Interaction between a dispersed flow of droplets and a heated wall beyond the Leidenfrost temperature

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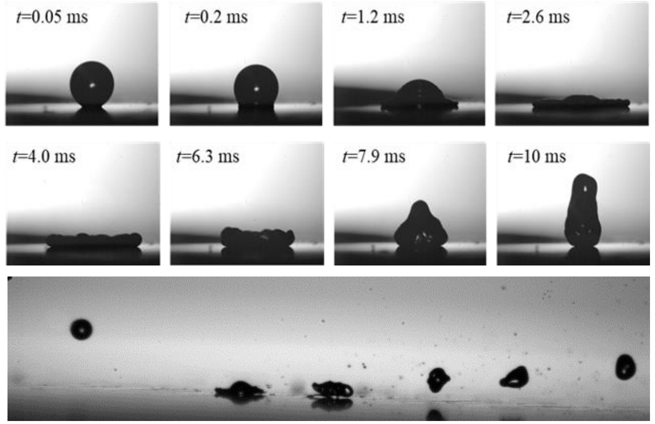
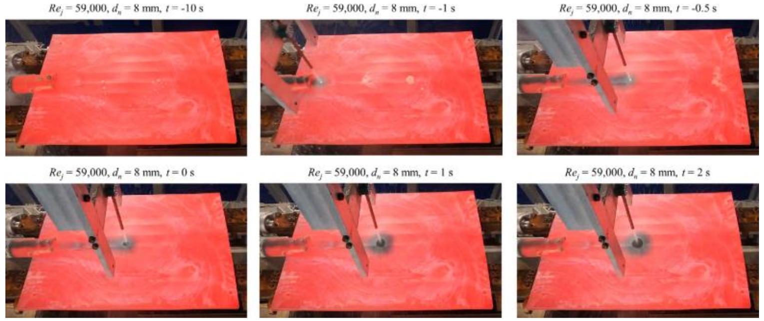
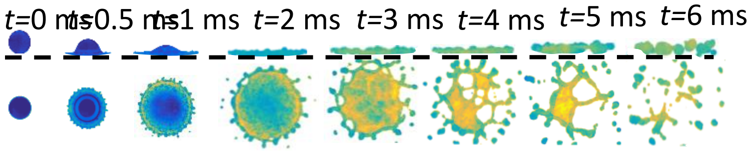
A few word about the research in the team

Heat and mass transfer phenomena

- Boiling, DFFB, Droplet, Atomization
- Phase change phenomena

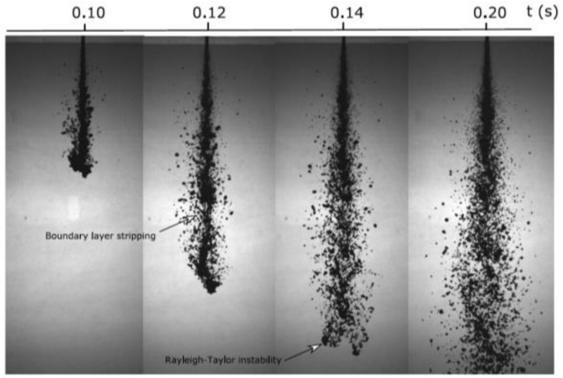


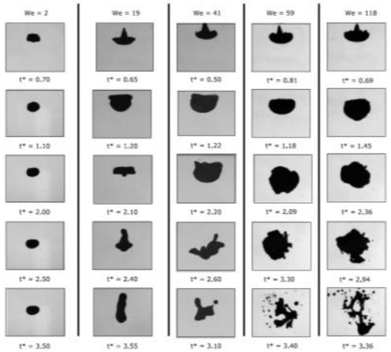




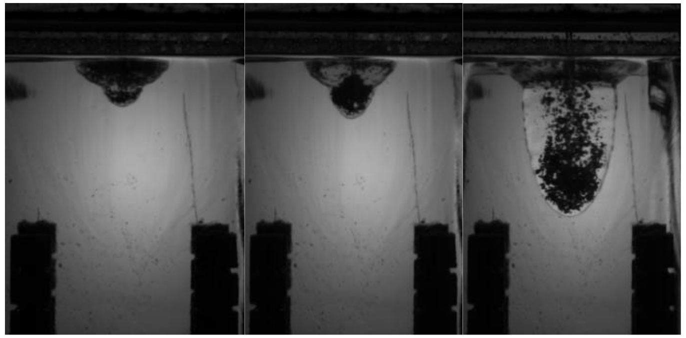
cooling

Icing





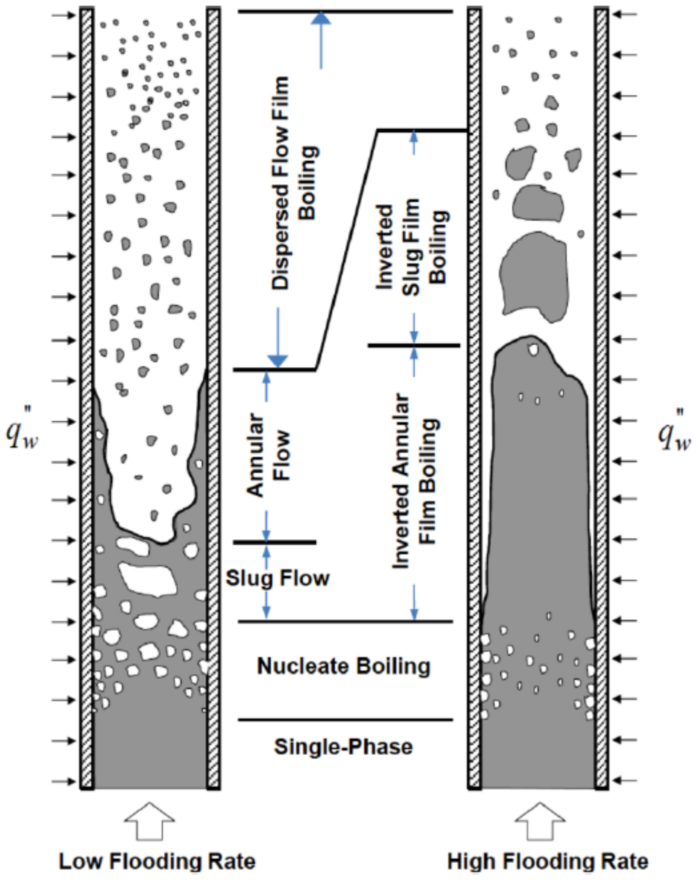
liquid-liquid atomization



ablation

Content

Introduction: Dispersed Film Flow Boiling



DFFB is the last stage of boiling process to obtain vapour flow:

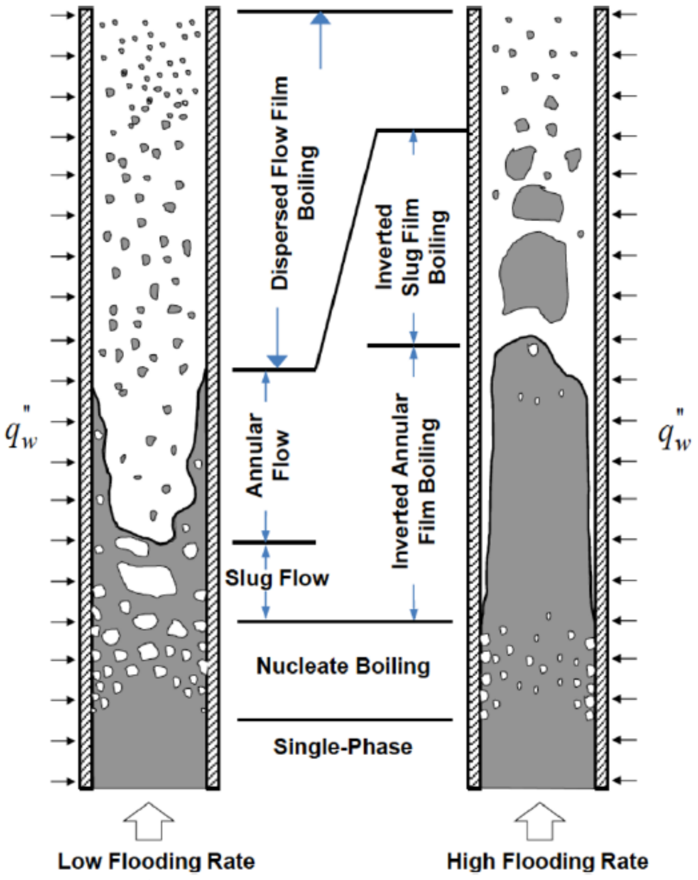
- Complex two-phase phenomena
- Non equilibrium effects (the heat goes more to the vapour)
- Only ~30 papers dealing with DFFB from 1968 to now!
- ~15 before 3/2011 and ~15 after (fukushima accident)

Motivations?

- Need some models (or correlations) to estimate the heat transfer
- **Predict the maximum temperature of the heat exchanger or fuel rod**
- **Predict the cooling in case of LOCA**
- Correlations are often satisfactorily
- But most of them don't account for complexity of dispersed flow (influence of droplets, distribution of the droplet)

Most of the correlations only account for wall-vapor convection
Some kinds of Dittus-Bolter with modified coefficient to try **to account for droplets**

Introduction: Dispersed Film Flow Boiling



In case of LOCA

key parameters in dispersed flow:

- Carrier fluid: mass flow rate, velocity, pressure, temperature, density
- Droplets : mass flow rate, size and velocity, temperature and also numbers
- Equilibrium or non equilibrium (≠ T, ≠ u)

Knowing that: mean parameters of the flow can be estimated

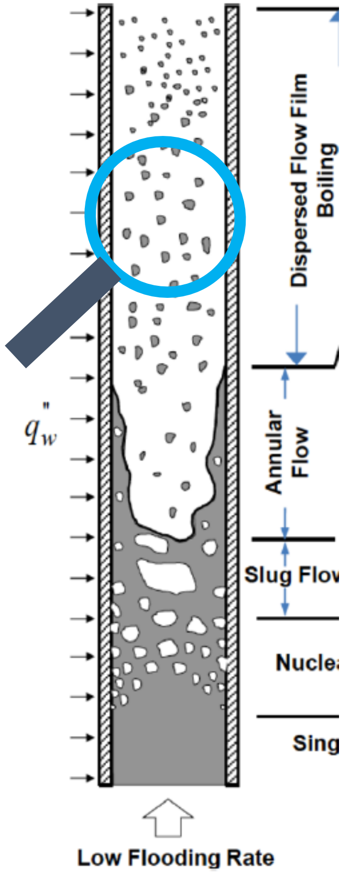
- Superficial velocities
- Dimensionless numbers: Re, Pr (to estimate HTC)

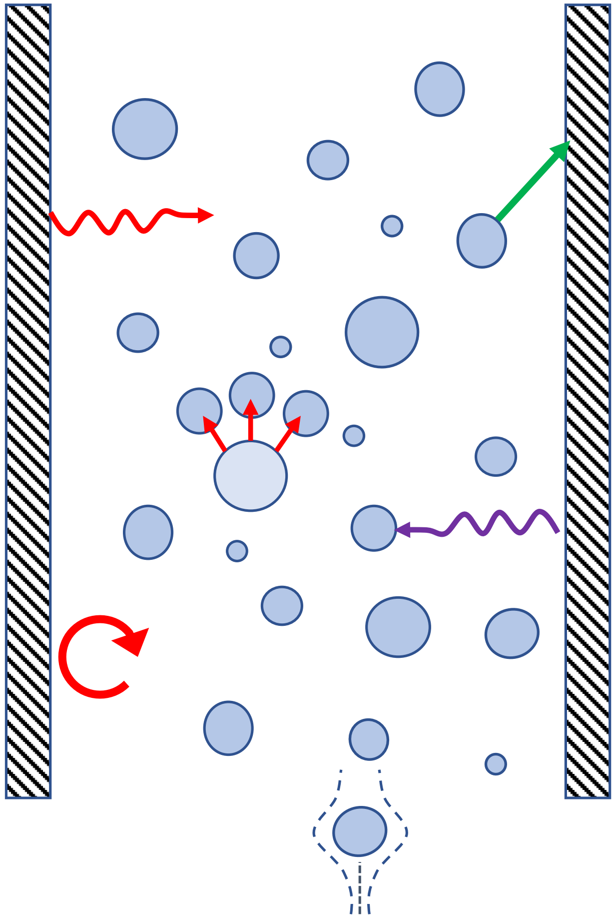
$$h_{tp,DB,g,a} = 0.023 Re_{g,a}^{0.8} Pr_{g,a}^{0.4} \frac{k_{g,a}}{D}$$

Correlation obtained from data of LN2 vertical upflow From R. P. Forslund, W. M. Rohsenow (1968)

From the review of V. Ganesan & Mudawar et al., International J. of heat and mass transfer, 2022

Introduction: Dispersed Film Flow Boiling





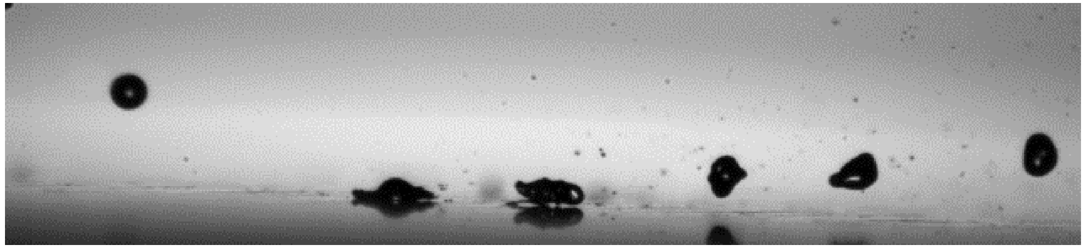
Simplified models of the flow to estimate Heat and mass transfer

- Wall/steam convection
- Wall/steam radiation
- Wall/droplet radiation
- Wall/droplet direct contact
- steam/droplet transfers
- Radial droplet distribution
- axial droplet distribution
- Coalescence or fragmentation

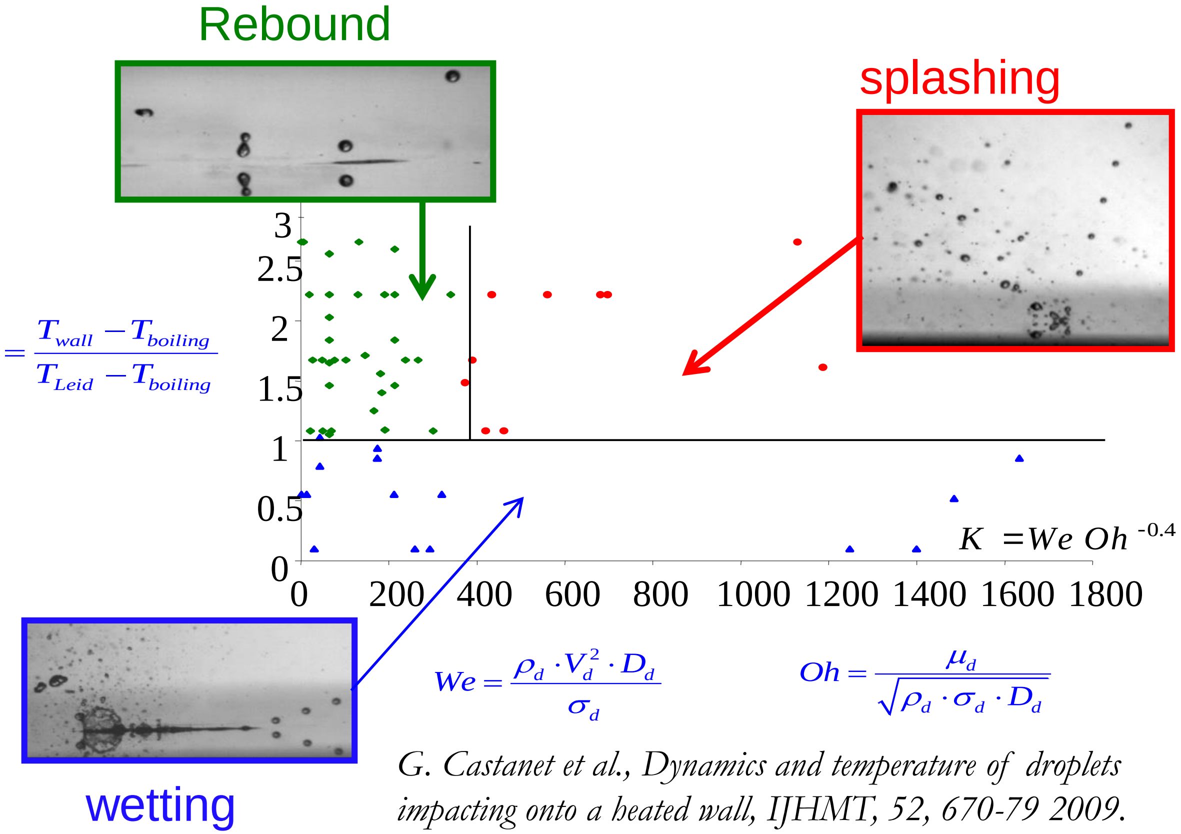
→ Build some « mechanistic » model to evaluate heat transfer at the wall

Droplet direct contact

Droplet direct contact



- → dynamics of the droplet : velocity, angle of impact
- → Properties of droplet: μ_L, σ, Cp_L, ρ_L, T_{sat}
- → Properties of its vapour: μ_V, Cp_V, ρ_V
- → heat transfer at the wall?



$$T^* = \frac{T_{wall} - T_{boiling}}{T_{Leid} - T_{boiling}}$$

$$We = \frac{\rho_d \cdot V_d^2 \cdot D_d}{\sigma_d} \qquad Oh = \frac{\mu_d}{\sqrt{\rho_d \cdot \sigma_d \cdot D_d}}$$

G. Castanet et al., Dynamics and temperature of droplets impacting onto a heated wall, IJHMT, 52, 670-79 2009.

Weber number

$$\boxed{We = \frac{\rho V^2 D_d}{\sigma}}$$

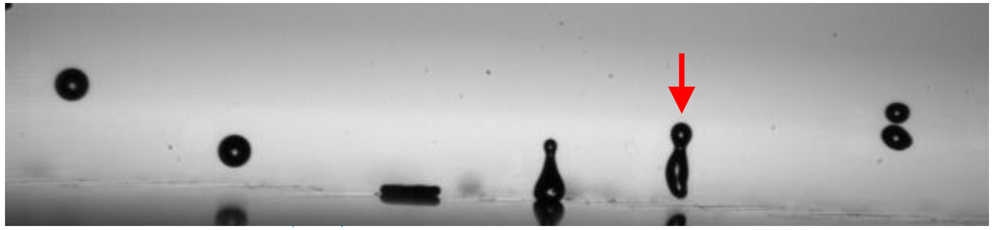
Ohnesorge number

$$\boxed{Oh = \frac{\mu}{\sqrt{\rho \sigma L}} = \frac{\sqrt{We}}{\mathrm{Re}}}$$

Temperature

$$\boxed{T^* = \frac{T_w - T_{eb}}{T_{Leid} - T_{eb}}}$$

Droplet direct contact



$T_{wall} > T_{Leidenfrost}$

- → resident time
- → spreading diameter
- → Temperature of the droplet
- → Temperature of the wall

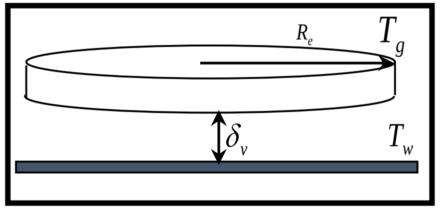
Energy due to direct contact

$$E_{DC} = \int_0^{t_R} \frac{\lambda_V \pi D_S^2 (T_W - T_{SAT})}{4 \times \delta_V(t)} dt$$

Resident time

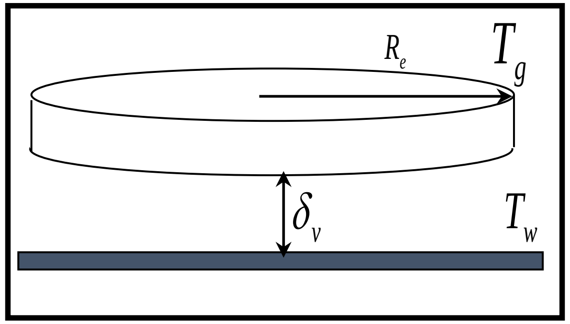
Spreading diameter

Vapour layer thickness



This model consider only conduction through the vapour cushion

Droplet direct contact



Model of Guo et al. (2002):

- Hypothesis: vapour thickness is constant, radiation is negligible
- The resident time is the Rayleigh time $t_R = \frac{\pi}{4}\sqrt{\frac{\rho_L D_d^3}{\sigma}}$
- spreading diameter is $D_S = 6.97 D_d \left(\frac{t}{t_R} - \left(\frac{t}{t_R}\right)^2\right)$
- Considering a vapour mass flow given by $G_V = \frac{k_V(T_W - T_{SAT})}{\delta_V h^*}$ $h^* = h_{LV} + C_{pV}(T_V - T_{SAT})$
- Then, they solved the laminar NS equation beneath the droplet to get δ_V $\delta_V(t) = \left(\frac{9\mu_V k_V(T_V - T_{sat})t_R d_o}{32 h^* \rho_L \rho_V u_{d,n}}\right)^{\frac{1}{4}}\left(\frac{d_S(t)}{D_d}\right)$

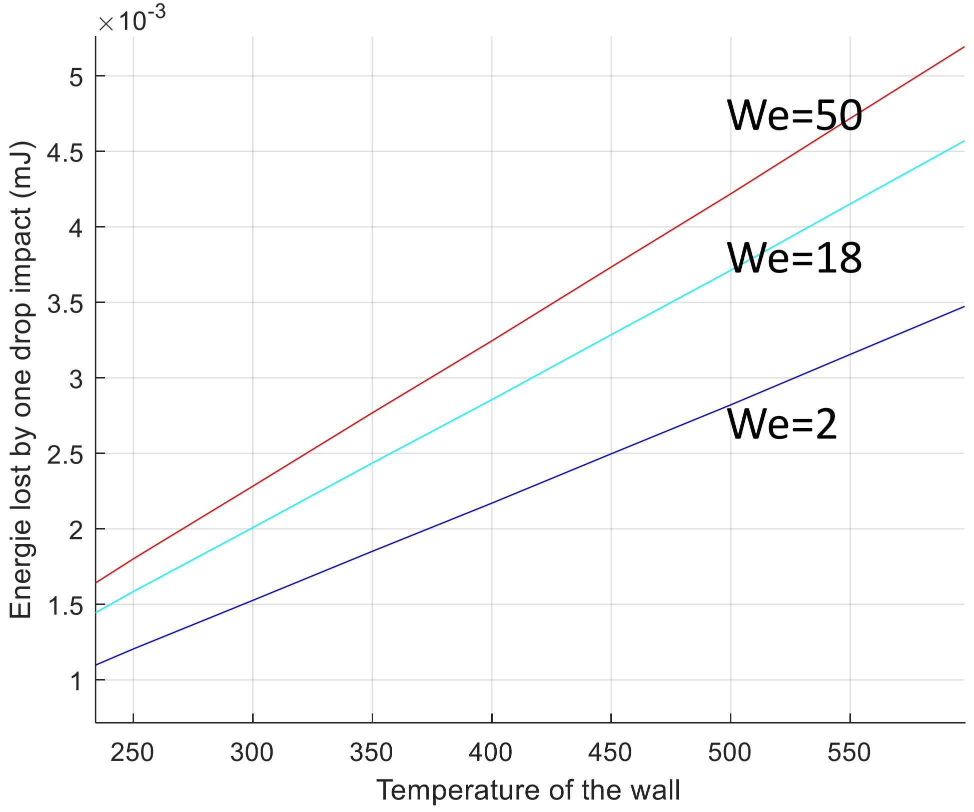
$$\boxed{E_{DC} = \frac{\pi k_V(T_p - T_{sat})t_R D_d^2}{4}\left(\frac{32\rho_L\rho_V h^* u_{d,n}}{9\mu_V k_V(T_W - T_{SAT})t_R D_d}\right)^{\frac{1}{4}}}$$

Guo Y., Mishima K., Experimental Thermal and Fluid science, Vol 26, pp 861-869, 2002.

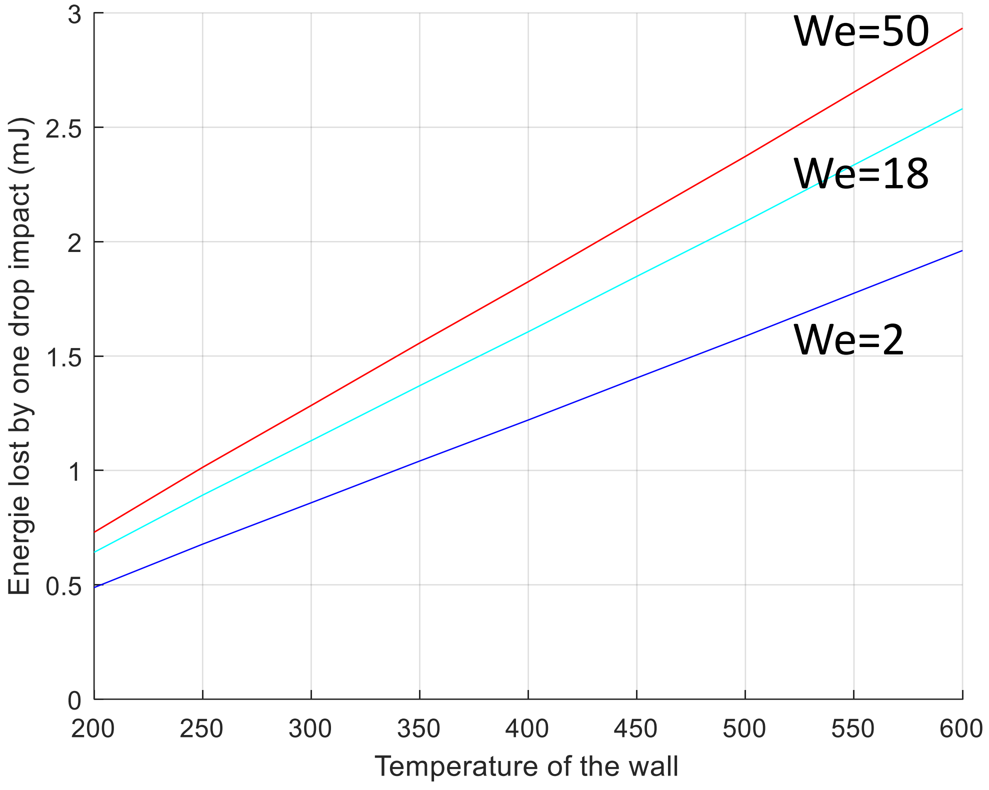
Droplet direct contact

Output of the model of Guo et al. (2002):

D_{10}=100µm



D_{10}=1mm

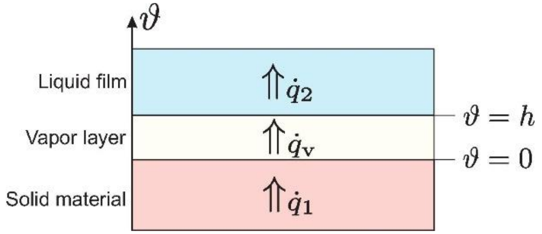


These energy are very small→ the temperature drop is small

Guo Y., Mishima K., Experimental Thermal and Fluid science, Vol 26, pp 861-869, 2002.

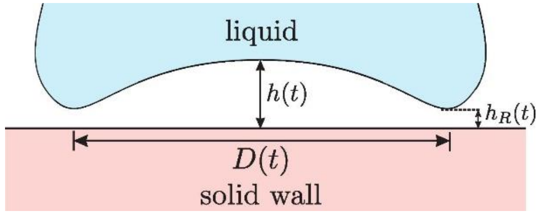
Droplet direct contact

Model of Breitenbach et al. (2017)



- Hypothesis: vapour thickness is not constant, radiation is negligible

But they consider that only the first stage of drop impact is important for Heat transfer



- The heat flux is thus modeled by $\dot{q}_V = \dfrac{k_V\left(T_{C,W} - T_{SAT}\right)}{\delta_V(t)}$

- Where Tc is $T_C = \dfrac{\sqrt{\pi}k_V\sqrt{t}T_{SAT} + e_W\delta_V(t)T_0}{\sqrt{\pi}k_V\sqrt{t} + e_W\delta_V(t)}$

- As $\dot{q}_1$ is $\frac{e_W(T_0-T_C)}{\sqrt{\pi}\sqrt{t}}$, a heat balance yields

$$\frac{e_W k_V (T_0 - T_{SAT})}{\sqrt{\pi}k_V\sqrt{t} + e_W\delta_V(t)} - \frac{\sqrt{5}e_f(T_{SAT} - T_{D0})}{\sqrt{\pi}\sqrt{t}} = \rho_f h_{fV}\frac{d\delta_V}{dt}$$

- Solving this ODE yields $\delta_V(t) = K\dfrac{e_W\,(T_0 - T_{SAT})}{\rho_f}\sqrt{t}$

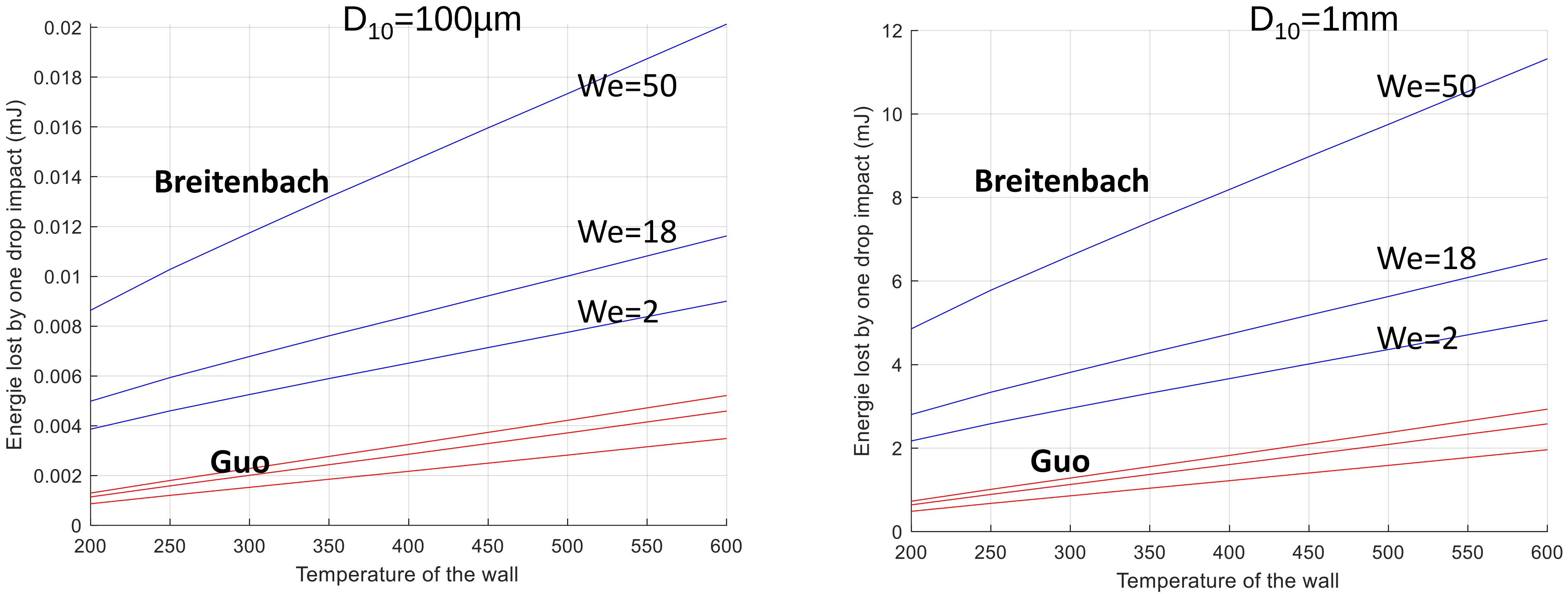
$$\boxed{E_{DC} = \int_0^{ti} \pi\dot{q}_1(t)R(t)^2 dt = \frac{4{,}63D_0^{2{,}5}Ge_W(T_0 - T_{SAT})}{U_0^{0{,}5}(K + 2G)}}$$

$$K = \sqrt{(B-G)^2 + \frac{4G}{\sqrt{\pi}}} - B - G\,;\; G = \frac{\sqrt{\pi}k_V\rho_f h_{fV}}{2(T_0 - T_{SAT})\,e_W^2}\,;\; B = \frac{\sqrt{5}(T_{SAT} - T_{D0})e_f}{\sqrt{\pi}(T_0 - T_{SAT})\,e_W}$$

Breitenbach et al, International Journal of Heat and Mass Transfer 110 (2017) 34–42

Droplet direct contact

Output of the model of Breitenbach et al. (2017)



These estimation have been performed considering a Ni wall

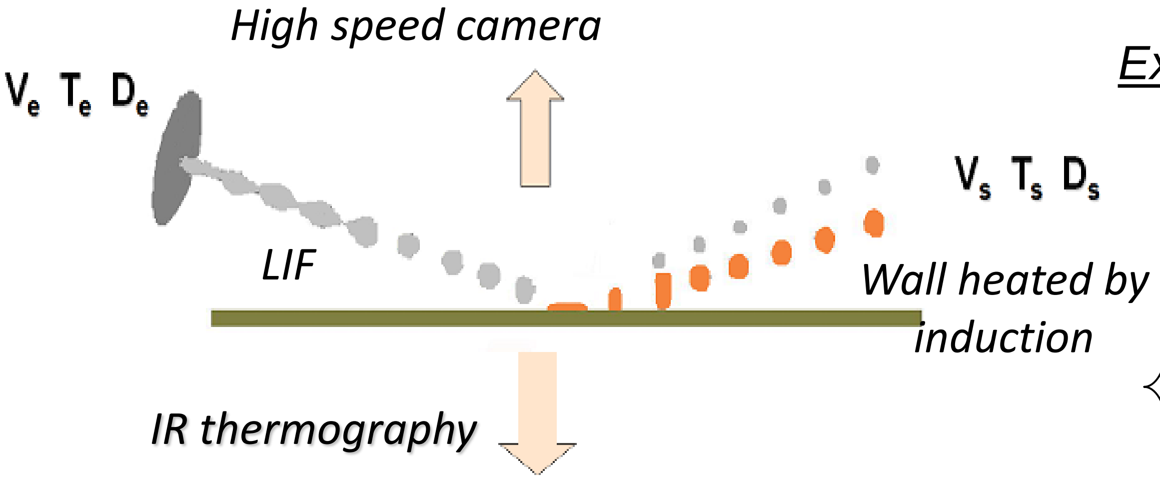
Breitenbach model takes into account instationnary heat transfer

Droplet direct contact

My experimental bench:

Optical diagnostics

- IR thermography
- LIF
- High speed camera

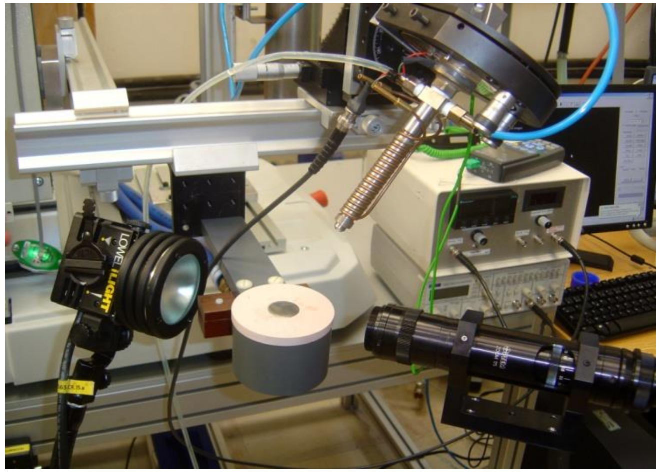


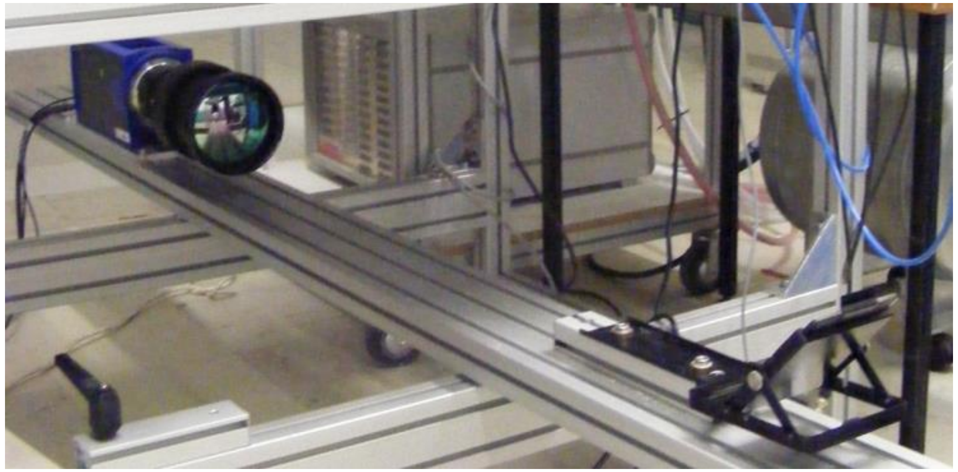
__Experimental condition :__

droplet
→ Diameter : 80 - 300µm.
→ velocity : 2 m/s - 10m/s,

Ambiant atmosphere
→ 1bar

Wall
→ Nickel, T~600-800°C,
→ Diameter ~25 mm, e = 500 µm,
→ variable incident angle

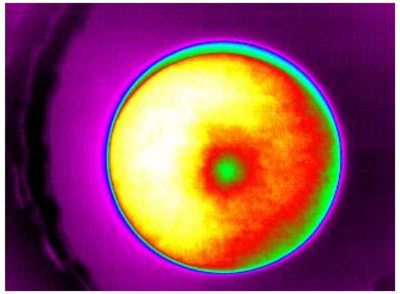


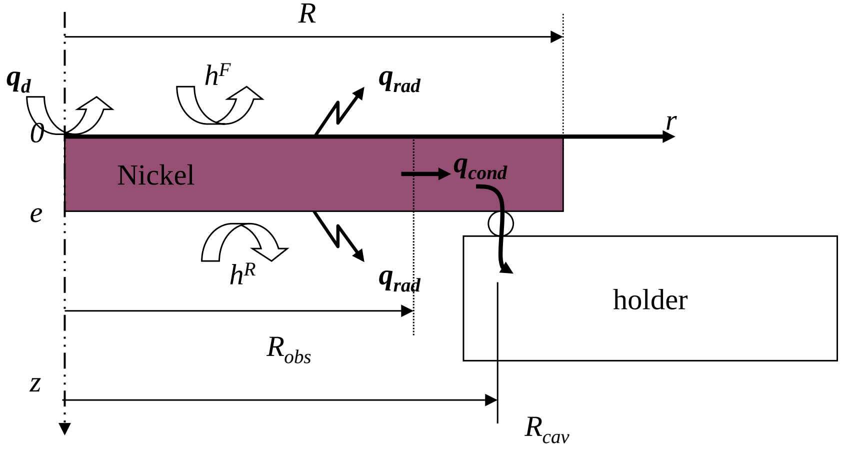


Droplet direct contact

My experimental bench: Optical diagnostics (IR thermography, LIF, High speed camera)

IR thermography





heat equation

$$\frac{\partial^2 T'}{\partial z^2}+\frac{\partial^2 T'}{\partial r^2}+\frac{1}{r}\frac{\partial T'}{\partial r}+\frac{1}{r^2}\frac{\partial^2 T'}{\partial \alpha^2}=\frac{1}{a}\frac{\partial T'}{\partial t}$$

Simplification of the heat equation

$$T(r,z,t)=\frac{1}{2\pi}\int_0^{2\pi} T'(r,\alpha,z,t)\,d\alpha$$

$$q_\beta(r,z,t)=\frac{1}{2\pi}\int_0^{2\pi} q'_\beta(r,\alpha,z,t)\,d\alpha \quad \text{avec} \quad \beta=R,F$$

$$\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}+\frac{\partial^2 T}{\partial z^2}=\frac{1}{a}\frac{\partial T}{\partial t}$$

What we want to estimate

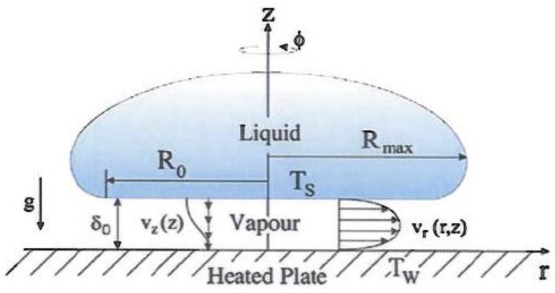
$$-\lambda\left.\frac{\partial T}{\partial z}\right|_{z=0}=h_F\ (T_F)\,(T_F-T_\infty)+\varepsilon_F\sigma(T_F{}^4-T_\infty^4)+\boxed{q_d(r,t)}$$

$$-\lambda\left.\frac{\partial T}{\partial z}\right|_{z=e}=h_R\ (T)\,(T-T_\infty)+\varepsilon_R\sigma(T^4-T_\infty^4)+K_{cond}\,\delta(r=R_{cav})(T-T_{ho})$$

$$-\lambda\left.\frac{\partial T}{\partial r}\right|_{r=R}=0 \qquad T=T_{init}(r,t) \qquad at\quad t=0$$

Droplet direct contact

To solve the previous set of equation: we use two integral transforms



$$\bar{g}(r,z,p)=\int_0^{\infty} g(r,z,t)e^{-pt}dt \quad and \quad \tilde{\bar{g}}_n(z,p)=\int_0^{R} \bar{g}(r,z,p)rJ_0(\alpha_n r)dr$$

Laplace Hankel

After some mathemathics….

$$\tilde{\bar{\theta}}_n^R-\tilde{\bar{Z}}_n^B(p+a\alpha_n^2)\frac{\tilde{\theta}_{\infty,n}}{p}-\tilde{\bar{Z}}_n^C(p+a\alpha_n^2)\left[\frac{\tilde{\theta}_{ho,n}}{p}-\bar{\theta}(r=R_{cav})\right]=-\tilde{\bar{Z}}_n^A(p+a\alpha_n^2)\tilde{\bar{q}}_{d,n}$$

$$\tilde{\theta}_n^R(t)-\left[\int_0^t e^{-a\alpha_n^2t'}\tilde{Z}_n^B(t')dt'\right]\tilde{\theta}_{\infty,n}-\left[\int_0^t e^{-a\alpha_n^2t'}\tilde{Z}_n^C(t')dt'\right]\tilde{\theta}_{ho,n}+\left[e^{-a\alpha_n^2t}\tilde{Z}_n^A(t)\right]*\theta(r=R_{cav},t)=-\left[e^{-a\alpha_n^2t}\tilde{Z}_n^A(t)\right]*\tilde{q}_{d,n}(t)$$

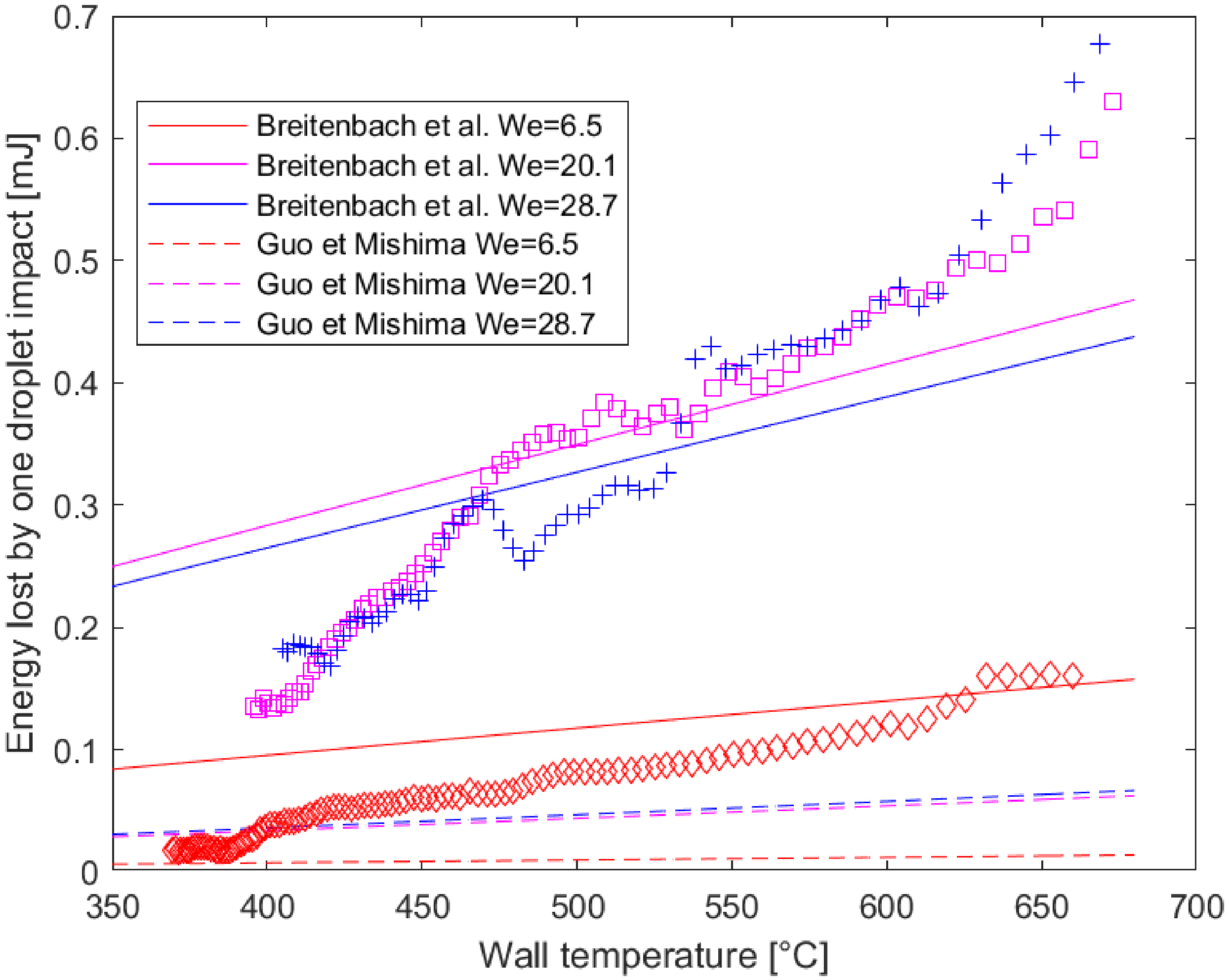
At the end….

$$\tilde{\theta}_n=X_n\tilde{q}_{d,n} \Rightarrow \tilde{q}_{d,n}=\left(X_n{}^tX_n\right)^{-1}X_n{}^t\tilde{\theta}_n \Rightarrow q_d(r,t)=\frac{2}{R^2}\sum_0^{nh}\frac{J_0(\alpha_n r)}{J_0^2(\alpha_n R)}\tilde{q}_{d,n}$$

$$q_d(t)=\int_0^R\left(\frac{2}{R^2}\sum_0^{nh}\frac{J_0(\alpha_n r)}{J_0^2(\alpha_n R)}\tilde{q}_{d,n}\right)2\pi r dr$$

$$\boxed{E_{1d}(t)=\frac{q_d(t)\Delta t}{n_{gouttes}}=\frac{q_d(t)}{f_{inj}}}$$

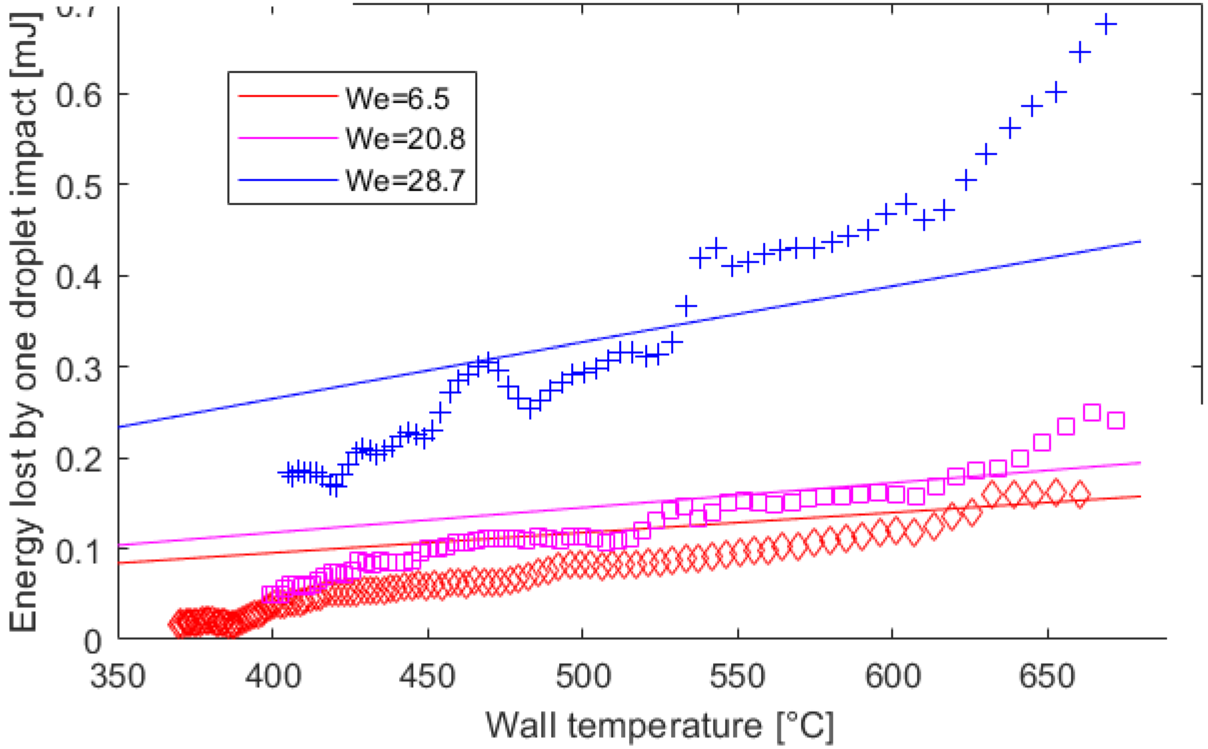
Droplet direct contact



Dd (µm) = 150.2 (+); 241.6 (o); 249.6 (x), Vn (m/s) = 1.76 (+); 2.44 (o); and 2.88 (x).

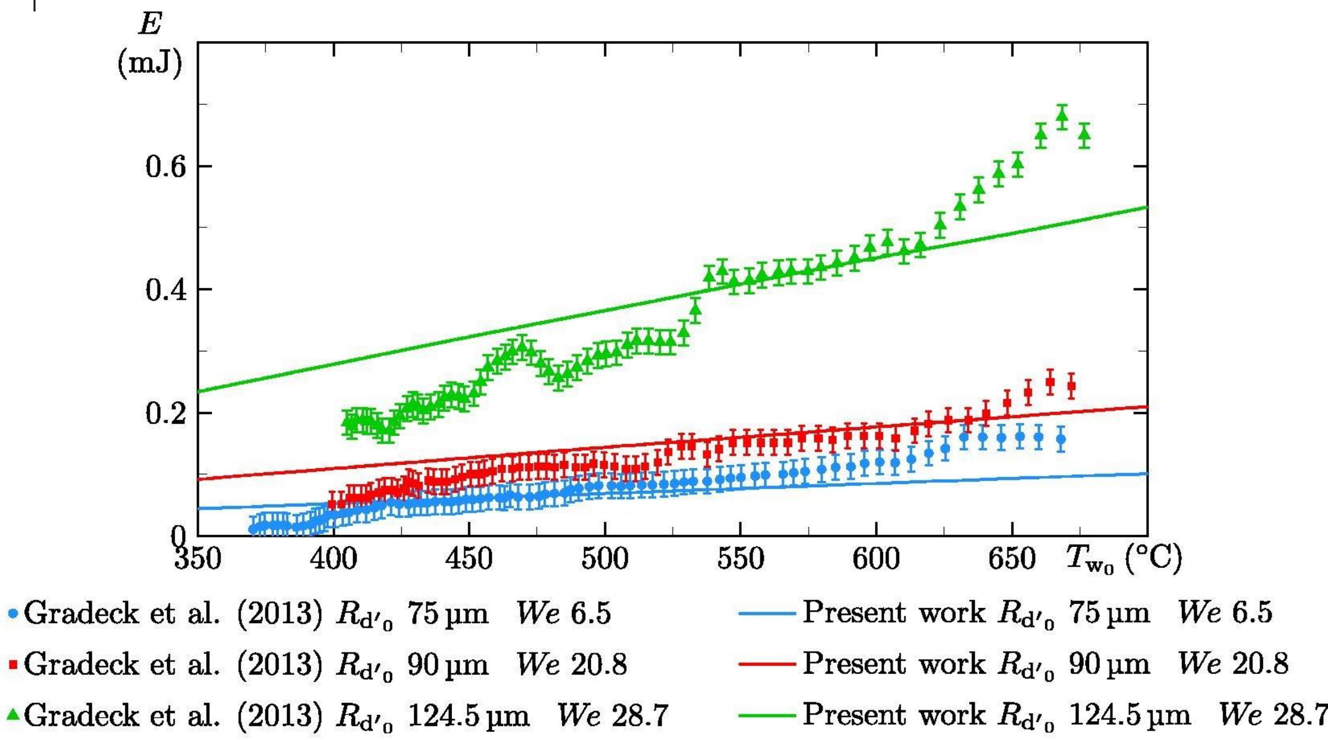
Experimental results compare to previous model (Guo et al, 2002)

Droplet direct contact



Other results compare to Breitenbach et al. model

A num. model from Rodolfo Ienny Martins et al, 2022

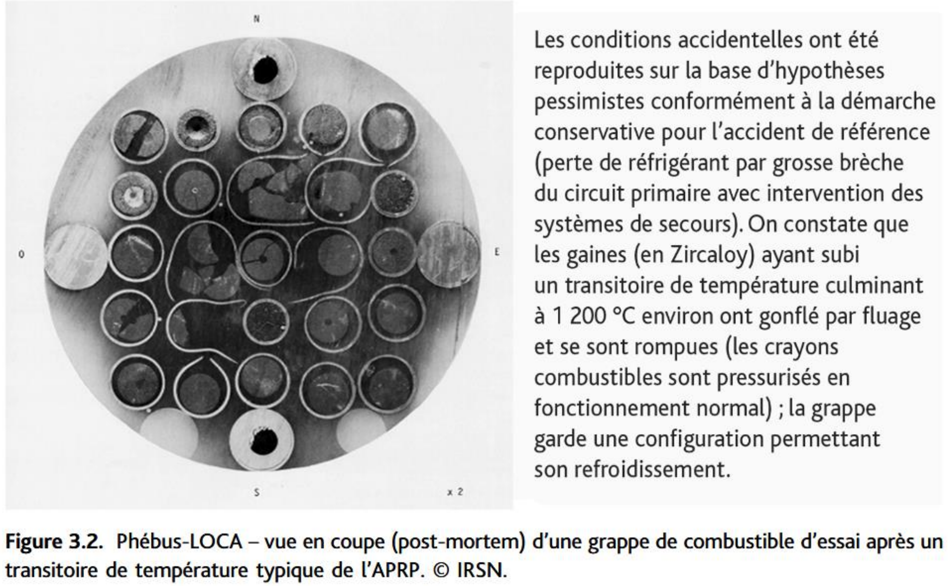


Droplet direct contact

Some models are available in the literature

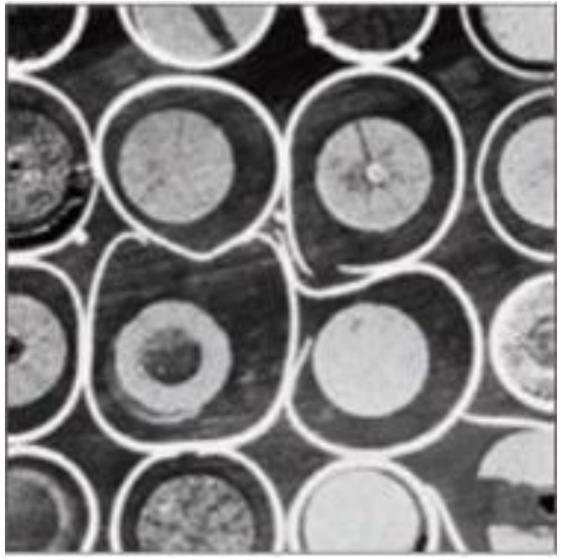
- The dynamic of the droplet (the spreading) must be taken into account as well as properties of the wall
- Due to the very small values, the estimation of the E_{DC} is very challenging (especially for small droplets)
- Estimation of overall heat transfer is quite easy
- …but estimating all the path of heat transfer demands realistic models

- in the context of nuclear safety where the reflood phase must ensure no melting of the core, it is very important to be able to simulate a lot of case with a good confidency.
- Unfortunately, the most damaged part will received much less flow…



Les conditions accidentelles ont été reproduites sur la base d'hypothèses pessimistes conformément à la démarche conservative pour l'accident de référence (perte de réfrigérant par grosse brèche du circuit primaire avec intervention des systèmes de secours). On constate que les gaines (en Zircaloy) ayant subi un transitoire de température culminant à 1 200 °C environ ont gonflé par fluage et se sont rompues (les crayons combustibles sont pressurisés en fonctionnement normal) ; la grappe garde une configuration permettant son refroidissement.

Figure 3.2. Phébus-LOCA – vue en coupe (post-mortem) d'une grappe de combustible d'essai après un transitoire de température typique de l'APRP. © IRSN.



DFFB and nuclear safety

Experiment in close LOCA conditions

- Measure heat transfer due to DFFB flow
- Model heat transfer using « simple modeling » from literature
- Estimate each path of heat transfer
- This help the modeling of the cooling of a reactor core in the reflood phase

Introduction : LOCA

Cause:

- Breach in the primary circuit

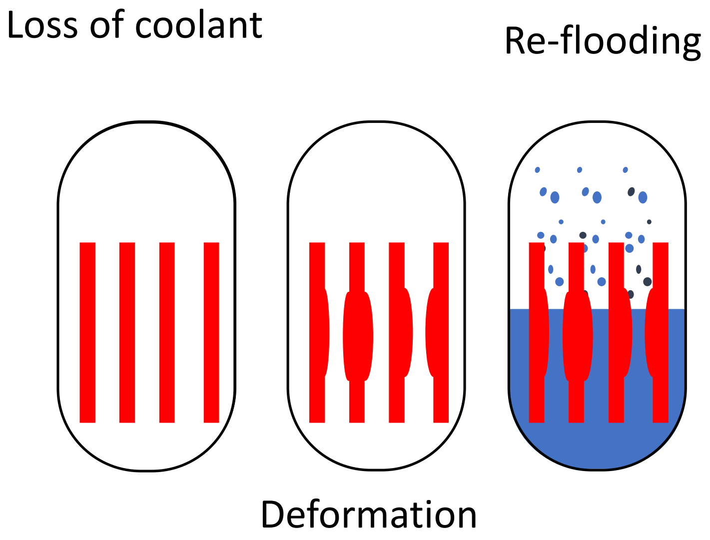
Consequence:

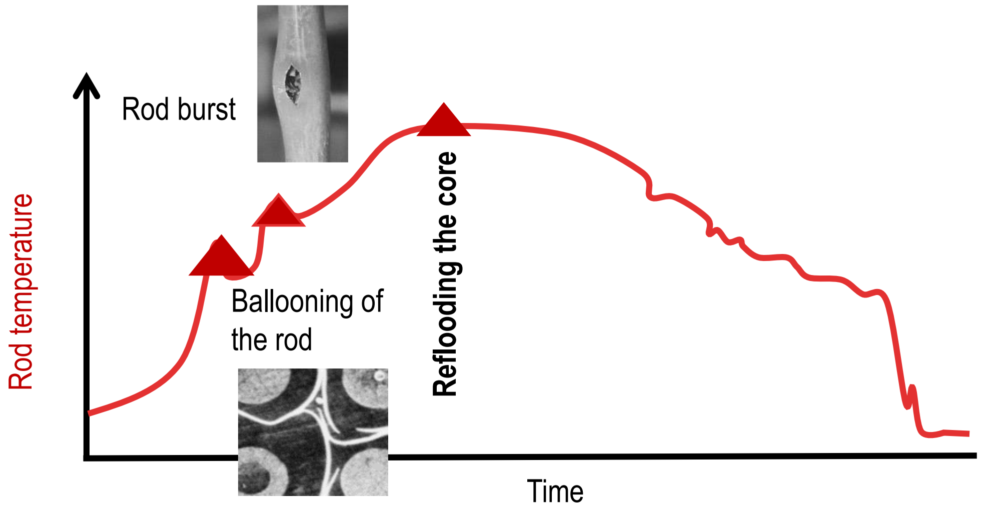
- Cooling failure
- Deformation of Zircaloy rods

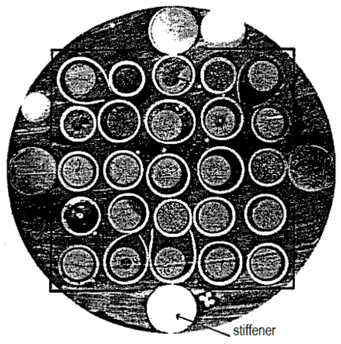
Security action?

- Re-flooding of fuel assemblies by safety systems

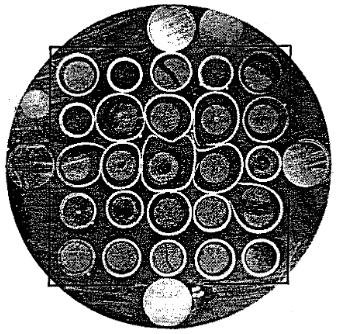
Residual power is almost 7% of the nominal power just after the stop





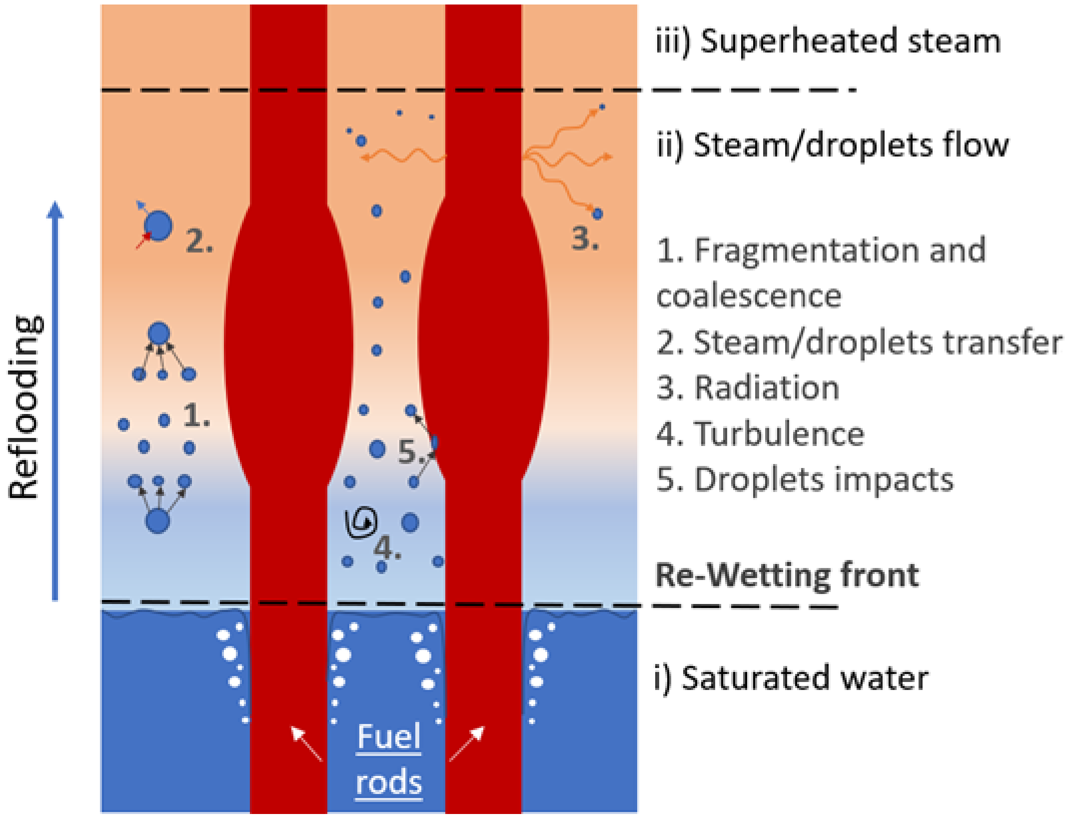


Elevation -285mm: blockage ratio= 36%



Elevation -252mm: blockage ratio= 48%

Introduction: LOCA



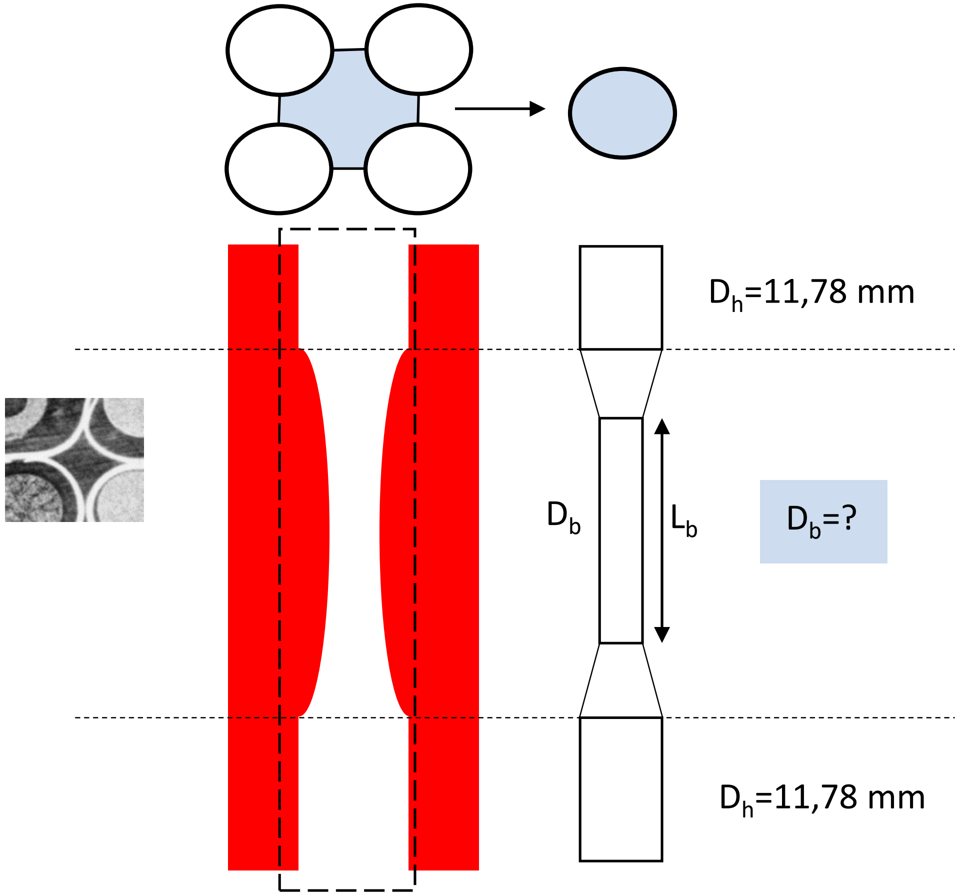
Heat and mass transfer phenomena in a LOCA

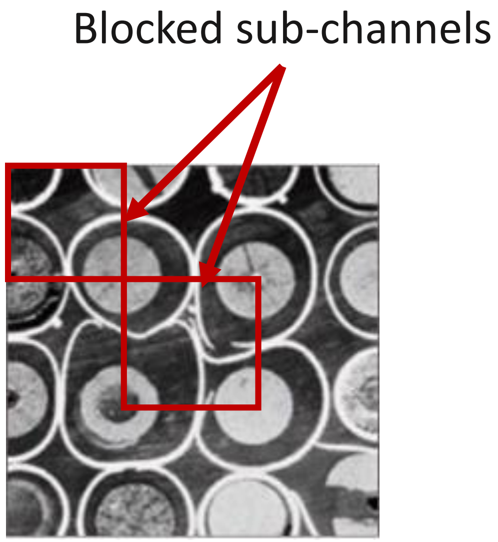
Typical values during a LOCA

Parameters	**Typical values**
Droplets diameter	50 µm -1300 µm
Droplets axial velocity	4 m/s -16 m/s
Droplets volume fraction	10^{-2} - 10^{-4}
Steam temperature	Up to 800°C
Wall temperature	300 °C - 1200 °C

DFFB and nuclear safety

Experimental bench dedicated to the study of DFFB in close LOCA conditions : what channel?





$$\tau_b = 1 - \frac{S_{blocked}}{S_{intact}} = 1 - \frac{D_b^2}{11{,}78^2 mm}$$

- Blockage ratio (τ_b) retained
- 0%: reference (11,78 mm)
- 61% (7,35 mm)
- 90% (3,72 mm)

*COLIBRI: **CO**o**LI**ng of **B**lockage **R**egion **I**nside a PWR Reactor.

DFFB and nuclear safety

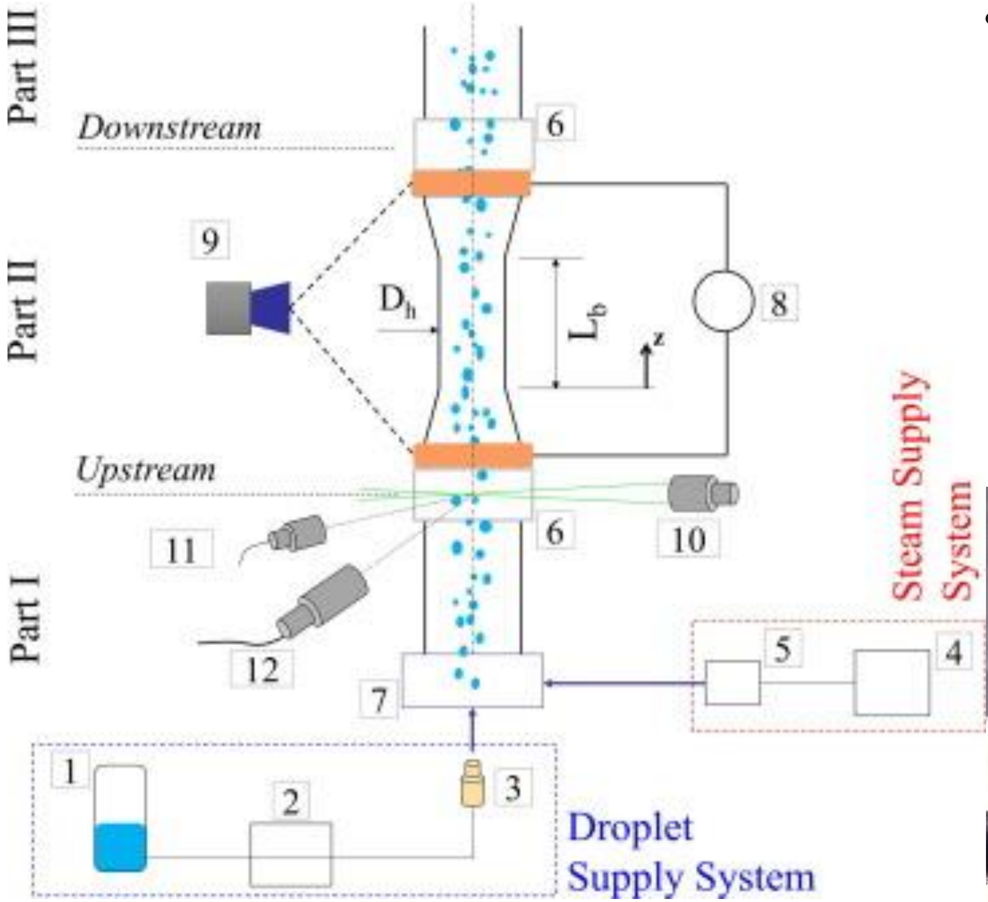
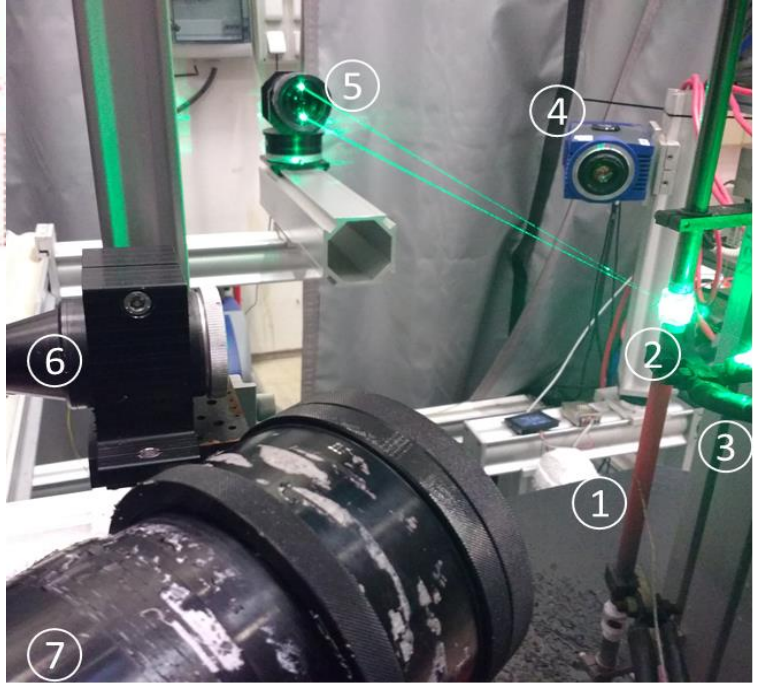


Diagram of the COLIBRI experimental installation

- Vertical Venturi tube in Inconel 625 heated up to 800°C reproducing intact or a partially blocked sub-channel
  - Wall Temperature change in the test section measured by infrared camera (IRT)
  - Measurement of droplets' size and velocity by Phase Doppler Analysis (PDA)
  - Droplet Temperature measured by Laser Induced Fluorescence (LIF)



(1) section d'essais,
(2) window
(3) Power supply
(4) IR camera
(5) Laser source
(6) LIF device
(7) PDA device

DFFB and nuclear safety

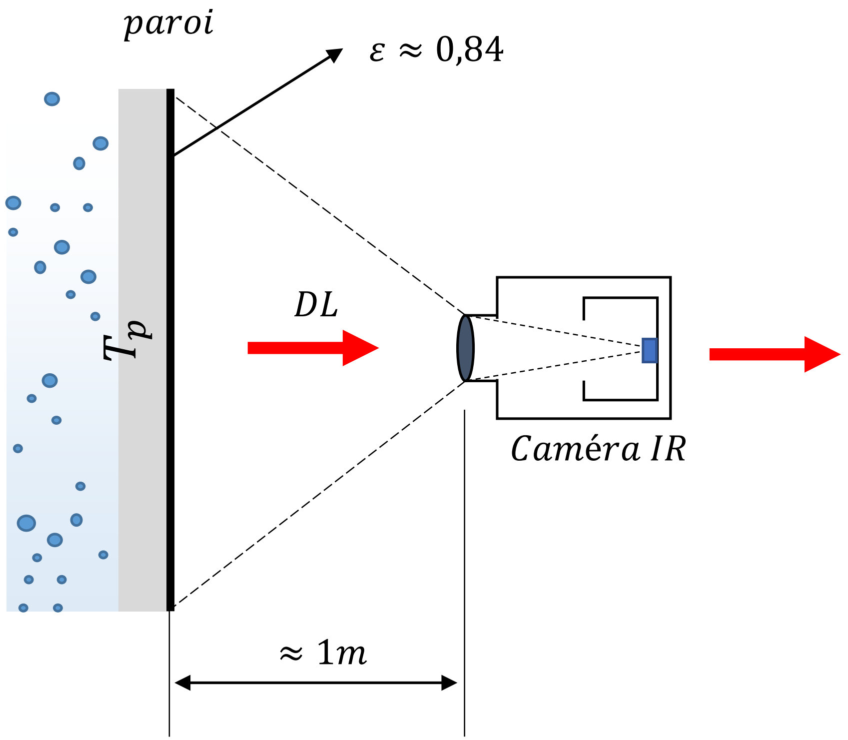
Available conditions with COLIBRI compares to LOCA ones

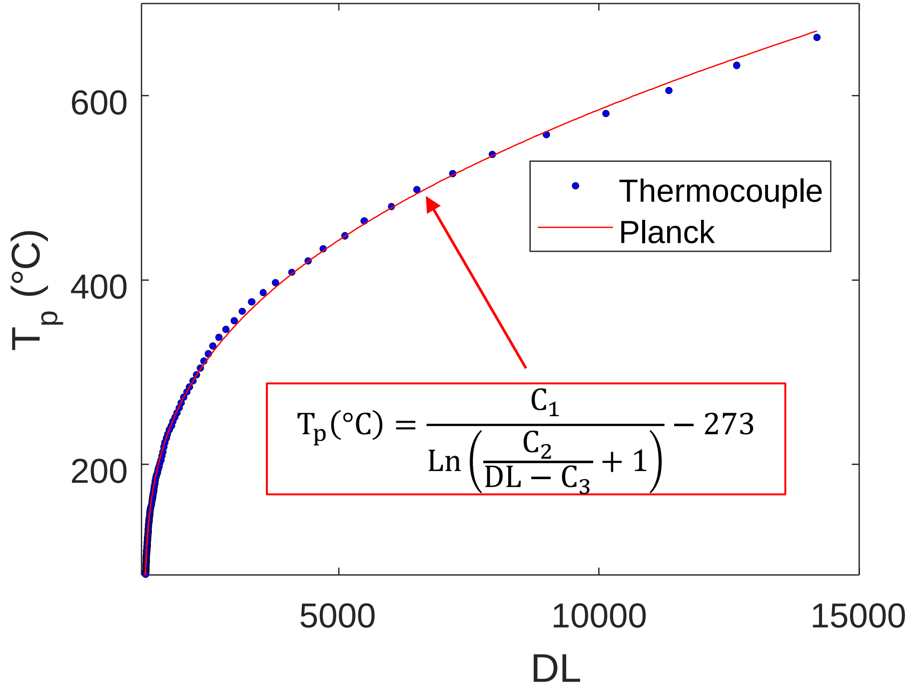
Parameter	LOCA	COLIBRI
Steam temperature(T_v)	$T_{sat} \leq T_v \leq 400°C$	**$T_{sat} \leq T_v \leq 200°C$**
Droplet temperature (T_g)	$T_g \leq T_{sat}$	**$20°C \leq T_g \leq 70°C$**
Steam velocity (u_v)	$1 \text{ m/s} \leq u_v \leq 25 \text{ m/s}$	**$10 \text{ m/s} \leq u_v \leq 40 \text{ m/s}$**
Droplet velocity (u_g)	$u_g \leq u_v$	**$u_g \leq 20 \text{ m/s}$**
Clad temperature (T_p)	$T_p \leq 1200°C$	**$T_p \leq 700°C$**
Droplet diameter (d_g)	$d_g \leq 1000\ \mu m$	**$d_g \leq 300\ \mu m$**
Pressure (p)	Up to 3 bars	**$\leq$ 0,2 bar**
Residual power	0.3 – 3kW/m	**0 – 2kW/m**

DFFB and nuclear safety

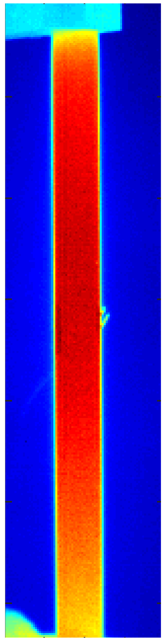
Measurement of wall **temperature** (T_p)

- Black paint ($\varepsilon \approx 0{,}84$)
- Planck law to rely DL→T





$$T_p(°\mathrm{C}) = \frac{C_1}{\mathrm{Ln}\left(\frac{C_2}{DL - C_3} + 1\right)} - 273$$

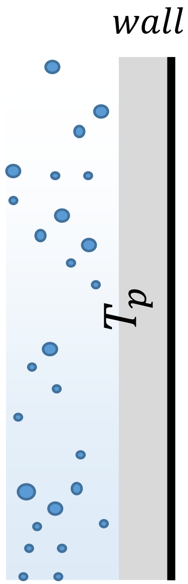


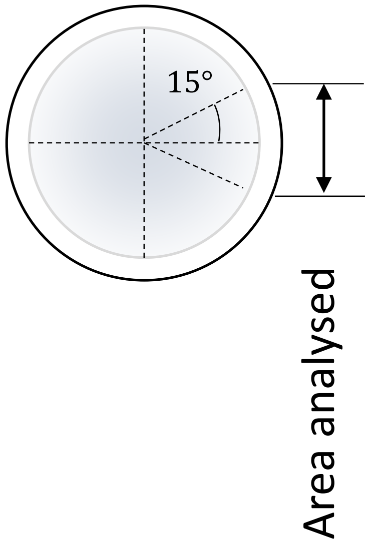
Narrow filter: [3,97 µm - 4,01 µm] → $T_{max,em}$=450°C
Frequency: 60 Hz
Integration time: 100 µs

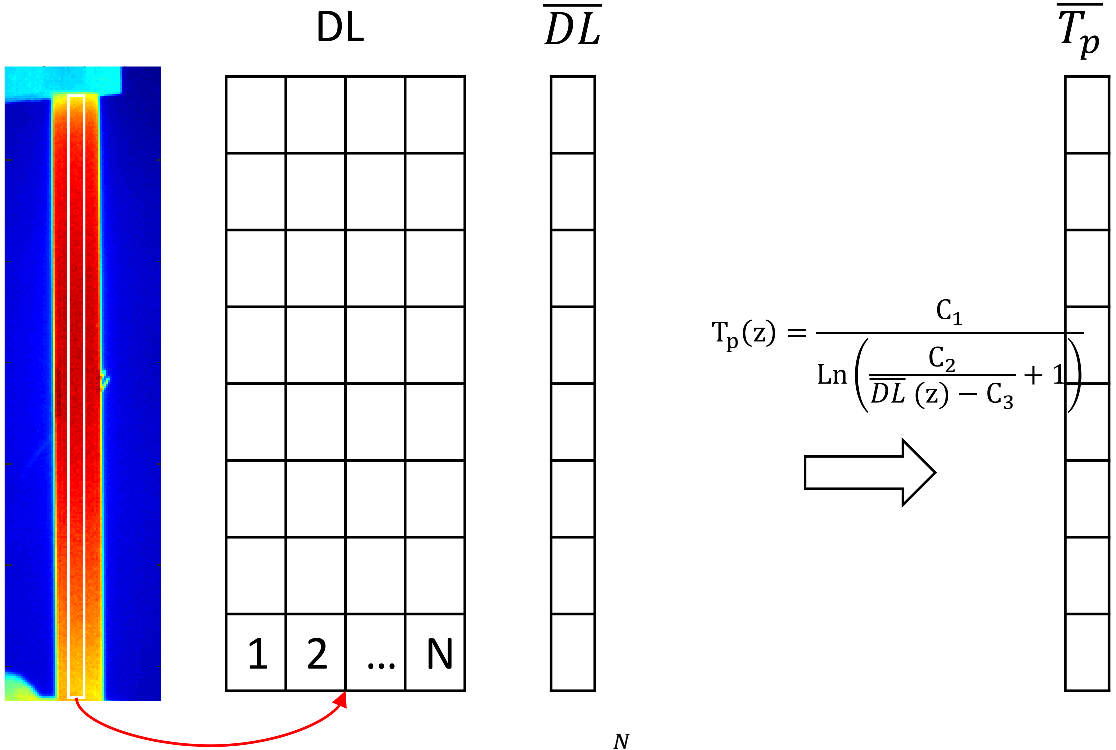
- Error max ±5°C

DFFB and nuclear safety

- Discretization of the « central line » [-15° 15°]
- Obtention of mean DL for each z position
- Estimation of T_p







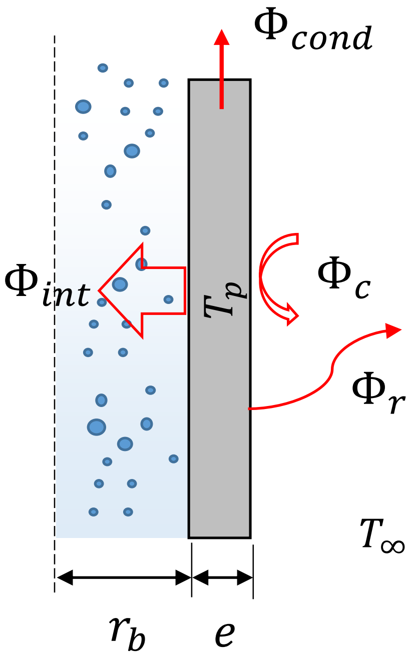
$$T_p(z) = \frac{C_1}{\mathrm{Ln}\left(\frac{C_2}{\overline{DL}\ (z) - C_3} + 1\right)}$$

$$\overline{DL}\ (z) = \frac{1}{N}\sum_{i=1}^{N} DL_i$$

DFFB and nuclear safety

Estimation of internal heat flux from IR measurement requires to model heat transfer…

- Hypothesis: 1D problem $(T_p(r_b, z, t) = T_p(\mathrm{r_b} + \mathrm{e}, z, t) = T_p(z, t))$ → (Bi << 1)



$$\Phi_{\mathrm{int}}(z,t) + \Phi_{\mathrm{loss}}(z,t) + \Phi_{\mathrm{cond,z}}(z,t) + \Phi_{\mathrm{joule}}(t) = \mathrm{m_p Cp_p} \frac{\mathrm{T_p(z,t)}}{\mathrm{dt}}$$

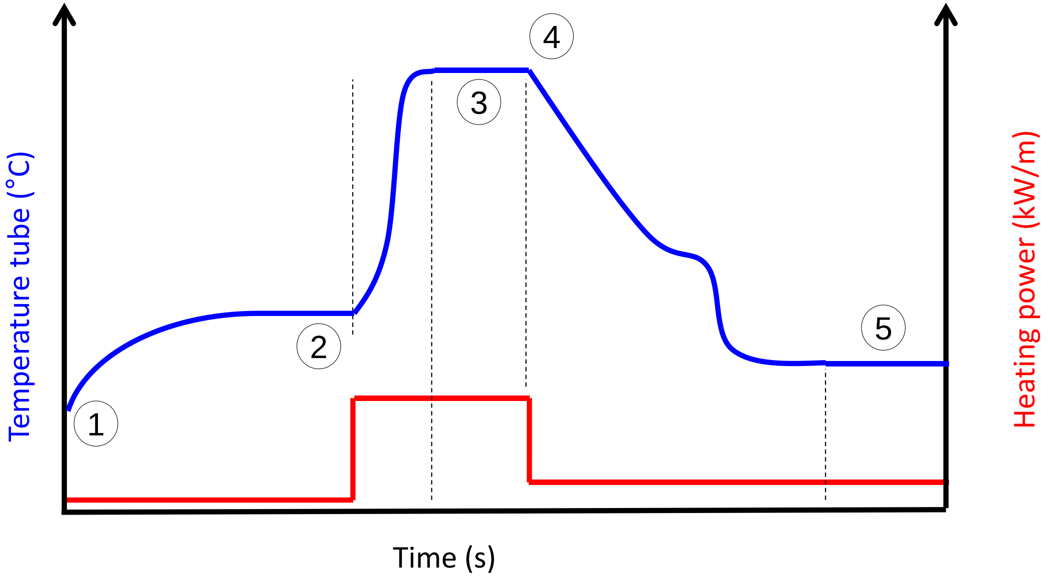
$$\Phi_{\mathrm{int}}(\mathrm{z,t}) = -\mathrm{m_p Cp_p} \frac{\mathrm{T_p(z,t)}}{\mathrm{dt}} - \Phi_{\mathrm{loss}}(z,t) - \Phi_{\mathrm{cond,z}}(z,t) - \Phi_{\mathrm{joule}}(t)$$

$$\Phi_{\mathrm{loss}} = \Phi_{\mathrm{c}} + \Phi_{\mathrm{r}}$$

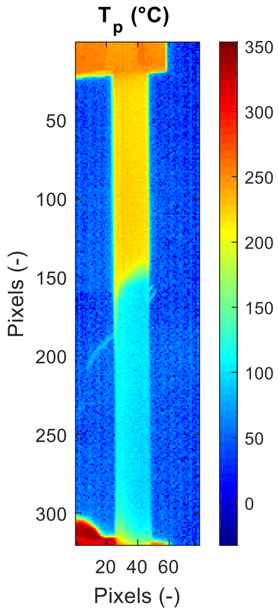
$$\Phi_{\mathrm{c}} = \mathrm{S}\frac{\mathrm{k_{air}}}{\mathrm{L}} 0.59\mathrm{Ra_L^{1/4}}(\mathrm{T_p} - \mathrm{T_\infty}) \qquad \Phi_{\mathrm{r}} = \mathrm{S}\varepsilon\sigma\left(\mathrm{T_p^4} - \mathrm{T_\infty^4}\right)$$

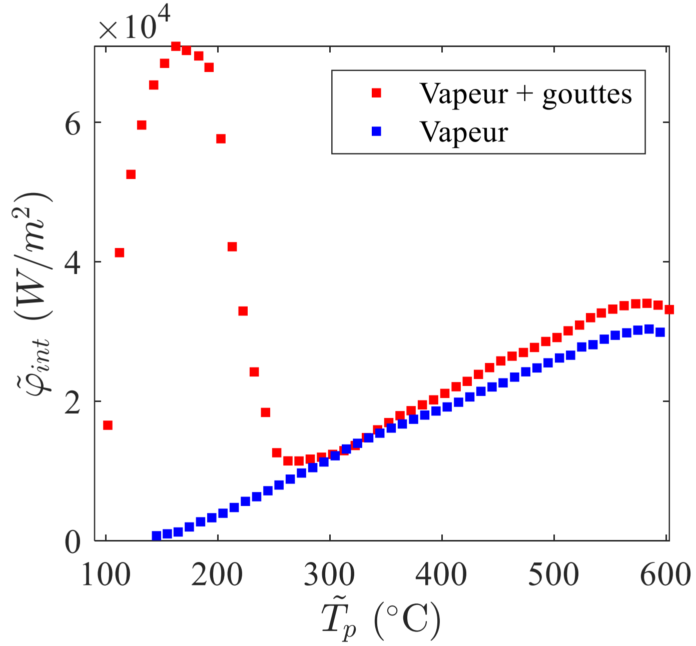
DFFB and nuclear safety

Then, once we had estimated all the losses (from correlation or relaxation test), heat from the internal DFFB flow can be finally get



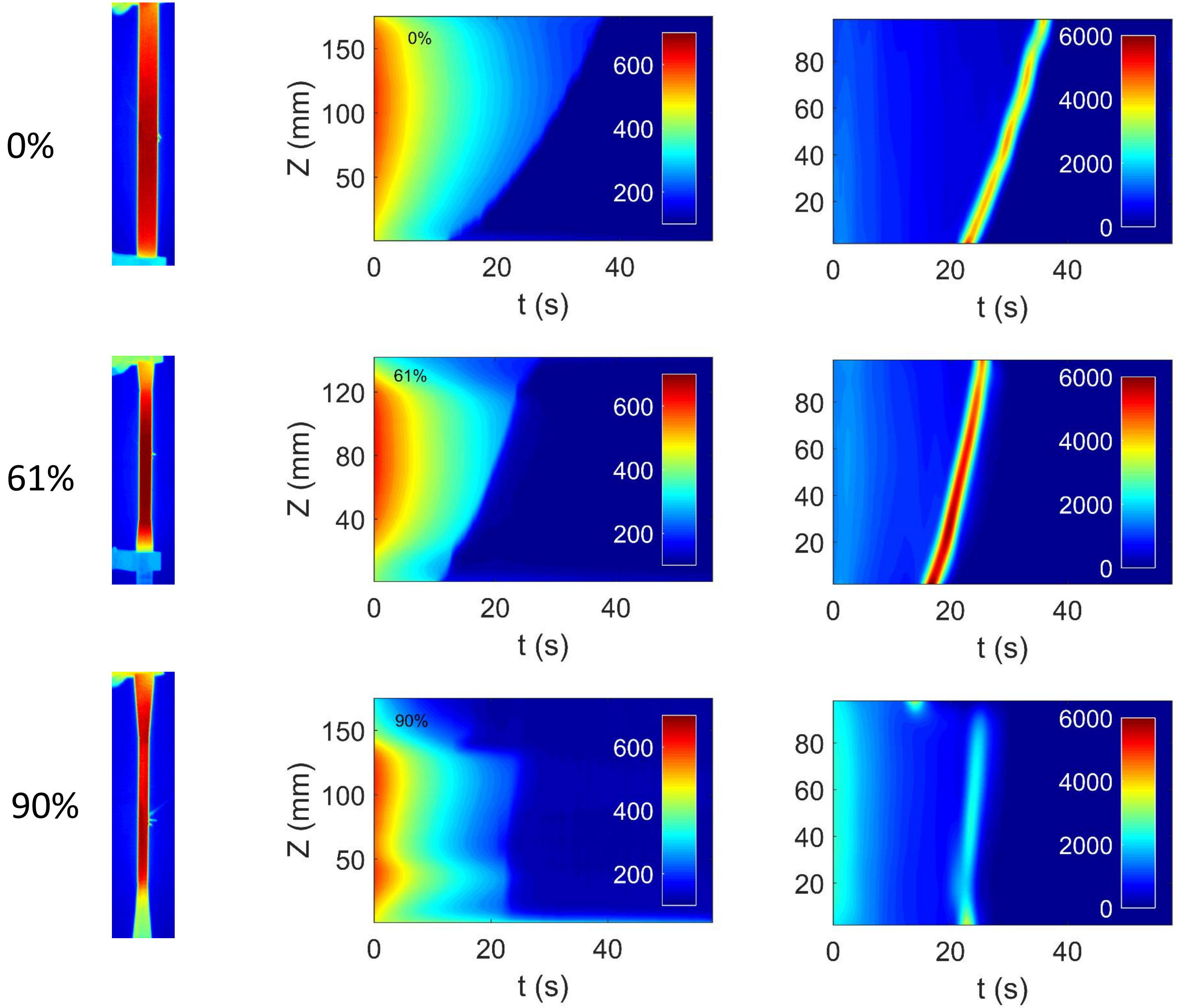
1. Injection of steam
2. Heating of test section + droplet injection
3. PDA + LIF (upstream and dowstream)
4. Stop heating. Simultaneous IRT, PDA and LIF dowstream
5. End of experiment (rewetting).

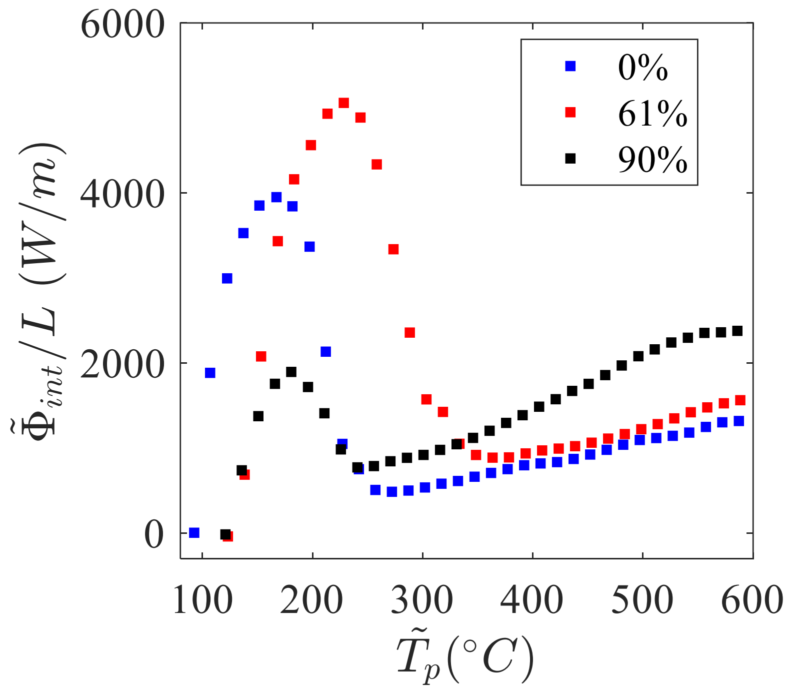




τ_b=0% ; $\dot{m}_v$ =4.3 kg/h ;T_{vap}=170°C
$\dot{m}_d$ =0.75 kg/h ; T_g=65°C, P=1.1 bar

DFFB and nuclear safety





droplet	
Temperature at injection point (°C)	62,5
Mass flow rate (kg/h)	0,75
steam	
Steam temperature at injection (°C)	170
Mass flow rate (kg/h)	4,3

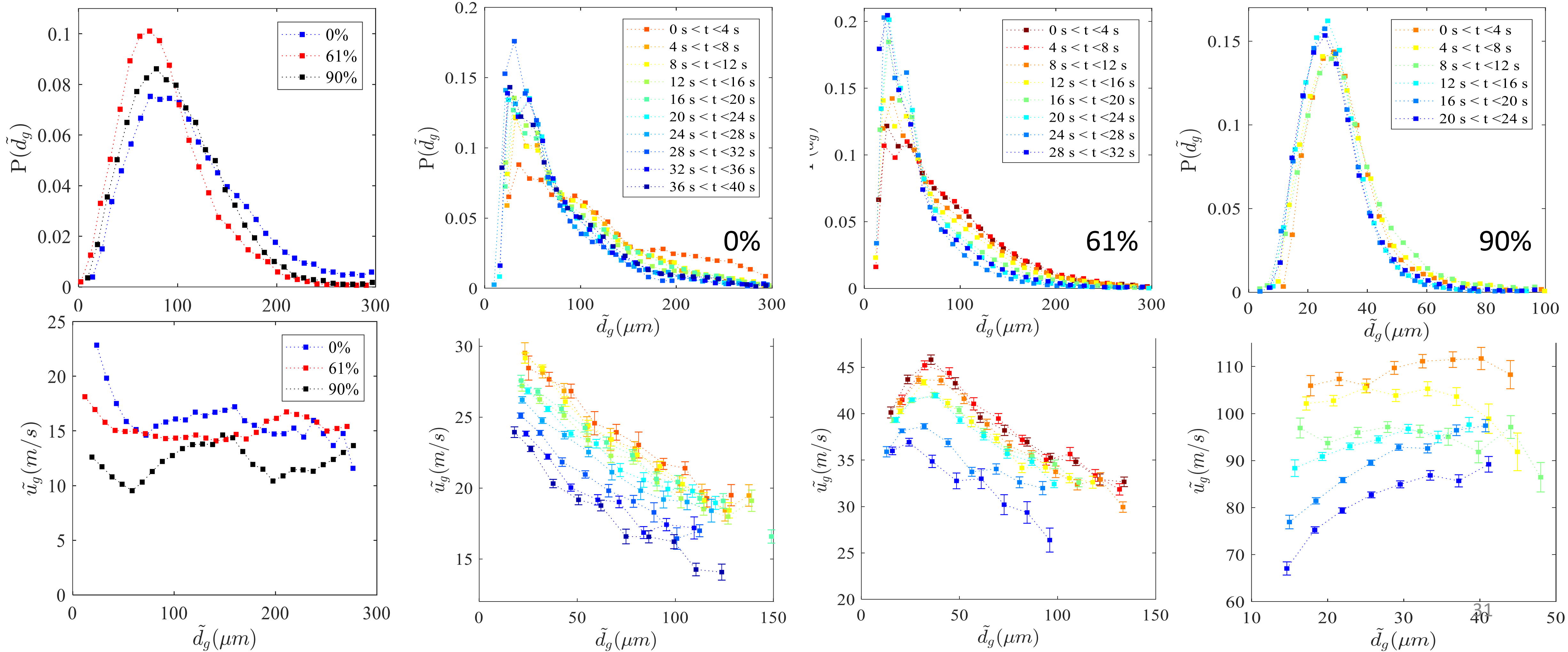
DFFB and nuclear safety

Influence of the blockage ratio

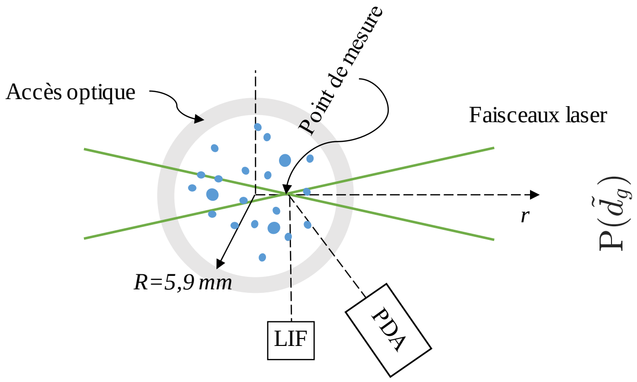
deformation	d_{10}, µm	$\widetilde{u_g}$, m/s
0%	110	16
61%	86	14.8
90%	98	13

Inlet conditions

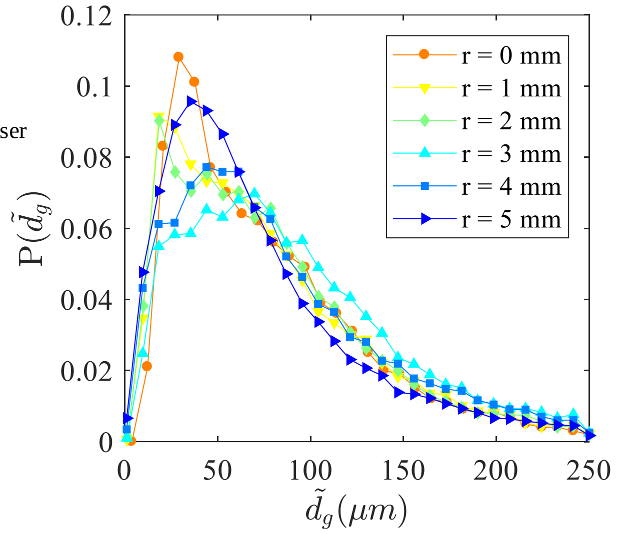
Outlet conditions

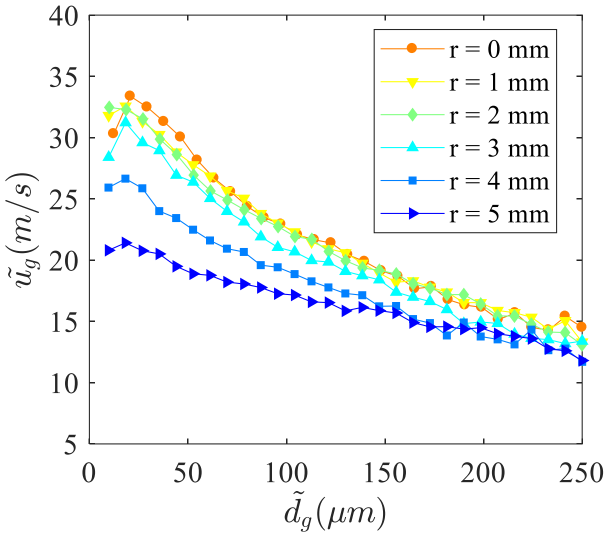


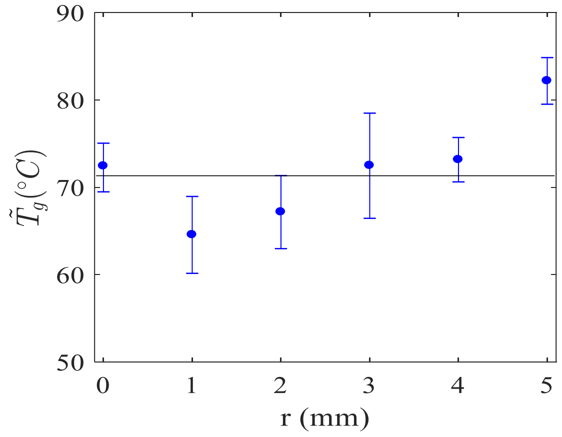
DFFB and nuclear safety

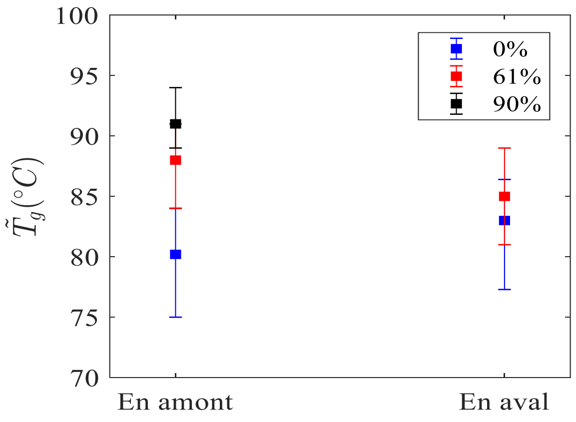


Mesure de Td upstream





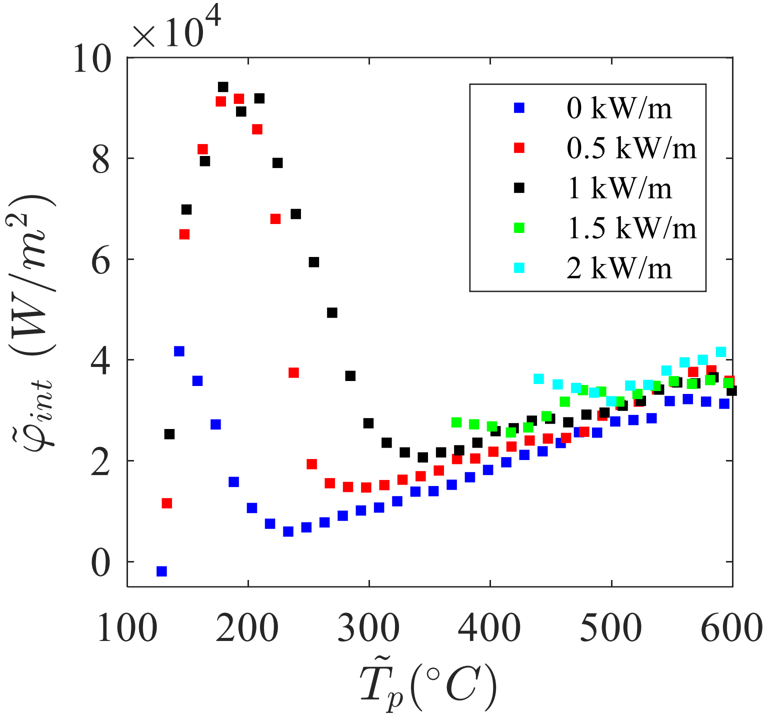


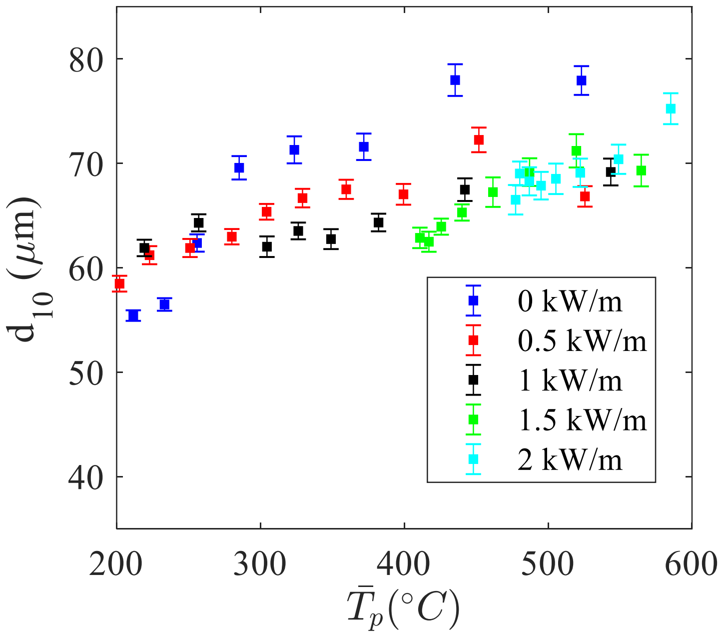


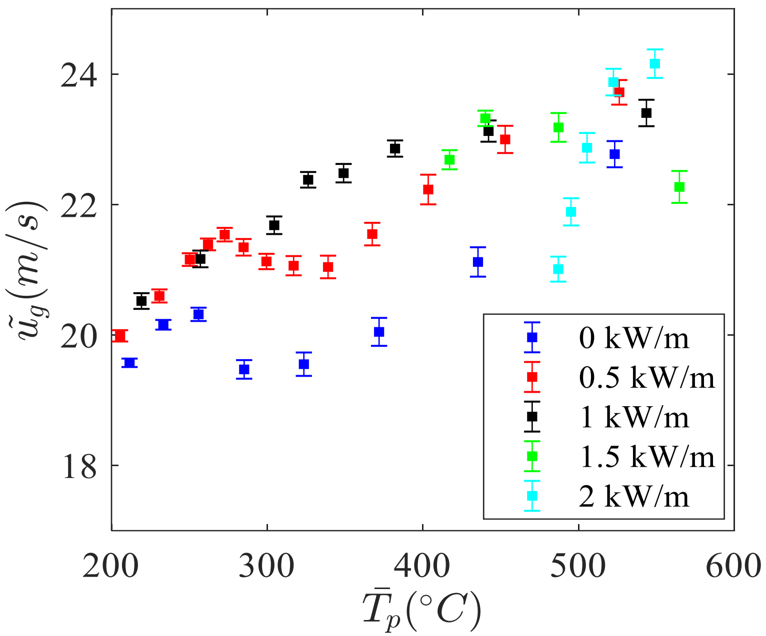
droplet	
Temperature at injection point (°C)	62,5
Mass flow rate (kg/h)	0,75
steam	
Steam temperature at injection (°C)	170
Mass flow rate (kg/h)	4,3

DFFB and nuclear safety

Effect of the residual power







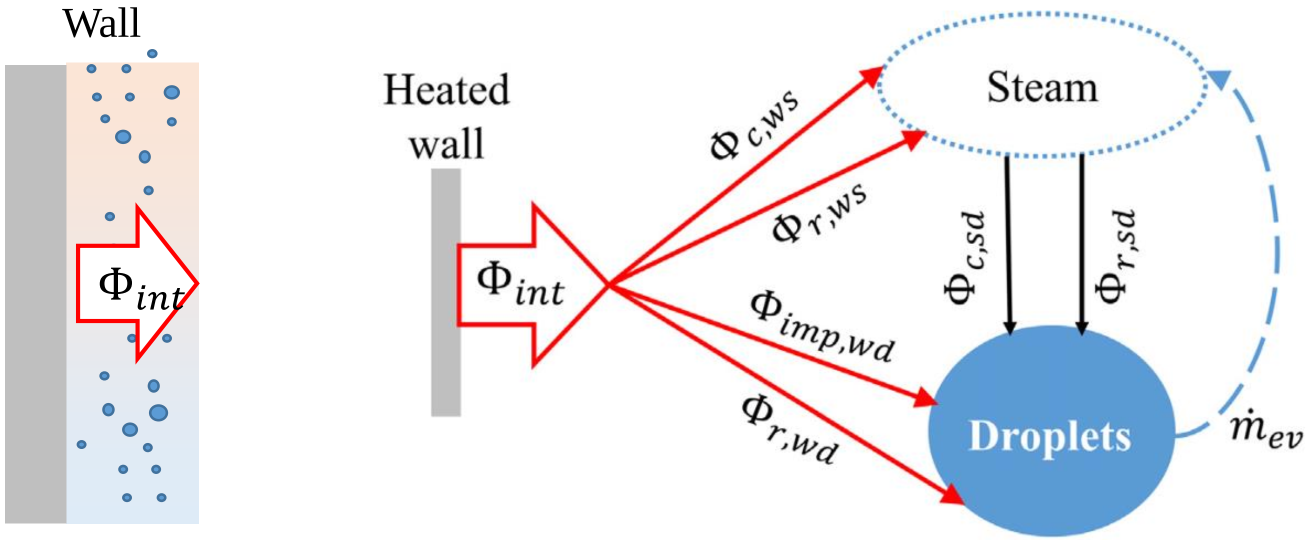
droplet	
Temperature at injection point (°C)	62,5
Mass flow rate (kg/h)	0,75
steam	
Steam temperature at injection (°C)	170
Mass flow rate (kg/h)	4,3

residual power influence strongly the Leidenfrost temperature but not much the other parameters of the flow

DFFB and nuclear safety

NECTAR Code

- Mechanistic model for two phase flow in thermal and dynamic non-equilibrium (same methodology as Guo et al. and Meholic et al. 2015)
- Six mechanisms modeled → Film boiling



$$\Phi_{int} = \Phi_{c,ws} + \Phi_{r,ws} + \Phi_{imp,wd} + \Phi_{r,wd}$$

- Wall to steam forced convection ($\Phi_{c,ws}$)
- Droplets impacts onto the wall ($\Phi_{imp,wd}$)
- Wall to steam ($\Phi_{r,ws}$), wall to droplets ($\Phi_{r,wd}$), and steam to droplets ($\Phi_{r,sd}$) radiation.
- Steam to droplets convection ($\Phi_{c,sd}$)

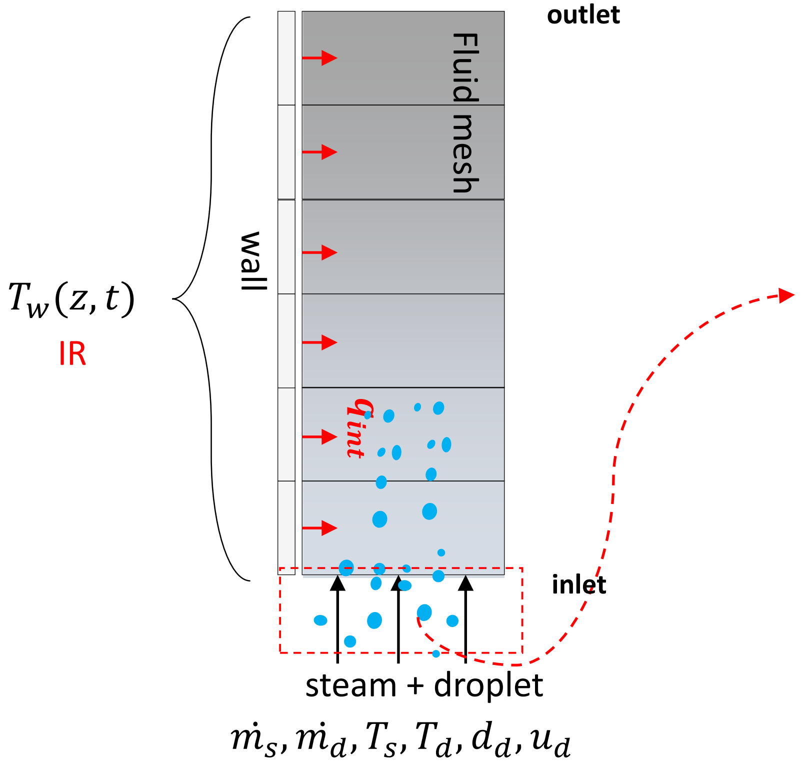
[1] NECTAR (**N**ew **E**xperimental **C**ode for **T**hermal-hydraulic **A**nalysis in a **R**epresentative geometry)

Oliveira, A. V. S., Peña Carrillo, J. D., Labergue, A., Glantz, T., & Gradeck, M. (2019). Mechanistic modeling of the thermal-hydraulics in polydispersed flow film boiling in LOCA conditions. *Nuclear Engineering and Design*, *357*(August 2019). https://doi.org/10.1016/j.nucengdes.2019.110388

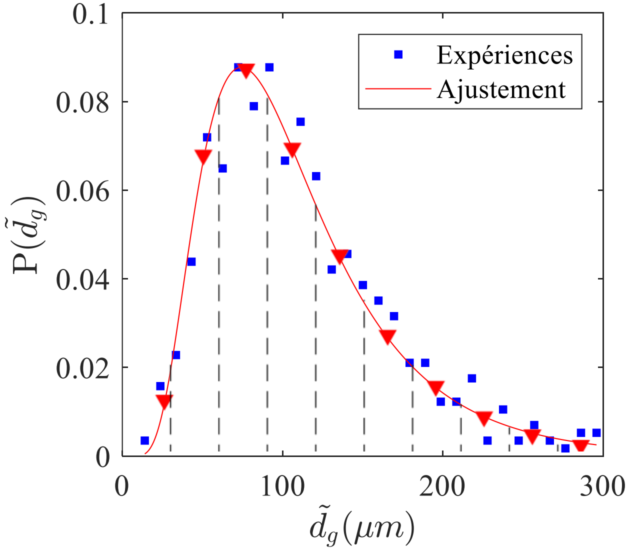
DFFB and nuclear safety

hypothesis

- 1D modeling (Discretization with N meshes)
- Lagrangian approach
- Fragmentation (Chou & Faith model) but no coalescence of the droplet
- Size Distribution of droplets → Log-normal (+ Discretization by size class)



$$P(d) = \frac{1}{\sqrt{2\pi}\sigma d_g} e^{\left(-\frac{\left(\ln\left(\frac{d_g}{d_{oo}}\right)\right)^2}{2\sigma^2}\right)}$$



m_s=4,3 kg/h, m_d=0,8 kg/h

$$\Phi_{r,wd}(z) = S \sum_{n=1}^{N_{classe}} \omega_{w\to d,n}\sigma_{SB}\left(T_w^4(z) - T_{sat}^4\right)$$

$$\Phi_{r,sd}(z) = \sum_{n=1}^{N_{classe}} a_{i,n}\omega_{s\to d,n}\sigma_{SB}\left(T_w^4(z) - T_{sat}^4\right)$$

$$\omega_{i\to j} = \frac{1}{\left(R_i + R_j + \frac{R_i R_j}{R_k}\right)}$$

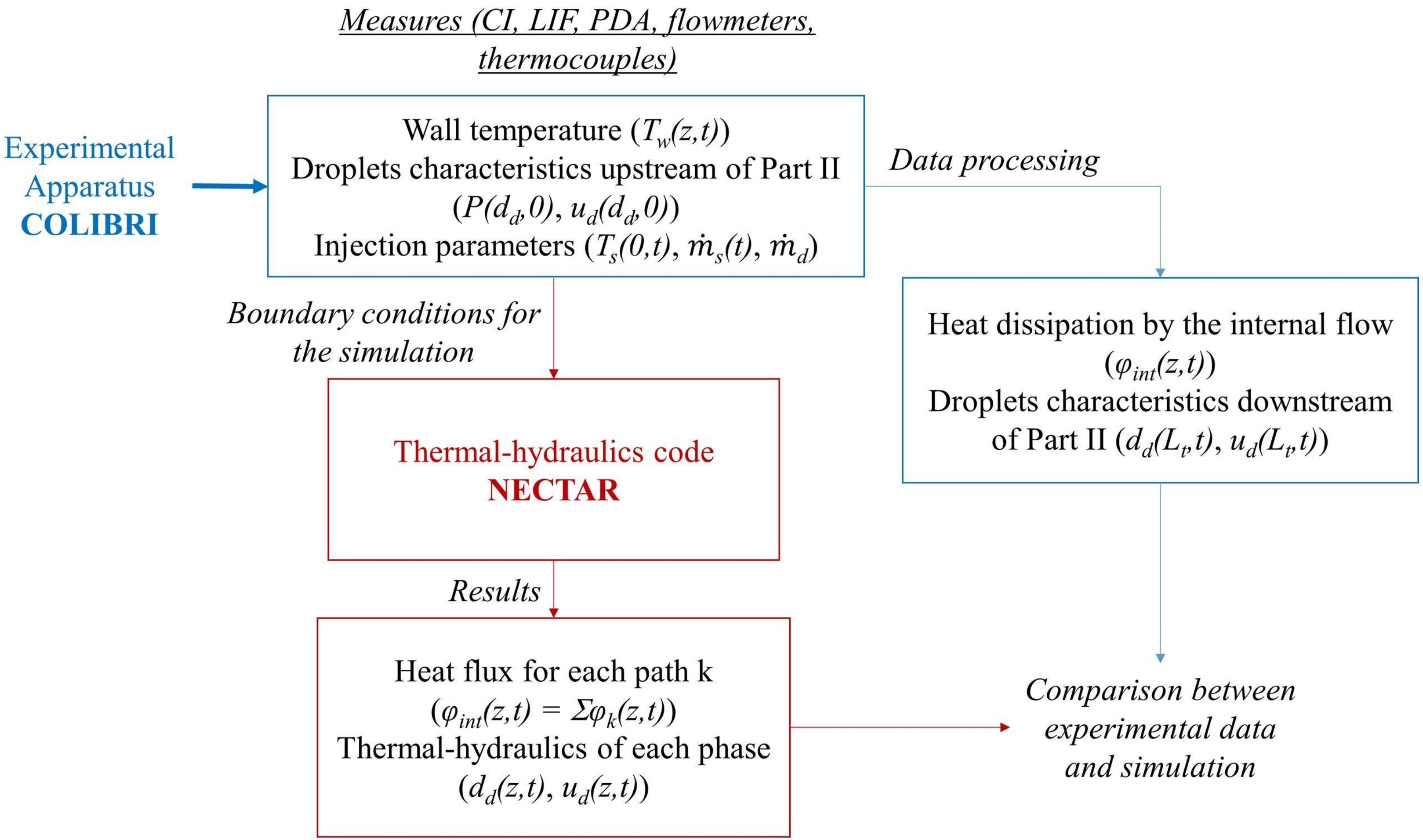
R_i , thermal resistance of media i

$$\Phi_{sd}(z) = \sum_{n=1}^{N_{classe}} a_{i,n}\left(\frac{k_v}{d_{s,n}}\right)\left(Nu_{sd,n}\right)\left(T_s(z) - T_{sat}\right)$$

$$\Phi_{i,wd}(z) = \sum_{n=1}^{N_{classe}} Q_{ipg,n}$$

DFFB and nuclear safety

Analysis of the experiments – comparisons with model (NECTAR code)



Measures (CI, LIF, PDA, flowmeters, thermocouples)

Experimental Apparatus
COLIBRI

Wall temperature ($T_w(z,t)$)
Droplets characteristics upstream of Part II ($P(d_d,0)$, $u_d(d_d,0)$)
Injection parameters ($T_s(0,t)$, $\dot{m}_s(t)$, $\dot{m}_d$)

Data processing

Heat dissipation by the internal flow ($\varphi_{int}(z,t)$)
Droplets characteristics downstream of Part II ($d_d(L_t,t)$, $u_d(L_t,t)$)

Boundary conditions for the simulation

Thermal-hydraulics code
NECTAR

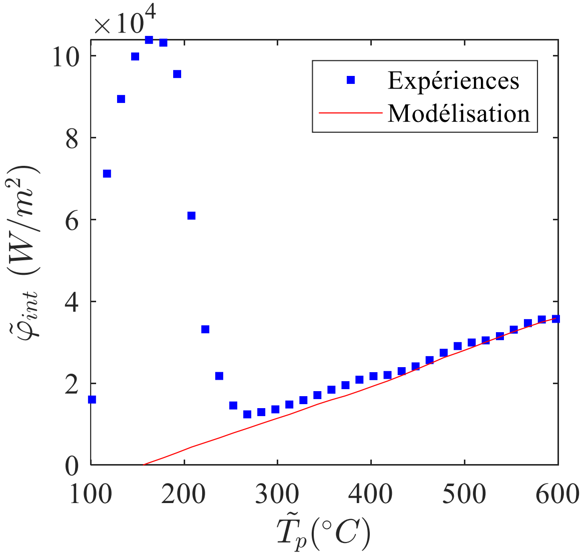
Results

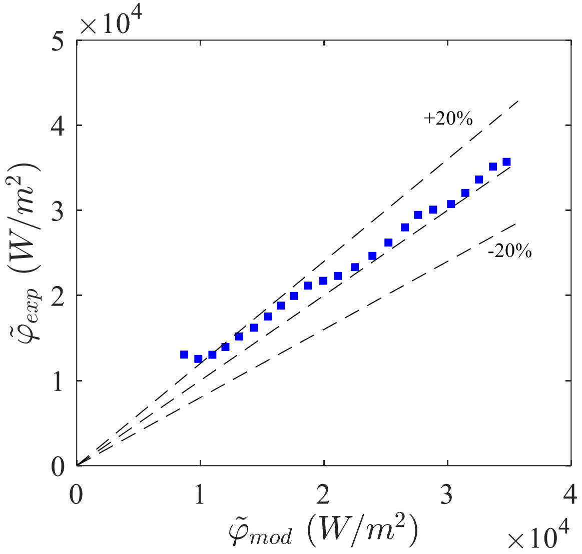
Heat flux for each path k
($\varphi_{int}(z,t) = \Sigma\varphi_k(z,t)$)
Thermal-hydraulics of each phase
($d_d(z,t)$, $u_d(z,t)$)

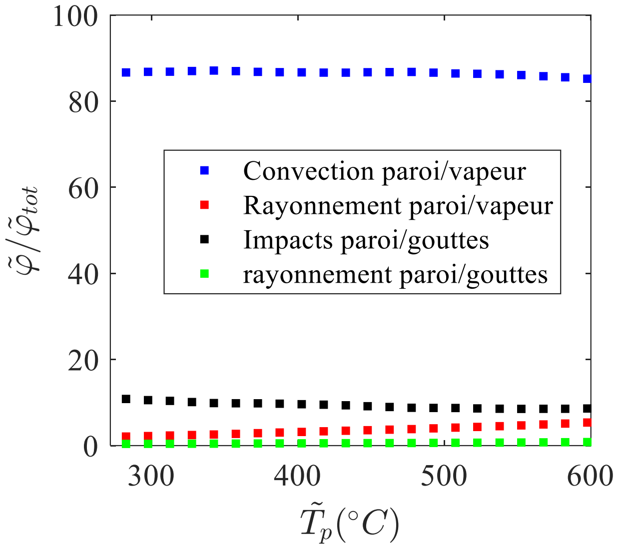
Comparison between experimental data and simulation

DFFB and nuclear safety

Analysis of the experiments – comparisons with model (NECTAR code)

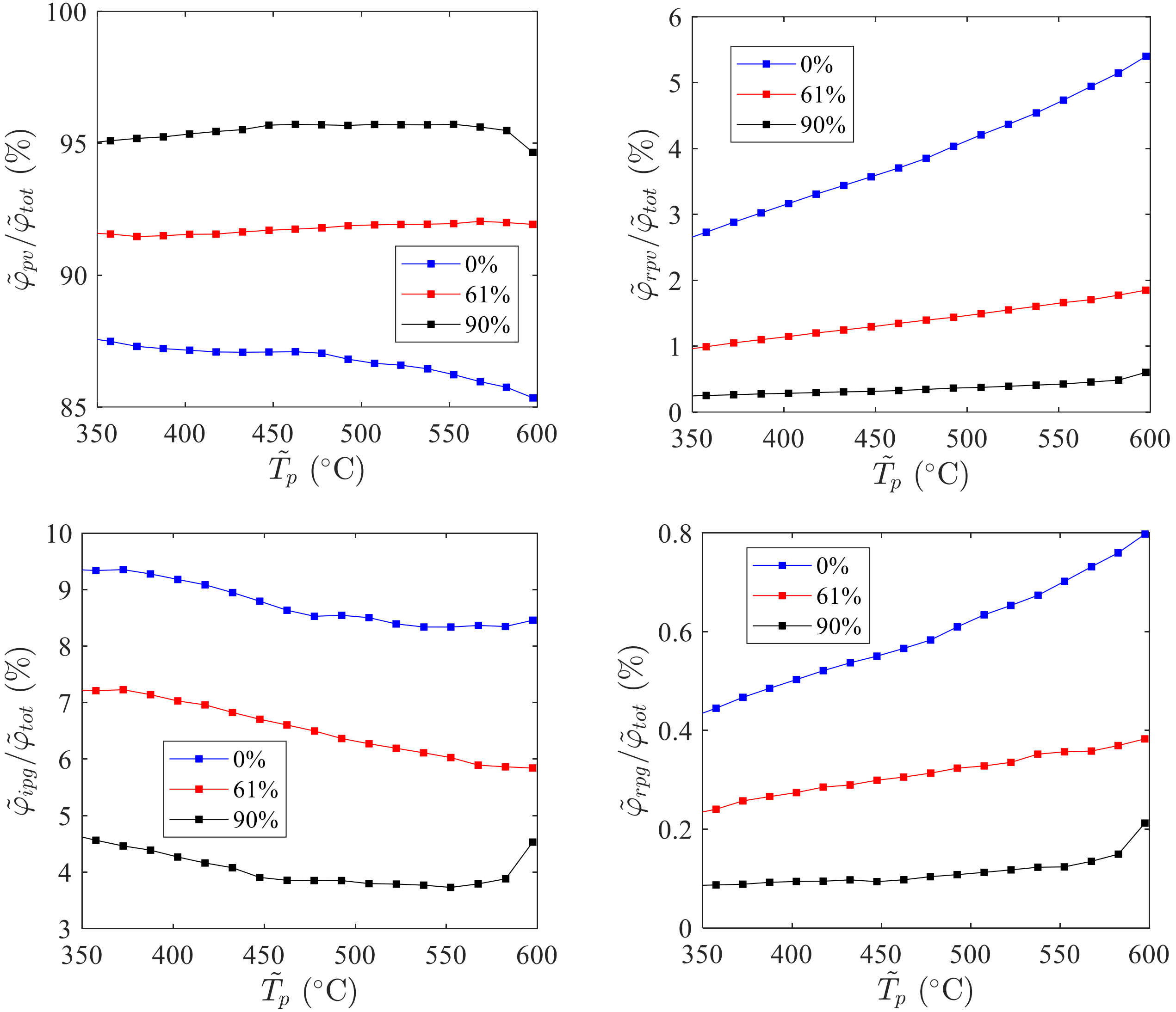






Lb (mm)	Steam mass flow rate (kg/h)	Droplet mass flow rate (kg/h)	Temperature of droplet (°C)
100	4.3	0.8	100

DFFB and nuclear safety



But the proportion change with the blockage ratio

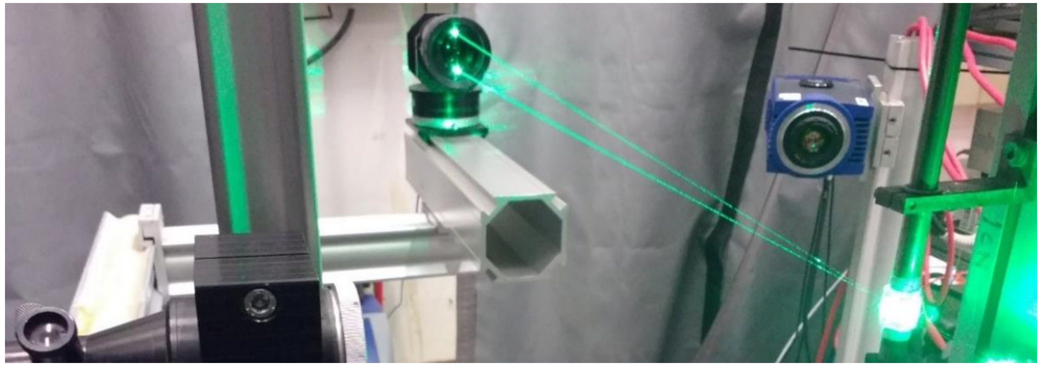
Conclusions

- Two Experimental bench: measurement of droplet impact heat flux + estimation of DFFB in vertical heated tubes

- 3 coupled optical diagnostics
  - IRT: temperature measurement and heat flux estimation
  - PDA: size and velocity distribution
  - LIF3c: mean temperature of droplet

- Provide data in close LOCA conditions

- NECTAR Code: helps to understand the path of heat flux



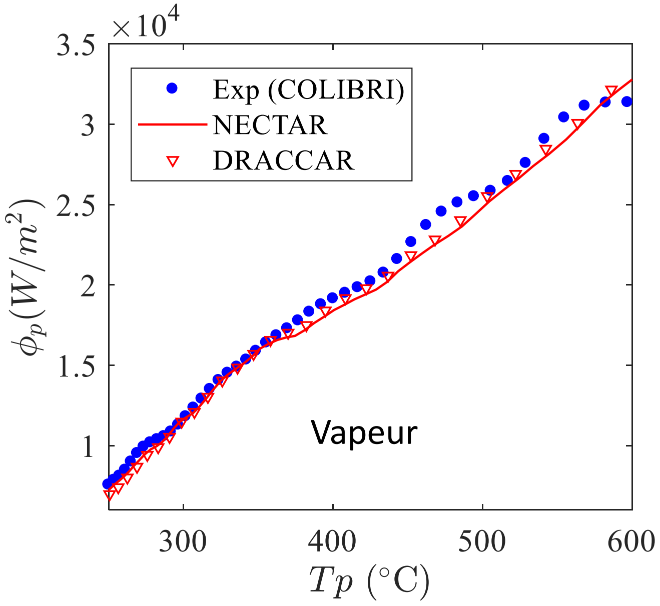
Conclusion

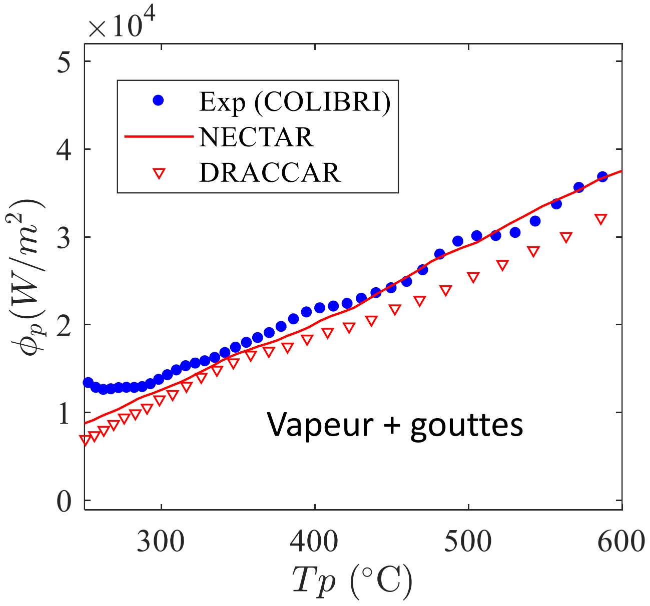
to be continued…

- Improvement of COLIBRI bench
  - Put a by-pass to simulate the vapour deviation to less blockage area
  - Change the system heating the steam to get a higher T_v

- Improvement of NECTAR:
  - 1D to 2D to account for the radial distribution…

- Perform simulation with the DRACCAR Code of IRSN





m_v=4,3 kg/h, m_g=0,8 kg/h, D_b=11,78 mm (0%), L_{brides}=180 mm

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A.V.S. Oliveira, D. Stemmelen, S. Leclerc, T. Glantz, A. Labergue, G. Repetto, M. Gradeck, Parametric effects on the flow redistribution in 7x7 ballooned fuel bundles evaluated by magnetic resonance velocimetry, *Experimental Thermal and Fluid Science (2021), https://doi.org/10.1016/j.expthermflusci.2021.110383*

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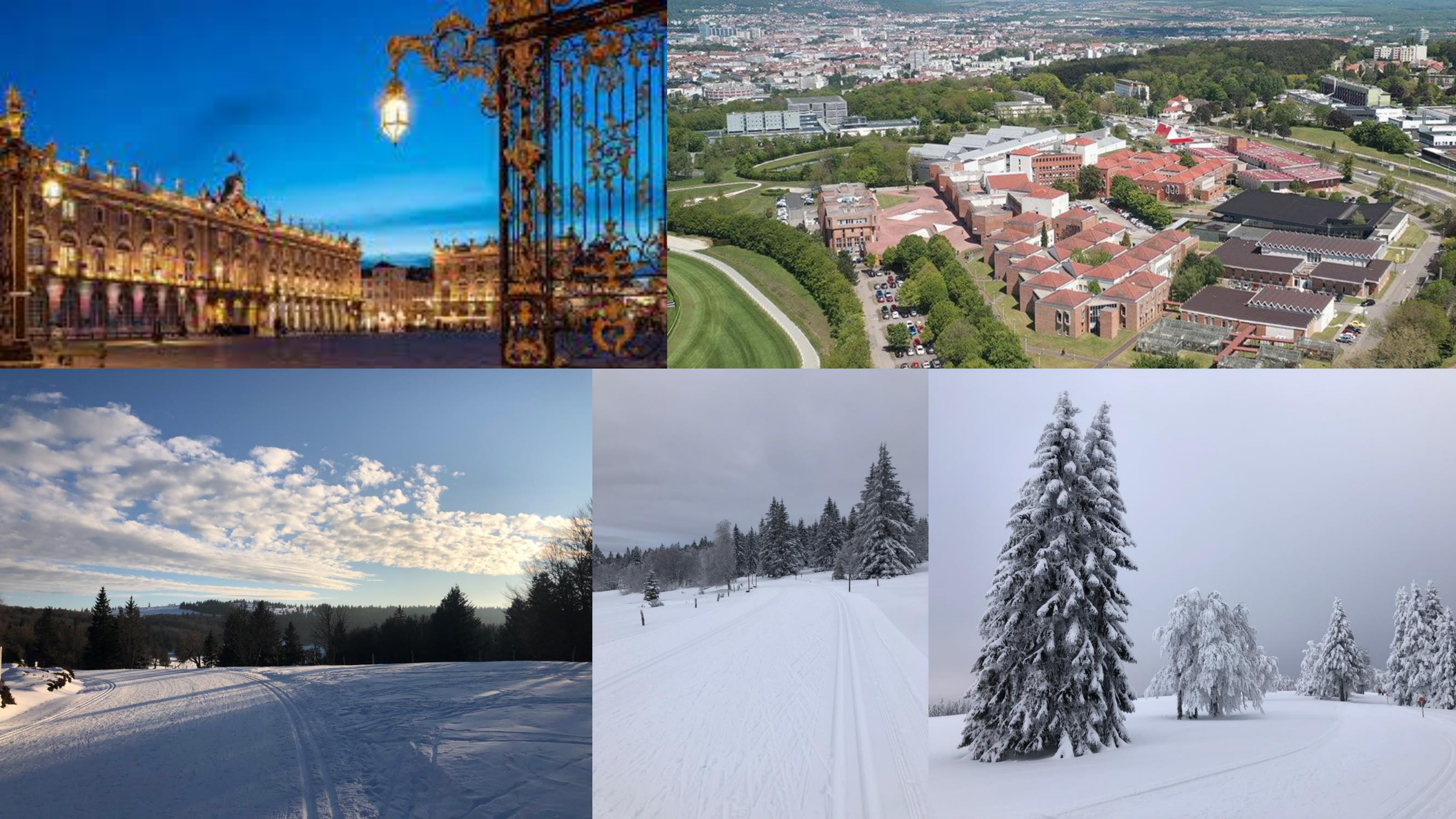

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Thanks !

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