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Sensitivity Study of Steam Explosion Energetics in Reference Nordic BWR using MC3D Code

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Abstract

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. And also 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. In the present study, initially, jet diameter of 30 cm is used to study the steam explosion impulses on side wall of the cavity. The case of CRGT and IGT equivalent diameter cases have also been stufdied. Moreover, the effect of water pool depth, jet velocity on the energetics of steam explosion is carried out.

Key words

Fuel coolant interactions, Steam explosion

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1. Introduction

In a hypothetical nuclear severe accident, there is possibility that the molten corium will breach the reactor pressure vessel bottom and fall into the containment cavity. Nordic Boiling Water Reactors (BWRs) employ a drywell cavity flooding technique as a nuclear severe accident management strategy. During core melt accident 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 have fragmentation, quenching and form a coolable debris bed into the water pool. The melt interaction with a water pool may cause an energetic steam explosion which may damage the surrounding structures 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.

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 energetic interaction of corium with the subcooled water pool may cause high impact loading on the walls as well as the bottom of containment, leading to an early failure. There are many factors responsible of the occurrence of steam explosion and its intensity. In earlier work, the analysis of Nordic BWR was carried out using MC3D code. The geometry conditions of BWR were considered from SERENA-II reactor case exercise. Effect of melt jet diameter, droplet size and water subcooling on the steam explosion impulses were studied.

There are several other factors responsible for the occurrence of steam explosion includes jet velocity, depth of water pool etc., which are considered in the present study. The geometry conditions of a reference Nordic BWR has been used in the analysis which differs from the earlier case of SERENA-II exercise.

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. And also 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. In the present study, effect of water pool depth, jet velocity on the energetics of steam explosion is carried out.

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 reference 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 details of geometry, initial/boundary conditions and melt are given as in Table 1.

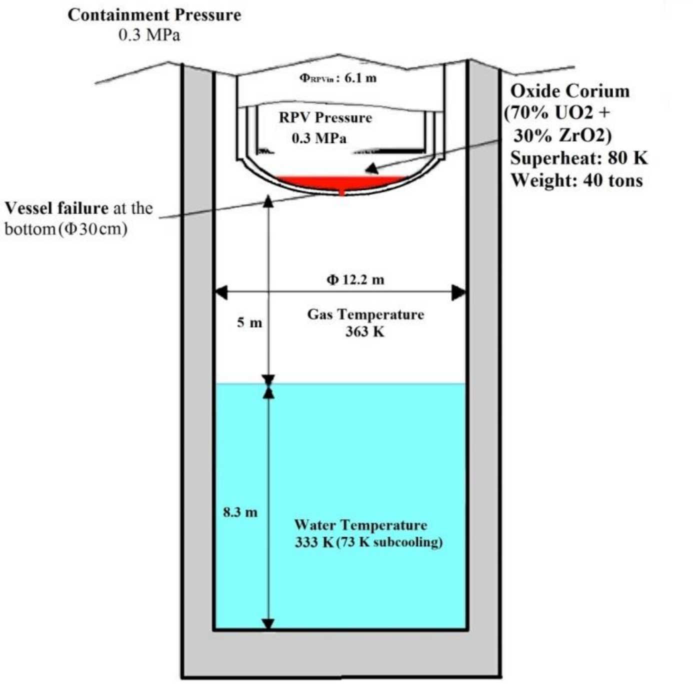


Figure 1 - Geometry of the flooded cavity

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. 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 12 m height from the bottom.

The new modified domain is as shown in fig. 2. The calculations using a full geometry are then carried out, only to calculate the actual jet diameter and velocity at 12 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. The mesh size used for the calculations is 161×81. This is considered as the basic case in the present study. The premixing and explosion phase calculations are carried out for all the cases.

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]	0.3/0.14/0.07
Melt mass [kg]	40000
Initial pressure difference between RPV and pedestal [MPa]	0
Containment (Lower Drywell) conditions	
Diameter [m]	12.0
Initial pressure [MPa]	0.3
Initial gas temperature [K]	363
Initial water pool temperature [K]	333
Water pool depth in the Lower Drywell [m]	8.3
Free fall height of jet in atmosphere [m]	5.0
Triggering [on centerline]	Maxi melt liquid mass according to criteria to be explained

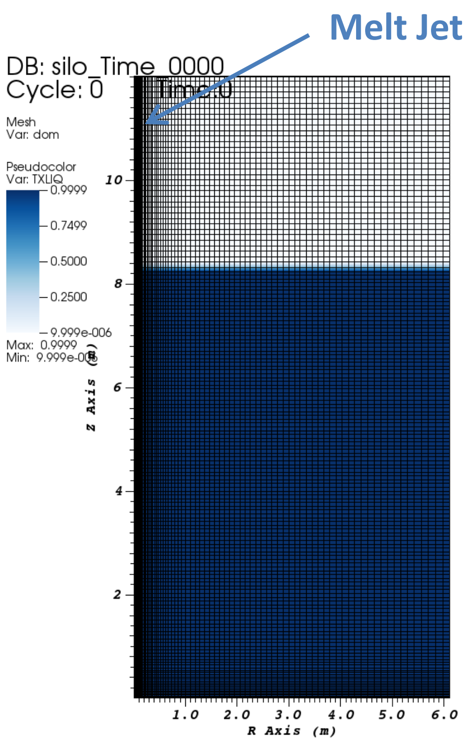
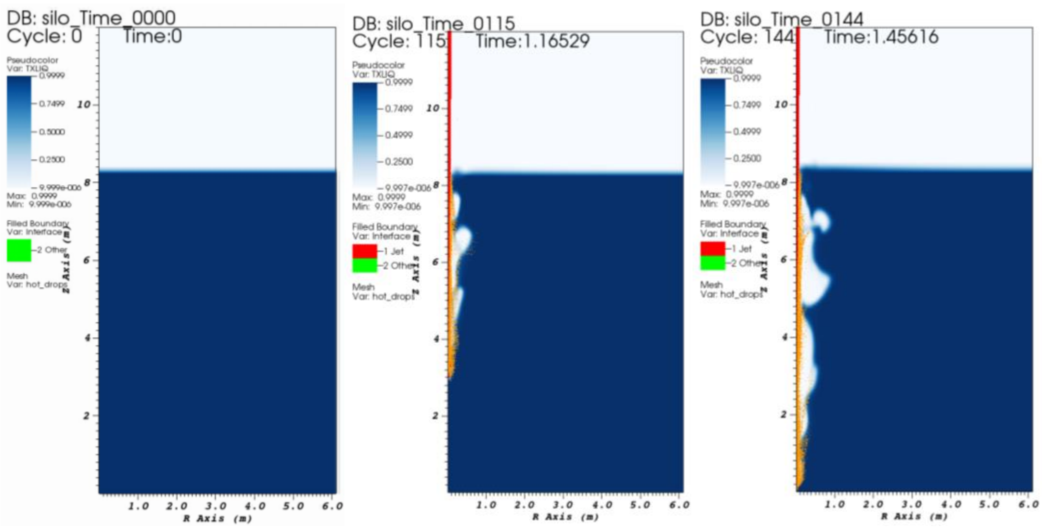


Figure 2 - Modified domain.

3. Results and discussions

Initially, the basic case calculations are carried out, for a jet diameter of 30 cm. 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. 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 12 m height is 1.45 s and the total time required from the RPV bottom is 1.97 s.

The droplet mass in contact with water or the low void region is decisive in the steam explosion triggering and also its intensity. The droplets in contact with the coolant also support to the global vaporization in the pool. Figure 5 shows details of the droplet mass formed from the jet fragmentation. It can be stated from the graph that, up to about 0.8 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 gradually. 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. 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.



a) 0s b) 1.165s c) 1.456s

Figure 3 - Flow patterns in the domain at different time intervals.

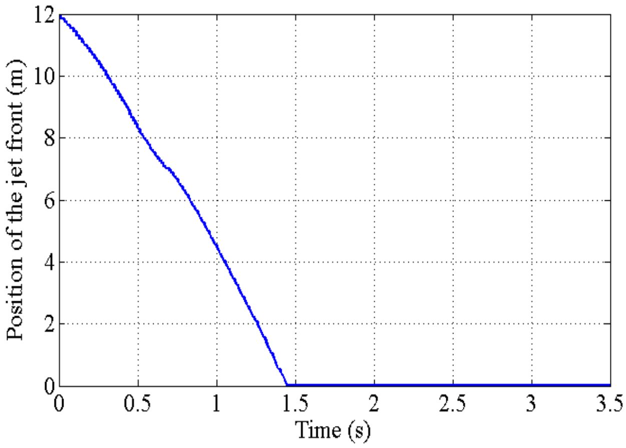


Figure 4 - Position of jet front with respect to time.

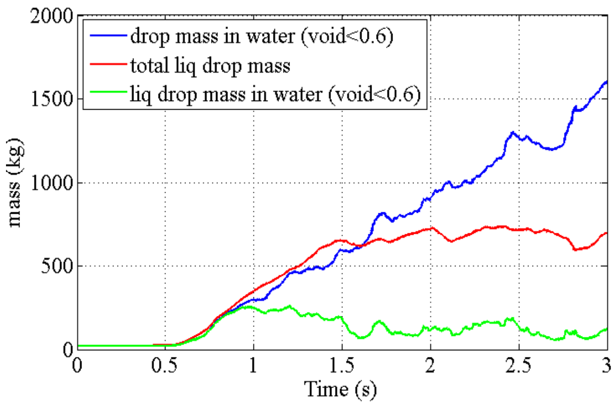


Figure 5 - Different droplet masses with respect to time.

The explosivity criteria (fig. 6) 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 the time when the curve reaches its peak (when the droplet mass is maximum). 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.

Fig. 7a-b shows the pressure achieved at different locations near wall and at the bottom of 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. 7c-d 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. The highest impulse on the wall is 30 kPa.s. Whereas, at the bottom floor it is slightly higher as compared to wall.

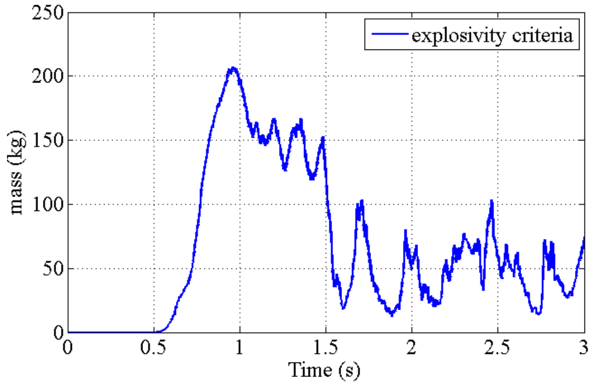


Figure 6 - Explosivity criteria.

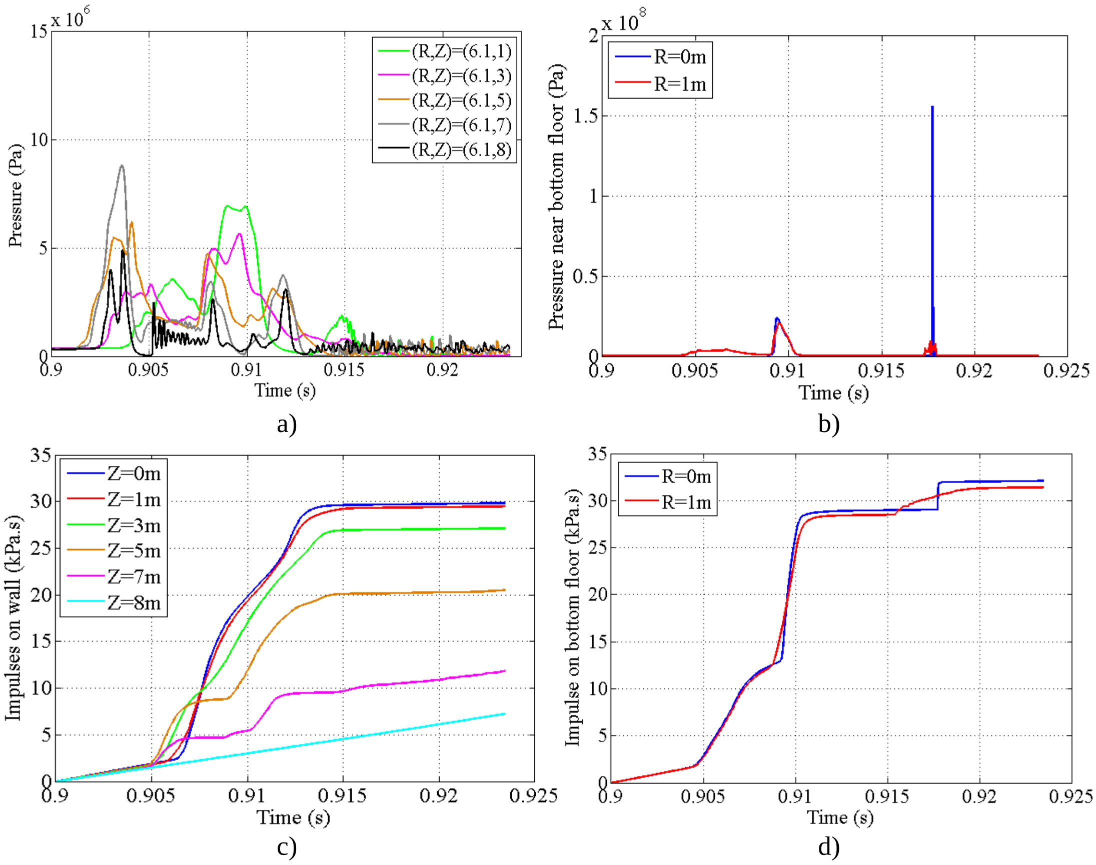
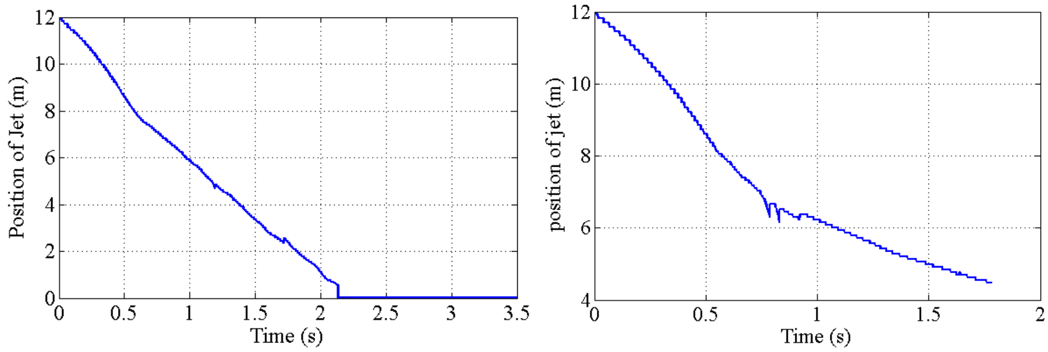


Figure 7 – a–b) Pressure attained at different locations in the cavity and on bottom floor, c-d) Impulses on side wall and at the bottom.

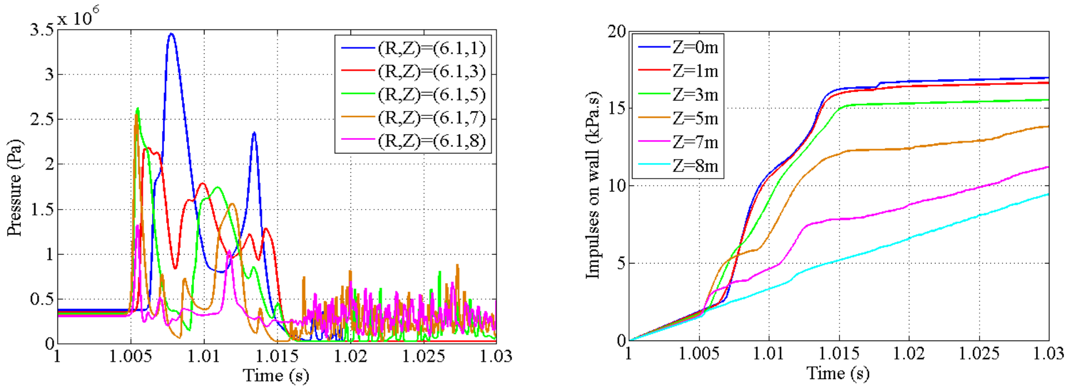
3.1 CRGT and IGT failure cases

Though the effect of jet diameter on the steam explosion energetics has been carried out in the previous study, the considered sizes of jet were bigger. Therefore in the present study the smaller jet diameters 14 cm and 7 cm are used in the calculations which are according to CRGT and IGT failure scenario. Fig. 8a shows the leading edge of the jet penetrating through water pool with respect to time. It illustrates that the jet reaches almost at the bottom without breakup. Similar to previous results with larger break, here the maximum pressure buildup and the maximum impulse is at the bottom of the side wall. However, the maximum impulse is around 17 kPa.s. In IGT case of 7 cm jet diameter, the premixing calculations could complete till jet reaches to the bottom (fig. 8b). Fig. 10 a-b illustrates that the pressure pulse and impulses are higher at the bottom of wall, also in IGT case. And the maximum impulse is around 12 kPa.s.



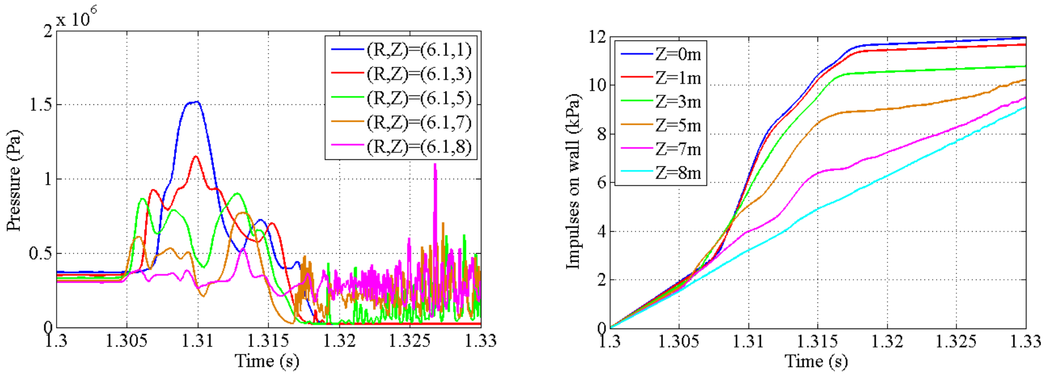
a) b)

Figure 8 - Jet front position for a) CRGT (14 cm jet diameter) and b) IGT (7 cm jet diameter) case.



a) b)

Figure 9 - a) Maximum pressure and b) maximum impulse on wall (CRGT case).



a) b)

Figure 10 - a) Maximum pressure and b) maximum impulse on wall (IGT case).

Comparing these results with 30 cm jet diameter case, the mass of liquid drop in water in the case of 30 cm diameter jet is more than 3 times than 14 cm case and around 10 times higher than of 7 cm case. Whereas, the impulse on wall for 30 cm jet diameter is 2 times and 2.5 times higher than 14 cm and 7 cm case respectively. Therefore, In addition to liquid drop mass, there may be other factors responsible for the intensity of steam explosion.

3.2 Effect of jet velocity

To study the effect of velocity, three different velocities ranging from 5 to 7 m/s have been used in the calculations. The jet diameter of 14 cm is used for these calculations. Fig. 11a shows the liquid droplet mass in contact with water which illustrates that the fragmentation rate increases with the jet velocity. It also shows larger liquid droplet melt mass for higher velocities. It may indicate higher rate of jet fragmentation into droplets as compared to formation of local void area, due to which more amount of liquid melt droplets are in low void zone. It may enhance the conditions for explosion and its intensity. Fig. 11b shows the maximum impulse on wall which clears that the impulses are higher for higher jet velocities.

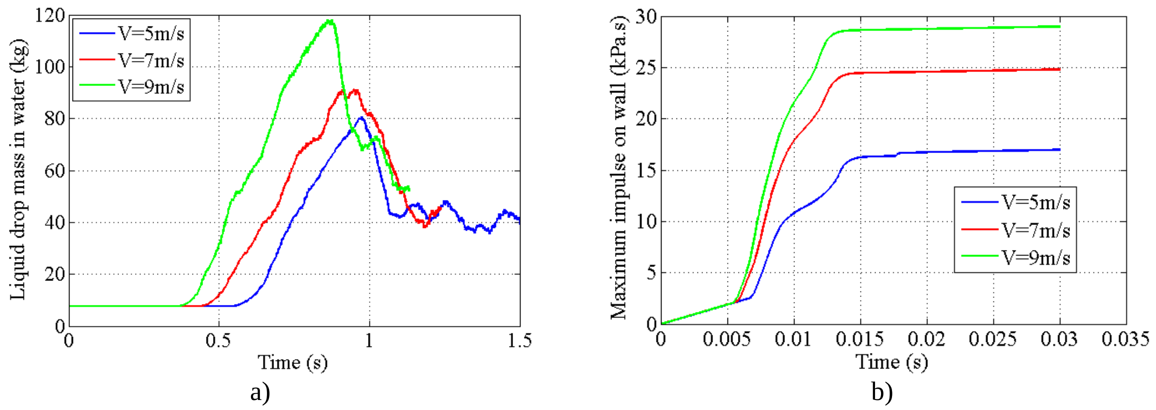


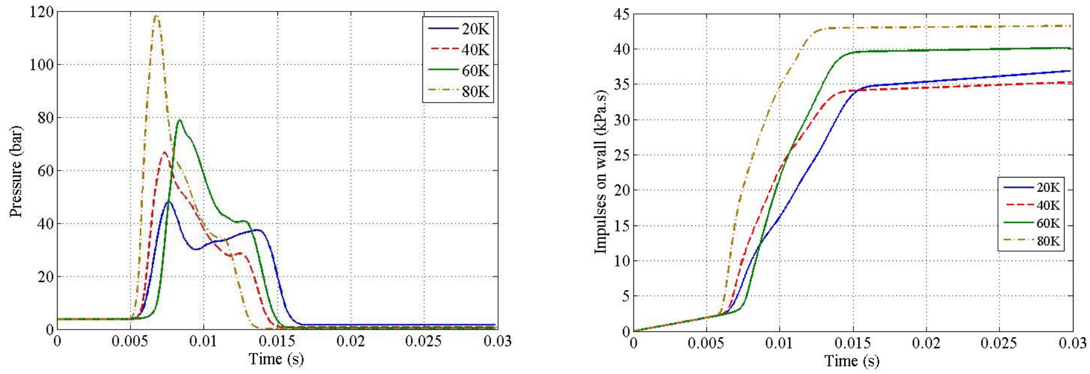
Figure 11 - Droplet mass comparison for different jet velocities [a) liquid droplet mass in water; b) maximum impulse on wall].

As a next step, the sensitivity analysis has been carried out using additional parameters. In order to optimize the calculation time, which was higher in earlier calculations, a coarser mesh is used (61 × 26 cells). The jet diameter of 30 cm has been used for these sensitivity calculations.

3.3 Effect of subcooling

In order to study the effect of coolant pool temperature on the energetics of fuel coolant interactions, premixing and explosion calculations are carried out for different subcoolings (20K, 40K, 60K and 80K). Fig. 12a shows the maximum pressure buildup near wall calculated from the explosion phase calculations. The pressure values are higher for higher subcooling and it leads to higher impulses on the wall which is clear from fig.12b.

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. Therefore most of the liquid melt droplets are in low void region in case of higher subcooling which creates high intensity impulses.

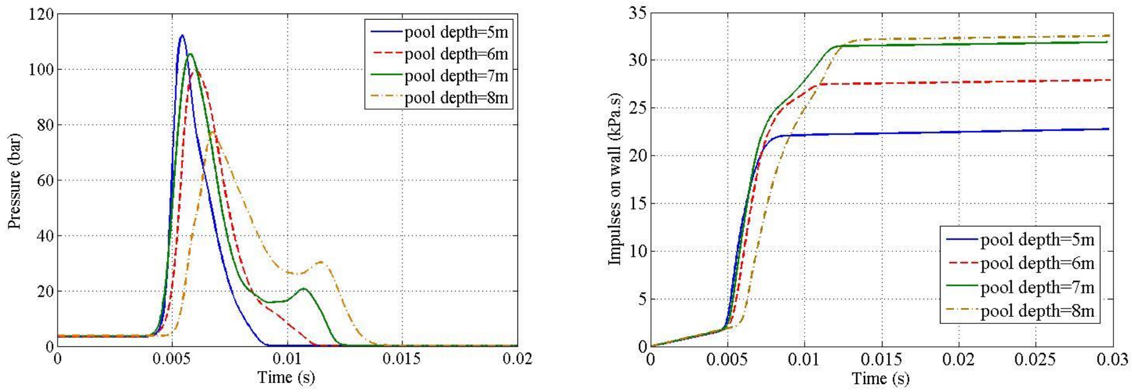


a) b)

Figure 12 - a) Maximum pressure and b) maximum impulse on wall, for different subcooling.

3.4 Effect of water pool depth

The depth of a water pool in a flooded drywell may have some effect on the steam explosion intensity. Therefore, in this case the different depth of water pool is used for the calculations: 5-8 m. Fig. 13a-b shows the maximum pressure buildup near the wall and the impulse on the wall. It illustrates that at smaller pool depths, pressure rise near the wall is higher however at larger pool depth, there is additional reflections of the waves from side walls and bottom which augment the impulses near bottom of wall. It can also be said that the area under curve for the pressure buildup curves (fig.13a) is higher for higher pool depths giving higher impulses which is the integration of pressure with time.



a) b)

Figure 13 - a) Maximum pressure and b) maximum impulse on wall, for different water pool depth.

4. Conclusions

The premixing and explosion phase calculations are carried out using MC3D code, for a reference Nordic BWR. Along with the case of large break (30 cm jet diameter), CRGT and IGT cases is also considered in the present analysis. Moreover, the sensitivity study is carried out using different jet velocities, subcoolings and water pool depth, the findings of which are as follows.

1. The 30 cm jet case created the maximum impulse on the wall near the bottom which is 30 kPa.s. Whereas, CRGT and IGT equivalent diameter cases created the maximum impulse on the wall are 17 kPa.s and 12 kPa.s respectively.
2. The higher jet velocities help to increase the intensity of steam explosion which is clear from the higher values of impulses obtained for higher values of jet velocities.
3. Larger water pool depths may lead to higher impulses on the wall.
4. Higher subcoolings may cause high pressure and impulses on the wall.

5. Acknowledgement

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6. Disclaimer

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