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Heat transfer of liquid drops subject to fragmentation

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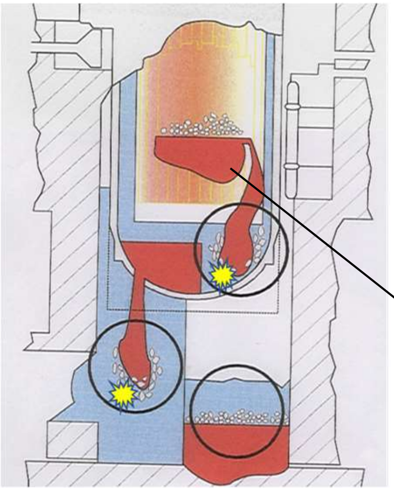
MEMBRE DE
ETSON

Context: Steam Explosion in Nuclear Power Plants

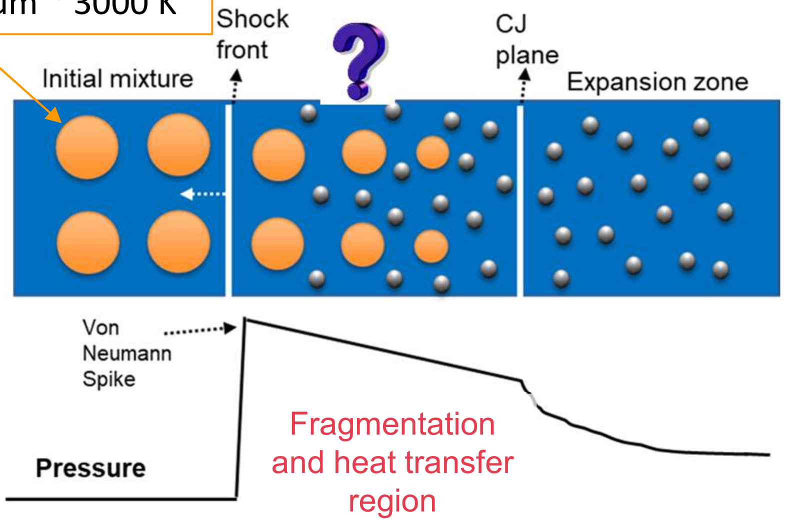
- Steam Explosion ?
  - Analog to a detonation process

    => **Due to fast release of heat from melt to the coolant during the fragmentation process**



Corium: *Mixture of melted fuel and other steels*

Corium ~ 3000 K



$$\tau_{fragmentation} \sim \tau_{cooling}$$

- Fragmentation has been recently addressed with DNS
- But few works on the associated heat transfer
- Note : this issue is problematic in many other processes

Context: status

Complex process involving strong heat transfer during fragmentation:

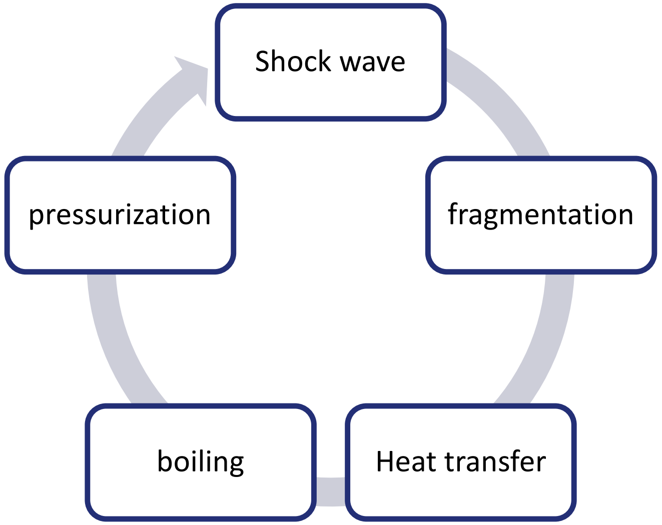
- Characteristic space scale < 100 µm
- time scale ~ 1 ms.

Experiments cannot give enough details of such process in small time/space scale

Direct Numerical Simulation (DNS) to improve understanding and modeling

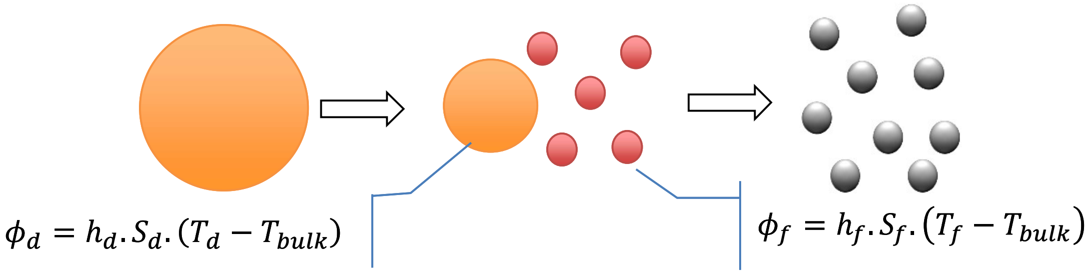
EXPLO: module of **MC3D** CFD software (developed by IRSN)

- Robust with acceptable results
- **But seeking for a new model in better agreement with the most recent DNS studies**.
- In particular the link between heat transfer and fragmentation



Shock wave
fragmentation
Heat transfer
boiling
pressurization

Current modeling of heat transfer with fragmentation in MC3D



$\phi_d = h_d . S_d . (T_d - T_{bulk})$

$\phi_f = h_f . S_f . (T_f - T_{bulk})$

Scheme of the modeling for the fragmentation of liquid drops and heat transfer

Simple decoupling between fragmentation and heat transfer

- fragmentation: reduction of diameter from large drops to smaller ones
- heat transfer = ∑ individual heat transfers of each drop and fragment

Fragmentation and heat transfers behave independently

Does it represent reality ? ⇐ DNS

Is it possible to improve modeling in MC3D based on DNS results?

Approach

- Validation against classical correlation for non deformable spheres
- Analysis of simulations results

1. dynamic aspect : drop **deformation** and **fragmentation:**

   - **verification against available data**

2. thermal aspect : **heat transfer characteristics** during deformation/fragmentation:

   – analysis of the “decoupling” hypothesis

   – understand impact of fragmentation and related heat transfer mechanism

Basilisk: Open-source PDE solver on adaptive Cartesian meshes

http://www.basilisk.fr/

Equations solved in this study :

- Incompressible: $\nabla \cdot \boldsymbol{U} = 0$
- Two phases by VOF method (color function f) : $\frac{\partial f}{\partial t} + \nabla \cdot (f\boldsymbol{U}) = 0$
- NS equation $\rho \frac{\partial \boldsymbol{U}}{\partial t} + \rho \nabla \cdot \boldsymbol{UU} = -\nabla P + \nabla \cdot \mu[\nabla \boldsymbol{U} + (\nabla \boldsymbol{U})^T] + \sigma k \boldsymbol{n} \delta_s$
- Temperature advection and diffusion: $(\rho C_p)\frac{\partial T}{\partial t} + (\rho C_p)\boldsymbol{U} \cdot \nabla T = \nabla \cdot (\lambda \nabla T)$

Physical properties in our simulation

$$\frac{1}{\lambda} = \frac{f}{\lambda_{drop}} + \frac{1-f}{\lambda_{liq}}$$

$$\rho = f \cdot \rho_{drop} + (1-f) \cdot \rho_{liq}$$

$$\mu = f \cdot \mu_{drop} + (1-f) \cdot \mu_{liq}$$

$$\rho C_p = f \cdot (\rho C_p)_{drop} + (1-f)(\rho C_p)_{liq}$$

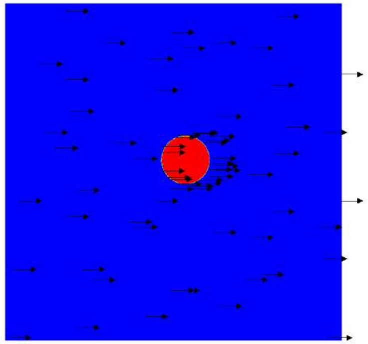
More information:

- Automatic mesh refinement:
- Preliminary investigations:
  - ○ **Temperature = simple scalar with no physical effect (no influence on the flow dynamics)**

    => NO solidification, NO boiling
  - ○ Constant physical properties in each phase

Validation of model against classical correlation

Cold flow pass through a hot and fixed sphere



Geometry

- D = 4.e-3m
- L=7D

Initial condition

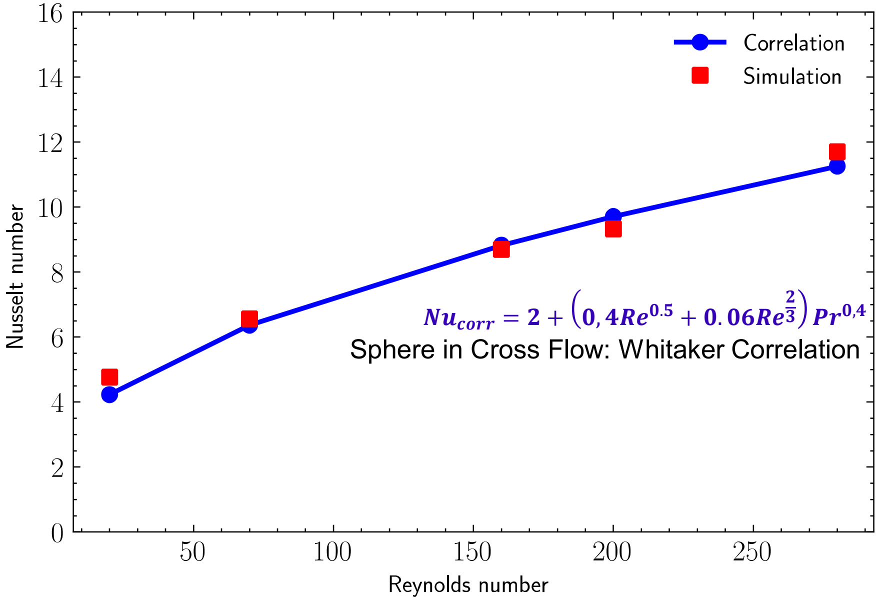
- $V_{liq} = U_0., V_{drop} = 0.$
- $T_{liq} = 0., T_{drop} = T_0.$

Boundary condition

- Left: $U_x = U_0; T = 0.;$
- Right: $P = 0.; \frac{\partial T}{\partial x} = 0.;$
- Side: sliding and adiabatic wall

The temperature and position of the sphere are reset, after each iteration.

The Nusselt number is calculated by integrating the heat flux through interface.



$$Nu_{corr} = 2 + \left(0,4Re^{0.5} + 0.06Re^{\frac{2}{3}}\right) Pr^{0,4}$$

Sphere in Cross Flow: Whitaker Correlation

Nusselt number (under steady state) calculated from the numerical 3D-simulations and classical correlation, Prandtl number=1

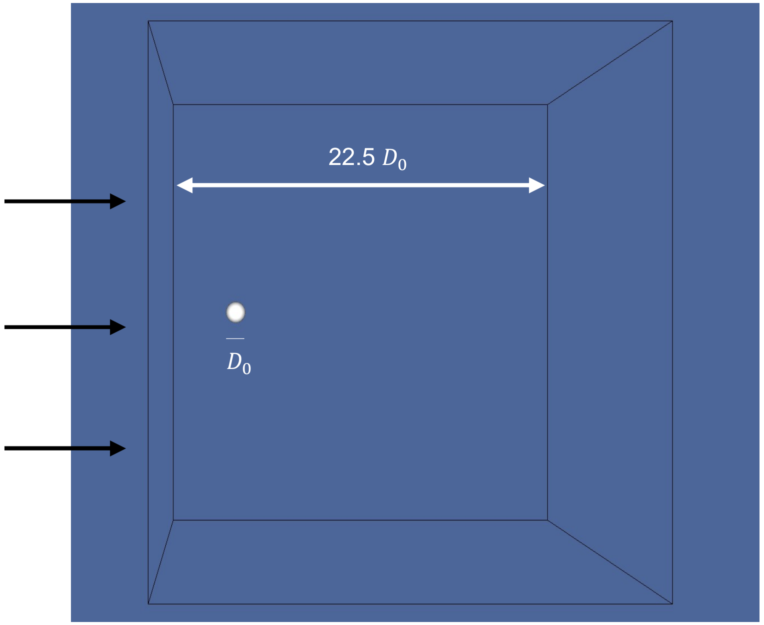
DNS using Basilisk software: heat transfer of a fragmenting drop

- **Characteristic time scale: ~ ms**
- **Characteristic space scale: << mm**

2-phase simulation :
No boiling – no solidification

- Initial condition
  - Liquid: uniform V, a low & homogenous T
  - Drop: at rest with a high & homogenous T
- Boundary condition:
  - Walls: sliding and adiabatic
  - Inlet: fixed V and fixed low T; Outlet: free flow

Initial and boundary conditions



Investigated $We = 2.5$ to 1280

Main number

- **Weber Numbers**: ratio of disruptive hydrodynamic forces to the stabilizing surface tension force

$$We = \frac{\rho_L U_0^2 D_0}{\sigma}$$

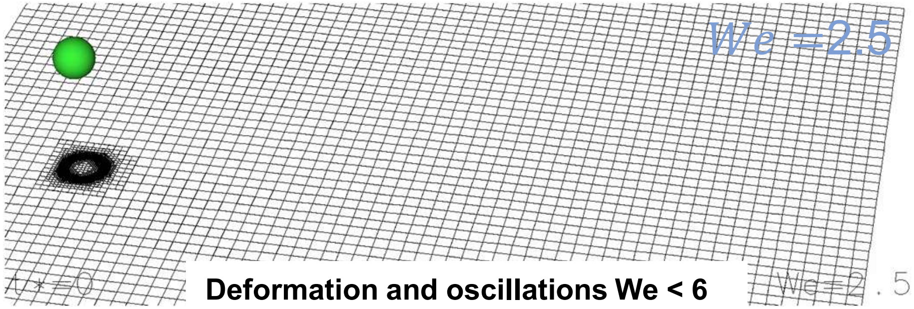
- **Ranger & Nicholls (RN) time**: <u>characteristic time scale for fragmentation</u>, from experimental observation

$$t_{RN} = \sqrt{\frac{\rho_D}{\rho_L}}\frac{D_0}{U_0} \qquad \boldsymbol{t^* = \frac{t}{t_{RN}}}$$

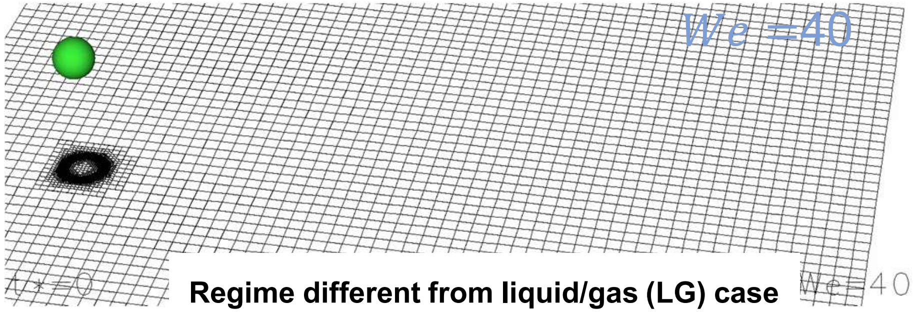
$$\boxed{\begin{array}{c} \tau_{fragmentation} \sim t_{RN} \\ \tau_{cooling} \sim ?\, t_{RN} \end{array}}$$

Dynamic aspect: drop deformation and fragmentation

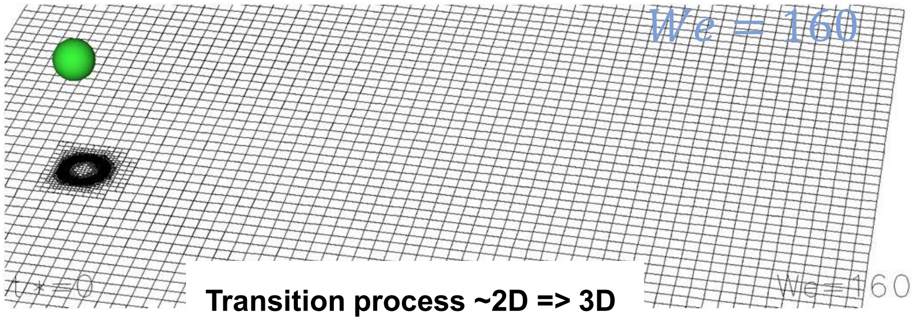
Simulations of Hadj-Achour experiments with drops of **Field’s metal** into water



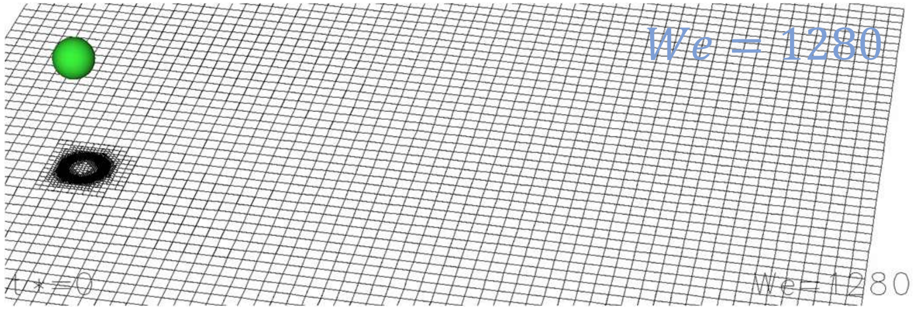
Deformation and oscillations We < 6



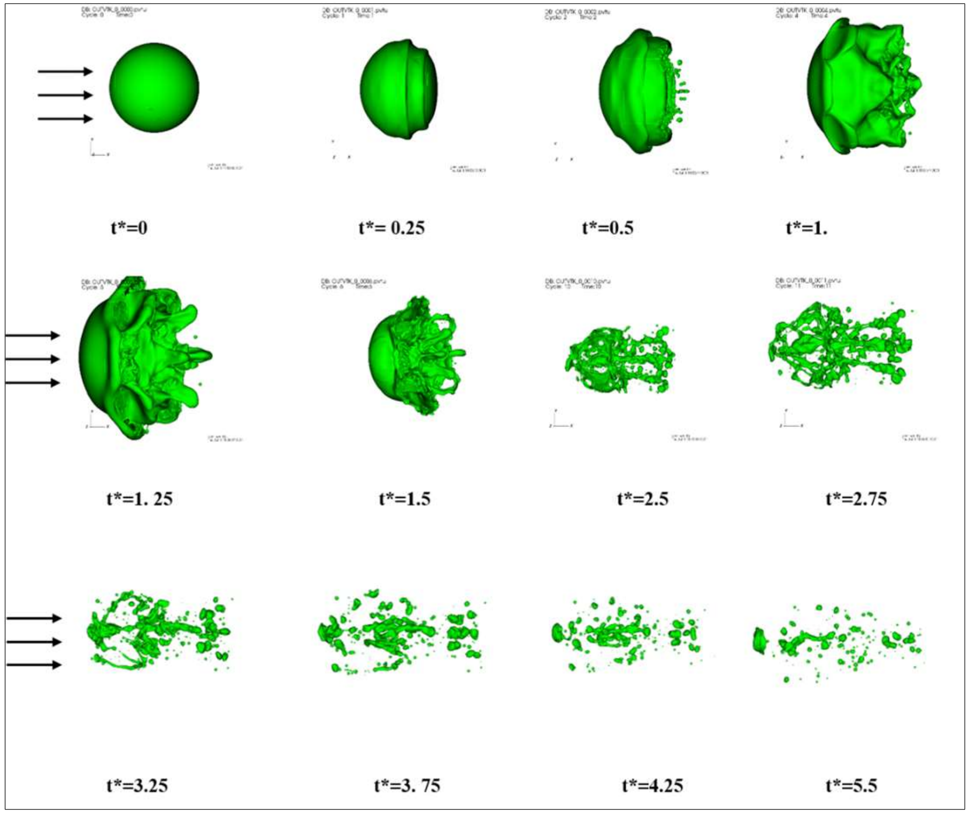
Regime different from liquid/gas (LG) case



Transition process ~2D => 3D

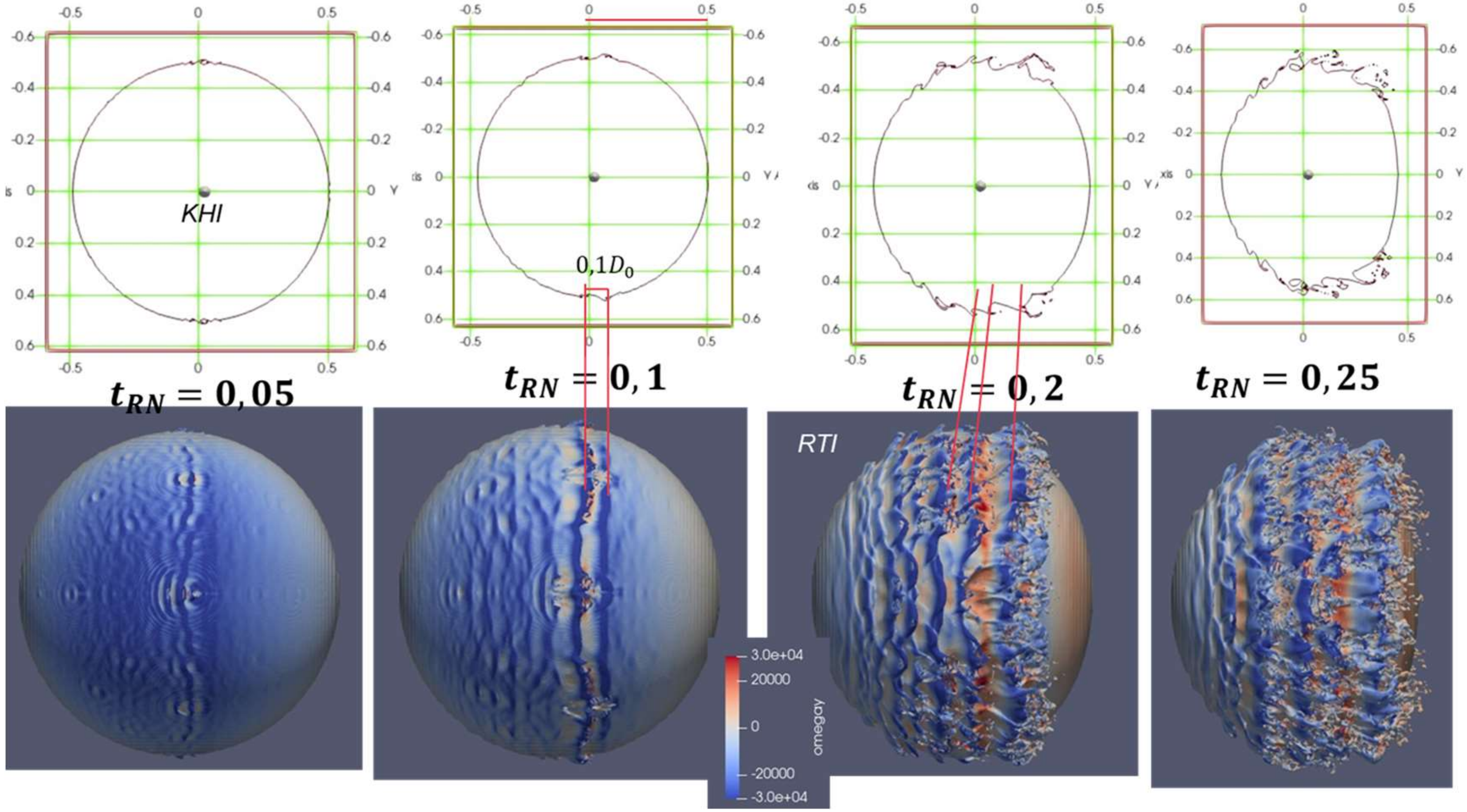


We=160: deformation – entrainment of melt into drop center – fragmentation

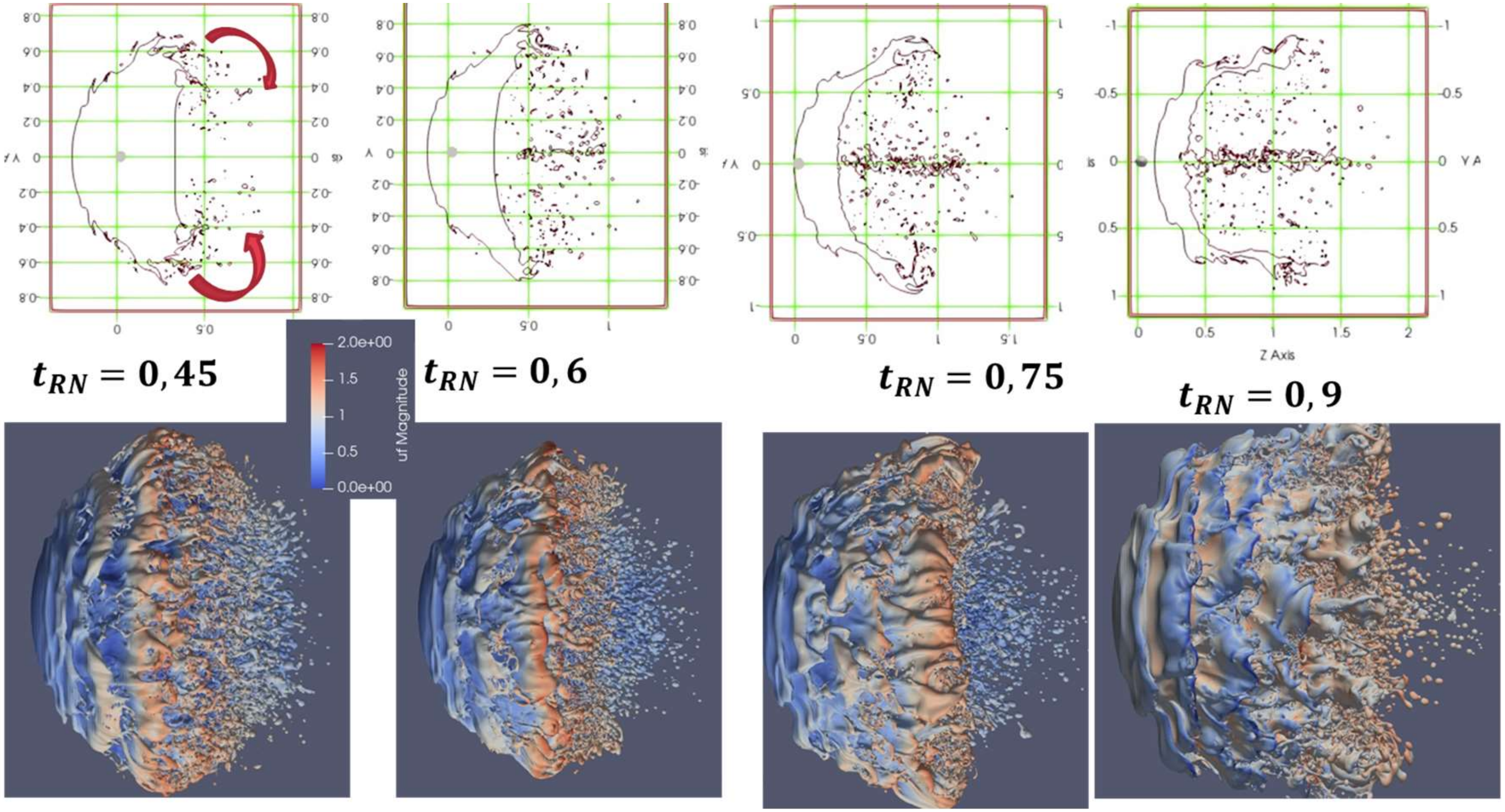


- Tangential instability, Kelvin Helmholtz instability => rapidly destabilized
- Formation of jets => towards the mixture center => fragmentation
- Important melt entrainment => formation of a local mixture (0.5~$2.\,t_{RN}$) => local-interaction zone

We=1280: KHI + stripping at boundary layer



We=1280: boundary layer stripping + fragmentation



$t_{RN} = 0,45$

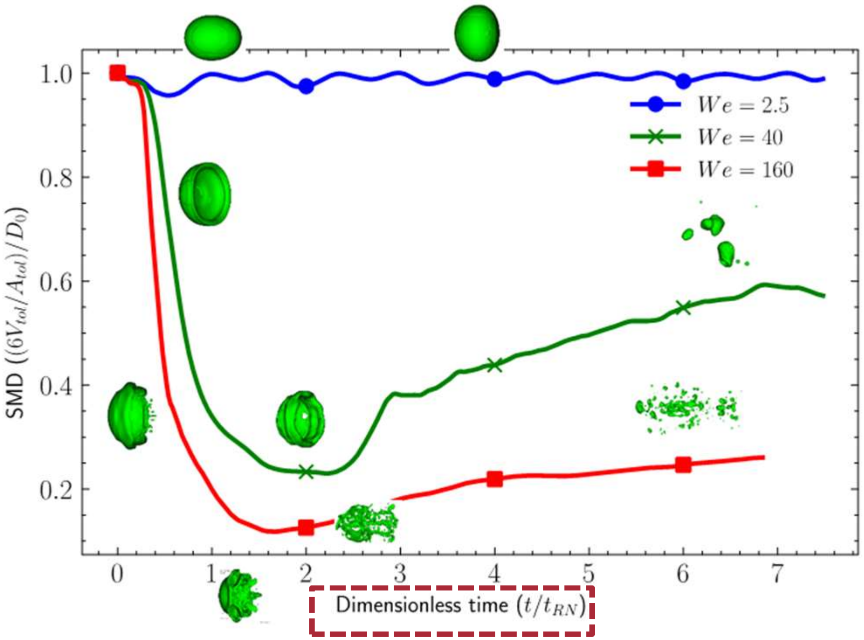
$t_{RN} = 0,6$

$t_{RN} = 0,75$

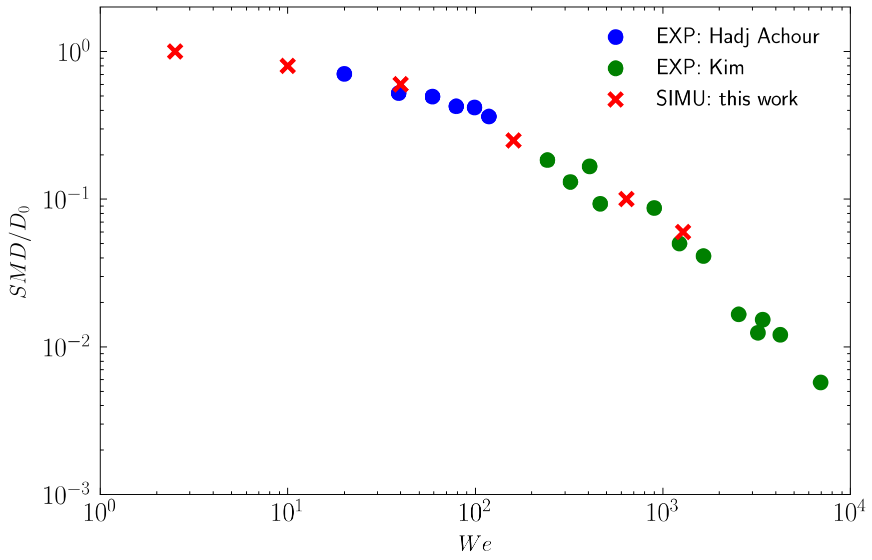
$t_{RN} = 0,9$

Sauter mean diameter (SMD)

- Sauter mean diameter (SMD): $SMD = \frac{6\sum_i V_i}{\sum_i A_i}$
- Important parameter for CMFD modeling to compute heat transfer



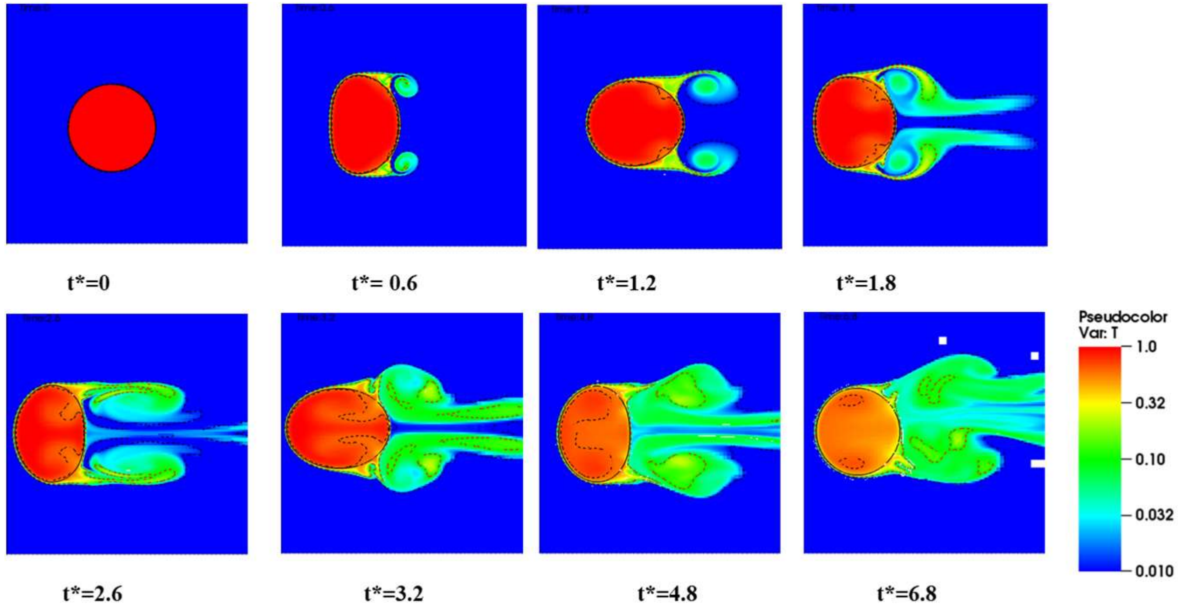
Variation of Sauter Mean Diameter (dimensionless)



*Sauter diameter of fragments (**SMD / D0**) as a function of the Weber number*

⇒ **Good agreement with experiment** (considering uncertainties in the measurements)

Heat transfer with the presence of oscillations (We < 6)



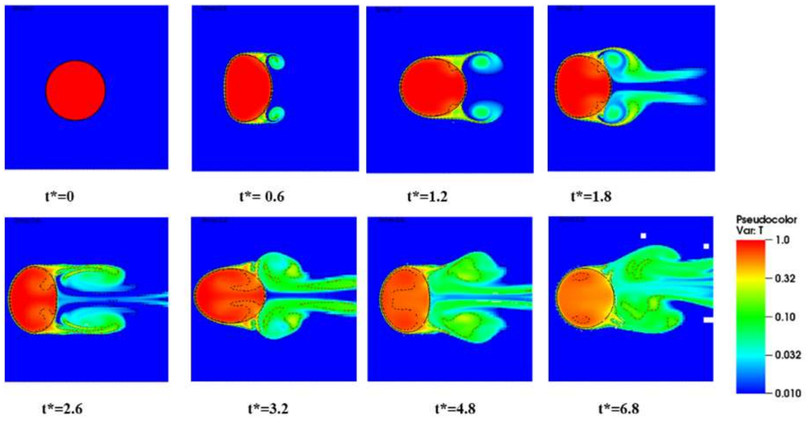
We = 2.5: Temperature field (zoomed axial cut).
The solid line represents the drop-liquid interface.

$$t^* = \frac{t}{t_{RN}}$$

- Movement of internal thermal boundary layer from the back to the center of drop
- Mixing => quite homogenous temperature inside the drop

Note on solidification modeling :
unlikely to form a thick crust

Heat transfer inside with presence of oscillations (We < 6)



From the drop side:

Average temperature: $\overline{T}=\frac{\sum_i V_i f_i T_i}{V_{tot}}$

Total energy of drop: $E = \rho_D C_p V_{tot} \overline{T}$

Heat flux through interface: $\Phi = \frac{dE}{dt}$

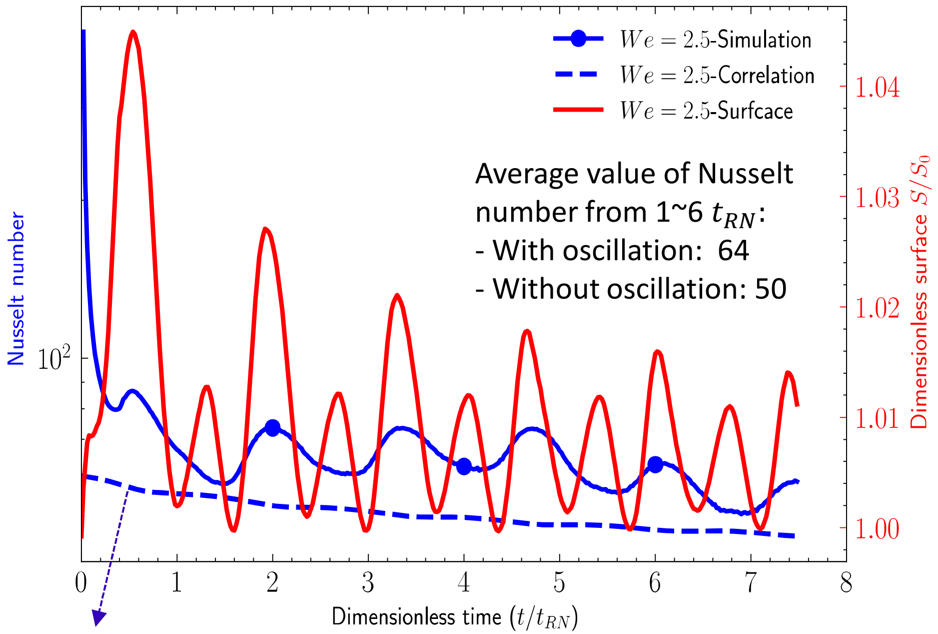
From the fluid side

Average HT coefficient: $h = \frac{\Phi}{S \cdot (\overline{T} - T_{inlet})}$

Average Nusselt number: $Nu = \frac{hD}{\lambda_L}$

$$D = D_0,$$
$$S = S_0$$

Average Nusselt number

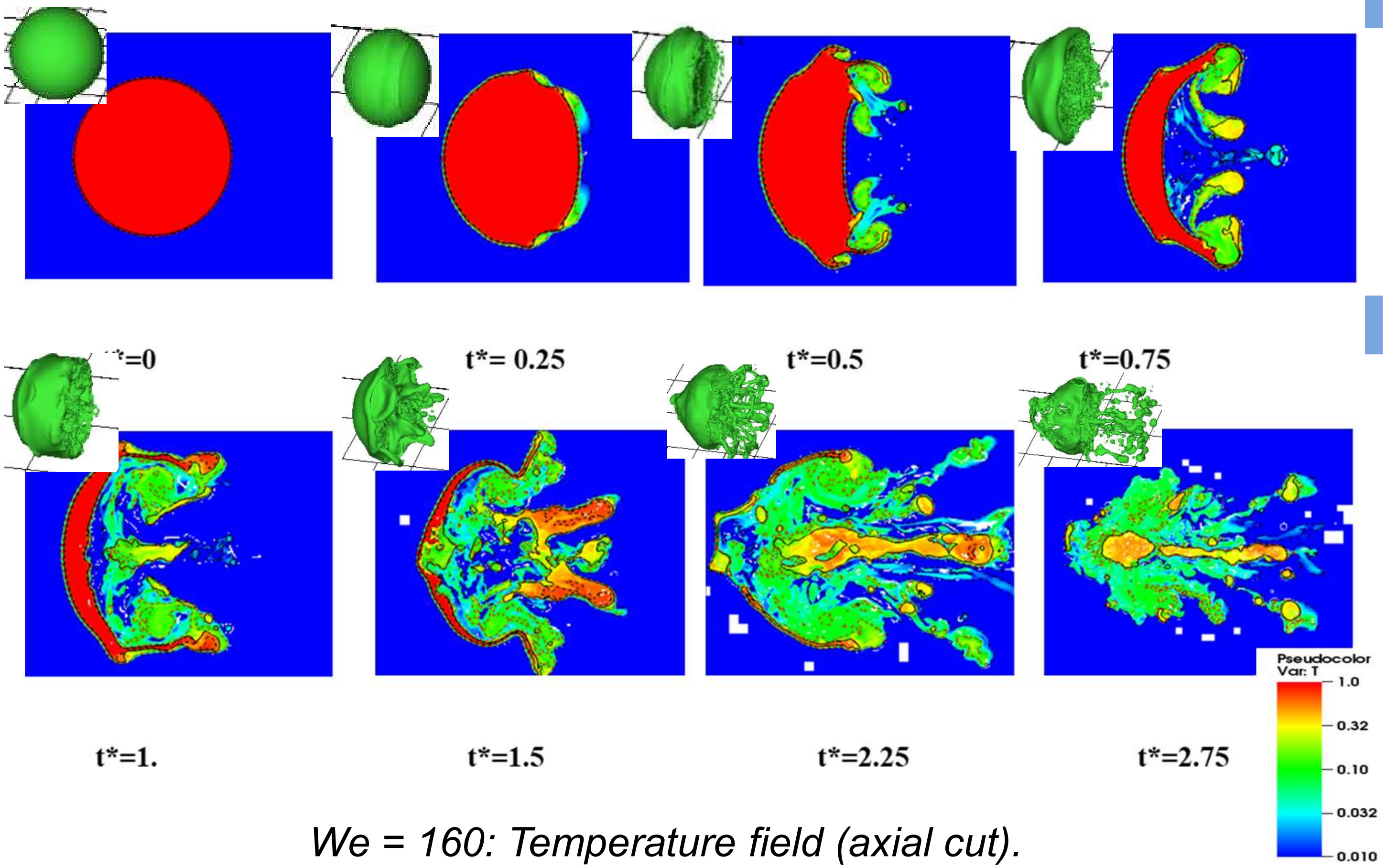


Average value of Nusselt number from 1~6 t_{RN}:
- With oscillation: 64
- Without oscillation: 50

For a non-deformable sphere: $Nu_{corr} = 2 + \left(0,4Re^{0.5} + 0.06Re^{\frac{2}{3}}\right) Pr^{0,4}$

Heat transfer are enhanced by 28%, due to interface area increasing, agitation and turbulence mixing

Heat transfer characteristics for we=160



We = 160: Temperature field (axial cut).

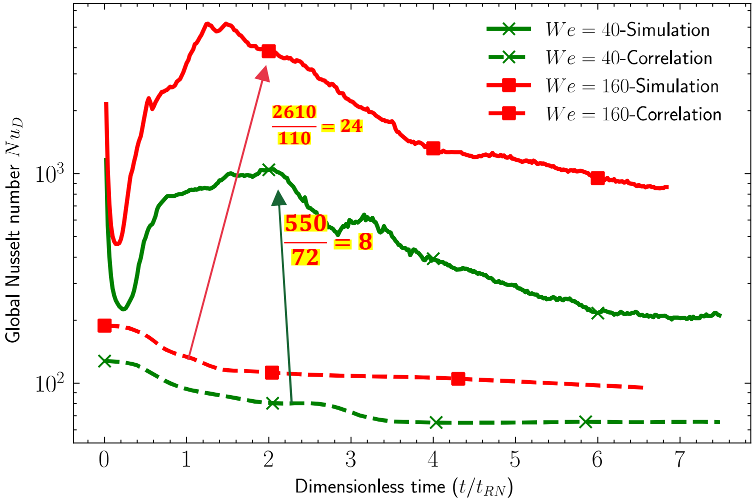
- Existence of interaction zone mixing the fragment and coolant with quite homogenous conditions
- Different from L-G cases: fragments swept away

- Decoupling of fragmentation-cooling?

Impact of fragmentation on the heat transfer

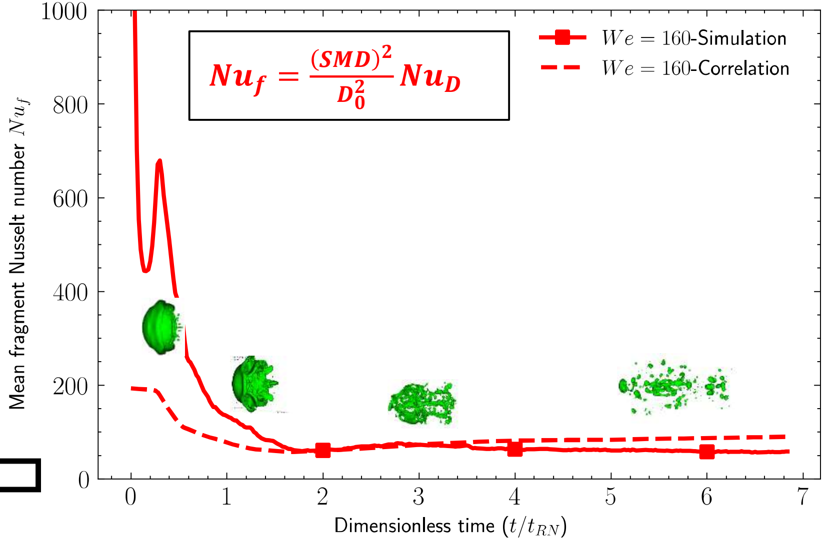
Global Nusselt number

$$h = \frac{\Phi}{\boldsymbol{S_0} \cdot (\overline{T} - T_{inlet})} ; Nu = \frac{h\boldsymbol{D_0}}{\lambda_L}$$



Heat transfer with fragmentation are much enhanced

Mean fragment Nusselt number

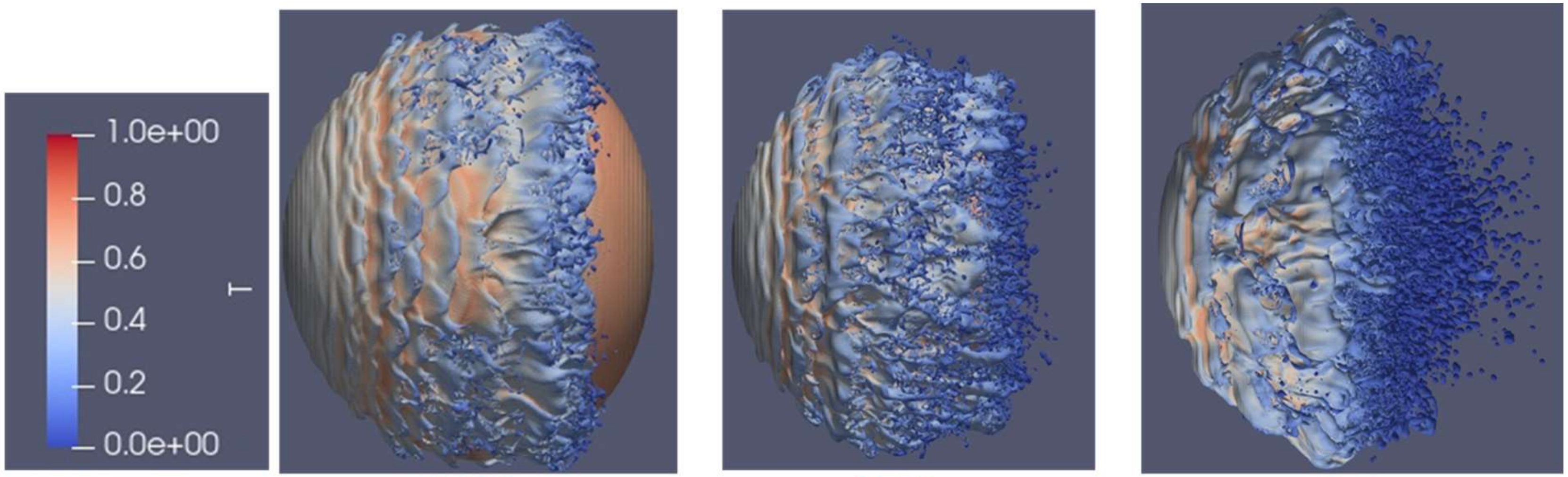


$$Nu_f = \frac{(SMD)^2}{D_0^2} Nu_D$$

The decoupling fragmentation-cooling
- valid only after the highly transient phase
- globally under-estimate the heat transfer

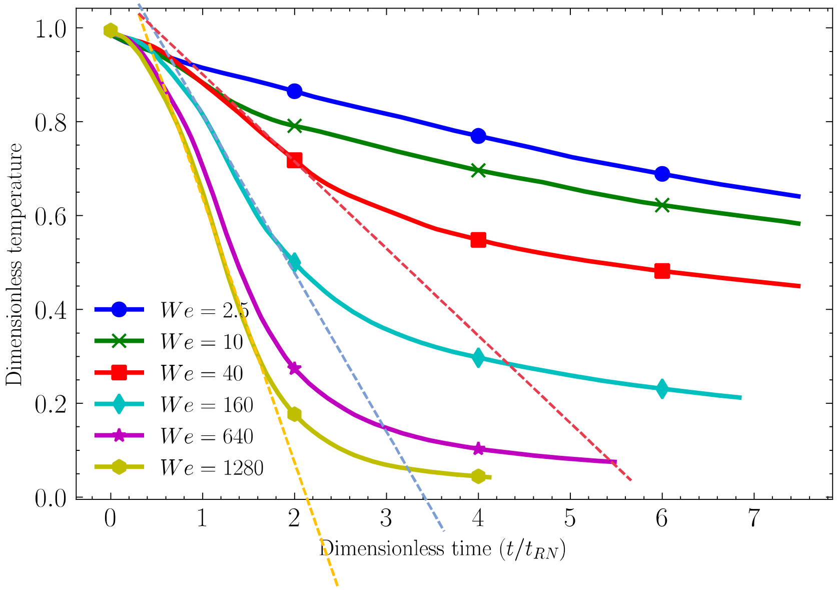
Impact of fragmentation on the heat transfer

- Cooling occurs rapidly on the surface at high We
- Generating cooled fragments (=> effect of solidification)



We=1280 $0.2t_{RN}$ $0.4t_{RN}$ $0.6t_{RN}$

Impact of fragmentation on the heat transfer



melt mean temperature (dimensionless)

- Characteristic time for cooling is not scaling with t_{RN} (in contrast with fragmentation)
- Cooling is comparatively more rapid at high Weber numbers
- Solidification should happen more rapidly at high Weber numbers

Conclusion & perspective

- A DNS approach is employed to better understand the process of heat transfer of a liquid drop being fragmented in another liquid. Investigated cases at We = 2.5 to 1280

- Main results:
  - Effect of drop oscillation:
    - noticeable enhancement of HT due to strong mixing
  - Existence of local interaction zone, in both mechanical and thermal aspect
    - assumption of decoupling fragmentation-heat transfer to be revisited
  - Cooling time scale decreases faster than fragmentation time scale => impact of solidification should limit fragmentation at high We

- Perspective
  - Comparison between the DNS simulation and MC3D results
  - Adaptation of the MC3D model

Thanks for your attention