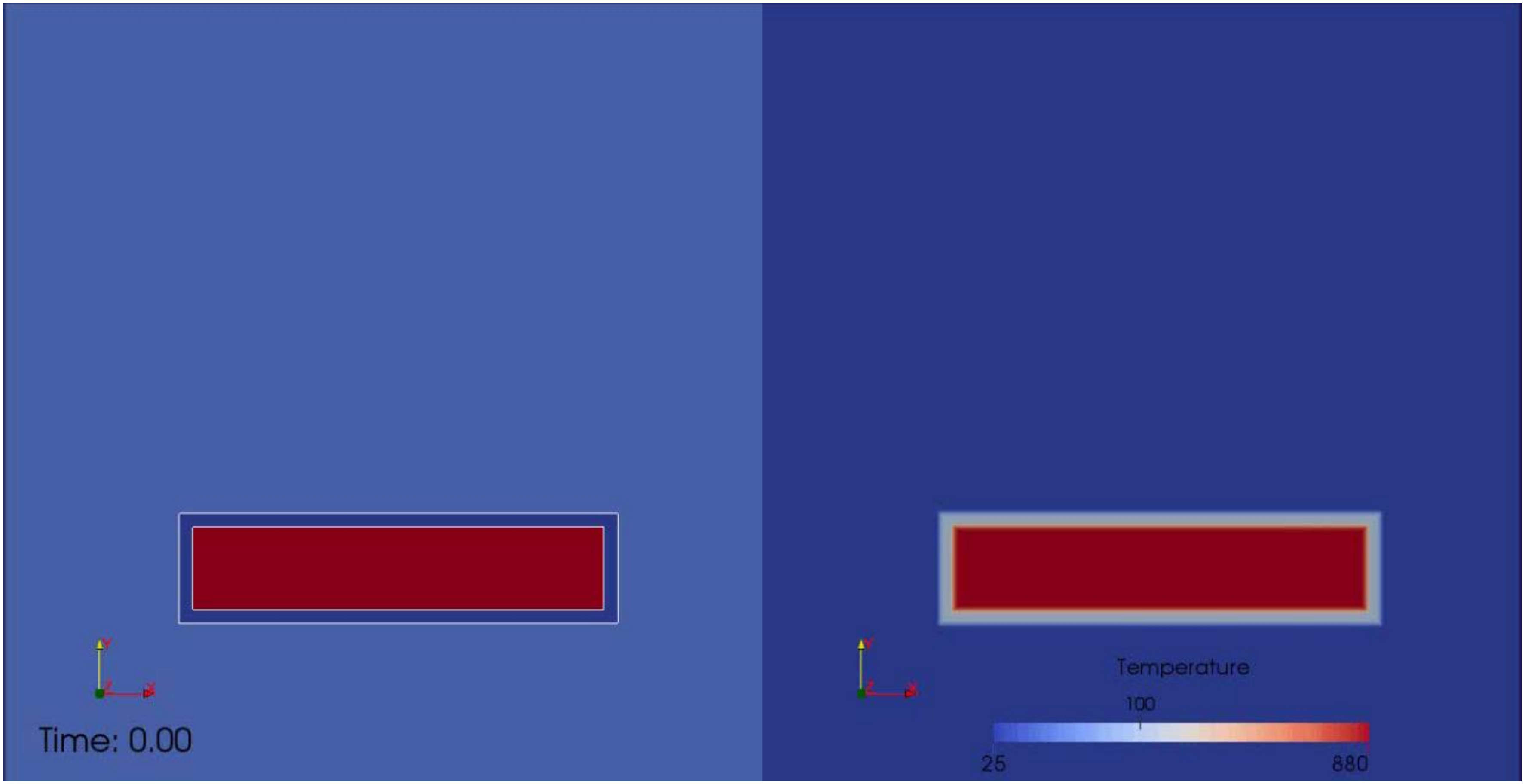
Industeel





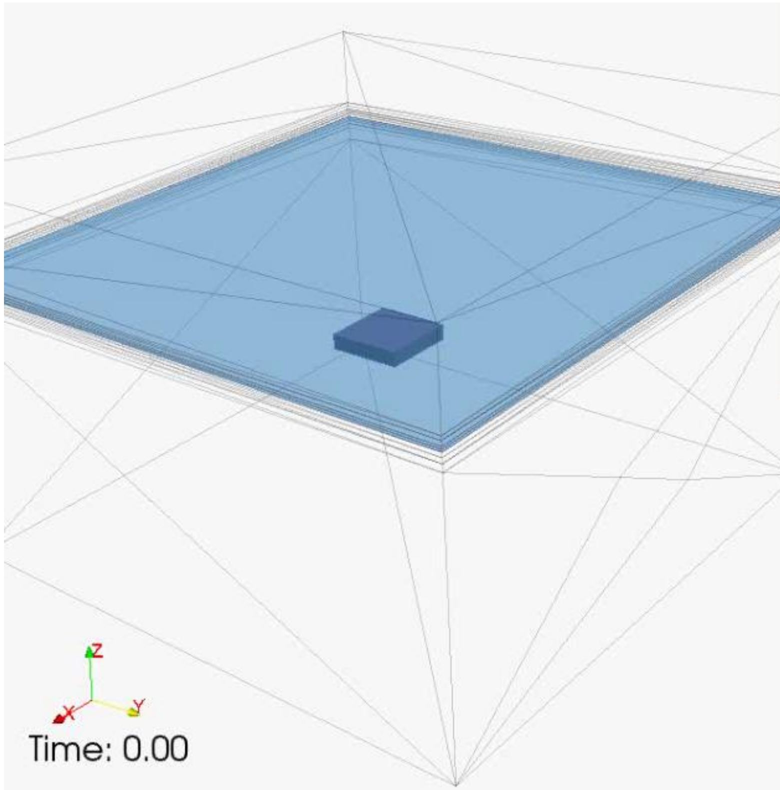
T(metal, t=0s) = 880°C
T(water, t=0s) = 25°C

Phase change

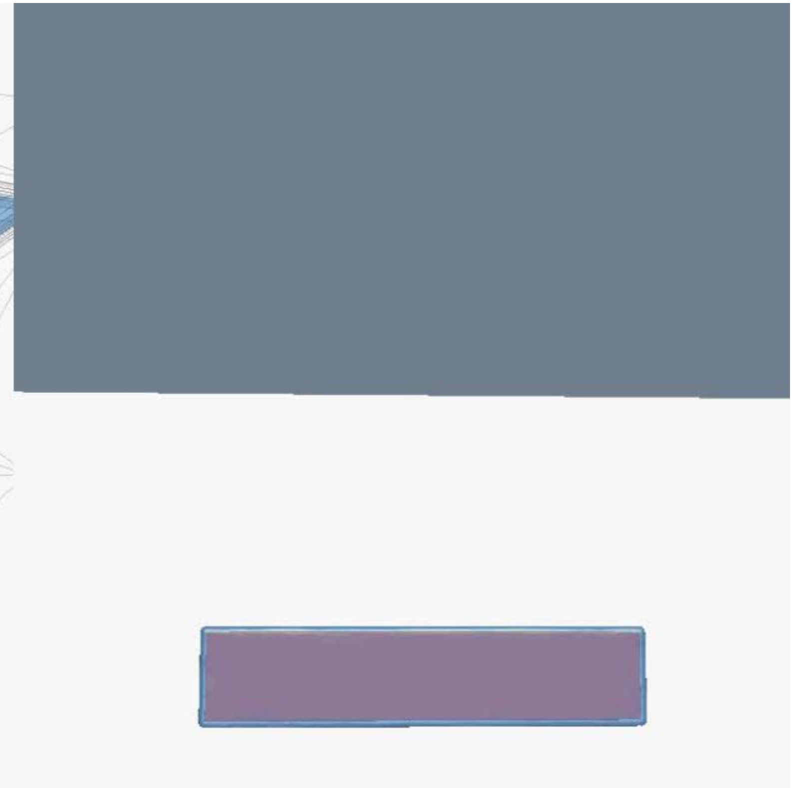


Density *Temperature (log scale)*

Phase change

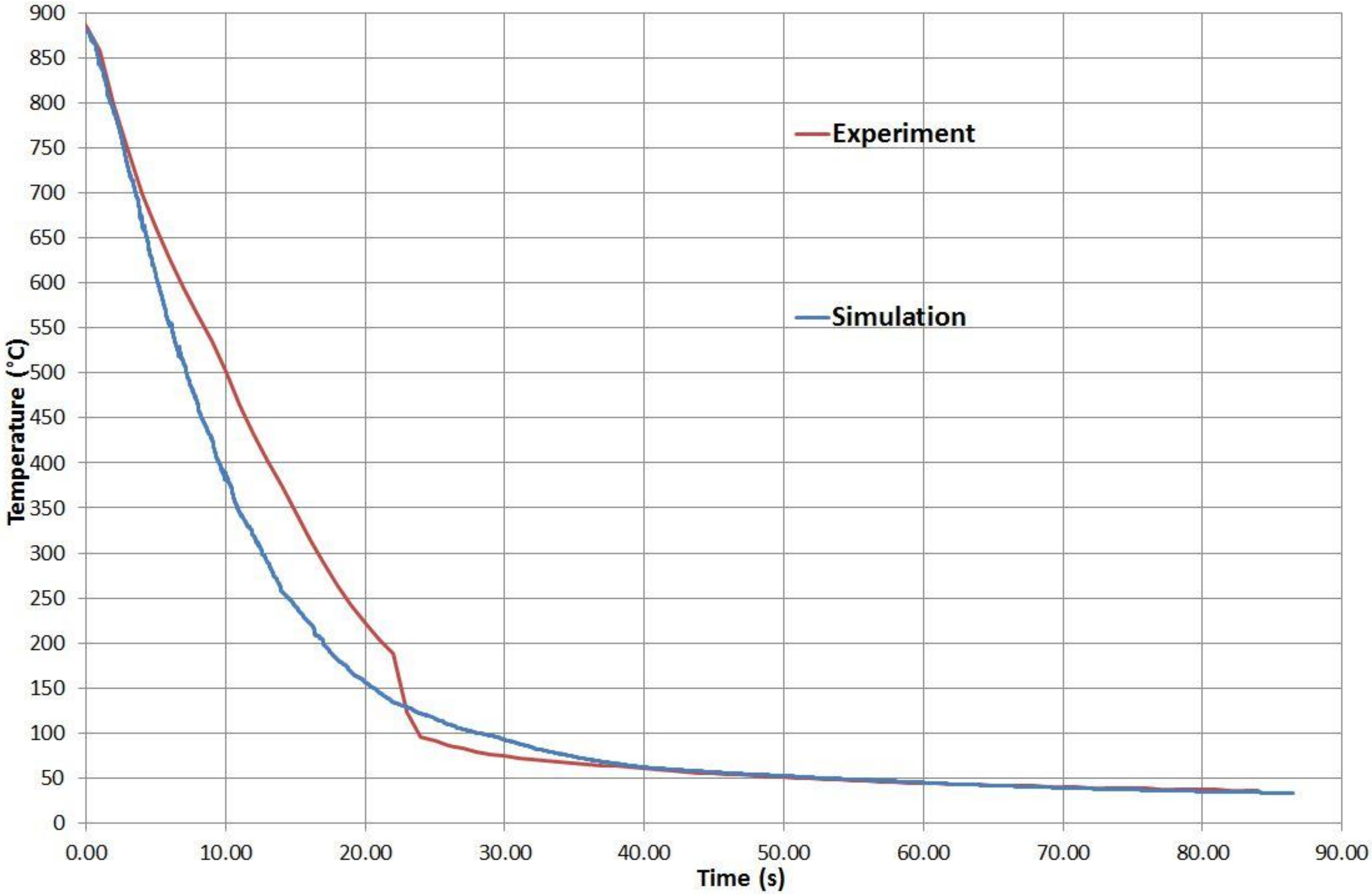


Perspective view

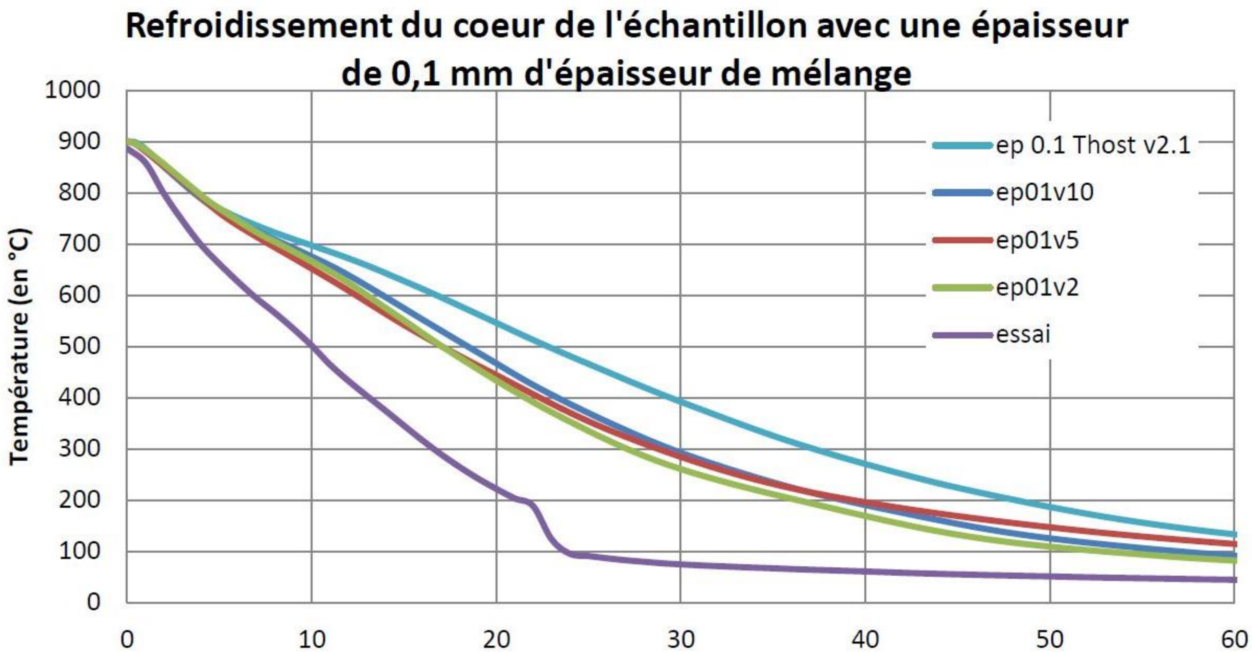


Front view

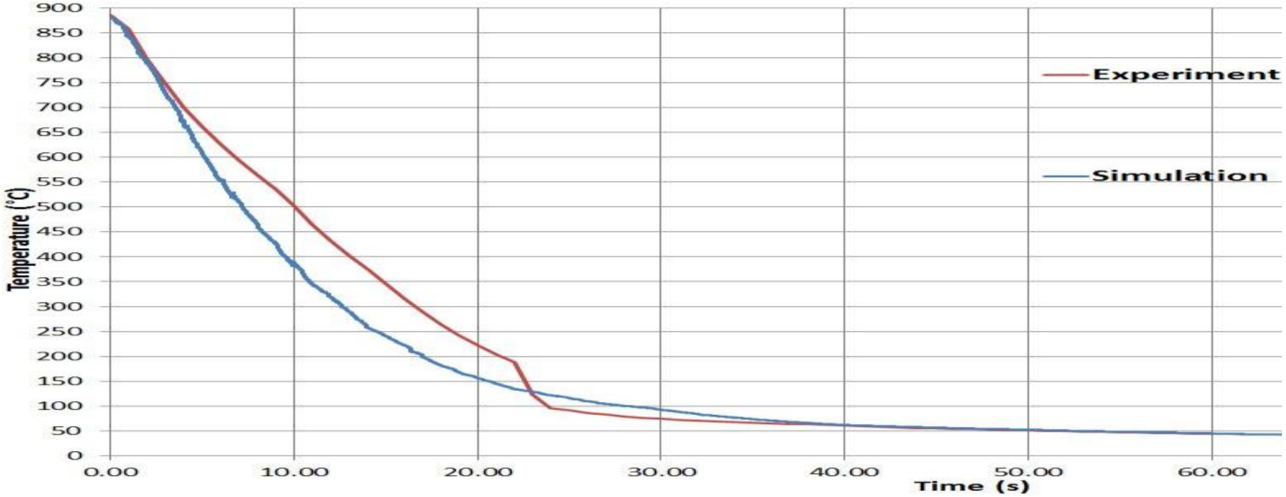
Phase change



Evolution of the temperature at the core of the sample - With phase change model



Without phase change model



With phase change model

Moving meshes for large displacements

- Problems with large boundary displacements

Thomas Toulorge

Traditional approaches

- Problems with limited boundary motion/deformation (e.g. aeroelasticity)
  → « Front tracking »: moving mesh + ALE
- Problems with large boundary motion/deformation (e.g. multi-phase flows)
  → « Front capturing »: level-set, phase-field, VoF…

Many problems fall « in-between »

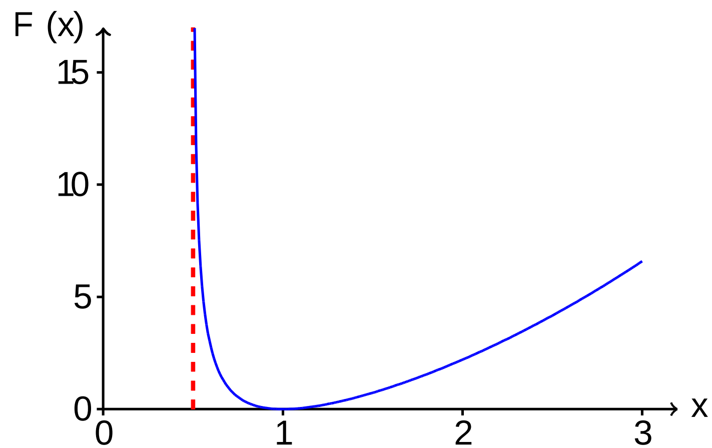
- High-Reynolds fluid dynamics applications with large boundary motion
- Resolving boundary layers: body-fitted meshes
- Objects with geometrical singularities subject to rigid-body motion: front capturing inappropriate
- Large boundary motion: pure moving meshes based on mechanical analogies often fail

Moving meshes for large displacements

- Ingredients for a robust « moving mesh » method

Optimization-based moving mesh techniques

- Node movement driven by opt. procedure
- Mesh validity: objective function of element Jacobian
- Mesh quality: objective function of aspect ratio
- Use barrier functions to impose minimum mesh validity/quality

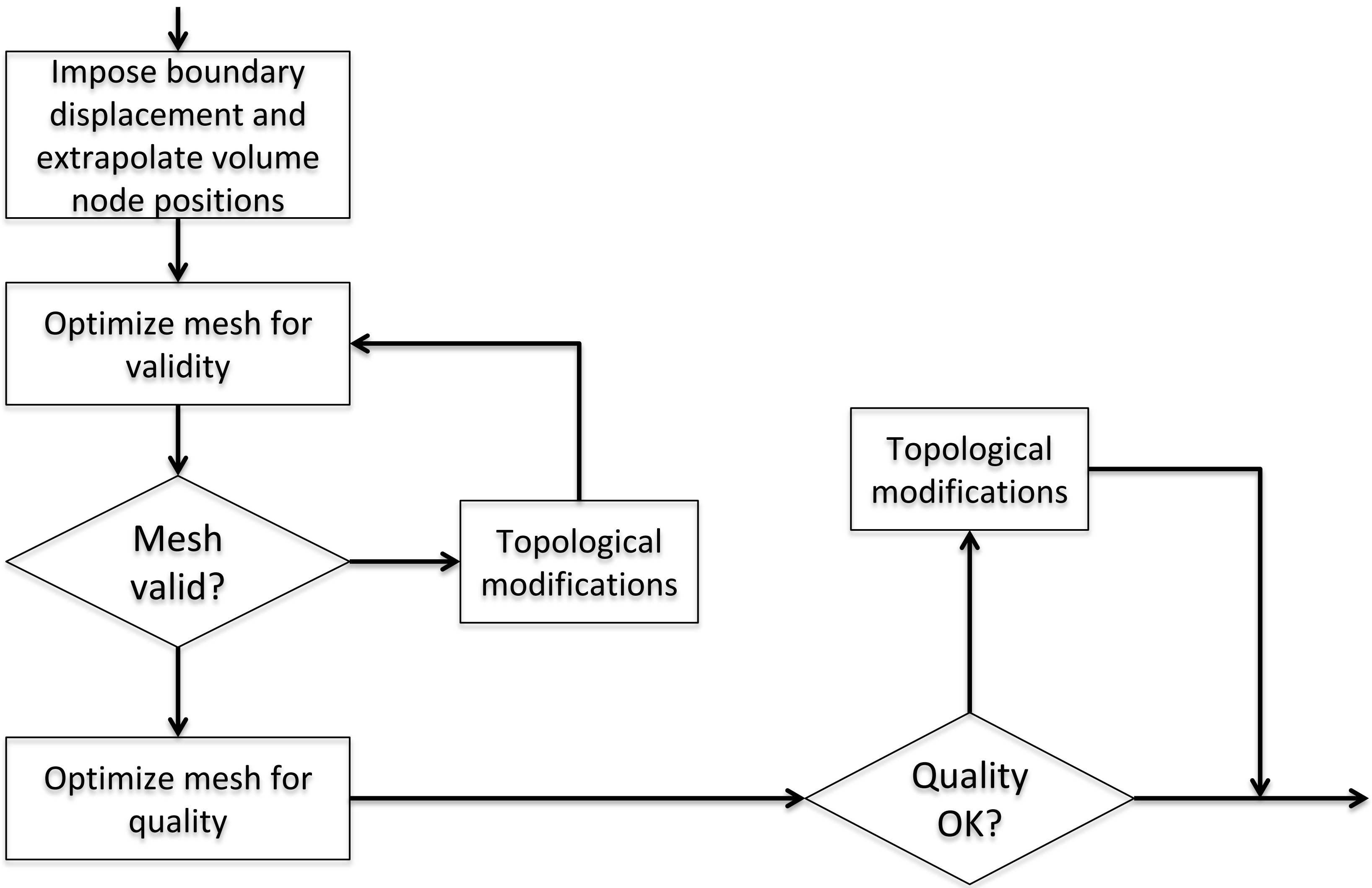


Topological modifications

- Triggered if moving mesh does not yield the required validity/quality
- General operator in cavity around mesh edge[1] without node addition or deletion

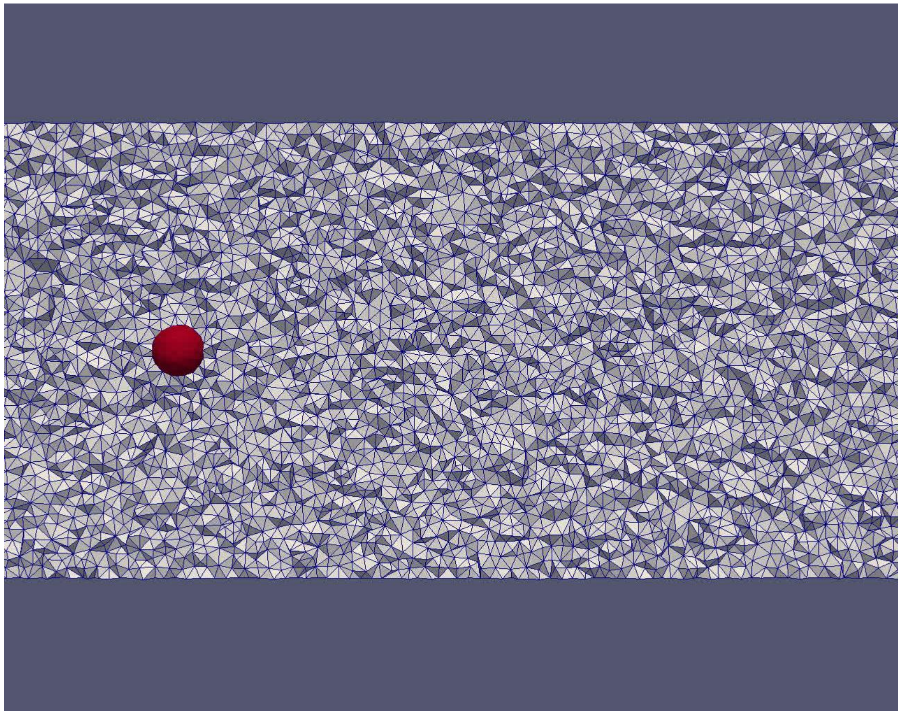
Moving meshes for large displacements

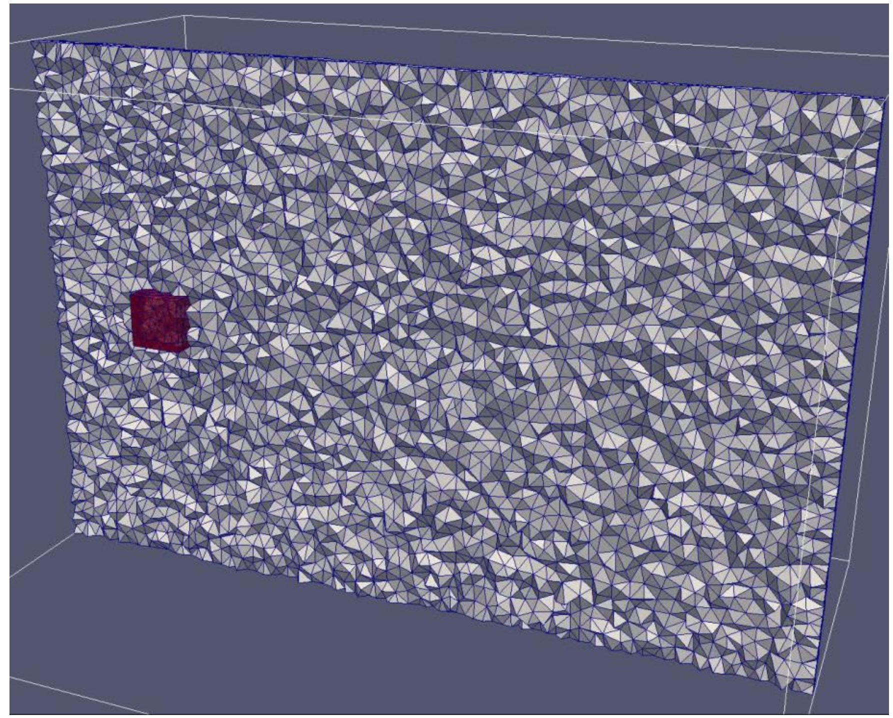
- General « moving mesh » algorithm



Moving meshes for large displacements

- First results

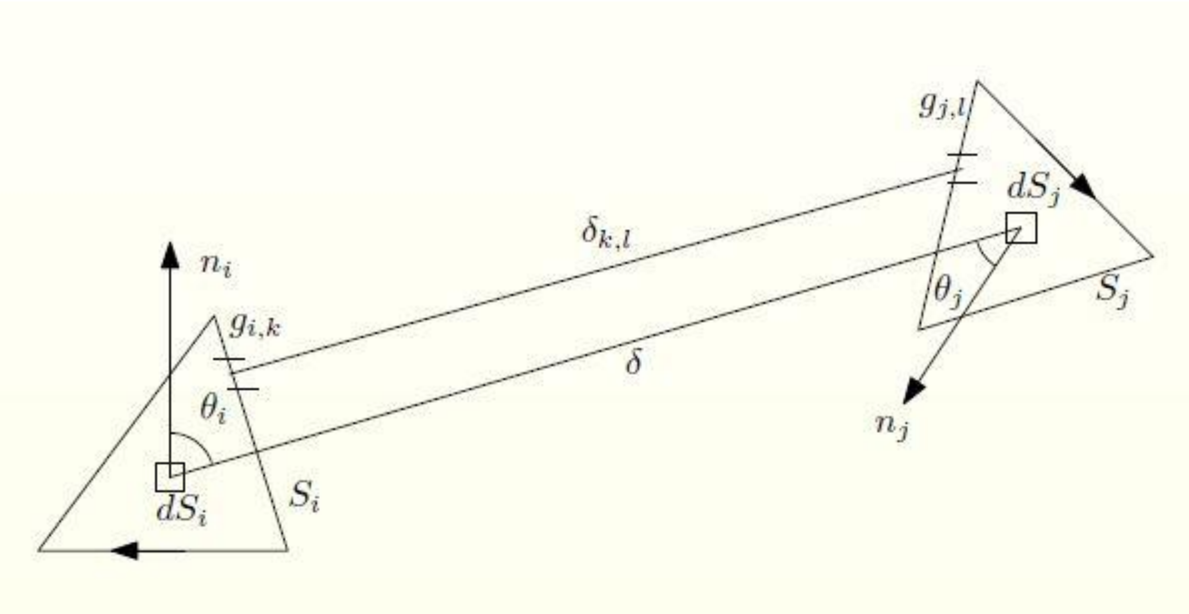




Test cases: F. Alauzet, A changing-topology moving mesh technique for large displacements, Engineering with Computers 30(2): 170-200.

Immersed Surface to Surface model

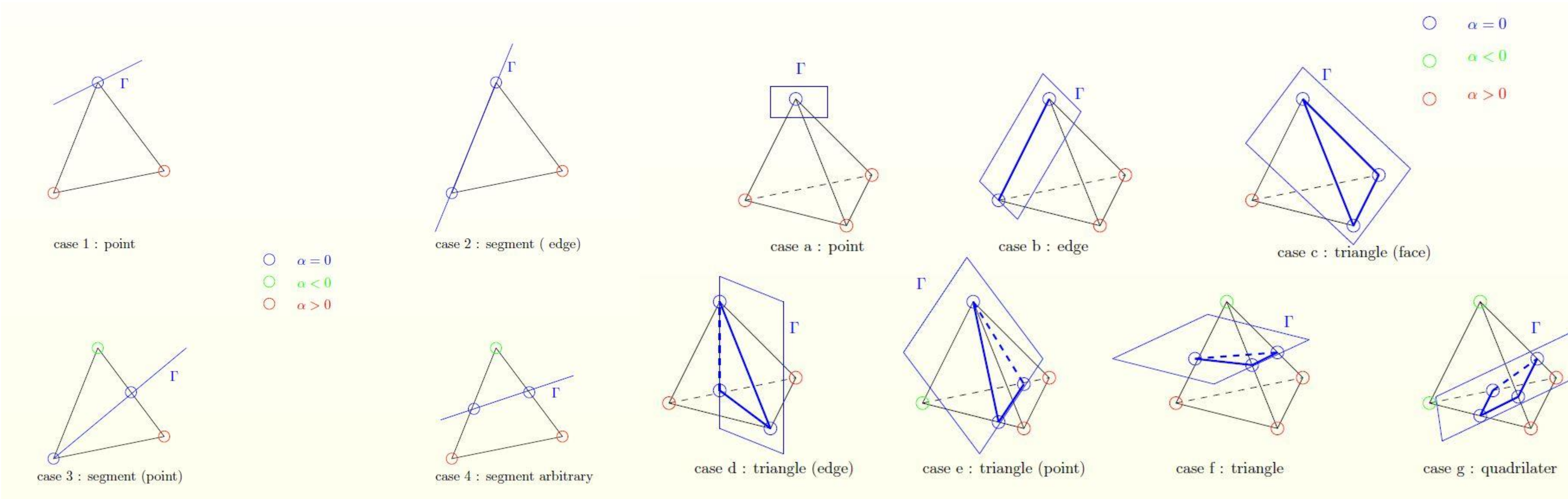
Quentin Schmid



View factor

Flux emitted : $\sigma_r T_i^4 S_i$ ➡ Issue with implicit interface description

Immersed Surface to Surface model

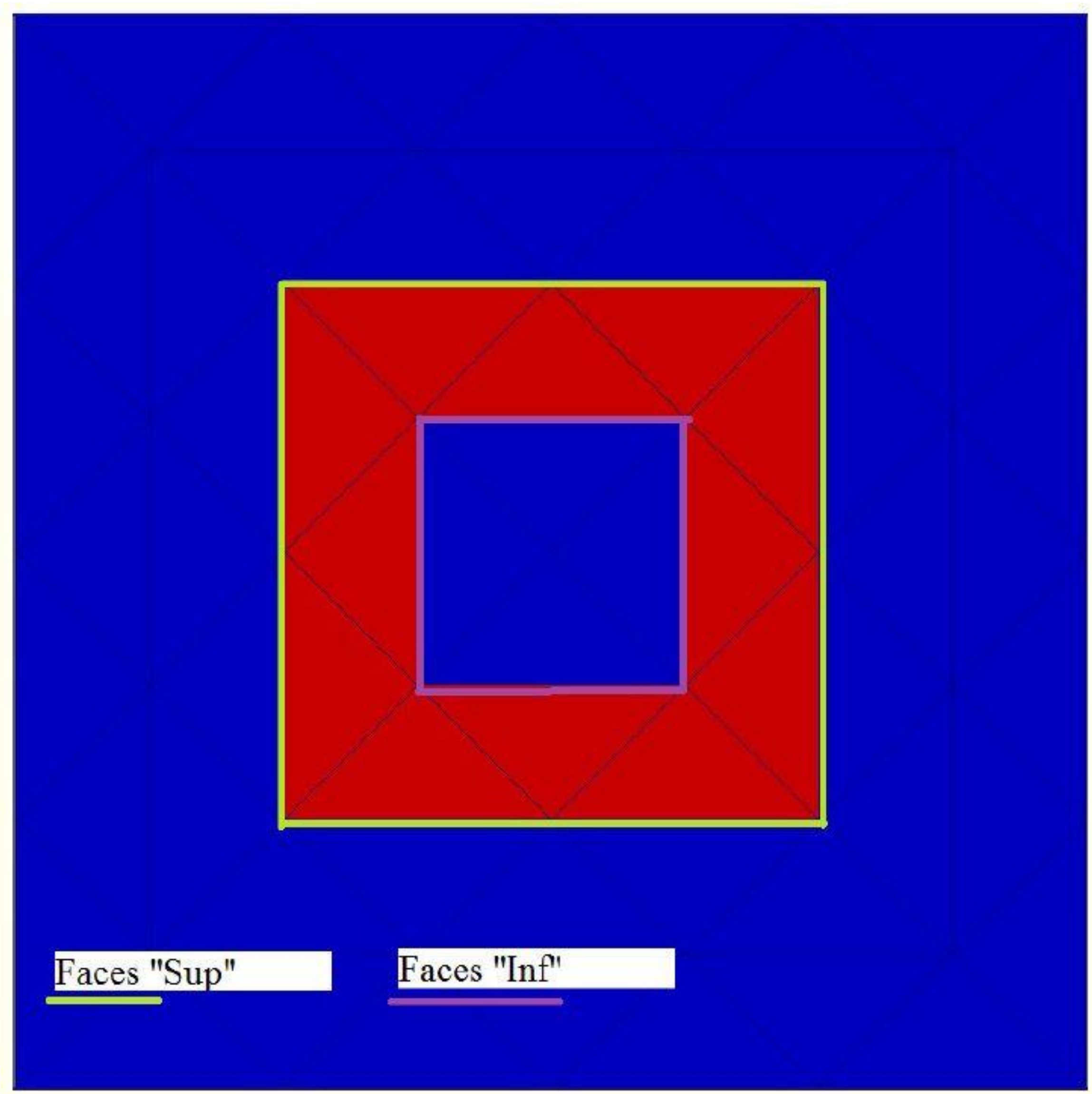


2D

3D

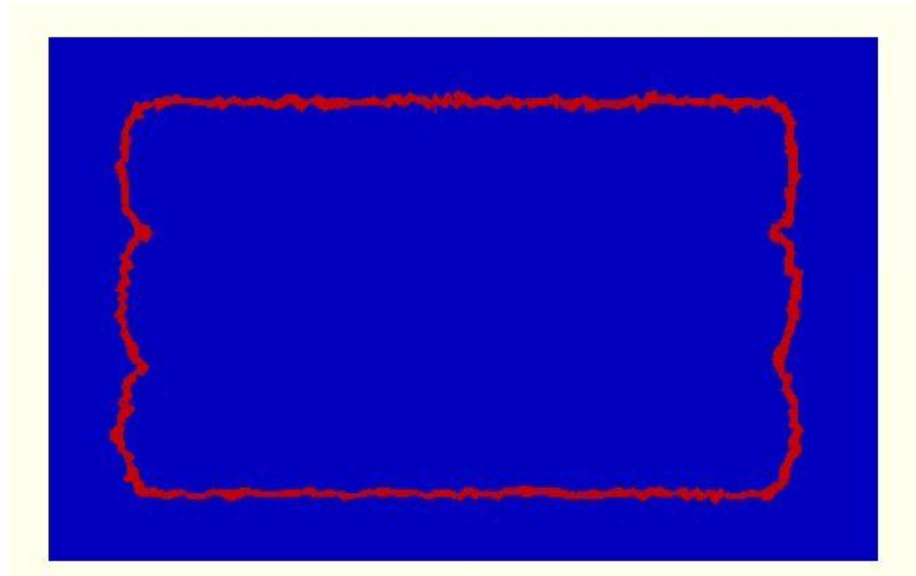
Construction of a “layer” of elements crossed by the zero isovalue of level set

Immersed Surface to Surface model



Immersed Surface to Surface model

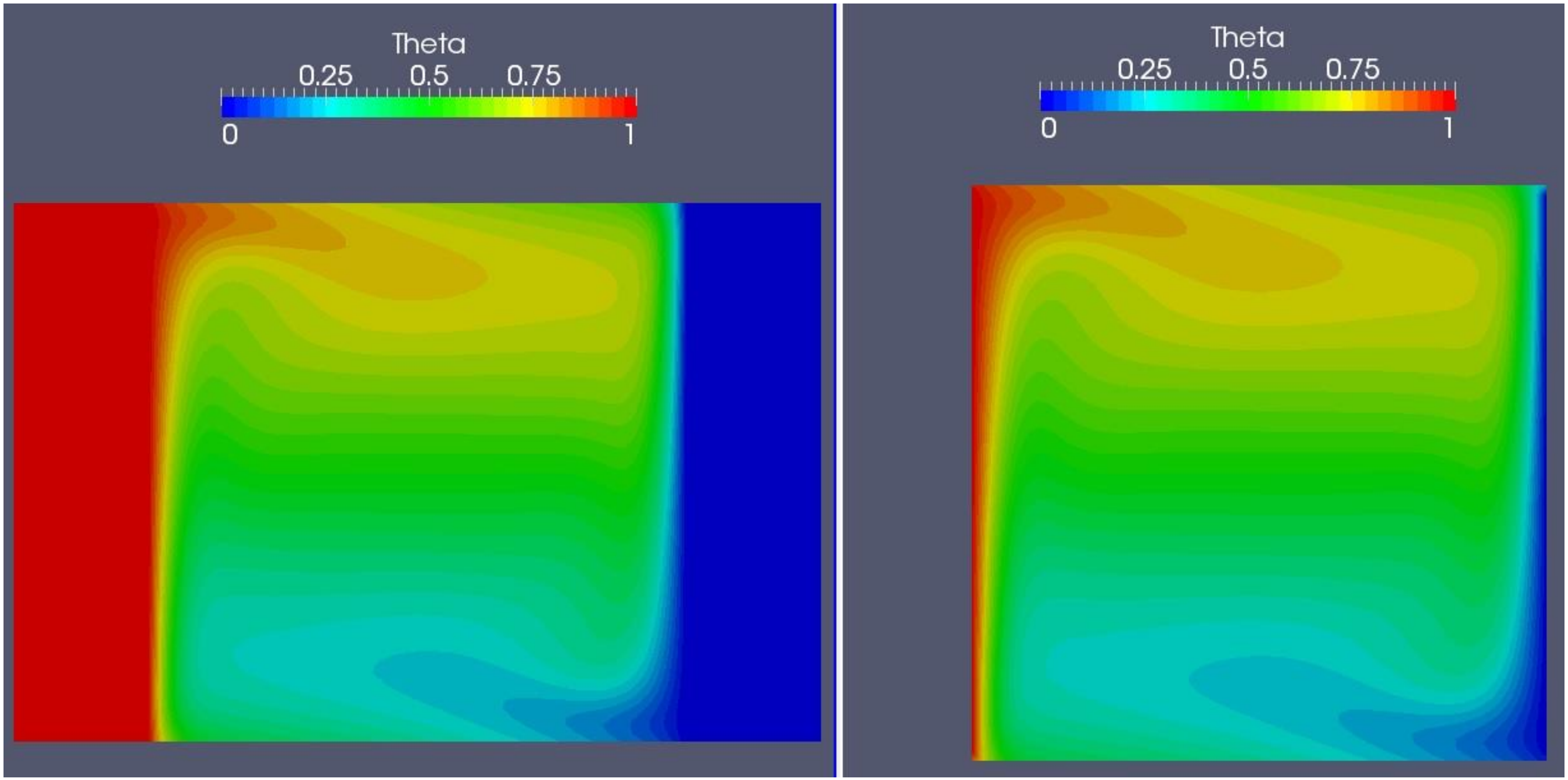
Industrial part



Sectional view

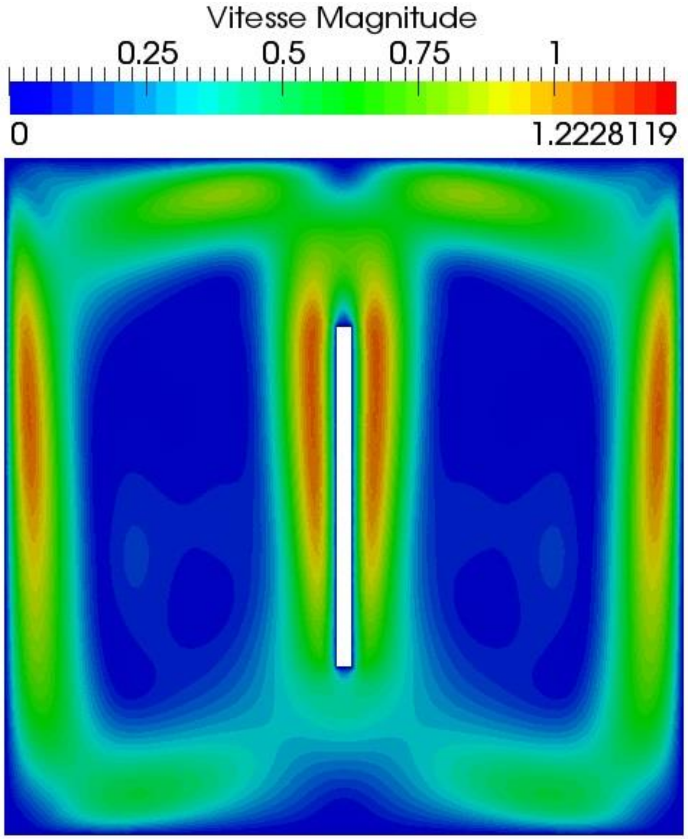
Immersed Surface to Surface model

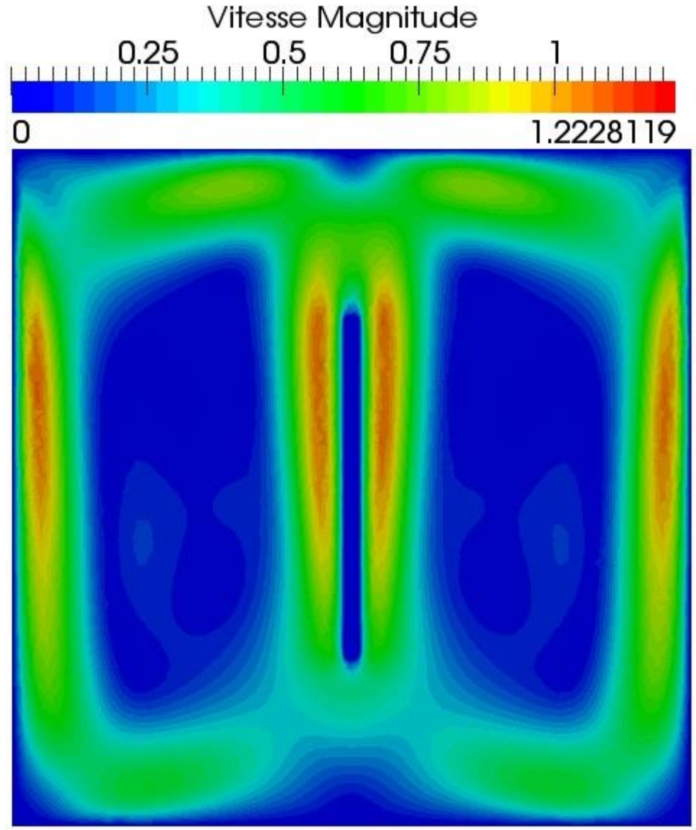
Validation



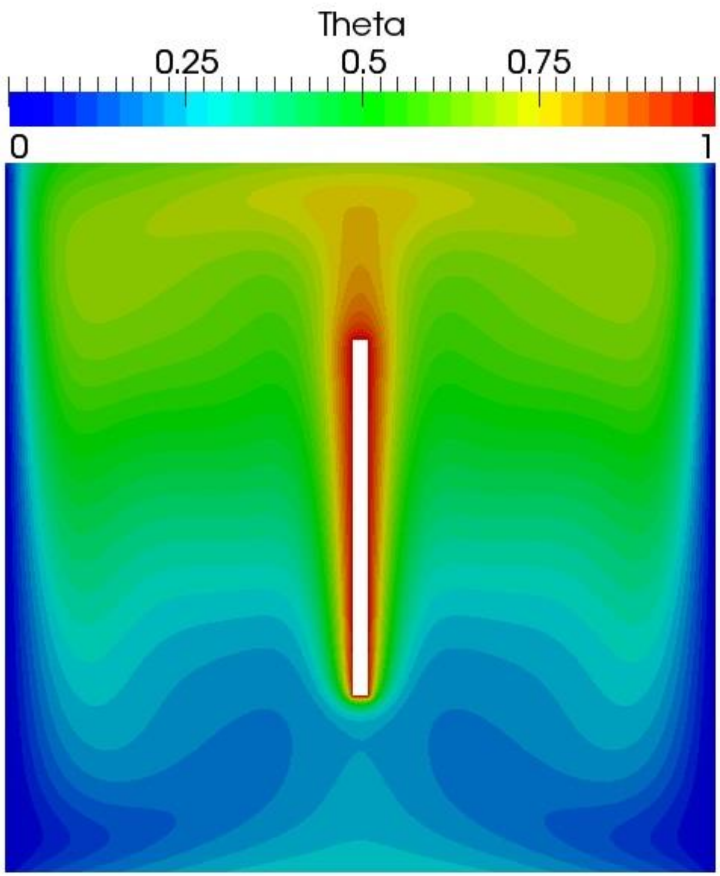
Immersed Surface to Surface model

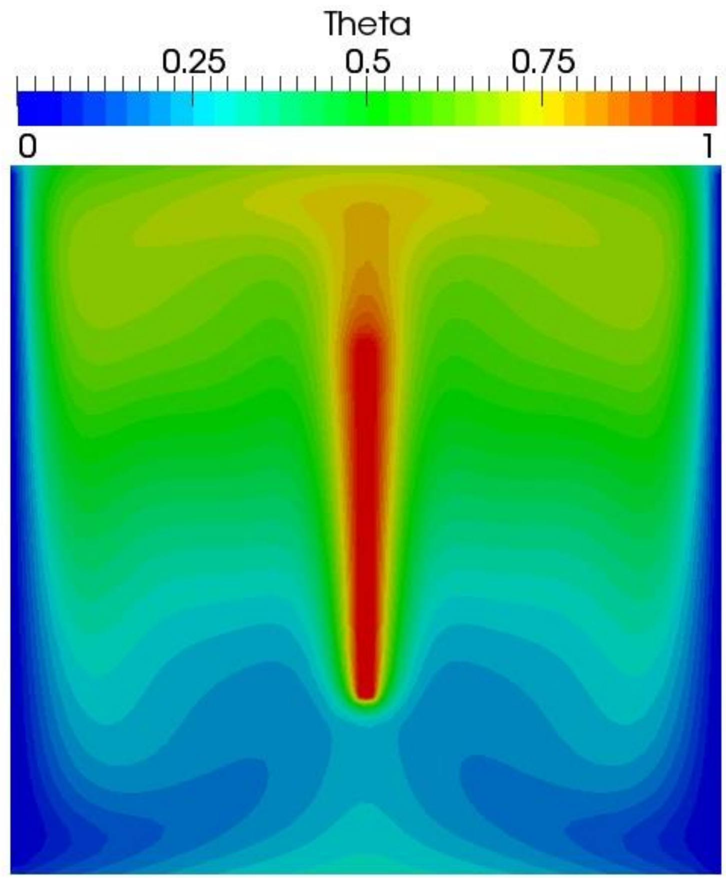
Validation



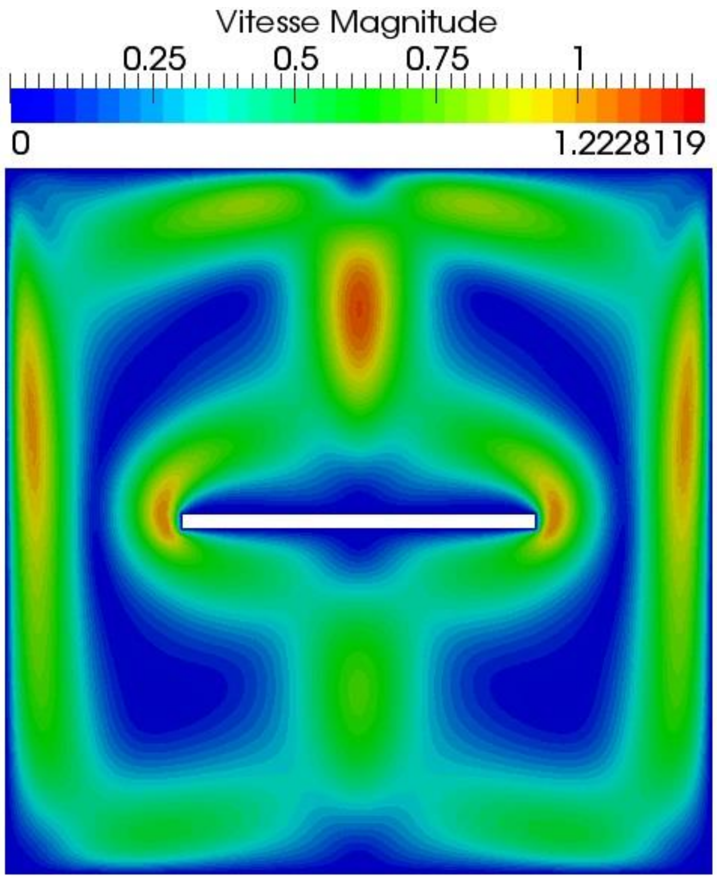


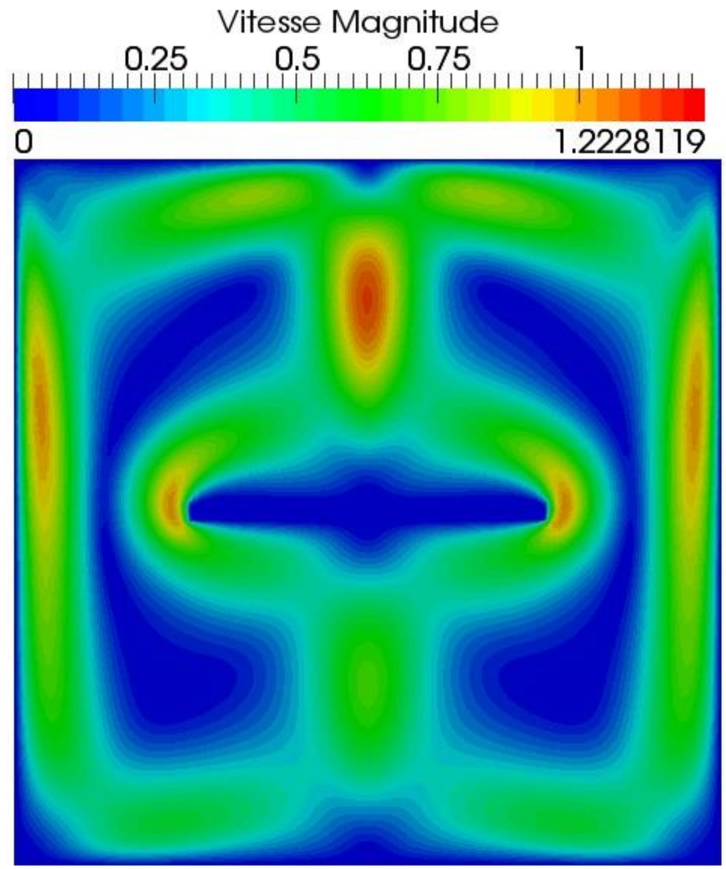
Immersed Surface to Surface model



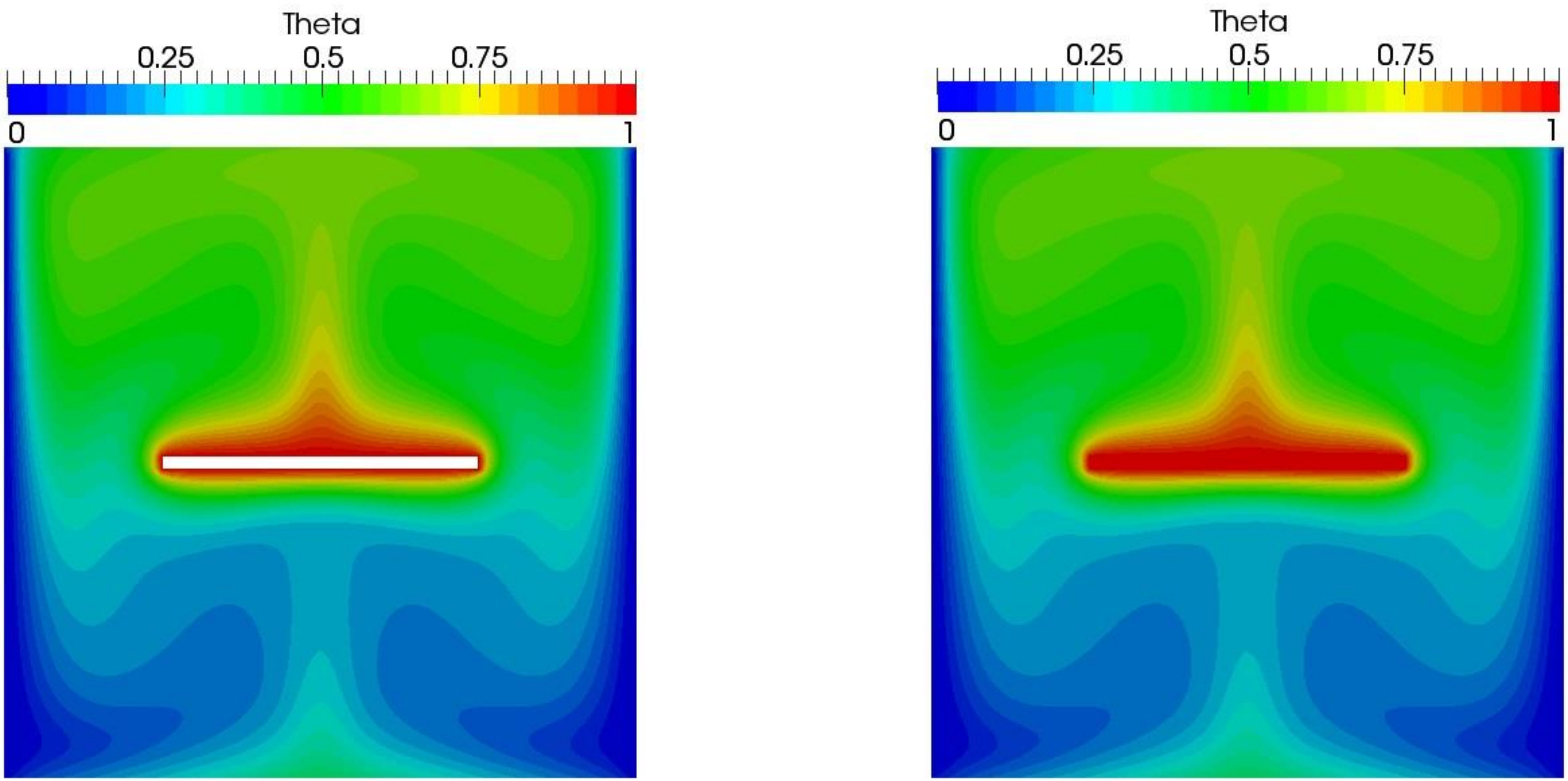


Immersed Surface to Surface model





Immersed Surface to Surface model



Conclusions & Perspectives

- 3D multiphase framework for quenching and boiling
- Validation in 2D & 3D for several benchmarks

- Industrial validations with experimental measurements
- Influence of the geometries on the dynamic the vapor film
- Coupling solid-fluid: computation of phase transformation
- Towards moving and deformable geometries

Thank you for your attention