THAI MULTI-COMPARTMENT CONTAINMENT EXPERIMENTS

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1. Introduction

To more precisely simulate the effects which may occur in an LWR containment in case of a severe accident conventional lumped-parameter codes are being continuously improved and advanced computational fluid dynamics (CFD) codes developed for containment applications. Both trends call for experimental validation. The THAI test programme (THAI = Thermal hydraulics, Hydrogen, Aerosols, Iodine) has been initiated to cover those validation requirements in the areas of containment thermal hydraulics, hydrogen distribution, combustion and mitigation, and behaviour of fission products, in particular of iodine and aerosols with respect to a possible source term. The work is being sponsored by the German Federal Ministry of Economics and Technology.

An overview on the THAI experiments performed up to now and on the future test programme will be presented, in combination with a selection of typical results to illustrate the multi-functionality of the THAI facility and the broad variety of the experimental programme.

2. Test facility

Figure 1 depicts the THAI facility including its auxiliary rooms provided for the application of radioactive I-123 tracer for iodine distribution measurements. Main component of the facility is a 60-m³ stainless steel vessel, 9.2 m high and 3.2 m in diameter, with exchangeable internals for multi-compartment investigations. The vessel is designed for a maximum overpressure of 1.4 MPa at 180 °C and can withstand moderate hydrogen deflagrations.

The standard configuration of the removable inner vessel structures and a typical arrangement of the instrumentation can be seen from Fig. 2. A large top flange and two man holes provide access to the interior of the vessel for modifications of internals and instrumentation. Measuring flanges on five levels at five circumferential positions allow installation of in-situ optical and conventional instrumentation, and of sampling lines.

The cylindrical part of the test vessel wall is equipped with three independent heating/cooling jackets over the height for controlled wall temperature conditioning by means of external thermal oil circuits. The heating/cooling power of each jacket is determined from measurements of oil mass flow and inlet/outlet
temperature difference. The sump water basin at the bottom of the THAI vessel has a diameter of 1.40 m and is equipped with a 20-kW electrical heating rod. The outer sides of the vessel including the heating/cooling jackets are thermally well isolated by rockwool. Operation of the three heating/cooling jackets and/or controlled injection of steam and gas allow arranging either a stratified atmosphere within the vessel volume or atmosphere mixing by natural convection. By natural convection flow velocities up to 0.2 m/s can be achieved along the outer vessel walls. Furthermore, an axial fan can be installed to reach higher flow velocities for special investigations.

Feed systems are available for injection of steam, air, gas (He or H₂), iodine and aerosols at variable positions. Elemental iodine (I₂), labeled with I-123 radiotracer, is produced within a small heated iodine reactor using a chemical reaction in solution (Dushman reaction: Iodide plus iodate yields elemental iodine) and transported by hot carrier gas into the test vessel. CsI aerosol is generated by vaporizing CsI salt in an induction oven and subsequent quenching by nitrogen gas. For hydrogen deflagration and mitigation tests spark igniters and a commercial Passive Auto-catalytic Recombiner (PAR) unit are available.

3. Instrumentation

Conventional thermal hydraulic instrumentation is provided for pressure, fluid and wall temperature, feed mass flow, wall heating/cooling power, water level and condensate mass measurements. It is supplemented by a 10-channel gas sampling system for continuous light-gas (H₂, He) concentration monitoring (measuring principle: heat conductivity), and by six sensors for dew-point temperature designed for humidity measurements under near-to-saturation conditions up to 140°C. Furthermore, a spectral photometer (FASP) is used for in-situ measurements of fog droplet size and airborne liquid water content. For flow field measurements THAI is equipped with vane wheel transducers, a 2-D Laser Doppler Anemometer, a Particle Image Velocimeter, and a Radio-Acoustic Sounding System which provides vertical flow velocity profiles over the vessel height at a variable radial position, see Fig. 2.

For iodine distribution measurements radioactive iodine I-123 is used as a tracer for inactive iodine, and liquid or gas samples are taken at numerous locations for immediate gamma-ray evaluation. To avoid errors by adsorption of gaseous iodine within the sampling lines several small gas scrubbers have been installed at the measuring points inside the test vessel. They are filled with an aqueous iodine absorber (0.5 % sodium thiosulfate solution) which retains the iodine from the gas sample sucked through the liquid. Filling, draining and purging of the scrubbers, and gas flow control are managed from outside. The iodine concentration in the vessel atmosphere is determined from the amount of I-123 tracer in the absorber liquid and from the gas flow through the scrubber. In addition, external Maypack filters are applied to discriminate molecular, organic and aerosol-borne iodine in the test vessel atmosphere [1].

Aerosol concentration and size distribution are measured by remote controlled filter samplers (each prepared for taking twelve filter samples) which are installed inside the test vessel to avoid sampling losses. Furthermore, low-pressure cascade impactors and an on-line quartz cascade impactor are applied. A condensation nuclei counter and a differential mobility analyzer are available for measuring extremely small particles.
Propagation of hydrogen flames is monitored by fast-response sheathed thermocouples of 0.25 mm outer diameter installed along the flame paths. Hydrogen recombination rate and efficiency of the PAR unit are determined from H$_2$ concentration and temperature measurements at the PAR inlet and outlet, and by inlet volume flow measurement using a vane wheel transducer.

4. Test program THAI-1

The highlights of the first THAI test program (2000 – 2003) are (i) thermal-hydraulic tests on development, stability and dissolution of stratified steam/air/light-gas atmospheres in a multi-compartment geometry, and (ii) iodine tests on the distribution of gaseous iodine within the test vessel atmosphere including iodine adsorption and desorption at the vessel walls. On some THAI-1 experiments and accompanying model calculations has been reported earlier, e.g. on test TH2 involving the gradual dissolution of an atmosphere stratification by moderate steam release near the vessel bottom [2 - 4], or on the outcome of a national benchmark exercise comparing blind pretest LP and CFD calculations with the results measured in THAI test TH7 [5]. Calculations for experiment TH10 involving steam-helium-air stratification and wall cooling are described in [6]. Iodine distribution tests have been performed with dry air, superheated steam-air, and condensing steam-air atmospheres [1], the data being used for code validation and improvement.

5. Test program THAI-2

The second THAI program (2003 – 2006) has wide-spread objectives: It includes thermal-hydraulic, iodine, aerosol and hydrogen related experiments. The data of thermal-hydraulic test TH13 on vessel atmosphere and condensate distribution resulting from helium and steam jet release periods have been used for the International Standard Problem ISP-47 Step 2, with 14 participating blind LP and CFD code predictions [7].

Figure 3 Predicted and measured helium distributions in ISP-47-THAI (t = 5600 s)

The ISP test started with a 2700-s period of helium jet release, followed by a steam jet release (t = 2700 – 4700 s) into the vessel dome (Fig. 3), resulting in a marked helium-steam-air stratification over the vessel height. Subsequently, during t = 4700 – 5700 s, steam was horizontally injected into the lower vessel area with the intention to break up the stratification and mix the vessel atmosphere. However, the mixing effect
ended at a level of about 1 m above the upper edge of the inner cylinder, and a stable helium-rich layer remained in the upper dome area until the test ended at $t = 7700$ s. Only 2 of 14 blind pre-test calculations succeeded to correctly predict the remaining He-rich layer (helium simulating the behavior of hydrogen), the others resulted in homogeneous mixing, see Fig. 3.

Other thermal-hydraulic tests have been devoted to the phenomenon of “wet” fission product resuspension from a boiling sump. During a severe accident sump water can boil in case of extreme heating, e.g. by core melt, or in case of rapid depressurization, e.g. due to containment venting. The steam bubbles bursting at the pool surface generate a large number of very small droplets containing fission products from the pool water, and contributing to a possible source term. In the THAI tests fission products have been simulated by CsCl and KI salts. The released droplets have been dried in the superheated vessel atmosphere, the residual salt particles being monitored by a Condensation Nuclei Counter to determine the number concentration, and by a Differential Mobility Analyzer to obtain the size distribution of the salt particles. Filter samples have been taken to determine the aerosol mass concentration. The tests yielded entrainment factors in the order of $5 \times 10^{-5}$, confirming former REST laboratory-scale test data [8]. However, as a result of the more sophisticated aerosol instrumentation applied in THAI, the size of the released droplets turned out to be significantly smaller, and the number of droplets to be higher by orders of magnitude compared to the data reported earlier. As a consequence, the respective input data for source term calculations should be reconsidered.

In the iodine area, several multi-compartment tests on iodine distribution and iodine transfer between gas and structure surfaces have been performed [1], [9]. Two more tests deal with the reaction of iodine and ozone, ozone simulating the effect of air radiolysis. Under reactor accident conditions the iodine-ozone reaction yields a long-term source for airborne radioactive IO$_x$ aerosols. Experiments on this item have been performed in the 60-m$^3$ THAI vessel in order to exclude possible scale deficiencies of laboratory tests. Fig. 4 depicts the IO$_x$ mass concentrations and the total iodine concentrations (I$_2$ + IO$_x$) measured in a THAI experiment. A remarkable result obtained in the THAI tests is the measured particle size distribution of the generated IO$_x$ aerosol showing a mass mean diameter in the order of 0.25µm. This is an unfavorable value for the design of the accident management measure filtered containment venting because filters normally show a minimum efficiency in this particle size range (“Greenfield gap”).

Concerning hydrogen, tests on “dry” resuspension of aerosol deposits by an H$_2$ deflagration, and tests on a possible interaction of CsI aerosols and catalytic H$_2$ recombiners are part of the THAI-2 program. A hydrogen deflagration has the potential to re-suspend previously deposited particles. In addition to existing laboratory scale tests some large-scale basic resuspension tests have been performed on this subject in the THAI vessel [10]. Significant portions of the deposited aerosol become re-suspended, and the resulting aerosol concentration is measured by filter sampling and by cascade impactors.

Figure 4  Iodine-ozone reaction leading to IOx aerosols

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6. Outlook on test program THAI-3

The third THAI program is scheduled to start in fall 2006 for a period of three years. A major part of the experiments is offered for international participation in the frame of an OECD project. THAI-3 will include the following issues and extend the investigated areas to the state depicted in Fig. 5.

(1) Slow hydrogen deflagrations near the ignition limits, i.e. at low H₂ concentrations. Hydrogen deflagrations cannot be completely ruled out by the use of PARs. But they can be limited to concentrations near the ignition limits. Therefore the proposed deflagration tests will focus on this concentration range. Size and shape of the THAI vessel allow deflagration investigations at a sufficiently large scale, i.e. with minor wall effects, and with vertical flame propagation whilst almost all existing test data refer to horizontal burns. Due to buoyancy effects upward deflagrations in the low-concentration range are significantly stronger than those in horizontal direction with the same gas composition. Test parameters to be varied are: Fluid and wall temperatures, hydrogen and steam concentrations, burn direction (up and down), as well as concentration and temperature gradients.

(2) Passive Autocatalytic Recombiner experiments. PARs are used in many pressurized water reactor containments for hydrogen mitigation. The THAI vessel is regarded as a suitable tool for investigations using a commercial PAR unit of technical size because its large vessel volume will not affect natural convection in the neighborhood during PAR operation. The proposed experiments will focus on three points of interest: (i) Onset of recombiner activity under adverse conditions, e.g. at high steam and low oxygen content or with spray droplets. (ii) PAR ignition potential. Ignition by a PAR has occurred in several experiments under higher hydrogen concentrations. Since PARs are used to recombine hydrogen without flame ignition such events appear to be undesired. Systematic data on the conditions for PAR ignition are not available in public literature. (iii) PAR efficiency under oxygen starvation conditions. Most PAR recombination rate tests have been done under lean hydrogen conditions with sufficient oxygen available. However, oxygen starvation will result in a reduction of recombiner efficiency and recombination rate already at slightly over-stoichiometric oxygen-hydrogen ratios.

(3) Experimental study on potential differences in atmospheric gas distribution by use of helium instead of hydrogen. Most hydrogen distribution experiments have been performed using helium as a substitution for hydrogen in order to avoid safety problems in the test facility. These helium test results have been applied to validate hydrogen distribution model calculations. However, helium and hydrogen differ in most of their material properties. Therefore it is proposed to demonstrate the transferability of He findings to H₂ problems by a pair of similar experiments: one with He, the other with H₂. The experimental procedure of the two tests shall be considered to be sensitive to gas distribution. A test procedure is proposed similar to that of the International Standard Problem ISP-47 Step 2 which finally (in its test phase 3, see Fig. 3) resulted in a stable He-rich gas layer. Some minor modifications in test duration and instrumentation shall be made for a better understanding of the detailed processes leading to the observed residual gas layer.

(4) Wash-down of fission products from wall surfaces by condensate. In the long-term phase of a severe accident the local distribution of the heat-producing fission products determines the thermodynamic conditions of the containment atmosphere. If the fission products are mainly airborne or located at dry surfaces a superheated atmosphere will result. If the fission products are, however, collected in the containment sump or in elevated flat water pools they will produce steam and a saturated atmosphere will
result. This can lead to different effects on containment pressure and source term due to the significantly different aerosol depletion behavior under wet and dry conditions. Therefore, wash-down processes which mainly determine fission product distribution are of particular interest. For the wash-down investigations two vertical coolers will be installed in the THAI vessel, one with a steel surface, the other with a painted surface. They will be subjected to different condensing atmospheres containing gaseous iodine, or soluble and insoluble aerosols. The condensate rates and the iodine and aerosol concentrations in the condensate will be determined as a function of the atmosphere conditions.

(5) Iodine-ozone reaction in the presence of a nuclear aerosol; impact of I$_2$-O$_3$ reaction on iodine volatility. The iodine-ozone tests in THAI-2 yielded a very fine IO$_x$ aerosol which remains airborne over a long period of time. An additional experiment is proposed to investigate whether the presence of a typical core-melt background aerosol could lead to a faster IO$_x$ aerosol depletion due to agglomeration effects.

(6) Iodine adsorption and desorption at steel and painted surfaces, and in case of intense convection. Previous THAI tests have been devoted to the exchange of iodine between atmosphere and structure surfaces by adsorption and desorption processes. In addition, possible effects of strong convective flows and of iodine reactions at surfaces on these processes will be studied.

(7) Basic experiments for stepwise validation of CFD field codes. To support the further qualification of CFD code application for containment problems a series of THAI tests is proposed for basic studies on adequate simulation of momentum exchange, mass transfer and heat transfer in reactor containments.

7. Conclusion

An overview has been given on the THAI containment test facility and its experimental programs which aim at providing experimental data for validation and further development of LP and CFD containment codes in the areas thermal hydraulics, hydrogen, aerosols and iodine. Examples of typical results have been presented to demonstrate the capabilities of the THAI facility and the broad variety of the experimental programs.

8. References