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Influence of Corium Droplets Cut-off Diameter on Steam Explosion

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ABSTRACT

Steam explosion experiments have revealed that there are important differences of behaviour between simulant and prototypical melts (the efficiency of steam explosions with prototypical melts is about one order of magnitude lower than with alumina melts), and that also with prototypical melts the fuel coolant interactions (FCI) depend on the composition of corium (eutectic corium may explode spontaneously, whereas non-eutectic corium never did).

To explore the ability of global FCI codes to adequately simulate the explosion phase if the premixture conditions at triggering would be known and to establish the influence of droplets freezing on the steam explosion, a number of explosion phase simulations of KROTOS experiment K-53 were performed with the code MC3D, starting from different predefined premixture and droplets conditions. In the performed parametric analysis the premixture radius and the corium droplets cut-off diameter were varied, assuming that corium droplets with a diameter smaller than the cut-off diameter can not participate in the explosion due to solidification. It was assumed that the phases in the premixture are distributed homogeneously. The phase fractions were determined based on experimental measurements of the average void fraction and the mass of released fuel.

The analysis showed that there is an important influence of droplets freezing on the strength of the steam explosion, since already a small variation of the cut-off diameter significantly changed the calculated pressure impulses. Therefore the influence of droplets freezing on the steam explosion should be considered in global FCI codes. With the best-fit cut-off diameter and premixture radius a quite good agreement of simulation results with experimental measurements could be obtained. This is an indication that at least in principle the explosion phase can be reasonably well predicted if the premixture conditions at triggering are adequately determined and if we could judge based on the droplet solidification conditions whether the droplet can effectively participate in the steam explosion or not.

1 INTRODUCTION

One of the most important remaining issues in core melt progression during a severe reactor accident is the likelihood and the consequences of a steam explosion, which may occur when the hot core melt comes into contact with the coolant water. Steam explosion experiments have indicated important differences of behaviour between simulant and prototypical melts, and that also with prototypical melts the fuel-coolant interactions (FCI) depend on the composition of corium. It appears and is under discussion that metal melt and alumina melt are vulnerable to explosions, i.e. they tend to be easily triggered and yield strong explosions, whereas binary and multi-component melts, like corium melt, exhibit low disposition to triggering and escalation [1]. In the KROTOS test series the steam explosion

energy conversion ratio from thermal to kinetic energy in experiments performed with corium melt (80%UO_2/20%ZrO_2) is about one order of magnitude lower than in experiments with alumina melt (Al_2O_3) [2]. The alumina melt explosions partly appeared spontaneous, while corium melt exploded only if an external trigger was applied. Recently, experiments with eutectic and non-eutectic corium compositions in the TROI facility indicated that also corium can explode spontaneously, if its composition is eutectic (70%UO_2/30%ZrO_2) [3].

The influence of the material properties on the steam explosion is very complex, since in the fuel-coolant interaction phenomenon multiple processes are involved during the coarse mixing, the triggering, the escalation and the propagation, and all these processes are inherently influenced by the material properties of the melt. The common characteristic of most global FCI codes, which are able to simulate the whole FCI phenomenon, is that the main FCI processes are considered and modelled mechanistically, but assuming that the melt droplets are homogeneous. Since the crust and mush zone formation during the cooling of the melt droplets in premixing is not modelled (based on the average droplet temperature only the solid-liquid status of the droplet as a whole is determined), this important material effect on the steam explosion can therefore not be treated adequately.

To explore the ability of global FCI codes to adequately simulate the explosion phase if the premixture and droplet conditions at trigger time would be known, a number of explosion phase simulations of KROTOS experiment K-53 starting from different predefined premixture and droplet conditions were performed with the global FCI code MC3D [4]. In the parametric analysis the radius of the premixture region and the corium droplets cut-off diameter were varied, assuming that corium droplets with a diameter smaller than the cut-off diameter can not participate in the explosion due to solidification reasons.

2 KROTOS TEST FACILITY

2.1 Facility Description

The KROTOS facility [2] consists of a radiation furnace, a release tube and a test section (Figure 1). The furnace includes a cylindrical tungsten heater element, which encloses the crucible containing the melt material. A series of concentric tungsten, molybdenum and steel radiation shields are placed around the heater element. The top and bottom parts of the heated zone are insulated with thermal screens to reduce heat losses to the surroundings. The crucible is held in place by means of a pneumatically operated release hook. The furnace is designed to operate from vacuum up to 1.0 MPa overpressure. The three-phase electric power supply has a maximum power of 200 kW. Depending on the crucible design and melt composition, melt masses in the range of about 1 to 6 kg can be produced. Maximum achievable temperatures are 3300 K. The melt temperature is controlled by an optical bi-chromatic pyrometer measuring the wall temperature of the crucible.

The lower part of the KROTOS facility consists of a pressure vessel and a test section, both made of stainless steel. Both have view ports for visualization purposes. The pressure vessel is designed for 4.0 MPa at 493 K. It is a cylindrical vessel of 0.57 m inner diameter and 2.0 m in height (volume: ~0.35 m^3) with a flanged flat upper head plate. The test section consists of a strong stainless steel tube of inner diameter 200 mm and outer diameter 240 mm. The water level is variable up to about 1.3 m. The bottom of the test section is closed with a plain closing plate or with a plate housing a trigger device. The trigger device consist either of a gas chamber (volume of 29.5 cm^3), which can be charged to a pressure of up to 20 MPa (nitrogen) and is closed by a 0.25 mm thick steel membrane, or an explosive charge. Its purpose is to produce a well-defined pressure pulse that is capable of initiating a steam explosion.

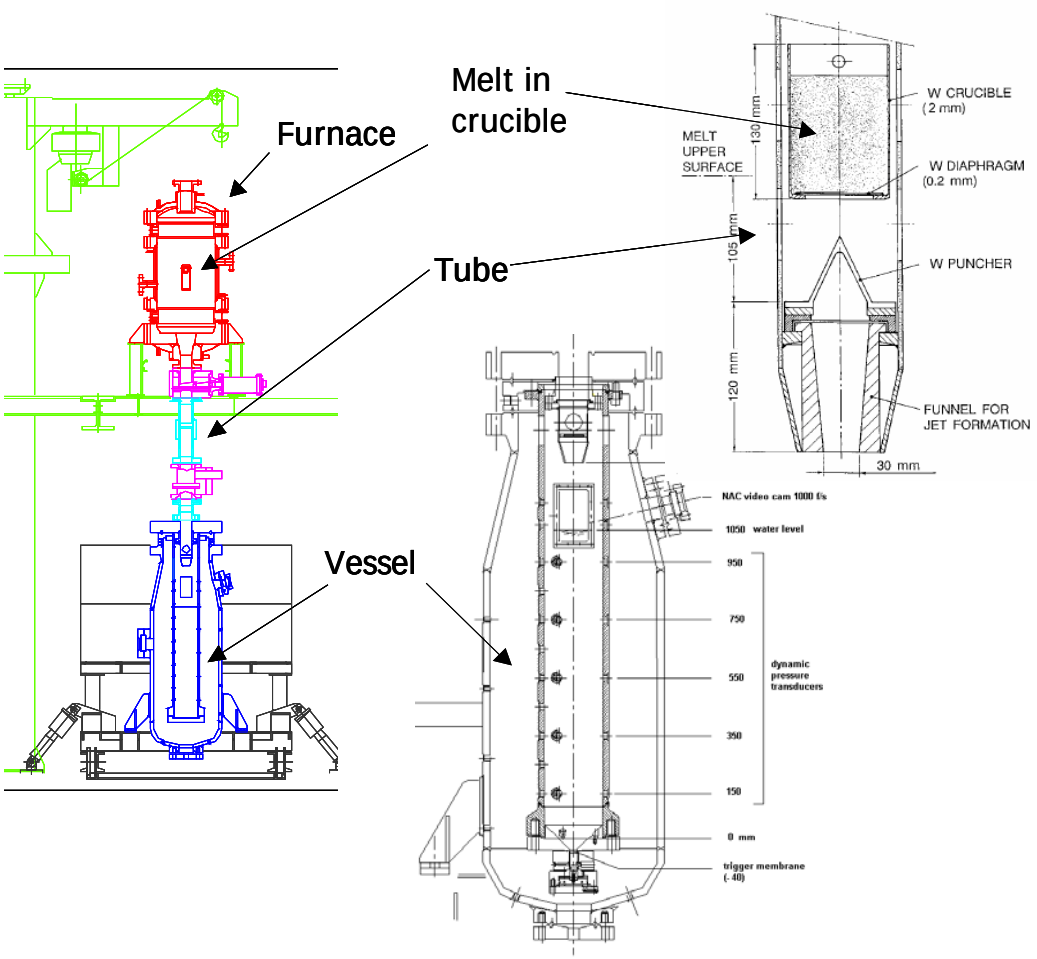


Figure 1**:** Scheme of KROTOS experimental facility

2.2 Test Procedure

After reaching the desired melt temperature, the crucible containing the melt is released from the furnace and falls by gravity through a ~5.2 m long release tube. Halfway down the tube, a fast isolation valve separates the furnace from the test section below. During its fall, the crucible cuts a copper wire, which sends a signal to close the isolation valve and generates a zero-time signal for the data acquisition. Finally, the crucible strikes a retainer ring at the end of the tube where a conical-shaped spike pierces the bottom of the crucible and penetrates into the melt allowing the melt to pour out through the openings in the puncher. The injection diameter of the melt jet is defined by guiding it through a funnel of high temperature refractory material with an exit diameter of 30 mm. The melt arrival is detected by sacrificial thermocouples and by a high-speed video camera (NAC) mounted in the upper view port of the test vessel. If the gas trigger device is used, it is activated by a time-delay circuit when the melt arrives at the desired mixing depth.

Dynamic pressures during the melt-water interaction are measured using piezo-electric transducers (bandwidth >100 kHz) mounted on the test section walls. These pressure measurements, recorded at 50 kHz, also allow the estimation of the starting location of the explosion and propagation speed, which are important for modelling. The integral void fraction during mixing is determined by measuring the water level in the test section at two locations and averaging. Measurements of vessel pressurization help to determine the steaming rates and possible pressurization due to hydrogen production during mixing, and also permit calculation of the steam explosion expansion work.

3 EXPERIMENT SIMULATION

3.1 KROTOS experiment K-53

For the explosion analysis the KROTOS experiment K-53 was selected, which is also the reference experiment for the KROTOS/PLINIUS experiment K-101 [5]. The initial conditions in this test are presented in Table 1 together with some integral results.

Table 1: Initial condition in KROTOS experiment K-53 with some integral results

Melt	composition	80% UO_2 - 20% ZrO_2
	loaded mass	3595 g
	temperature	3129 K
	superheat	279 K
	initial jet diameter	3 cm
	free fall in gas	44 cm
Water	column height	110.5 cm
	pool diameter	20 cm
	temperature	290 K
	subcooling	122 K
Vessel	gas composition	He
	initial pressure	3.6 bar
	freeboard volume	0.230 m^3
Gas Trigger	volume	15 cm^3
	pressure	152 bar
	energy	228 J
Results Mixing	integral void fraction at trigger time	3.0 %
	pressure at trigger time	4.2 bar
	collected debris mass	3368 g
	energy conversion ratio	0.05 %

It was assumed that in experiment K-53 the droplets size distribution during premixing was the same as the final debris size distribution in the premixing experiment K-37 (Table 2), which was performed in similar conditions (high water subcooling) but did not result in a steam explosion [6]. The droplet diameters used in the code MC3D are Sauter diameters, which are average droplet diameters giving the same interfacial surface area for the same volume of the dispersed phase. The mean Sauter diameter can be calculated from the droplets size distribution with

$$D^{Sauter} = \frac{\sum_i f_i}{\sum_i \frac{f_i}{D_i}}, \qquad (1)$$

where D_i is the average diameter of the droplets in the size group i and f_i is the corresponding droplets mass fraction. Expression (1) was obtained by considering the relations between the size group average droplet surface S_{id} and volume V_{id}, the size group droplets total volume V_i and the droplets total surface S^{tot}

$$S^{tot} = \sum_i \frac{V_i}{V_{id}} S_{id} = \frac{m^{tot}}{\rho} \sum_i \frac{6 f_i \pi (D_i)^2}{\pi (D_i)^3} = \frac{6 m^{tot}}{\rho} \sum_i \frac{f_i}{D_i},$$
$$S^{tot} = \frac{\sum_i V_i}{V^{Sauter}} S^{Sauter} = \frac{6 m^{tot}}{\rho} \frac{\sum_i f_i}{D^{Sauter}}, \quad (2)$$

where m^{tot} is the droplets total mass, ρ is the droplets density and S^{Sauter} and V^{Sauter} are the surface and volume of a droplet with the Sauter diameter.

Table 2: Debris size distribution in KROTOS experiment K-37

Sieve size (mm)	Mass (g)	Mass fraction (%)	Mass (g) less than sieve size	Mass fraction (%) less than sieve size
0.020	4.4	0.15	4.4	0.15
0.038	9.4	0.32	13.8	0.47
0.045	4.4	0.15	18.2	0.62
0.106	23.0	0.79	41.2	1.41
0.25	75.0	2.56	116.2	3.97
0.5	164.5	5.63	280.7	9.60
1	490.8	16.78	771.5	26.38
2	1263.0	43.18	2034.5	69.56
4	848.0	28.99	2882.5	98.55
>4	42.3	1.45	2924.8	100.00

3.2 MC3D simulation of experiment K-53 considering droplets freezing

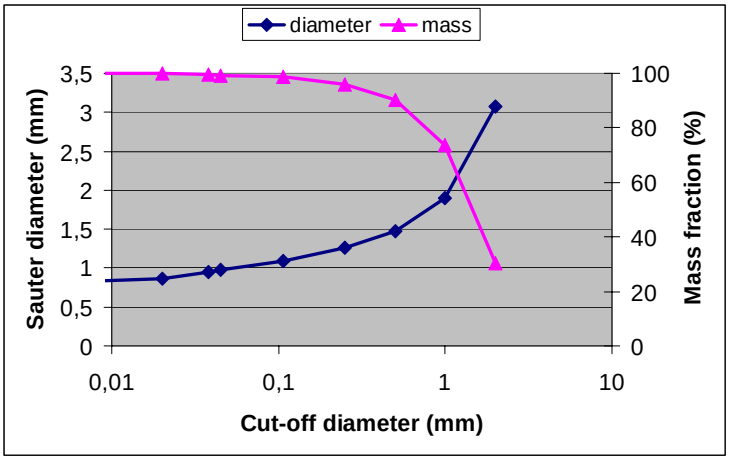
The simulations were performed with the MC3D computer code, which is being developed by CEA and IRSN, France [4]. MC3D is a code for the calculation of different types of multiphase multi-component flows. It has been built with the fuel coolant interaction calculations in mind. It is, however, able to calculate very different situations and has a rather wide field of potential applications. MC3D is a set of two fuel coolant interaction codes with a common numeric solver, one for the premixing phase and one for the explosion phase. The premixing module focuses on the modelling of the jet, its fragmentation into large drops and the coarse fragmentation of large drops. The fine fragmentation phase is dealt with the explosion module. This application focuses on the fine fragmentation of large drops and heat exchanges between the produced fragments and the coolant. In general the steam explosion simulation with MC3D is being carried out in two steps. In the first step the distribution of the melt, water and vapour phases at steam explosion triggering is being calculated with the premixing module. These premixing simulation results represent the input for the second step, when the escalation and propagation of the steam explosion through the pre-mixture is being calculated with the explosion module.

Since the objective of our analysis was to explore the ability of MC3D to adequately simulate the explosion phase if the premixture and droplets conditions at triggering time would be known, only explosion phase simulations have been performed assuming various predefined premixtures. A comprehensive parametric analysis has been performed varying the premixture radius and the corium droplets cut-off diameter, assuming that corium droplets with a diameter smaller than the cut-off diameter can not participate in the explosion since they are frozen and consequently can not fragment in fine particles, which is the driving force of the explosion. With increasing the cut-off diameter the melt mass participating in the

explosion decreases, since a larger fraction of the melt is solidified, and the Sauter diameter of the remaining liquid melt droplets calculated by equation (1) consequently increases, as is presented in Table 3 for the assumed droplet size distribution provided in Table 2.

Table 3: Mean Sauter diameter and corium mass fraction in KROTOS experiment K-37 as a function of the cut-off diameter

Cut-off diameter (mm)	Sauter diameter (mm)	Mass fraction (%)
0	0.7659	100.00
0.020	0.8640	99.85
0.038	0.9521	99.53
0.045	0.9847	99.38
0.106	1.0899	98.59
0.25	1.2623	96.03
0.5	1.4804	90.40
1	1.9027	73.62
2	3.0732	30.44

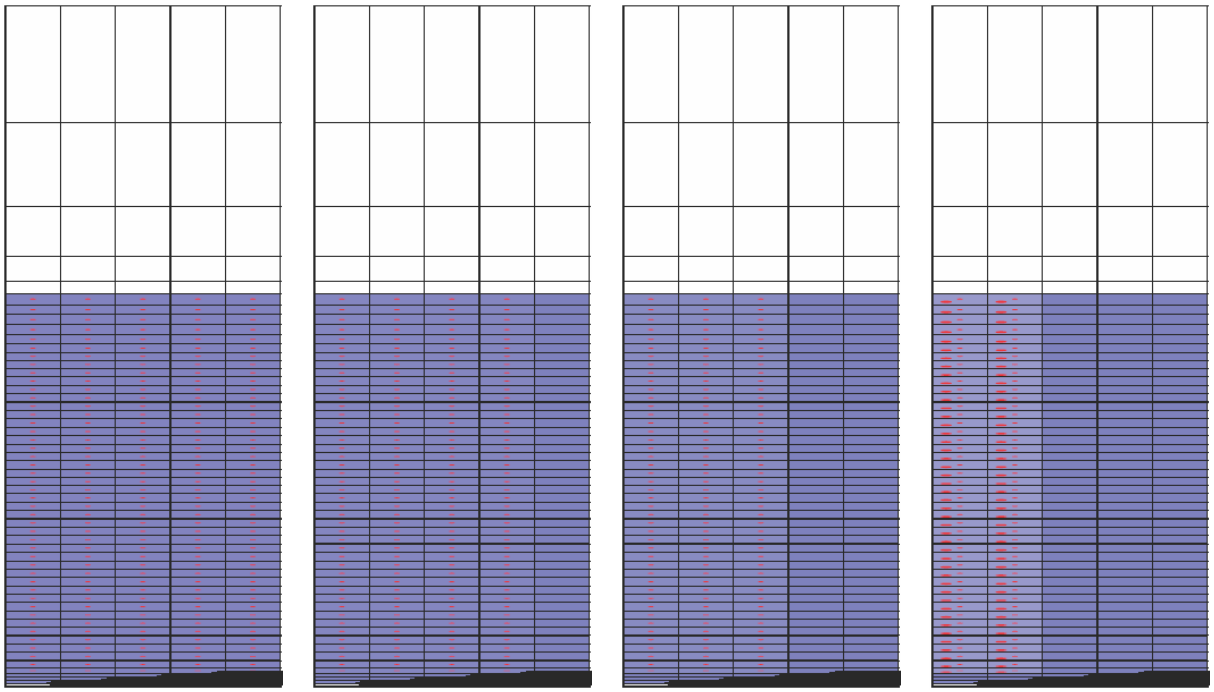


For the sake of simplicity, it was assumed that the phases in the premixture are distributed homogeneously and that the melt droplets in the premixture have the same size, equal to the mean Sauter diameter. The phase fractions were determined based on the experimental measurements of the average void fraction and the mass of the released fuel (Table 1). In Table 4 the simulated cases are presented together with the calculated vapour and melt fractions in the premixture, considering the corresponding melt mass fractions provided in Table 3.

Table 4: Simulated cases with premixture conditions

Case	Cut-off diameter (mm)	Radius of premixture (cm)	Vapour fraction (%)	Melt fraction (%)
R10	0	10	3.00	1.18
R10CUT05	0.5	10	3.00	1.07
R10CUT1	1	10	3.00	0.87
R10CUT2	2	10	3.00	0.36
R8	0	8	4.69	1.85
R8CUT05	0.5	8	4.69	1.67
R8CUT1	1	8	4.69	1.36
R8CUT2	2	8	4.69	0.56
R6	0	6	8.33	3.29
R6CUT05	0.5	6	8.33	2.97
R6CUT1	1	6	8.33	2.42
R6CUT2	2	6	8.33	1.00
R4	0	4	18.75	7.40
R4CUT05	0.5	4	18.75	6.69
R4CUT1	1	4	18.75	5.45
R4CUT2	2	4	18.75	2.25

On Figure 2 the geometry, the numerical mesh and the initial distribution of the phases are presented for the basic explosion simulations (R10-R4) with various premixture radii (10 cm – 4 cm) assuming that all released melt may participate in the explosion (no cut-off diameter). The trigger was modelled as a 150 bar pressurized gas cell at the utmost bottom of the test section at the axis. Due to the void build up during premixing an adequately increased water level of 1.14 m, established from the integral void fraction at trigger time (Table 1), was taken for the explosion simulations.



R10 R8 R6 R4

Figure 2**:** Geometry, numerical mesh and initial conditions for explosion simulation of basic cases R10 to R4 (Table 4)

3.3 Simulation results

For the various assumed predefined premixtures, presented in Table 4, the explosion phase simulations have been performed with the code MC3D version 3.5. On Figures 3 and 4 the calculated pressure curves in the test section at different levels are compared with the experimental measurements. In the experiment the pressure in the test section was measured at the location of the trigger and at locations 15 cm, 35 cm, 55 cm, 75 cm and 95 cm above the bottom of the test section. On Figures 3 and 4 the pressure curves at these locations are denoted with 00 to 95.

We see that all simulated pressure curves not considering droplets freezing (R10 to R4 without cut-off diameter) are significantly overestimating the measured pressure irrespectively of the assumed premixture radius. This was expected since in the experiment the dispersed melt at triggering was presumable already partially frozen and so not all the released melt could efficiently participate in the steam explosion. By increasing the cut-off diameter the fraction of the melt mass which may participate in the explosion is reduced and consequently the pressure escalation is less expressive and the explosion propagation speed decreases. In addition, with the resulting increased mean Sauter diameter the droplets surface area for fine fragmentation is decreased, which inhibits the development of a strong steam explosion.

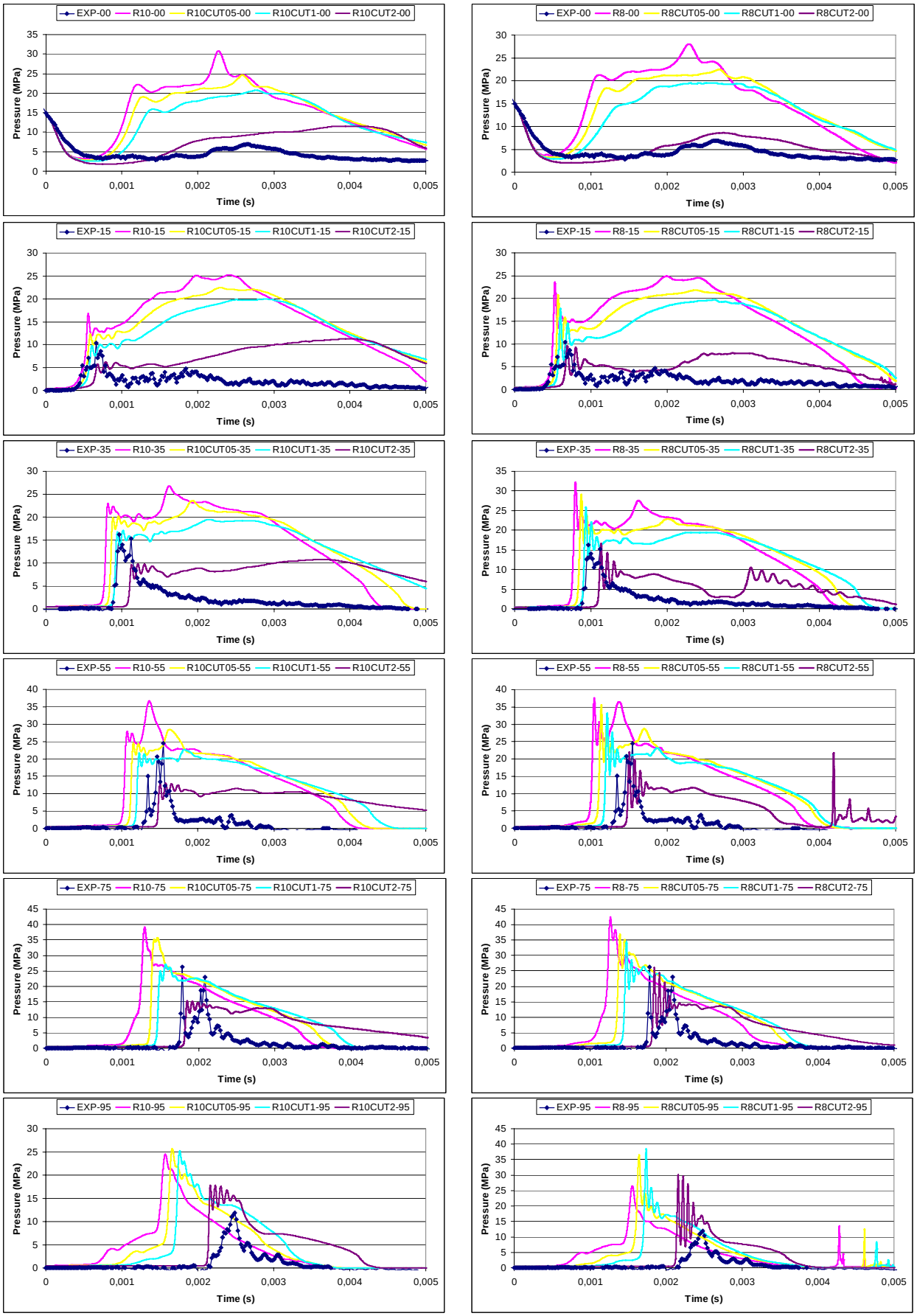


Figure 3**:** Simulated pressure histories for experiment K-53 for premixtures with radii 10 cm (left) and 8 cm (right) at different levels in comparison with experimental measurements

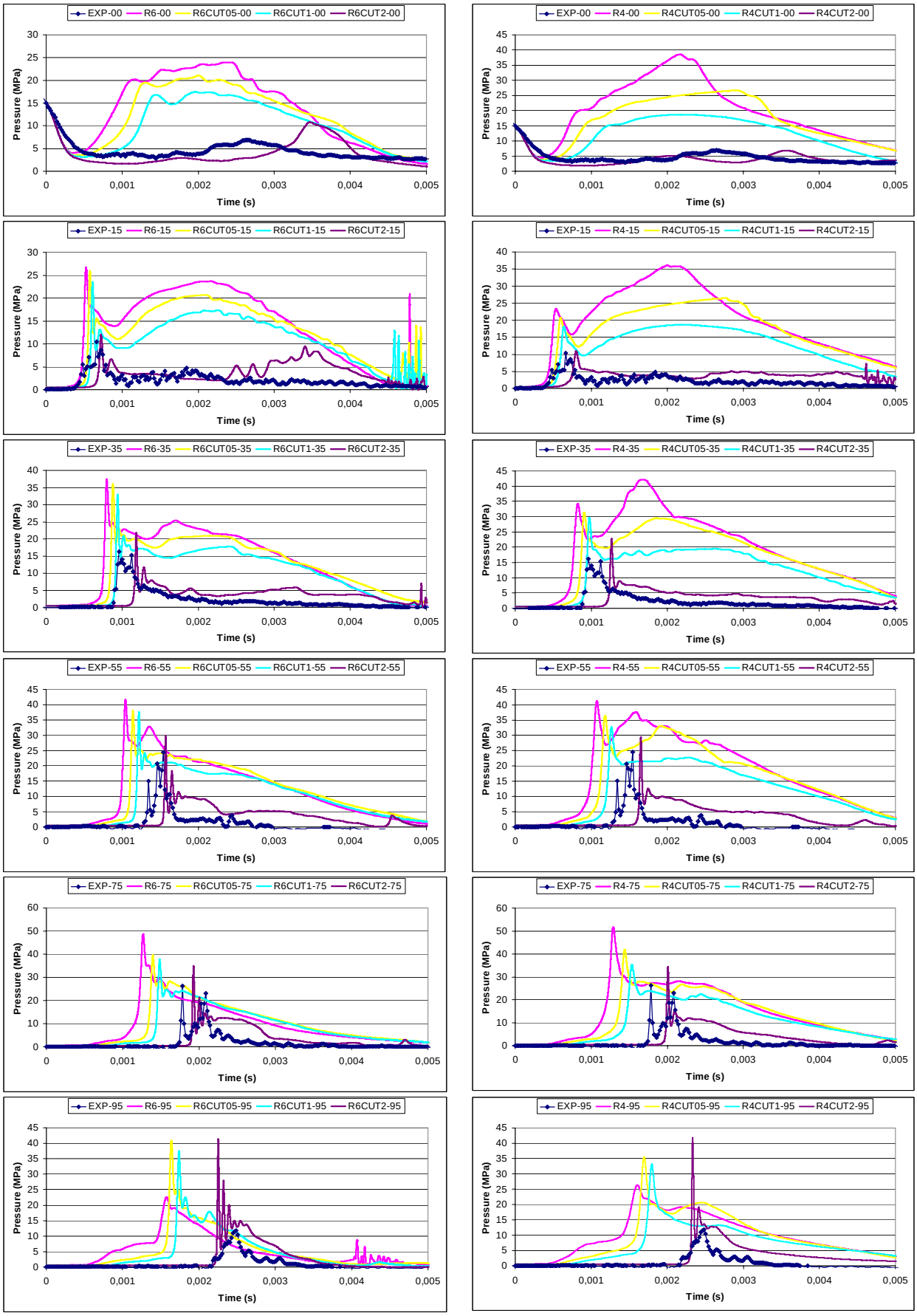


Figure 4**:** Simulated pressure histories for experiment K-53 for premixtures with radii 6 cm (left) and 4 cm (right) at different levels in comparison with experimental measurements

For a cut-off diameter 2 mm implying that nearly 70 % of the melt can not participate in the explosion due to droplets freezing, the calculated pressure impulses (integral of pressure over time) are significantly reduced and become comparable with the measured ones. In these conditions an influence of the premixture radius is evident. The pressure impulses are reduced with decreasing the premixture radius. An explanation for this could be that at a smaller premixture radius the vapour fraction in the premixture is increased (Table 4), what inhibits the development of an efficient steam explosion.

For a cut-off diameter 2 mm and an assumed premixture radius 4 cm the simulation results are in quite good agreement with the experimental measurements (Figure 4). This is an indication that at least in principle the explosion phase can be reasonably well predicted if the premixture conditions at triggering time are adequately determined and if we could judge based on the droplet solidification conditions (like crust and mushy zone thickness) whether the droplet can effectively participate in the steam explosion or not.

4 CONCLUSIONS

To establish the influence of droplets freezing on the steam explosion and to explore the ability of the global FCI code MC3D to adequately simulate the explosion phase if the premixture and droplet conditions at triggering would be known, a number of explosion phase simulations of KROTOS experiment K-53 was performed, starting from different predefined premixture and droplet conditions. In the parametric analysis the premixture radius, resulting in different premixture vapour and melt fractions, and the corium droplets cut-off diameter, assuming that corium droplets with a diameter smaller than the cut-off diameter are frozen and can not participate in the explosion, were varied.

The analysis revealed that there is an important influence of droplets freezing on the strength of the steam explosion. With more extended freezing the amount of molten corium, which may participate in the steam explosion, is decreased and so in overall less thermal energy is available for water vaporization. Already a small variation of the cut-off diameter significantly changes the calculated pressure impulses. Therefore it is very important that the influence of droplets freezing on the steam explosion is adequately considered in the global FCI codes. The radius of the premixture, resulting in different premixture vapour and melt fractions, had only a minor influence on the simulation results. For a cut-off diameter 2 mm and an assumed premixture radius 4 cm the simulation results are in quite good agreement with the experimental measurements. This is an indication that at least in principle the explosion phase can be reasonably well predicted if the premixture conditions at trigger time are adequately determined and if we could judge based on the droplet solidification conditions whether the droplet can efficiently participate in the steam explosion or not.

Due to the uncertainties in steam explosion understanding and modelling and more generally due to the complexity of the FCI process itself, the solidification effects can presently not be taken into account in detail in the global FCI codes. The influence of the droplets crust and mushy zone properties (e.g. thickness, mechanical properties, …) on the steam explosion triggering, escalation and propagation are not known, and beside that we are not even able to reliable calculate the crust and mushy zone growth on a droplet since the heat transfer conditions during premixing are so complex. Despite all these difficulties we should strive to develop adequate fit-for-purpose models considering the effects of droplets freezing, since the influence of droplets freezing on the steam explosion is so important, and incorporate them in global FCI codes, thus enabling more reliable reactor simulations and consequently more reliable conclusions for reactor safety issues.

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