DE LA RECHERCHE À L'INDUSTRIE

Ablation of a solid by a hot liquid jet

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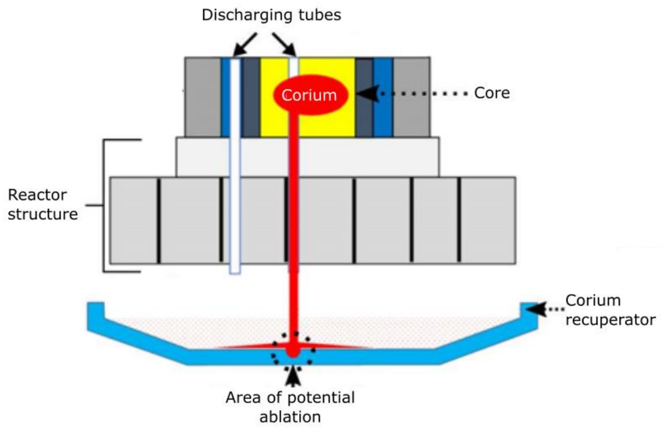
SUMMARY OF THE PRESENTATION

1. General context : severe nuclear accidents

- In the design of 4th generation reactors, mitigation of severe accidents is included.
- During a severe accident in a reactor, the core can be partially of totally molten, and the resulting molten material is called *corium*.
- For FNR-Na (Fast Neutron Reactors cooled with Sodium), discharging tubes replace some of the assemblies of fuel. The corium has to be discharged out of the core through these tubes to prevent recriticality.
- How to dimension the core-catcher so that is does not get pierced when discharging the corium ?



What are the important dimensionless numbers for this problem ?

$$Re = \frac{U_j D_j}{\nu}$$ the Reynolds number

$$Pr = \frac{\nu}{\alpha}$$ the Prandtl number

$$B = \frac{c_{p,j}(T_j - T_s)}{L + c_{p,s}(T_s - T_{s,0})}$$ the melting number

(B compares the energy of the jet with the energy necesary to melt the impinged solid)

Other numbers can have an importance such that ρ_j/ρ_s , H/D_j (with H the distance between the nozzle and the impinged surface), …

Notations : ν cinematic viscosity of the fluid, α diffusivity of the fluid, U_j velocity of the jet, D_j diameter of the jet, c_p specific heat of the solid (s) or of the jet (j), T the temperature and L the latent heat of the solid. $T_{s,0}$ is the initial temperature of the solid

The purpose of this PhD is to simulate a free-surface round jet impinging a solid with melting. Alexandre Lecoanet's PhD (2021) allowed to study the ablation with a simulant, water and ice, instead of corium. We now want to simulate this problem and validate the simulation with the experimental results.

It was decided for the first part of the PhD to eliminate the free surface and to consider an immersed jet in the simulations. New experiments were conducted with slight modifications on the *HAnSoLO* facility.

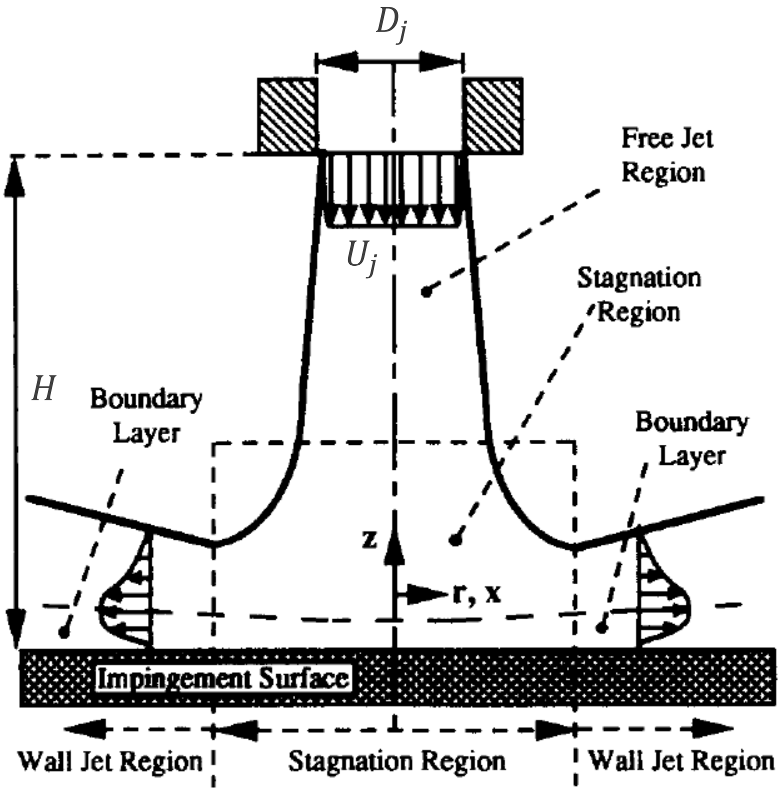
-> These experiments should allow to validate the first results of the simulations.

The free surface jet case will be considered later once the results with the immersed jet are validated.

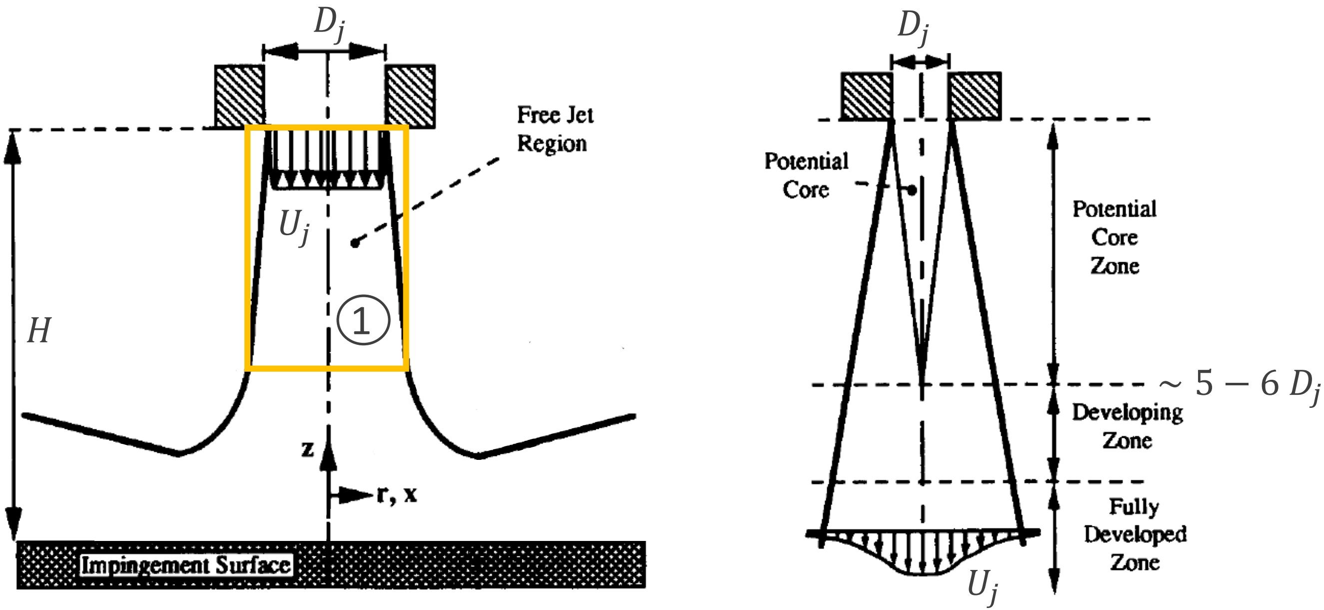
The simulations were performed with **OpenFOAM** due to the fact that numerical methods to simulate the melting of a solid are already implemented (the simulations were supposed to be performed with TrioCFD, a CEA software, but difficulties were encountered).

I – Immersed round jet impingement

Impinging immersed jet without ablation: 3 regions according to literature.



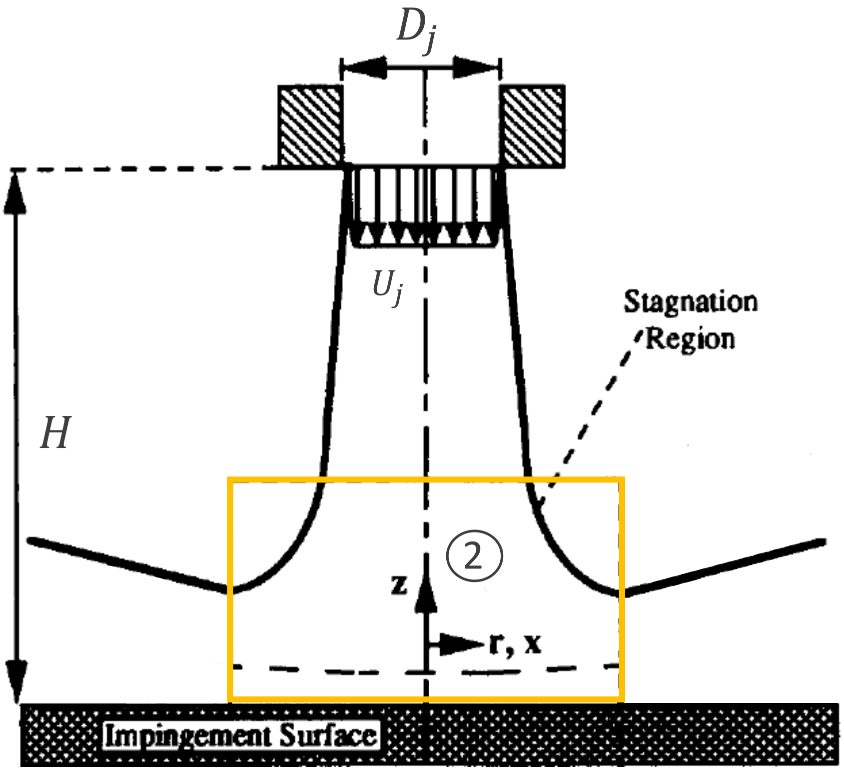
Impinging immersed jet without ablation: 3 regions according to literature



(1) Free jet region (Gauntner *et al.*, 1970)

- Potential core with constant center velocity
- Fully developped zone: turbulence created by the interaction between the surrounding fluid and the jet reaches the center of the jet $\rightarrow T, U$ decrease at the center.

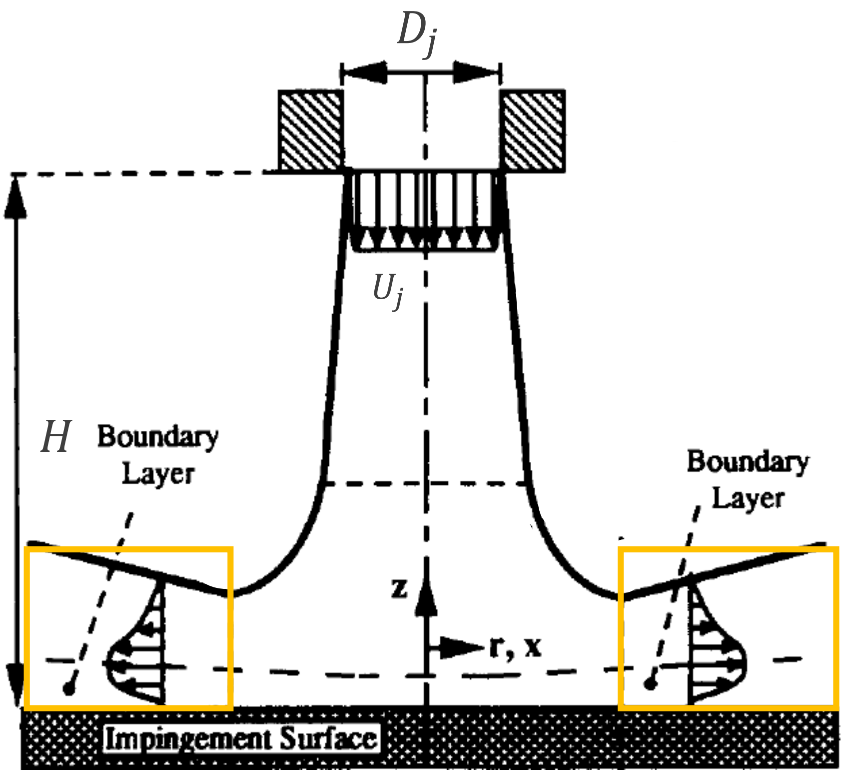
Impinging immersed jet without ablation: 3 regions according to literature



② Stagnation region (Tani and Komasu, 1966)

- Maximal heat transfer with the wall.
- **Laminarization of the flow in the boundary layer** for a an impinging potential core (high pressure).
- **Boundary-layer's width is almost constant.**

Impinging immersed jet without ablation: 3 regions according to literature



③ Wall jet region (Glauert, 1956)

- The region closest to the wall is called the inner layer, the effect of the wall is important.
- Region further from the wall can be considered as a free jet region (effect of the wall is neglectible) and is called outer layer.

Heat transfers between a solid and a fluid are characterized with the Nusselt number Nu :

$$Nu = \frac{hD_j}{\lambda_j}$$

With h the convective coefficient, λ the thermal conductivity. For a jet impinging on a solid wall of iso-temperature T_w, h is written:

$$h(T_j - T_w) = \lambda_s \frac{\partial T}{\partial n}$$

Correlation between $Nu_0 = Nu\ (r = 0)$, Re and Pr is usually written as:

$$Nu_0 = C\ Re^m\ Pr^n$$

For a water jet, Webb and Ma (1995) give $n = 0{,}42$.

An analysis for a laminar jet give $m = \frac{1}{2}$ according to Liu et al., this value is good for a turbulent jet impinging in its potential core but might be underestimated according to Vikanta, 1993.

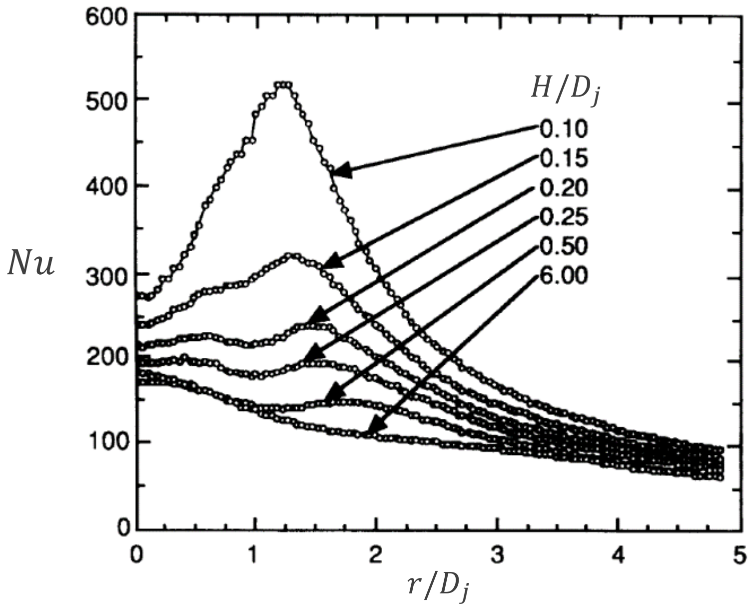
The factor C depends essentially on the value of H/D_j .

Nu has a high dependence to the nozzle-to-plate space (H/D_j) for the immersed jet.

-> It depends on which part of the free jet region reaches the wall.

We use $H/D_j = 10$ in our experiments.

$Re = 23\ 000$



Viskanta, 1993

Closure law on ablation velocity V_{abl} (velocity of the melting interface):

$$h\left(T_j - T_s\right) = V_{abl}\,\rho_s\,[L + c_{p,s}\left(T_s - T_{s,0}\right)]$$

Rewriting the previous equation to make melting number B appear:

$$\rho_s V_{abl} = \frac{h}{c_{p,j}}\, B \text{ where } B = \frac{c_{p,j}(T_j - T_s)}{L + c_{p,s}(T_s - T_{s,0})}$$

Knowing the local velocity of ablation V_{abl}, we can deduce the local Nusselt number with

$$Nu = \frac{\rho_s D_j\, c_{p,j}}{B\,\lambda_j} V_{abl}$$

We will try to find a correlation between the Nusselt number in the jet axis $Nu_0(t)$ and t such as:

$$Nu_0 \propto t^{\gamma}$$

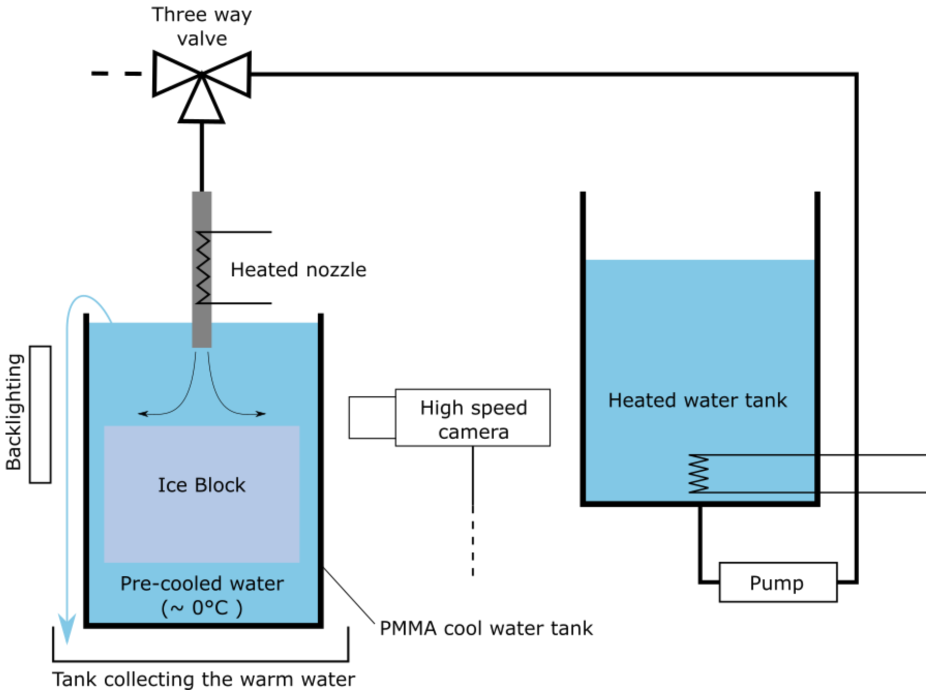
We will also try to find a correlation on the **initial** Nusselt number in the jet axis Nu_0^{ini} such as :

$$Nu_0^{ini} = C\, Re^m\, Pr^{0.42}$$

This correlation can be compared to the correlations obtained for non-melting surfaces, since the solid is initially plane.

II – Experimental results

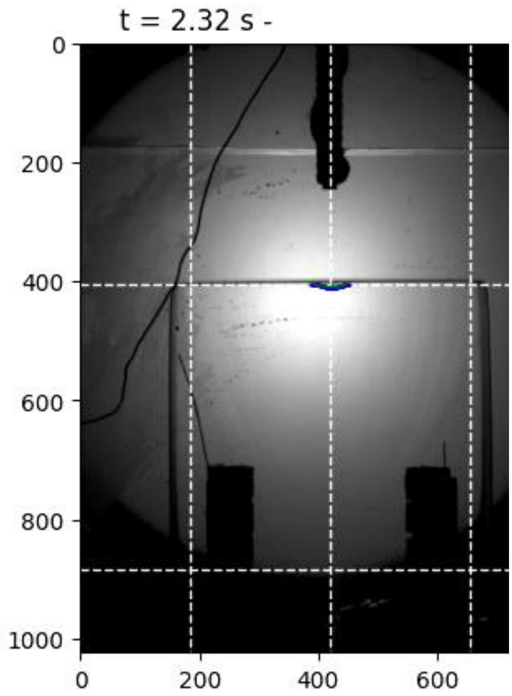
The point here is to have experimental results in order to compare with the results of the future simulations with a simpler case than the free-surface jet.
The experimental system *HAnSoLO* was modified to do so:



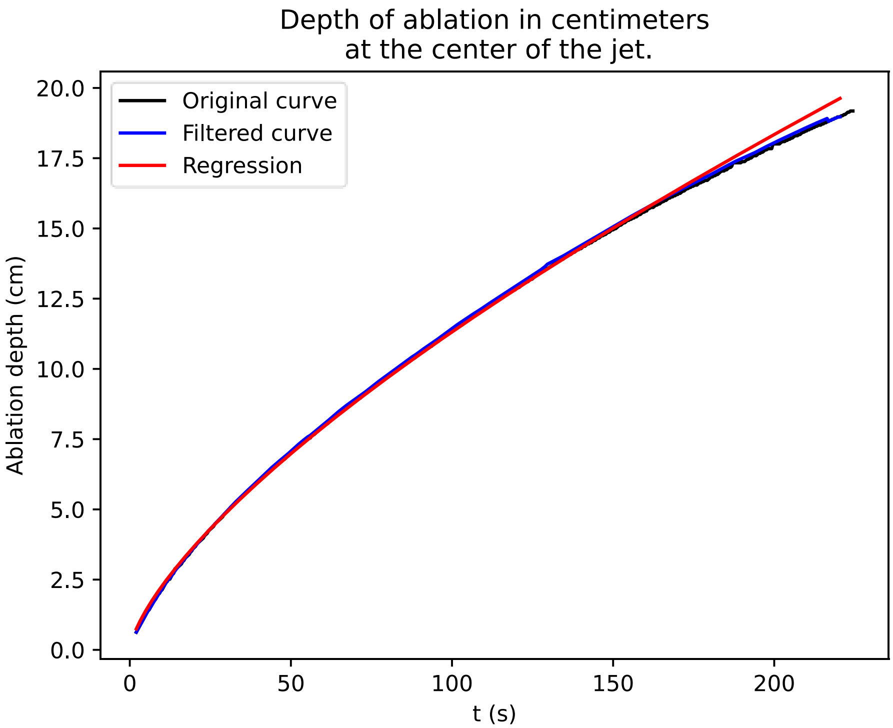
$$Re \in [10\,000; 150\,000]$$

$$T_j \in \{30; 50; 70\}\,°C$$

Cavity shape evolution over time with $T_j = 50\ °C$ and $V_j = 5\ m/s$



$$v_j = 5\ m/s \text{ et } T_j = 50°C$$



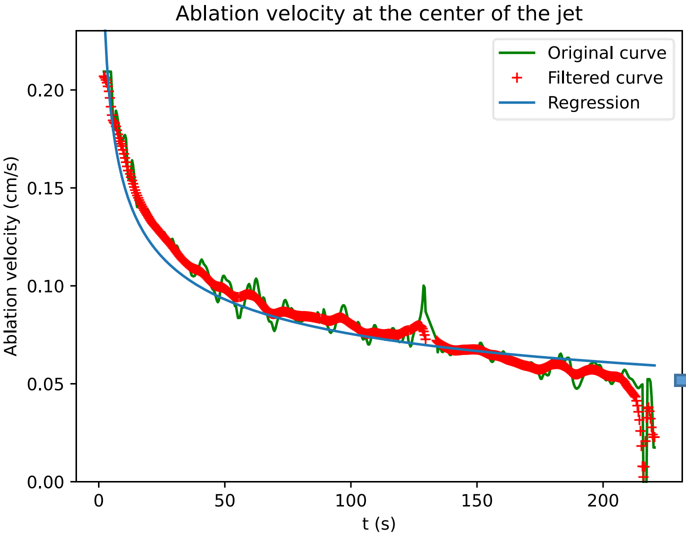
Regression:

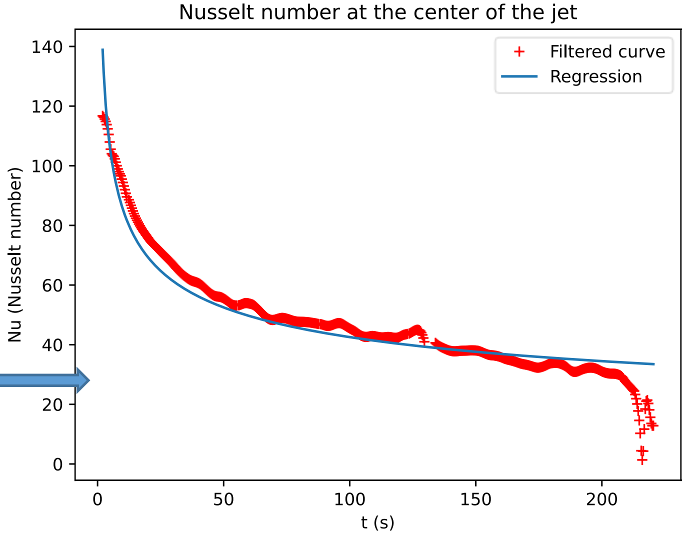
$$Nu_0 = 0.45\ t^{0.7}$$

-> Those coefficients will have to be interpreted.

The ablation velocity is obtained by derivating the depth curve with respect to the time.
We then get $Nu = f(t)$ through:

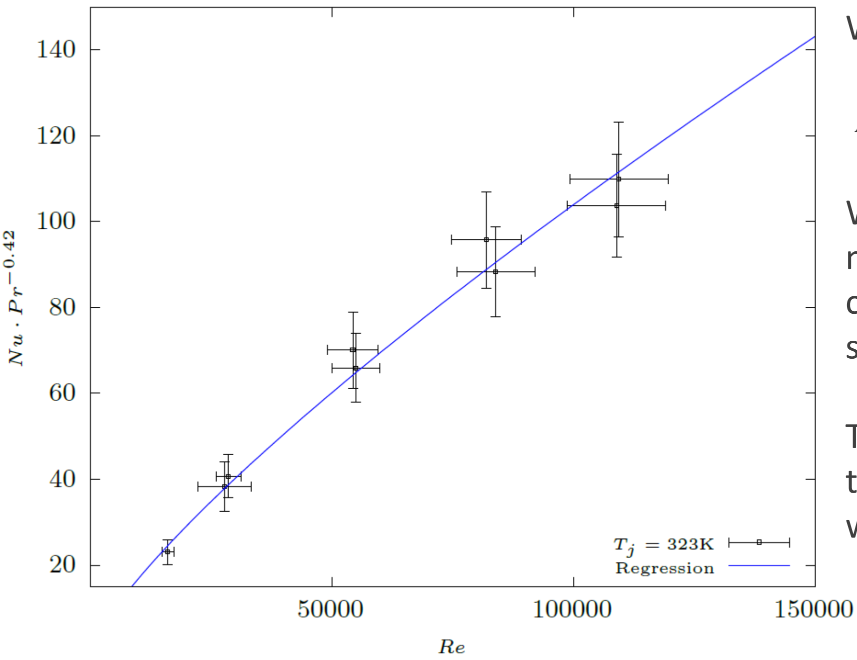
$$Nu = \rho_s V_{abl} D_j \frac{L + c_{p,s}(T_s - T_{s,0})}{\lambda_j (T_j - T_s)} \simeq \frac{\rho_s V_{abl} D_j L}{\lambda_j (T_j - T_s)}$$





$v_j = 5\ m/s$ et $T_j = 50°C$

Correlation for the experiments with $T_j = 50°C$



We get:

$$Nu_0^{ini} \cdot Pr^{-0.42} = 0.0118 \cdot Re^{0.789}$$

Where Nu_0^{ini} is the initial Nusselt number (the solid is plane so the comparison with non-melting plane surfaces can be done).

The coefficient on Re is higher than the one expected for a laminar jet with no melting (1/2).

The difference of exponent could be explained partially by the effect of the cold molten solid and also by the fact that our jet is turbulent at the impingement due to the fact that it is fully developed.

III – First numerical results

Solidification in OpenFoam for pure materials: penalization method based on the enthalpy (Voller and Prakash, 1987; Brent *et al.*, 1988)

Introducing volume fractions of liquid g_l and of solid g_s $(g_l + g_s = 1)$

Adding a source-term based on g_l in Navier-Stokes equations so that $\underline{u} = \underline{0}$ in the solid:

$$\underline{S} = C \frac{(1-g_l)^2}{g_l^3+q} \underline{u}$$

with C, q numerical parameters.

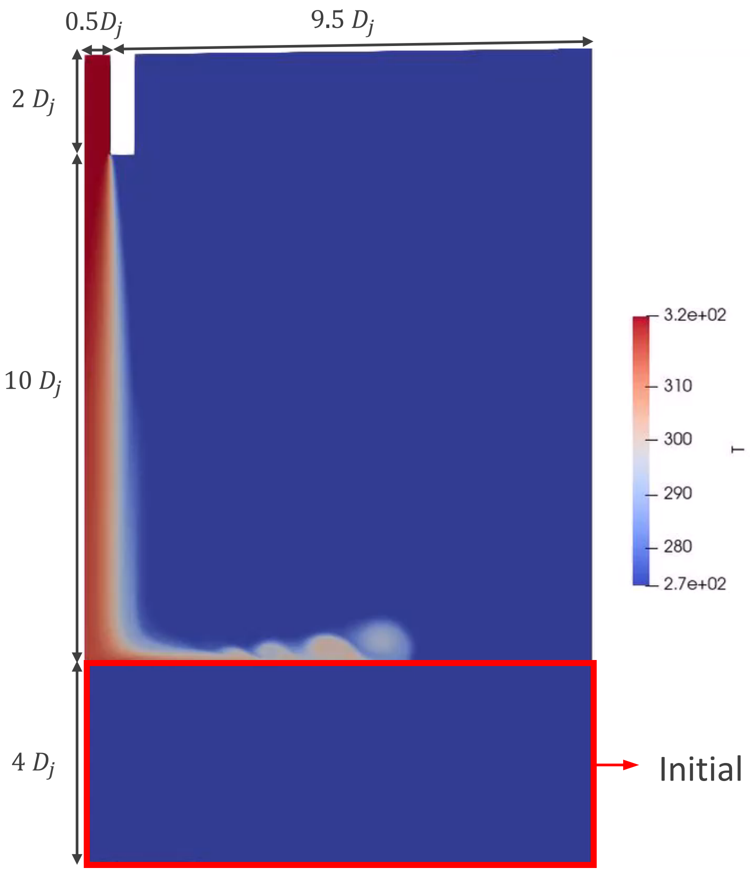
At each time step, the new volume fractions are evaluated with the value of the temperature computed with the energy equation:

$$g_l = g_l^{old} + l_{relax} \frac{c_p(T-T_s)}{L}$$

with l_{relax} a sub-relaxation coefficient.

Then iterations on the energy equation until convergence with computed value of g_l .

A Large Eddy Simulation approach is used to solve the turbulence.

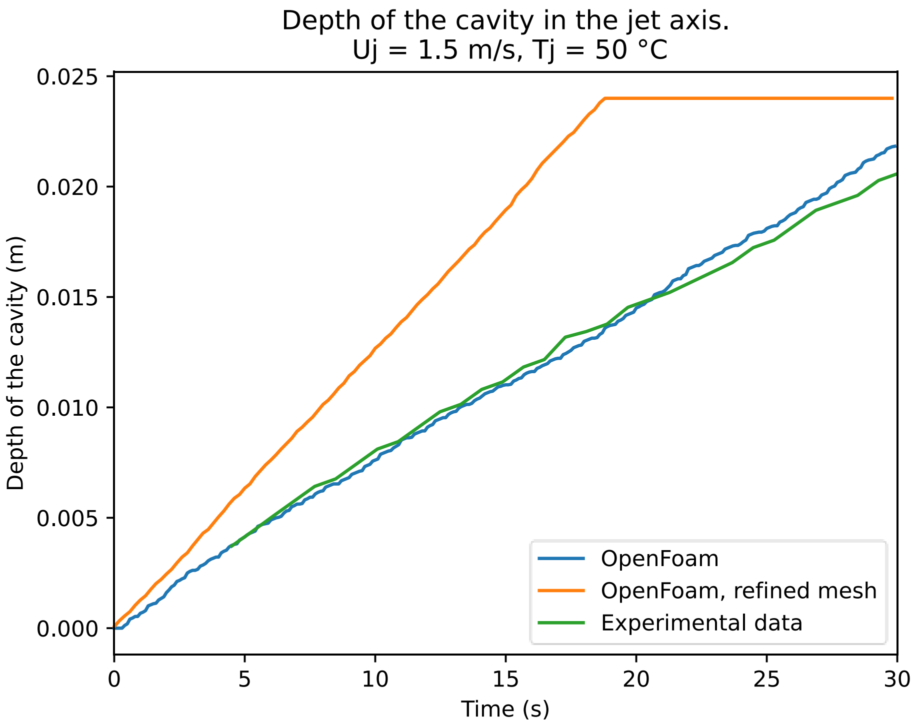


$V_j = 1{,}5\ \mathrm{m/s}\ , T_j\ =\ 50°\mathrm{C}$

2D Axisym. simulations at the moment.

To visualize the jet and the evolution of the solid we represent the temperature in the numerical domain.

Initial solid zone ($H = 4D_j$, $L = 10D_j$)

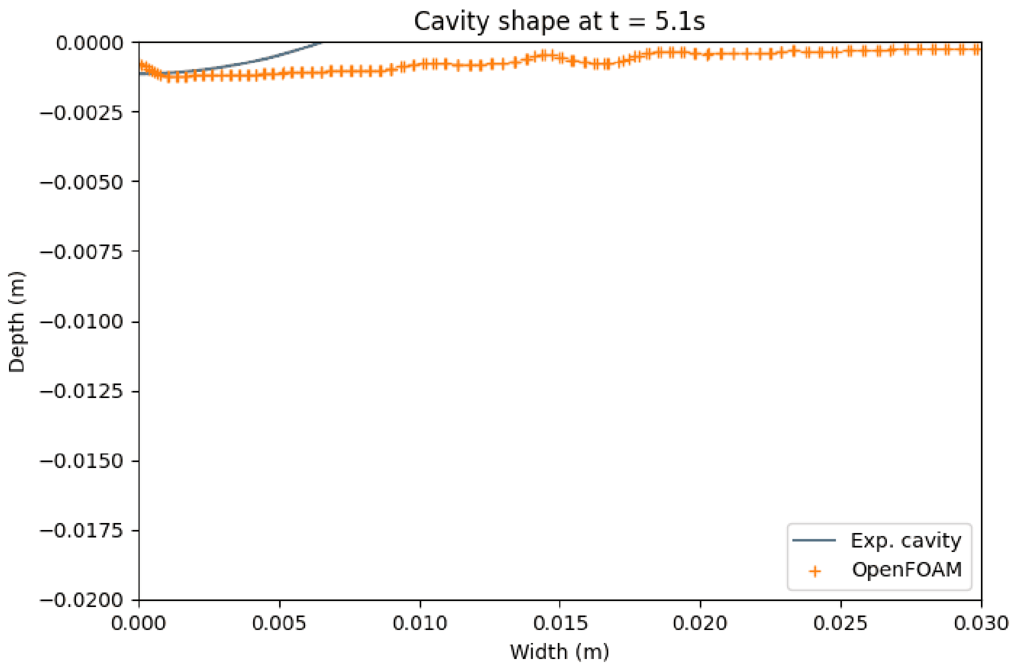


Simulation in 2D Axi.

The refined mesh gives over-estimated values of the transfers at the wall

Hypothesis : at the moment nothing triggers turbulence between the jet and the surrounding fluid…
-> This could lead to a hotter jet impinging the solid than in the reality.

$$V_j = 1{,}5\ \mathrm{m/s}\ ,\ T_j\ =\ 50°\mathrm{C}$$



The image treatment allows to get the experimental cavity shape in order to compare it to the one obtained with OpenFOAM.

Conclusions, perspectives

Part of the experiments are still in treatment. A study of the evolution of the coefficients of the regressions $Nu = b \cdot t^a$ with Re is in progress.

OpenFOAM does not allow easily to take into account the variation of density between the solid and the fluid. It has been done by Faden *et al.*, 2019, but with an older version of OpenFOAM and their code is not implemented in distributed versions.

Turbulence has a key role, especially for immersed jets due to the interaction with the surrounding fluid.
-> 3D simulation would be necessary with initialization of the turbulence at the inlet (synthetic turbulence is available).

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Merci de votre attention !