Study of the ablation of a solid wall by a liquid jet

ASTROFLU V

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DE LA RECHERCHE À L'INDUSTRIE

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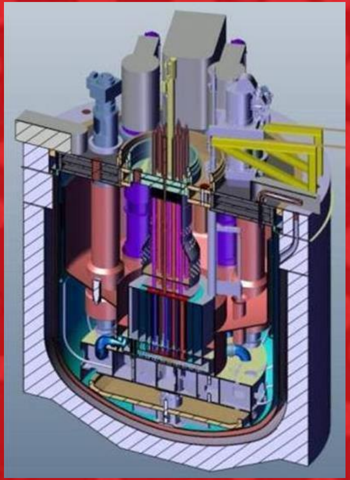

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General context / Introduction

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R&D context: Nuclear Severe Accident

- 4th generation: Sodium Fast Reactors (SFR)
- Integrate lessons learnt from previous accidents

Coping strategy for future SFR

Discharge tubes DT:

- Relocation toward Core-catcher as fast as possible

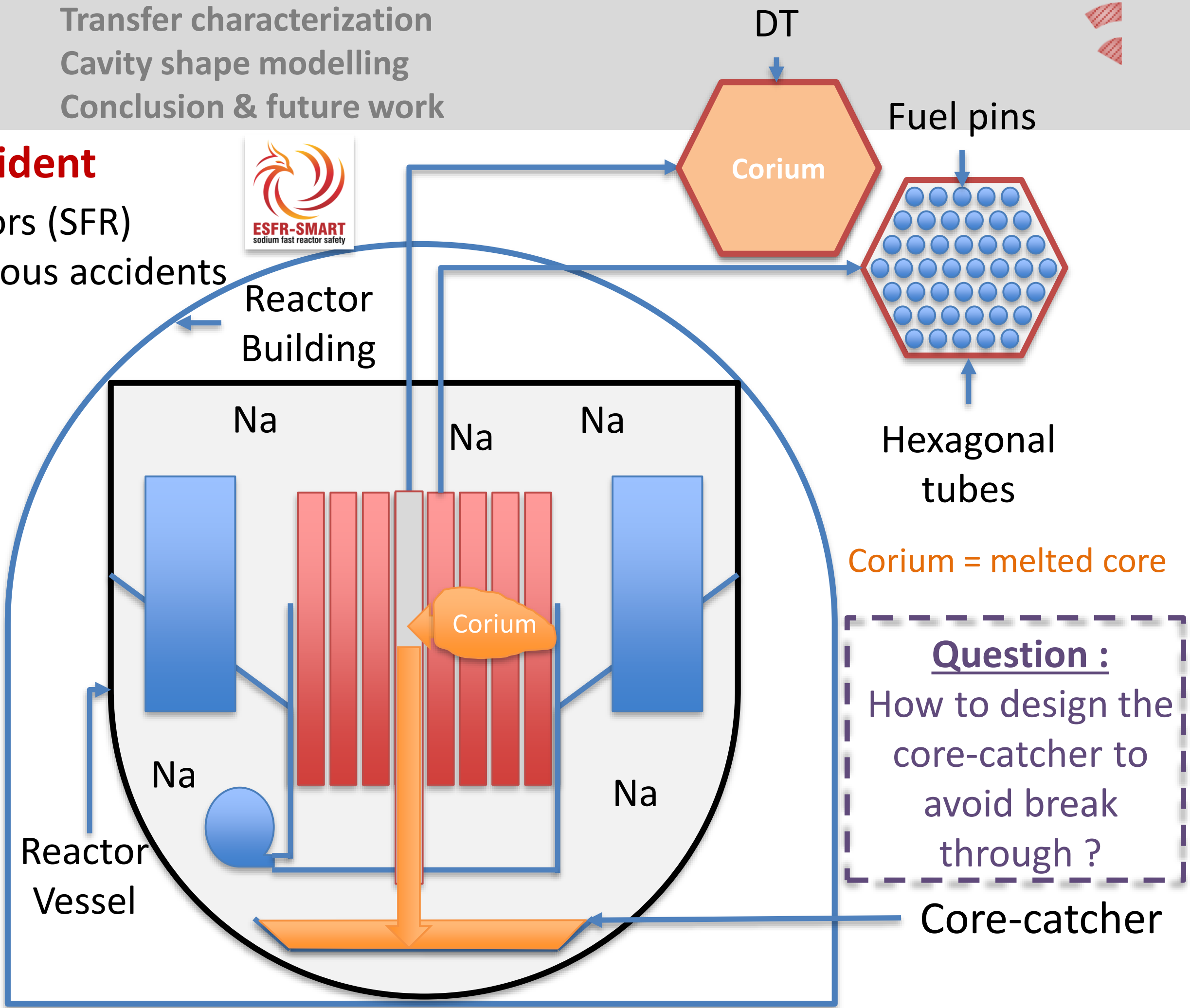
Core-catcher:

- Corium stabilization

In-vessel retention

Advantages

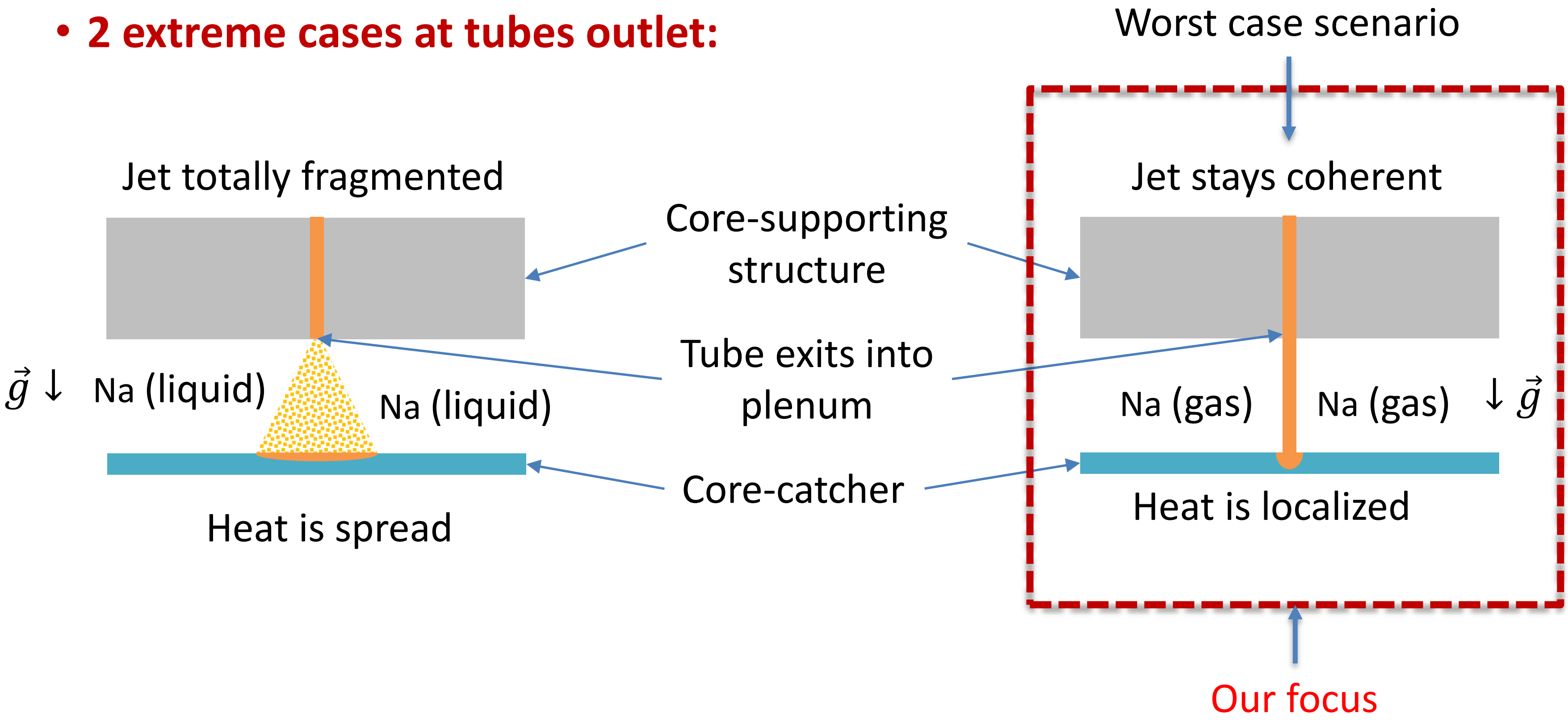
- Reduce corium mass avoid recriticity
- Know corium path in advance



Corium = melted core

Question :
How to design the core-catcher to avoid break through ?

- **2 extreme cases at tubes outlet:**



Worst case scenario

Jet totally fragmented

Jet stays coherent

Core-supporting structure

Tube exits into plenum

$\vec{g}$ ↓ Na (liquid)

Na (liquid)

Na (gas)

Na (gas) ↓ $\vec{g}$

Core-catcher

Heat is spread

Heat is localized

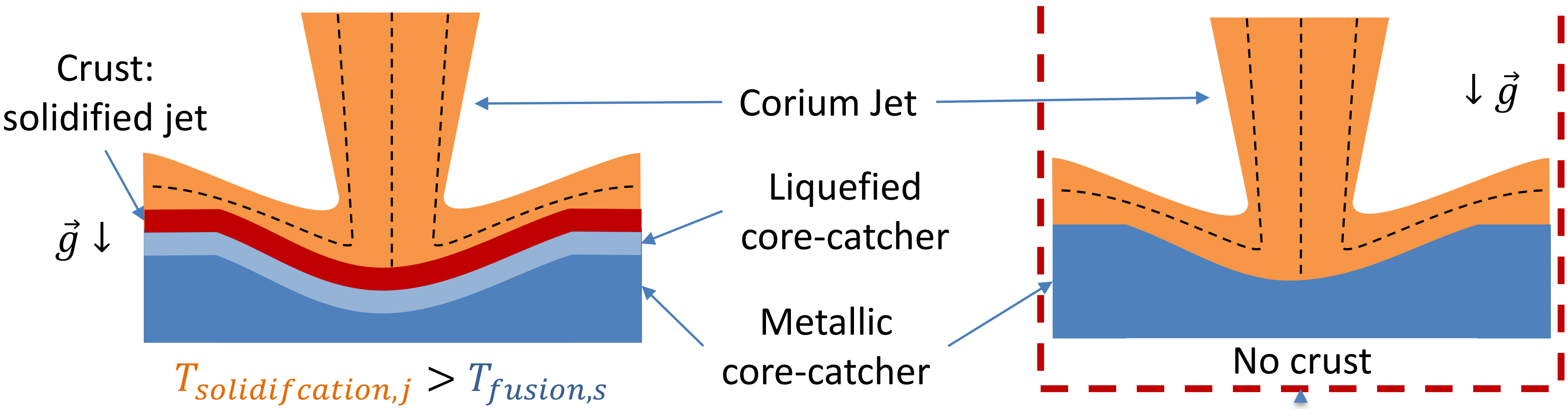
Our focus

- **Coherent jet / 2 types of interactions:**
  - Depending on jet / core-catcher relative compositions

Corium:
- oxide from nuclear fuel
- steel from structure

Molten oxide jet

Molten metal jet



Crust: solidified jet

$\vec{g}\downarrow$

Corium Jet

Liquefied core-catcher

Metallic core-catcher

$\downarrow\vec{g}$

No crust

$T_{solidifcation,j} > T_{fusion,s}$

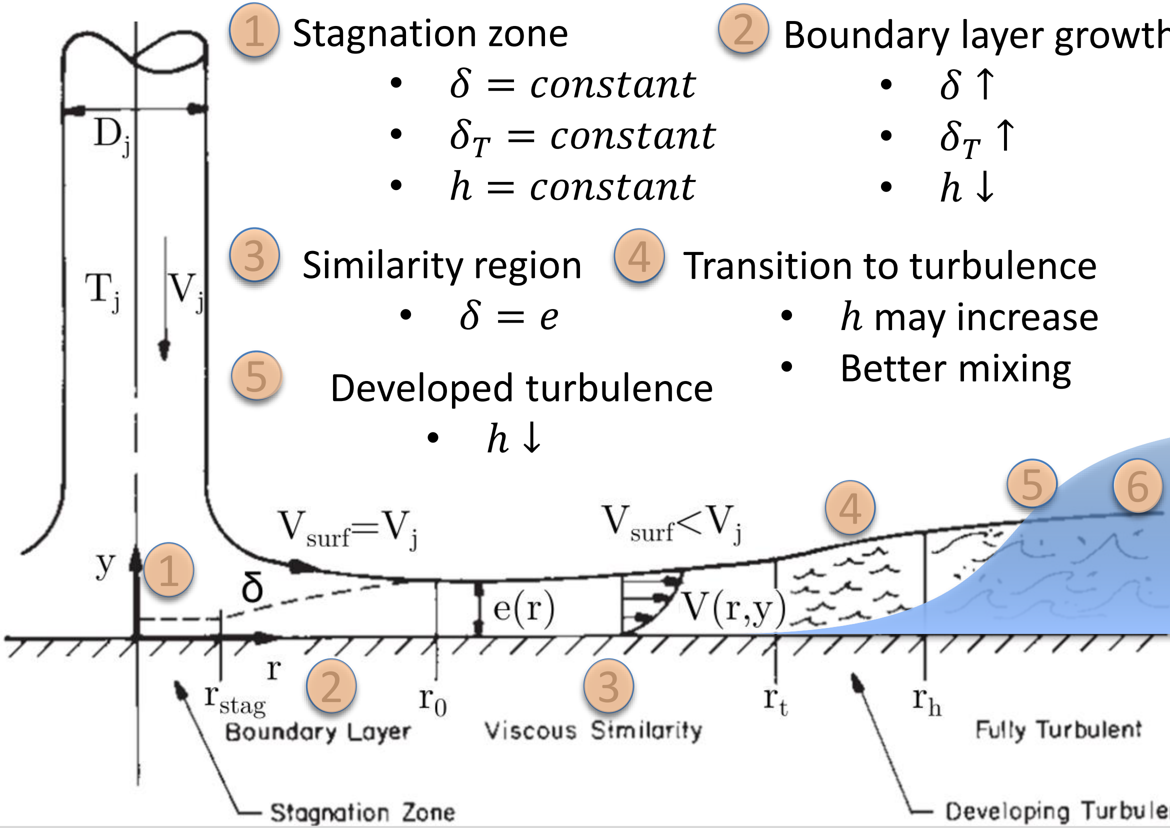
Crust acts as **thermal resistance**

Worst case scenario

- Obtain quantitative data on ablation Jet / Solid same nature
- Improve understanding of ablation phenomenon

Goals ← Focus

Academic context: Jet spreading - laminar jets Watson (1964) + Lienhard (2006)



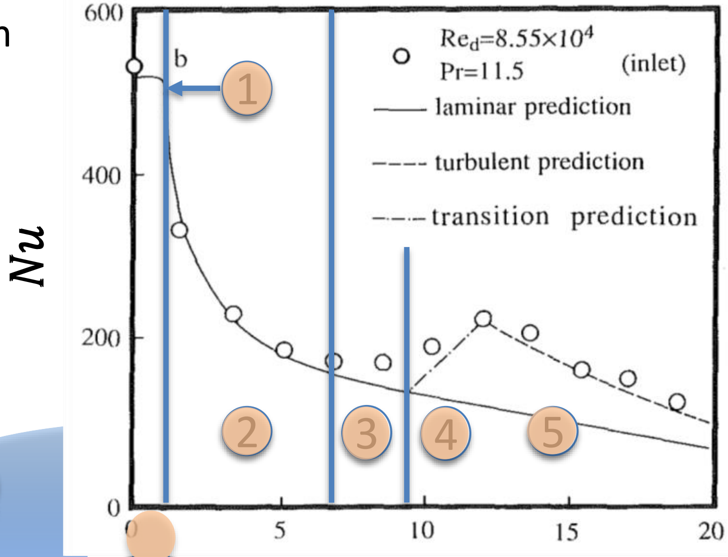
① Stagnation zone
- $\delta = constant$
- $\delta_T = constant$
- $h = constant$

② Boundary layer growth
- $\delta \uparrow$
- $\delta_T \uparrow$
- $h \downarrow$

③ Similarity region
- $\delta = e$

④ Transition to turbulence
- h may increase
- Better mixing

⑤ Developed turbulence
- $h \downarrow$



- $e \uparrow\uparrow$
- $h \uparrow$ then $\downarrow$
- Can occur in any zone

$$Nu = \frac{h\,D_j}{k_j}$$

Academic context: heat transfer - turbulent jets Stevens et al. (1991) + Lienhard et al. (2006)

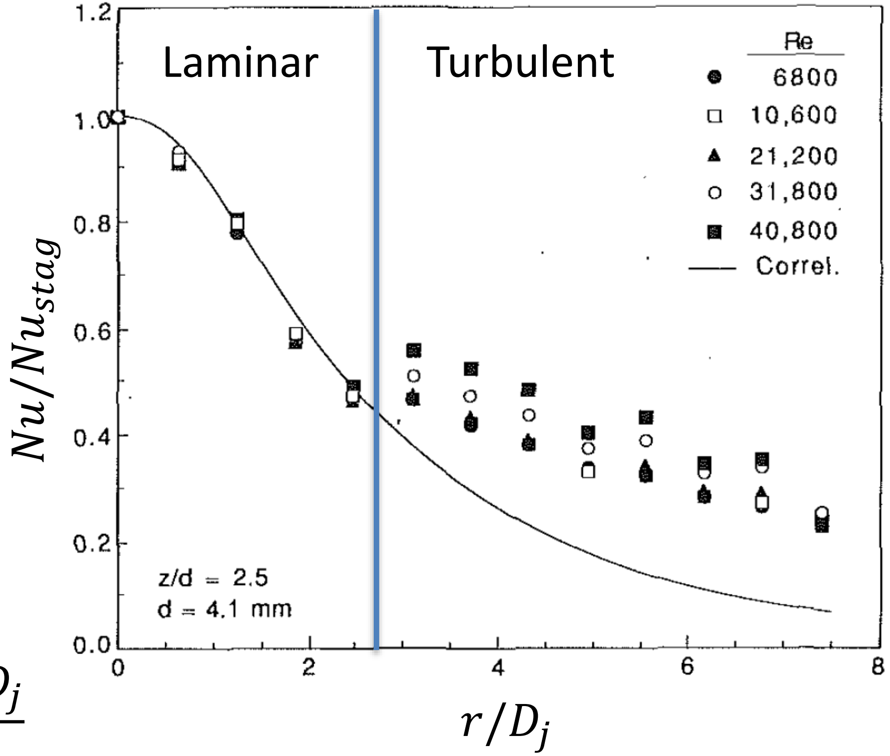
- SFR: Turbulent jets

- Flow laminarization at stagnation Tong (2003)

- Two regimes Stevens et al. (1991) + Lienhard (2006):
    - Laminar: Nu/Nu_{stag} independent of Re
    - Turbulent: Nu/Nu_{stag} depends on Re

- Transition:
    - Induced by jet surface oscillations
    - closer for turbulent jets
    - independent of Re
    - $h \uparrow$

$$Nu = \frac{h\,D_j}{k_j}$$



- **Dimensionless numbers**

Mechanical

Reynolds

Inertia vs. viscosity

$$Re = \frac{\rho_j D_j V_j}{\mu_j}$$

Froude

Inertia vs. gravity

$$Fr_j = \frac{V_j}{\sqrt{g D_j}}$$

Weber

Inertia vs. surface tension

$$We = \frac{\rho_j V_j^2 D_j}{\sigma_j}$$

Thermal

Nusselt

Convective vs. conductive transfer

$$Nu = \frac{h\ D_j}{k_j}$$

Melting number (Stefan)

Heat bring by jet vs. needed to melt

$$B = \frac{C_{p,j}\left(T_j - T_{s,f}\right)}{L + C_{p,s}\left(T_{s,f} - T_{s,0}\right)}$$

Stanton

Convective transfer vs. inlet heat flow

$$St = \frac{h}{\rho_j C_{p,j} V_j}$$

Prandtl

Compares mechanical / thermal BL growth

$$Pr = \frac{\mu_j C_{p,j}}{k_j}$$

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Experimental setup: HAnSoLO

Hot AblatioN of a SOlid by a Liquid - Observations

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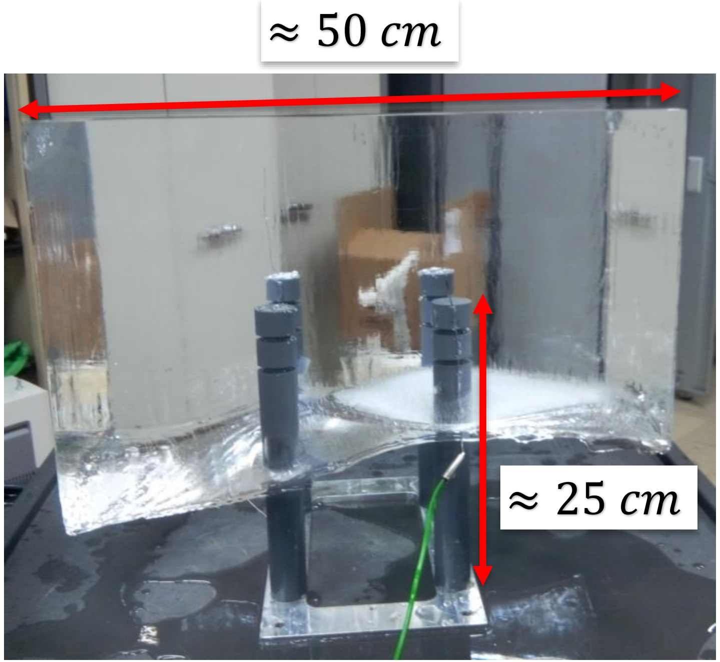
- **System studied: Water / Transparent ice**

- Pros:
  - Solid / Jet: same nature (no crust)
  - Safe
  - Cost effective
  - Real-time visualizations

Safe, Cost effective: Large number of experiments

- Cons:
  - Simulant not prototypical
  - No undercooling (cracks)



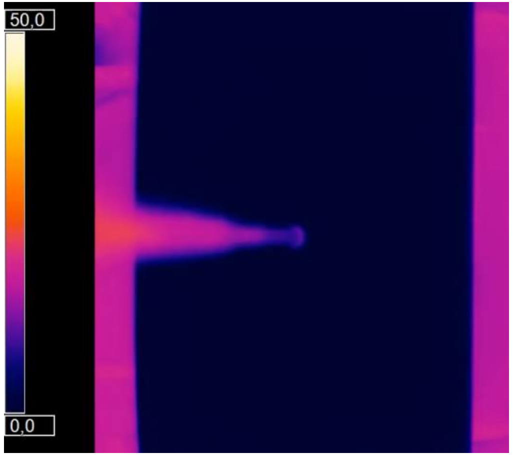
- **The experiment**

Test referenced:
612

$$T_j = 31\,°C$$
$$V_j = 2.8\, m/s$$
$$D_j = 5.8\, mm$$
$$Re = 21\,000$$
$$Pr = 5.30$$

Example of recordings

IR camera



Test referenced: 623

$T_j = 50\ °C$

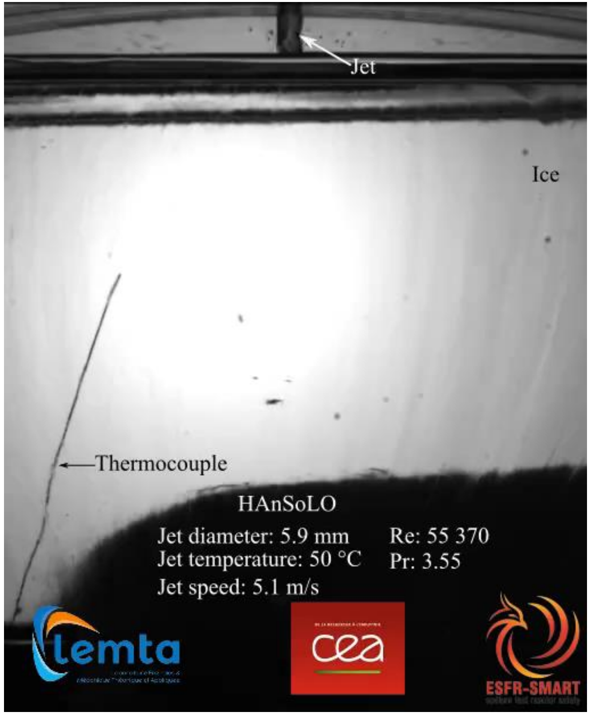
$V_j = 5.1\ m/s$

$D_j = 5.9\ mm$

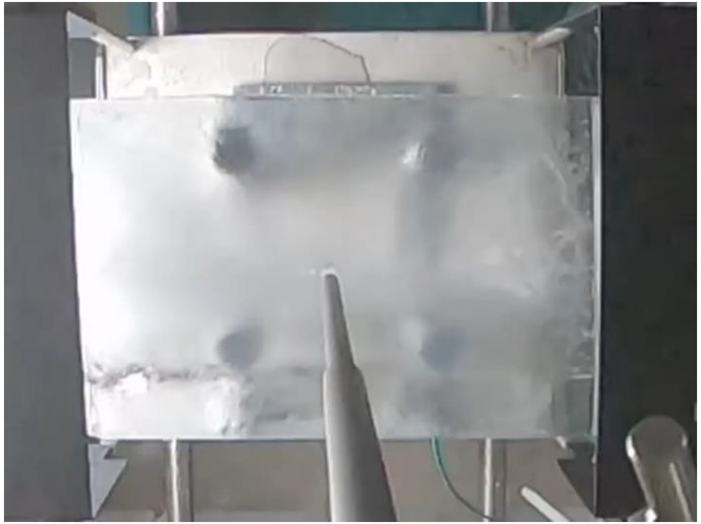
$Re = 55\ 000$

$Pr = 3.55$

High speed camera



Standard camera



POOL REGIME

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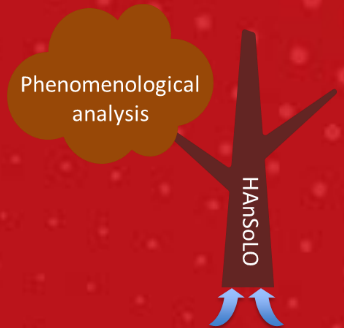
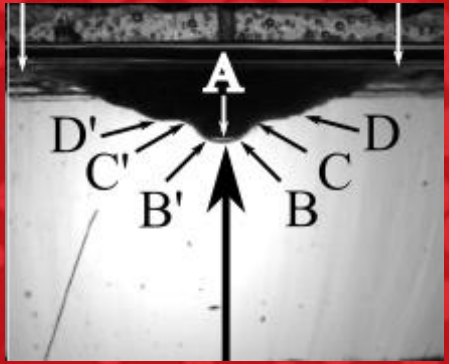

Phenomenological analysis

HAnSoLO

Context / introduction



Phenomenological analysis

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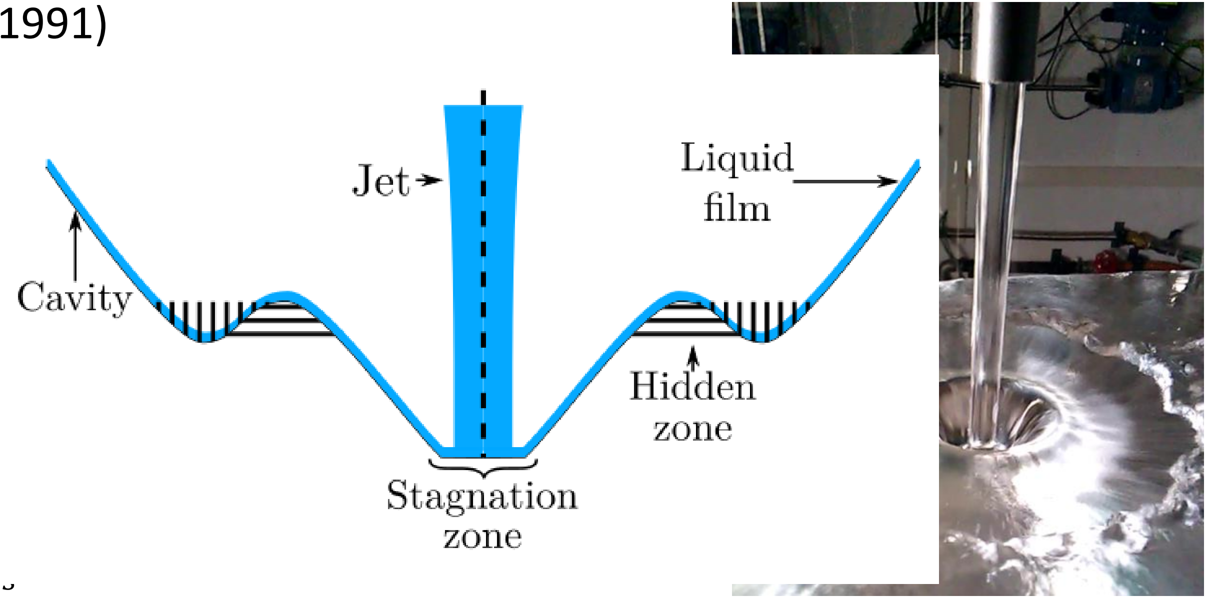
- **Cavity actual shape**

Sato et al. (1991)
steel/ste
316L

$D_j = 18.8\ mm$
$T_j = 1703\ °C$
$V_j = 3.1\ m/s$

R
P
T

HAnSoLO
Water / Ice



$D_j = 8.1\ mm$
$T_j = 30\ °C$
$V_j = 1.6\ m/s$

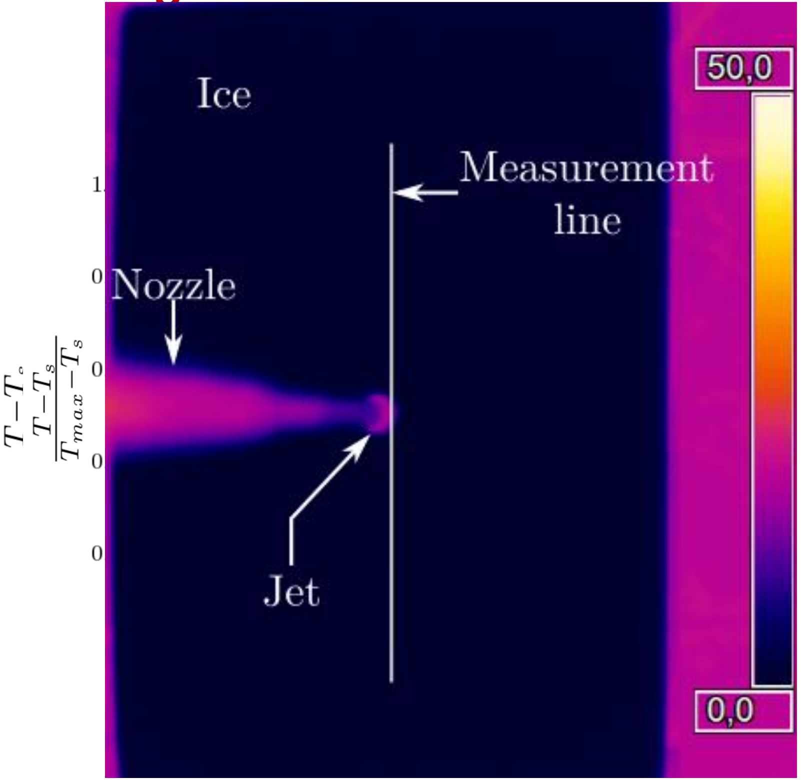
$Re = 19\ 000$
$Pr = 5.38$
$T_s = 0\ °C$

- Shape not due to considered system

Film surface temperature: film regime

- Temperature along segment crossing jet
- T independent of time
- $T \downarrow$ at fixed r/D_j
  - For $V_j > 2.5\ m.s^{-1}$
- Independent of Re
  - Due to turbulence

    Cf. Stevens et al. (1991)



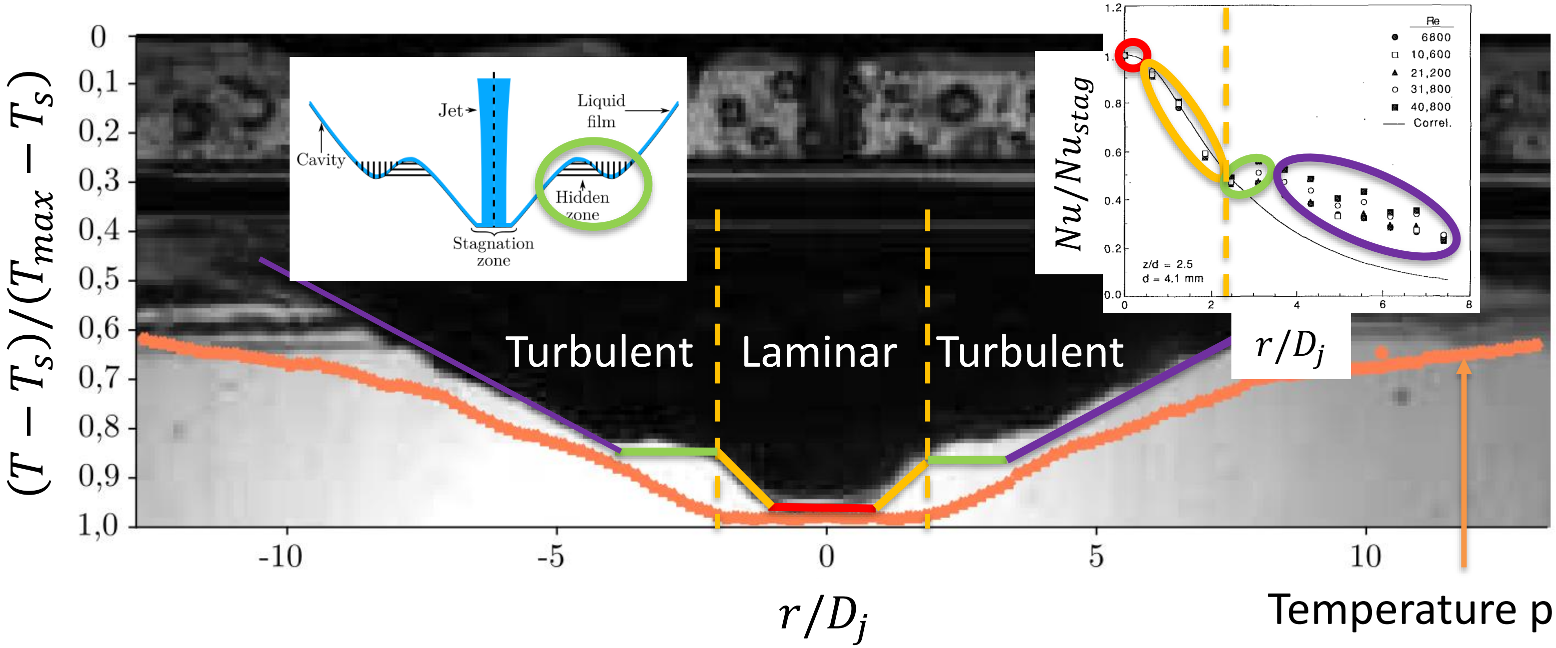
623
$T_j = 50\ °C$
$V_j = 5.1\ m/s$
$Re = 55\ 000$
$Pr = 3.55$

615
$T_j = 30\ °C$
$V_j = 5.1\ m/s$
$Re = 77\ 000$
$Pr = 5.35$

634
$T_j = 71\ °C$
$V_j = 7.6\ m/s$
$Re = 112\ 000$
$Pr = 2.52$

• Comparison: surface temperature / cavity shape

Stevens et al. (1991)



623
$T_j = 50\ °C$
$V_j = 5.1\ m/s$
$D_j = 6\ mm$
$Re = 55\ 000$
$Pr = 3.55$

Temperature profile

Shoulder in cavity shape = decrease of surface temperature
Liquid film becomes turbulent

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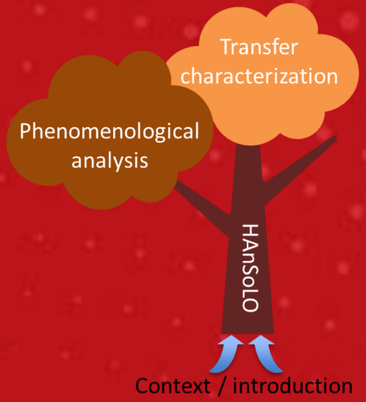
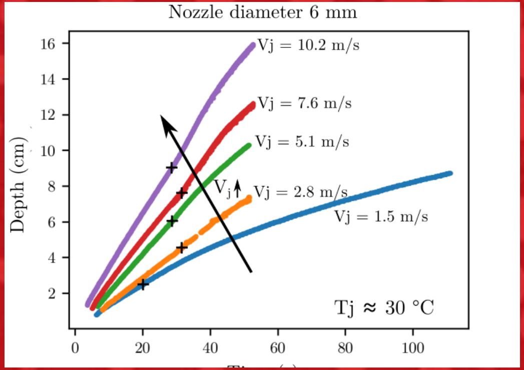


Transfer characterization

Phenomenological analysis

HAnSoLO

Context / introduction



Transfers characterization

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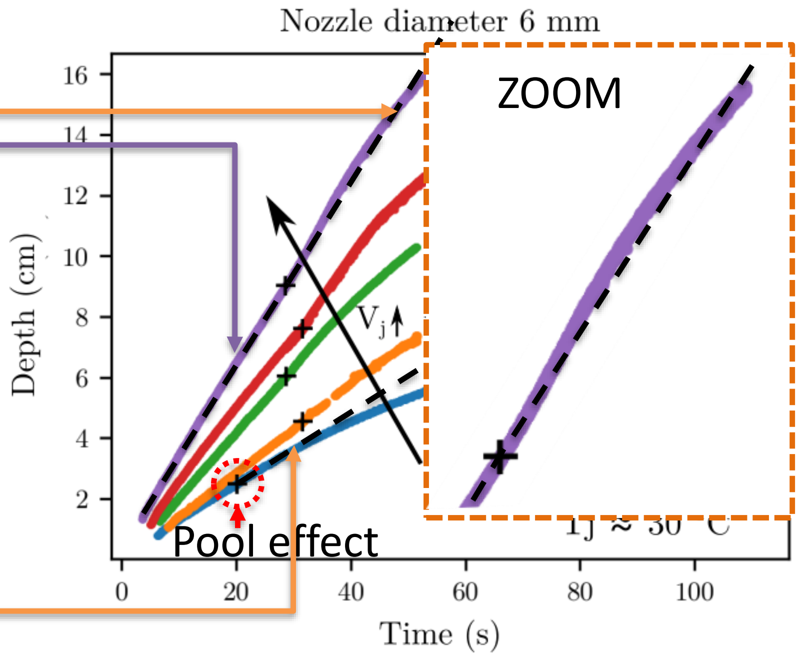
Raw results example

- Film regime
  - Constant ablation velocity
  - $V_f \uparrow$ with T_j & V_j
  - $V_f \uparrow$ when $D_j \downarrow$
  - h & Nu from jump condition + Newton's law + constant V_f

$$h = \frac{V_f \rho_s \left[L + C_{p,s}\left(T_{s,f} - T_{s,0}\right)\right]}{\left(T_j - T_{s,f}\right)} \Longleftrightarrow \frac{\rho_s V_f}{\rho_j V_j} = StB$$

$$Nu_f = K\, Re^n Pr^m$$

- Behavior change in pool effect
  - Not linear
  - Potential $V_f \uparrow$



$$Nu_f = \frac{h\, D_j}{k_j} \qquad Re = \frac{\rho_j V_j D_j}{\mu_j} \qquad Pr = \frac{\mu_j C_{p,j}}{k_j}$$

$$B = \frac{C_{p,j}\left(T_j - T_{s,f}\right)}{L + C_{p,s}\left(T_{s,f} - T_{s,0}\right)} \qquad St = \frac{h}{\rho_j C_{p,j} V_j}$$

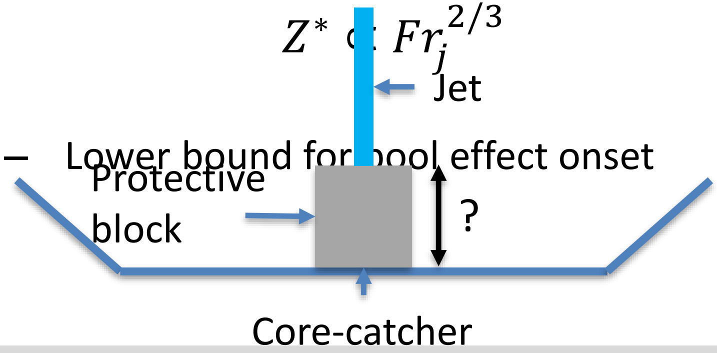
Transition to pool effect

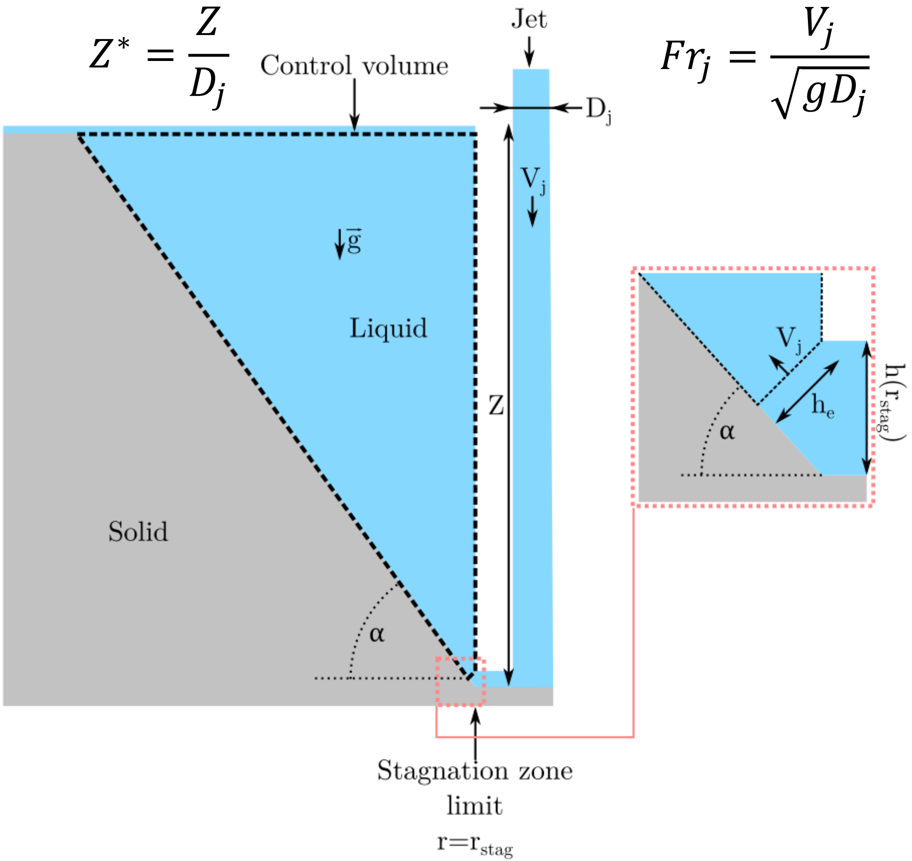
- 1st measurements
- Data well represented with Z^* & Fr_j
- Saito's et al. (1990) criterion does not work ($Z^* > 4$)

- Our model:
  - Momentum balance on truncated cone

$$Z^* \propto Fr_j^{2/3}$$

  - Lower bound for pool effect onset





$$Z^* = \frac{Z}{D_j}$$

$$Fr_j = \frac{V_j}{\sqrt{gD_j}}$$

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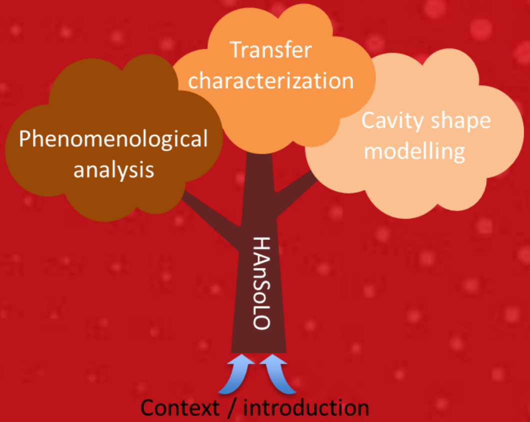

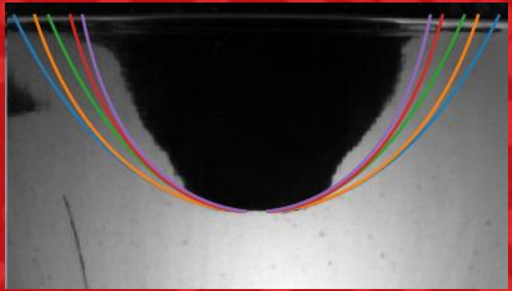

Cavity shape modelling

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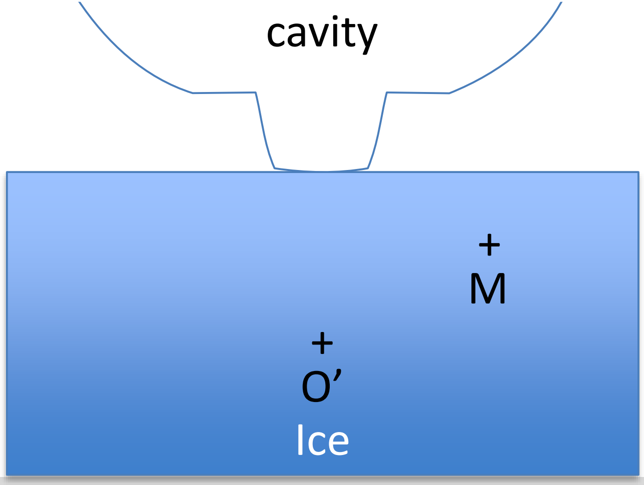
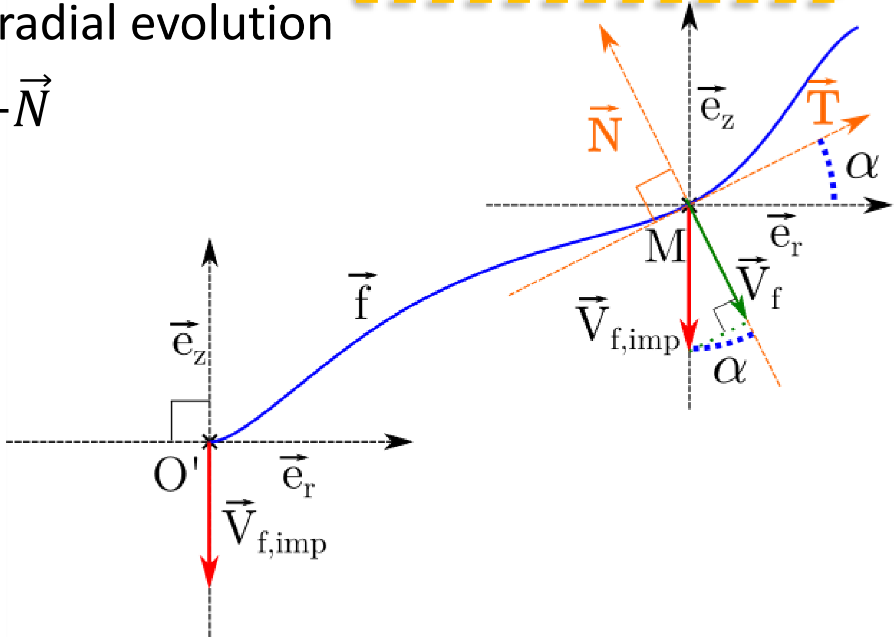
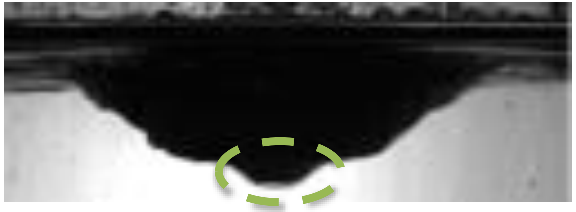
- **Link between cavity local angle (α) & local ablation velocity (V_f) – FILM REGIME**
  - Cavity maintains its shape : it unfolds
  - Interface points move at constant velocity
  - Cavity shape from melting velocity radial evolution
  - Points displaced by melting along $-\vec{N}$

$$\alpha = \arccos\left(\frac{V_f}{V_{f,imp}}\right)$$





Modelling: Boundary layer growth



- Constant film temperature
  - IR measurements
  - Only h evolve with r

$$V_f = \frac{h\left(T_{film} - T_{s,f}\right)}{\rho_s\left[L + C_{p,s}\left(T_{s,f} - T_{s,0}\right)\right]}$$

- Evolution from scaling law without melting Lienhard (2006):
  - z evolution from α

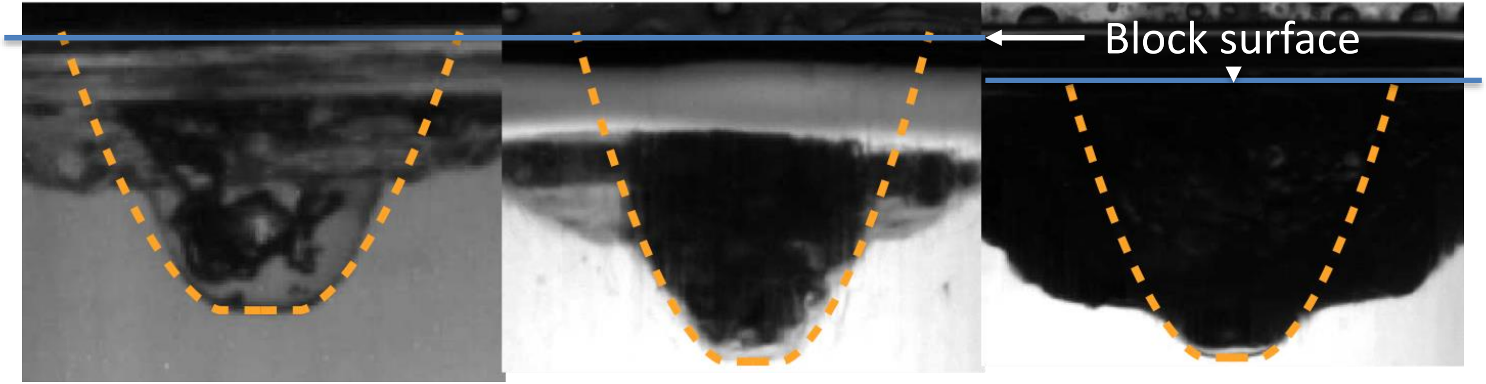
$$Nu_{stag} = 0.745\, Re^{1/2} Pr^{1/3} \qquad Nu = 0.632\, Re^{1/2} Pr^{1/3} \sqrt{\frac{D_j}{r}}$$

$$\underbrace{\frac{V_f}{V_{f,imp}} = \frac{h}{h_{stag}} = \frac{Nu}{Nu_{stag}} \qquad \& \qquad z = \int_0^r \sqrt{\left(\frac{V_f}{V_{f,imp}}\right)^2 - 1}\, d\mathcal{L}}_{\text{Cavity shape prevision}}$$

Modelling: Boundary layer growth (comparisons)

- At pool effect transition: $T_j = 50\,°C, D_N = 6.0\,mm$

$V_j = 1.2\,m/s$	$V_j = 2.3\,m/s$	$V_j = 5.1\,m/s$
$Re = 13\,000$	$Re = 24\,000$	$Re = 55\,000$
$Pr = 3.70$	$Pr = 3.55$	$Pr = 3.55$



▬ ▬ Calculated shape

• Modelling: constant h - T_{film} ↓ modelling

Hypotheses

- T uniform along e
- Newton law at interface $\varphi = h(T - T_{s,f})$
- Steady state
- Perfect fluid
- No transfers in stagnation zone

Balances

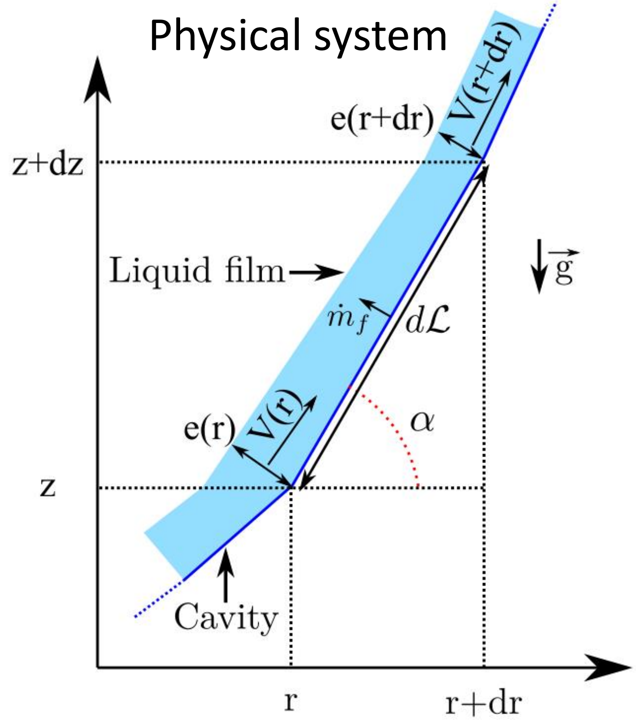
- Mass
- Heat
- Momentum

ODE system

3 Dimensionless numbers

$$B = \frac{C_{p,j}(T_j - T_{s,f})}{L + C_{p,s}(T_{s,f} - T_{s,0})} \qquad St = \frac{h}{\rho_j C_{p,j} V_j} \qquad Fr_j = \frac{V_j}{\sqrt{g D_j}}$$

Physical system



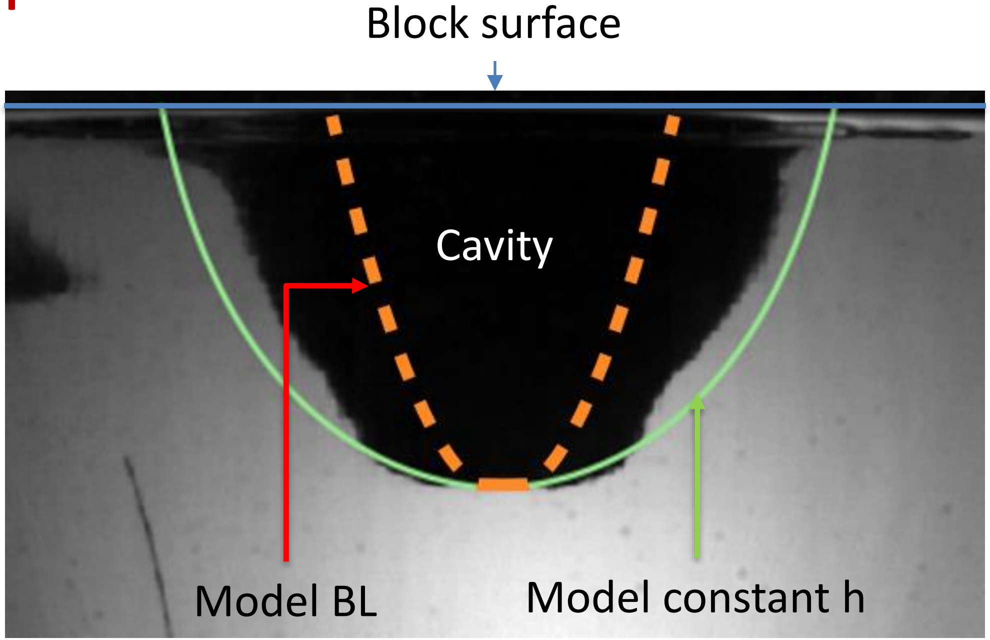
• Modelling: constant h - Comparison

- Model describes well global cavity shape with no laminar part

- Interesting estimates of cavity width

$$\begin{cases} \dfrac{d}{dr^*}(r^*e^*V^*) = \dfrac{StB\theta}{\cos(\alpha)} \\ \dfrac{1}{r^*}\dfrac{d}{dr^*}(r^*e^*V^*\theta) = -\dfrac{St\theta}{\cos(\alpha)} \\ \dfrac{1}{r^*}\dfrac{d}{dr^*}(r^*e^*V^{*2})\sin(\alpha) = -\dfrac{e^*}{Fr_j^2}\dfrac{1}{\cos(\alpha)} \\ \dfrac{dz^*}{dr^*} = \sqrt{\left(\dfrac{\theta}{\theta_0}\right)^2 - 1} \end{cases}$$

$$\alpha = \arccos\left(\frac{\theta}{\theta_0}\right)$$



$T_j = 71\,°C$
$V_j = 10.1\; m/s$

$Re = 147\;000$
$Pr = 2.54$

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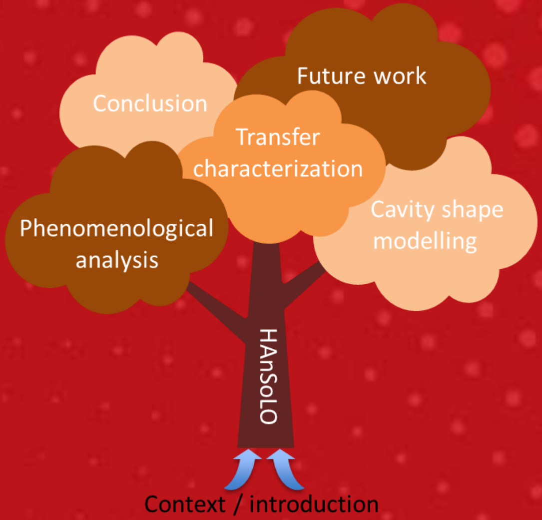

Future work

Conclusion

Transfer characterization

Cavity shape modelling

Phenomenological analysis

HAnSoLO

Context / introduction

Conclusion and Current Work (Antoine Avrit)

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