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Analysis of Ex-Vessel Steam Explosion Pressure Loads

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An ex-vessel steam explosion in a nuclear power plant may develop when the reactor vessel fails and the molten core interacts with the coolant water in the reactor vessel. At the fuel coolant interaction a part of the corium energy is intensively transferred to water in a very short time scale. The water vaporizes at high pressure and expands, inducing potentially severe dynamic loadings on surrounding systems, structures and components that may lead to an early release of radioactive material into the environment.

To get a better understanding of the ex-vessel steam explosion phenomenon, various scenarios analyses for a typical pressurized water reactor cavity were made. A detailed analysis was performed varying the melt release location, the cavity water temperature, the primary system over-pressure at vessel failure and the triggering time for explosion calculations. The main purpose of the analysis was to determine the most challenging ex-vessel steam explosion cases and to estimate the expected pressure loadings on the cavity walls. The performed analysis shows that for some ex-vessel steam explosion scenarios significantly higher pressure loads are predicted than were obtained in the OECD programme SERENA.

The detailed analysis of the most challenging central melt pour scenario revealed that the calculated high pressure loads are also a consequence of the axial symmetric geometry of the cavity model and the probably over-predicted melt droplets amount involved in the steam explosion.

Keywords: fuel-coolant interaction, steam explosion, severe accident, simulation

0 INTRODUCTION

The steam explosion process is commonly divided into four phases, i.e. premixing, triggering, propagation and expansion [1]. Premixing covers the interaction of the melt (e.g. corium) with the coolant (e.g. water) prior to any steam explosion. At the interaction the coolant vaporizes around the melt-coolant interface, creating a vapour film. The system may remain in a meta-stable state for a period ranging from a tenth of a second up to a few seconds. During this time the continuous melt (jet) is fragmented into melt droplets of the order of several mm in diameter, which may be further fragmented by the coarse break up process into melt droplets of the order of mm in diameter. If then a local vapour film destabilization occurs, the steam explosion may be triggered, which causes fine fragmentation of the melt droplets into fragments of the order of some 10 μm in diameter. The fine fragmentation process rapidly increases the melt surface area, vaporizing more coolant and increasing the local vapour pressure. This fast vapour formation spatially propagates throughout the melt-coolant mixture causing the whole region to become pressurized by the coolant vapour. Subsequently, the high pressure coolant vapour expands and performs work on its surrounding. The time scale for the steam explosion itself is in the order of ms.

Safety analyses of nuclear power plants revealed a low probability of steam explosion occurrence as a severe reactor accident consequence. Nevertheless, steam explosions are an important nuclear safety issue since they can potentially jeopardise the primary system and the containment integrity of the nuclear power plant [2] and [3]. Direct or by-passed loss of the containment integrity can lead to an early radioactive material release into the environment.

Although the steam explosion events have been studied for several years, the level of knowledge is still not adequate. To increase the steam explosion process and the understanding of the consequences, the OECD (Organisation for Economic Co-operation and Development) established the SERENA (Steam Explosion REsolution for Nuclear Applications) programme in the year 2002 [4]. The SERENA programme had three main objectives. The first programme objective was to evaluate the capabilities of the

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current generation of FCI (Fuel-Coolant Interaction) computer codes in predicting the steam explosion induced loads. In FCI codes the mass, momentum and energy balance equations, together with the constitutive laws (e.g. interface friction, mass source terms, heat exchanges), are solved for each phase (coolant, vapour, melt droplets, jet). The second objective was to identify key FCI phenomena and associated uncertainties impacting the predictability of the steam explosion energetics in reactor situations. The third objective was to propose confirmatory research for the reduction of uncertainties to acceptable levels for the steam explosion risk assessment. Two main SERENA programme outcomes were obtained for in-vessel and ex-vessel steam explosions. First, the calculated loads are far below the typical reactor vessels capacity in case of an in-vessel steam explosion. However, for ex-vessel steam explosions the programme outcome was that the calculated loads are above the capacity of the typical reactor cavity walls and also that the safety margins can not be adequately quantified due to uncertainties in steam explosion understanding, modelling and scaling.

The purpose of the paper is to present the performed comprehensive ex-vessel steam explosion phenomenon analysis in a typical pressurised water reactor cavity. In the analysis simulations of various ex-vessel steam explosion scenarios were performed with the FCI computer code MC3D [5] and [6]. The results revealed that the predicted pressure loads may be significantly higher than those obtained in the SERENA programme [4].

In the paper first the main results of the performed comprehensive study are summarized, and then a detailed analysis of the most challenging central melt pour scenario is presented to highlight the issue of the predicted very high pressure loads. The reasons for the obtained high pressure loads are discussed in more detail. Finally, conclusion remarks are given.

1 REACTOR CAVITY MODEL

A series of ex-vessel steam explosion scenarios simulations were performed in a simplified 2D geometry model of a typical pressurised water reactor cavity [5]. The model was defined to reflect the conditions in a real 3D reactor cavity qualitatively and quantitatively and as closely as possible. The simulations were performed with two different 2D representations of the 3D pressurized water reactor cavity: the axial symmetric model and the slice model (Fig. 1).

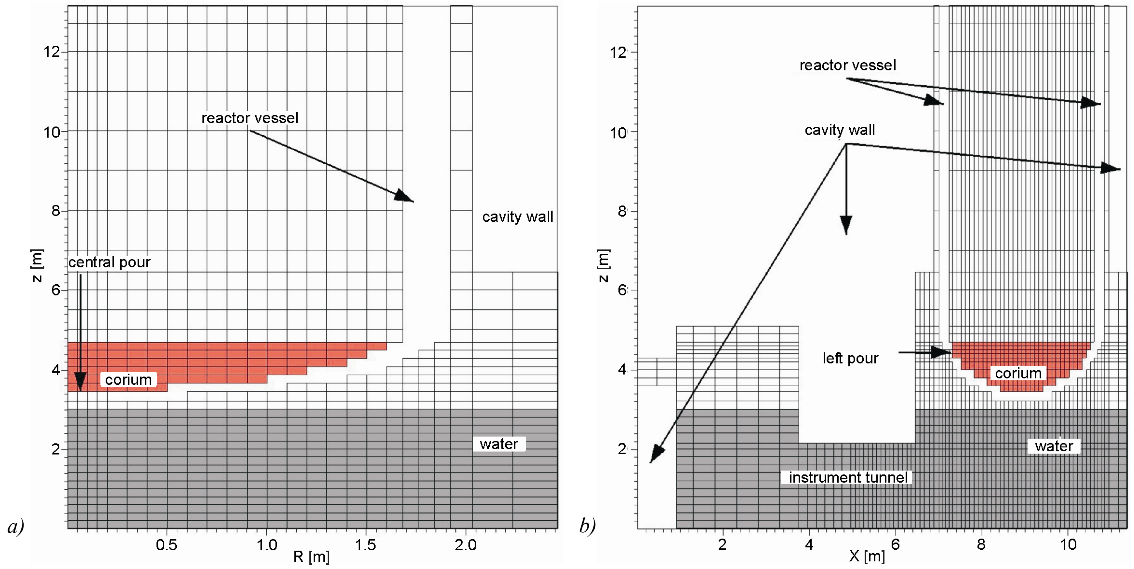

Fig. 1. *a) Geometry and mesh of the axial symmetric reactor cavity model, b) the slice model for the left side melt pour [5]*

Due to its axial symmetry the axial symmetric model is limited on the axial symmetric phenomena treatment with axial symmetric initial conditions in the axial symmetric part of the reactor cavity directly below the reactor vessel and around it [5]. The axial symmetric model use is conservative since the venting through the instrument tunnel can not be directly considered in the model. The reactor cavity model geometry and dimensions were set for a typical pressurized water reactor cavity. In the axial symmetrical model the radius of the cavity cylindrical part was ~2.5 m and its height was ~13 m. The mesh size was 25 x 35 cells. The reactor cavity model is given in Fig. 1. The numerical mesh was adequately refined in central regions, which were more important for the FCI phenomenon modelling. The mesh size was comparable with meshes used in simulations performed in the frame of the OECD SERENA programme [4].

Contrary to the axial symmetric model, which treats only the reactor cavity cylindrical part, the slice model treats the whole reactor cavity [5]. However the slice model does not take into account the 3D geometry and the nature of the 3D steam explosion phenomena. The cylindrical part of the reactor vessel and the cavity are treated as plan-parallel plates. In the slice model the instrumentation tunnel was determined in a way which corresponds to the real 3D reactor cavity geometry. Again the model geometry and dimensions were set for a typical pressurized water reactor cavity. For the slice model the cavity length was ~10.5 m and the height was ~13 m. The mesh sizes were 77 x 39 cells for the left melt pour and 62 x 39 cells for the right melt pour. For illustration the left melt pour model is given in Fig. 1. Also for both slice models the numerical mesh was adequately refined in the melt pour regions.

2 ANALYSES OF MELT POUR SCENARIOS

The steam explosion simulations were performed using models, presented in Chapter 1 and in Fig. 1, with the computer code MC3D version 3.5, patch 1 [5] and [6]. In the Eulerian MC3D code a finite volume numerical method is applied. MC3D is built mainly for the complex FCI phenomenon evaluation. MC3D has two main applications, which are being developed for the premixing and the steam explosion calculations. The premixing application describes the jet break-up from the jet into the melt droplets (order of some mm in diameter), the melt droplets coalescence to the jet, the coarse melt droplets break up (order of mm in diameter) and the melt droplets fine fragmentation into the fine melt fragments (less than 100 µm in diameter). The explosion application deals with the fine fragmentation of the melt droplets and the heat exchange between the produced melt fragments and the coolant.

The steam explosion simulations were performed using default or recommended numerical and model parameters values provided in MC3D [6]. The Microsoft Windows operation system was used for the simulations.

2.1 Initial Conditions

In the performed ex-vessel steam explosion study various relevant scenarios were analysed to capture the most severe steam explosions [5]. One goal of the study was to evaluate the influence and importance of different accident conditions on the FCI outcome. The initial conditions were set reasonable according to the expected conditions at vessel failure during a severe accident in a typical pressurized water reactor. Similar initial conditions were used also in the ex-vessel reactor simulations in the OECD programme SERENA [4].

Premixing phase simulations of the central (designator C), left (designator L) and right (designator R) side melt pours were performed and a parametric analysis was done varying the primary system over-pressure (designators 0 for 0 bar and 2 for 2 bar) and the cavity water temperature (designators 60 for 60 °C, 80 for 80 °C and 100 for 100 °C). The reactor vessel failure opening had a radius 0.2 m for the central melt pours. At both side melt pours the opening height was 0.2 m and the length was 1 m. The initial pressure in the domain was set to the containment pressure of 1.5 bar. The water saturation temperature at containment pressure is 111.4 °C. The water's level in the reactor cavity was 3 m. Default MC3D corium material properties were used. In the reactor vessel lower head 50 t of molten corium was placed, resulting in a pool height of 1.25 m. The temperature of molten corium, which was poured into the flooded cavity, was 3000 K. The solidus temperature of the used corium was 2700 K. Above 2800 K the corium was treated as liquid. A constant pressure boundary condition at the reactor cavity openings was assumed.

2.2 Steam Explosion Simulation Results

The premixing phase was simulated for 10 s after the start of the melt release [5]. Typical CPU times of premixing simulations ranged from a day for the central pour to a week for the side pours. The premixing phase simulation was used to determine the initial conditions for the explosion simulation. The times to trigger the steam explosion were chosen in a way to capture the most important stages of the case specific melt releases. The triggering times were based on the melt pour location and the primary system pressure and on the calculated explosivity criteria, which represent the liquid melt droplets volume in contact with water. The explosion phase was simulated for 0.1 s after the artificial steam explosion triggering with a trigger pressure of 20 bar. The steam explosion was triggered in the cell, where the local cell explosivity criterion was the highest. Typical CPU times of explosion simulations were ranging from an hour for the central pour to a day for the side pours.

In Fig. 2 the maximum calculated pressures inside the cavity and the maximum calculated pressure impulses at the cavity bottom or at the lateral walls are presented for the simulated cases. In the pressure impulse calculations the initial containment pressure was subtracted from the calculated absolute pressure since the dynamical pressure loads on the cavity walls are caused by the pressure difference. The main simulation results are summarized in Table 1. In general the highest maximum pressures and maximum pressure impulses were reached at higher cavity water sub-cooling. The highest maximum pressure was near 300 MPa, and the highest pressure impulse was close to 0.7 MPa·s. As seen from Table 1 the maximum pressure loads significantly over-predict the pressure obtained in the SERENA programme and significantly exceed the pressure impulses, which could be detrimental for the reactor cavity integrity and are estimated to be of the order of some tens of kPa·s. The obtained SERENA programme pressure loads given in Table 1 were calculated for a central melt pour on the lateral cavity walls.

The most explosive central melt pour case C2-60 is discussed in detail in Section 3.

2.3 Interpretation of the Results of Premixing and Steam Explosion Simulation

In the side melt pour cases the strength of steam explosions is decreased by increasing the primary system over-pressure (Fig. 2) as in the pressurized primary system cases the melt was ejected sideward on the cavity wall, sliding then into the water at the wall, which formed a less extensive explosive mixture. Additionally, the obtained pressure loads were lower due to the creation of highly voided regions below the vessel when gas from the pressurised primary system starts to flow through the reactor vessel opening into the reactor cavity and pushes the water out of the cavity through the instrument tunnel.

The results in Fig. 2 for the initial stage of the central melt pour cases show that at lower water temperature stronger explosions occur due to lower void build-up. On the contrary, at later times stronger steam explosions occurred at higher water temperature due to lower droplet solidification. Also, the increased jet fragmentation at higher primary system pressure resulted in stronger steam explosions. It turned out that after the initial stage of the melt release the primary system over-pressure had no significant influence on the explosion strength anymore. The primary system pressure influence on the explosion strength became important again once the melt was nearly completely released from the reactor vessel and the gas started to flow through the vessel opening promoting the jet break-up.

The high calculated pressure loads in the side melt pour cases were over-predicted due to the 2D reactor cavity treatment in the slice modelling. In the slice modelling the venting and pressure relief are under-predicted. Also the 2D approach did not take into account the 3D geometry and the nature of the 3D steam explosion phenomena. It it for these reasons that the left and the right side melt pour simulations provide only a qualitative FCI behaviour insight.

On the other hand the central pour scenarios simulations use the axial symmetric

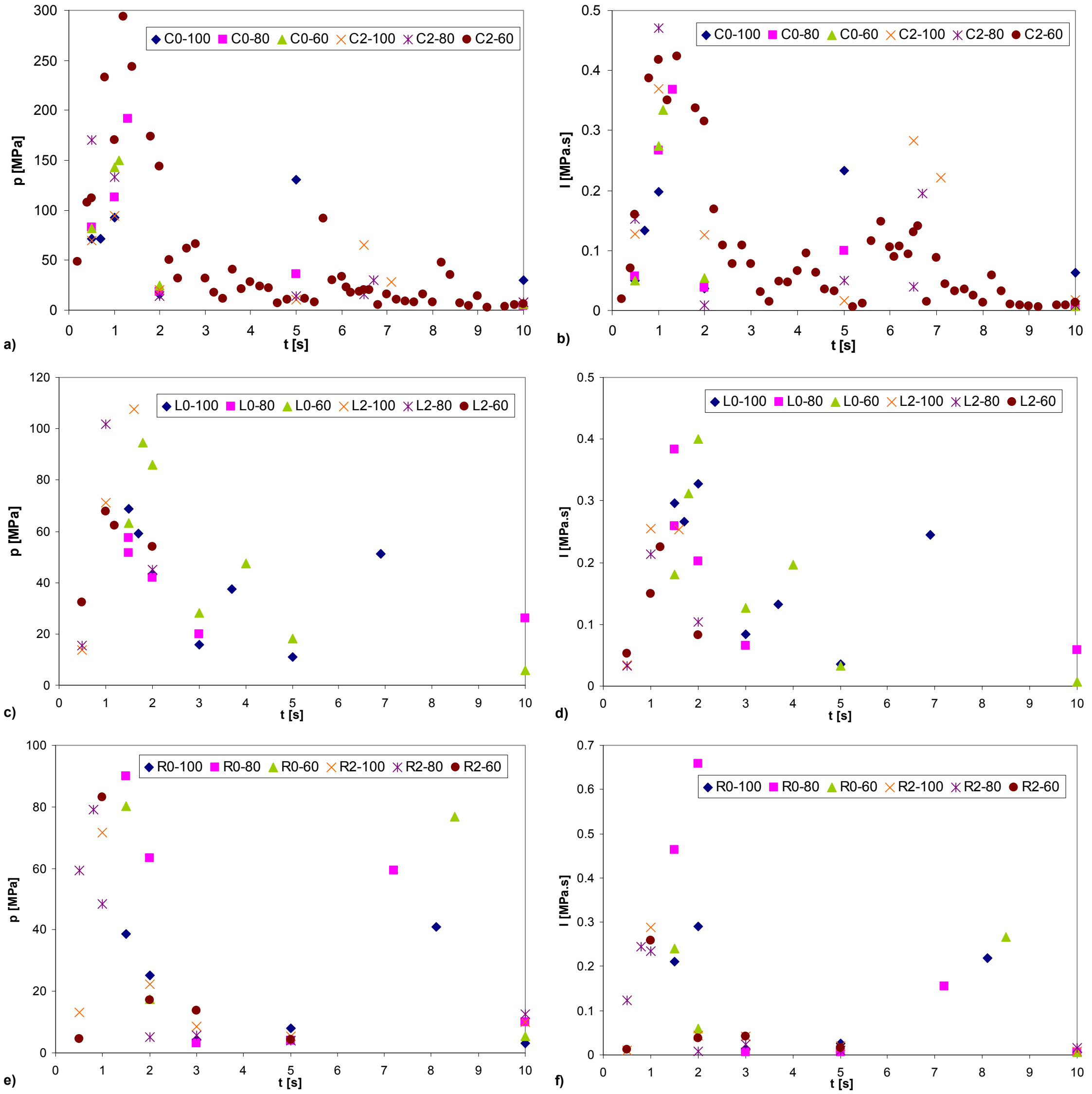

Fig. 2. *Maximum calculated pressure p in cavity and maximum calculated pressure impulse I at cavity walls for simulated cases at different explosion triggering times [5]; a) pressure for central pour case, b) impulse for central pour case, c) pressure for left pour case, d) impulse for left pour case, e) pressure for right pour case and f) impulse for right pour case.*

Table 1. *Summarised maximal calculated pressures and pressure impulses in comparison with OECD programme SERENA results [4] and [5]*

Pour location	*Maximum pressure*		*Maximum pressure impulse*	
	p [MPa]	*case*	*I [MPa·s]*	*case*
Central	292.9	C2-60	0.47	C2-80
Left side	107.8	L2-100	0.40	L0-60
Right side	90.1	R0-80	0.66	R0-80
SERENA-central	up to 40 MPa on the lateral cavity wall		up to 0.1 MPa·s on the lateral cavity wall	

representation which is quite suitable for considering the 3D nature of the steam explosion phenomena in such conditions. Also, the applied FCI models are adjusted to such geometry. Consequently, the reliability of central melt pour simulation results is larger.

3 DISCUSSION OF THE MOST EXPLOSIVE CENTRAL MELT POUR SCENARIO

Among the performed analyses, the maximum pressure was gained for the central melt pour scenario at 2 bar primary system over-pressure and water temperature of 60 °C, i.e. C2-60 case (Table 1 and Fig. 2). In this section the reasons for high pressure loads are highlighted and discussed in detail.

The detailed premixing phase simulation was performed on the 64 bit Linux operating system. The steam explosion was triggered 1.3 s after the start of the melt release. The steam explosion triggering time was chosen based on the calculated explosivity criteria and on the simulation results in Fig. 2. The main steam explosion simulations results are presented in Fig. 3. The explosion phase was simulated for 0.1 s. The maximal calculated pressure was 249.1 MPa. The maximal pressure impulse was 0.48 MPa·s at the cavity bottom and 0.27 MPa·s on the lateral cavity wall.

The detailed steam explosion analysis showed that the melt droplets thermal fragmentation was crucial for spontaneous steam explosion triggering and initial pressure field development (Fig. 4). In the thermal fragmentation the destabilisation of the steam film surrounding the melt droplet leads to the melt droplet surface fragmentation after a direct contact between the liquid and melt droplet surface occurs. Essential for spontaneous triggering in the most explosive scenario were the melt droplets around the jet stem, which were of a temperature still above the solidus state temperature (Fig. 4). The melt droplets were created during the premixing phase by the jet break-up and large melt droplets fragmentation. It is obvious that the premixing phase simulation is crucial for an appropriate prediction of the amount of melt droplets, which can be involved in the steam explosion process (active melt droplets). In the MC3D application the active melt droplets can potentially fragmentise during the steam explosion process, and therefore contribute to the steam explosion escalation, if the melt droplets bulk temperature is higher than the corium solidification temperature (Fig. 4) [6]. This MC3D presumption probably over-predicts the active melt droplets amount. Consequently, the pressure loads are over-predicted as in reality, during premixing, a crust is formed on the melt droplets probably much earlier than the melt droplets bulk temperature drops below the solidification temperature [7] to [9]. The crust inhibits the fragmentation process and if the crust is thick enough it completely prevents it. We can conclude that for better pressure loads predictions, the influence of the crust formation on the corium droplets surface has to be taken into account.

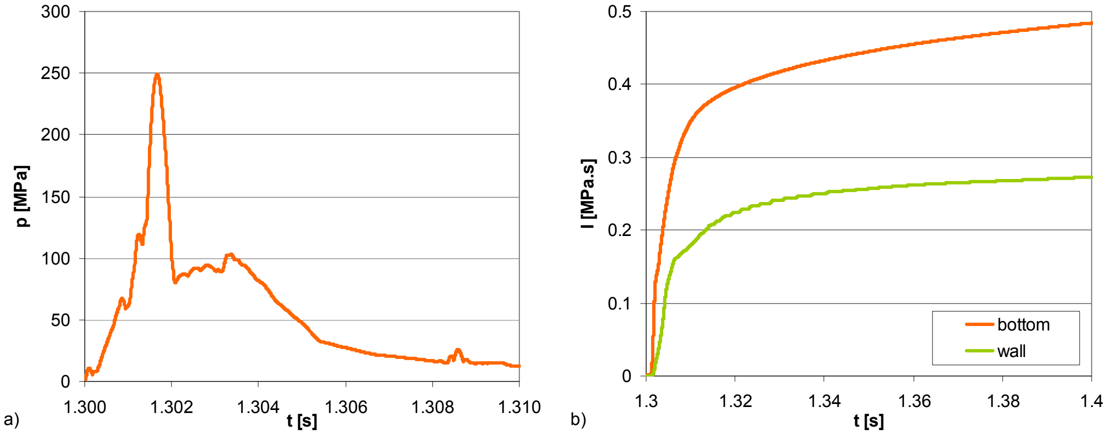

Fig. 3. *a) Time development of maximal pressure p in cavity and b) maximal pressure impulses I on cavity bottom and cavity lateral wall, during the steam explosion simulation (case C2-60, triggered at 1.3 s)*

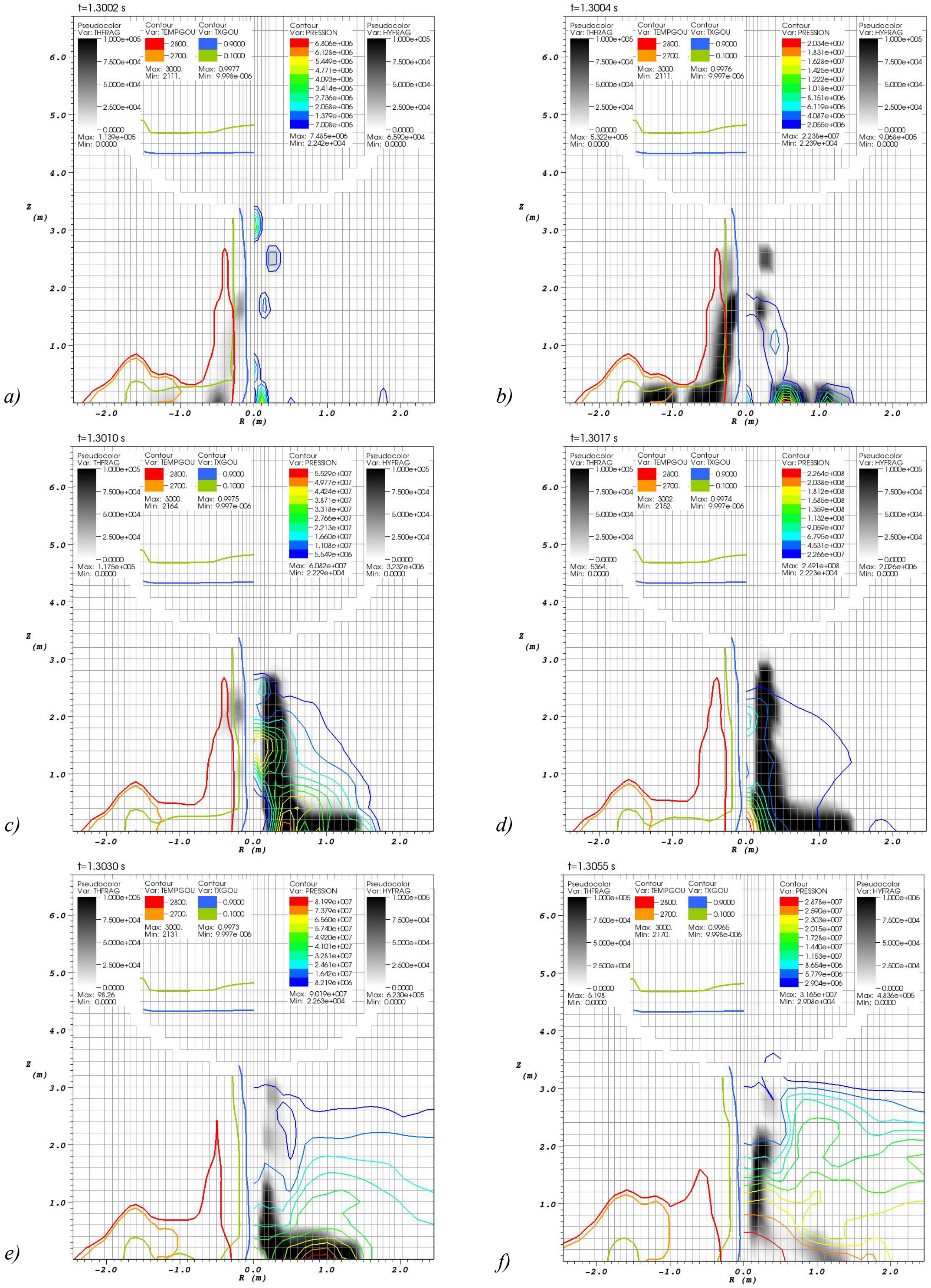

Fig. 4. Thermal (THFRAG) and hydrodynamic (HYFRAG) fragmentation together with the pressure field (PRESSION) and the temperature (TEMPGOU) and volume fraction (TXGOU) of the melt droplets; all the scales are constant in time except for the pressure field; a) at time 1.3002 s, b) at time 1.3004 s, c) at time 1.3010 s, d) at time 1.3017 s, e) at time 1.3030 s and f) at time 1.3055 s.

In the initial stage of the steam explosion simulation the pressure field development occurred due to the thermal and hydrodynamic fragmentation of the melt droplets along the jet steam (Fig. 4). The hydrodynamic fragmentation prevailed over the thermal fragmentation at the time around 1 ms after the steam explosion simulation beginning. The hydrodynamic fragmentation is caused by the relative velocity of the melt droplets to the surrounding medium. The hydrodynamic fragmentation mode implemented inside the MC3D code is sheet striping, where the droplet surface is continuously eroded [6]. For more reliable pressure loads predictions, further investigations of the thermal and particular hydrodynamic fragmentation modelling influence on the pressure loads would be needed.

At earlier steam explosion simulation times an intense thermal and hydrodynamic fragmentation of the jet sourced droplets on the reactor cavity bottom was also present (Fig. 4). Furthermore, here the hydrodynamic fragmentation prevailed over the thermal fragmentation at the time around 1 ms. The jet sourced droplets are droplets which were artificially created from the jet field (continuous corium field) in the transition from the premixing to the explosion calculations inside the MC3D code [6]. The jet sourced droplets on the cavity bottom were a very important active melt droplets source [10]. Consequently, the hydrodynamic fragmentation of the jet sourced droplets on the cavity bottom was recognized to be an important contributor to the calculated high pressure impulses. The jet sourced droplets enable the stratified steam explosions treatment, but can due to the simple modelling approach potentially lead to the active melt droplets amount over-prediction and consequently to the pressure loads over-prediction. This indicates the importance of the appropriate transition between the premixing and explosion phase simulation on the correct active melt droplets amount prediction.

The maximal pressures were reached at the time interval between 1 and 2 ms after the beginning of the steam explosion simulation at the central axis on the reactor cavity bottom (Fig. 3 and Fig. 4). Due to the focusing effect of the pressure field in the centre of the 2D reactor cavity axial symmetrical cylindrical model, the maximal pressures were probably over-predicted. After the maximal pressure peak was reached the pressure development was governed by the hydrodynamic fragmentation of the jet sourced droplets on the cavity bottom. The pressure development stopped once the jet sourced droplets on the cavity bottom were completely fragmented (Fig. 4). Finally, the pressure started to stabilize.

4 CONCLUSIONS

Several steam explosions simulations were performed with the MC3D code to establish the most challenging ex-vessel steam explosion scenarios and to estimate the expected pressure loadings on the reactor cavity walls. The melt pour scenarios simulations were performed in similar conditions as selected in the SERENA programme. The results revealed that the maximum calculated pressure loads significantly over-predict the pressure loads obtained in the SERENA programme. This was expected since in the presented study a number of simulations were performed, systematically searching for the strongest steam explosions, whereas in the SERENA only one central melt pour scenario was analyzed with the purpose of comparing the simulation results of different FCI codes. The high calculated pressure loads in the side melt pour cases could be attributed to the 2D reactor cavity slice modelling, which is not capable to take into account the 3D geometry and the 3D steam explosion phenomena nature. The simulations of central melt pour cases are closer to reality. However, also in the central melt pour scenarios high pressure loads were predicted.

The motivation for the presented specific analysis was to explore why some calculated pressure loads during an ex-vessel steam explosion were so high. The detailed analysis of the most explosive central melt pour case (2 bar primary system over-pressure and water temperature of 60 °C) was performed. Important reasons for the obtained high pressure loads were the pressure focusing in the centre of the simulation domain due to the 2D axial symmetrical geometry and the probable active melt droplets amount over-prediction due to the unconsidered melt droplets crust formation. An important additional active melt droplets source were the jet sourced droplets, which were created from the jet field (continuous corium field) by the MC3D application in the transition between the premixing and the explosion phase simulation. Although the jet sourced droplets enable the jet surface fragmentation treatment during the steam explosion, they could be an important potential source of active melt droplets amount over-prediction.

The detailed central melt pour scenario analysis revealed that FCI codes should be able to establish the proper active melt droplets mass when the steam explosion occurs. The transition of the continuous molten corium field between the premixing and the explosion phase should be appropriately considered. The influence of the melt droplets crust formation on the steam explosion development should also be taken into account. Finally, the appropriate choice of the melt droplets fragmentation modelling on the pressure loads prediction should be evaluated. All these identified topics will be appropriately addressed in the frame of the OECD programme SERENA-2 and in the Network of Excellence SARNET-2 (Sever Accident Research NETwork) within the 7th EU Framework Program.

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