CFD Analysis for Natural Convection Induced by Steam Condensation in the THAI Facility

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1. Introduction

An active system like as spray water is not installed for cooling down the containment of a pressurized water reactor (PWR) in Germany. It is therefore that a natural convection developed in the steel containment may be an ultimate heat sink during a sever accident of the PWR. A series of tests were performed to investigate this design feature of the PWR in Germany. One of the tests was to investigate the dissolution of a steam-air stratification by natural convection in the THAI (Thermal hydraulics, Hydrogen, Aerosol, and Iodine) facility of 9.2 m height and 3.2 m diameter [1]. In addition, the test results are used as validation data for development of numerical models in the lumped parameter codes and the computational fluid dynamics (CFD) codes for simulating the multiphase flow field in the containment. In this study, STAR-CCM+ 9.04 was used to evaluate its models for simulating the dissolution of a steam-air stratification induced by the natural convection in the THAI facility.

2. Experimental Results [1,2]

2.1 Test Facility and Test Procedure

Main component of the facility is a cylindrical stainless steel vessel of 9.2 m height and 3.2 m diameter with a total volume of 60 m^3 (Fig. 1). The inner cylinder with 1.38 m diameter and 4.14 m height was installed at the lower region in the test facility. In order to set the predefined temperature boundary conditions, the middle and lower mantles were heated and the upper vessel mantle was cooled. The oil flow rates in the heating and cooling mantles were kept constant for the whole test duration. The upper and lower vessel heads were heated continuously during the test by use of the electrical heaters to avoid steam condensation on these surfaces. Condensation could occur only on the cooled part of the cylindrical vessel walls. To establish a light gas cloud in the upper vessel plenum, steam injection was carried out with a vertical injection nozzle of 138 mm diameter. The steam nozzle was installed at the location of H = 6.8 m, radius R = 1.14 m, and angle φ = 70°. A thermocouple (366 STFxx) was installed at the nozzle outlet to measure the injected steam temperature (Fig. 1).

The THAI vessel was equipped with total 51 thermocouples on vessel walls as well as in the gas space. For measuring the vertical atmospheric temperature gradient, a refined grid of thermocouples was arranged at the elevation where the transition between hot and cold vessel wall is located. Four fast thermocouples (repetition rate of 1 kHz) were installed in the upper plenum to capture thermal fluctuations arising due to the mixing of steam with the surrounding air. Additionally, 17 thermocouples were installed on the vessel wall to see the heat transfer through the wall. Flow velocities were measured by five vane wheels. The mass spectrometer for measuring the steam concentration took samples at 15 positions. The condensation running down the cooled vessel mantle was collected in the upper condensate gutter (H = 6.6 m). Subsequently the collected water is transferred outside the vessel by a drainage line and measured continuously.

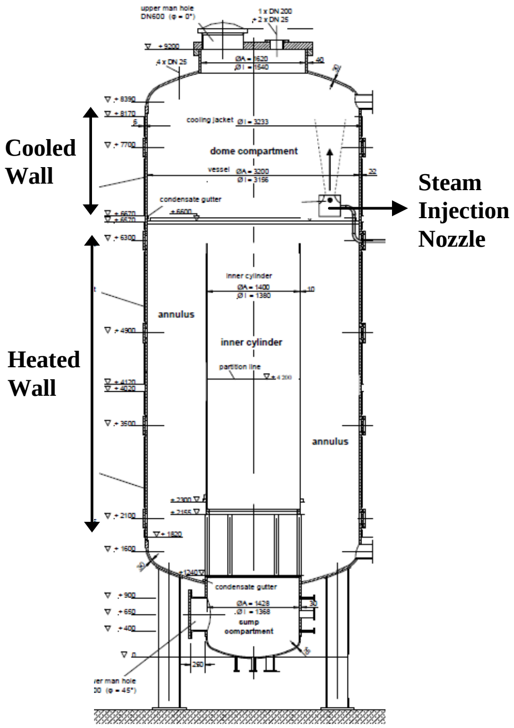


Figure 1. THAI Facility

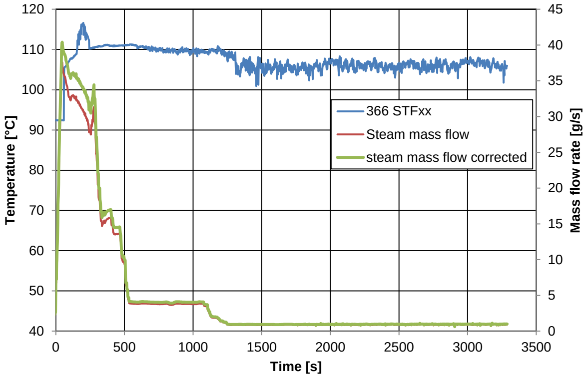


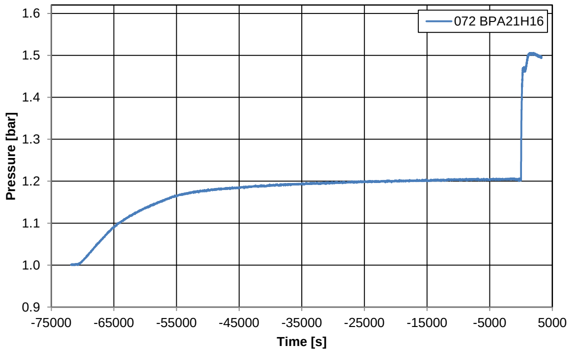
Figure 2. Injected Steam Mass Flow Rate and Temperature

The experimental procedure used in the test was as follows:

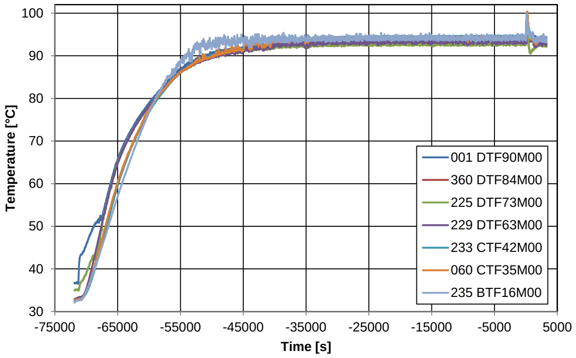
1. Closing the vessel under normal conditions (ambient pressure and temperature).
2. Heating the lower and middle vessel mantle and cooling the upper mantle.
3. When the temperature at the heated mantles has reached 100 ℃, the heating power is reduced and regulated to keep a level of 100 ℃, similarly the cooling mantle is regulated to reach a constant wall temperature of 60 ℃.
4. Start of the steam injection (at elevation 6.8 m, radius 1.14 m, angle φ = 70° by a nozzle of 138 mm diameter, vertically upward) at t= 0 s to build up a stable steam-air stratification in the upper plenum.
5. Observation of the stratification dissolution process.

2.2 Discussion on Test Results

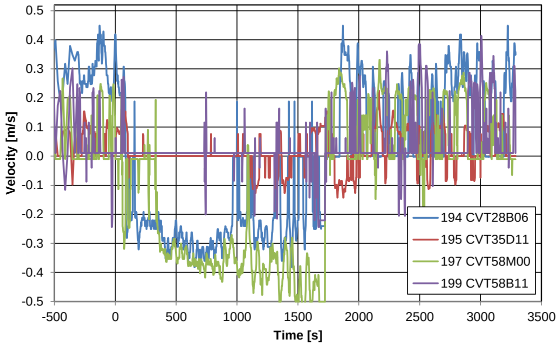
The experimental pressure transient is shown in Fig. 3 (a). During the heat-up phase the pressure rises in correspondence to the rising gas temperatures. At t = 0 s the steam injection starts which leads to a rapid increase of the vessel pressure up to 1.505 bar. A slow pressure decrease (0.7 Pa/s) towards the end of the measurement is caused by the activation of the steam concentration sensor systems or a slightly higher condensation rate compared to the continuous steam injection. The initial partial pressure of steam in the THAI vessel was found to be 0.105 bar, measured after the heat up phase but before the steam injection phase. The steam injection itself increases the partial pressure of steam from 0.105 bar to 0.402 bar which corresponds to a steam volume fraction of 8.7 % before the steam injection and 26.8 % at the stationary late phase of the experiment, after the steam stratification is completely dissolved.



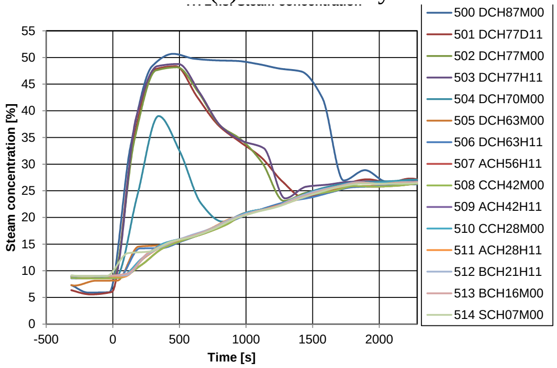
(a) Pressure



(b) Gas Temperature



(c) Gas Velocity



(d) Steam Concentration

Figure 3. Test Results

Gaseous temperatures are shown in Fig. 3 (b), ahead of the steam injection the spread of temperatures along the vessel axis is between 92.5 ℃ and 94.5 ℃. The hot steam injection leads to a rapid increase to a local maximum temperature of 100 ℃. After the dissolution of the steam stratification (t > 2000 s) the temperature distribution on the vessel axis balances again between 92.5 ℃ and 94.5 ℃. During the heating phase a natural circulation motions stabilizes which leads to an upward directed motion inside the inner cylinder, indicated by the signal at sensor positions 194 and 197, plotted in Fig. 3 (c). During the steam stratification and dissolution phase this atmospheric flow motion changes its flow direction, leading to a pronounced downward motion inside the inner cylinder. After the steam stratification is completely eroded the flow falls back to its initial state. The flow motion at sensor location 195 and 199 in the annulus is undetermined during the stationary phases and indicate temporary upward or downward motions. Nevertheless during the steam injection phase both sensors come to stagnation approximately until t = 1350 s (Fig. 3 (c)). Zero flow velocity data by vane wheels shown in Fig. 3 (c) cannot be taken literally, because the sensors cannot operate below absolute velocities of 0.1 m/s - 0.2 m/s.

The steam concentration measurements (Fig. 3 (d)) show that the lower cloud edge is between 6.3 m and 7.0 m, above the upper end of the inner cylinder (elevation 6.3 m). Compared to the helium stratification in TH22 [3] the steam cloud is smaller which can be explained by the smaller density gradient between the light gas and the vessel atmosphere and continuous condensation of the steam. The steam injection causes a variety of changes in the temperature distribution. The temperature of the injected steam (105 ℃ - 115 ℃) is higher than the air temperature in the vessel (93 ℃), so the temperature at the upper plenum increases. During the steam cloud formation and stabilization the temperature drops in the upper plenum by nearly 5 ℃ before it increases back to 93 ℃ along with the steam cloud erosion process (Fig. 4). The remaining convection flow from the temperature gradient and the vessel walls causes an erosion of the steam-rich cloud. As a consequence, the lower edge of the cloud moves upward until the cloud is fully dissolved and the entire vessel atmosphere is mixed again. Steam from the lower cloud edge is entrained into the convective flow of the lower atmospheric layer and homogeneously distributed in this layer. Such kind of cloud erosion has been investigated earlier in the THAI experiments TH22 [3,4] (helium stratification erosion by natural convection TH12 and TH13, cloud erosion by steam plume from below).

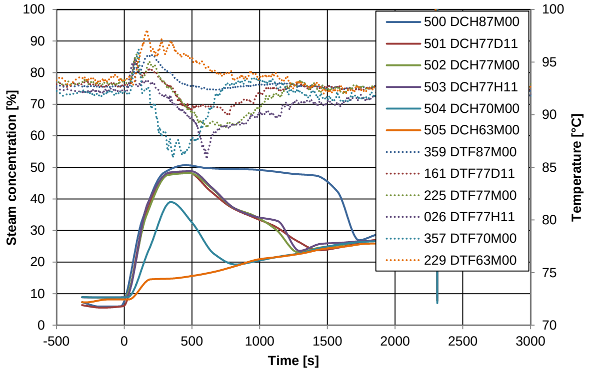


Figure 4. Steam Concentration and Temperature at the Upper Plenum

3. CFD Analysis

3.1 Grid Model and Flow Field Models

A 3-dimensional grid model (Fig. 5) representing the THAI facility was generated by the polygon and tetra cells with a cell length of about 1 - 10 mm. The generated cell number in the grid model was about 2,188,940. Very fine mesh distribution in the grid model was generated around the steam jet nozzle (region A in Fig. 5) and the upper plenum (region B in Fig. 5) to accurately simulate the steam jet behavior. The measured mass flow rate and temperature of the steam jet (Fig. 2) were given on the upper region the steam jet nozzle as the inlet boundary condition. The wall condition with constant temperatures of 60 ^{o}C and 100 ^{o}C was applied on the outer surface of the cooled wall and heated wall in the THAI vessel, respectively. Wall temperatures on other outer surfaces of the vessel walls and the inner cylinder were given according to the measure data.

The numerical models used for the natural convection induced by the steam condensation were the multi-component model, the multiphase interaction model, the fluid film model, and the buoyancy model implemented in the STAR-CCM+ 9.04 [5]. The fluid film model can simulate evaporation and condensation in a thin boundary layer by using a correlation method [5]. In addition, the conjugate heat transfer model was used to accurately predict the inner wall temperature affected by the heat transfer through the vessel wall. Turbulent flow was modeled using the realizable k-ε model and two-layer all y+ wall treatment. A transient calculation of about 1200 s with a time step of 1.0×10^{-6} s to 5.0×10^{-3} s was used to have the converged solution of the energy equation simulating the steam condensation.

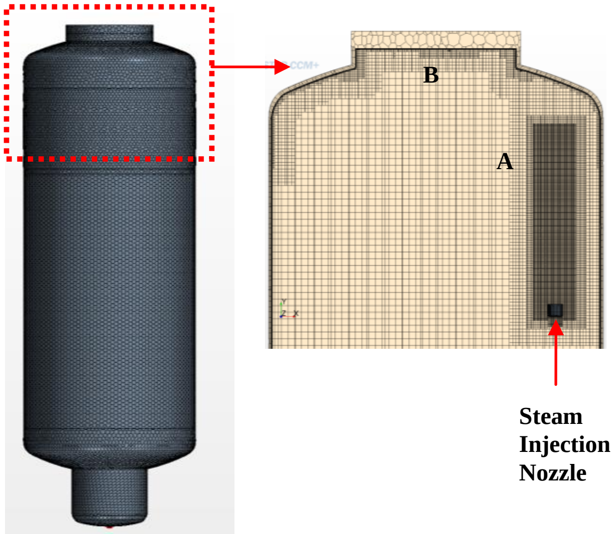


Figure 5. Grid Model

3.2 Discussion on the CFD Results

A comparison of the pressure behavior at the height of 2.1 m in the vessel between the test and CFD results (Fig. 6) showed that the CFD results accurately predicted a rapid increase to about 1.5 bar resulted from the steam injection in the test with an error range of about 10%. The calculated steam concentrations at the height 7.7 m (Fig. 7 (a)) showed a good agreement between the test results and CFD results for a formation of steam cloud and an erosion process due to a convection loop developed at the lower region with an error range of about 20%. In addition, the CFD results simulated a continuous increase of the steam concentration at the height 6.3 m with an error range of about 10% (Fig. 7 (b)). This increase may be explained by the fact that the steam located around the lower cloud edge in the upper region was entrained in the lower convection loop developed by an upward flow along the walls of the inner cylinder.

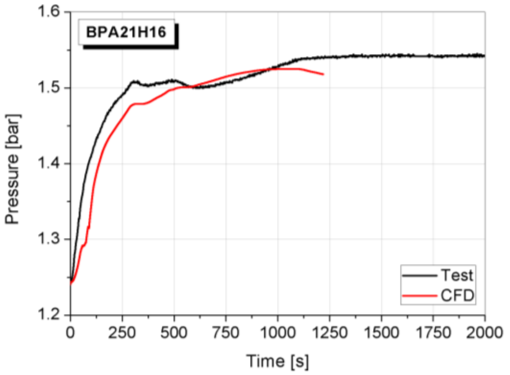
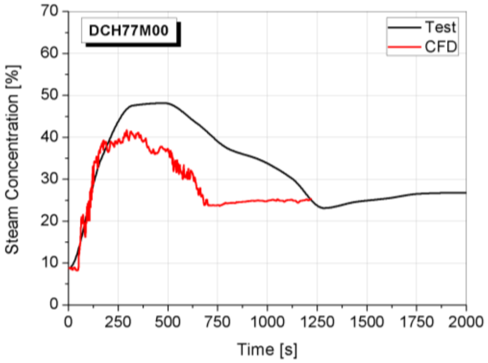
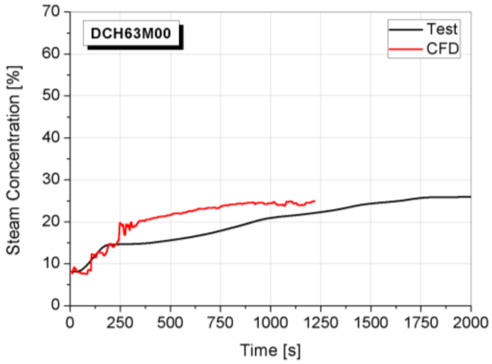


Figure 6. Comparison of Pressure between the CFD Results and Test Data



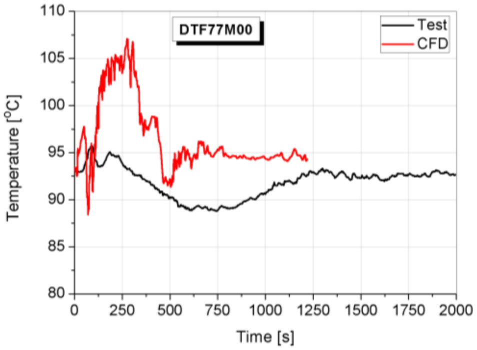
(a) H = 7.7 m



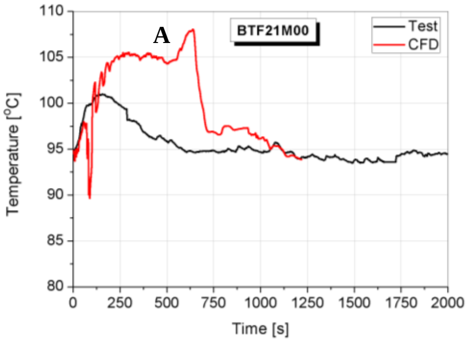
(b) H = 6.3 m

Figure 7. Comparison of Steam Concentration between the CFD Results and Test Data

The CFD results for the temperature behavior at 7.7 m showed a similar trend when compared to the test data (Fig. 8 (a)). However, the CFD results overestimated the temperature increase with an error range of about 10%. This may be explained by the fact that the injected steam arrived at the height 7.7 m with less heat loss while moving from the steam nozzle when compared to the test results. The calculated temperature in the lower plenum accurately predicted a trend of the temperature change shown in the test results (Fig. 8 (b)). However, the CFD results overestimated the maximum temperature with an error range of about 15%. In addition, the CFD results predicted the instant time to start the decrease 200 s later than the measured data (region A in Fig. 8 (b)). This discrepancy between the CFD results and test results may be resulted from that the strong natural convection induced by the heated walls and the blocked convective flow inside the upper inner cylinder [2]. The stronger convective flow in the simulation may be caused by the overestimated conjugate heat transfer from the outer wall to inner wall by the CFD analysis (Fig. 9). Thus, a detailed analysis on the conjugate heat transfer through the vessel walls should be performed to produce more accurate CFD results.

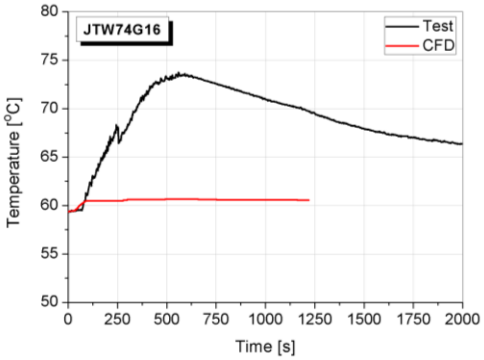


(a) H = 8.7 m

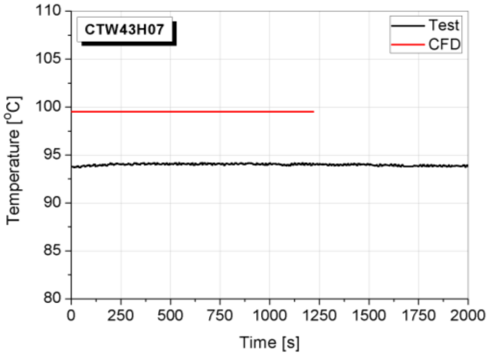


(b) H = 2.1 m

Figure 8. Comparison of Gas Temperature between the CFD Results and Test Data



(a) Vessel Wall Temp. at H = 7.4 m



(b) Inner Cylinder Wall Temp. at H = 4.3 m

Figure 9. Comparison of Wall Temperature between the CFD Results and Test Data

4. Conclusion and Further Research

Through the comparison of the simulated results with the test results performed in the THAI facility, we found that STAR-CCM+ 9.04 with the fluid film model simulating the steam condensation predicted the steam concentration, the gas temperature, and the vessel wall temperature with an error range of about ±20%. In order to decrease the discrepancy between the CFD and test results, a detailed analysis on the fluid film model and the conjugate heat transfer through the vessel wall should be performed. Furthermore, the total calculation time should be extended to about 2000 s for better comparison between the CFD results and test data.

ACKNOWLEDGEMENTS

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