Validation of AC² – COCOSYS regarding light gas stratification build-up and dissolution

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ABSTRACT

Various investigations indicate that in case of severe accident scenarios the radiative component of heat transfer cannot be neglected for typical temperature differences occurring in containments. Nonetheless there is only few systematic investigations on the ratio of radiative heat transfer to convective heat transfer in such cases. The tests TH-32 to TH-34 conducted at the THAI test facility aim at investigating the influence of heat radiation on the light gas stratification build-up and dissolution in containments.

The three tests are simulated using the lumped parameter code COCOSYS 3.0.1 (Containment Code System) which is part of the software package AC² 2019.1. Simulations of the tests show that COCOSYS can capture the influence of CO_2 on the heat transfer adequately for above mentioned THAI tests.

INTRODUCTION

In case of a loss-of-coolant accident (LOCA), core degradation might occur if emergency measures fail. In this case, a considerable amount of hydrogen may be generated by the oxidation of the fuel rod cladding. If the hydrogen leaks into the containment of a pressurized water reactor (PWR), it can lead to a stratified atmosphere and form a combustible mixture with the air. In case of ignition by a spark, pressure peaks might occur that damage the containment or other safety equipment. As a result, radioactive fission products might be released into the environment. Since the velocity of the combustion and thus the gradient and magnitude of the pressure peak depend amongst others on the local hydrogen concentration, knowledge of the hydrogen distribution in the containment is of importance for reactor safety research.

Stratification build-up and dissolution are influenced by heat transfer processes at structures. This heat transfer between structures and a surrounding fluid has a convective, a conductive and a radiative component. Various investigations indicate that in case of severe accident scenarios the radiative component cannot be neglected for typical temperature differences occurring in containments. Nonetheless only few investigations on the ratio of radiative heat transfer to convective heat transfer in such cases have been conducted so far.

The tests TH-32 to TH-34 that were conducted at the THAI test facility (cf. Figure 1) operated by Becker Technologies GmbH aim at investigating this influence of heat radiation on the light gas stratification build-up and dissolution in containments. For these tests the condensate trays displayed in Figure 1 were removed but the inner cylinder was retained. The vessel was filled with dry air in all three tests. In case of test TH-33 about 5 vol.% CO_2 and in case of TH-34 about 30 vol.% CO_2 were added, partly replacing the dry air and modifying the optical thickness of the atmosphere. In all three tests a steady-state natural convection was established by differential heating of the vessel walls. The upper oil mantle

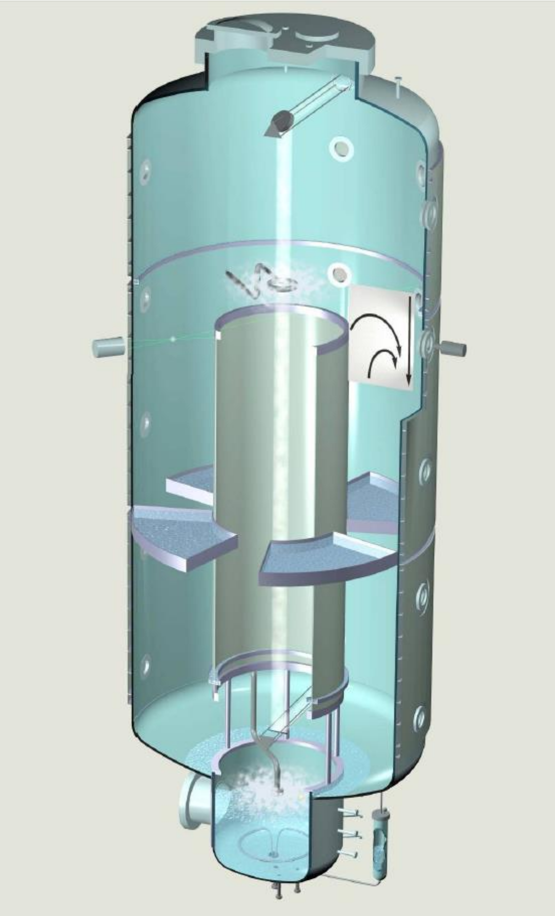

Figure 1: THAI test facility [1]

was cooled to 40 °C and the lower two oil mantles were heated to 120 °C. A rapid helium injection into the upper part of the test vessel established a helium stratification. This helium stratification build-up was finished after about 236 s in all three tests. The helium stratification was then dissolved by the established natural convection over about 3360 to 3600 s. The experimentators concluded, that differences in the results of the three tests lie within the relative experimental uncertainty and that no pronounced difference related to the CO_2 content and thus to a different heat-transfer mechanism is observed.[1],[2]

In the following chapters COCOSYS (Containment Code System) version 3.0.1 which is part of AC^2 2019.1 is validated regarding the influence of optical thickness on the stratification dissolution using afore mentioned tests TH-32 to TH-34. The dataset used for these simulations is based on the dataset developed for the open benchmark simulations of test TH-22 conducted by Burkhardt and Koch [3] and was further developed for the blind and open benchmark exercise on test TH-32 [4],[6] and again for the simulations at hand.

MODELLING

The nodalisation of the THAI test vessel comprises 114 zones on 25 levels (c.f. Figure 2) and was already used for the open benchmark on test TH-32. Since radial temperature gradients and counter flow are expected, the individual compartments of the vessel are subdivided into rings to allow for those phenomena to develop. The condensate gutter at a height of 6.57 m in the test vessel is not modelled in the dataset as this produced good results in the benchmark simulations of test TH-22 [3]. In order to capture the helium stratification and its dilution, the height of the zones in the upper part of the test vessel (between 6.245 and 8.39 m) is chosen to about 6.8 % of the vessel diameter. This is in good accordance with the recommendation of the COCOSYS user manual (5-10 % of the diameter [5]). The helium injection is modelled at a height of 6.674 m (experiments 6.7 m [2]) and by a conical plume with an opening angle of 15° which is also in accordance with examples in the manual [5].

The total loss coefficient (VZET) on all atmospheric junctions is set to 0.3 (from 1.0 in the benchmark simulations of TH-22). The heat transfer and condensation models FRC (free convection), FOC (forced convection), COD (wall condensation) and WGR (wall gas radiation) are used. The simulation is started 5 s before the beginning of the helium injection (at t = -5 s). The atmosphere temperatures inside the test vessel at the time of start of helium injection in the experiment are taken as starting conditions for the simulations. Heating and cooling power from the experiments are modelled as heat injection into the corresponding vessel wall structures (negative for the upper oil mantle, positive for the lower two mantles). The three experiments show small differences in heating power, helium mass flow and starting temperatures (t = -5 s) as well as starting pressure (t = -5 s) which were considered for the simulations.

The maximum time step size (HMM) was chosen to a comparatively low value of 0.5 s as variation calculations showed a small but noticeable influence of time step size on stratification dissolution phenomena.

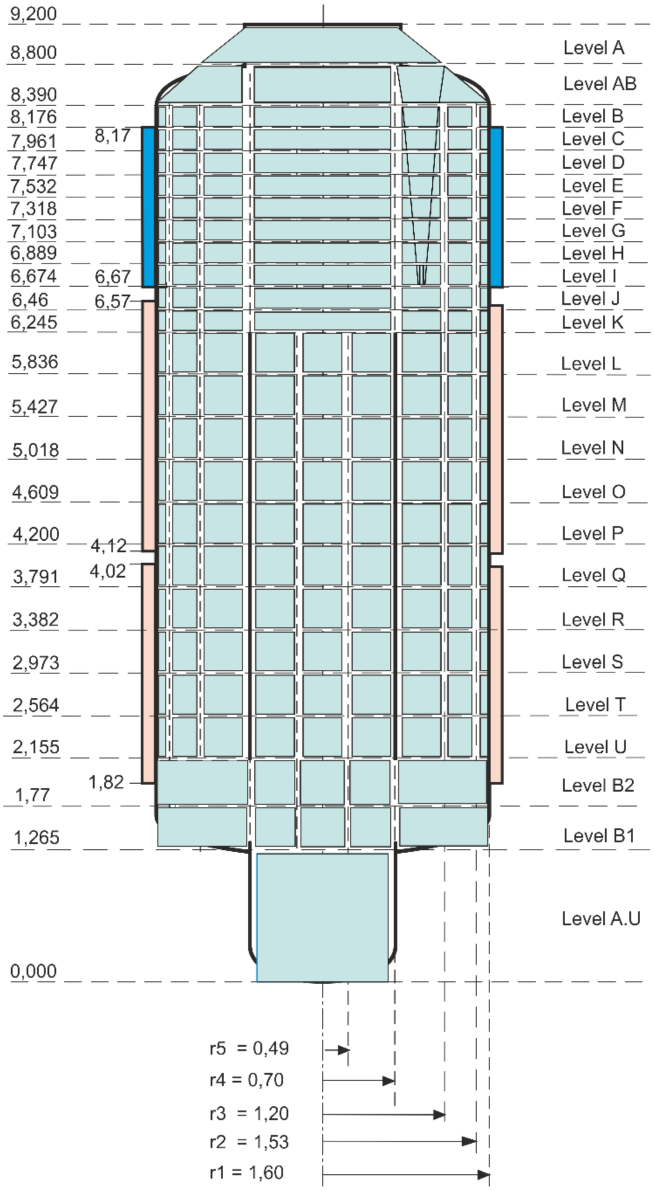

Figure 2: Nodalisation of the THAI test vessel

RESULTS

Figure 3 (left) shows the pressure evolution between t = -500 s and t = 4500 s for the experiments as well as the corresponding simulations. The vessel pressure before the beginning of the helium injection is 1.21 bar for test TH-32, 1.19 bar for test TH-33 and 1.18 bar for test TH-34. The vessel pressure increases by about 0.2 bar during the helium injection (between 0 and 236 s test time) in all three experiments and corresponding simulations. The vessel pressure remains almost constant throughout the following dissolution phase. Overall the pressure evolution is well predicted by the simulations.

On the right side of Figure 3 the helium concentration as function of height in the vessel is plotted at the time of stop of helium injection (t = 236 s). The helium concentration above the injection height is generally predicted well with a slight overestimation of peak concentration in case of tests TH-32 and 33. The concentration between a height of four meters and the injection height is noticeably overpredicted by the simulation. This is in part caused by the lumped parameter concept of the simulation and partly caused by early onset of the dissolution process. The concentration below four meters is again predicted quite well by the simulation.

Figure 4 and Figure 5 show the evolution of helium concentration over time at different heights in the test vessel. The left side of Figure 4 shows the concentration evolution about 20 cm below injection height (6.5 m) and the right side the evolution about 20 cm above the injection height (6.9 m). In the simulation the helium concentration above the injection slowly decreases to the final concentration of about 15 vol.% after about 3500 s test time. In the experiments the concentration quickly drops to 7 vol.% and then increases steadily to 15 vol.% at about 3500 s test time. This shows, that in the simulations the atmosphere below the injection is not as well mixed as in the experiments.

The helium concentration at a height of 7.5 m rises to between 47 and 50 vol.% in the experiments and to about 45 vol. in the corresponding simulations (c.f. Figure 5, left). After the peak the concentration slowly decreases by about 5 vol.% in the experiments (between 1600 s and 2000 s test time). After that the concentration quickly drops to about 10 vol.%. The simulation results show a similar progression as the experimental results but the onset of quick drop of helium concentration is delayed by about 700 s on average. The helium concentration at a height of 9 m (cf. Figure 5, right) which corresponds to the uppermost zone in the COCOSYS simulation rises to about 50 to 53 vol.% in the experiments and slowly declines to 44 vol.% at 2800 to 3200 s test time. After that the helium concentration quickly drops to the final concentration of 15 vol.% helium. The evolution of helium concentration in the corresponding simulations is very similar, but the final concentration drop is not quite as steep as in the experiments and the time of complete dissolution of the stratification is delayed by about 500 to 800 s.

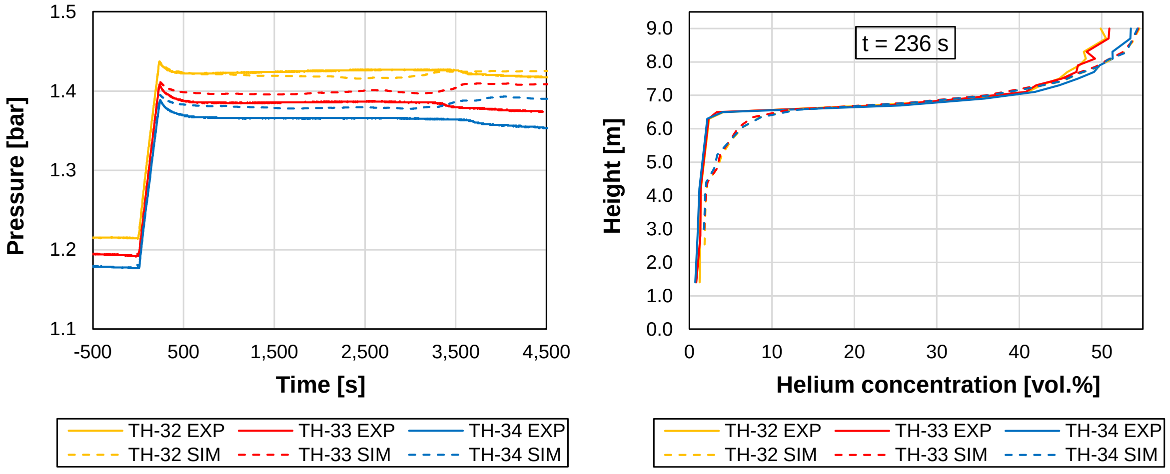

Figure 3: Pressure evolution in the experiments and simulations (left) and helium concentration as function of elevation after stop of helium injection (right)

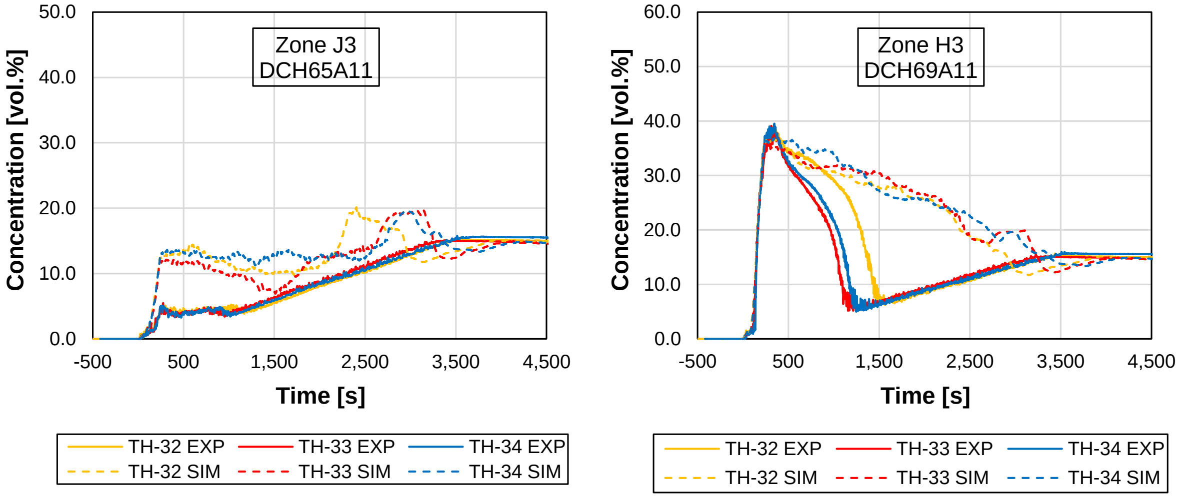

Figure 4: Evolution of helium concentration at different heights (left 6.5 m, right 6.9 m)

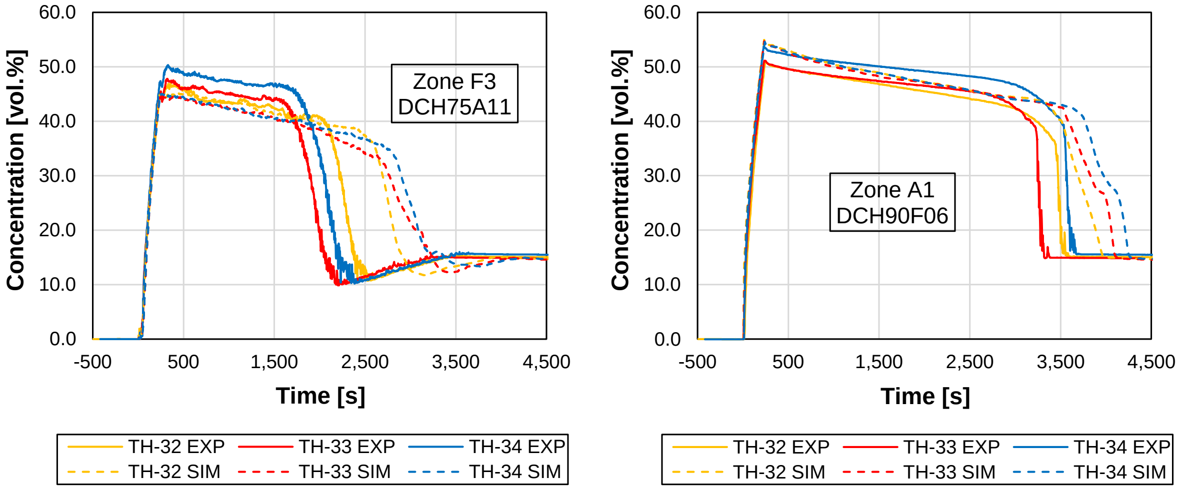

Figure 5: Evolution of helium concentration at different heights (left 7.5 m, right 9 m)

The afore mentioned less steep final drop of helium concentration is at least partly caused by the lumped parameter (LP) concept. Furthermore, the measuring locations from the experiments mostly do not match the center of the corresponding zone from the simulation which introduces an additional error in the evaluation of the simulation results.

The temperature evolution for a selected zone (E3 at a heigt of 7.7 m) is plotted in the graph on the left side of Figure 6. Before the beginning of the injection phase the temperature is 90 °C in the experiments as well as the simulations. During the helium injection phase (0 to 236 s) the temperature begins to drop in both the experiments and the simulations. At t = 500 s the temperature in the three experiments stabilizes at around 60 °C. After the local dissolution of the helium stratification at the height of the temperature measurement (t = 2100 to 2400 s) the temperature quickly rises to 90 °C again. In the simulation the temperature at t = 500 s is 73 °C but remains on a slow downward trend until local stratification dissolution at around t = 2800 to 3200 s after which it quickly rises to 93 to 96 °C.

On the right side of Figure 6 the vessel height is plotted over the time when the normalized helium concentration drops below 0.5. It can be concluded that the upward movement of the helium cloud front in the simulations is delayed by about 200 to 1000 s compared to the experiments and depending on the height. The durations until complete dissolution of the helium stratification in the experiments vary by about 300 s which falls inside the limits of experimental uncertainty specified by the experimenters [2]. The time of complete dissolution of the stratification in the simulations also varies by about 300 s.

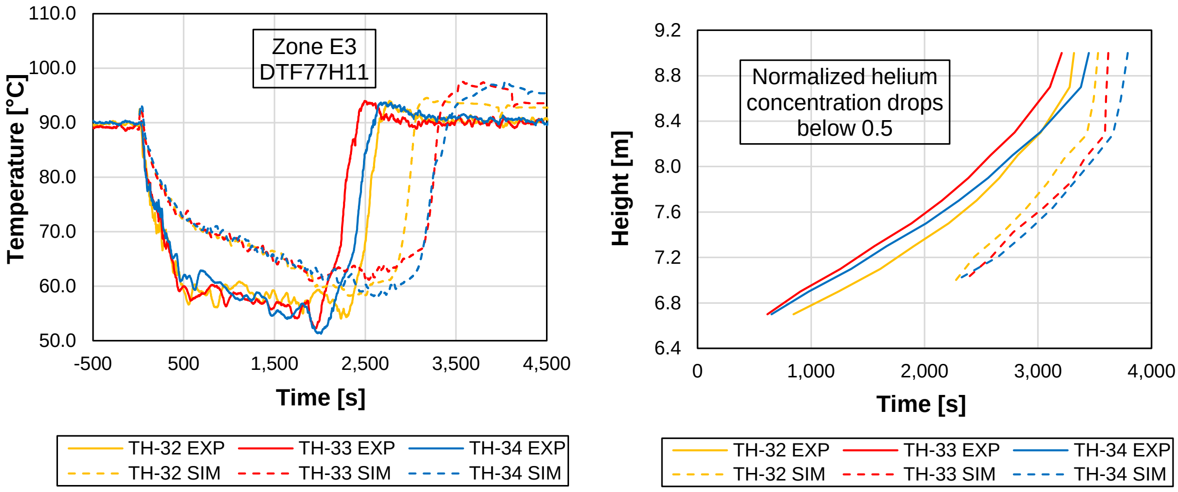

Figure 6: Temperature evolution at a height of 7.7 m (left) and upward move of helium cloud front (right)

The velocity of upward travel of the stratification edge is slightly lower in test TH-34 than in the tests TH-32 and 33 both in the experiment and the simulation. The velocity in the experiments TH-32 and 33 is very similar as in TH-34, but the onset of stratification dissolution is about 200 s later in test TH-32. The velocity in the simulations of tests TH-32 and 33 is also very similar but in case of the simulations the onset of stratification dissolution in case of TH-33 is about 100 s later than in test TH-32.

CONCLUSION

The stratification build-up is satisfactorily reproduced by the COCOSYS simulations of tests TH-32 to 34 but the helium concentration between a height of 4 m and the injection height is slightly overestimated at the end of the injection. The pressure evolution in the experiments is also reproduced adequately by the simulations. The complete dissolution of the helium stratification is delayed by 200 to 500 s depending on the test which can partly be traced to a noticeably higher temperature in the upper part of the vessel during a large part of the dissolution phase. The differences in the results of tests TH-32 to 34 lie within the relative experimental uncertainties [2]. The experimenters concluded, that a pronounced difference pointing to a different heat transfer mechanism due to the addition of CO_2 could not be identified [2]. The variations in the results of the simulations are of a similar magnitude than in the experiments which indicates, that COCOSYS does not predict a significant influence of CO_2 on overall heat transfer and thus on stratification dissolution which is in good accordance with the experiments. Further analysis is needed to confirm or reject the conclusions drawn from the shown simulations.

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