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## Ablation of a solid by a circular immersed or free-surface jet

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### Abstract

Experiments are performed with water and ice in order to characterize the ablation of a solid either by the impingement of an immersed jet or of a free surface jet. The initial nozzle-to-plate used is  $H/D_j = 10$  and the Reynolds number ranged between  $10^4$  and  $1.5 \cdot 10^5$ . The heat transfer between the jet and the solid are studied, depending on the Reynolds number  $Re$  and the temperature of the jet. For an immersed jet, it is found that the Nusselt number at the stagnation point scales as  $Re^{0.8}$  and the ablation cavity shape is found to be auto-similar. For a free surface jet, the effect of the roughness of the impinging surface is also considered. If the characteristic size of the solid's roughness is large enough, the ablation velocity is greatly increased at the stagnation point. Two types of cavity shapes can be observed depending on the roughness characteristic size.

### Introduction

The safety design of Sodium-cooled Fast Reactor (SFR) requires that in the event of an hypothetical severe accident leading to a core meltdown, the melt, called *corium*, should be evacuated through discharge tubes leading to a core-catcher, where it spreads and is cooled. This issue involves a free-surface molten corium jet, passing through gaseous sodium, and impinging a steel plane recuperator. The impingement of the hot corium ( $\sim 1500\text{K}–3000\text{K}$ ) leads to the thermal ablation of the core-catcher, which has to be designed to avoid a breakthrough.

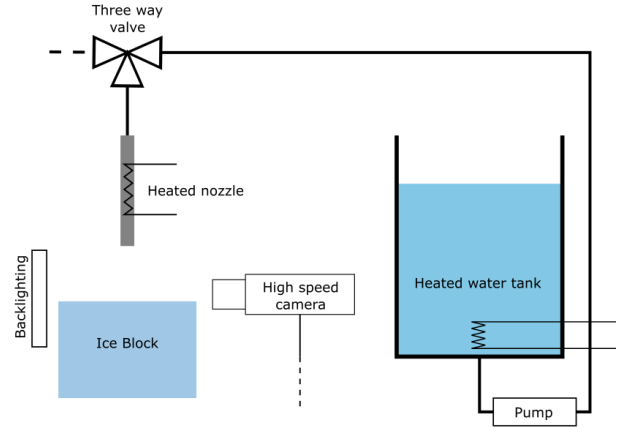
Experiments have been carried with simulants (water and ice) due to the impossibility of using real corium. Immersed and free-surface jets have been used in order to validate future simulations. The numerical code used should then allow simulations with real physical corium properties. A description of the experiments and of the results is given below.

### Experimental Facility

The experimental apparatus is called Hot Ablation of a SOLid by a Liquid - Observation (*HAnSoLO*), which is described in details by Lecoanet et al. (2021). This apparatus allows one to perform either impinging immersed jet experiments or free surface jet experiments. A simplified vision of it is given in Figure 1.

The diameter of the nozzle is set to  $D_j = 6$  mm and the initial nozzle-to-plate distance  $H$  is set such that  $H/D_j = 10$  in all the experiments. The ice blocks are transparent so that the evolution of the cavity formed by the melting of the solid can be recorded with a high speed camera. Using the images of the camera and a post-processing python-based algorithm, the maximum depth and the shape of the cavity can be obtained versus time.

An energy balance equation for impinging jets inducing solid melting is given by Sato et al. (1991) as:



**Figure 1:** Simplified vision of the apparatus for the free-surface jet configuration. A tank filled with cooled water can be added in order to perform the immersed jet experiments.

$$h(T_j - T_m) = V_m \rho_s [L + C_{p,s}(T_m - T_{s,0})] \quad (1)$$

with  $h$  the convective heat transfer coefficient and  $V_m$  the ablation velocity;  $L$  is the latent heat of fusion,  $T_j$  is the jet temperature,  $T_m$  is the solid melting temperature,  $C_{p,s}$  is the solid specific heat capacity,  $\rho_s$  is the solid density and  $T_{s,0}$  is the solid initial temperature, which is considered uniform.

The ablation velocity is defined here as the local interface velocity. At the stagnation point, with  $y_d$  the depth of the cavity and  $t$  the time,  $V_m$  can be written as:

$$V_m = \frac{\partial y_d}{\partial t} \quad (2)$$

The Nusselt number, that characterizes the increase of heat transfer at the solid surface due to jet convection, is defined

as:

$$Nu = \frac{hD_j}{\lambda_j} \quad (3)$$

where  $\lambda_j$  is the fluid thermal conductivity. With these relations, it is possible to link  $Nu$  and  $y_d$ , and thus evaluate the heat transfer at the stagnation point from the solid-liquid interface evolution.

Furthermore, for the melting of immersed ice balls in a turbulent water flow, Machicoane et al. (2013) obtained  $Nu \propto Re^{0.8}$ . This correlation will be compared to the immersed jet experiments results.

For the free-surface jets, in order to have a controlled roughness in the experiments, circular holes are created at the impinging surface (by applying a piece of metal), and the roughness characteristic size  $\epsilon$  considered is the height  $h_c$  and the diameter  $D_c$  of the holes. In our experiments,  $\epsilon = h_c = D_c \in \{0, 0.2, 0.5, 1\}$  mm. The holes are mapped on a square and regularly spaced by a center-to-center distance of 4 mm. The results will be compared to smooth surface impingement experiments performed by Lecoanet et al. (2021).

## Results and Discussion

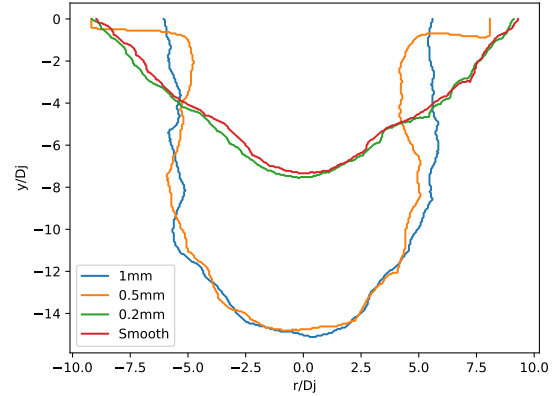
For the immersed jet, we first consider the heat transfer at the stagnation point for several values of  $Re$  in the experiments in order to establish a correlation of the form  $Nu \propto Re^m$ . For a given depth, we compare the values of  $Nu$  obtained for each value of  $Re$  and compute a linear regression to obtain the exponent  $m$  of the correlation. Doing correlations between  $Nu$  and  $Re$  for several depths (from  $y/D_j = 0$  to  $y/D_j \sim 10$ ) gives a mean value  $m \simeq 0.802 \pm 0.053$ , which is an exponent very close to the exponent given by Machicoane et al. (2013). The cavity shape is auto-similar with respect to time for depths lower than  $y/D_j \sim 10$  and can be compared to the cavity shapes obtained by Lecoanet et al. (2021) for a free-surface jet. For higher depths, another type of cavity shape appears, which might be caused by the increasing width of the impinging jet with the depth of the cavity; this last cavity shape can be compared to the shape obtained by Lecoanet et al. (2021) with a free-surface jet once the cavity is filled with the jet water (the "pool-effect" phenomenon).

For the free-surface jet experiments, two types of ablation appear depending on the characteristic size  $\epsilon$  of the roughness used. In the case of a free-surface jet, the impingement ablation velocity is constant as long as the cavity is not filled with liquid (Sato et al. 1991; Lecoanet et al. 2021). This allows an easier evaluation of  $V_m$  and  $Nu$ . A linear regression on  $y$  with respect to time gives  $V_m$  as the slope of the curve. Using this method for the experiments with  $\epsilon = 1$  mm and  $\epsilon = 0.5$  mm, a correlation  $Nu \propto Re^m$  is found with  $m \simeq 1.123 \pm 0.013$ , whereas Gilpin (1973) gives a value of  $\sim 0.8$  for an impinging free-surface water jet on ice, with uncontrolled roughness. For the smooth surface experiments, the value  $m \simeq 0.596 \pm 0.052$  is obtained, which is close to the value of  $\sim 0.65$  given by Gilpin (1973).

The experiments with  $\epsilon = 0.2$  mm gives results close to the smooth surface experiments for low values of  $Re$  and results closer to the experiments performed with  $\epsilon = 0.5$  mm

and  $\epsilon = 1$  mm for higher values of  $Re$ . The transition seems to happen at  $Re \simeq 9.5 \cdot 10^4$ .

Two types of cavity shapes can be observed depending on  $\epsilon$ , one similar to what has been described by Lecoanet et al. (2021) obtained with a smooth surface or a low value of  $\epsilon$  and one obtained with rough surfaces. These two types of shapes are given in Figure 2 for  $Re \simeq 5.5 \cdot 10^4$  and  $T_j = 323$ K for  $t = 20$  s after impingement of the jet.



**Figure 2:** Two types of cavity that can be obtained, depending on the roughness of the impinging surface, in the free-surface configuration ( $Re \simeq 5.5 \cdot 10^4$  and  $T_j = 323$ K).

## Conclusion

The ablation of a solid by an immersed jet is characterized, with the impingement Nusselt number and the cavity shape. For the free-surface jet, the transition towards a different type of ablation, induced by roughness, is highlighted, and leads to a quicker ablation and a less wide cavity. This effect should be further studied and taken into account for the reactor design. Both configurations' results should be used to validate simulations with a CFD software in order to simulate the reactor case.

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