A TWO-SCALE APPROACH FOR MODELING THE CORIUM MELT FRAGMENTATION DURING FUEL-COOLANT INTERACTION

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ABSTRACT

In the case of a severe accident in a nuclear power plant, the molten core may flow into water and interact with it. The consequences of this fuel-coolant interaction (FCI) for the follow-up of the accident may be numerous so the phenomenon needs to be described accurately. First, FCI may produce a global system pressurization, more or less coolable debris and large amounts of hydrogen. This stage, called premixing, may be unstable and lead to a steam explosion which may, in particular, endanger the reactor containment. The strength of the explosion is fully dependent on the configuration of the premixing in which it will propagate. The premixing itself is fully dependent on the way the fragmentation of the melt proceeds. This paper is focused on describing the complex fragmentation process during the premixing stage of FCI through the implementation of sub-grid models in the computational multi-fluid dynamics code MC3D. Following some recent analyses, it appears that melt breakup is a multi-scale process. Thus, a new approach for modeling fragmentation is presented, making the distinction between large and small scale processes with two different sub-grid models to describe the global jet breakup (primary breakup) and the local fragmentation of dispersed corium (secondary fragmentation). The present models have been validated against experimental data and Direct Numerical Simulations results, reproducing correctly the dynamics of breakup regarding generated droplet size, jet breakup length, dispersion and influence of velocity gradient.

KEYWORDS
Fuel-Coolant Interaction, corium fragmentation, Computational Fluid Dynamics, two-scale breakup, Direct Numerical Simulation

1. INTRODUCTION

During a severe accident in a nuclear reactor, the reactor core may melt to produce a so-called corium. The mixing of this material with the coolant fluid (water for PWRs, BWRs or PHWRs) can lead to a complex interaction named Fuel-Coolant Interaction (FCI); The interaction between corium melt jet and water starts by the coarse jet fragmentation, generating millimetric ligaments, droplets and corium blobs. This process goes hand to hand with heat exchange, phase change of coolant (boiling) and generation of hydrogen by corium oxidation. This first stage of the interaction is known as premixing and it conditions the following stages of the accident (see Figure 1). The most important and dangerous of the potential consequences is

the steam explosion, which can affect the nuclear reactor containment and provoke the release of fission products in the environment.

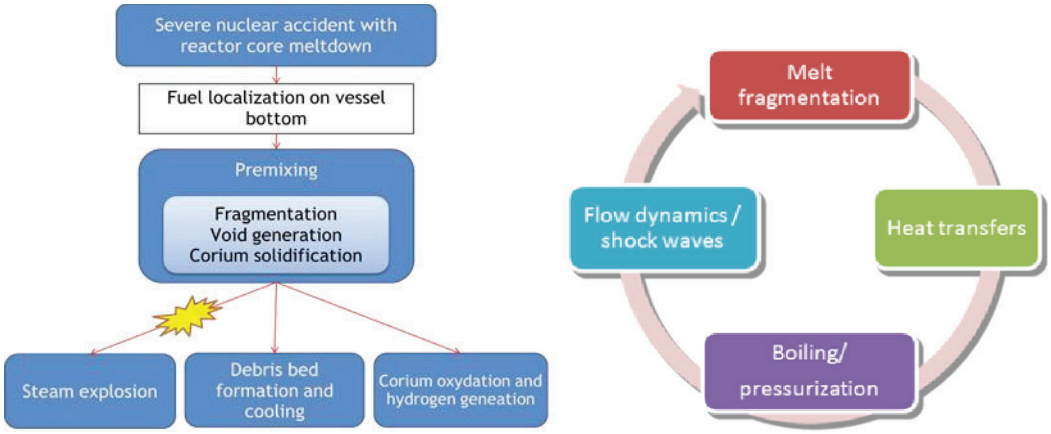

Figure 1. Left: proceedings and major consequences of FCI. Right: physics of melt fragmentation during FCI

The steam explosion is a fast interaction between the corium and coolant where the heat transfer characteristic time is small compared to the pressure wave relaxation time. The intensity of explosion depends on the quantity of liquid corium surrounded by liquid water, which can be easily converted into steam at its contact with small fragments generated by fine droplet fragmentation. The dynamics of these processes depend on the premixing characteristics, namely, corium dispersion, physical state of particles, void fraction, etc. Currently, most of the studies of FCI are focused on the risk of steam explosion in the ex-vessel configuration where the corium interacts with water in the nuclear reactor pit, following a failure of the vessel. Indeed, different studies [1,2] have shown the weak risk of direct release of fission products due to a steam explosion in the in-vessel configuration and therefore that configuration has receive less attention. Regarding the premixing, the difference between the two configurations is related to:

- The temperature of the water, which may be at saturation in the in-vessel case and somewhat subcooled in the ex-vessel one;
- The velocity of the melt, which is due to gravity in the in-vessel case whereas the ejection out of the vessel might occur with some pressure difference (and thus high velocity); in the ex-vessel situation, the jet might also not be vertical;
- The configuration of the melt in-flow which might occur as multiple jets in the in-vessel case, whereas the ex-vessel should occur with a single jet with an undefined shape.

Although, premixing should not depend fundamentally on the exact configuration, we nevertheless focus here on the conditions related to ex-vessel situation. The premixing phase and the explosion stage are in fact a cyclic interaction (Figure 1, right) but at different time scale: the corium fragmentation leads to a vaporization of coolant, which puts the coolant fluid in motion with a direct feedback on the fragmentation process. It is commonly accepted that the jet breakup is principally due to hydrodynamic perturbations characterized by shear instabilities that develop on the jet surface. The intense heat transfer between corium and water creates a boiling environment and intense counter flows that intensify the shear and jet fragmentation. The large structures generated and detached from the jet, can be subjected again to intense hydrodynamic perturbations and follow further fragmentation, generating and dispersing poly-disperse droplets on the water pool.

Corium fragmentation (primary and secondary breakup) is one of the key points for understanding and modeling FCI due to the rapid increase of exchange surface, affecting directly heat transfer, oxidation and

solidification. Despite the numerous studies about the subject [3–7], experimental devices devoted to FCI like KROTOS, FARO, DEFOR, etc. and recent research programs (SERENA-I and SERENA-II), the main mechanisms responsible for breakup are not clearly identify and further theoretical, numerical and experimental studies need to be carried on.

2. DESCRIBING CORIUM FRAGMENTATION

The primary fragmentation usually describes the detachment of blobs and droplets from the jet and the secondary fragmentation deals with the further fragmentation of these generated corium structures. In reality, it is difficult to distinguish the highly deformed jet from the ligaments and droplets due to the mixed spatial scales. In fact, fragmentation starts by the surface deformation due to shear Kelvin-Helmholtz instabilities along the jet. These weak interface deformation state can be described by linear instability models; the interface is further deformed, where non-linear and more complex effects take place. Breakup happens finally when the restoring forces are overcome by the destabilizing effects and new liquid metal blobs are generated.

The tip of the jet should undergo a specific fragmentation pattern. However, it is in general considered that the fragmentation at the tip of the jet is of small importance and most of the current models neglect it. The efforts are then concentrated on the fragmentation along the jet. Fragmentation depends on the initial jet conditions (diameter, vertical or lateral ejection, injection velocity, turbulence, etc.) as well as materials composition. Additional factors like physical properties variation during premixing (i.e. oxidation process [8,9]), solidification and potential non-Newtonian characteristics of corium can modify strongly the breakup behavior and the generated droplet characteristics.

The study of jet breakup for FCI differs from the most common liquid-gas configurations studied in the case of fuel injectors for the automotive and aeronautic industry. Even for those well establish configurations, the comprehension of the phenomena is limited. The fragmentation rates reported in configurations with hot melts in water are much close to those reported for the liquid-liquid configuration (with non-miscible liquids). Nevertheless, this later configuration has received very low attention. Thus, the study of the adiabatic (or with small temperature difference) low melting point metal jet – water interaction can help to improve the understanding of the melt breakup process in FCI.

One particular difficulty in the study of the FCI configuration is to take into account the multiphase nature of the ambient flow around the jet and to extend the knowledge of fragmentation from the two-phase cases (liquid-gas or liquid-liquid). We have to consider the presence of a steam layer around the jet which thickness depends on the local conditions (in particular drop size and water subcooling). It has also been evidenced from both, experiments using x-ray (KROTOS) and numerical simulations that the steam film is not stable and large steam/liquid structures (waves) are formed along the jet. These large intermittent structures travel up due to buoyancy and might provoke intense fragmentation.

Modeling fragmentation is then a difficult task due to the very specific conditions, the small number of available data and the potentially important scaling and geometrical effects in a real reactor situation. Basically, a fragmentation model should have three components:

- The fragmentation model itself, which should be applicable at least for two-phase flow (e.g. liquid/gas or liquid/liquid);
- The account of two-phase nature of the ambient fluid in an extension of the previous fragmentation model;
- The solidification and oxidation of the melt which might modify the material properties and then the ability to fragment.

This paper focuses on the first component of the model and describes the proposed new two-scale approach sketched in Figure 2. In contrast, with the current available models, we propose a decoupling of the scales where the fragmentation rate (primary fragmentation) is dictated by large scale motions, and where the drop size is dictated, through secondary fragmentation models, by local effects.

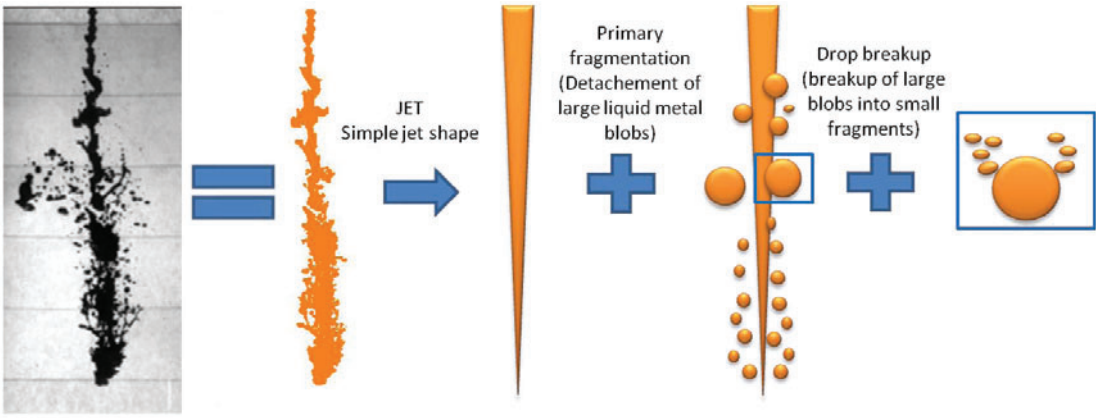

Figure 2. Scheme of the two-scale melt jet fragmentation. Left: Jet breakup image taken from [10]

It is important to notice that, in fact, what we call primary fragmentation might not be completed. There is a competition of effects at different scales and direct stripping of small drops is often observed at large jet interface disturbance. As a direct and precise modeling is out of reach, the model is aimed at reproduced a global behavior, thus the large blobs obtained after the primary "fragmentation" might in reality simply be large jet distortions of instabilities. The major hypothesis is then that the final fragmentation can be approximated by models for drop fragmentation. Some particular adjustments might be necessary for this. Secondary breakup modeling takes advantages of the implementation of a multi-size group approach to describe the dispersed phase. We present here more particularly the path followed for the description of secondary breakup, including direct numerical simulations (DNS) of isothermal fragmentation of drops in water. The outcomes of the implementation of these models in the computer code MC3D is finally presented and discussed. Before going into this presentation, we rapidly describe the general premixing model of MC3D.

3. MODELLING PREMIXING WITH MC3D

Due to the general complexity of the phenomenon and still remaining uncertainties, a detailed simulation of the whole FCI process seems far from practical applications. The common procedure consists to look for approximations and transpose them in simplified models that can be integrated in FCI codes. Regarding premixing, several theoretical 1-dimensional models have been proposed in the past [11–13] using, in general a configuration with three different layers (jet, steam layer and water), variable physical properties, etc. The fragmentation model could be very complex, based, i.e. on the full resolution of the Orr-Sommerfeld equation. Nevertheless, these models are now considered too restrictive regarding the hypotheses and possibilities of use, with limited confidence for the extrapolations to reactor applications.

Currently, the modeling of FCI is done through the development of Computational Multi-Fluid Dynamics (CMFD) codes that can simulate in a practical way the premixing and explosion stage of FCI, even in reactor configurations (Figure 3). The sub-grid models (i.e. fragmentation models) are nevertheless necessarily limited in complexity.

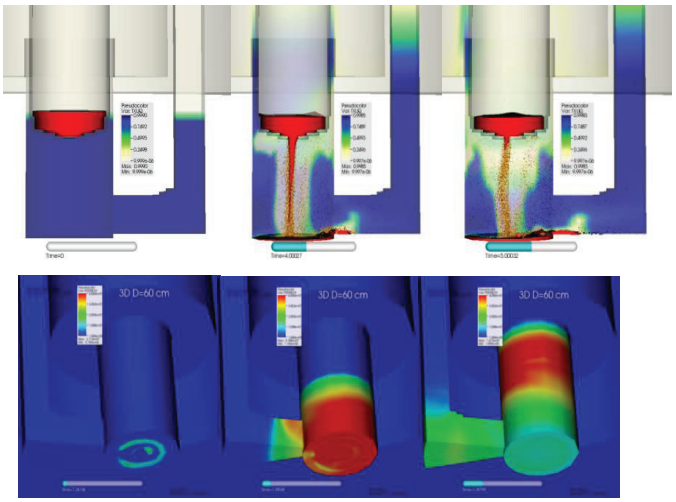

Figure 3. Numerical simulation of FCI using the MC3D code. Top: Premixing (flow of corium out of the nuclear vessel and fragmentation). Bottom: explosion phase (pressure field on the pit walls)

The MC3D code is a multi-component thermal-hydraulic 3D software, developed by IRSN. This code uses a combined method of finite volume and finite differences to solve the mass, momentum and energy conservation equations described in an Eulerian way using a staggered grid. This code has been built with the idea of modular applications which are defined by a set of material components that can be grouped in volume mixtures (same volume, e.g. gases), momentum mixtures (same velocity) and energy mixtures (same temperature or enthalpy) supplemented with a set of models for the interactions among various components (frictions, energy transfer, phase transfer, chemistry, etc.).

In MC3D, the premixing stage is modeled with the application named PREMEL (or PREMIX) composed of five component fields (liquid water, steam, jet, droplets and non-condensable gases) [5]. The spatial resolution used in current simulation performed with the MC3D-PREMEL code is not sufficient to solve the small flow scales (highly deformed interface, droplets, etc.). Therefore, sub-grid models need to be implemented in order to simulate the unresolved scales in the most realistic manner. A fragmentation sub-grid model must compute the mass transfer rate between the jet and droplets and the generated droplet characteristics (size, surface, velocity, temperature and shape).

Recently, a sub-application of PREMEL, called PREMEL_MD has been developed where the drops are described on the basis of a MUSIG approach, with several classes with different fixed droplets diameters. This new description will be called here after MUDROPS. The primary aim of this modeling is to better resolve the solidification of the drops. It also allows refining the fragmentation model itself, which is the main topic of this paper.

Several preliminary hypotheses need to be done. First, the jet is always considered totally liquid during its free fall on gas and during its penetration on the water pool. Indeed, we have verified this hypothesis for common FCI conditions: the rate of fragmentation is always large compared to the rate of jet solidification by radiation (heat convection is of second order). The impact of solidification of the drops is much more delicate as discussed in [5]. In our study, we use the standard MC3D model where the solidification (i.e. cut-off of fragmentation) is decided upon a criterion related to the drop temperature. Also, none of the models for advection and breakup of jets and droplets consider a possible non-Newtonian behavior of the corium. This hypothesis is currently under investigation.

Finally, we consider that fragmentation is primarily due to hydrodynamic perturbations generated by the velocity gradient between the liquid corium (jet and droplets) with the surrounding fluid (steam, non-

condensable gases and water). Thus, we neglect the effects of thermal interaction evidenced on De Malmazet droplet breakup videos [14].

Our fragmentation model proposes correlations for the following parameters:

- Fragmentation rate
- Droplet size
- Velocity of generated droplets

These three characteristics are generally described using one unique shear instability fragmentation model, namely one-step model. This approach seems to be limited because it cannot take into account the various scales involved in the interaction. In fact, we propose a new model considering two-different scales:

- Integral scale (large scale) that pilots the global jet destabilization and its fragmentation (i.e. fragmentation rate)
- Local scale (droplet scale/cell size) which pilots the final fragmentation process and therefore, the droplets final size.

The proposed models are tested and validated against experimental data. We nevertheless limit here the discussion to the simpler case of isothermal flows, where the jet is obtained from low melting point metal alloys. First, we discuss the small scale breakup model and validate it against academic liquid–liquid isothermal droplet fragmentation experiments and from a DNS analysis that we have conducted. The primary fragmentation model is then validated using low melting point metal jet injected into water at different velocities disregarding boiling and heat transfer.

3.1. Local Scale (Drop) Fragmentation

The present small-scale breakup model is based on the theory issued from spherical droplet breakup by shockwave disturbances. As the theoretical and experimental data concerning the liquid-liquid breakup is limited, we based our model on the general description for liquid/gas environments and adjusted it for liquid/liquid cases.

The breakup of droplets starts by a phase of deformation of the spherical droplet into an ellipsoid or a disc, as described by the DDB model [15,16]. Later, the disc can be disrupted in different ways depending on the Weber number which defines the different breakup regimes [17–19]. It is common to use the Ranger and Nicholls characteristic breakup time [20] in order to put in a dimensionless form the transient behavior of fragmentation. The breakup itself occurs following various regimes depending on the Weber number (if the viscosity is sufficiently low, which is our case in this study). It is remarkable that, whatever the breakup regime, the deformation time is always in the order of $2\tau_d$ and the total fragmentation time about $6\tau_d$.

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

The temporal data can be used in order to compute the fragmentation rate and the mother mass depletion within time. Concerning the size of generated droplets, several correlations have been proposed based in liquid/gas configuration data. These correlations allow computing the final diameter of droplets taking into account the initial hydrodynamic parameters. However, in the work of [21] where the authors compare different secondary breakup correlations ([22,23], classical Kelvin-Helmholtz, constant characteristic Weber number), none of them agrees with the experimental data for the liquid/liquid configuration obtained from [18,24]. Also, we have to consider than in a computational multi-fluid dynamics code, secondary breakup will be computed every time step, using hydrodynamic conditions that evolve with time. A strict validation of the secondary breakup model needs to be performed in order to verify the correct final diameter of daughter droplets and the temporal behavior of mother mass depletion.

3.1.1. Overview of results of our DNS study on drop breakup

The information available in the work of [18,24] does not give detailed information about the main mechanism leading to breakup, neither a clear visualization of the droplet deformation and generation of daughter droplets. In order to better understand the breakup of droplets, we have decided to take the advantage of direct numerical simulation (DNS). The simulations have been performed on the CFD code GERRIS [25] that uses an adaptive mesh refinement method, allowing a good compromise between spatial resolution and computational time. We use mesh refinement criteria based on the gradient of mass fraction, the gradient of vorticity and the curvature, ensuring good spatial resolution of deformed structures of fluid and of vortex inside and outside the droplet. Different Weber numbers have been studied leading to the identification of different potential breakup regimes. We perform simulations for $We < 1500$ that correspond to reasonably high Weber number for droplets in the premixing stage. The simulations are focused mostly in a qualitative and quantitative analysis of the breakup process and we attempt to evaluating the breakup characteristics like drop deformation, entrainment, drop fragmentation rate, particle size distribution, etc. Detailed information about the simulations will be the object of a future publication.

In Figure 4, we compare the different regimes of breakup for the liquid/gas [19] and for liquid/liquid, from our DNS study. For Weber numbers below 10, droplets oscillate with a frequency variable in function of the Weber number $\left(f^* \approx \sqrt{1.489 * We^{-1} - 0.113}\right)$[1] and without any breakup. Whereas in the liquid/gas system the fragmentation at Weber number between 10 and 30 leads to a pulverization through the bag breakup mechanism, we obtain for the liquid/liquid system a weak variation of the SMD (Sauter Mean Diameter). In fact, we observe from the simulations the existence of two regimes: the elongation breakup, which leads to big daughter droplets and the "forward bag breakup" where small droplets generated from the bag breakup coalesce into the rim, leading to a relative big SMD.

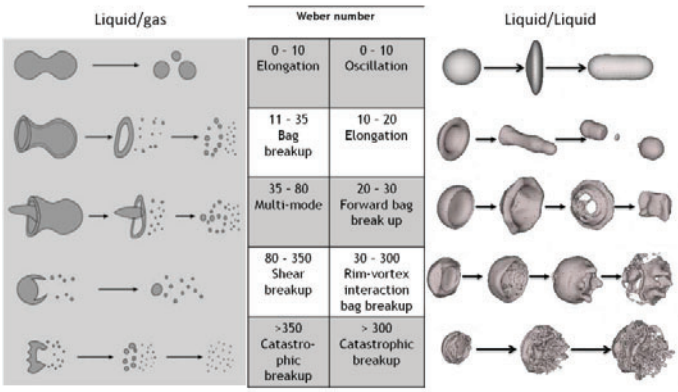

Figure 4. Droplet breakup regimes classification. Left : Liquid/gas classification obtained from [19]**. Right: Proposed classification for the Liquid/liquid systems based on DNS results.**

For liquid/liquid systems, fragmentation seems to occur for Weber numbers greater than 30. Several big structures coming from the rim breakup and coalescence are also present at the end of breakup, generating a two crest droplet size distribution. The major conclusion from this study is that the drop breakup in the liquid/liquid system is effective for Weber numbers larger than 30, i.e. with an import delay compared to the usual estimates from the observations in the liquid/gas system.

[1] Oscillation frequency is given as the physical frequency multiplied by the characteristic breakup time τ_d

Here after, we expose the model for computing breakup during premixing with the MUDROPS model (details on the fragmentation in the standard MC3D model can be found in [5]). First, some details of the MUDROPS description are given.

3.1.2. Mudrops description

The approach for the MUDROPS model is based on the MUSIG method [26] and considers several droplet classes, each one representing one different diameter of droplets. Each one of these droplet classes has its proper mass and energy conservation equation. Two different methods have been implemented, homogeneous and heterogeneous, considering that all the classes have the same velocity (homogenous) or grouped in three different velocity fields (heterogeneous). However, the calculations show that the homogenous model is not sufficiently accurate due to the fast entrainment due to the generated small fragments (mother drop has the same velocity as the fragment). Thus, we give here only results with the heterogeneous model.
The proposed model is based on the high Weber number breakup regime (catastrophic breakup) as shown in the scheme of Figure 5. Red lines represent the small stable daughter droplets generated from the stripping of the boundary layer and the blue lines represent the new mother droplet diameter.

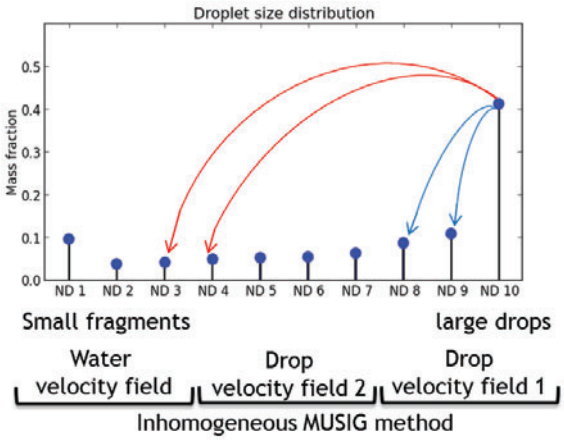

Figure 5. Description of MUDROPS model. Red lines: Generated daughter droplets. Blue lines: Mass transfer to a smaller class due to mother drop depletion

We suppose that the daughter droplets diameter is given by a characteristic Weber number (We_{ch}), i.e. daughter droplets are created with this characteristic Weber number:

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

Ideally, the characteristic Weber number should be equal or smaller than the critical Weber number of stability, e.g. 30 in the liquid/liquid system, and 10 in the liquid/gas system.
The fragmentation rate ($\Gamma_{frag,drop\to drop}$) is determined using the classical total fragmentation dimensionless time of Ranger and Nicholls. Mother droplet depletion is computed considering a constant number of mother droplets during the computational time step.

$$\Gamma_{frag,drop\to drop} = \frac{1}{t_{frag}} \frac{\alpha_{d,i}\Delta V_{dc}}{D_{d,i}} \sqrt{\rho_d \rho_c} = \alpha_{d,i}\rho_d \frac{\tau_{d,i}}{t_{frag}} \qquad d_f = D_d \left(1 - \frac{\Gamma_{frag,drop\to drop}\Delta t}{\rho_d \alpha_d}\right)^{\frac{1}{3}}$$

Where d_f is the mother droplet diameter after breakup.

3.1.3. Secondary breakup results

In order to validate our models for liquid/liquid systems and verify also the correspondence of the DNS with reality, we compare the numerical results with the experimental data obtained from [18,24], the only experimental data of liquid metal droplet breakup under water hydrodynamic disturbances at our disposal. Currently, at the LEMTA laboratory, experiments of drop breakup are performed using a drop-on-demand device to generate a 3 mm Field's metal droplet that falls in a water pool by the effect of gravity. The qualitative and quantitative analysis of the fragmentation process is achieved using images took with a high-speed camera and analyzing the solidified debris. These studies are under preliminary phase and will be also presented in future papers.
In Figure 6, we present the normalized final Sauter mean diameter as a function of the Weber number for experimental data, DNS and MUDROPS model, using a characteristic Weber number of 30.

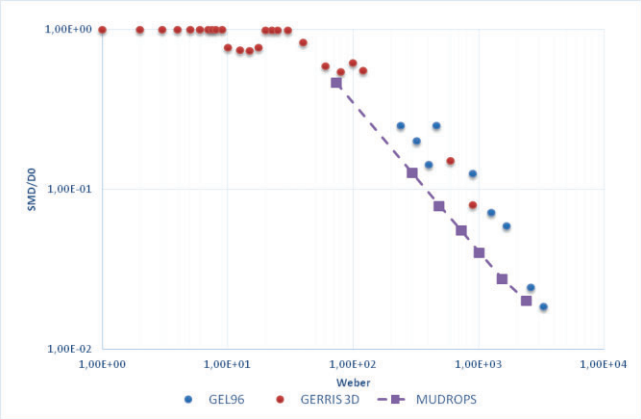

Figure 6. Final normalized Sauter Mean diameter of generated droplet at different Weber numbers. Experimental data obtained from [18,24]

The simulations have been performed using the physical properties of Gallium. We see a very good agreement between DNS numerical simulations and the experimental results. We also obtain a reasonable agreement with the MUDROPS model. It seems that the different entrainment of the generated small and big droplets during breakup plays an important role determining the final droplet size. This might explain the discrepancy for the part.

3.2. Jet (Primary) Fragmentation

Now that we know how droplets break up in the liquid/liquid system, we need to model how they are generated from jet. In our case, we consider that primary fragmentation is generated from large structures that detach from jet. We suppose that the process is described by the Kelvin-Helmholtz instability. Table 1 resumes the differences on the primary breakup models following the two different dispersed field approaches of MC3D. We associate the fragmentation parameters using a Kelvin-Helmholtz instability model though the most unstable wavelength which grows at the jet interface, using proportional relationships between the growth rate of the instability with the jet fragmentation rate and the most unstable wavelength with the droplet size, using two parameters N_f and N_d, respectively. However, for the MUDROPS model with the two-scale approach, as we make the assumption that the drop size is finally computed with the local flow characteristics, the drop size obtained with the jet fragmentation model does not affect considerably the final result, therefore, we set the N_d parameter at an arbitrarily high value, namely 10. We will nevertheless also discuss the one-scale method, i.e. without considering secondary fragmentation, to evaluate the impact of the two-scale approach.

Table 1. Chart of primary breakup model following the two different approach for the dispersed phase

	PREMEL	MUDROPS
Mass source term	$\Gamma_{frag} = N_f \frac{\sigma_{max}}{C_i} = N_f \frac{\Delta V_{dc}\sqrt{\frac{1}{2}\rho_d\rho_c}}{\rho_d + \rho_c}$	
Droplet Sauter mean Diameter	$SMD = N_d \lambda_{max} = N_d \frac{3\pi\sigma(\rho_d + \rho_c)}{\Delta V_{dc}^2 \rho_d \rho_c}$	
Droplet characteristics	$\Gamma_A^+ = \frac{\Gamma_{frag}}{SMD}$	Droplet probability distribution; log-normal distribution defined by the SMD and $D_{0,50}$

As for the small (secondary) breakup, the advantage of the MUDROPS approach is the possibility to take into account a probability density function (PDF) of droplets generated by primary fragmentation at each cell containing jet interface. Several studies have discussed about the droplet size distribution generated from liquid/gas jet fragmentation, e.g. Marmottant [27] reported that this PDF normalized by the ligament size is independent of the velocity gradient (constant function shape). We suppose then, a log-normal droplet size distribution for primary breakup with a fixed standard deviation, which is computed using a fixed ratio between the Median Mass diameter ($D_{0,50}$) and the SMD.

Based on experimental results of liquid metal jet breakup, the ratio $D_{0,50}/SMD$ has values around 1.2 as seen in Figure 7. These values vary following the different conditions of the interaction (e.g. temperature difference between liquid metal and water, material, etc.), however, in our analysis, these variations are neglect.

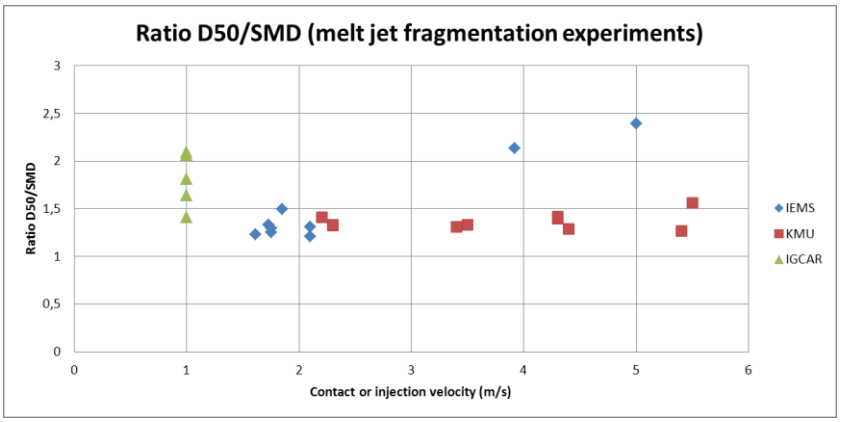

Figure 7. Ratio between $D_{0,50}$ and SMD at different injection velocities. Experimental data are obtained from IEMS [28]**, KMU** [29]**and IGCAR** [30]

3.3. One Scale Vs Two Scale Model

We recall that the one-scale model considers only one single flow scale for determining both the fragmentation rate and the drop size. Once created, the drops cannot be fragmented anymore. The droplet size parameter N_d can be obtained from physical justifications, but here, we adjust it to fit at best the experimental results. The two-scale model considers that the primary fragmentation is computed with the model explained in section 3.2 and secondary breakup is computed with the models presented in section 3.1.2.

On Figure 8, we present an example of the multi-scale behavior of jet fragmentation. The figures were taken from [31], where the authors perform a DNS simulation of a liquid jet injected at different velocities into a gas. We see a schematic of different structures that develops behind the jet tip of the same length scale than the jet diameter (large scale) generating large jet surface instabilities. Inside these structures, we can also see (from vorticity contours) several vortex of length scale similar to the droplet diameter (small scales). These small scales affect directly the ligament and droplet breakup behavior, involving local hydrodynamic parameters.

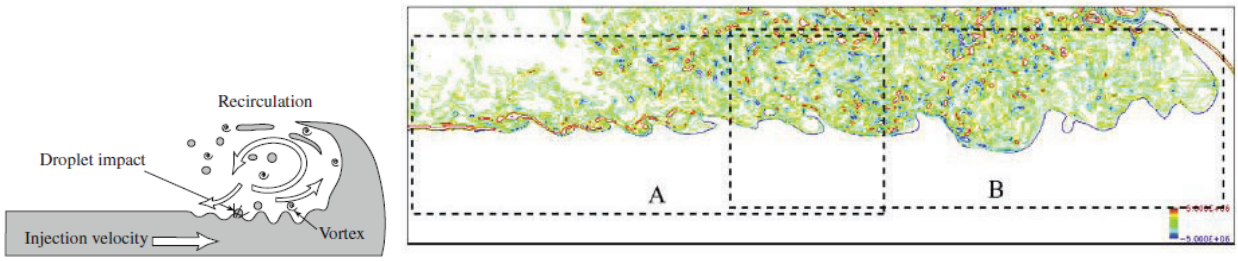

Figure 8. Schematic of disturbance transmission paths and vorticity contours around the jet interface (images obtained from [31]**)**

We see in Figure 8 the presence of different length scales that act differently on the breakup process. The model proposed in this work try to simulate these complex behavior with two sub-grid models in order to take into account, in first place the large structures (computed by an averaging procedure of the hydrodynamic parameters around the jet surface) and in second place, by computing the small structures influencing droplet and ligament breakup (computed using hydrodynamic parameters at the computational cell length scale). Therefore, the two-scale model should reproduce better the jet fragmentation dynamics.

3.4. Low Melting Point Jet Breakup Simulations

We validate our models simulating the injection of a liquid metal jet of 28.5 mm diameter into a water pool at different injection velocities. The Weber numbers based on the jet diameter vary from 150 to 10000. We use physical properties of Woods metal. It is important to notice that there is a large uncertainty concerning the surface tension value, which in the literature differs by a factor larger than 2 (from 0.4 to 1 N/m). As the drop size depends inversely on this property, we primarily seek here for a qualitative agreement of the global variation of the drop size with the jet velocity. The secondary breakup parameters have been taken exactly as the ones found in section 3.1.3. The primary breakup model parameters are adapted in order to obtain the best agreement with experimental data.

Table 2. Numerical parameters for fragmentation models

One step fragmentation
$N_d = 4$
$N_f = 0.25$

Two step fragmentation	
Primary fragmentation	Secondary fragmentation
$N_d = 10$	$C_0 = 1.0$
$N_f = 0.25$	$We_{cr} = 30$

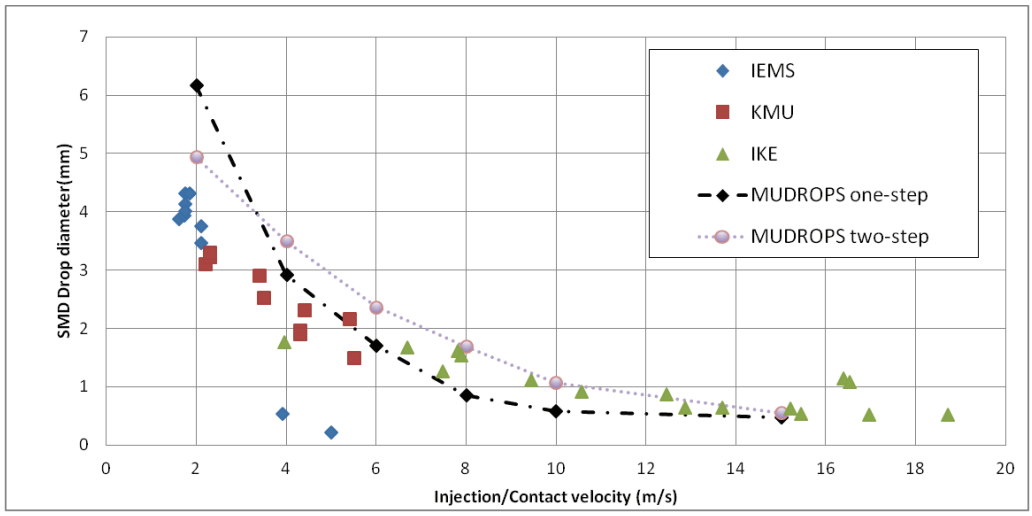

Figure 9. Final Sauter mean diameter at different injection velocities. Experimental data obtained from: IEMS [28]**, KMU** [29]**, IGCAR** [30] **and IKE** [32]

The different parametric studies performed show that the jet breakup length (not shown here) is highly dependent on the fragmentation rate parameter N_f (as expected) and weakly dependent on the N_d and final SMD. In fact, in this validation case the dynamic around the jet impacts weakly its fragmentation rate. On the other hand, we see the influence on the final SMD if a secondary breakup model is used. The dynamics of breakup are better reproduced with the fully two-scale model because primary fragmentation generated droplets that follow further fragmentation until their Weber number become small than the critical Weber number (We_{cr}).

4. CONCLUSIONS

The interaction of fuel and water (FCI), starts by the coarsen fragmentation of a corium jet at its contact with water. The fragmentation process goes hand to hand with different complex phenomena (boiling, solidification and oxidation) with strong feedback on the droplet generation process. In order to model the fragmentation and considering the spatial resolution used for practical simulations, two sub-grid models have been implemented on MC3D. These models allow combining two different spatial scales (large and small). We consider that the jet fragmentation depends firstly on the large scales (in the order of the jet diameter) of the flow and secondly, the generated blobs will be fragmented following the small scales of the flow (droplet or computational cell scale).

In order to supplement the lack of experimental data and understanding of the drop fragmentation in liquid/liquid configuration, the small scale breakup has been studied using direct numerical simulations. Breakup regimes have been identified for the first time and they are found to be very different from the common liquid/gas regimes at low Weber number. Also, the final mean Sauter diameter of the droplet distribution agrees very well with the few available experimental data. A sub-grid model for secondary breakup based on phenomenological aspects of secondary breakup have been validated and the multi-size approach (MUDROPS) shows its advantage for better representing the droplet breakup under several orders of magnitude of the Weber number. A primary breakup model has been also proposed based on the Kelvin-Helmholtz instability model and different approaches using only the primary breakup or the couplet primary/secondary breakup models are tested in a low melting point jet breakup simulation. The coupled approach allows reproducing correctly the final droplet diameter over the entire range of studied Weber numbers; for the high injection velocity range, a small difference between the one step and two step models seems to confirm the weak impact of secondary breakup on the final droplet size. Further studies need to be performed, from the DNS point of view and from the MC3D implemented models in order to reproduces

correctly the corium fragmentation behavior in the real case of fuel coolant interactions, i.e. with the impact of boiling of the coolant.

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