Separate Effects Tests on Hydrogen Combustion during Direct Containment Heating Events in European Reactors

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ABSTRACT

In case of a core melt accident in a European light water nuclear reactor the pressure vessel may fail, in spite of depressurization of the primary circuit, still at an elevated pressure of 1 to 2 MPa. Then, the molten core debris will be ejected forcefully into the reactor cavity and beyond, depending on the specific reactor design. This may pressurize the reactor containment building beyond its failure pressure. The pressurization of the containment is due to the debris-to-gas heat transfer but also to a large part to hydrogen combustion. Hydrogen combustion contributes to peak containment pressure if the energy release rate is greater than the heat transfer rate to structures and occurs concurrent with the debris-to-gas heat transfer. This paper presents experimental and analytical results of the combustion of hydrogen jets blown into a scaled reactor containment with a prototypic atmosphere of air, steam and preexisting hydrogen. Experimental data are the pressure and temperature histories in the containment and pre- and posttest gas species concentrations. These data are used to validate models in the combustion code COM3D, and once validated will be used to extrapolate to prototypic scale.

INTRODUCTION

In the frame of the program for the investigation of melt dispersal and direct containment heating (DCH) phenomena during a severe accident in European reactor geometries experiments were performed in the DISCO facility using an iron-alumina melt as model fluid [1,2]. The analysis of these experiments showed that the containment is pressurized by the debris-to-gas heat transfer but also to a large part by hydrogen combustion [3]. Whether these two sources of energy transfer to the containment atmosphere are fully additive depends on the concurrence of the two processes. The critical question is how much hydrogen burns during the period of debris dispersal [4]. A time shift could arise if the flow paths for debris and hydrogen reaching an oxygen rich atmosphere are different. Furthermore, the rate of combustion determines the time scale of heat transfer to the atmosphere and thereby the peak containment load. Hydrogen combustion cannot contribute to peak containment pressure unless the energy release rate is greater than the heat transfer rate to structures. The experimental data base for hydrogen burns during direct containment heating events is, however, not sufficient for model development particularly for scaling effects. The need for separate effects experiments was evident.

Experiments were performed in the same facility (DISCO) without melt but otherwise similar conditions. The objective of this series of experiments is to study the effect of hydrogen combustion separately from the debris-to-gas heat transfer. The data are being used to validate models in the combustion code COM3D and to extrapolate to prototypic scale.

In these experiments, the fraction of hydrogen, that is produced during steam blow down by oxidation of the metal part with steam in DCH experiments or in real case, is filled into the RSC/RPV vessel pre-test and is blown out together with the other gases used, i.e. nitrogen or steam, through a hole in the lower head of the RPV. Since generally most of the oxidation takes place within the cavity, this simulation of hydrogen production should not have a major impact on the outcome of the experiment. The atmosphere in the containment was varied in these tests, containing either air or a mixture of air and steam with different amounts of pre-existing hydrogen.

GEOMETRY AND DIMENSIONS

The geometry of the DISCO-H facility represents the EPR reactor cavity (Fig. 1). The model of the containment pressure vessel has an outer diameter of 2.20 m and a height of 4.60 m. The total freeboard volume including the subcompartment is 13.75 m³. The subcompartment is an annular space around the cavity with a volume of 1.74 m³, modeling the volumes of the pump and steam generator rooms. The flow path from the cavity into the subcompartment is along the eight stubs modeling the main cooling lines (total flow cross section is 0.0308 m²). The top cover of the subcompartment has four openings with a diameter of 130 mm. No direct flow path from the cavity into the containment exists. The RCS-RPV pressure vessel models the volumes of both the reactor cooling system (RCS) and the reactor pressure vessel (RPV) and has a total volume of 0.076 m³. The pressure vessel (inner diameter 0.20 m) is heated electrically, and is insulated over the whole length and on the top. The linear scale of the experiment relative to the EPR-reactor is 1:18.

The test facility has been changed in some parts to simplify the geometry for base case investigations (Fig. 2). The subcompartment cover was removed and four of the eight exits from the cavity to the subcompartment (along the main cooling lines) were connected to a pipe each. The other four exits were closed by steel plates. Thereby the total flow cross section was kept similar as before. This configuration provides simple initial conditions for code calculations, and parameter studies were performed with this set up. In a second step the original, more prototypic configuration has been tested to study the effect of this simplification.

Because of the absence of melt droplets no natural igniters for the hydrogen are available. Therefore, it was decided to place thermite igniters, so-called sparklers, at the end of each pipe exit. The igniters must sustain a steam atmosphere and should have an ignition capability within a certain volume. Conventional thermite sparklers have been made steam-tight by coating with a water-resistant lacquer. They are started by electric resistance heating 1.2 seconds before initiating the blow down. They can ignite a hydrogen-air mixture in a radius of approximately 5 cm. They furnish sparks for a period of approximately 10 seconds, which is sufficient to guarantee ignition when the conditions are right.

The blow down speed should be similar as in tests with melt. In those experiments three stages of flow existed, single-phase melt flow, two-phase flow and single-phase gas flow. Consequently, the blow down was slow at the start and became faster with decreasing liquid fraction. A shake down test with hydrogen had shown, that the blow down was too fast, compared to the tests with melt, because of the absence of the melt and the high sound velocity of hydrogen. Therefore, the hole size in the RPV was reduced from 50 mm to 25 mm diameter in the first test. Additionally, starting with test G02 a ball valve instead of a rupture disk was being applied to model the break of the lower head and the existence of melt. The opening time of a rupture disk is only in the order of 2 ms, while the valve opens the flow cross section gradually. Opening times were deduced from the gradient of the pressure curves. These times were 192 ms (G02, G03), 120 ms (G04-G07) and 68 ms (G08). The RPV exit is now formed by a pipe with an inner diameter of 25 mm and a length of 65 mm.

INSTRUMENTATION AND CONDUCT OF THE EXPERIMENT

Ten thermocouples, with an outer diameter of 0.36 mm, are placed at different locations in the subcompartment and containment vessel to measure the gas temperature. A total of 11 strain gauge-type pressure transducers measure the transient pressures in the RCS/RPV pressure vessel, the cavity, the subcompartment and the containment dome. Four video cameras with 50 frames/second were used. Two cameras were looking down from the top cover, one had a horizontal view from a

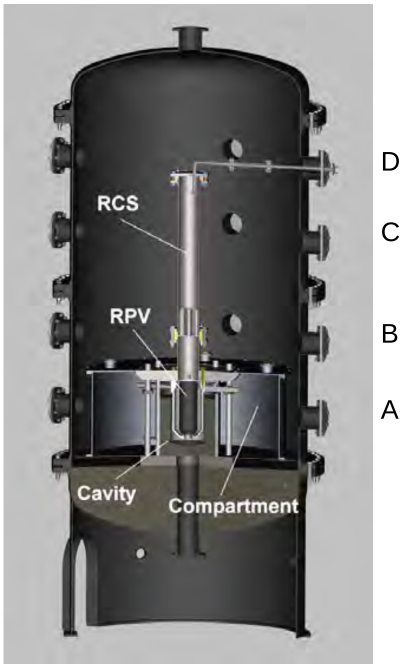


Figure 1. The DISCO-H facility

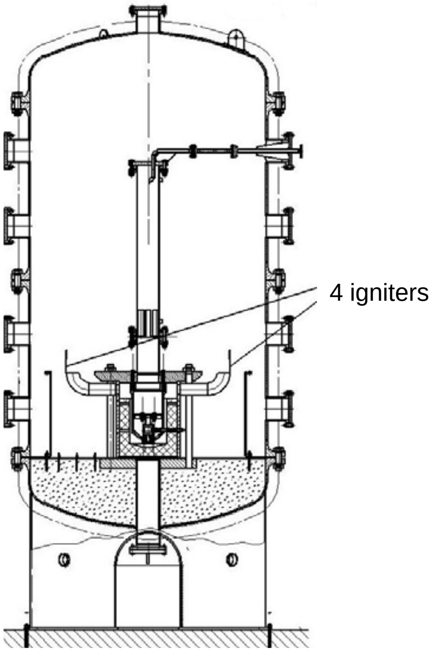


Figure 2. Geometry for base cases

level B port, and one used an endoscope introduced in a level A port. Nine pre-evacuated gas grab sample bottles are used to collect dry-basis gas samples at three positions, in the subcompartment and two different heights in the containment. The sample lines and the sample bottles are at room temperature, thus the bottles are being filled with non-condensable gases and steam, that condenses. One pretest sample collects background information just prior to the start of the blowdown. One sample at all three stations each is taken 10 seconds and one 5 minutes after the blowdown.

The containment vessel is heated over a time period of approximately 12 hours by filling with steam additional to the atmospheric air until the vessel pressure reaches 0.2 MPa. The condensate water is drained at the bottom of the vessel from time to time. The average gas temperature and the wall temperature inside the vessel is 373 K (100°C) at the end of the heat-up. A metered amount of hydrogen gas is added to the vessel at the end of heat-up while fans are running inside the vessel. Then the RCS/RPV vessel is filled with the projected amount of hydrogen, the fans are stopped and the experiment is ready to start by initiating the computer controlled sequence. If a mixture of steam and hydrogen is foreseen as blowdown gas, steam is filled into the RCS/RPV vessel by opening a valve in the line connected to a steam accumulator placed outside the containment vessel for the period of one second. Then the sparklers are ignited and after one second the ball valve is opened to start the blowdown.

TEST PARAMETERS

The projected initial pressure was 2 MPa in the RPV and 0.2 MPa in the containment. The table below lists the nominal parameter matrix regarding the hydrogen, steam and air contents. Tests G02 through G06 were done in the simplified geometry (Fig. 2) while the more prototypic geometry (Fig.1) was applied in tests G07 and G08. It should be noted that experiments using 100g of hydrogen in the RPV reached the initial pressure of 2 MPa without any extra gases introduced into the RPV. Only the initial filling of nitrogen at atmospheric pressure was in the vessel together with the hydrogen.

Table 1. Matrix of nominal initial test parameters

		G02	G03	G04	G05	G06	G07	G08
RPV: H_2 + N_2 or H_2 + steam		N_2	N_2	steam	steam	N_2	N_2	steam
RPV: Hydrogen mass	g	100	50	50	50	100	100	50
CON: Hydrogen mass	g	-	50	50	100	100	100	50
CON: Atmosphere: Air + …		-	-	steam	steam	steam	steam	steam

Table 2. Initial Conditions, Results and Analysis

		G02	G03	G04	G05	G06	G07	G08
RPV pressure	MPa	1.96	1.99	1.87	2.02	2.18	2.67	1.95
Steam concentration in cont.	mol %	0	0	37.67	33.41	38.62	35.23	36.19
H_2 concentration in cont.	mol %	0	2.22	2.58	7.02	4.96	6.00	2.69
Initial H_2 in containment	mol	0	24.8	23.3	64.4	48.5	54.5	24.8
RPV-blow down H_2	mol	48.5	23.8	24.8	25.7	51.0	53.0	26.2
Total available H_2	mol	48.5	48.6	48.2	90.1	99.5	107.5	51
Burned H_2 (N_H)	mol	36	27	30	81	74	72	24
Fraction burned	-	0.73	0.55	0.58	0.86	0.78	0.67	0.46
H_2 post test concentration	mol %	1.2	1.9	2.2	1.1	1.7	3.6	2.9
Measured peak pressure increase	MPa	0.13	0.11	0.11	0.27	0.23	0.25	0.09
Theor. maximum Δp_{theo}	MPa	0,25	0,16	0,18	0,50	0,46	0,44	0,15
Efficiency $\Delta p_{exp}/ \Delta p_{theo}$	-	0,52	0,67	0,60	0,54	0,50	0,56	0,61

RESULTS AND ANALYSIS OF THE EXPERIMENTS

The achieved initial conditions are listed in table 2, together with the most important results. Generally the parameters were close to the planned, exceptions are test G05, where the initial hydrogen content in the containment was higher, and G07 with a higher initial RPV pressure.

The pressure gradient in the RPV vessel, shown in Fig. 3, is different for different gas mixtures, due to the different sound velocity of the gases. The fastest decrease is found for tests G02, G06 and G07. Here only hydrogen with a very small fraction of nitrogen was in the vessel. A slower blowdown is observed for the mixture of hydrogen with steam, and the slowest is for the mixture of hydrogen with nitrogen (G03).

The containment peak pressures (Fig. 4) are reached generally after 1 second (time for prototypic scale would be 18 seconds), with the exception of test G06, where it is reached only after 2 seconds. An explanation for this behavior can be found in the code analysis below. In test G05, having the highest hydrogen concentration of 7% in the containment, the hydrogen began to burn when the igniters started 2 seconds before blowdown commenced. The results regarding the height of the peak pressure in the containment fall into two groups. Tests G05, 6 and 7 with total hydrogen amounts close to 100 mol, and the other tests with amounts of 50 mol.

From the pre- and post-test gas analysis the amount of hydrogen that burnt was determined. The data of the three measurement stations were averaged. The uncertainty of these results is in the order of 5% of the final data given in the table. The main contributions to the uncertainty are the limit of quantification of the gas samples and the incomplete gas mixing in the vessel.

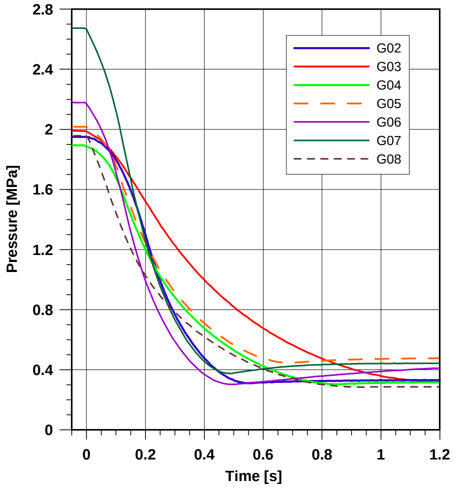


Figure 3. Blowdown pressures in the RPV vessel

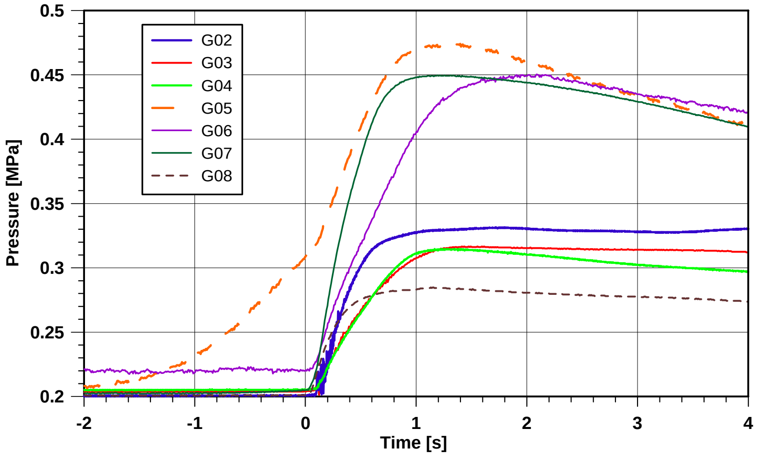
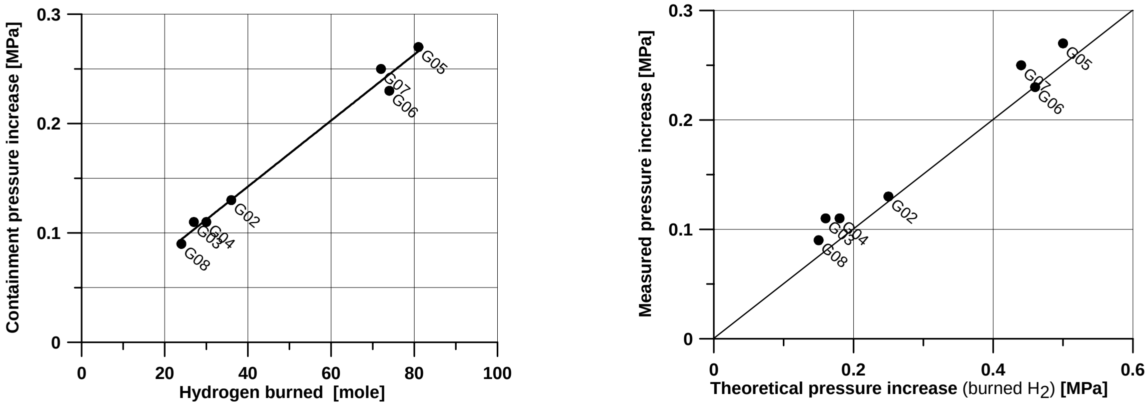


Figure 4. Containment pressures



(a) (b)

Figure 5. Pressure increase versus burned hydrogen (a), comparison of possible maximum pressure increase due to burned hydrogen with measured pressure increase (b).

The measured pressure increase does not correlate with the amount of blow down hydrogen. The correlation between pressure increase and total available hydrogen gives two clusters of data, one for high and one for low amounts of hydrogen. Within the cluster there is no correlation between pressure increase and hydrogen mass. The measured pressure increase is, with small scatter, a function of burnt hydrogen (Fig. 5a). A small part (order of 0.01 MPa) of the pressure increase is due to the additional gas added by the blow down.

The theoretical possible pressure rise resulting from the energy release by hydrogen burning can be obtained by combining the caloric equation of state with the ideal gas law,

$$\Delta p = \frac{\kappa - 1}{V} \Delta Q_H \tag{1}$$

with κ the ratio of gas specific heats and V the containment volume (V= 13.75 m^3). When we have a mixture of air and steam in the containment, we take κ = 1.35 as a rough estimate, with air κ = 1.4. The steam in the containment is at saturation and does not quite obey the ideal gas law. Furthermore, there is always some fog, which consumes energy for vaporization. Nevertheless, we calculate the pressure increase with $\Delta Q_H = \Delta q_H N_H$ and Δq_H = 242 kJ/mol burnt H_2 (with N_H number of burnt hydrogen moles) and obtain the data shown in table 2. The ratio of measured peak pressure increase to theoretical pressure increase according to Eq. 1 is the efficiency of the process, a measure for all heat losses involved. The efficiency lies between 50% and 67% for the tests with steam, the average is 58%. The data are shown in Fig. 5b.

RESULTS AND ANALYSIS OF THE CODE CALCULATIONS

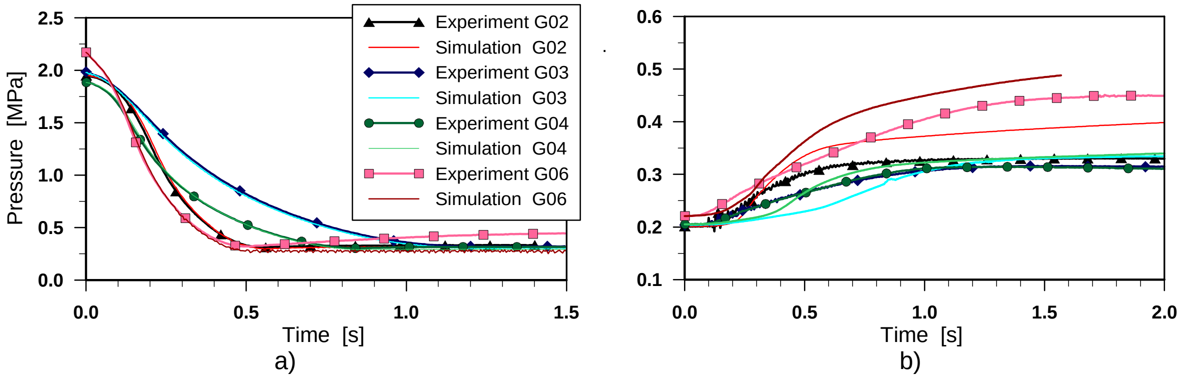
With the aim to understand the details of the underlying physical processes and to have a possibility to predict potential effects of DCH events in real reactor scale, a set of numerical simulations of several DISCO-H experiments was performed. The simulations were carried out using the COM3D code [5]. The COM3D code was developed at FZK with the focus on the numerical simulation of turbulent reacting flows. The code solves the 3D unsteady, compressible Navier-Stokes equations using both RANS and LES turbulence modeling technique combined with a number of combustion models ranging from EBU (eddy-break-up) to 'presumed' β-PDF (probability density function). The numerical solver employs an explicit shock capturing second-order algorithm realized on a rectangular equidistant grid. In the present work for combustion simulation a phenomenological model CREBCOM [6] was used. Since the model includes adjustable constants and because it is intended to achieve model scalability on reactor-relevant dimensions, the CREBCOM numerical model was calibrated against experimental data from a series of DISCO-H tests.

The set of simulations, which will be discussed in this paper, was intended to identify the most important characteristics of considered events and make a conclusion about the applicability of the proposed approach. Therefore, it is considered as a preliminary attempt and for that reason was limited to four experiments only: G02, G03, G04 and G06, out of seven made in the experimental series. The choice of the tests was dictated by the necessity to represent preferably all most important phenomena of the problem under consideration, e.g.:

- In the tests G02, G03 containment and RPV atmosphere consists of H_2-N_2 mixture, while in tests G04 and G06 N_2 is replaced by steam. This can clarify the role of additives to the atmosphere.

- Test G02 initially has no H_2 in the containment, G03 and G04 has 50 g in the containment and in test G06 initially there were 100 g of H_2 in the containment. This can clarify the role of initial H_2 concentration on the combustion regime.
- In the tests G02, G03 and G04 the total hydrogen inventory is 100 g while in the G06 test it was increased to double the value equal to 200 g. This variation on the total H_2 amount will allow to study the effect on the residual amount of H_2 after combustion.

All the tests were calculated using the same simplified model of the installed geometry. Due to the fact that in the DISCO facility, which is almost completely cylindrically symmetric (see Figure 1 and Figure 2), in this test series four exits from the cavity were used, it was possible to use a quarter vertical cut of the whole set-up. The calculation domain consisted of 54 x 197 x 54 computational nodes with 2 x 2 x 2 cm each.

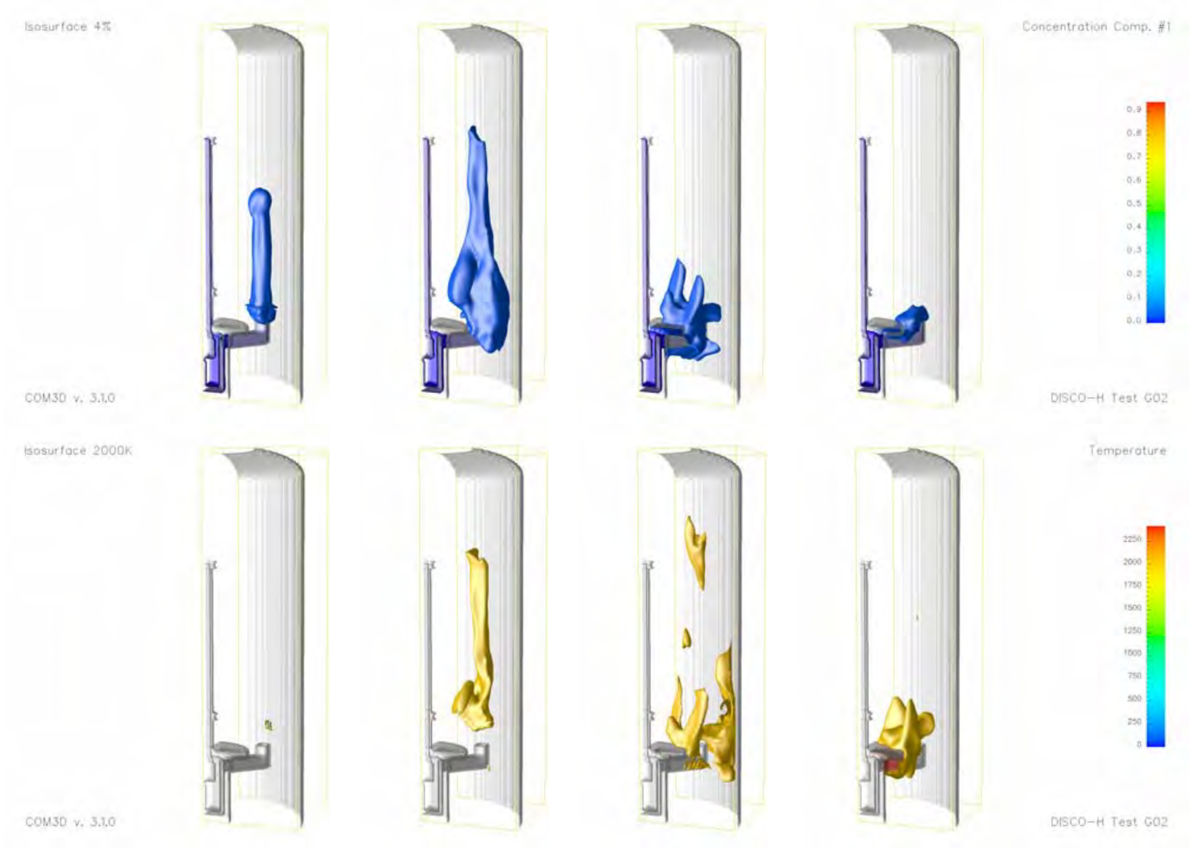


a) b)

Figure 6. a) Comparison between experimental and calculated pressure decrease in RPV for four simulated experiments. Pressure transducer is located in the upper part of the RPV volume. b) Comparison of the calculated pressure buildup in the containment with observed in the experiments. The pressure sensor is located in the upper part at the outer wall of the containment.

With the intention to simplify the set-up for the simulations and to identify the significance of different physical processes a set of trials revealing the role of turbulence in these tests was made. In view of the fact that the injected gas forms a highly turbulent jet, it could seem that the mixing process can noticeably influence the combustion progression. The simulation of test G02 was performed both with standard k-ε model and without any turbulence model. A comparison of the advance of the pressure increase in the containment for both cases demonstrated that the difference between them appeared to be insignificant and therefore, for the sake of clarity and of improvement of computational performance, all further simulations were carried out without turbulence modeling. Similarly, taking into account the relatively high degree of uncertainty in modeling overall heat losses in such combustion processes, and to avoid ambiguity connected with competition between heat release during combustion and heat losses, accounting of all heat losses was excluded in this first set of simulations. The experimental procedure of hydrogen injection from RPV into the containment included opening a valve in the line between RPV and cavity. A nonlinear increase of the valve opening cross-section (see initial phase of RPV blow-down in Figure 3) brought additional complications into the modeling procedure. Since this initial phase appeared to be important for the modeling of the entire DCH, a special routine for exact reproduction of the hydrogen injection rate was developed. In Figure 6a a comparison between experimental and calculated blow-down pressure in the RPV is shown. All these measures based on the listed simplifications, assumptions, and special routine permitted to concentrate on key features of the utilized combustion model.

The phenomenological combustion model, which was used for the simulation of the burning processes, sets down a predefined visible flame speed using variation of the fundamental flame speed K_0, depending on the process conditions, e.g., degree of local obstruction, initial level of turbulence, mixture composition, etc. In the series of simulations for each of the four modeled experiments the constant K_0 was tuned to obtain the closest agreement with the experimental data. The obtained best value of fundamental flame speed K_0 was equal to 0.3 m/s (this corresponds to laminar flame speed in H_2-air mixtures with a concentration of H_2 equal to 12%); and this value was used for ultimate modeling of all tests. Generally the containment pressure predictions obtained in the simulations with the tuned constant were satisfactorily good. In Figure 6b the comparison between calculated and experimental data is shown. The overall predictions of the behavior of pressure buildup reflect all most important stages in pressure development. In Figure 7 an evolution of the hydrogen distribution synchronized with the development of the flame surface are shown. A remarkable result is that the maximum flame surface is observed at the time about 0.4 s when the maximum pressure growth was detected. Note however, that despite generally adequate pressure buildup reproduction, in the initial phase of gas injection from RPV into containment, a slight holdup in the pressure growth was seen. The reasons of this fact are not completely clear and possibly can be connected with the peculiarities of the combustion processes in lean mixtures.



0.14 s 0.21 s 0.37 s 0.91 s

Figure 7. Evolution of hydrogen distribution (shown iso-surface of lower flammability level (LFL) 4% vol.) and corresponding temperature (iso-surface of 2000° K) in test G02. From left to right: amount of burned hydrogen is equal to 1%, 9.5%, 37%, 54%.

Summarizing the simulation results of the DISCO-H experiments, it can be concluded that, depending on initial concentration of H_2 in the containment, three regimes of the combustion can be distinguished.

In the first regime, which is realized in case of low initial hydrogen concentration, the hydrogen injection will lead to the formation of the attached diffusion flame and the pressure growth in this case is defined by the hydrogen injection rate only. In the series of the presented experiments the test G02 can be regarded as a typical example. When the pressure in the containment is equalized with pressure in the RPV, hydrogen injection and respective further containment pressure growth are completed.

In the second regime the hydrogen concentration in the containment is slightly below lower flammability limit (LFL). The containment atmosphere is not burnable, however an injection even of small amounts of H_2 can lead to fast formation of large-scale burnable mixtures and thus drastically change the regime of heat release. The rate of heat release in this case is defined by the competition between hydrogen injection, mixing of the injected gas and burnout of the newly formed combustible mixture. After burnout of the volumetric hydrogen a formation of the attached diffusion flame, similarly to the first regime, is expected. The test G06 and tests G03 and G04 to a minor degree can be taken as a good illustration of this regime. Modeling of this regime is the most complicated since it involves simulations of the combustion process in the vicinity of LFL. The commonly accepted value of LFL equal to 4% H_2 vol. [7] often is violated by uncertain or unclear factors, e.g. in test G06 the containment H_2-concentration was measured equal to 4.96% meanwhile it was not ignited before the injected hydrogen reached containment. A set of simulations with the different definitions of LFL demonstrated that the model is extremely sensitive to relatively small changes of its value. In Figure 8 a comparison of the pressure development in the containment for the test G06 for the combustion models with definitions of LFL differing 1% is shown.

The third regime is characterized by higher initial H_2-concentrations. In this regime the initial containment H_2-concentration is higher than LFL. An ignition of the burnable cloud results in different modes of premixed combustion. The flame speed in this case and connected pressure growth can be different depending on turbulence level, obstruction of the volume, etc. After burnout of the containment hydrogen, again formation of the attached diffusion flame is expected. Tests G05 and G07 are the examples of the third regime.

The second and third case lead to the delayed peak of heat release: in DISCO-H experimental conditions, if it is assumed that premixed combustion is propagated through the containment (2-5 m) during 1 s – 2 s (typical time of heat release growth), an estimate for flame speed will be 1 m/s – 5 m/s, which appears to be rational for flames initiated by turbulent jet release.

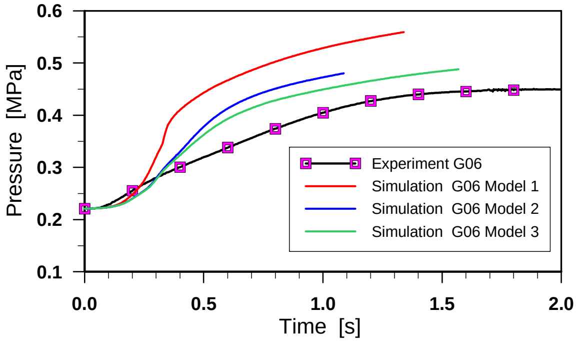


Figure 8. Pressure growth in the containment for the combustion models with different definitions of LFL value. Model 1 corresponds to 4% vol. H_2, model 2 to 5% vol. H_2, model 3 to 6% vol. H_2.

CONCLUSION

Summarizing the discussion of the numerical simulation results, the following main conclusion can be made:

- a role of turbulence is not so important and the processes can be modeled using phenomenological combustion models without taking into account turbulence generation;
- replacement of nitrogen by steam does not reveal any noticeable differences;
- the accurate accounting of the flame behavior near LFL is highly important. The proposed models are able to predict combustion with acceptable accuracy; however for better predictions the combustion model has to be further improved .

For the prediction of the possible pressure loads in the course of DCH events an accurate accounting on the heat losses is required. For the geometry conditions relevant to NPP environment it could be expected that heat losses due to radiation will play the dominant role comparing with convective heat losses connected with flow interaction with containment internal structures. However, this statement requires direct confirmation. This work is underway.

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