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Simulations of Ex-vessel Fuel Coolant Interactions in a Nordic BWR using MC3D Code

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Abstract

Nordic Boiling Water Reactors (BWRs) employ a drywell cavity flooding technique as a nuclear severe accident management strategy. In case of core melt accident where the reactor pressure vessel will fail and the melt will eject from the lower head and fall into a water pool, may be in the form of a continuous jet. It is assumed that the melt jet will fragment, quench and form a coolable debris bed into the water pool. The melt interaction with a water pool may cause an energetic steam explosion which creates a potential risk towards the integrity of containment, leading to fission products release into the atmosphere.

The results of the APRI-7 project suggest that the significant damage to containment structures by steam explosion cannot be ruled according to the state-of-the-art knowledge about corresponding accident scenario. In the follow-up project APRI-8 (2012-2016) one of the goals of the KTH research is to resolve the steam explosion energetics (SEE) issue, developing a risk-oriented framework for quantifying conditional threats to containment integrity for a Nordic type BWR. The present study deals with the premixing and explosion phase calculations of a Nordic BWR dry cavity, using MC3D, a multiphase CFD code for fuel coolant interactions. The main goal of the study is the assessment of pressure buildup in the cavity and the impact loading on the side walls. The conditions for the calculations are used from the SERENA-II BWR case exercise. The other objective was to do the sensitivity analysis of the parameters in modeling of fuel coolant interactions, which can help to reduce uncertainty in assessment of steam explosion energetics.

The results show that the amount of liquid melt droplets in the water (region of void<0.6) is maximum even before reaching the jet at the bottom. In the explosion phase, maximum pressure is attained at the bottom and the maximum impulse on the wall is at the bottom of the wall. The analysis is carried out using two different triggers, but there is little effect of trigger found on the impulses on wall. The pressure attained and impulses on the wall are higher for bigger jet diameters, bigger melt droplets and higher subcoolings.

Key words

Steam explosion energetics, Nordic BWR containment, Melt droplets, melt jet

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Contents

1. Introduction

Nordic Boiling Water Reactors (BWRs) employ a drywell cavity flooding technique as a nuclear severe accident management strategy. In case of core melt accident where the reactor pressure vessel will fail and the melt will eject from the lower head and fall into a water pool, may be in the form of a continuous jet. It is assumed that the melt jet will fragment, quench and form a coolable debris bed into the water pool. The melt interaction with a water pool may cause an energetic steam explosion which creates a potential risk towards the integrity of containment, leading to fission products release into the atmosphere.

The results of the APRI-7 project suggest that the significant damage to containment structures by steam explosion cannot be ruled according to the state-of-the-art knowledge about corresponding accident scenario. In the follow-up project APRI-8 (2012-2016) one of the goals of the KTH research is to resolve the steam explosion energetics (SEE) issue, developing a risk-oriented framework for quantifying conditional threats to containment integrity for a Nordic type BWR.

The energetic interaction of corium with the subcooled water pool may cause high impact loading on the containment walls as well as the bottom, leading to an early failure of containment. There are several factors responsible for the occurrence of steam explosion includes melt composition and superheat, water pool temperature, system pressure, jet fragmentation and void generation.

When a melt jet falls into water, it starts breaking up into fragments while penetrating through the water pool, which accelerates the heat transfer and also causes lot of vapor generation. These fragments subsequently undergo film boiling and the vapor film around the droplet resist the further heat transfer keeping the droplet still in liquid form. Due to unstable film boiling, some droplets come directly in contact with water and the rapid vapor generation forms a shock wave locally, disturbing the film of surrounding droplets. It makes the condition more severe causing a spontaneous steam explosion and the droplets undergo a catastrophic breakup forming very small fragments of the order of tens and hundreds of micrometer.

It is known that the conditions are quantitatively different for the actual reactor scale case comparing to the prototypical experiments. Therefore, the computational codes can be used to assess the fuel coolant interactions in reactor scale scenario. MC3D is CFD code devoted to multiphase flow studies and evaluations in the field of nuclear safety. It is mostly used for FCI calculations, which initially carries out the premixing phase calculations and then using this data it calculates the explosion phase. This code has been validated with many important FCI experiments (Meignen, 2005), (particularly FARO (Magallon and Huhtiniemi, 2001) and KROTOS (Huhtiniemi et al., 2002)).

The present study deals with the premixing and explosion phase calculations of a Nordic BWR dry cavity, using MC3D, a multiphase CFD code for fuel coolant interactions. The main goal of the study is the assessment of pressure buildup in the cavity and the impact loading on the side walls. The conditions for the calculations are used from the SERENA-II BWR case exercise. The other objective is to do the sensitivity analysis of the parameters in modeling of fuel coolant interactions, which can help to reduce uncertainty in assessment of steam explosion energetics.

2. Problem formulation and numerical methodology

As mentioned earlier in the text, the present work is to analysis the steam explosion energetics in the flooded drywell of a Nordic BWR using MC3D code. This is the assumed case of reactor pressure vessel (RPV) failure where a molten corium ejects from the breach at the bottom, in the form of jet and falls into a flooded drywell. The geometry of domain is as shown fig. 1. The assumed conditions taken from SERENA-II BWR exercise are given as in Table 1.

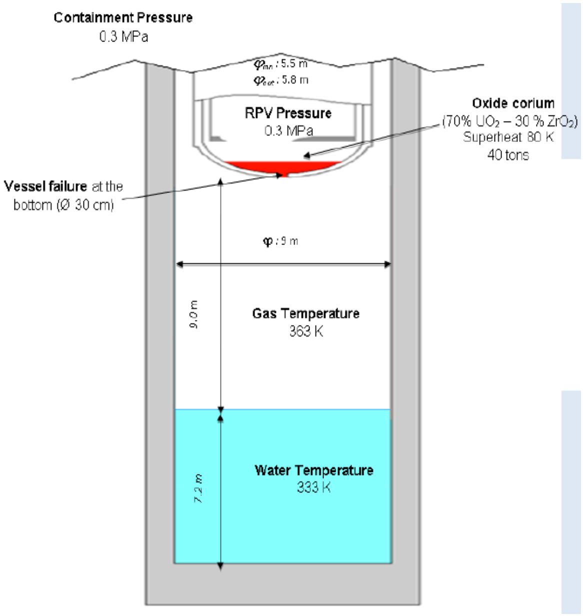


Figure 1 - Geometry of the flooded cavity

Table 1 - Assumed cavity conditions (SERENA-II, BWR case (SERENA-II report, 2012))

Melt pool and jet input parameters	Values
Melt composition	70 % UO2 - 30 % ZrO2
Initial Melt temperature [K]	80 K superheat
Melt jet diameter [m]	0.3
Melt mass [kg]	40000
Initial pressure difference between RPV and Pedestal [MPa]	0
Containment (Lower Drywell) conditions	
Diameter [m]	9.0
Initial pressure [MPa]	0.3
Initial gas temperature [K]	363
Initial water pool temperature [K]	333
Water pool depth in the Lower Drywell [m]	7.2
Free fall height of jet in atmosphere [m]	9.0
Triggering [on centerline]	1. At 3.6 m at melt arrival at this level 2. Maxi melt liquid mass according to criteria to be explained

The conditions mentioned in table 1 are employed in MC3D, and the 2D problem is formulated using axi-symmetric conditions. The domain consists of a central axis, a side and bottom wall, and the constant pressure is specified at the top boundary. The air is considered as a non-condensable gas. There are two jet fragmentation models in MC3D [4], of which, CONST model is employed in the present study. The CONST model needs a droplet diameter as an input and it takes the local physical properties of melt to calculate the jet fragmentation rate. The melt droplet diameter is considered as 2.5 mm, which is the available average size from most of the experiments. In the process, the jet will fall from the bottom of RPV into the water pool. The expected optimum mesh size is larger taking longer time for calculation. Initially the preliminary calculations are carried out considering the full domain. Fig. 2 shows the contour plots of the jet interaction with water pool. The calculations time for this geometry size is longer, even using a coarser mesh size (especially when jet interacts with a water pool). Therefore, as a next step, in order to reduce mesh size and refine mesh near crucial area, the domain was restricted to 10 m height from the bottom. The new modified domain is as shown in fig. 3. The calculations using a full geometry are then carried out, only to calculate the actual jet diameter and velocity at 10 m height, to be used in the further analysis. The constant pressure is specified at the upper boundary of the modified domain. The mesh is refined near the centre area and the bottom, where there is maximum jet coolant interaction. This is considered as the basic case in the present study. The premixing and explosion phase calculations are carried out for all the cases.

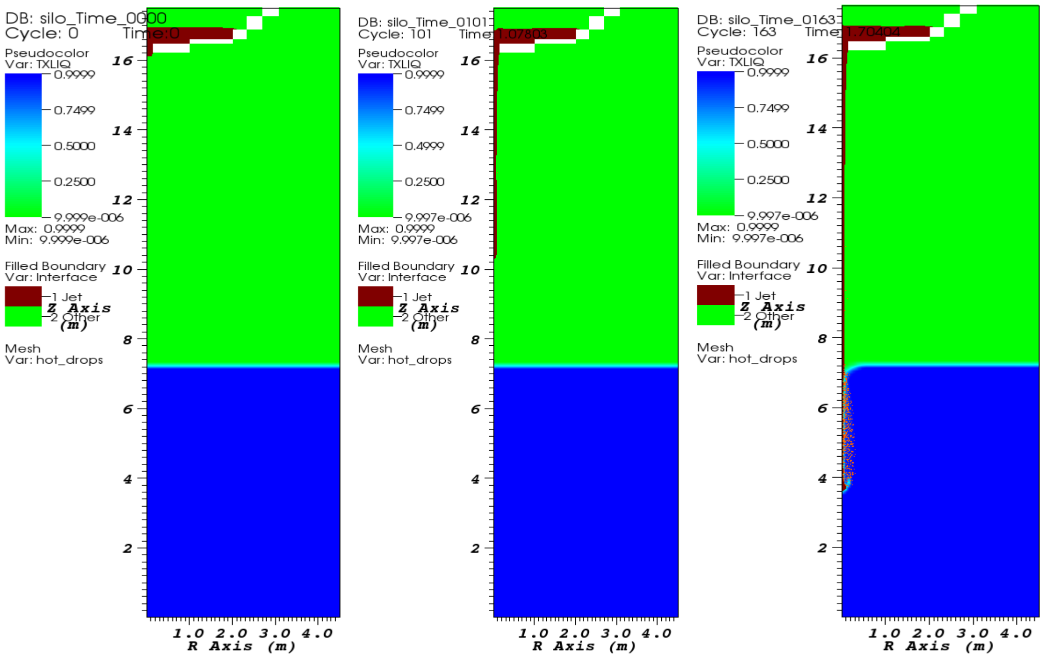


Figure 2 - Preliminary calculations plots considering full geometry.

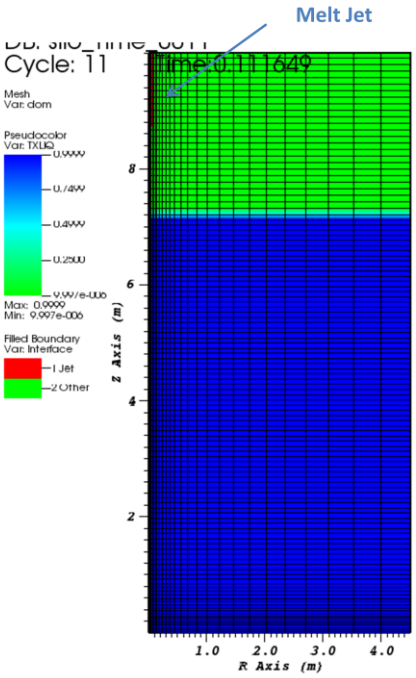


Figure 3 - Modified domain.

3. Mesh independence test

In order to maintain the accuracy of the solution, mesh independence test is carried out. The different size meshes are used: 106 × 25, 140 × 40 and 200 × 100. The mass of the droplets resulting from premixing phase calculations is used for comparison (fig. 4). The total melt droplet mass is well comparable at least till the time jet reaches to the bottom. Therefore the coarse mesh was used for then used for the further calculations, seeing the negligible dependence of mesh on the parameters and the economy in calculation time.

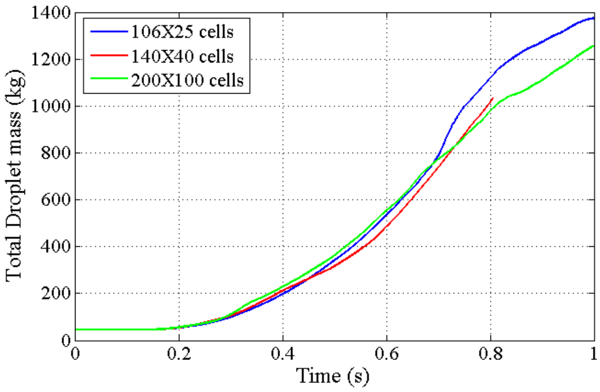


Figure 4 - Comparison of the total droplet mass for different mesh sizes.

4. Results and discussions

Initially, the basic case (BWR conditions considered in SERENA-II) calculations are carried out. The premixing calculations are carried out firstly, followed by an explosion phase. Fig. 5 shows the contour plots illustrating the flow patterns of jet in the water pool. It shows the fragmentation enhances when the jet enters into the pool. The area around the jet contains more void due to rapid evaporation of the coolant at the jet-coolant interface and also from the fragmented droplets. There is a highly wavy pocket of vapor around the jet, which may initiate the turbulence in the water pool. From the results, it is clear that the jet reaches the bottom without breakup. The reason may be the bigger jet diameter due to which it reaches to the bottom without breakup instead of having larger free fall height allowing the jet to reach near its terminal velocity. Fig. 6 shows the position of the jet front with respect to time. The time required for the jet to reach the bottom from the 10 m height is 0.84 s and the total time required from the RPV bottom is 2.01 m.

Fig. 7 shows the details of the droplet mass with respect to time. It can be stated from the graph that, up to about 0.65 s, the total fragmented drops are in liquid state and, since the amount of void is less, almost all the droplets are in contact with the coolant. Afterwards, the total droplet mass increases with the same rate, but the liquid droplet mass in water (void<0.6) reaches its peak and starts to decrease. This may be due to the fact that there is enough amount of void generated by this time, in the region around the jet and therefore most of the fragmented liquid droplets are in high void region. The droplets in contact with the coolant also support to the global vaporization in the pool. It is known that, the amount of liquid droplets in contact with coolant (or in the low void region) is responsible for occurrence and the severity of explosion. Therefore, from the mass of the liquid droplets in water, it can be deduced that the conditions of explosion prevails even before reaching the jet to the bottom.

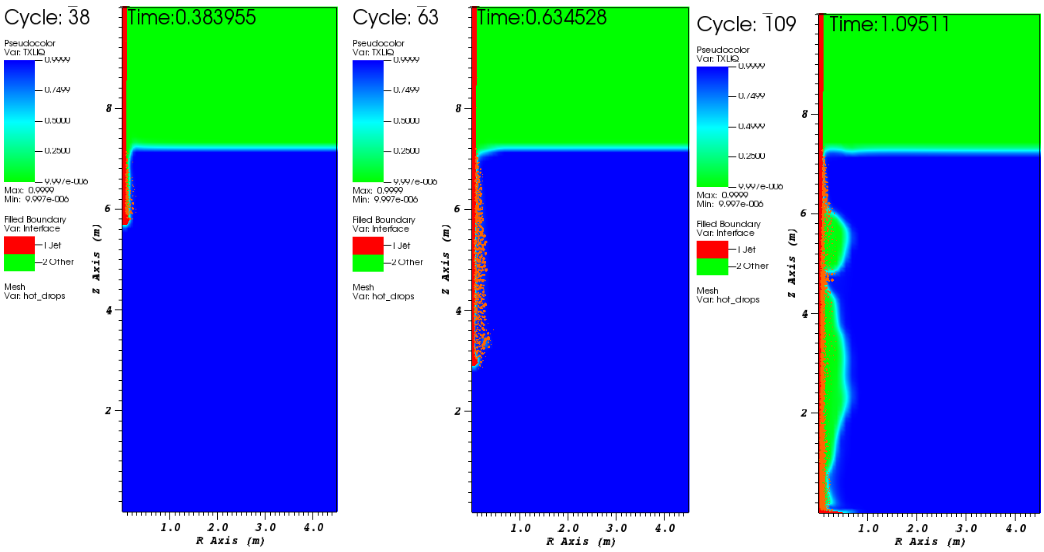


Figure 5 - Flow patterns in the domain at different time intervals.

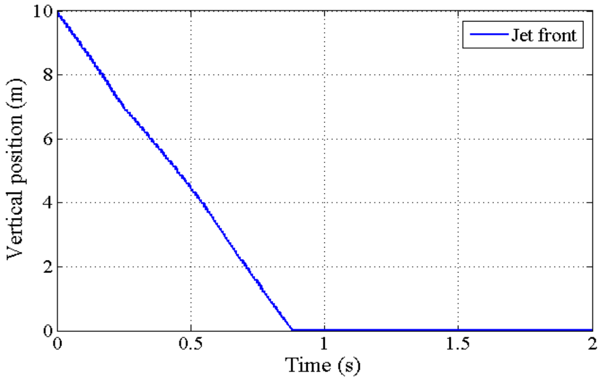


Figure 6 - Position of jet front with respect to time.

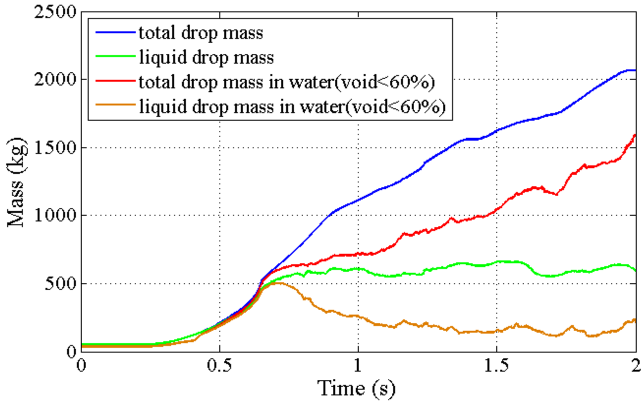


Figure 7 - Different droplet masses with respect to time.

The explosivity criteria is calculated in MC3D while premixing phase calculations, which is the mass of liquid droplets in region of void<0.7. The triggering for initiation of explosion phase is carried out at two different time instants (trigger 1 and trigger 2), as mentioned earlier in the table 1. The details are a shown in fig. 8. There is a provision in the code for specifying the triggering zone, where an explosion can occur, and it searches the favorable location for the start of explosion.

Initially, calculation with trigger 1 is carried out. Fig. 9a shows the pressure achieved at different locations in the cavity during explosion. It is found that the maximum pressure is attained at the bottom floor, and, among the side wall locations, peak pressure is at its bottom side. Fig. 9a illustrates that, initially the pressure wave propagates to the wall (initial peak at 5 m height), then it augment at the bottom with high pressure. Fig. 9b shows the impulses on side wall at different location. It can be clearly seen the higher impulses strike on the bottom side of the wall. From the bottom of the wall to the height of 3 m, the impulses are between 70-80 kPa.s, which are significantly larger as compared to the higher locations.

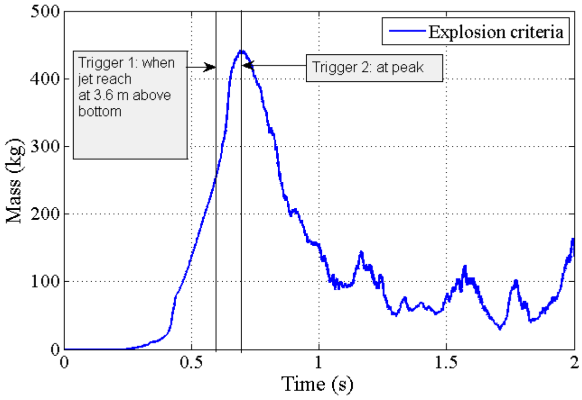
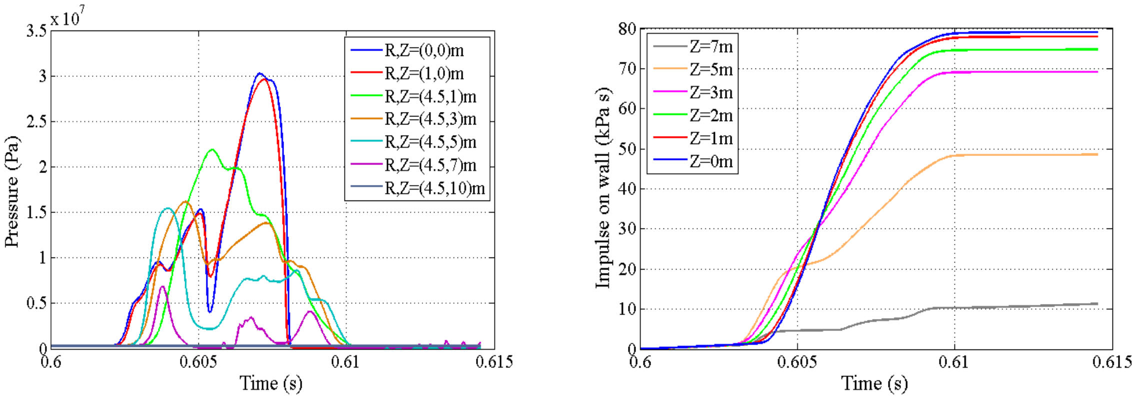
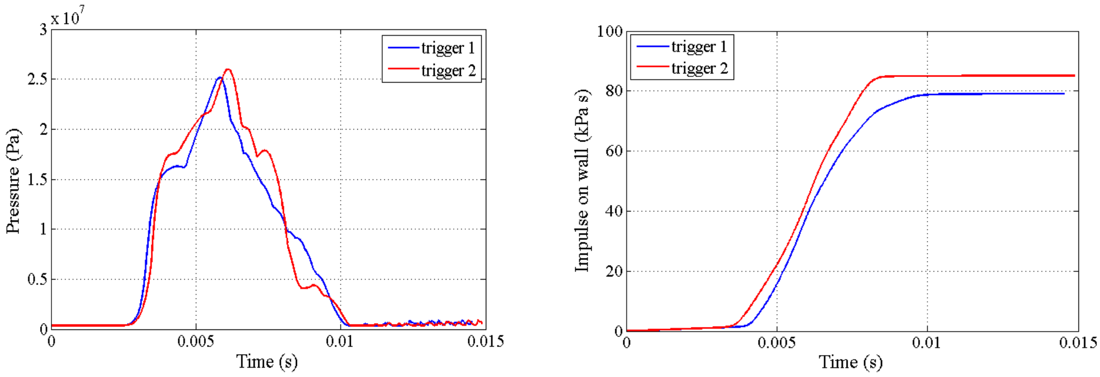


Figure 8 - Explosivity criteria.



a) b)

Figure 9 – a) Pressure attained at different locations in the cavity, b) Impulses on side wall.



a) b)

Figure 10 - Comparison of a) the maximum pressure near wall, and b) maximum impulse on wall.

Explosion phase calculations are also carried out using trigger 2, which is initiated when explosivity criteria is maximum. Fig. 10a compares the maximum pressure achieved near the wall calculated using two different triggers. Fig. 10b shows the comparison of the maximum impulse on wall. No significant difference is found in the maximum pressure as well as maximum impulse, between two cases. By the time when the trigger 2 is executed, there is more void in the pool, which may damp the pressure waves reducing its intensity. This may be the probable reason, not to have significant difference in the pressure and impulses between two trigger cases.

4.1 Effect of melt jet diameter

In order to study the effect of melt jet diameter on the explosivity and ultimately the impact loading on the side wall, simulations with different jet diameters have been carried out. Fig. 11 shows the positions of the jet front for different jet diameters and shows no difference in the time to reach the jet at the bottom floor, though 20 cm diameter jet takes slightly longer time. Fig. 12 shows the mass of the liquid droplets in water for different melt jet diameters. It illustrates that, in each case the droplet mass reaches to a certain peak and thereafter decreases. The rate of increase of droplet mass is higher for bigger jet diameters and the mass is significantly higher for the 60 cm jet diameter. For the initiation of the explosion phase, the triggering is done at the same time (same as trigger 1 in earlier case), in all the cases. Fig. 13a and fig. 13b shows the maximum pressure near wall and maximum impulse on the wall respectively. The attainment of maximum pressure near the wall does not vary significantly, though it is less in case of 20 cm. The maximum impulse on the wall is higher for bigger jet diameters. The no difference between 30 and 40 cm jet diameter case in both the figures (fig. 13a and 13b) may be due approximately same amount of liquid droplet mass at the time of trigger.

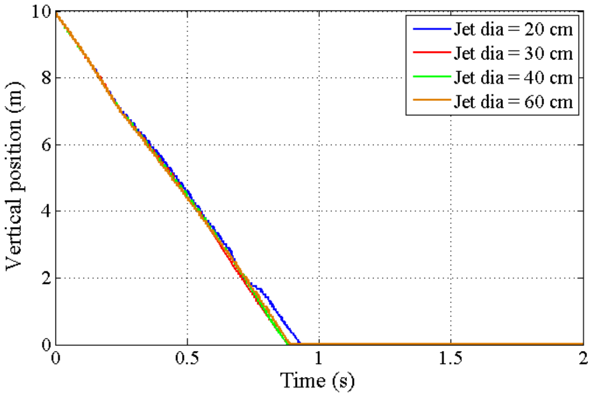


Figure 11 - Jet front positions of different jet diameters.

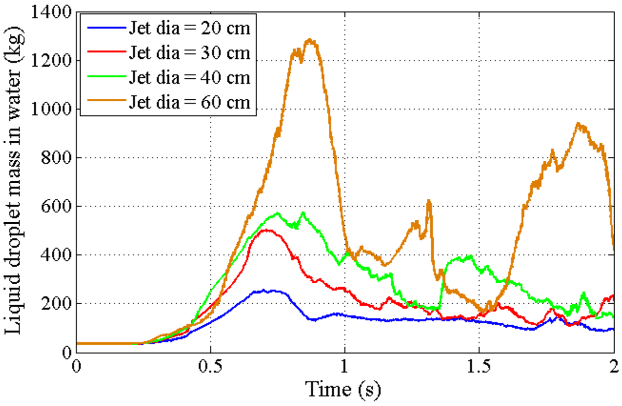
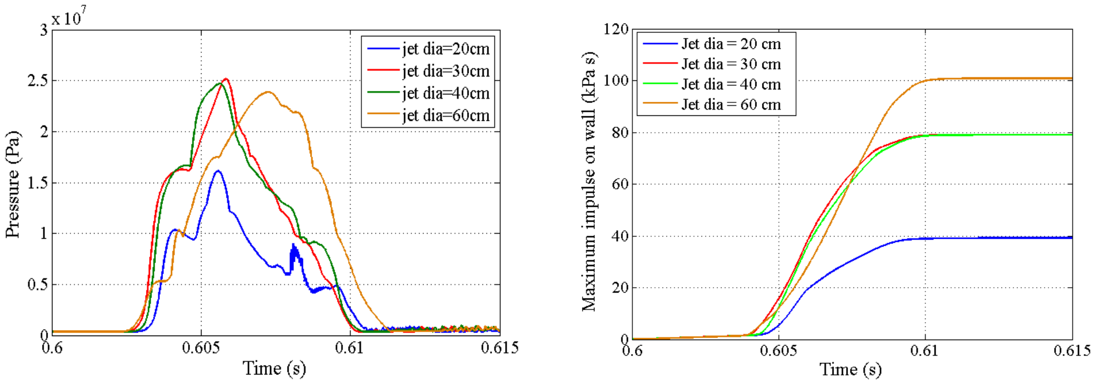


Figure 12 - Comparison of the liquid droplet mass in water.



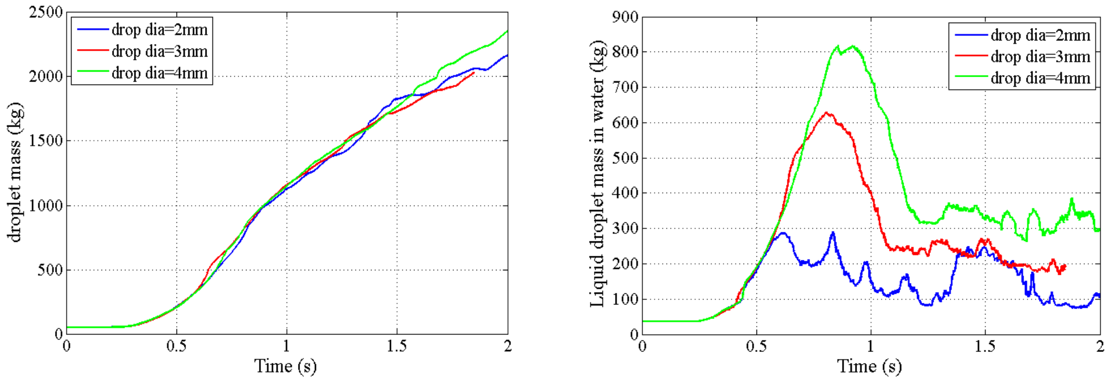
a) b)

Figure 13 - a) Maximum pressure and b) maximum impulse on wall, for different jet diameters.

4.2 Droplet size sensitivity

As explained earlier, the melt droplet size is taken as a input by the CONST fragmentation model, taking the local physical properties of melt it calculates the jet fragmentation rate. The premixing and explosion calculations for different droplet size cases have been carried out to analyze its effect on the energetics of steam explosion. The droplet sizes taken into consideration are 2mm, 3mm and 4 mm. From premixing calculations, it shows that the total droplet mass in all the cases is same (fig. 14a), while the mass of the liquid droplets is more for bigger diameters (fig. 14b). It is quite obvious that the smaller size droplets will cool faster and solidify, and the vaporization will be more due to larger surface area exposed to the coolant.

The triggering is initiated at the maximum explosivity criteria. In the explosion phase calculations, it shows that the maximum pressure near the wall is higher for bigger droplets case (fig. 15a) and also it gives maximum impulses (fig. 15b). Therefore, it can be stated that, if the droplet size from the jet fragmentation is bigger, droplets will not solidify rapidly. And, the vapor generation will be comparatively lesser due to less surface area in contact with the coolant. This may cause to enhance the intensity of the explosion, if any occurs.



a) b)

Figure 14 - Droplet mass comparison for different droplet size [a) total droplet mass; b) liquid droplet mass in water].

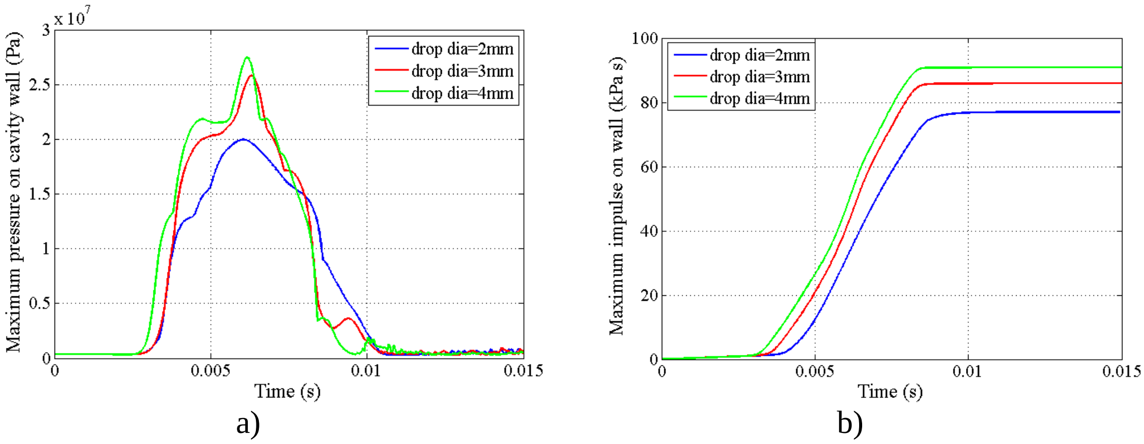


Figure 15 - a) Maximum pressure and b) maximum impulse on wall, for different droplet sizes.

4.3 Effect of subcooling

In order to study the effect of coolant temperature on the energetics of fuel coolant interactions, premixing and explosion calculations are carried out for different subcoolings (20K, 40K and 60K). Fig. 16a and 16b show the total mass of the droplets and the mass of the liquid droplets, respectively. It illustrates that there is no significant difference in the total mass of the droplets formed from jet fragmentation, for different subcoolings. Whereas, the mass of the liquid droplets in the water (void<0.6) is higher for higher subcooling. This is due to the fact that vapor generation is comparatively less in case of higher subcooling. Most of the heat from the melt primarily goes into heating the coolant till saturation and therefore the overall void generation is less. The effect of condensation is also higher in case of high subcooling. On the other hand, for lower subcooling, small amount of heat is needed to heat the water and most of the heat goes into vaporization of coolant, resulting higher void formation.

The triggering of explosion phase is carried out at maximum explosivity criteria for each case. Fig. 17a and 17b show the maximum pressure achieved near the wall and the maximum impulse respectively, for different subcoolings. The maximum pressure attained and the impulses on the wall are higher for higher subcoolings.

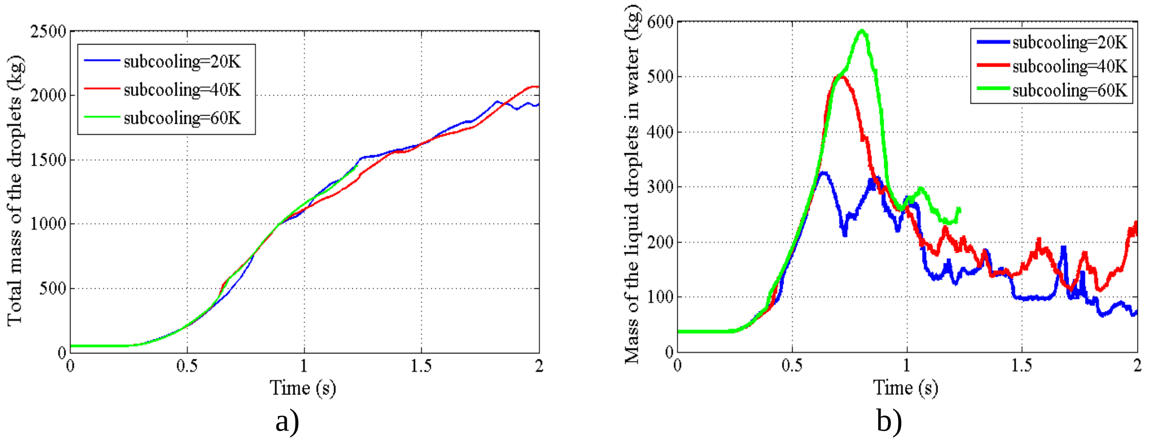
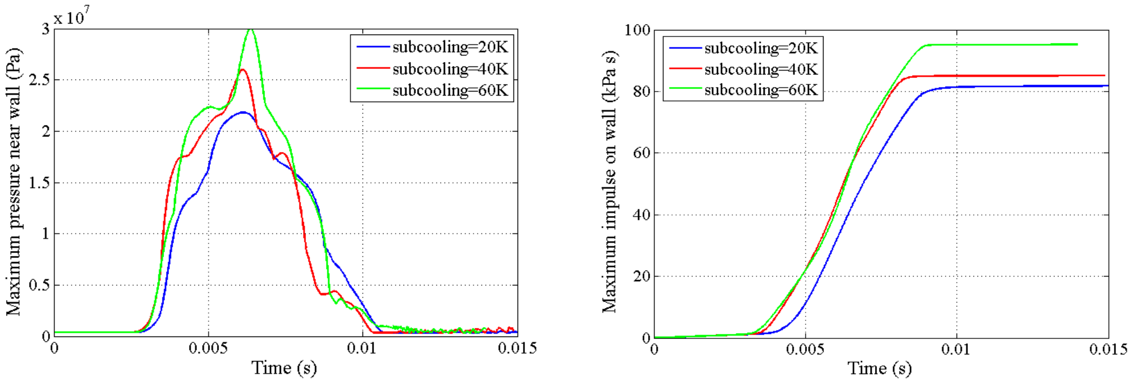


Figure 16 - Droplet mass comparison for different subcooling [a) total droplet mass; b) liquid droplet mass in water].



a) b)

Figure 17 - A) Maximum pressure and b) maximum impulse on wall, for different subcooling.

5. Conclusions

The premixing and explosion phase calculations are carried out using MC3D code, for a Nordic BWR considering the conditions provided in SERENA-II reactor exercise. This is considered as a base case in the analysis. The mesh independence test is carried out to maintain the accuracy in the results. The results show that the amount of liquid melt droplets in the water (region of void<0.6) is maximum even before reaching the jet at the bottom. In the explosion phase, maximum pressure is attained at the bottom and the maximum impulse on the wall is at the bottom of the wall. The analysis is carried out using two different triggers, but there is little effect of trigger found on the impulses on wall. Moreover, the parametric study is carried out using different jet diameters, droplet sizes and subcoolings, the findings of which are as follows.

1. The pressure attained and impulses on the wall are higher for bigger jet diameters, though there is little variation found between 30 cm and 40 cm jets.
2. The amount of liquid melt droplets in water is higher for bigger droplet size and thus, the pressure attained and impulses on the wall are higher.
3. For higher subcoolings the more liquid droplets are in contact with the coolant causing high pressure and impulses on the wall.

6. References

Huhtiniemi I., Hohmann H., Magallon D., “FCI experiments in the corium/water system”, *Nuclear Engineering and Design*, Vol. 177, 2002, pg. 339-349.

Magallon D. and Huhtiniemi I., “Corium melt quenching tests at low pressure and subcooled water in FARO”, *Nuclear Engineering and Design*, Vol. 204, Issues 1-3, 2001, pg. 369-376.

Meignen R., “Status of the qualification program of the multiphase flow code MC3D”, Proceedings of ICAPP’05, paper 5081, Seoul, Korea 2005.

Meignen R., Picchi S., “MC3D Version 3.7p1, User’s guide”, IRSN report, PSN-RES/SAG/2012-00063.

SERENA-II report, 2012.

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