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Research Article

Analysis of TROI-13 Steam Explosion Experiment

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The prediction of steam explosion inducing loads in nuclear power plants must be based on results of experimental research programmes and on simulations using validated fuel-coolant interaction codes. In this work, the TROI-13 steam explosion experiment was analysed with the fuel-coolant interaction MC3D computer code. The TROI-13 experiment is one of several experiments performed in the TROI research program and resulted in a spontaneous steam explosion using corium melt. First, the TROI-13 premixing simulations were performed to determine the initial conditions for the steam explosion simulations and to evaluate the melt droplets hydrodynamic fragmentation model. Next, a number of steam explosion simulations were performed, varying the steam explosion triggering position and the melt droplets mass participating in the steam explosion. The simulation results revealed that there is an important influence of the participating melt droplets mass on the calculated pressure loads, whereas the influence of the steam explosion triggering position on the steam explosion development was less expressive.

1. INTRODUCTION

A steam explosion in a nuclear power plant may develop when the molten corium interacts with the water inside the reactor vessel or in the reactor cavity. During the fuel-coolant interaction (FCI), the corium thermal energy is intensively transferred to the water. The water vaporizes at high pressure and expands, doing work on its surroundings. Although the steam explosion has a low probability of occurrence, it is an important nuclear safety issue in case of a severe reactor accident. Namely, the high pressures occurring during a steam explosion can potentially induce severe dynamic loadings on surrounding safety relevant systems, structures, and components of the nuclear power plant. One of the most severe potential consequences of an ex-vessel steam explosion in a nuclear power plant is an early containment integrity loss, which can lead to an early radioactive material release into the environment. [1]

The prediction of steam explosion induced loads must be based on results of experimental research programs (e.g., TROI, KROTOS, FARO) and on simulations using validated FCI models (e.g., MC3D, IKEMIX, COMETA). Experiments provide experimental data for the steam explosions fundamental issues investigation, the structural loadings evaluation, and the severe accident management improvement. Since the experimental results are in general not directly applicable to reactor conditions, above all due to the different scales, FCI models are needed for experimental findings extrapolation to reactor conditions. To be able to make reliable predictions, the FCI models have to be validated on experimental data. In the complex FCI phenomenon, multiple processes are involved during the different steam explosion stages, that is, premixing (corium fragmentation when mixing with water), steam explosion triggering, explosion propagation (the corium thermal energy is converted into coolant thermal energy), and expansion (the coolant thermal energy is converted into mechanical energy), which have to be adequately modelled. The modelling contributes to the FCI phenomenon understanding and highlights issues that are not well understood or require further experimental investigation and model validation. Only adequate FCI processes and consequences understanding enable the FCI codes development to a sufficient high level, appropriate for steam explosion risk assessment in nuclear power plants. [2–4]

Among several experiments performed in the TROI research program, the TROI-13 FCI experiment was chosen for the simulation with the FCI computer code MC3D. The

TROI-13 experiment was selected since in this experiment the steam explosion occurred spontaneously and resulted in the strongest explosion among the TROI experiments performed with corium melt. The purpose of the performed analysis was to establish the modelling capabilities of the MC3D code and to get additional insight into the complex FCI phenomenon.

As follows, first, the description of the TROI facility and the main TROI-13 experimental results is provided. Next, the simulation results of the TROI-13 steam explosion experiment are being presented and discussed in comparison with the experimental measurements. Finally, conclusion remarks are given.

2. TROI-13 EXPERIMENT SET UP AND RESULTS

Test for real corium interaction with water (TROI) is one of the research programs, which was established to provide experimental data to investigate the steam explosions fundamental issues, to enable the structural loadings evaluation, and to improve the severe accident management in nuclear power plants. The program started in 1997 at Korea Atomic Energy Research Institute (KAERI). [5]

As shown in Figure 1, the TROI facility has a 3D geometry and consists of a furnace vessel, a pressure vessel, and a sliding valve. The furnace vessel contains a cold crucible (copper tubes), a release assembly (plug and puncher), and instrumentation for transient pressure (designator FSVP) and melt temperature (pyrometer) measurements. The melt is prepared in the cold crucible. The sliding valve is opened after the melting is completed. The melt is being released when the plug is removed and the puncher breaks the crust formed at the melt bottom. The puncher actuation time is the starting time for the dynamic data acquisition system and the camera. The melt is delivered into the pressure vessel, which contains the test section and the instrumentation for the measurement of the coolant temperature (designator IVT), the dynamic pressure in the coolant (designator IVDP), the dynamic load at the test section bottom (designator IVDL), the atmosphere temperature (designator PVT), the transient pressure (designator PVSP), the dynamic pressure (designator PVDP), the gas sampling (designator GAS), and the visualization (cameras). The melt is poured into the water inside the test section, which is 150 cm high and has an inner diameter of 60 cm. Due to FCI, a steam explosion may develop inside the test section. [5]

Among several experiments performed in the TROI facility, the TROI-13 experiment was chosen for the simulation with the MC3D code (Section 3). In the TROI-13 experiment, a eutectic corium composition was used. The mass fraction of UO_2 was 70%, and the mass fraction of ZrO_2 was 30%. In the crucible, 13.7 kg of corium were heated to a temperature of nearly 3500 K. Melted corium with the mass 7.735 kg was then poured into the test vessel, which was filled up to 67 cm with water at a temperature 292 K. The free fall height of the molten corium was 3.8 m. The free volume of the pressure vessel was 8.032 m^3, and the initial air pressure was 0.108 MPa. [5]

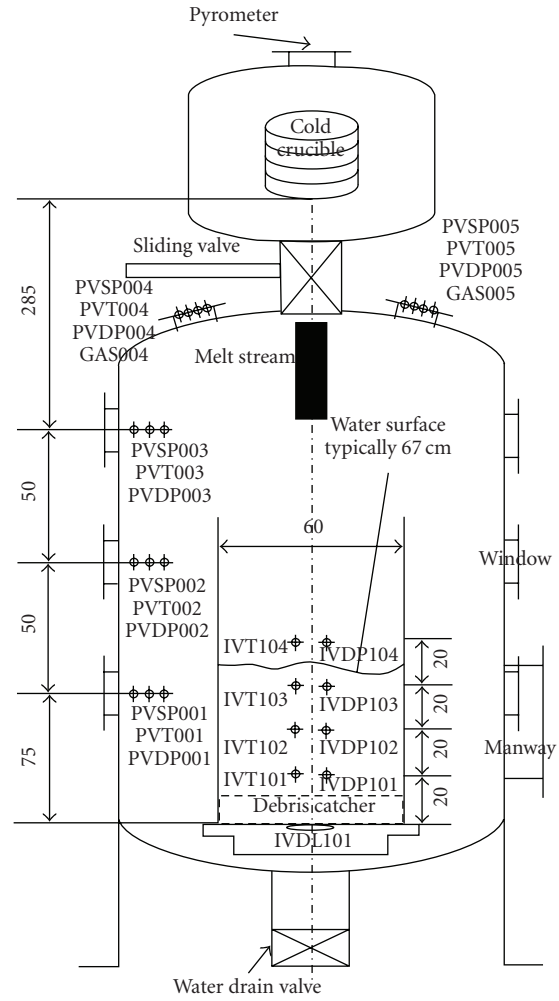

Figure 1: Schematic diagram of TROI facility (not in scale; unit in cm) [5].

In the TROI-13 experiment, a spontaneous steam explosion occurred. The steam explosion energy conversion ratio from thermal to mechanical energy was 0.4%. The steam explosion started at about 1220 milliseconds, when the jet reached the test vessel bottom. A pressure peak of 7 MPa and duration of 1 millisecond was measured at 1224 milliseconds. At the test vessel bottom, the dynamic load was measured. The dynamic force was higher than 250 kN, and the duration of the pressure load was about 15 milliseconds. The most important TROI-13 experimental measurements results are summarized in Table 1. In Table 1, also specific results of some other TROI experiments, which had a similar experimental set up as the TROI-13 experiment, are given. [5]

As seen in Table 1, not all experiments resulted in a spontaneous explosion. Based on the TROI experimental program and other comprehensive experimental programs (e.g., KROTOS, FARO), one can conclude that the explosivity of the premixture and the strength of the steam explosion depend on a number of conditions [2, 4], the most important are the following:

Table 1: Selected experimental results from TROI facility [5]. SDM is the mean Sauter diameter of the debris, $X_{<0.425\,\mathrm{mm}}$ is the mass fraction of debris particles whose size was lower than the sieve size of 0.425 mm, SE indicates whether a spontaneous steam explosion occurred or not, p_{dynamic} is the dynamic pressure peak, and F is the dynamic force peak at the test vessel bottom.

Result	Unit	TROI-9	TROI-10	TROI-11	TROI-12	TROI-13	TROI-14
SDM	mm	1.87	1.08	2.99	0.68	0.71	0.81
$X_{<0.425\,\mathrm{mm}}$	%	2.3	8.7	0.5	20.9	18.9	15.7
SE	N/A	No	Yes	No	Yes	Yes	Yes
p_{dynamic}	MPa	N/A	No data	N/A	1.0	7.0	0.8
F	kN	N/A	No data	N/A	210	250	210

(i) melt material properties (the energy conversion ratio in steam explosion experiments with prototypic materials was one order of magnitude lower than with stimulant materials),

(ii) melt pouring mode (multiple pours form a more extended premixture than single pours),

(iii) system confinement (confined systems allow more time for heat transfer between the melt and coolant),

(iv) water subcooling (with higher water subcooling, the premixture void fraction is lower, resulting in a stronger steam explosion),

(v) noncondensable gases (noncondensable gases hinder the direct melt water contact, reducing the explosivity of the premixture),

(vi) system pressure (with a higher system pressure, the vapour film around the melt droplets becomes more stable, reducing the explosivity of the premixture).

3. SIMULATION OF TROI-13 EXPERIMENT

The TROI-13 experiment was simulated and analyzed with the computer code MC3D, version 3.5, patch 3 [6, 7]. MC3D is being developed by IRSN, France. MC3D is built mainly for the complex FCI phenomenon evaluation. MC3D has two main applications, which are being developed for the premixing and steam explosion calculations. The geometry model of the TROI-13 experiment, which was used for the premixing and steam explosion simulation, is given in Figure 2.

The melt description in the MC3D premixing application is made with three fields, describing the continuous corium, the melt droplets, and the melt fragments. The corium continuous field is used to describe the corium jet. The second field corresponds to the melt droplets (order of cm in diameter) issued from the jet fragmentation. The last field is used to describe the melt fragments (less than 100 μm in diameter) issuing from the melt droplet fine fragmentation. In the TROI-13 premixing simulation, the melt fragment field was not taken into account, since in the TROI experiments the amount of melt fragments smaller than 0.425 mm was small if the steam explosion did not occur (Table 1). The relations of jet fragmentation and coalescence are used to describe the mass transportation between the continuous corium and the melt droplets field. Inside the melt droplets field, the melt droplets hydrodynamic fragmentation is driven by the coarse drop break up process. [6]

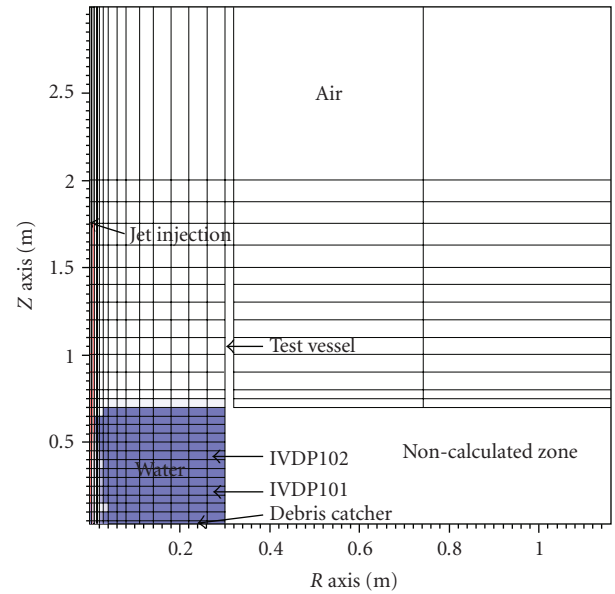

Figure 2: Geometry and mesh of the TROI-13 experiment model.

The appropriate melt droplets amount determination during the premixing simulation is important, since the melt droplets drive the heat transfer and also present the source for fine fragmentation in the MC3D steam explosion application [6].

In the simulations, the creation of the noncondensible hydrogen during the interaction of corium with water vapor was not modelled. Noncondensible gases in general reduce the strength of the steam explosion since they increase the premixture void fraction and hinder the direct melt water contact [2].

3.1. Premixing simulation

The initial conditions for the premixing simulations were obtained or estimated based on [5]. The jet was injected at a height of 1.75 m with a velocity of 7.35 m/s and a diameter of 2 cm [5, 8]. The MC3D default or recommended numerical and model parameters values were used as far as possible in the premixing simulation, although information from [5, 8, 9] was used to estimate those

simulation parameters which could have an influence on the jet fragmentation mechanisms, the coalescence process, the melt droplets hydrodynamic fragmentation, and the melt droplets solidification effects.

Both, the jet fragmentation and the coalescence processes depend on the molten corium material properties, which had to be defined reasonably. First, the appropriate poured molten corium temperature (T_{jet}) was established, since the experimental measurements of T_{jet} were not reliable. On one hand, the measured melt temperature was given to be 2600 K, what is below the corium solidus temperature, but on the other hand, the temperature was estimated to be most probably near 3500 K or even higher [5]. Therefore, the temperature of 3300 K was chosen, based on the simulations performed in the scope of the OECD program SERENA [8]. Next, the appropriate temperature ($T_{sol\text{-}liq}$), below which the melt droplets fragmentation and coalescence is suppressed due to droplets solidification, had to be determined. In the MC3D code, the temperature $T_{sol\text{-}liq}$ presents the threshold temperature below which the melt droplets are treated as solid spheres. In MC3D, the melt droplets temperature is defined with the melt droplets bulk temperature. So, if the melt droplets bulk temperature is higher than $T_{sol\text{-}liq}$, the melt droplets are treated as liquid, allowing droplets fragmentation and coalescence, otherwise the melt droplets are treated as solid. The droplets bulk temperature is a good measure for the droplets solid/liquid state only if the melt inside the droplet is well mixed. However, it is believed that the melt inside the droplet is not well mixed, and that consequently, a solid crust forms on the droplet much earlier than the droplets bulk temperature decreases below the solidification temperature [9]. Since in MC3D the droplets crust formation is not modelled, for $T_{sol\text{-}liq}$ a temperature higher than the default corium solid temperature 2800 K has to be taken. We decided to perform our simulations using for $T_{sol\text{-}liq}$ the temperature 2820 K, where corium is still liquid and which is only slightly higher than the default one.

For the melt droplet hydrodynamic fragmentation, the coarse drop break up model is used in the MC3D code. The model is based on wave crest stripping followed by catastrophic break up, and depends on the Weber's number (We). If the melt droplets We are above the critical value (We_{crit}), then melt droplet hydrodynamic fragmentation could occur. Below We_{crit}, internal forces inside the melt droplet cannot overcome the cohesive forces of the melt droplet surface tension and the hydrodynamic fragmentation stops. For We_{crit}, the most commonly used value 12 was taken. The coarse drop break up correlation used in MC3D should hold only for We above 350. For We below 350, two additional damping functions are introduced to take into account also other hydrodynamic fragmentation modes presented at lower We. The first damping function is introduced for We below 20, and the second damping function for We below 350. A sensitivity study was performed to evaluate the damping functions influence on the premixing results (Figure 3). [6]

On Figure 3(a), the simulated mean Sauter diameter (SDM) results are given. SDM is defined as the mean sphere diameter that has the same volume/surface area ratio as

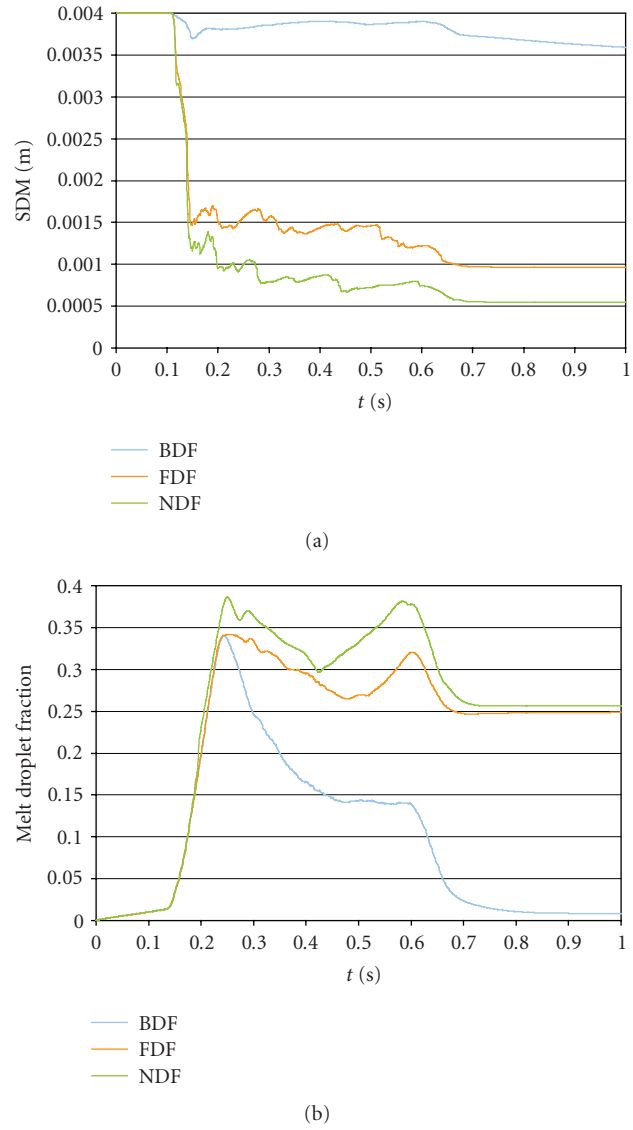

Figure 3: Mean Sauter diameter (SDM) history (a) and melt droplets fraction history (b) for TROI-13 premixing simulations using different melt droplets fragmentation modelling options.

the particles of interest. Based on the nonexplosive TROI-9 experiment, a SDM of around 2 mm could be expected in the premixing phase (Table 1). In the case of the nonexplosive TROI-11 experiment, SDM was overestimated since part of UO_2 pellets was not fully melted. The comparison of simulation results with the experimental results in Table 1 indicates that the use of both damping functions (designator BDF—both damping functions) overestimates SDM. If both damping functions were suppressed (designator NDF—no damping function), SDM was strongly underestimated due to the hydrodynamic fragmentation process overestimation. By suppressing, only the second damping function SDM is still underestimated (designator FDF—first damping function). The SDM values for FDF were around 1.5 mm as long as the effect of the melt droplets coalescence did not become dominant. Therefore, one can conclude that the simulated

SDM for case FDF is in reasonable agreement to the expected 2 mm in the nonexplosive cases. The final SDM decrease (to around 1 mm in case FDF) was due to the coalescence of larger melt droplets, which were still liquid at the end of the premixing phase. The results indicate that there is a need for further investigation of the melt droplet hydrodynamic fragmentation modelling.

Additionally, Figure 3(b) shows also the melt droplets fraction with regard to the total injected corium jet mass. The melt droplets coalescence was estimated to be low in TROI-13-like experiments, since no information about an observed cake was given in [5]. Although it was expected to achieve a low coalescence with the increased $T_{\text{sol-liq}}$ (from the default 2800 K to 2820 K) and by selecting the lower T_{jet} (SERENA value 3300 K instead of quite probable 3500 K or even higher), the coalescence still remained important once the jet reached the test vessel bottom at premixing time around 0.25 second (Figure 3). Since the steam explosion occurred already before the coalescence could become significant, we did not try to improve the coalescence modelling in our premixing simulations. As seen on Figure 3, the suppression of damping functions (FDF, NDF) strongly influences the SDM values and the coalescence. The coalescence reduction for smaller melt droplets could be explained with more extensive melt droplets freezing, since frozen droplets cannot coalescence. The coalescence was overestimated in all simulated cases if compared to the experimentally observed low coalescence. A way to improve the coalescence behavior is to improve the melt droplet solidification model.

3.2. Initial conditions for explosion simulation

The initial conditions inside the test vessel for the TROI-13 steam explosion simulations were determined based on the FDF premixing simulation case (Figure 4), where the agreement with experimental measurements was the best. The steam explosion was triggered at premixing time 0.25 second, which was selected based on general experimental observations that a spontaneous steam explosion usually triggers by the contact of the molten corium with the bottom of the test vessel.

In the explosion simulation, the area of water inside the test vessel was initially divided into three zones (interaction zone, trigger zone, and bulk zone). It was estimated from the premixing results (Figure 4) that the interaction zone extends from the water surface (0.70 m) to the test vessel bottom (0.03 m) and has a radius of 4 cm. A homogenous distribution of the melt droplets, vapour, and water was set. The volume fraction of melt droplets in the interaction zone was determined based on the corium jet mass entered in the water at time 0.25 second (~1.9 kg). The volume fraction of melt droplets participating in the steam explosion was varied in the performed simulations to consider the influence of the incomplete jet break up and the influence of droplets freezing. Based on the premixing simulation, the molten droplets temperature and diameter were set to 3150 K and 1.6 mm (Figure 3). The vapor volume fraction 0.43 and the vapor temperature 2760 K inside the interaction zone were set to values estimated from premixing results. Since the

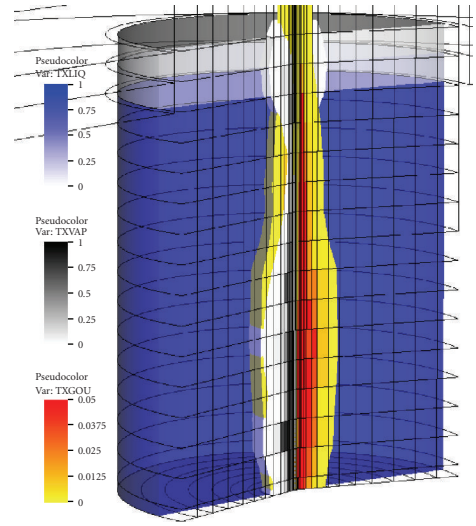

Figure 4: Volume fractions of water (TXLIQ), vapor (TXVAP), and melt droplets (TXGOU) inside the test vessel at triggering time in the premixing simulation.

sum of the volume fractions must be 1 by definition, the water volume fraction inside the interaction zone was set according to the vapor and melt droplets volume fractions. The water temperature in the interaction zone was set to 310 K and was also estimated from premixing results. The steam explosion triggering was modelled with a trigger zone placed inside the interaction zone at the central axis. The conditions in the trigger zone were set reasonable according to the interaction zone conditions. The triggering pressure of 1 MPa was chosen based on a sensitivity study, where the triggering pressure influence on the steam explosion results was investigated. It turned out that the triggering pressure has a negligible influence on the simulation results if set inside a reasonable range. The position of the trigger zone in vertical direction was varied to establish the influence of the assumed trigger location on the steam explosion development. In the bulk zone, only water and vapor were present. The vapor volume fraction in the bulk zone was estimated from the premixing results and was set to 0.01. The water temperature in the bulk zone was set to the initial premixing water temperature (292 K) and the vapour temperature to the saturation temperature. In the simulation, also the increase of the water level, due to the presence of the jet and vapor in the premixture, was taken into account based on premixing results.

3.3. Results of explosion simulation

The main steam explosion simulations results are given on Figure 5. Additionally, also a part of the experimentally measured dynamic pressure, digitalized from [5], is shown for comparison. The time delay between the calculated and measured pressure peak on Figure 5 should not be taken into consideration, since in the experiment pressure fluctuations occurred already before the strong pressure escalation, and so the time shift depends on the definition of the spontaneous

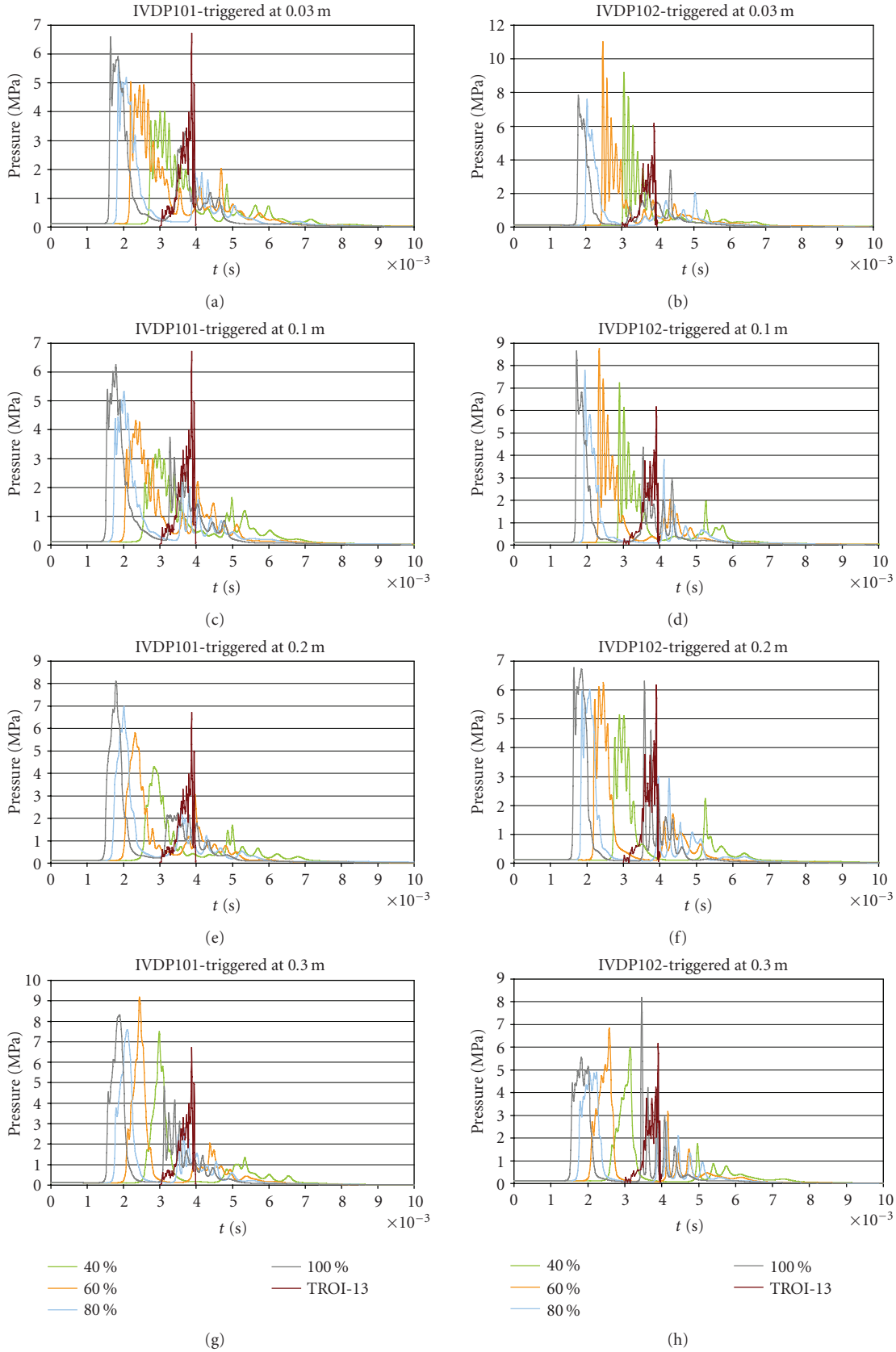

Figure 5: Simulated pressure histories at the positions of pressure detectors IVDP101 and IVDP102 in comparison to TROI-13 experimental measurements. Triggering was performed at positions 0.03, 0.1, 0.2, and 0.3 m. The melt droplets mass involved in the steam explosion is given as 40%, 60%, 80%, and 100% fractions of the total corium mass entered in the water at the steam explosion triggering time. Time zero on the figures corresponds to steam explosion triggering.

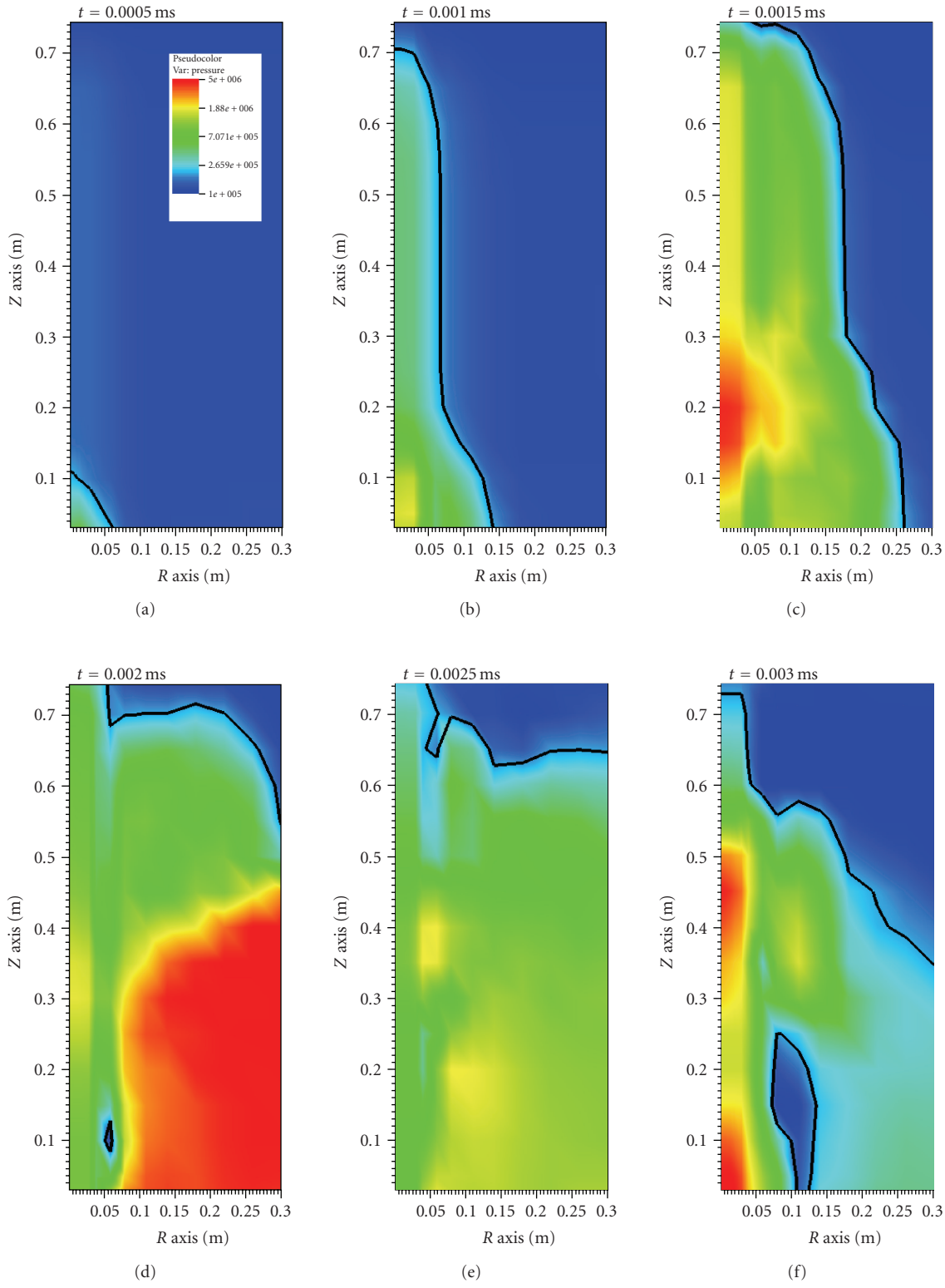

Figure 6: Calculated pressure field inside the test vessel between 0.5 and 3 milliseconds with time step 0.5 millisecond. The explosion was triggered in the test vessel center at position 0.03 m. The initial conditions were set for premixing time 0.25 second. The melt droplets mass fraction was 80% of the corium mass entered in the water at triggering time.

triggering time in the experiment. The simulation results are given for different trigger zone positions. In the simulations, the steam explosion was triggered between the bottom (0.03 m) and the near-mid (0.3 m) parts of the test vessel. The melt droplets mass participating in the steam explosion was set to fractions 40%, 60%, 80%, and 100% of the total corium mass entered in the water at triggering time. The pressure was tracked at the pressure detectors IVDP101 and IVDP102 positions (Figures 1 and 2).

The results on Figure 5 reveal that the melt droplets mass significantly influences the pressure peak height and its position. With a larger melt mass, more melt droplets are available for fine fragmentation, resulting generally in higher pressure peaks and larger pressure impulses. With larger melt droplets mass, also the steam explosion develops faster due to more intense interactions, and so the pressure peaks occur earlier. The calculated pressure peak becomes comparable with the measured data if around 40–80% of the injected corium mass in the water, presented as melt droplets, were taken into account in the explosion simulations. This observation is in agreement with the premixing simulation results, where around 80% of the jet inside the water were fragmented into melt droplets at triggering time, and we have to consider that part of these corium droplets is already frozen and so cannot efficiently participate in the steam explosion [9]. The so established melt droplets mass involved in the steam explosion (i.e., fine fragmentation) is comparable also with the experimentally measured mass of fine fragments (smaller than 0.425 mm) in Table 1. On Figure 5, we see that the influence of the assumed triggering position on the steam explosion development is quite stochastic and less expressive. So, we can conclude that the strength of a steam explosion is governed mainly by the premixture conditions at triggering time.

Figure 6 shows the pressure field propagation inside the test vessel during the steam explosion. The steam explosion was triggered at the test vessel bottom. It was assumed that in the interaction zone 80% of the corium mass are in form of molten droplets, which can participate in the steam explosion. The pressure field first developed along the interaction zone and then propagated towards the test vessel wall, where also the pressure detectors IVDP101 and IVDP102 were placed (Figures 1 and 5). The pressure increase near the wall was due to the incoming and reflecting pressure superposition. After the heat transfer process from the hot melt to water ceased, the pressure started to decrease.

4. CONCLUSION

Fuel coolant interaction computer codes have to be validated with steam explosion experimental data to be able to perform reliable simulations. The purpose of the presented work was to model the TROI-13 steam explosion experiment with the computer code MC3D to establish the modelling capabilities of the code and to get additional insight into the FCI phenomenon. The experiment was modelled according to public available experimental data, applying recommended or default MC3D numerical and model parameters. For the explosion simulation, the correct determination of the premixture conditions at steam explosion triggering is essential. Therefore, first, the premixing conditions were simulated and discussed in details to enable the appropriate determination of the mass, size, temperature, and distribution of the corium droplets at steam explosion triggering. The corium droplets are so important because they drive the heat transfer and represent the source for fine fragmentation during the steam explosion.

The comparison of premixing results with experimental measurements revealed that the premixing simulations overestimate the melt droplets mean Sauter diameter if the MC3D coarse drop break up model damping functions are used, and underestimate it if they are suppressed. The melt droplet coalescence was overestimated in any case, if the damping functions were used or if they were not used. It turned out that using only the first damping function, quite reasonable premixing results are obtained in the initial stage of the melt pour, lasting also beyond the steam explosion triggering time. Therefore, these premixing results were used to define the initial conditions for the steam explosion simulations. The steam explosion simulations results were in reasonable agreement with the experimental measurements. The results revealed that there is an important influence of the involved melt droplets mass on the steam explosion process. The influence of the assumed steam explosion triggering location on the steam explosion strength was less expressive. Due to the importance of the adequate active melt droplets mass prediction at triggering time on the subsequent development of the steam explosion, it is of utmost importance to appropriately consider in the FCI codes also melt droplets solidification phenomena.

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