Melting of a solid surface by a hot liquid jet

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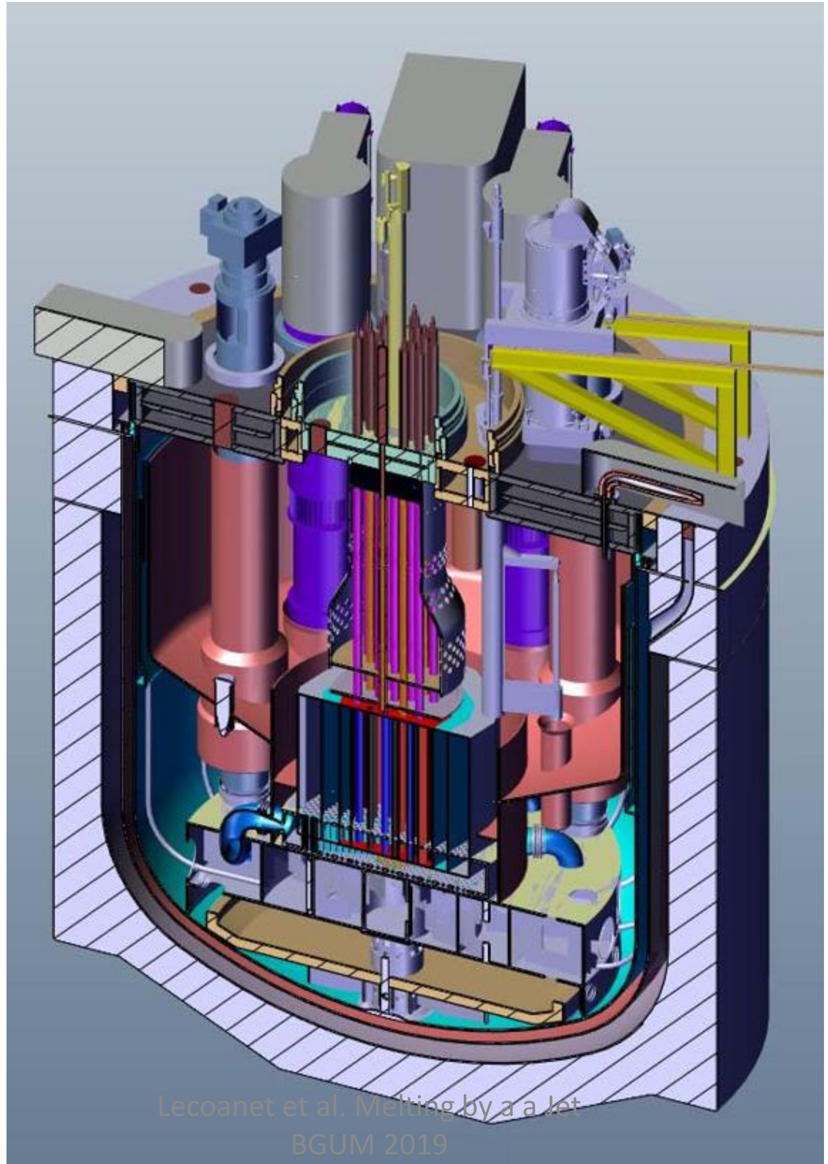
ASTRID as a prototype Na-FBR

Sodium
Fast-Breeder
Reactor



Four Different Cases

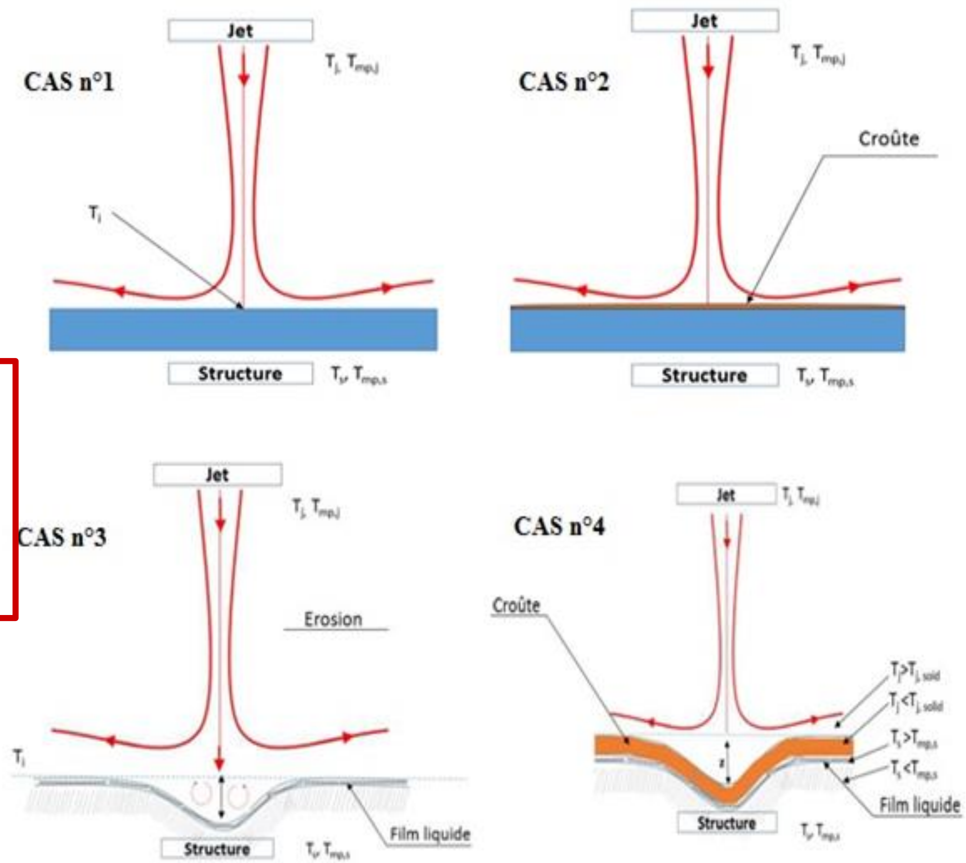
- **Case 1** No thin liquid layer, liquid transfer is maximum
- **Case 2** The jet solidifies on impact and the crust is formed

$T_i \leqslant T_{j,mp}$ et $T_i \leqslant T_{s,mp}$ $T_{j,mp} \leqslant T_{s,mp}$

- **Case 3** The solid structure creates a liquid film on its surface and the heat transfer is decreased $T_i \geqslant T_{j,mp}$

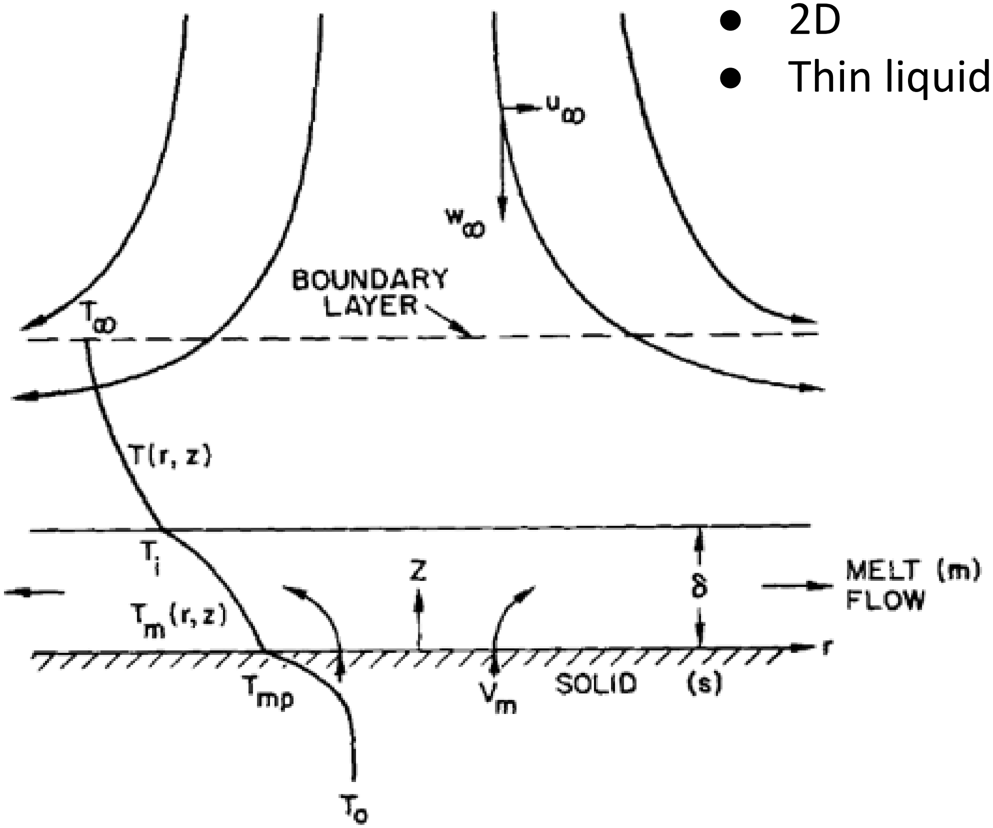
- **Case 4** The most complex with the presence of crust and liquid film

$T_i \leqslant T_{j,mp}$ $T_i \geq T_{s,mp}$



Roberts and Swedish model

- 2D
- Thin liquid film between jet and structure to be ablated



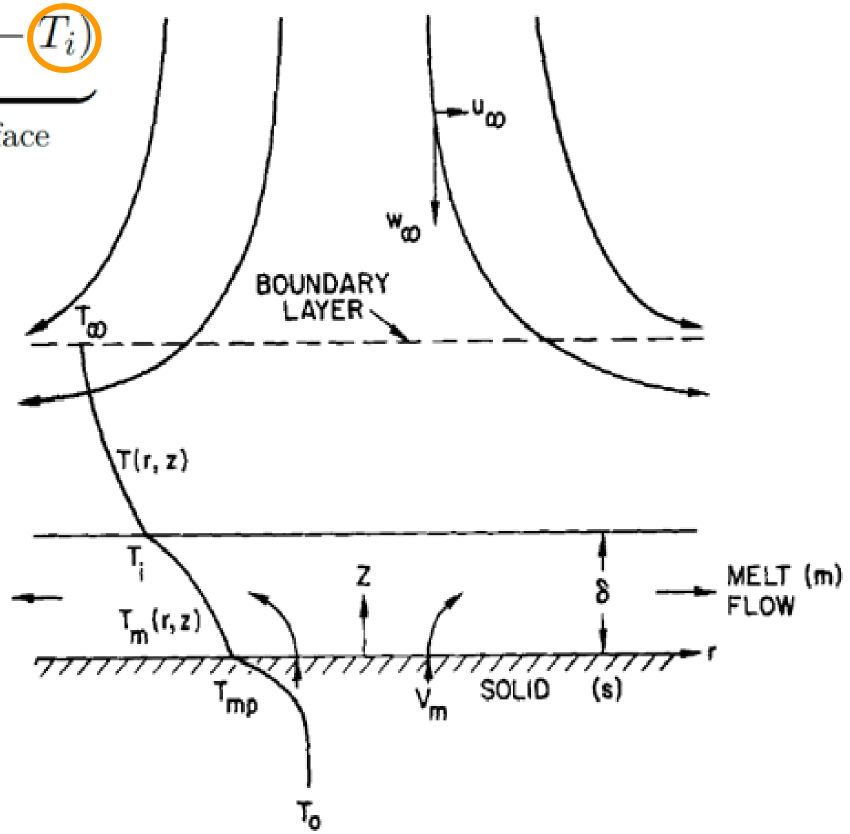
Parameters of the problem

- The speed of the jet (V_j)
- Falling distance: h
- The thickness of the sample (Z)
- The diameter of the jet (D_j)
- The jet temperature (T_j) and (T_i)
- The angle of the jet
- The materials

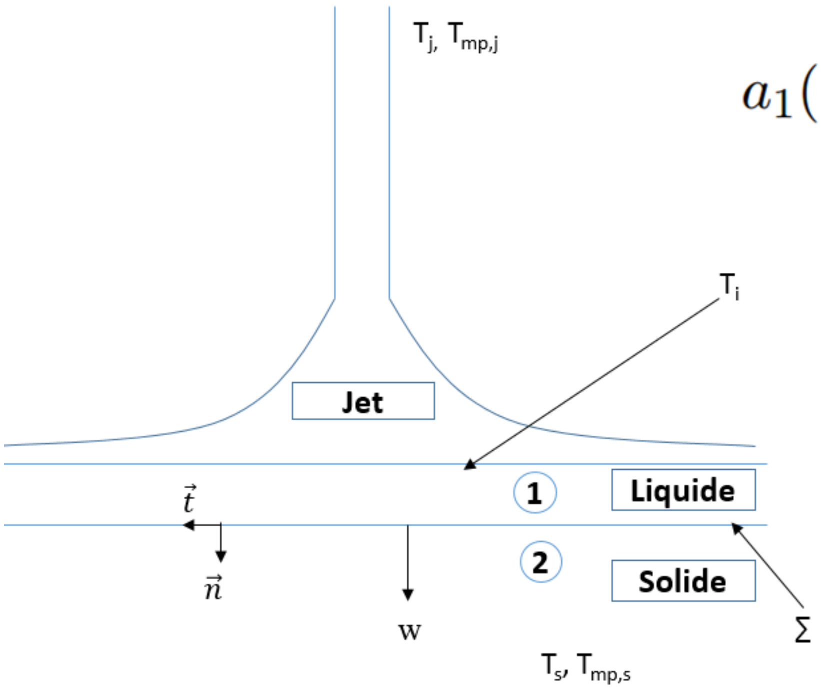
Roberts and Swedish model

$$\underbrace{V_m \rho \left[L + c_s(T_{s,mp} - T_s)\right]}_{\text{flux de chaleur à l'interface où la fusion s'effectue}} = \underbrace{\left(k\Pi'(0)\sqrt{2a/\nu}\right)(T_j - T_i)}_{\text{flux de chaleur à l'interface jet/film liquide}}$$

- T_i and V_m are unknown
- Resolution with equations of fluid mechanics by adimensioning the problem



Ablation Rate



"Jump" conditions

$$a_1(W - \vec{v_1}\vec{n_1}) - a_2(W - \vec{v_2}\vec{n_2}) = (\vec{\alpha_1} - \vec{\alpha_2})\vec{n_1}$$

$$W = V_m$$

Enthalpic balance

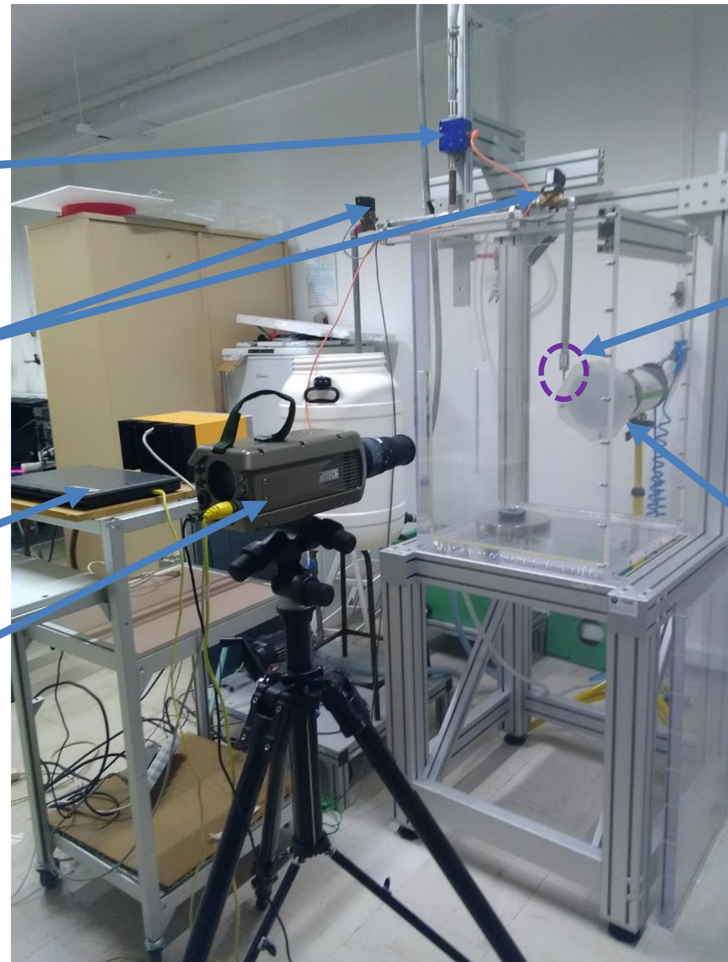
$$h_{eff}\left(T_j - T_{mp,s}\right) = V_m \rho_s \left(L_f + C_p\left(T_{mp,s} - T_s\right)\right)$$

Erosion rate

$$V_m = \frac{\left(Cste\,\mathrm{Re}^{\alpha}\,\mathrm{Pr}^{\beta}\right)\rho_j C_{pj} V_j \left(T_j - T_{mp,s}\right)}{\rho_s\left(L_f + C_p\left(T_{mp,s} - T_s\right)\right)}$$

EXPERIMENTS

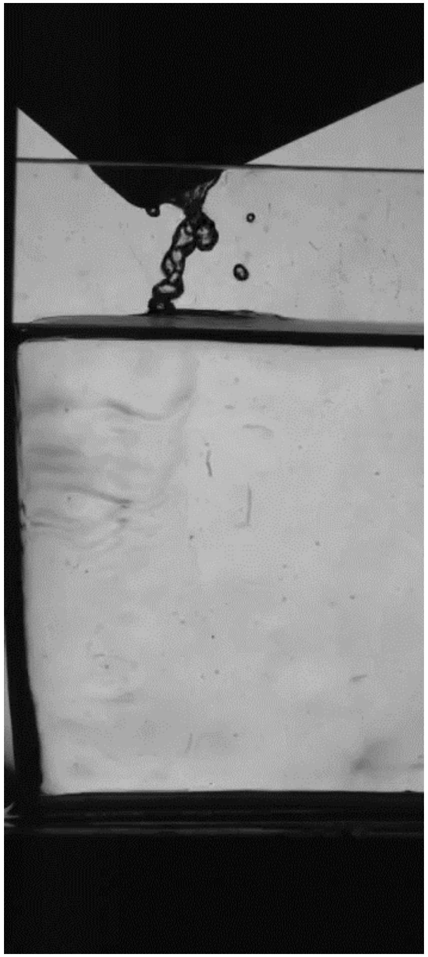
Experimental setup



Example of Results

- Experimental conditions:
  - Jet temperature: 30°C
  - Jet diameter: 1 mm
  - Flowrate : 5,5m/s
  - Reynolds : 8 824
  - Prandtl : 5,42

- Recording:
  - frames per second;



Example of Results

- Experimental conditions:
  - Jet temperature: 23°C
  - Jet diameter: 3,21 mm
  - Flowrate : 2,78L/min -> 5,7m/s
  - Reynolds : 19 482
  - Prandtl : 6,49
  - Nozzle to ice distance 2 cm

- Recording:
  - 200 frames per second;

Cavity Shape Evolution

Ablation rate : constant | Decreases linearly with time

0 s | 2,5 s | 4 s | 15 s | 22 s | 65 s

Impact spreading

Visible cavity formation

Liquid sheet formation

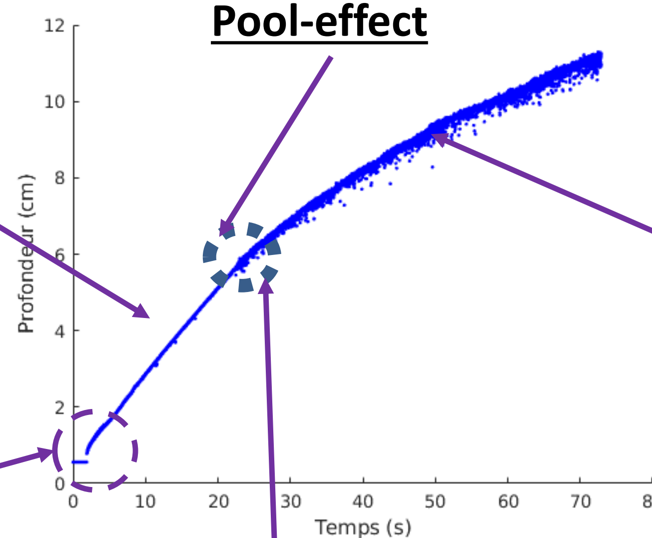
Liquid sheet vanishes

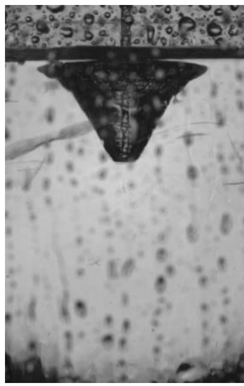
Transition <1s

Pool-effect

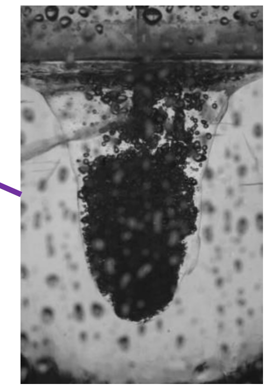
Ablation Depth & Speed Evolution

Pool-effect





Splashing :
Ablation speed
Constant = 0,23 cm/s



First moments :
unreachable

Transition: 1 s

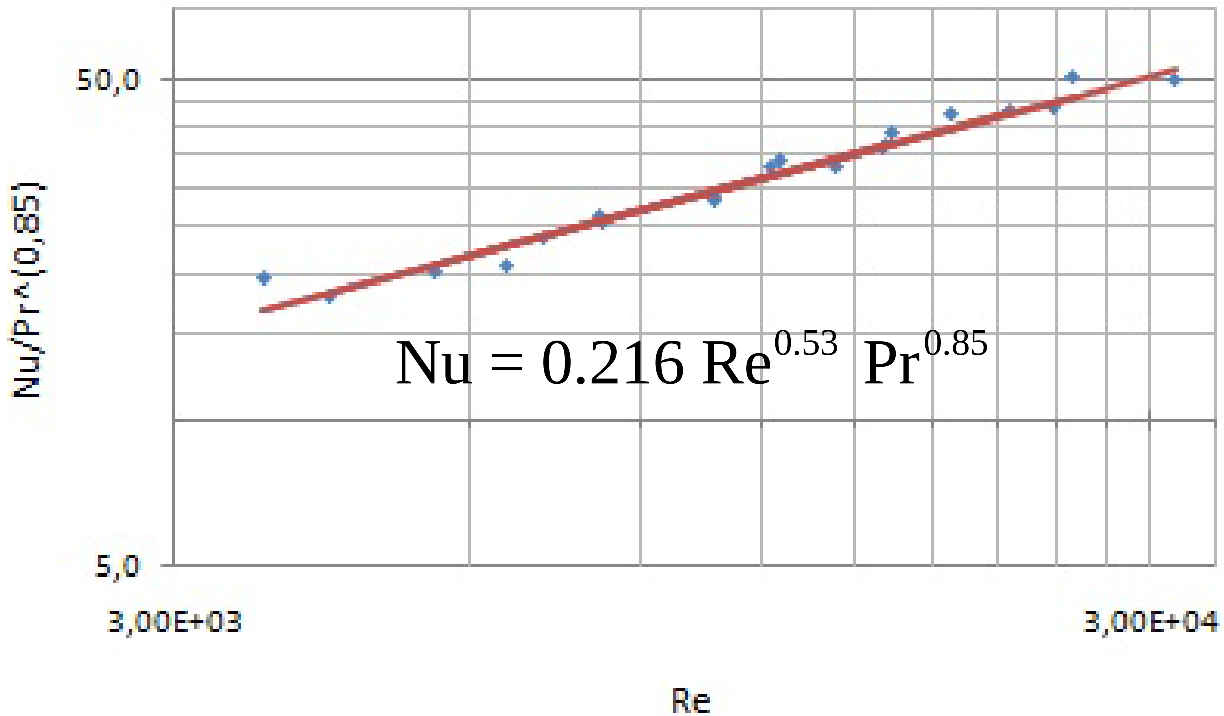
Pool-effect:
- Cavity shape changes
- Ablation speed decreases
Here :
V_m (cm/s) = 0,20 – 0,0020 t

Correlation Obtained

- From measurement of *Vm*
  - h_{eff} is determined
  - Nusselt number

$$h_{eff} = \frac{V_m \rho_s \left(L_f + C_{p,s}\left(T_{mp,s} - T_s\right)\right)}{\left(T_j - T_{mp,s}\right)}$$

$$\mathrm{Nu} = \frac{h_{eff} D_j}{k}$$



- Parameter Range
  - $2.56 < Pr < 5.41$
  - $3710 < Re < 31\,900$
  - 30°C < T < 70°C

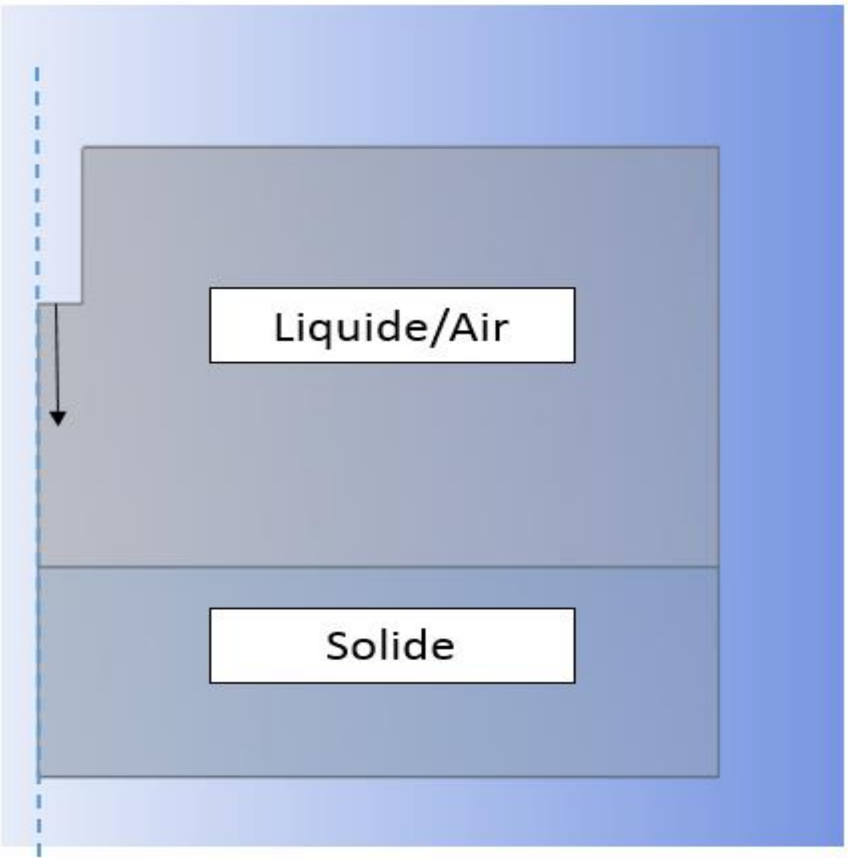
Numerical Simulations

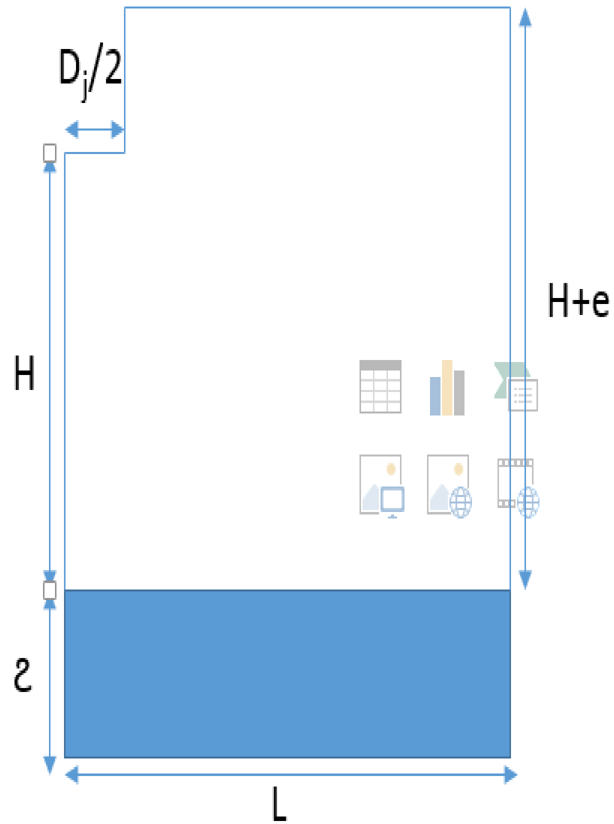
- Goals
  - Understand the jet/melt mixing
    - In the thin flowing film
  - Is there an interfacial temperature?
    - Hot liquid/cold liquid
      - Swedish: gas-liquid
  - First attempt: Fluent
    - Pseudo multiphasic (2 phases flows)
    - Fully multiphasic (3 phases flow)
  - Current attempt: Basilisk

Voller's enthalpy model

- Equations solved
  - Continuity $$div\left(\mathbf{v}\right)=0$$
  - Momentum $$\frac{\partial \rho \mathbf{v}}{\partial t}+div\left(\rho \mathbf{v}\otimes \mathbf{v}\right)=-\nabla P+div\left(\mu \nabla \mathbf{v}\right)+\mathbf{S}$$
  - Enthalpy $$\frac{\partial \rho h}{\partial t}+div\left(\rho h\mathbf{v}\right)=div\left(k\nabla T\right)$$
  - Closure (front capturing) $$\text{if } h<h_f \quad \mathbf{S}=-K\mathbf{u}$$

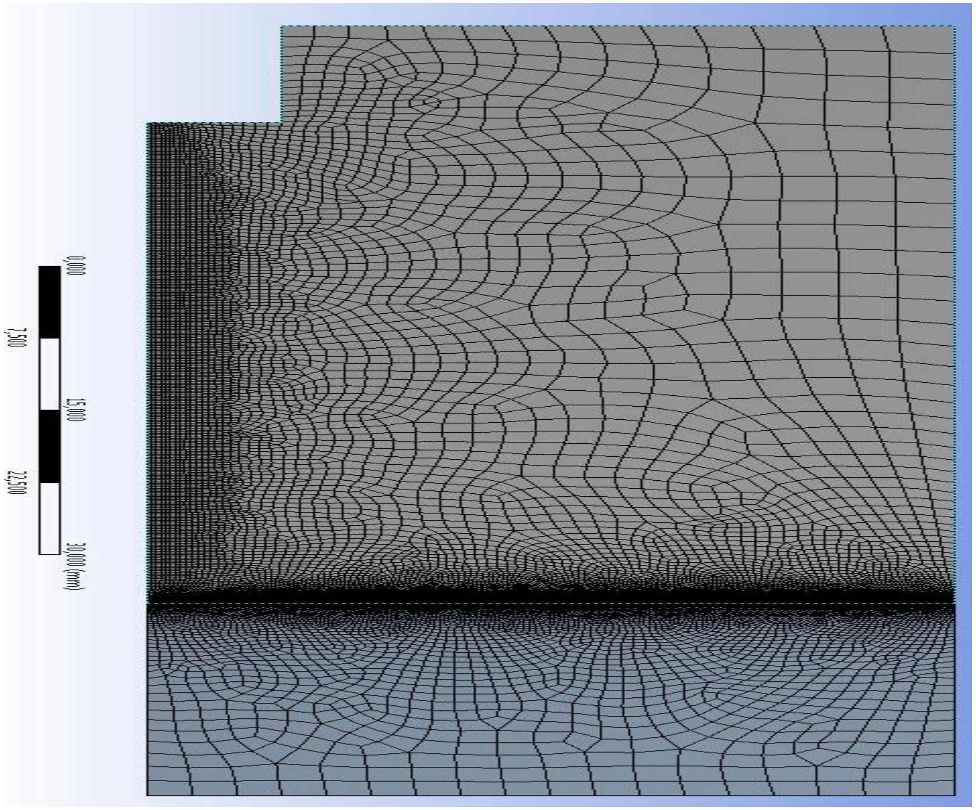
2D axisymmetric





- $D_j/2 = 4$ mm
- H = 35 mm
- ɛ = 10 mm
- L = 40 mm
- H+e = 45 mm

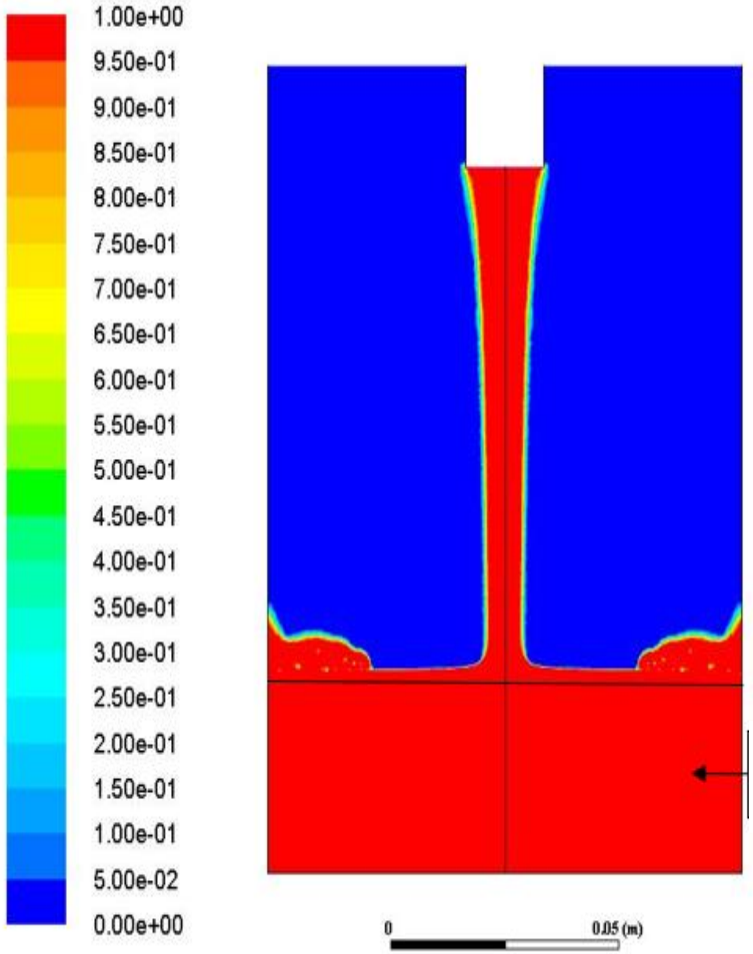
Meshing



Re=6819

Data	Tj (K)	Ts (K)	Vj0 (m/s)	Dj (m)
Simulation	300	268	0,2	0,008

Preliminary results one

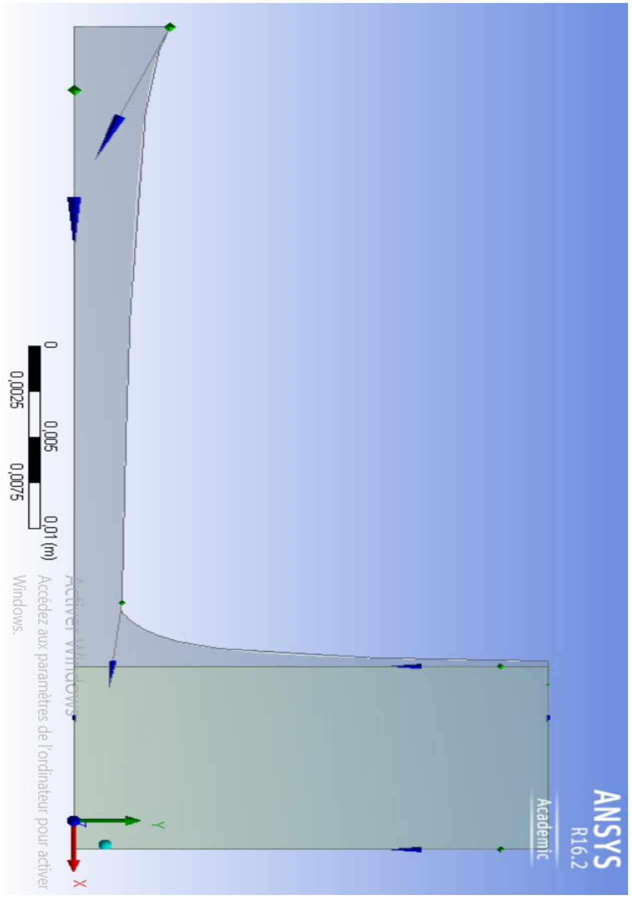


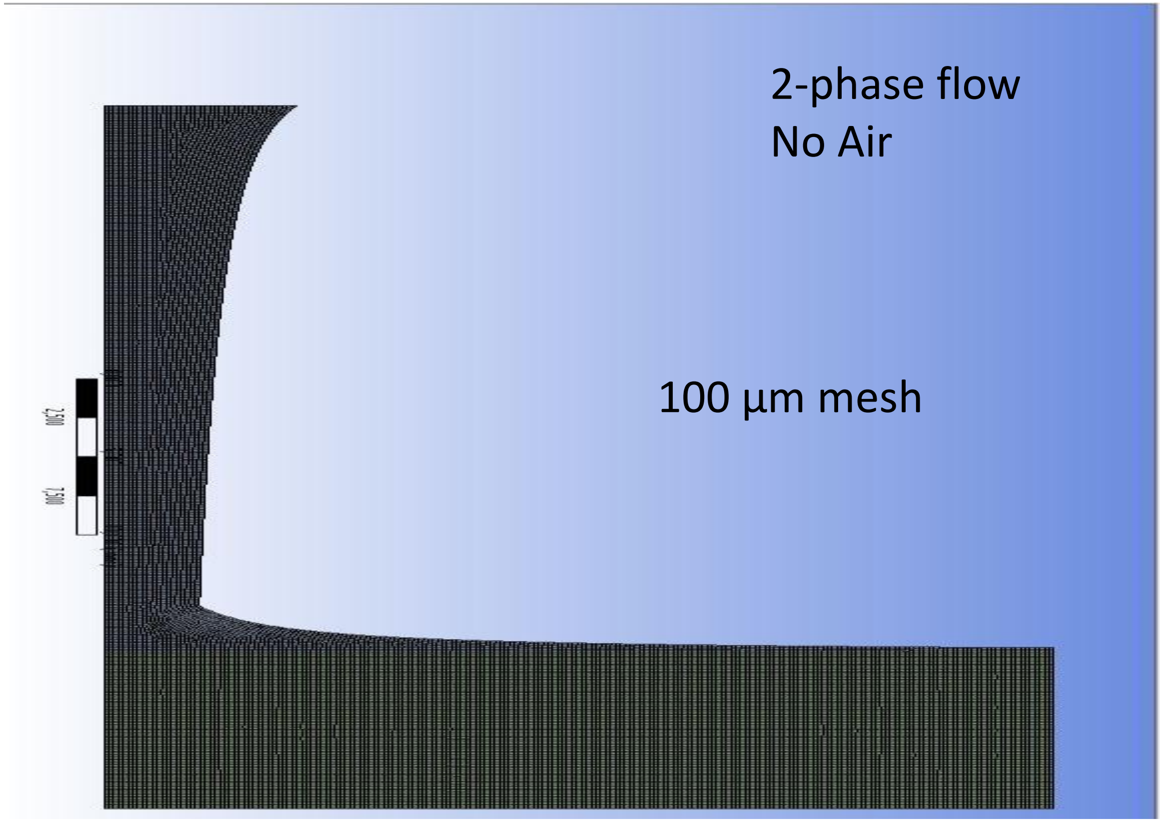
Solid

- 2-phase flow
- No Fusion
- Hydraulic Jump
- Long Computation
  - VOF
    - Explicit
  - Courant Condition

$$C = \frac{v\Delta t}{\Delta x} < 1$$

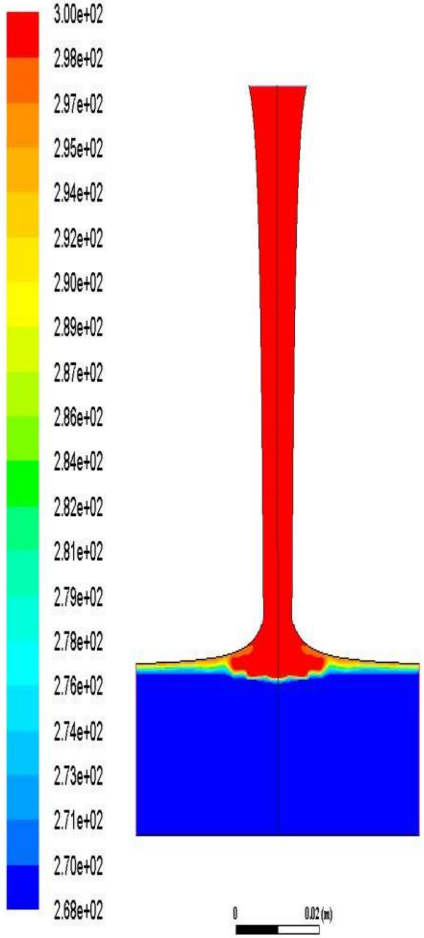
Preliminary results two



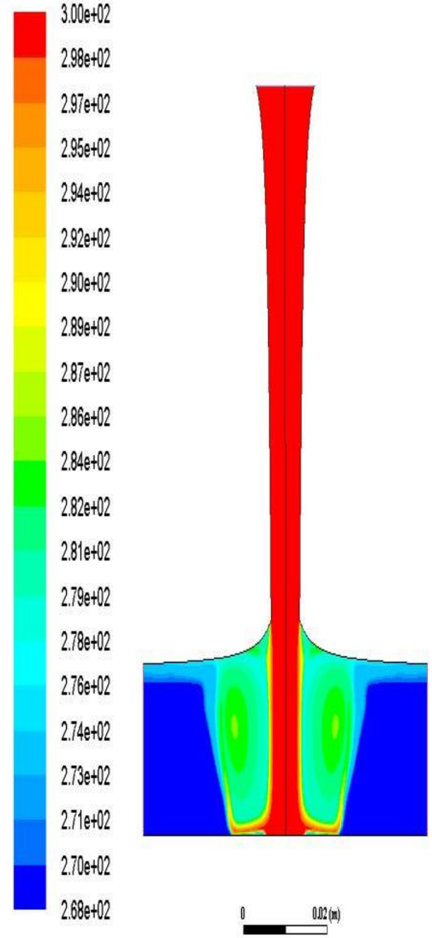


Results (Temperature)

T=0.09s

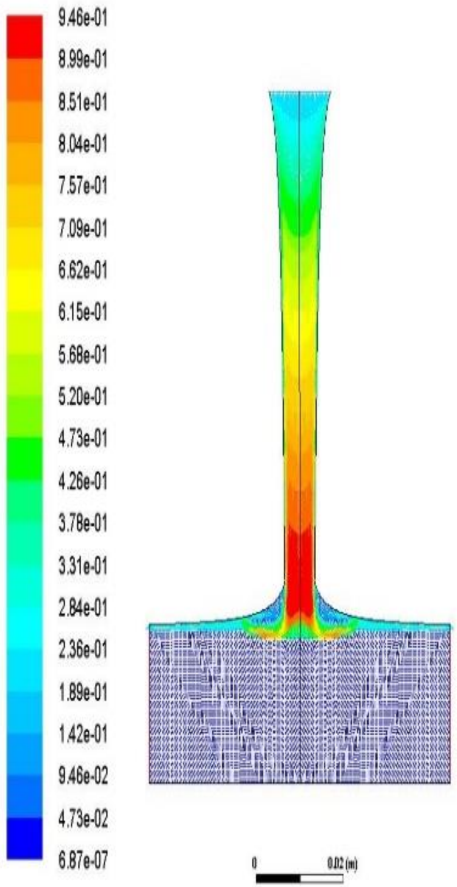


T=1.02s

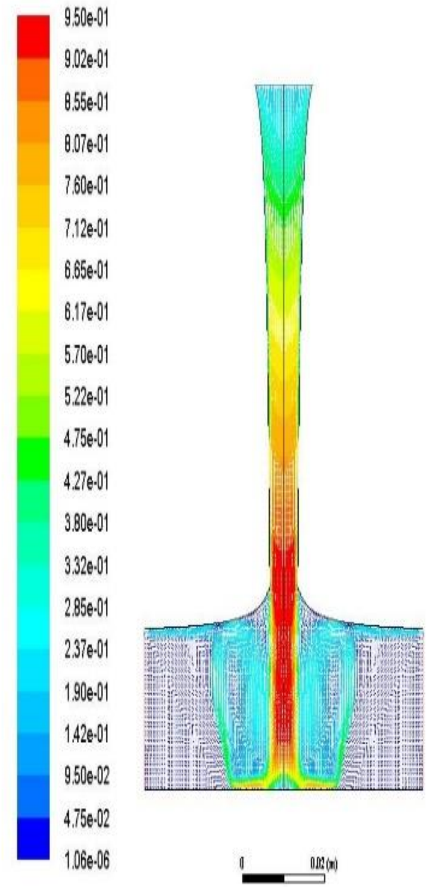


Results (Velocity)

T=0.09s



T=1.02s



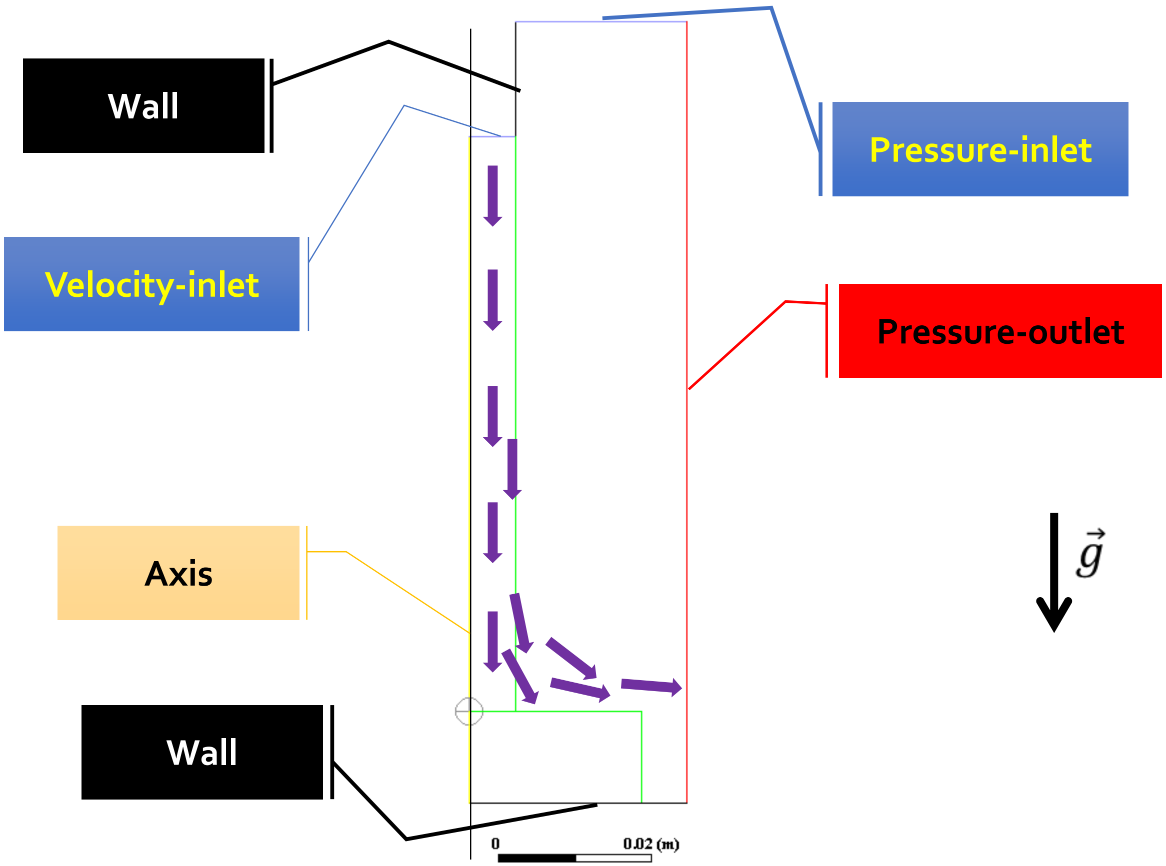
$$V_j = 0.851 m/s \simeq \sqrt{2gH}$$

Full Multiphasic Model

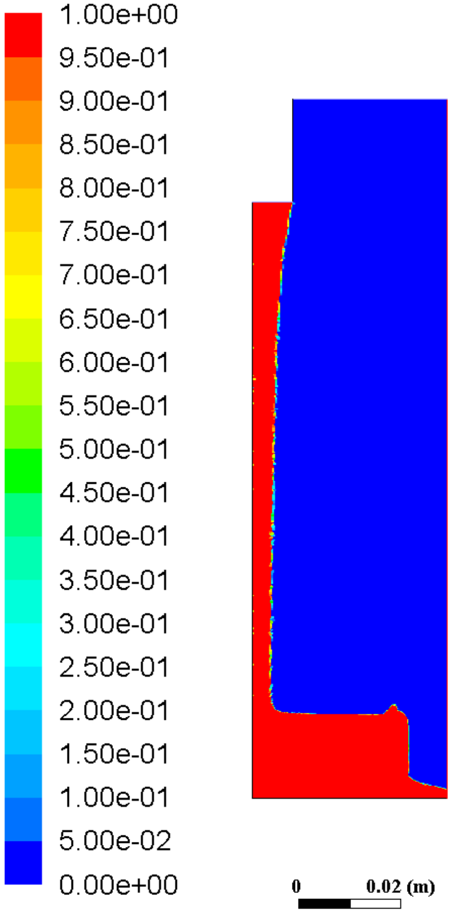
- Three phases model:
  - Water (fluid and solid)
  - Air (fluid)
- Fluent Modules :
  - Solidification/Melting
  - Volume Of Fluids (VOF)
- UDF to initialize the shape of the jet
- Laminar (i.e. no turbulent viscosity)

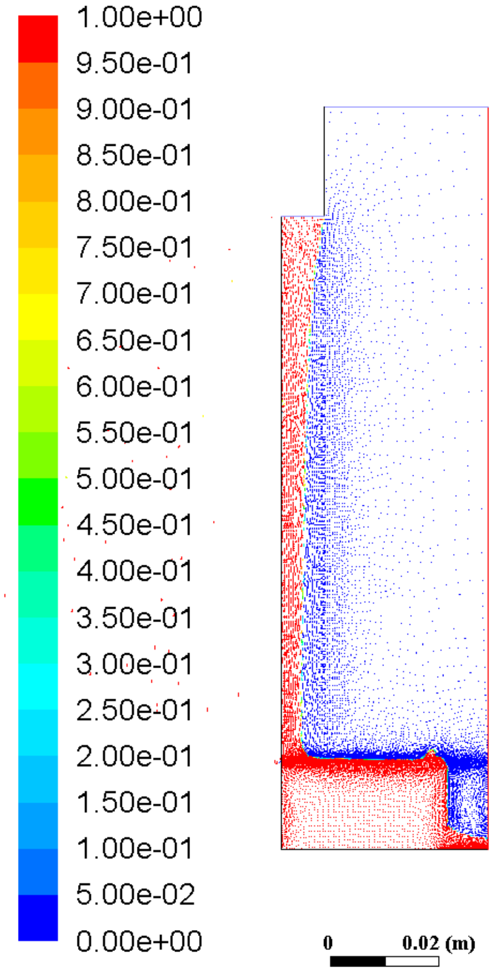
Configuration

Parameter	T_j (K)	T_s (K)	D_j (m)	V_j (m/s)
	300	268	0.008	0.2



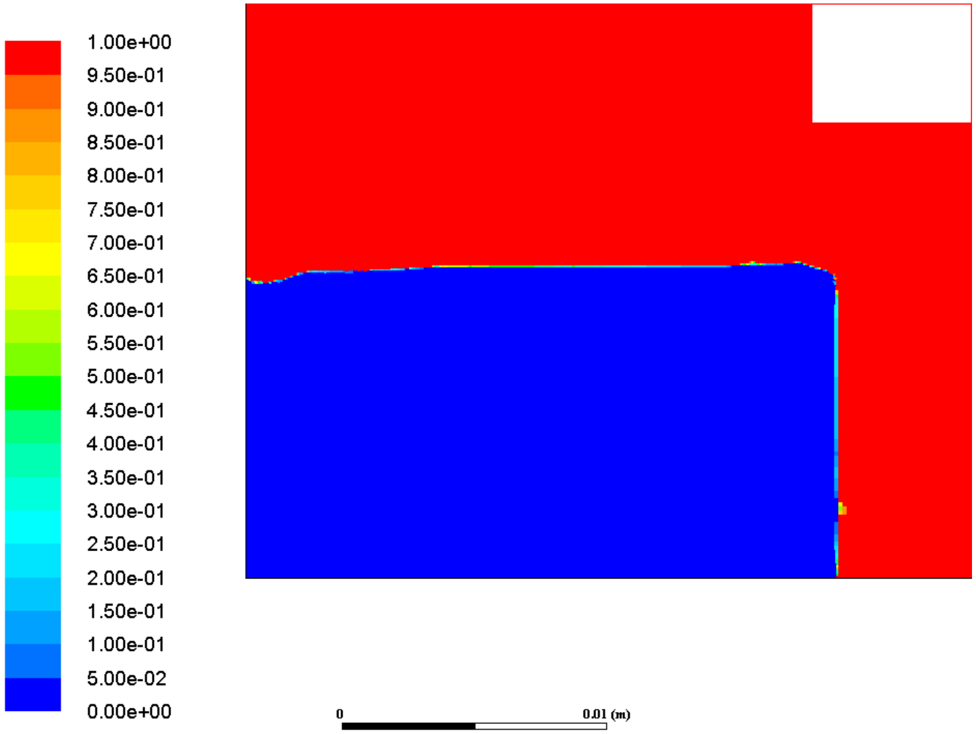
Results


1.00e+00
9.50e-01
9.00e-01
8.50e-01
8.00e-01
7.50e-01
7.00e-01
6.50e-01
6.00e-01
5.50e-01
5.00e-01
4.50e-01
4.00e-01
3.50e-01
3.00e-01
2.50e-01
2.00e-01
1.50e-01
1.00e-01
5.00e-02
0.00e+00
0
0.02 (m)

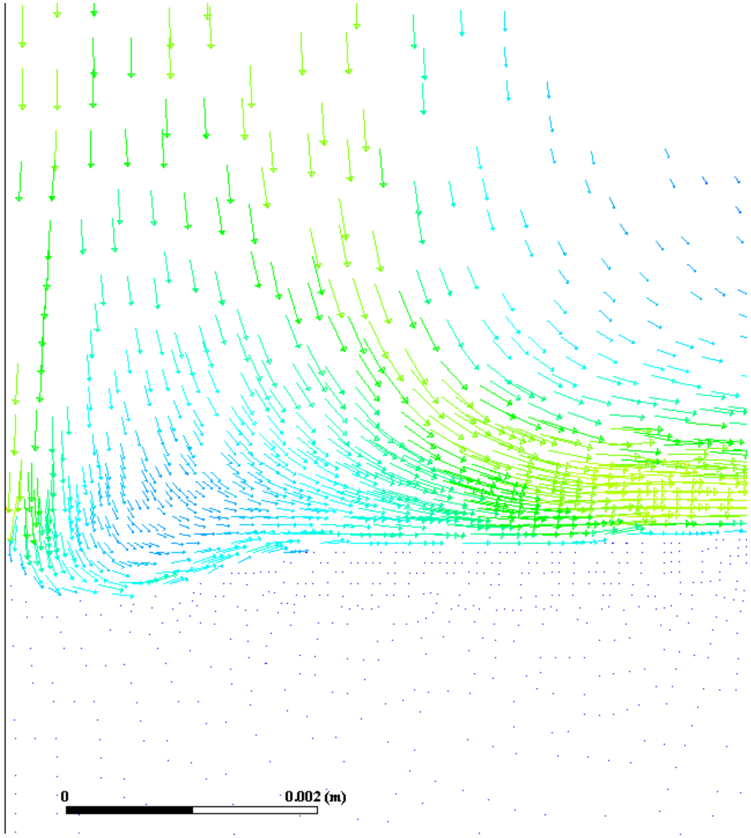

1.00e+00
9.50e-01
9.00e-01
8.50e-01
8.00e-01
7.50e-01
7.00e-01
6.50e-01
6.00e-01
5.50e-01
5.00e-01
4.50e-01
4.00e-01
3.50e-01
3.00e-01
2.50e-01
2.00e-01
1.50e-01
1.00e-01
5.00e-02
0.00e+00
0
0.02 (m)

Impact Zone

- Volume Fraction



- Velocity Field

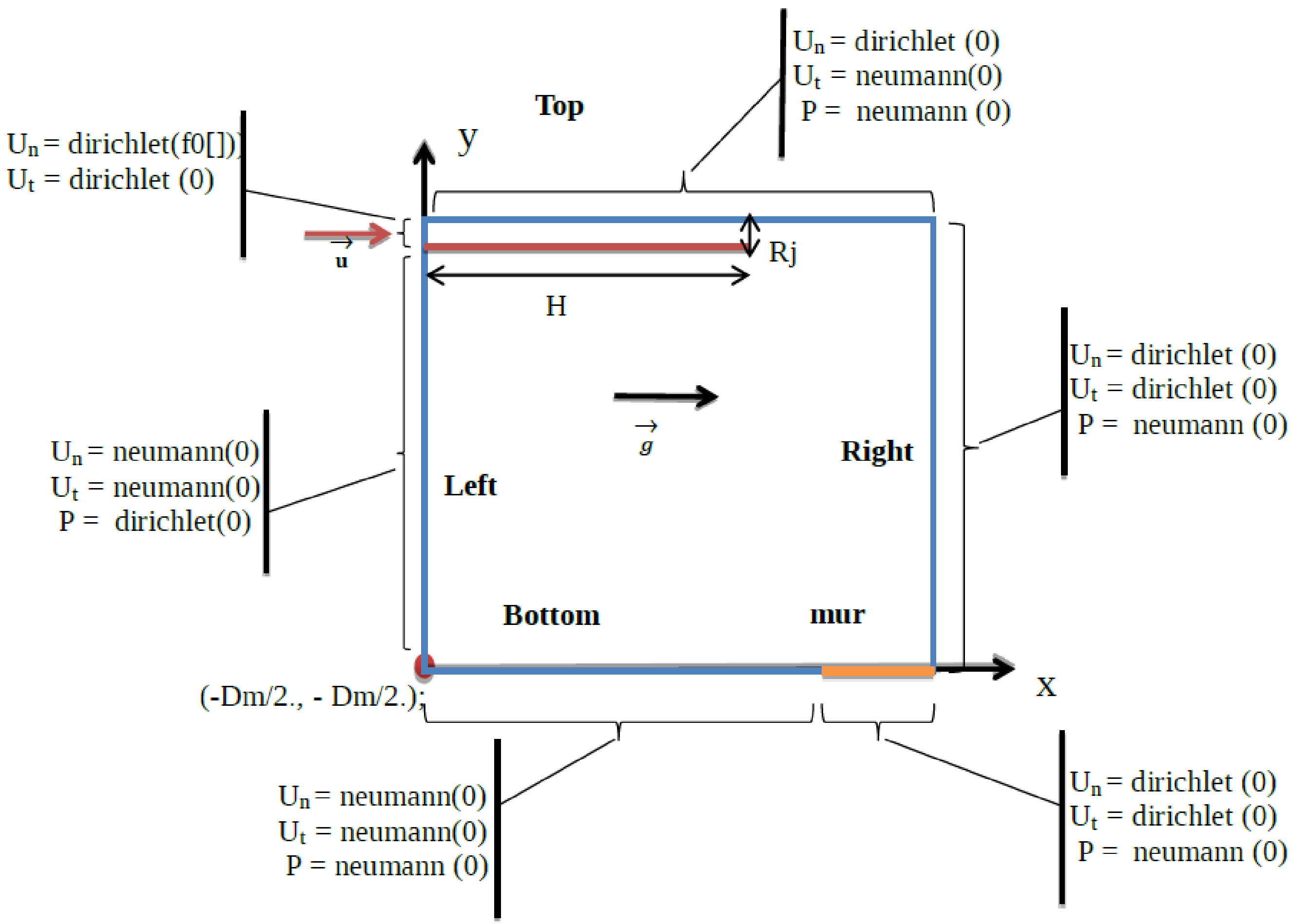


Too expensive!

Switching to Basilisk

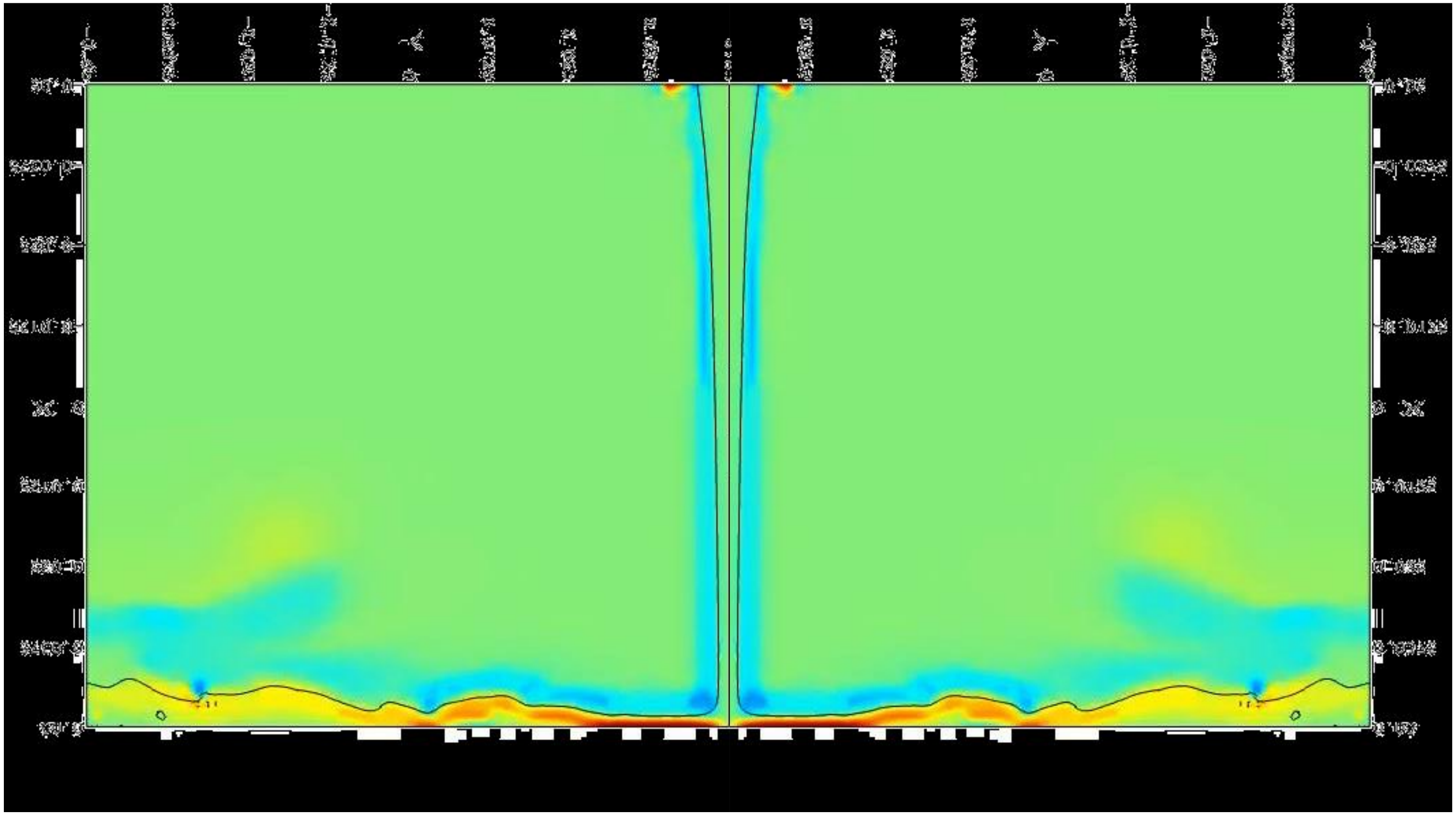
- AMG Refinement
- Parallelisation
- First test:
  - hydraulic jump
- Objective:
  - Three phases flow
  - Heat transfer
  - Implementing Voller’s model

Boundary conditions



First Basilisk Result

- Hydraulic Jump



Conclusion

- Experiments
  - Four Stage
    - Impact
    - Splashing
    - Hydraulic Jump
    - Pool Effect
  - Cavity Shape is different
    - Laminar
    - Turbulent
- New experimental setup
  - Nearly ready
- Theory
  - Main mechanisms
    - Are being sorted out
- Numerics
  - Still a lot of work to do…

Thanks to

- ESFR-SMART European Project
  - European Sodium Fast Reactor Safety Measures Assessment and Research Tools
- Masters Students (UL)
  - Internship
    - Célien Zaccharie
    - Reda Zaccharia
    - Essaadia Ben Moussa
  - Project
    - Théo Michel
    - Séléna Audhasse
    - Mohamed Haj Khlifa
- Technical Staff (LEMTA)
  - Mechanics
    - Jean-Yves Morel
    - Franck Demeurie
    - Jérémie Bianchin
  - Instruments
    - Mathieu Weber
    - Jamel Ouhajjou
    - Simon Becker