Secondary breakup in the context of Fuel Coolant Interactions (FCI)

Sebastian Castrillon Escobar[1,2,3], Renaud Meignen[1],

Nicolas Rimbert[2,3], Michel Gradeck[2,3]

(1) Institut de Radioprotection et Sûreté Nucléaire (IRSN), France

(2) LEMTA, Université de Lorraine, France

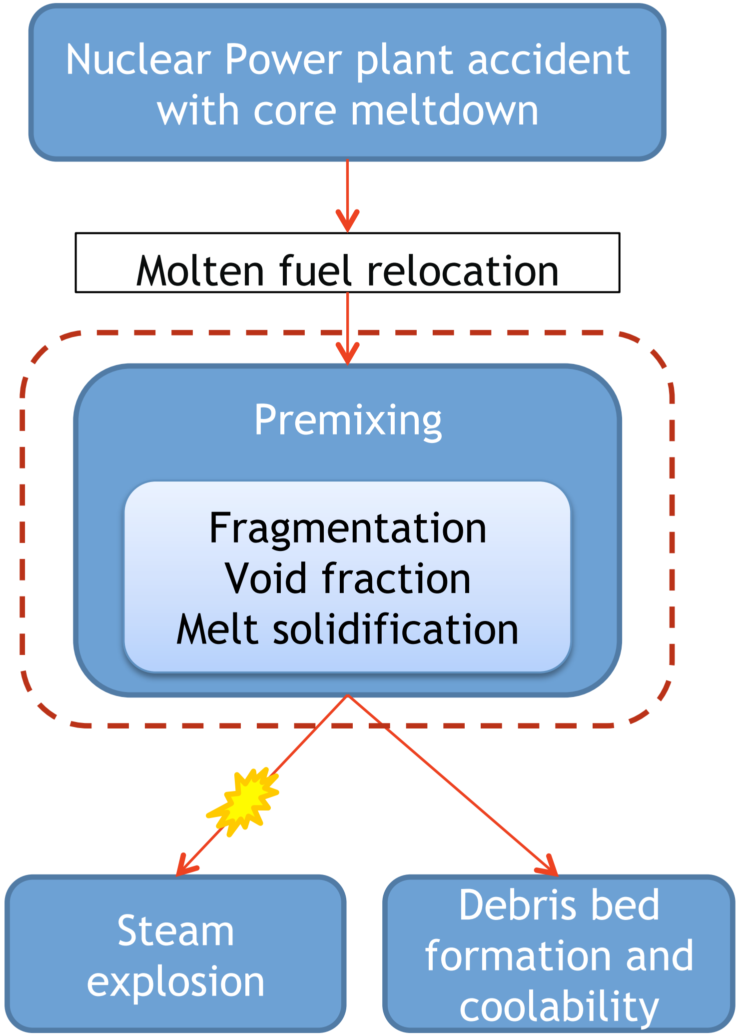
(3) CNRS, UMR 7563, Nancy, France

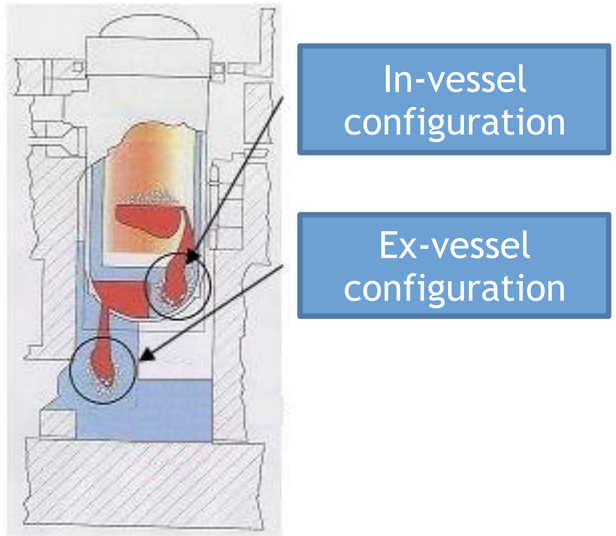
Sebastian.castrillonescobar@irsn.fr

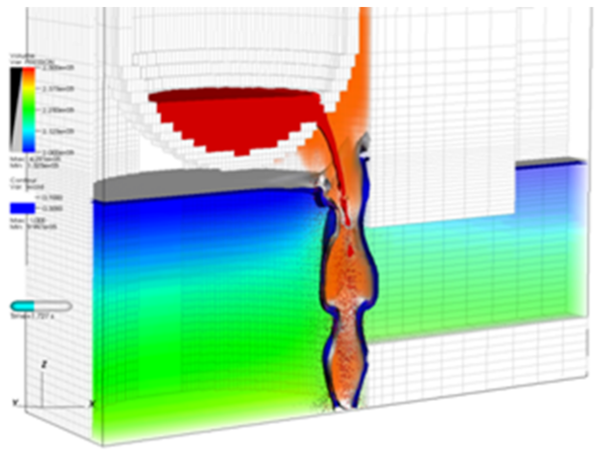
Planning

- General description of Fuel Coolant Interactions (FCI)
- Numerical resources at IRSN to evaluate FCI: MC3D
- Primary and secondary fragmentation
- Secondary fragmentation during FCI
- Drop breakup in liquid/gas and liquid/liquid environments
- Some results using MC3D
- Drop breakup using Gerris code
- Some results and ways of improvement

Fuel Coolant Interactions (FCI)



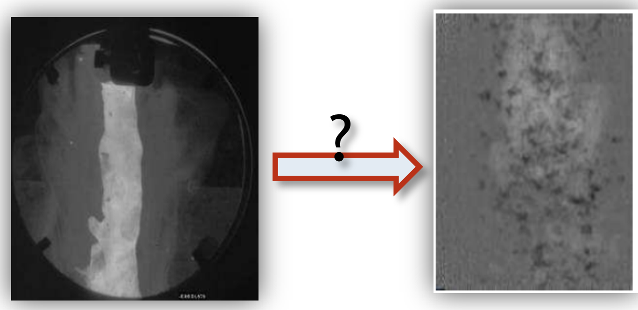




Example of a 3D calculation with MC3D

Position of the problem of corium fragmentation

How a coherent melt jet is transformed into droplets or fragments ?



Krotos KS4

Particular difficulties :

- **Highly non-linear and unstable phenomenon with strong feedback**
- **Impact of melt solidification and oxidation with complex melt compositions**
- **physical properties quite uncertain**

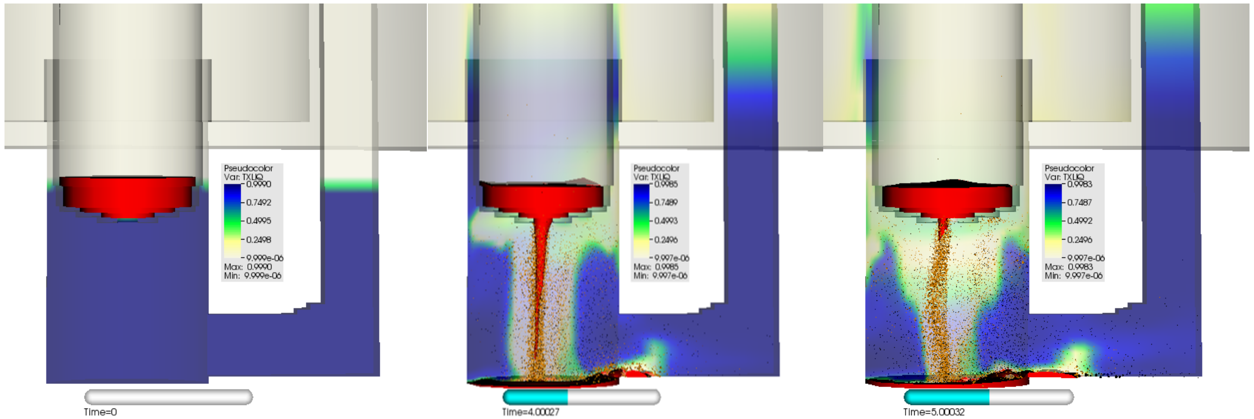
FCI simulation at IRSN; CFD code MC3D

Multiphase code MC3D

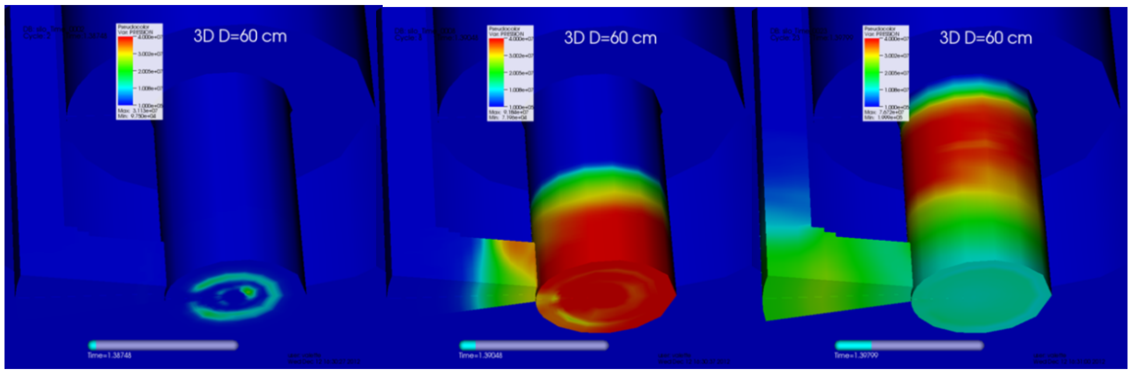
Different fluid fields:

- Liquid coolant and steam + non condensable gases (H2, O2 …)
- Jet (Unfragmented melt, with an interface tracking VOF-PLIC method)
- Dispersed melt droplets

PREMIXING



EXPLOSION



Melt jet fragmentation during premixing

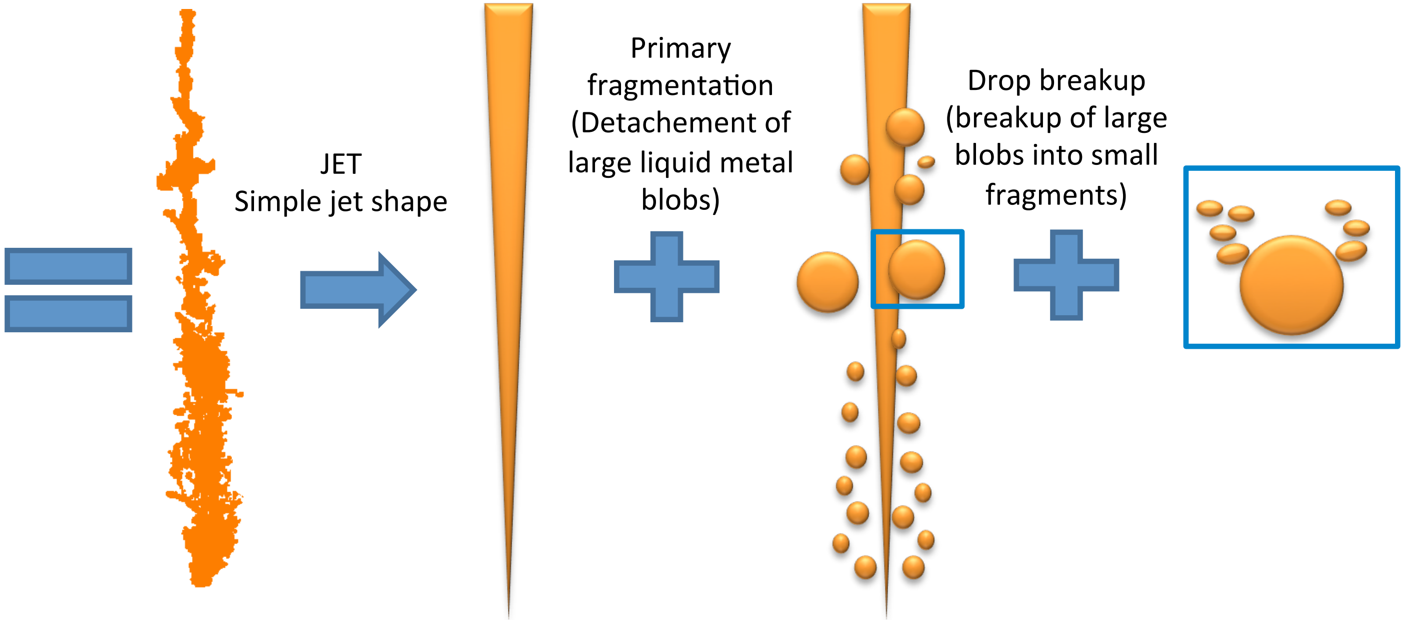
- <u>Primary fragmentation</u>

  Large scale jet destabilisation – Detachement of large blobs from jet

- <u>Secondary fragmentation</u>

  Breakup of blobs and droplets following local scale hydrodynamic conditions

Matsuo et al. 2008



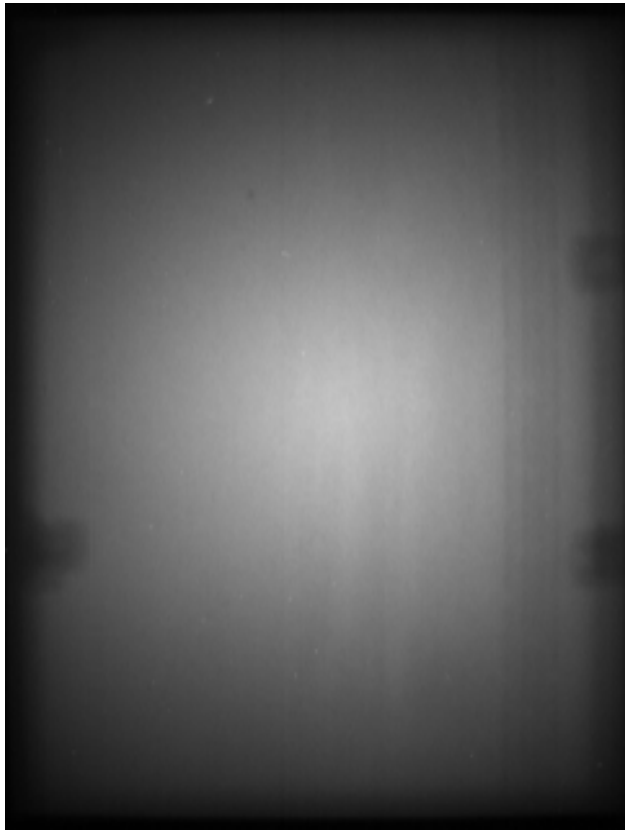
Secondary fragmentation on FCI

Jet injection and premixing zone

Secondary breakup during:

- Free fall of jet
- Contact of corium blobs with water flow
- High speed counter flow

Watching the premixing zone with X-ray !!!



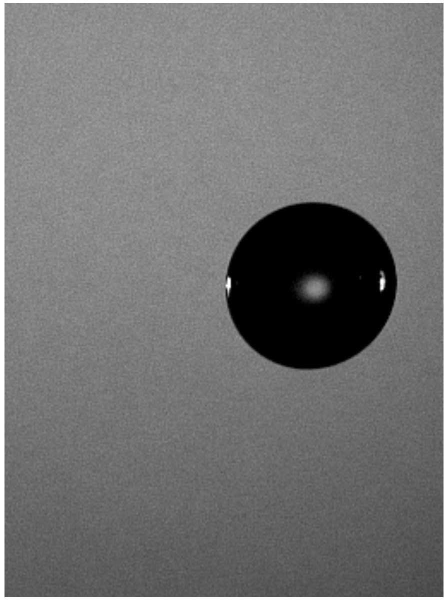
Krotos KS4

Secondary fragmentation on FCI

Liquid Metal-liquid configuration
1000°C Tin droplet in water

De Malmazet 2009

Liquid-gas configuration



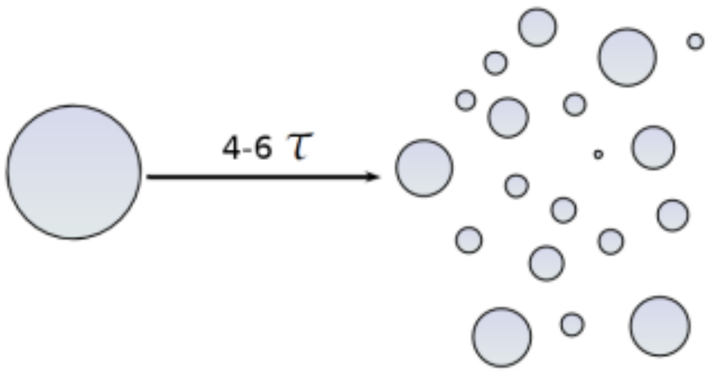
Theofanous et al. 2012

Preliminary hypothesis on secondary breakup during FCI:

- Hydrodynamic fragmentation controls the global behavior of breakup
- Weak influence of local thermal interactions
- Weak influence of steam film around droplets
- Breakup following pure liquid/gas or liquid/liquid configuration

Modelling hypothesis

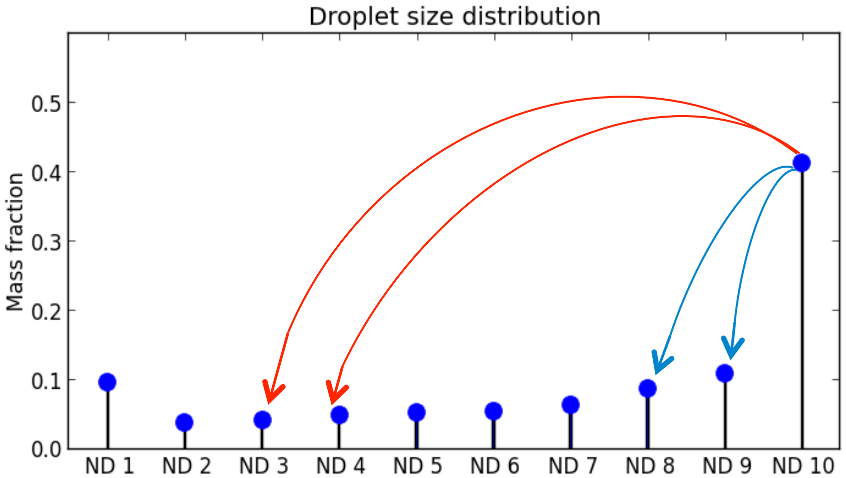
- Drop breakup
  - when the Weber number > critical value
- Drop fragmentation models
  - shear breakup regime
- Fragmentation ends in
  - 4 to 6 characteristic Ranger and Nicolls time



$$\tau_d = \frac{D_d}{\Delta V_{dc}} \sqrt{\rho_d / \rho_c}$$

- Low Ohnesorge number
- No solidification

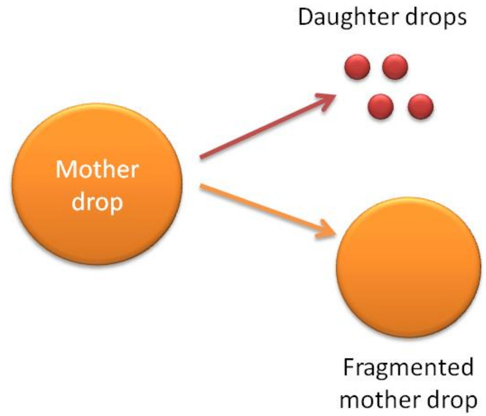
Dispersed phase modelling in MC3D



Small fragments large drops

Water velocity field | Drop velocity field 2 | Drop velocity field 1

Inhomogeneous MUSIG method



Drop fragmentation rate

$$\Gamma_{frag,drop\to drop} = \alpha_d \rho_d \, c_{frag} \frac{\Delta V_{dc}}{D_d} \sqrt{\frac{\rho_c}{\rho_d}}$$

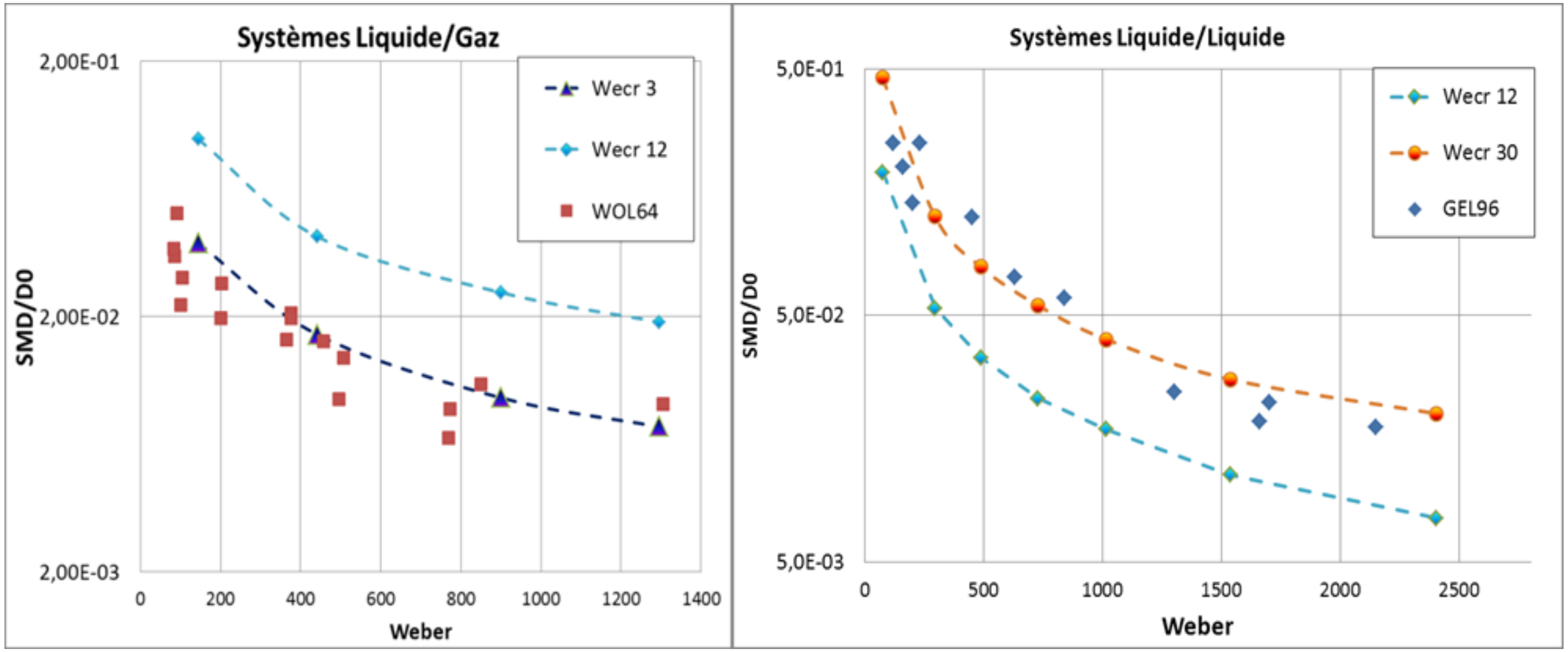
Generated fragment size

$$d_{daughter} = \frac{We_{ch}\sigma}{\rho_c (\Delta V_{dc})^2}$$

$$We_{ch} = Constant$$

Best results using a constant characteristic Weber number

Drop breakup validation



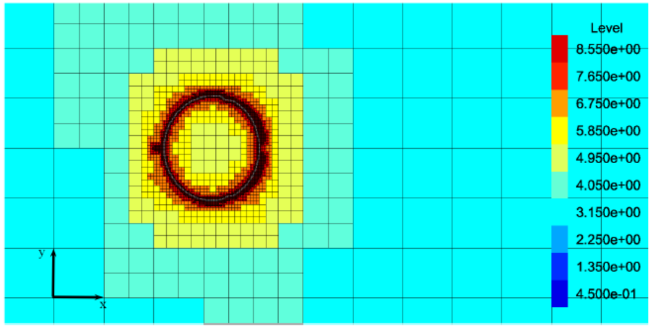
- Different droplet size coefficient values for liquid/gas and liquid/liquid environments.
- Same fragmentation rate for L/L and L/G cases.
- Model is still too much user-dependent

Impove analysis of fragmentation process

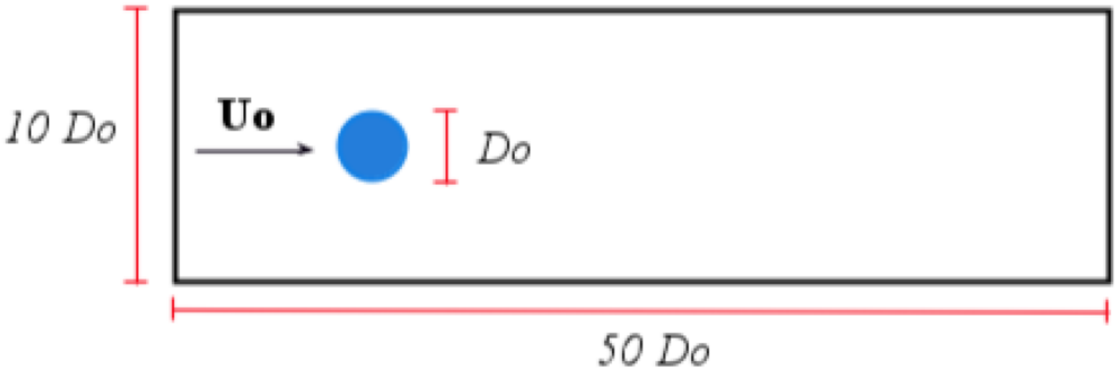
- Difference between L/L and L/G
- Influence of physical properties
- Drag coefficient during breakup

Simulation of drop breakup using Gerris

- Why gerris???
  - Adaptive mesh refinement (AMR)
  - Parallel calculations / Fast calculation time
  - Previous studies of drop breakup performed with this CFD code
  - Internship with a Master student from UMPC (Azzara Annunziato)
  - Outputs for droplet size distribution



- Calculation parameters and domain
  - Liquid/Liquid (Gallium/Water) configuration (Surface tension of 0.7 N/m)
  - Weber number until 1300 => Range of FCI premixing stage



Mesh criteria and simulation cases

- Based on a characteristic Weber number
  - Imposed minimum daughter size

$$\alpha = \frac{D_{probl}}{D_{daughter}} = \frac{We_{probl}}{We_{frag}}$$

  - Ratio between mother drop and box length size

$$L = \beta \cdot D_0$$

  - Gamma: Minimum number of cells per droplet

$$\gamma = \frac{D_{min}}{\Delta X_{min}} = 4.$$

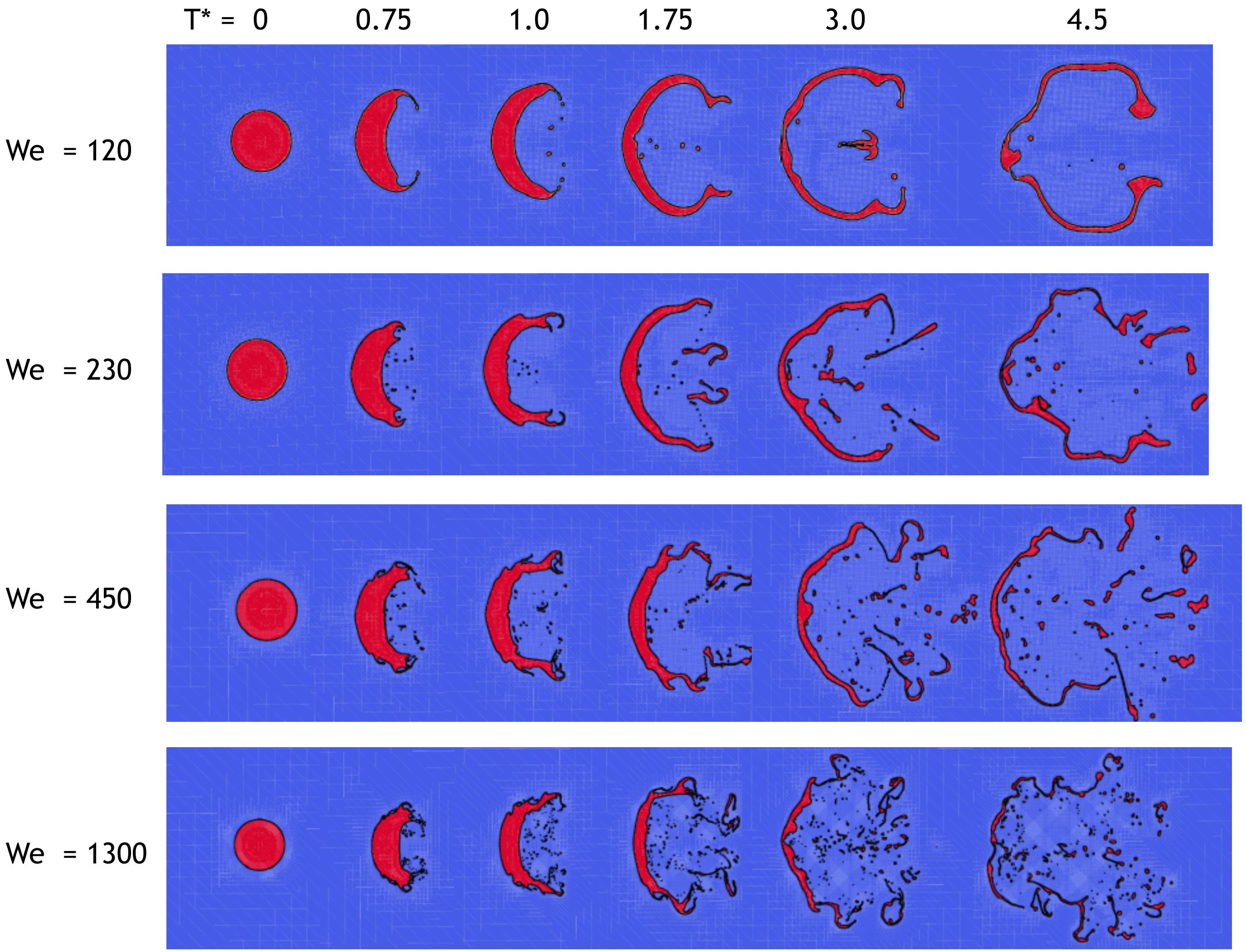
  - Maximum refinement level

$$LEVEL = \frac{\ln(\alpha \cdot \beta \cdot \gamma)}{\ln 2}$$

Parameter	*Symbol*	*Formula*	*Value*
Density ratio	ρ^*	ρ_d/ρ_c	6.07
Viscosity ratio	μ^*	μ_d/μ_c	1.6
Reynolds number	Re	$\frac{\rho_c D_0 u_0}{\mu_c}$	16 692–58 956
Weber number	We	$\frac{\rho_c D_0 u_0^2}{\sigma}$	120–1300

ID	D_0 (mm)	*We*	*Re*	τ (s)	α	*Level*
a	3.3	120	16692	$1.61 \cdot 10^{-3}$	10.0	9
b	4.2	160	21744	$2.00 \cdot 10^{-3}$	13.3	9
c	4.2	230	26071	$1.67 \cdot 10^{-3}$	19.2	10
d	2.4	200	18377	$7.72 \cdot 10^{-4}$	16.7	10
e	2.8	450	29775	$6.49 \cdot 10^{-4}$	37.5	11
f	3.3	630	38246	$7.02 \cdot 10^{-4}$	52.5	11
g	3.8	1300	58956	$6.04 \cdot 10^{-4}$	108.3	12

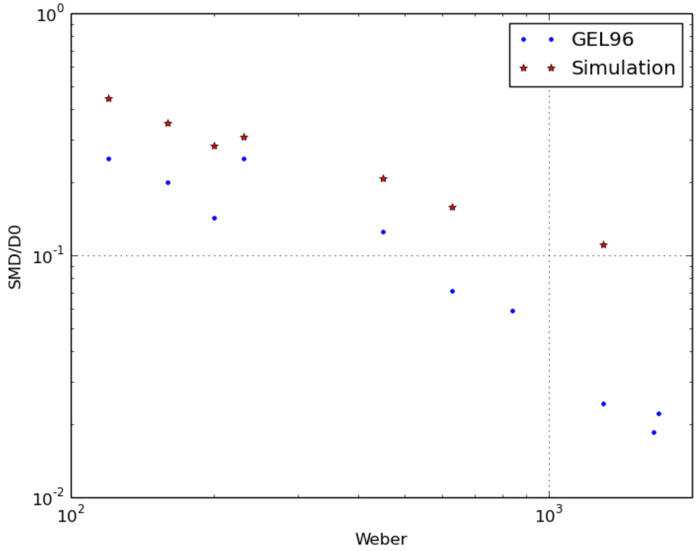
Some results (2D calculations)

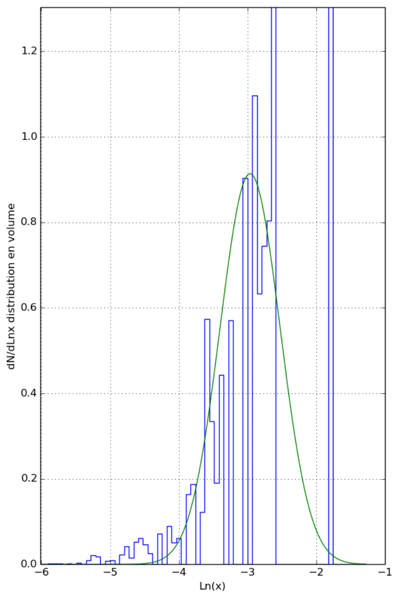


Droplet size distribution

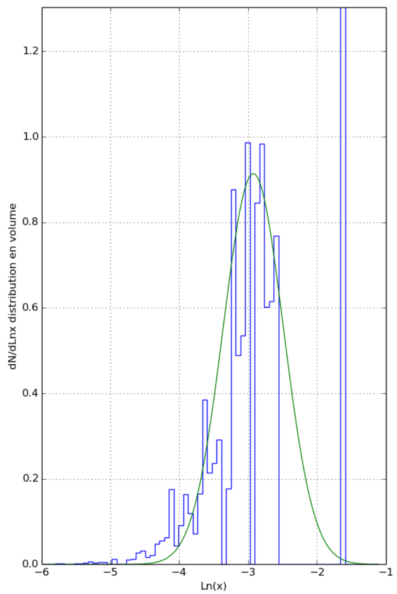
- Overestimation of the final Sauter Mean Diameter

- Results are not easily fitted with a log-normal distribution (no many simulations available to perform a statistical study)

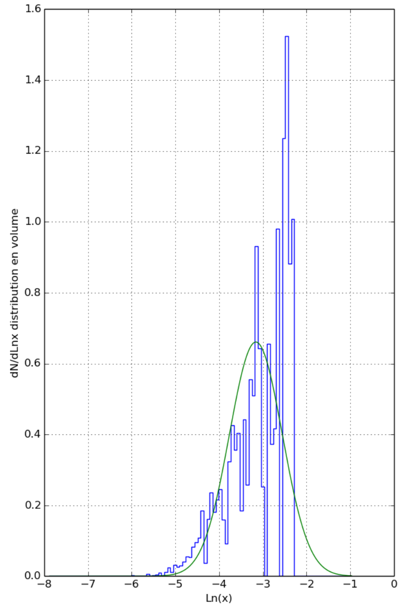




We = 450
D50/SMD = 1.1



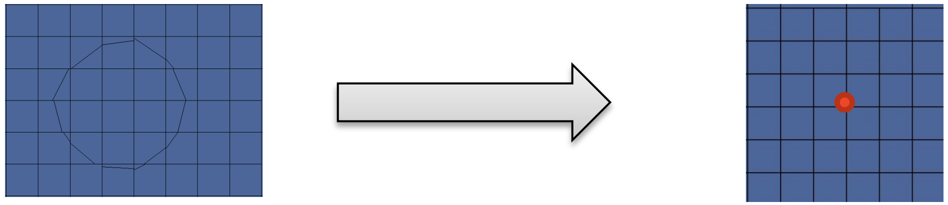
We = 630
D50/SMD = 1.1



We = 1300
D50/SMD = 1.2

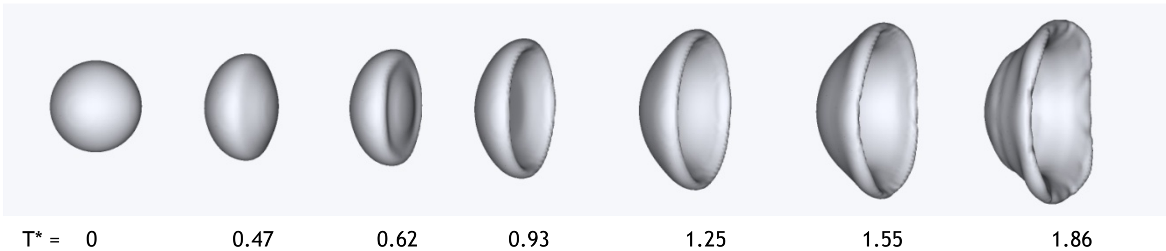
How to improve simulations ???

- Convert VOF droplets into point-lagrangian particle when they become too small (They are generally stable => no further fragmentation)

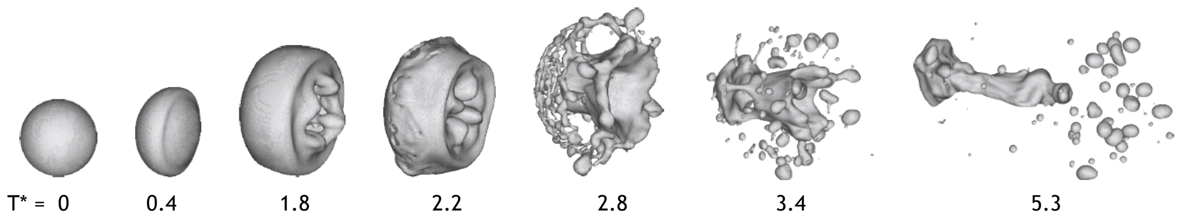


- Perform 3D simulations at different Weber numbers

We = 30



We = 120



- Better mesh refinement criteria (Higher refinement level)

What's next???

- Introduce Lagrangian particules
- Perform data post-processing
  - Droplet size distribution
  - Droplet deformation
  - Drag coefficient
- Comprehension of droplet breakup in Liquid/Liquid systems and comparison with droplet breakup in FCI
  - Main mechanism for fragmentation
  - Effect of steam film (comparing drop entrainment)
- Deduce correlations or propose a new model to be implemented on MC3D
- Validation using the inhomogeneous MUSIG method

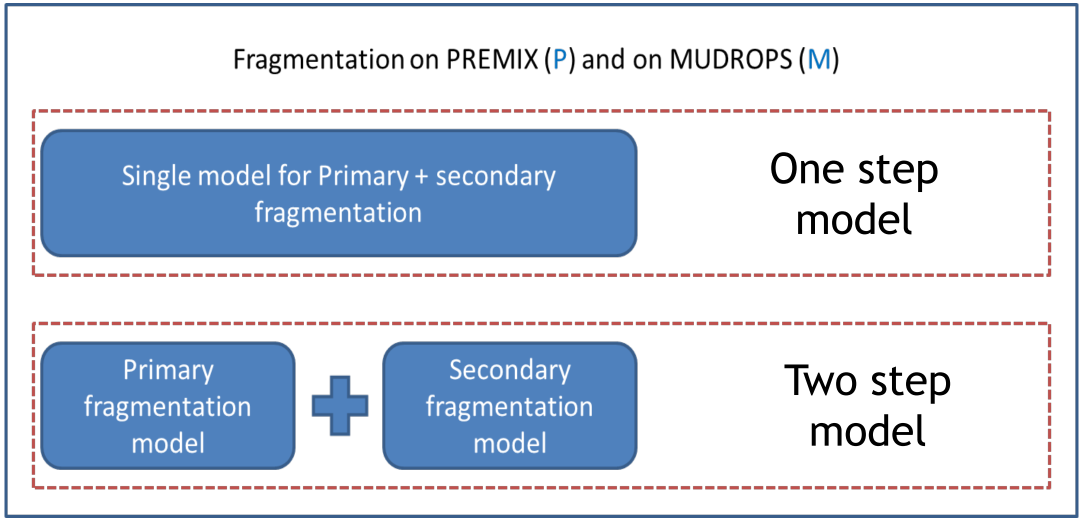
IRSN
INSTITUT
DE RADIOPROTECTION
ET DE SÛRETÉ NUCLÉAIRE

Lemta
Laboratoire d'Energétique et de
Mécanique Théorique et Appliquée

Thank you

Scope of work

1. Introduction, evaluation and analysis of fragmentation source terms
   - ✓ Primary and secondary breakup
   - ✓ coupled fragmentation models

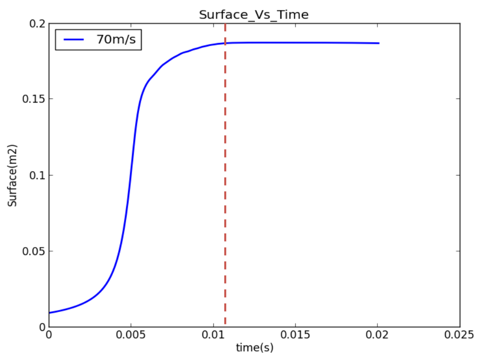
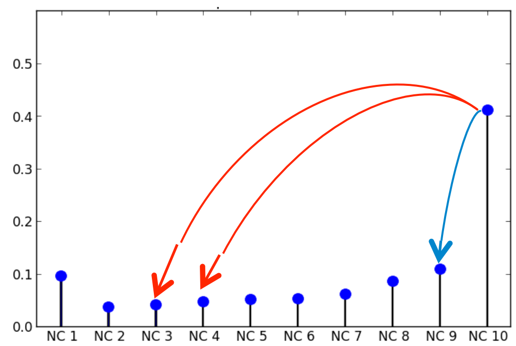


2. Introduction of Multi-Size Group (MUSIG) approach
   - ✓ Homogeneous: One velocity field
   - ✓ Inhomogeneous: Multi-velocity

Take into account polydisperse droplets and improve:

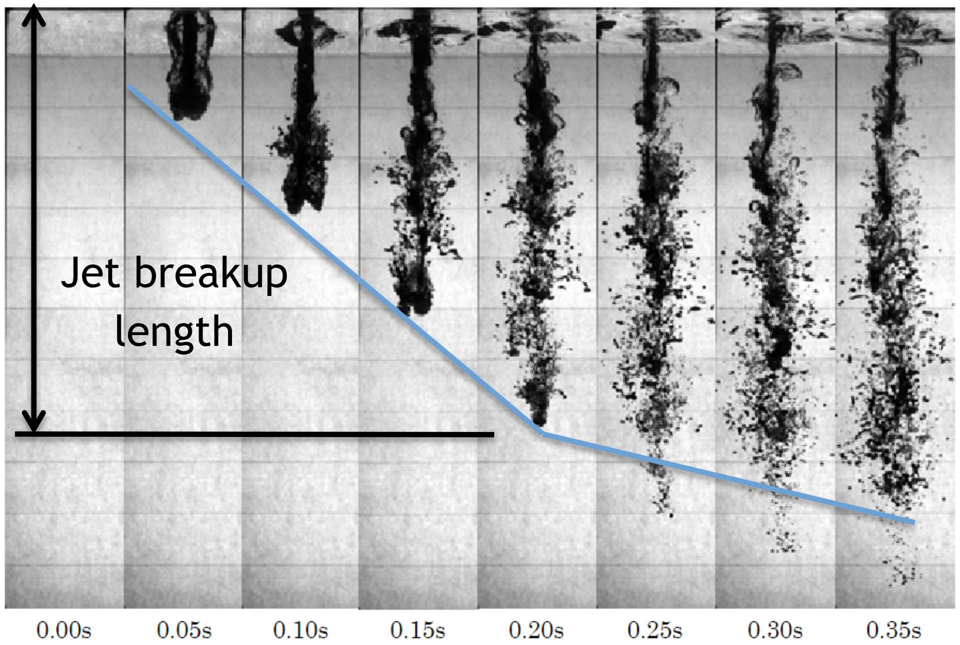
- Heat transfer
- Oxydation
- Solidification
- Breakup process

Fragmentation source terms

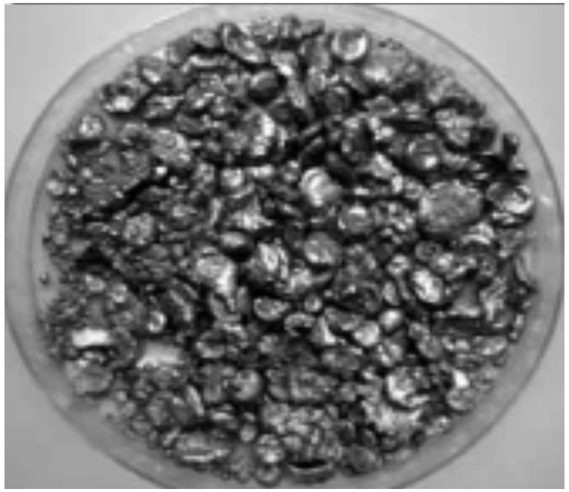
	PREMEL (one droplet field + droplet area equation)	MUDROPS (Several droplet classes)
Primary fragmentation	- Mass transfer from jet to droplet field $\Gamma_{frag}^{+,jet\to drop}$ - Droplet area creation $\Gamma_{A}^{+,jet\to drop}$	- Mass transfer from jet to several droplet classes $\Gamma_{frag}^{+,jet\to drop}$
Secondary fragmentation	- Droplet area creation $\Gamma_{A}^{+,drop\to drop}$ 	-Mass transfer between droplet classes $\Gamma_{frag}^{+,drop\to drop}$ 

Available experimental data / Validation

Liquid metal jet breakup experiments



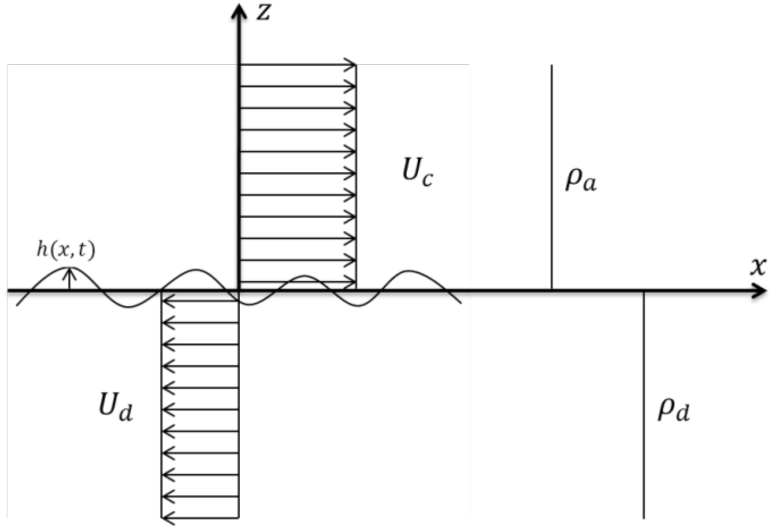
- Final SMD
- Jet breakup length
- Droplet size distribution (for few experiments)

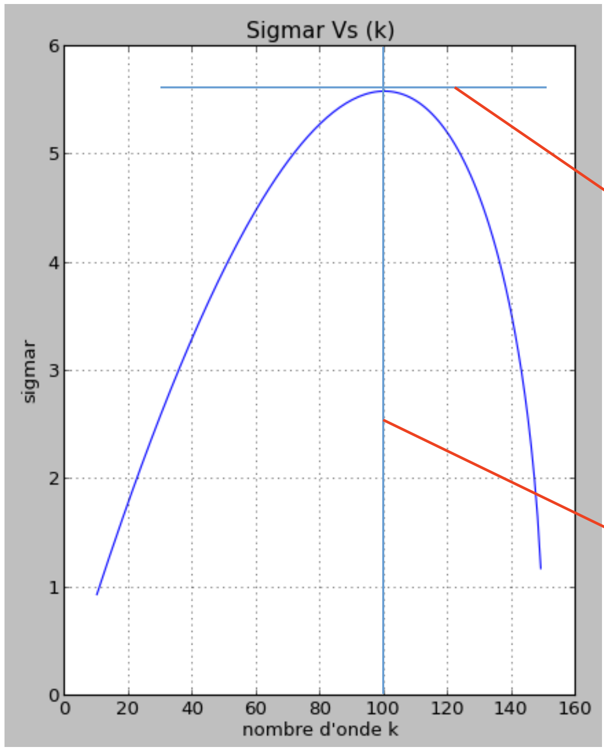


Solid fragments for a jet injection velocity of 2,10 m/s (ABE, et al., 2006)

Modelling hypothesis

Primary breakup related to the most unstable wave at the sheared interface





Instability growth rate

$\sigma\downarrow r,maximum$

(c↓i =

Proportational factor

$N\downarrow f$

Jet Fragmentation rate

$\Gamma\downarrow frag = N\downarrow f\ c\downarrow i$

most unstable wavenumber corresponding to the maximum growth rate

$(\lambda\downarrow maximum = 2$

Proportational factor

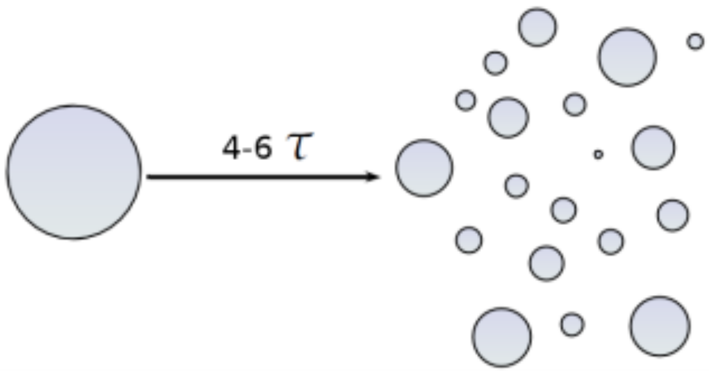
$N\downarrow d$

roplet siz

$D\downarrow d,creation = N\downarrow d\ \lambda\downarrow m$

Modelling hypothesis

- Drop breakup
  - when the Weber number > critical value
- Drop fragmentation models
  - shear breakup regime
- Fragmentation ends in
  - 4 to 6 characteristic Ranger and Nicolls time



$$\tau_d = \frac{D_d}{\Delta V_{dc}}\sqrt{\frac{\rho_d}{\rho_c}}$$

•Low Ohnesorge number

•No solidification

MUDROPS modelling

Primary fragmentation

Droplet size distribution: Log-normal distribution characterized by:

$$SMD = N_d \, 3\,\pi\sigma(\rho_d + \rho_c)/\Delta V_{dc}^{2} \, \rho_d \rho_c \qquad SMD/D_{0,50} = 1{,}2$$

Fragmentation rate: $\Gamma_{frag,drop \to drop} = N_f \, \Delta V_{dc} \, \sqrt{1/3 \, \rho_d \rho_c} \, / \rho_d + \rho_c$

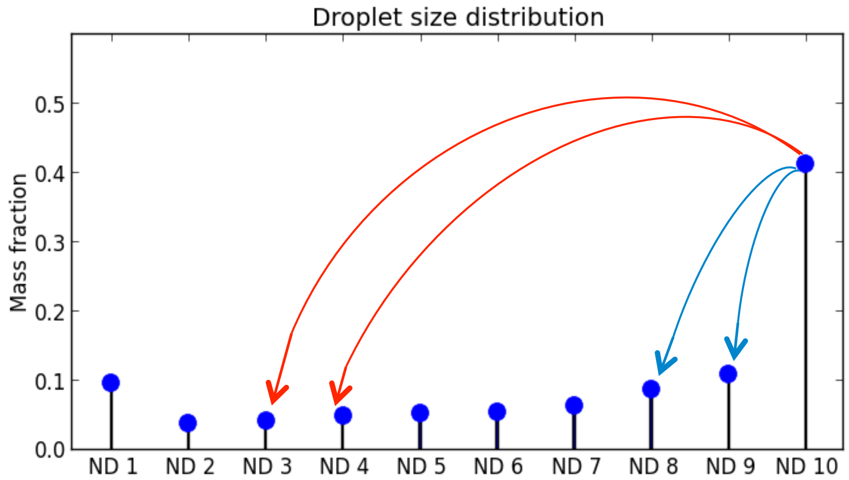
MUDROPS modelling

Secondary fragmentation

Drop fragmentation rate $\Gamma_{frag,\,drop\to drop} = \alpha_d \rho_d\, c_{frag}\, \Delta V_{dc} / D_d \sqrt{\rho_c / \rho_d}$

Generated fragment size $d_{daughter} = We_{ch}\, \sigma / \rho_c\, (\Delta V_{dc})^2$

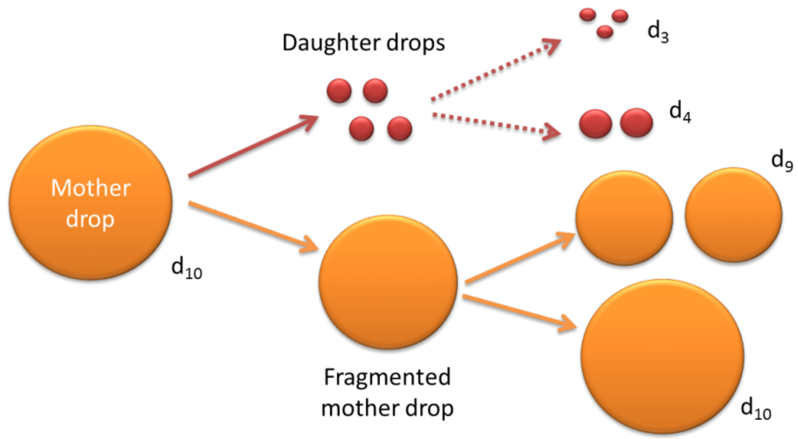
$$We_{ch} = Constant$$



Small fragments large drops

Water velocity field | Drop velocity field 2 | Drop velocity field 1

Inhomogeneous MUSIG method



Jet breakup with MIF and MCF

- PIF model overestimates the final droplet SMD at low injection velocities (important effect of secondary breakup)
- PCF agrees with experimental data at different injection velocities. The simulation results follow a 1/V function
- At high injection velocity, secondary breakup seems to have weak impact on the final droplet diameter.

References

[Gui09] Guildenbecher D. R, Lopez Rivera C, Sojka P. E: *Secondary Atomization*, Experiments in Fluids, Vol. 46, Issue 3 (2009), 371-402

[Hsi92] Hsiang L. P, Faeth G. M: *Near-limit drop deformation and secondary breakup*, International Journal of Multiphase Flow, Vol. 18, N° 5 (1992), 635-652

Hydrodynamic Secondary breakup: Drop size

Much more problematic:

- The constant Weber number assumption seems the most accurate (global shape)
- We_{cr} differs for Liquid/Gas and Liquid/Liquid systems

- Constant characteristic Weber number

$$We_{fragment} = We_{critical} = Constant$$

- Classical Kelvin-Helmholtz instability

$$k = 2/3 \ (\Delta V_{dc})^2 \rho_d \rho_c / \sigma(\rho_d + \rho_c) \ ,$$

$$d_{daughter} = C_0 \lambda = C_0 2\pi/k$$

- Reitz et al. 1987

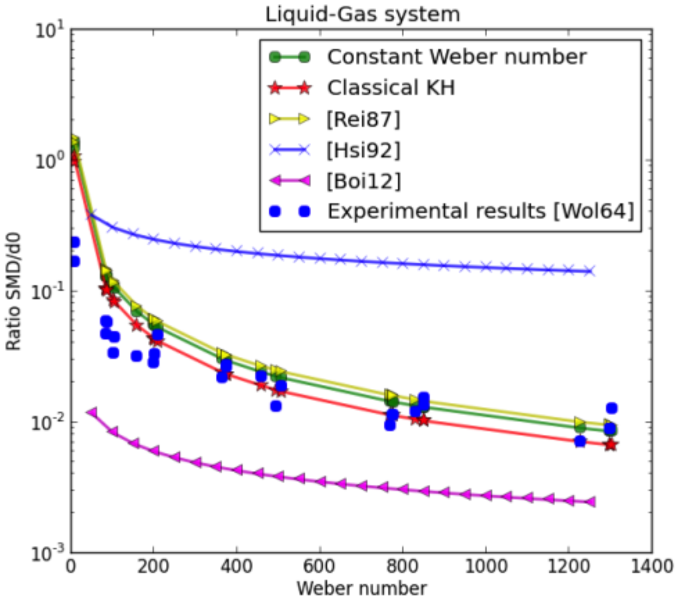
$$\lambda = 9.02 D_d \ (1+0.45 \sqrt{Oh})(1+0.4 T^{0.7})/(1+0.865 We^{1.67})^{0.6} \qquad T = Oh \sqrt{We}$$

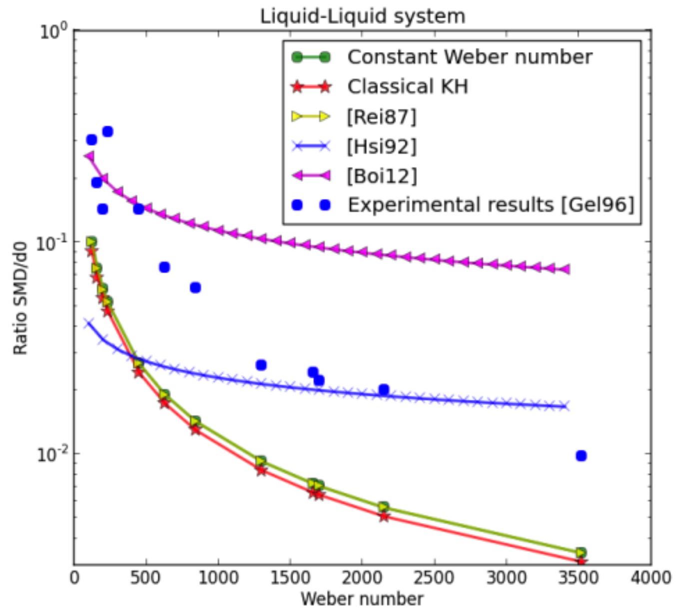
$$d_{daughter} = 2B_0 \lambda \qquad (B_0 = 0.61)$$

- Hsiang et al. 1992

$$We_{ch} = C_s (\rho_d / \rho_c)^{1/4} \ [\mu_d / \rho_d D_d \Delta V_{dc}]^{1/2} \ We_0 \qquad We_0 = \rho_c D_d (\Delta V_{dc})^2 / \sigma$$

- Boiko et al. 2012





PREMIX APPLICATION

Previous model

PREMEL

Dispersed field described by:

-One mass conservation equation

- A specific droplet area transport equation

-One momentum equation

-One energy equation

New model

MUDROPS

Dispersed field described by:
- Several classes each one with its own mass conservation and energy equation

- One or multiple momentum equation
    - Homogeneous MUDROPS (One velocity field)
    - Heterogeneous/inhomogeneous MUDROPS (Three velocity fields)

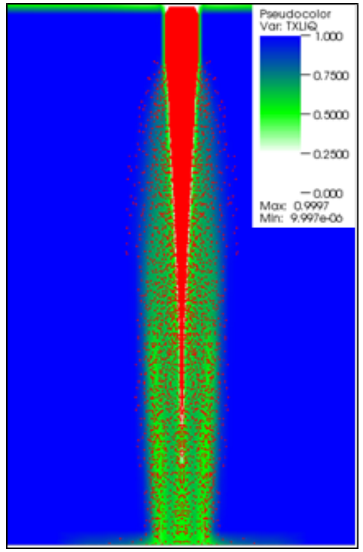
CFD code MC3D

Primary breakup
(Jet to drops)

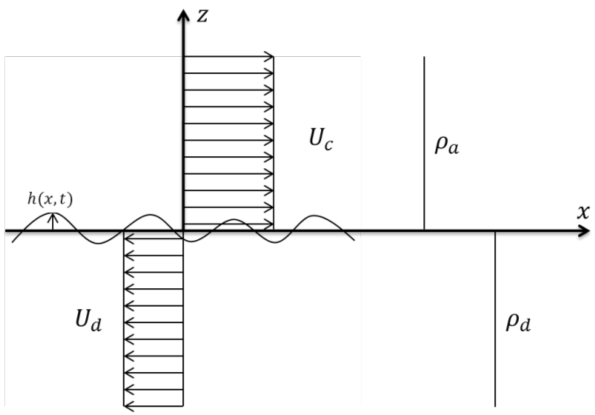
Secondary breakup
(Drops to Drops)
existing but not satisfactory

Hypothesis for our work :

- Primary instability/fragmentation driven by large scale (integral scale)
- Secondary fragmentation driven by local conditions

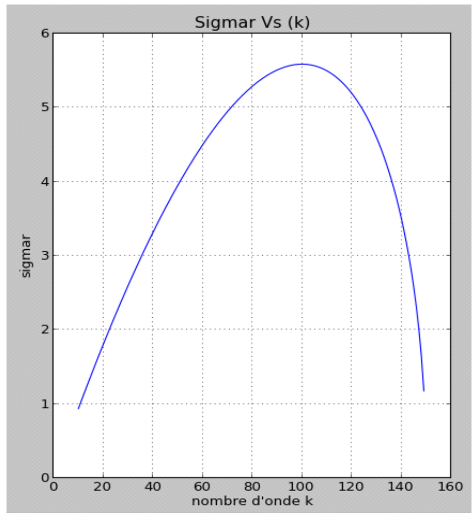


Kelvin-Helmholtz model for primary jet fragmentation



$$\sigma_r = kC_i = \sqrt{\frac{\rho_c \rho_d k^2 (\Delta V)^2}{(\rho_c+\rho_d)^2} - \frac{\gamma k^3}{(\rho_c+\rho_d)}}$$

- C_i = characteristic velocity of perturbation growth
- $\Gamma_{frag}(primary) = N_f C_i \; (N_f > 0)$



Hydrodynamic Secondary breakup

Hypothesis : Hydrodynamic forces cause the droplet to deform and to breakup (thermal aspects are neglected)

$$We = \rho_c D_d \Delta V_{dc}^2 / \sigma$$

$We_0 < We_{cr}$ Stable drop, no secondary drop breakup

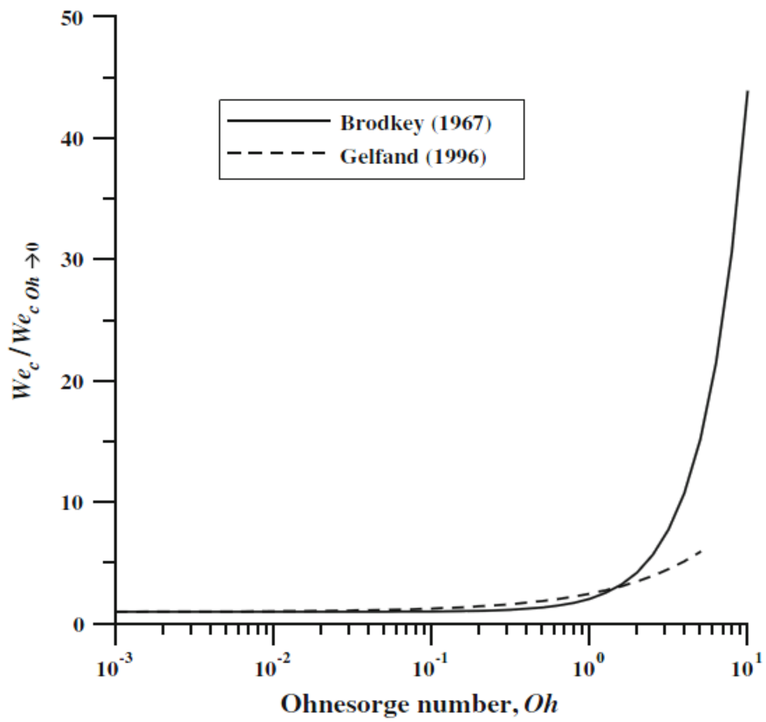
$We_0 \geq We_{cr}$ Drop will breakup

We_{cr} is usually a function of the Ohnesorge number

$$Oh = \mu_d / \sqrt{\rho_d D_d \sigma} = \sqrt{We} / Re$$

In our case, $Oh \sim 10^{-3}$

Viscosity should have no impact.



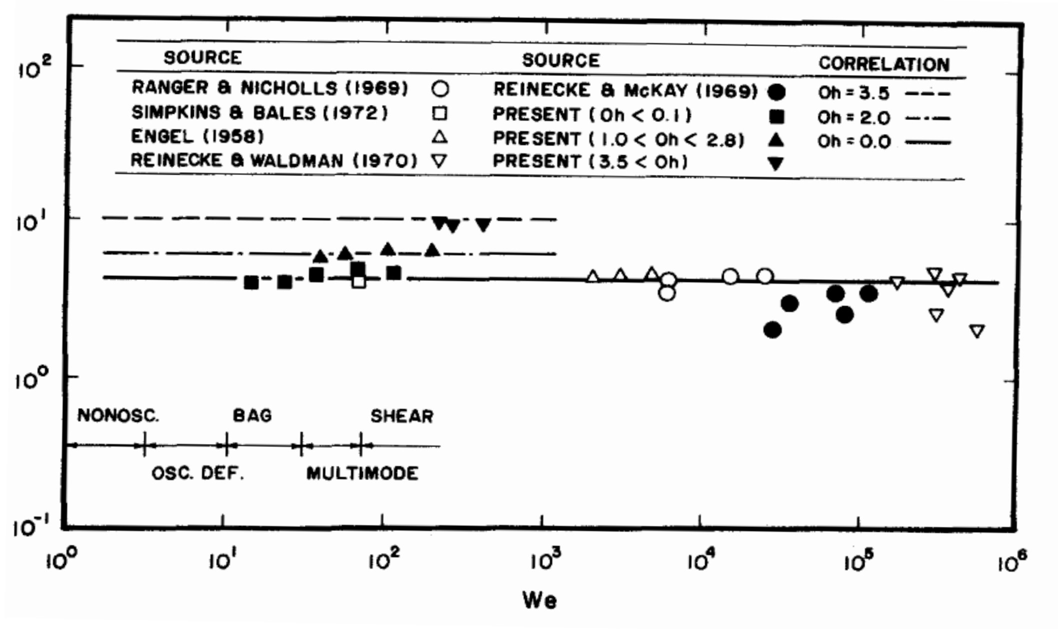
Guildenbecher et al. 2009

Hydrodynamic Secondary breakup: Fragmentation rate

Drop breakup divided in two stages:

- Drop deformation (1 or 1,5 τ_d)
- Drop breakup (4 to 6 τ_d)

t/τ_d



Hsiang et al. 1992

$$\tau_d = \frac{D_d}{\Delta V_{dc}} \sqrt{\frac{\rho_d}{\rho_c}}$$

- Total drop breakup time is nearly independant of the drop breakup regime
- Instantaneous volumetric drop fragmentation rate

$$\Gamma_{frag} = c_{frag} \frac{Drop\ Volume}{\tau_d}$$

Hydrodynamic Secondary breakup: Drop size

Much more problematic:

- The constant Weber number assumption seems the most accurate (global shape)
- We_{cr} differs for Liquid/Gas and Liquid/Liquid systems

- Constant characteristic Weber number

$$We_{fragment} = We_{critical} = Constant$$

- Classical Kelvin-Helmholtz instability

$$k = \frac{2}{3} \frac{(\Delta V_{dc})^2 \rho_d \rho_c}{\sigma(\rho_d + \rho_c)},$$

$$d_{daughter} = C_0 \lambda = C_0 \frac{2\pi}{k}$$

- Reitz et al. 1987

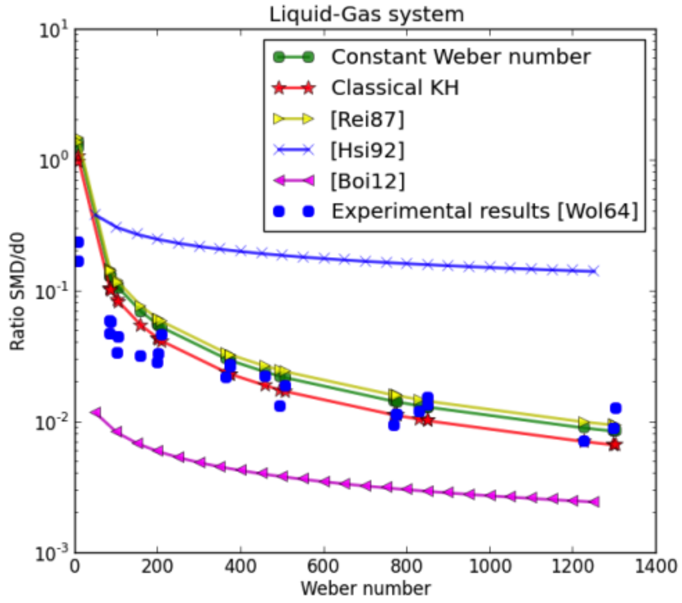
$$\Lambda = 9.02 D_d \frac{(1+0.45\sqrt{Oh})(1+0.4T^{0.7})}{(1+0.865 We^{1.67})^{0.6}} \qquad T = Oh\sqrt{We}$$

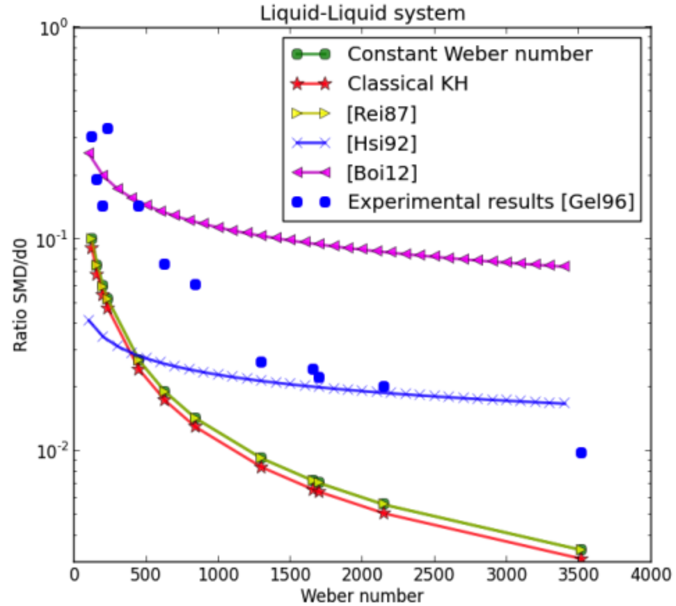
$$d_{daughter} = 2B_0 \Lambda \qquad (B_0 = 0.61)$$

- Hsiang et al. 1992

$$We_{ch} = C_s (\rho_d/\rho_c)^{1/4} \left[\frac{\mu_d}{\rho_d D_d \Delta V_{dc}}\right]^{1/2} We_0 \qquad We_0 = \rho_c D_d (\Delta V_{dc})^2/\sigma$$

- Boiko et al. 2012





Hydrodynamic Secondary breakup

Drop fragmentation rate

$$\Gamma_{frag} = c_{frag}\,\alpha_d \frac{\Delta V_{dc}}{D_d}\sqrt{\rho_d \rho_c} = \alpha_d \rho_d\, c_{frag} \frac{\Delta V_{dc}}{D_d}\sqrt{\rho_c/\rho_d}$$

Advantage: Each drop breaks up following local hydrodynamic conditions

Generated fragment size

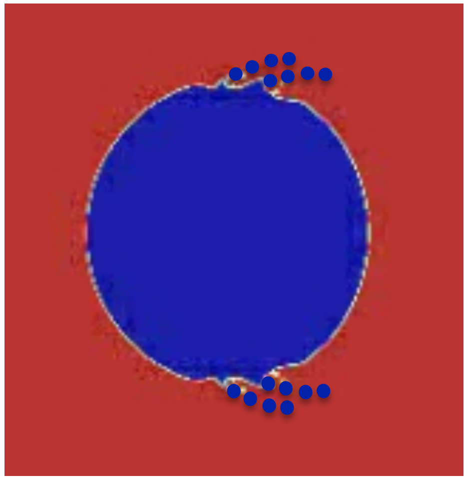
$$d_{daughter} = We_{ch} \frac{\sigma}{\rho_c (\Delta V_{dc})^2}$$

$$We_{ch} = We_{critical} = Constant$$

Variation on the Mother droplet size (drop number conservation)

$$m_{final} = m_0 - \Gamma_{frag}\,\Delta t$$

$$d_f = D_d \left(1 - \Gamma_{frag}\,\Delta t / \rho_d \alpha_d\right)^{1/3}$$



Secondary Fragmentation scheme

The MUSIG model

To limit the computational time, we must limit the number of velocity fields

- 1st approach : homogeneous

- 2nd approach : heterogenous with 3 fields, one being the water field : hydrodynamical equilibrium with water (no further fragmentation)

Mass transfert by stripping, generated fragments (e.g red lines)

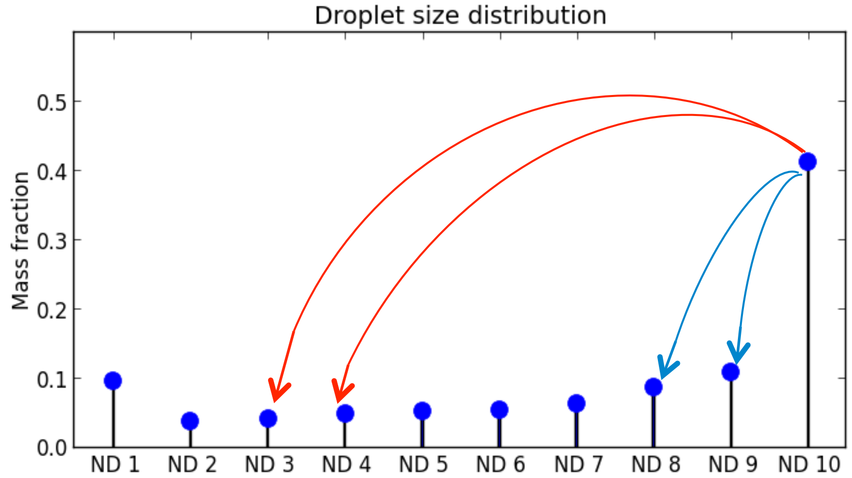
$$\Gamma_{D_d \to d_1} = \Gamma_{frag} (d_1 d_2 - d_1 d_{daughter})/d_{daughter}(d_2 - d_1)$$

$$\Gamma_{frag} = \Gamma_{D_d \to d_1} + \Gamma_{D_d \to d_2}$$

Mass transfert by mother drop mass depletion (e.g blue lines)

$$\Gamma_{D_d \to d_1} = (\alpha_d \rho_d / \Delta t - \Gamma_{frag})(d_1 d_2 - d_1 d_f)/d_f (d_2 - d_1)$$

$$\Gamma_{D_d \to d_2} = \Gamma_{frag} - \Gamma_{D_d \to d_1}$$

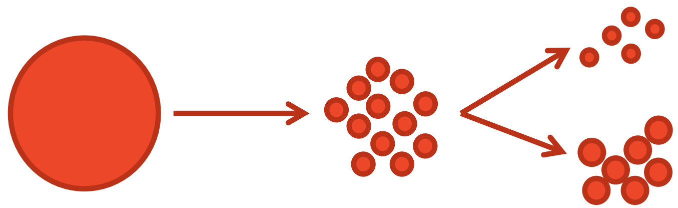


Small fragments — large drops

Homogeneous MUSIG method

Water velocity field	Drop velocity field 2	Drop velocity field 1

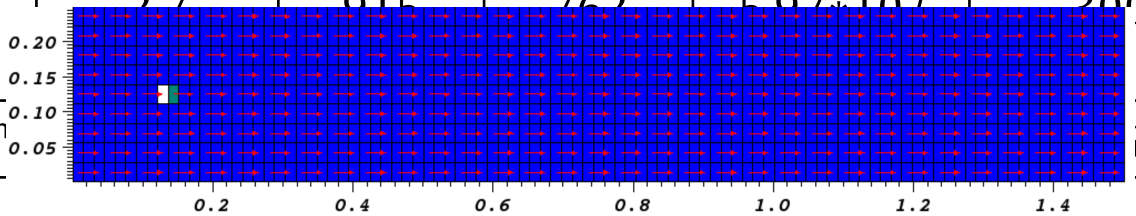
Inhomogeneous MUSIG method

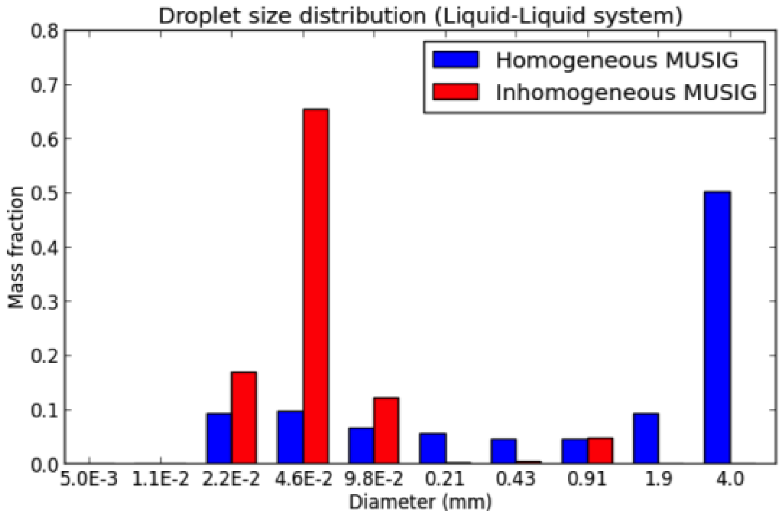


N_{D_1}

Validation : single drop fragmentation

Physical properties		Initial drop diameter (mm)	Drop Density kg/m^3	Density ratio	Dynamic Viscosity $Pa*s$	Dynamic viscosity ratio	Surface Tension N/m
Liquid/Gas	Bis[illegible]	2.7	915	762	$5.97*10^{[illegible]}$	300	0.0276
Liquid/Liquid	Galliun[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.7036



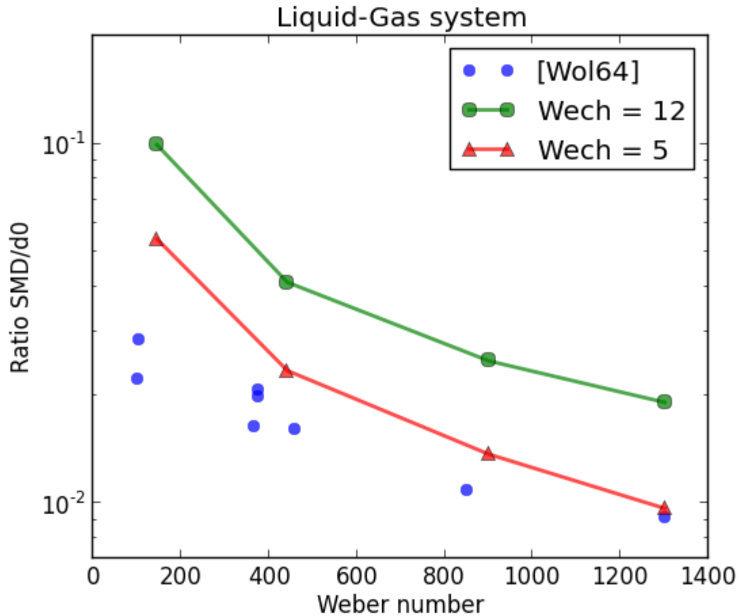


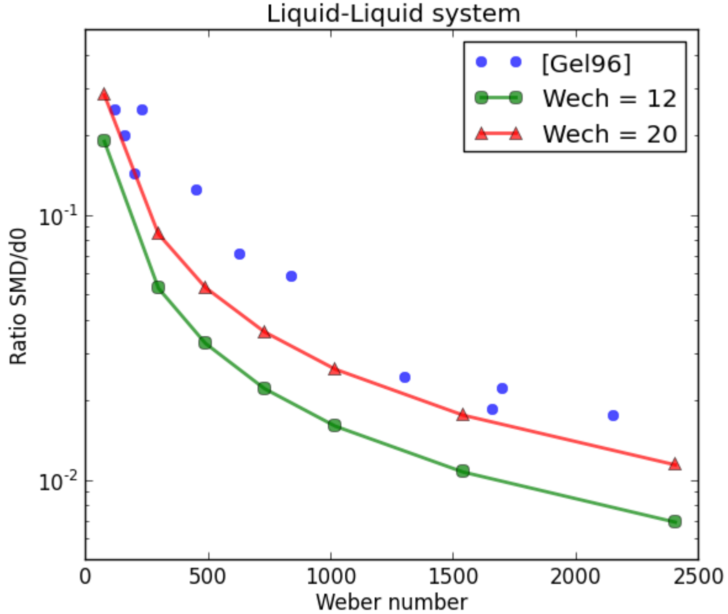
$t \gg 5\tau_d$

Homogenous MUSIG method not satisfactory because a large fraction of large drops are not fragmented.

- Due to a too important entrainment with the small fragments

Validation : single drop fragmentation





Typical characteristic Weber number: $We_{ch}=12$

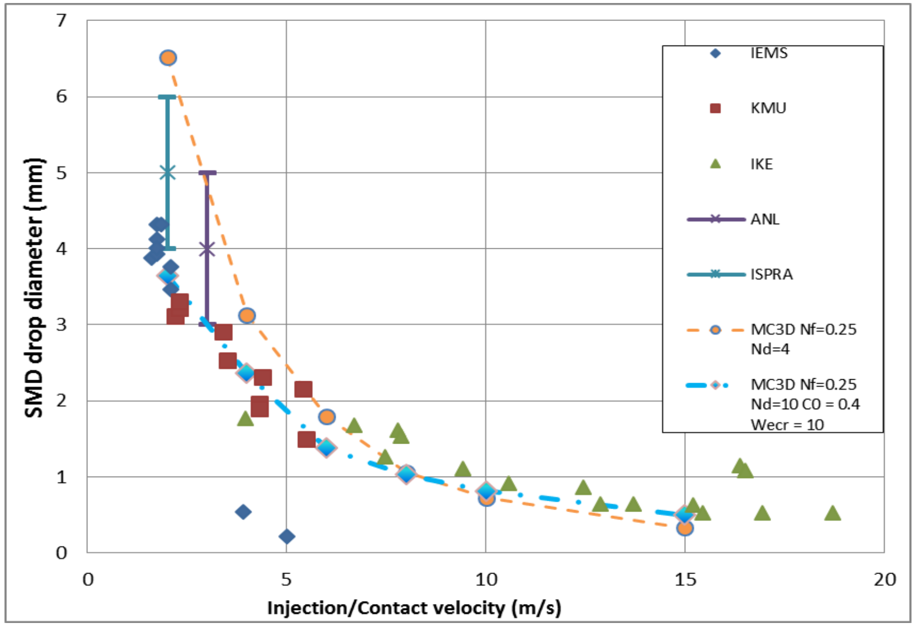
Correct general tendency but different characteristic Weber number for the best fit with experimental results:

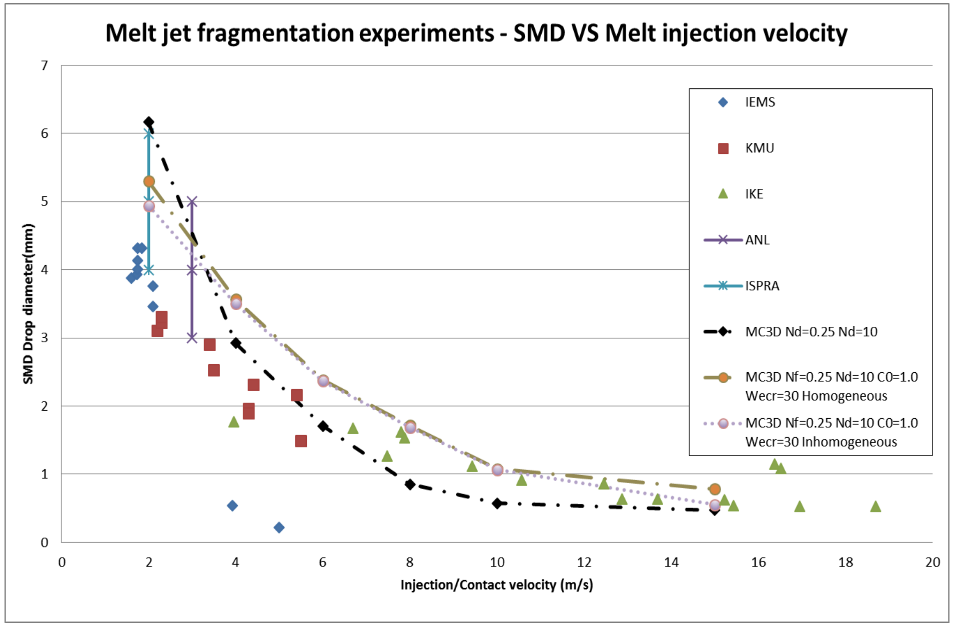
- Liquid/Gas systems $We_{ch}=5$
- Liquid/Liquid systems $We_{ch}=20$

Possible causes:

- Drop entrainment: Present drag law $C_d=\max(\min(0{,}5\,;2d/3\,\sqrt{g(\rho_d-\rho_c)/\sigma});24/Re\,(1+0{,}1\,Re^{0{,}75}))$
- Drop stretching (Deformation) : liquid is entrained before fragmentation
- More complex fragmentation process

Liquid metal jet breakup





One step fragmentation
$N_d = 4$
$N_f = 0{,}25$

Two step fragmentation	
Primary fragmentation	Secondary fragmentation
$N_d = 10$	$C_0 = 1{,}0$
$N_f = 0{,}25$	$We_{cr} = 30$

Conclusions and Perspectives

- ✓ A secondary fragmentation model was introduced in the MC3D code, based on a MUSIG approach.
- ✓ The homogenous approach is not appropriate for liquid/liquid systems
- ✓ Use of 3 velocity field gives satisfactory results in first analysis

Continuation / Improvements:

1. Improve analysis of fragmentation processes (with a simulation tool in particular)
   - difference L/G and L/L ?
   - impact of viscosity ?
2. Analysis of drag coefficient during fragmentation
3. Influence of multiphase environments for application to FCI
4. New experimental setup for validation of melt fragmentation process

References

[Gui09] Guildenbecher D. R, Lopez Rivera C, Sojka P. E: *Secondary Atomization*, Experiments in Fluids, Vol. 46, Issue 3 (2009), 371-402

[Hsi92] Hsiang L. P, Faeth G. M: *Near-limit drop deformation and secondary breakup*, International Journal of Multiphase Flow, Vol. 18, N° 5 (1992), 635-652