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SIMULATION OF INTERNATIONAL STANDARD PROBLEM NO.44 "KAEVER" EXPERIMENTS ON AEROSOL BEHAVIOR WITH THE CONTAIN CODE

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ABSTRACT

Experiments on aerosol behavior in a vapor-saturated atmosphere, which were performed in the KAEVER experimental facility and proposed for the OECD International Standard Problem No. 44, were simulated with the CONTAIN thermal-hydraulic computer code. The purpose of the work was to assess the capability of the CONTAIN code to model aerosol condensation and deposition in a containment of a light-water-reactor nuclear power plant at severe accident conditions. Results of dry and wet aerosol concentrations are presented and analyzed.

1. INTRODUCTION

During an unmitigated severe light-water-reactor accident with core meltdown, radioactive fission and activation products would be released into the containment as gas, vapor or, to a great extent, adsorbed on aerosols. Since the time-dependence and distribution of fission products and aerosols are very important to mitigate the accident, a detailed knowledge of fission products and aerosol behavior and a relevant analytical prediction capability are of great importance.

The OECD-CSNI (Committee on the Safety of Nuclear Installation) International Standard Problem No. 44 (ISP-44) addressed the issue of modeling and simulation of the behavior (volume condensation and deposition) of aerosols in a containment atmosphere with well-defined thermal-hydraulic boundary conditions ([1], [2]). The specific purpose of the ISP-44 was to investigate the capability of current computer codes to model and calculate with sufficient accuracy aerosol distribution and settlement in a nuclear power plant containment at accident conditions, when the atmosphere is saturated with coolant vapor.

Experiments, which were proposed for the ISP-44, were performed in the KAEVER test facility at Battelle GmbH in Eschborn (Germany). The "Jozef Stefan" Institute Reactor Engineering Division (JSI RED) participated in the ISP with the thermal-hydraulic computer code CONTAIN 2.0 [3].

The following KAEVER tests were considered for the ISP-44:

– K188: test with CsOH aerosol (soluble),
– K123: test with CsI aerosol (soluble),
– K148: test with Ag aerosol (non-soluble),
– K186: test with mixed aerosol of Ag and CsOH,
– K187: test with mixed aerosol of Ag, CsOH and CsI.

For "open" tests K188, K186, K123 and K148, time-dependent experimental results were provided to the participants whereas for "blind" test K187, only a single experimental value for each considered variable was initially provided.

Physical variables which describe thermal-hydraulic conditions as well as aerosol behavior inside the test vessel were investigated. In the present work, time-dependent concentrations of dry and wet aerosols, obtained from simulations performed at the JSI RED with the CONTAIN code, are presented.

2. EXPERIMENT

2.1 Experimental Facility

The KAEVER test facility is a horizontal cylindrical steel vessel with plane faces, where short rectangular doorways are attached on both sides (Fig. 1). The vessel has an inner free volume of 10.595 m^3. Some walls of the test vessel are equipped with heater mats between the insulation and the inside steel. During condensation of steam, the condensate accumulates on the bottom of the cylindrical part, but the sump level of the cylindrical part does not reach the elevated floors of the doorways. A detailed description of the facility and experimental procedures is provided in the ISP-44 specification [1].

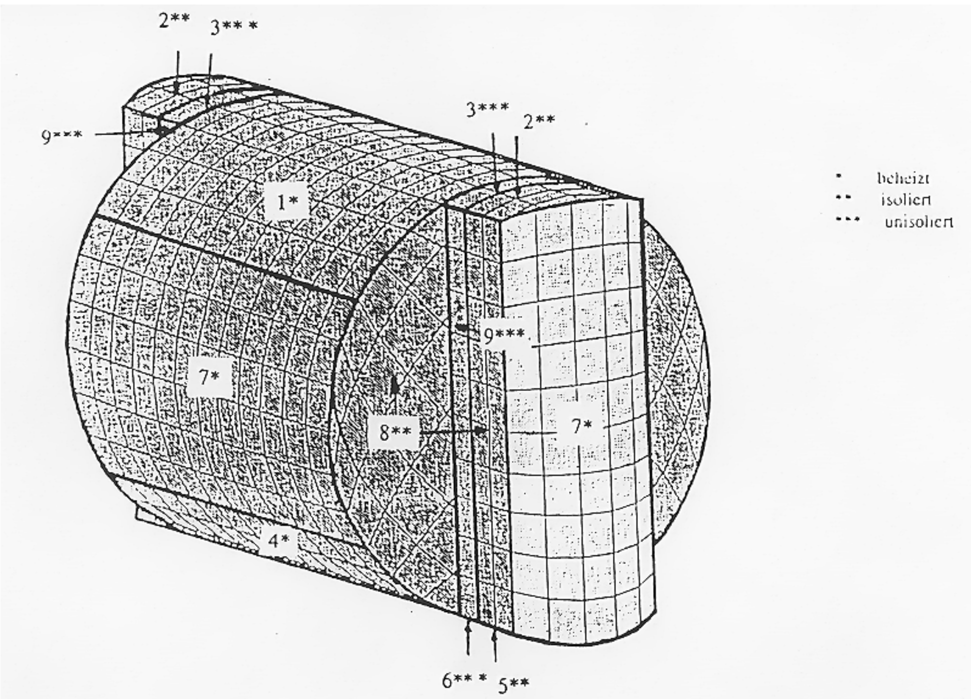

Figure 1. Perspective view of test vessel KAEVER (from [1])
(*: heated wall with external insulation, **: wall with external insulation, ***: wall without external insulation)

2.2 Description of Experiments

The thermal-hydraulic behavior of the test vessel was determined by the operation of the electric heater elements, the injections, the heat losses and the leakage. Injections of steam and nitrogen were provided. The aim was to obtain slightly "supersaturated" atmosphere conditions (relative humidities of 100% and weak fog formation).

The atmosphere inside the vessel was well mixed. The thermal gradients introduced by the non-insulated wall parts lead to a natural convection loop, which mixed the vessel atmosphere within several minutes.

Aerosol generation and injection were established by inductive heating of crucibles with evaporating materials and a nitrogen carrier gas flow to transport the condensation aerosols into the test vessel.

Each test consisted of two phases:

I Preconditioning phase, which lasted about 10 hours, during which quasi-stationary conditions in the test vessel were obtained.

II Execution of experiment, during which aerosols were injected and their behavior observed.

3. INPUT MODEL

3.1 Test Vessel

At the JSI RED, the lumped-parameter code CONTAIN 2.0 was used to simulate the tests. The KAEVER vessel was modeled as a single CONTAIN "cell", whereas the environment was modeled as another cell.

If the test vessel was not heated (test K148), walls equipped with heater mats were modeled as single structures consisting of layers of outside steel plating, insulation and inside steel.

If the test vessel was heated (tests K123, K188, K186 and K187), walls equipped with heater mats were modeled as two separate heat structures (insulation with outside steel plating and inside steel), separated by a "fictive" intermediate cell, and a heat flux was applied to the surfaces exposed to the intermediate cell. The heat flux specified in the input data was thus partitioned into a fraction applied to the insulation and a fraction applied to the inside steel.

If the test vessel was heated only during part of the preconditioning phase (tests K188, K186 and K187), the simulation was carried out in two parts with two distinct inputs. During the first part, heated walls were modeled as separate structures, as described above. The first part of the simulation ended when the heat flux was stopped. The simulation was then continued with a second input model, in which walls equipped with heater mats were modeled as single structures and where conditions calculated at the end of the first part were taken as initial conditions.

3.2 Aerosol Modeling

The following aerosol parameters were provided in [2]: volume median particle diameter, number median particle diameter, particle size distribution, geometric standard deviation of size distribution, dry density, molecular weight, surface tension, solubility, dynamic shape factor and agglomeration shape factor.

The CONTAIN code includes models for aerosol condensation, agglomeration, deposition and transport. Two condensation models are available: the fixed-grid and the moving-grid models. The moving grid model must be invoked to treat solubility and Kelvin effects in the condensation modeling. Four agglomeration processes are treated: particle Brownian diffusion, differential gravitational settling, turbulent shear, and turbulent acceleration in eddies. Also, four deposition processes are treated: gravitational settling, diffusiophoresis, thermophoresis, and particle diffusion.

In the simulations, the aerosol size range was divided into 20 sections with the particle diameter ranging from $1.0 \cdot 10^{-7}$ m to $1.0 \cdot 10^{-4}$ m.

As recommended in [2], surface tension was not considered for tests K123 and K188 (so that the Kelvin effect was not modeled) whereas for test K148, surface tension was included in the input model.

For test K148, the calculation stopped due to convergence problems in aerosol calculations unless option DROPOUT was used. This option causes liquid water in the atmosphere, which may be present if steam is saturated, to be dropped instantly on the cell floor and assume the resulting temperature of the liquid pool. For consistency, option DROPOUT was prescribed in all simulations.

In tests K186 and K187, mixtures of aerosols were present. According to [2], surface tension should be taken into account only for Ag aerosols, whereas solubility had to be included only for CsOH and CsI aerosols. However, CONTAIN does not allow separate considerations of surface tension for separate components. Besides, the calculation stopped due to convergence problems in aerosol calculations if the surface tension was prescribed. Therefore, the simulation of these tests was carried out without taking surface tension into account, thus neglecting the Kelvin effect. Average densities, based on total respective masses of injected aerosol components, were prescribed for aerosol mixtures.

3.3 Initial and Boundary Conditions

Initial and boundary conditions (initial pressure in the test vessel, initial temperature of the atmosphere and heat structures, environment temperature, heat injection, gas injection and removal, liquid removal, aerosol injection) were included in the CONTAIN input model as specified in [2]. However, the steam injection and gas removal rates during the preconditioning phases of tests K186, K187 and K148, as well as the nitrogen injection rate during the preconditioning phase of test K148 were somewhat modified to obtain a closer agreement between measured and calculated thermal-hydraulic conditions at $t = 0$ s (beginning of phase II).

4. RESULTS AND DISCUSSION

The following phenomena and physical variables were investigated in the frame of the ISP-44:

- pressure in the test vessel,
- temperature in the test vessel atmosphere and vessel sump area,
- wall temperatures at inner and outer test vessel wall (insulated) and inner and outer doorway wall (not insulated),
- relative humidity in the test vessel atmosphere,
- dry aerosol concentration in the atmosphere, total and for each component,
- volume median diameter of dry aerosols,
- wet aerosol volume concentration,
- wet aerosol median diameter,
- volume condensation rate,

– particle size distribution.

The discussion in the present work is limited to the concentration of dry and wet aerosols in the test vessel. All the simulation results are presented in [4] and [5].

Figures 2 to 11 show the mass concentration of dry aerosols as well as volumetric (test K188) and mass (tests K186, K187, K123 and K188) concentrations of wet aerosols. Figures 5, 6, 7, 9 and 11 were provided by GRS Köln.

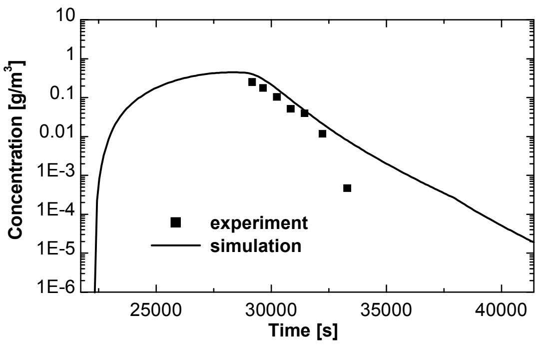

Figure 2. Total dry aerosol mass concentration in test vessel (test K188)

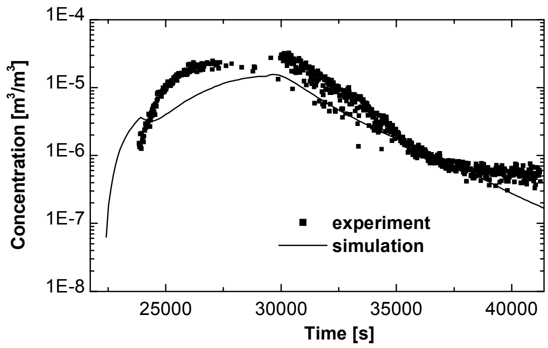

Figure 3. Total wet aerosol volumetric concentration in test vessel (test K188)

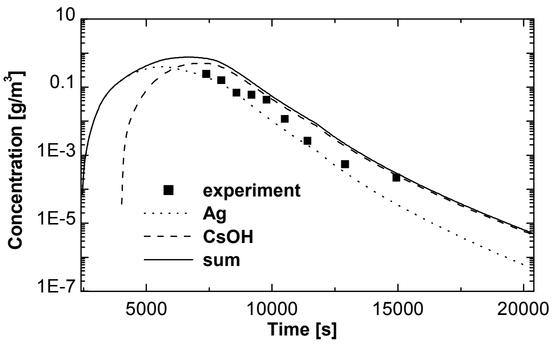

Figure 4. Total dry aerosol mass concentration in test vessel (test K186)

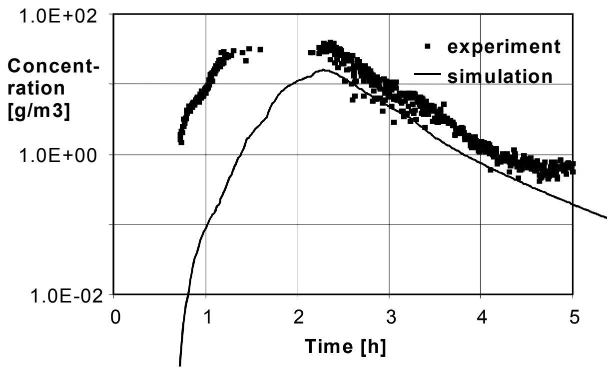

Figure 5. Total wet aerosol mass concentration in test vessel (test K186)

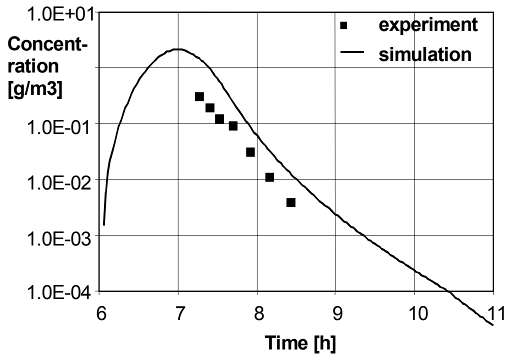

Figure 6. Total dry aerosol mass concentration in test vessel (test K187)

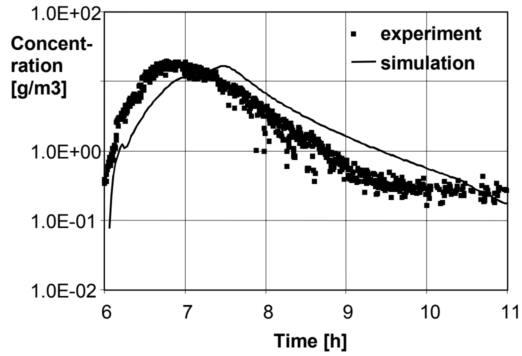

Figure 7. Total wet aerosol mass concentration in test vessel (test K187)

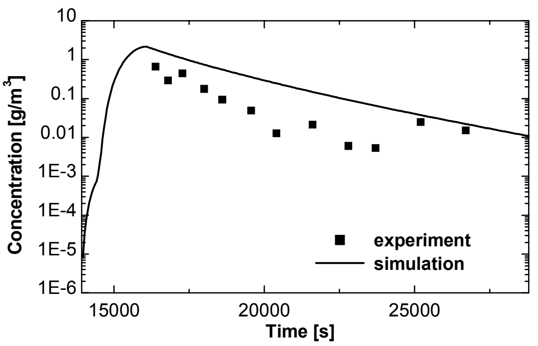

Figure 8. Total dry aerosol mass concentration in test vessel (test K123)

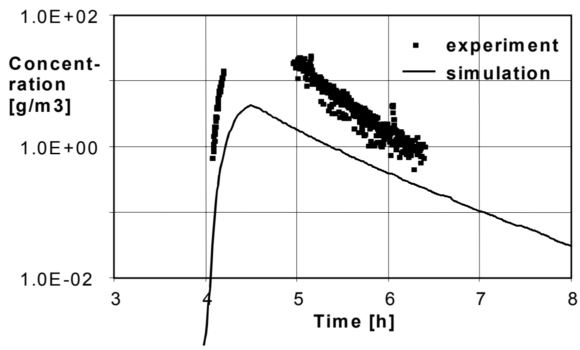

Figure 9. Total wet aerosol mass concentration in test vessel (test K123)

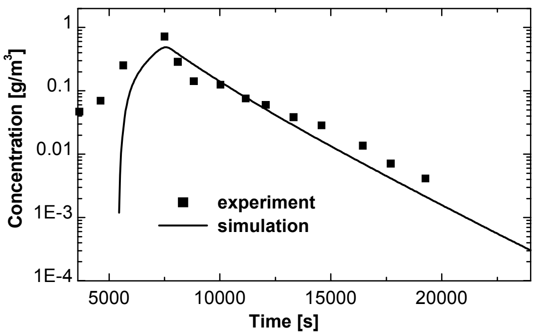

Figure 10. Total dry aerosol mass concentration in test vessel (test K148)

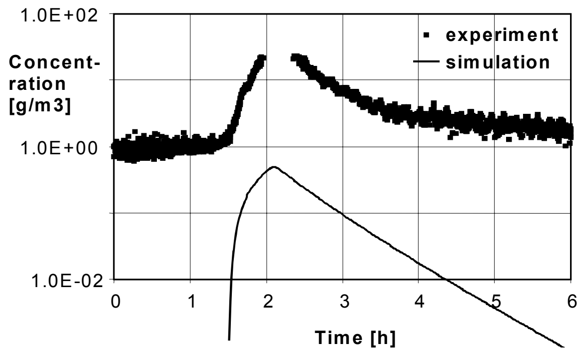

Figure 11. Total wet aerosol mass concentration in test vessel (test K148)

In general, the calculated time-dependent concentrations of dry aerosols agree well with measurements. Although some discrepancies may be noted, it seems that the CONTAIN code adequately reproduces the concentration of dry aerosols in a saturated atmosphere.

The agreement between measured and calculated concentrations of wet aerosols is good for tests K188, K186 and K187 (except for the aerosol injection phase during test K186, Fig. 5). Apparently, the non-inclusion of the Kelvin effect for aerosol mixtures did not have a significant influence.

The discrepancy between measured and calculated concentrations of wet aerosol in test K123 is mostly due to the inadequate modeling of thermal-hydraulic conditions inside the test vessel. Namely, the partitioning of the heat flux, described in section 3.1, was prescribed so that a good agreement between measured and calculated conditions was obtained for test K188. During this test, the vessel was heated only during part of the preconditioning phase. For consistency, the same partitioning was used for other tests. As shown in [4] and [5], this partitioning proved to be adequate for tests K186 and K187, during which the vessel was also heated during part of the preconditioning phase. However, the use of the same partitioning for test K123, during which the vessel was heated during the entire test, resulted in an inadequate prediction of thermal-hydraulic conditions [4], which apparently influenced the condensation rate on aerosols.

The discrepancy between measured and calculated concentrations of wet aerosols during test K148 shows that in this case, condensation on aerosols was significantly underpredicted as the consequence of the option DROPUT in the input model. Namely, this option caused the vapor to become non-saturated shortly after the start of vapor condensation on aerosols, as there was no more liquid water at saturation temperature present in the atmosphere. The atmosphere would periodically become saturated again during short intervals due to additional injection of steam. Apparently, this did not influence much the concentration of wet aerosols in the simulations of other tests, which were performed with at least one soluble aerosol component. However, as the aerosol used in the test K148 was non-soluble, the simulation of condensation in a non-saturated atmosphere was significantly affected.

5. CONCLUSIONS

Within the OECD-CSNI International Standard Problem No.44 "KAEVER", simulations of tests K188, K186, K187, K123 and K148 were carried out with the CONTAIN computer code. All the tests were performed in a saturated atmosphere. A single-cell input model of the test vessel was developed.

Most of the initial and boundary conditions were modeled as specified in the ISP-44 specification. Due to limitations of the CONTAIN code, the Kelvin effect could not be modeled for aerosol mixtures.

In general, a good agreement between calculated and measured time-dependent dry aerosol concentrations was obtained for all tests. For the calculated aerosol wet concentrations, a relatively good agreement was obtained for tests K188, K186 and K187. The discrepancies in the remaining tests are mostly due to inadequate modeling of thermal-hydraulic conditions in the test vessel.

The results show that the CONTAIN code may provide a reasonably good prediction of aerosol condensation and deposition in a saturated atmosphere, if the thermal-hydraulic conditions are well simulated.

ACKNOWLEDGMENTS

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