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Simulation of KAEVER Experiments on Aerosol Behavior in a Nuclear Power Plant Containment at Accident Conditions with the ASTEC Code

Ivo Kljenak, Borut Mavko
"Jožef Stefan" Institute
Jamova 39, Ljubljana, Slovenia
Ivo.Kljenak@ijs.si, Borut.Mavko@ijs.si

ABSTRACT

Experiments on aerosol behaviour in saturated and non-saturated atmosphere, which were performed in the KAEVER experimental facility, were simulated with the severe accident computer code ASTEC CPA V1.2. The specific purpose of the work was to assess the capability of the code to model aerosol condensation and deposition in the containment of a light-water-reactor nuclear power plant at severe accident conditions, if the atmosphere saturation conditions are simulated adequately. Five different tests were first simulated with boundary conditions, obtained from the experiments. In all five tests, a non-saturated atmosphere was simulated, although, in four tests, the atmosphere was allegedly saturated. The simulations were repeated with modified boundary conditions, to obtain a saturated atmosphere in all tests. Results of dry and wet aerosol concentrations in the test vessel atmosphere for both sets of simulations are compared to experimental results.

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, vapour or, to a great extent, adsorbed on aerosols. Since the knowledge of time-dependent distributions of fission products and aerosols is very important to mitigate accidents, relevant prediction capabilities are of great importance. Experiments with aerosols are thus being used to assess the capabilities of severe accident codes to simulate aerosol behaviour. In the present work, experiments that have been performed in the KAEVER experimental facility, which was located at Battelle GmbH in Eschborn (Germany), are considered. The tests have already been simulated within the OECD International Standard Problem No. 44 (ISP-44) [1,2], which addressed the issue of modelling and simulation of the behaviour (volume condensation and deposition) of aerosols in a containment atmosphere with well-defined thermal-hydraulic boundary conditions. The Jozef Stefan Institute participated in the ISP-44 with the severe accident code CONTAIN [3-5].

The severe accident code ASTEC is being developed jointly by the Institut de Radioprotection et de Sureté Nucléaire (France) and by the Gesellschaft für Anlagen und Reaktorsicherheit (Germany) [6-8]. The ASTEC code consists of several modules, which have been developed for modelling specific systems and phenomena in a nuclear power plant. The purpose of the ASTEC CPA (Containment Part of ASTEC) module is the simulation of containment thermal-hydraulics as well as aerosol and fission product behaviour in the containment during a severe accident. The assessment of physical models, implemented in the ASTEC code, is being carried out within the Severe Accident Research Network of Excellence (SARNET), which is part of the 6th EU Framework Programme.

To assess the capability of the ASTEC CPA V1.2 code to model aerosol behaviour, the following tests performed in the KAEVER facility were simulated [9]:

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

The tests were first simulated with the boundary conditions, specified in the experiment descriptions in the ISP-44 specification. A satisfactory agreement of calculated time-dependent aerosol dry concentrations in the vessel atmosphere with measured values was obtained in general, whereas significant differences between measured and calculated aerosol wet concentrations were observed. Although a good agreement was obtained between experimental and simulated pressure and atmosphere temperature in the vessel, the saturation of the atmosphere was not simulated adequately during four of the tests, when the atmosphere was allegedly saturated. Thus, the discrepancy between measured and calculated wet aerosol concentration could be due also to the inadequate simulation of the saturation conditions and not necessarily only to deficiencies in the modelling of aerosol behaviour. Thus, the tests were simulated again, with the boundary conditions modified in such a way to obtain a saturated atmosphere. Simulation results are presented and analysed.

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 (Figure 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].

2.2 Experimental Procedure

The thermal-hydraulic behaviour 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 (used as carrier gas for aerosols) were provided. The aim was to obtain slightly "supersaturated" atmosphere conditions (relative humidities of 100% and weak fog formation).

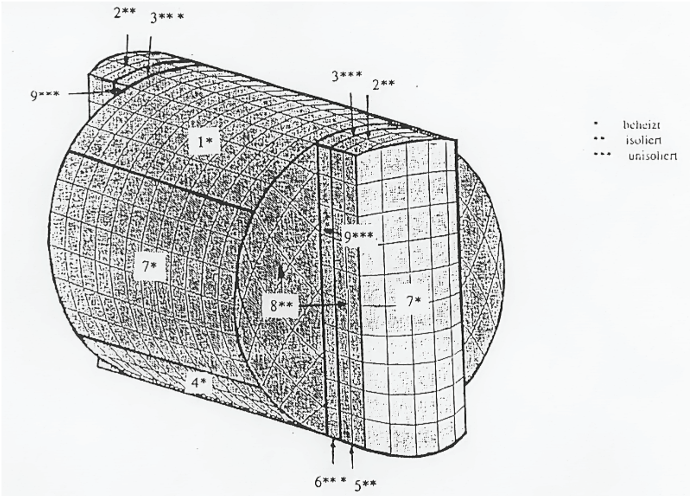

Figure 1: Perspective view of test vessel KAEVER [1]
(*: heated wall with external insulation, **: wall with
external insulation, ***: wall without external insulation)

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,
— II: execution of experiment.

During the preconditioning phase, quasi-stationary conditions in the test vessel were obtained. The vessel was flushed with steam and electric heating was applied to reach elevated wall temperatures. This phase lasted about 10 hours.

During the execution of experiments, thermal-hydraulic conditions in the vessel were first slightly readjusted by controlled steam injection and electric heating, in order to reach a quasi-stationary state that may differ from the final state of phase I. Then, aerosols were injected by turning on inductive heating of aerosol generators until the material in the crucibles was completely evaporated. Finally, the depletion of aerosols was observed without further change in the injection or boundary conditions.

The times of start and end of aerosol injection phases are shown in Table 1. The time t=0 s corresponds to the start of phase II.

Table 1. Timing of experiments

Test	**Start of aerosol injection [s]**	**End of aerosol injection [s]**	**End of test [s]**
K123	13920	16040	28800
K148	3600	7800	24000
K188	22300	29400	41400
K186	2400	7800	20400
K187	21700	25900	39600

3 INPUT MODEL

3.1 Test Vessel

The vessel was modelled as a single ASTEC CPA control volume ("zone"). The various fittings were simulated as an additional wall of 8.0 m^2, as in previous simulations with the CONTAIN code [3-5]. The heater mats between the insulation and the inside steel were modelled explicitly within the walls. The leaking flow junction was modelled with the value of the flow resistance coefficient set to 1.35 (based on [1]). The gas removal during the pre-conditioning phase was also taken into account. As ASTEC CPA allows only the prescription of volumetric flow rate for atmosphere removal (and not of mass flow rate, which was provided in the experiment descriptions), the volumetric flow rate was adjusted to obtain a good agreement between measured and calculated pressure at the start of phase II.

3.2 Aerosol Modelling

Aerosol parameters were prescribed in the input models as close as possible to the ISP-44 specification [1]. For tests K123 and K188, the ISP-44 specification suggests, that the Kelvin effect is not modelled. This was implemented in the ASTEC input models.

For test K148, the ISP-44 specification suggests, that the Kelvin effect be modelled. However, when this was implemented in the input model, the calculation stopped before reaching the end, after about 8000 s. Thus, the test was simulated without the modelling of the Kelvin effect.

For tests K186 and K187, the Kelvin effect ought to be considered for non-soluble aerosol components and not for soluble components. As ASTEC CPA does not allow the separate modelling for separate components, the Kelvin effect was not included in the input model.

The aerosol size range (diameters from $5 \cdot 10^{-8}$ m to $1 \cdot 10^{-4}$ m) was divided into 20 sections. Log-normal size distributions were prescribed.

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 flux, gas injection and removal, liquid removal, aerosol injection) were included in the ASTEC input model as specified in ref. [1]. However, as in previous simulations with the CONTAIN code, the steam injection and gas removal rates during the preconditioning phases of tests K186 and K187 were somewhat modified to obtain a closer agreement between measured and calculated thermal-hydraulic conditions at the start of phase II.

The simulations started at time -36000 s, to simulate the 10-hours preconditioning phase, and lasted until the time, indicated in Table 1 (the time t=0 s corresponds to the start of phase II).

Two sets of simulations were performed. In the first set, apart from the above modifications, the boundary conditions obtained from the experiment descriptions were prescribed. Although a satisfactory agreement was obtained between experimental and simulated pressure and atmosphere temperature in the vessel, the saturation of the atmosphere was not simulated adequately during four of the tests, when the atmosphere was allegedly saturated: K148, K188, K186 and K187. The tests were then simulated again, with the boundary conditions modified in such a way to obtain a saturated atmosphere, without an unreasonable difference between experimental and simulated thermal-hydraulic conditions. The following boundary conditions were slightly modified:

— mass flow rate and specific enthalpy of the injected steam,
— heat flux applied to the heater mats in the vessel walls,
— temperature of the carrier gas.

For tests K148, K188, K186 and K187, the calculated results of dry and wet aerosol concentration with a saturated simulated atmosphere are considered as relevant for the assessment of the capability of the ASTEC CPA V1.2 code to model aerosol behaviour in an NPP containment at accident conditions. For test K123, results obtained with a non–saturated simulated atmosphere are considered as relevant, whereas results obtained with a saturated atmosphere are an interesting parametric study.

4 RESULTS AND DISCUSSION

Figures 2-11 show the measured and simulated pressure and atmosphere temperature for the five considered tests. In these as well as in other figures, "default" denotes the results, obtained with the boundary conditions specified in the experiment descriptions [1], whereas "saturated" denotes the results, obtained with modified boundary conditions so that a saturated atmosphere was simulated.

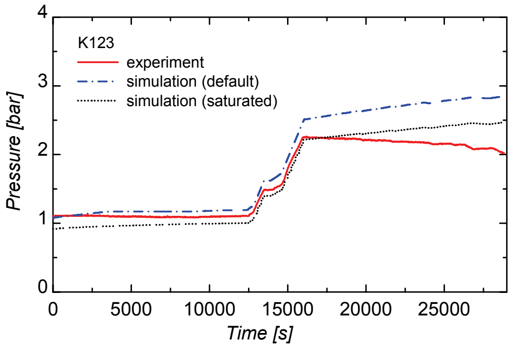

Figure 2: Test K123 - Pressure in test vessel

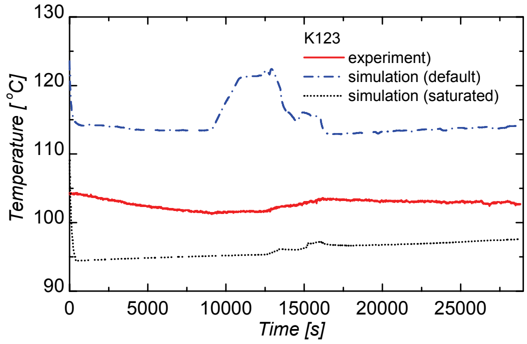

Figure 3: Test K123 – Temperature of test vessel atmosphere

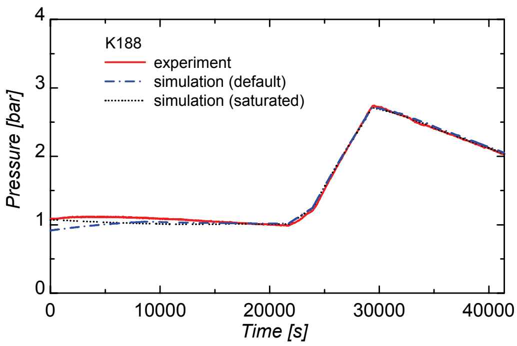

Figure 4: Test K188 - Pressure in test vessel

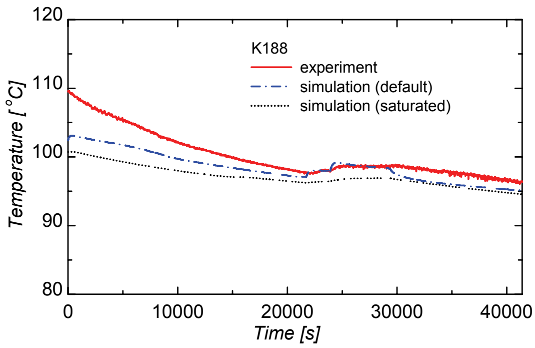

Figure 5: Test K188 - Temperature of test vessel atmosphere

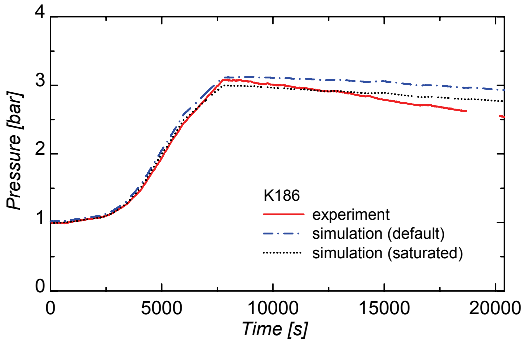

Figure 6: Test K186 - Pressure in test vessel

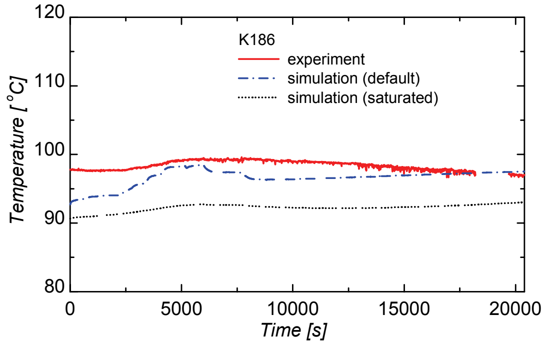

Figure 7: Test K186 - Temperature of test vessel atmosphere

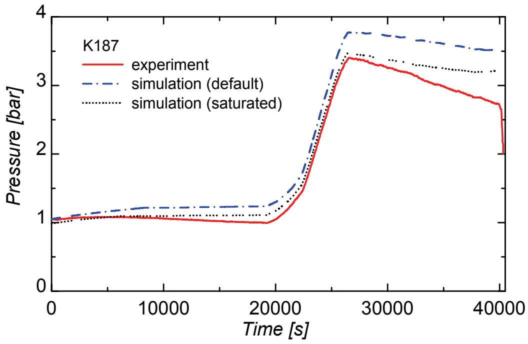

Figure 8: Test K187 - Pressure in test vessel

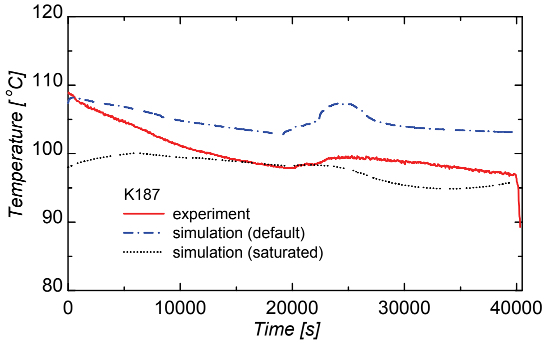

Figure 9: Test K187 - Temperature of test vessel atmosphere

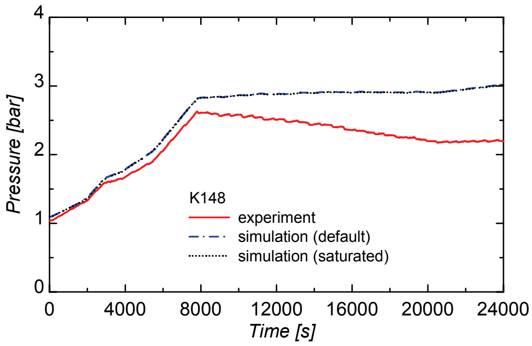

Figure 10: Test K148 - Pressure in test vessel

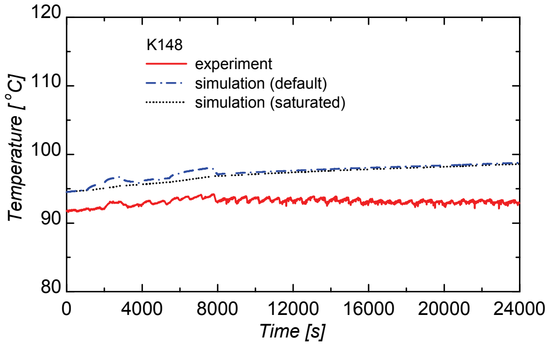

Figure 11: Test K148 – Temperature of test vessel atmosphere

Figures 12-21 show the simulated dry and wet aerosol concentrations in the vessel atmosphere, together with experimental results. The results obtained when the atmosphere saturation was not simulated adequately (that is, saturated atmosphere for test K123, and non-saturated atmosphere for tests K188, K186, K187 and K148) are shown only to illustrate the influence of the saturation on simulated aerosol behaviour and will not be commented.

The simulated maximum dry aerosol concentration during test K123 (Figure 12, "default") agrees very well with the measured value. After the maximum is reached, the simulated decrease of the concentration also agrees quite well with the experiment. The pattern of the simulated wet aerosol concentration (Figure 13, "default") agrees very well with the pattern of the measured concentration. However, the shift between the experimental and simulated results shows a serious deficiency in the modelling of aerosol behaviour.

For tests K188, K186 and K187, the maximum dry aerosol concentration is well predicted (Figures 14, 16 and 18, "saturated"). However, the simulated dry aerosol concentration drops too fast, except for test K188. As for the wet aerosol concentrations (Figures 15, 17 and 19, "saturated"), the timings of the increase of the concentration and the maximum values are well predicted in general, although it should be noted that the simulated rate of concentration increase in test K188 is too high. However, the simulated depletion rates are much too slow, which indicates a deficiency in the modelling of aerosol deposition.

For test K148, the maximum value of the dry aerosol concentration also agrees very well with the measured value (Figure 20, "saturated"), but then drops too fast. The timing of the increase of the wet aerosol concentration (Figure 21, "saturated") is well predicted (experimental points in the period prior to the start of aerosol injection are probably due to some homogenous condensation in the vessel atmosphere). The maximum value is not as well predicted as for dry aerosol concentration. Also, the simulated concentration does not drop much after the maximum is reached.

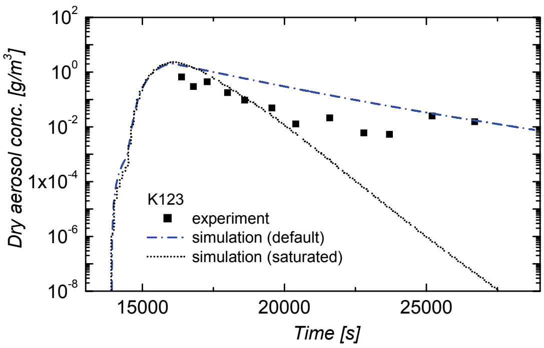

Figure 12: Test K123 - Total dry aerosol mass concentration in test vessel

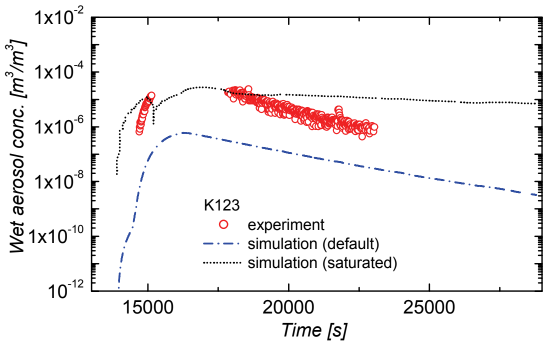

Figure 13: Test K123 - Total wet aerosol volumetric concentration in test vessel

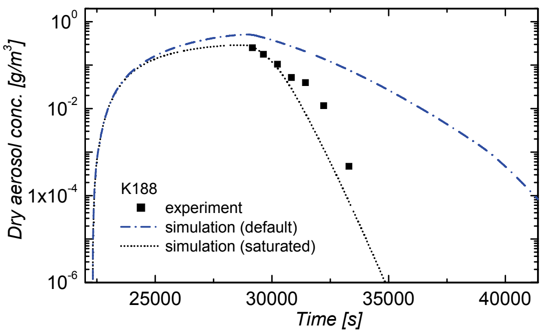

Figure 14: Test K188 - Total dry aerosol mass concentration in test vessel

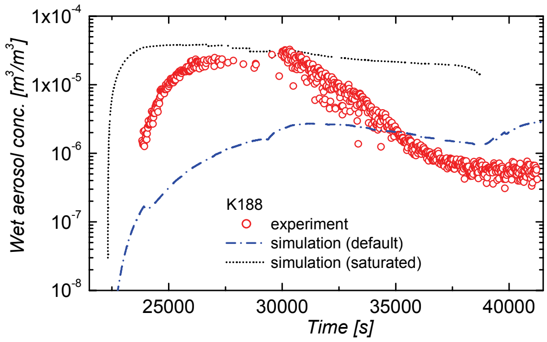

Figure 15: Test K188 - Total wet aerosol volumetric concentration in test vessel

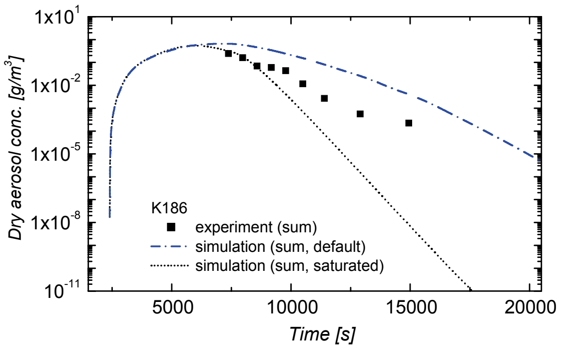

Figure 16: Test K186 - Total dry aerosol mass concentration in test vessel

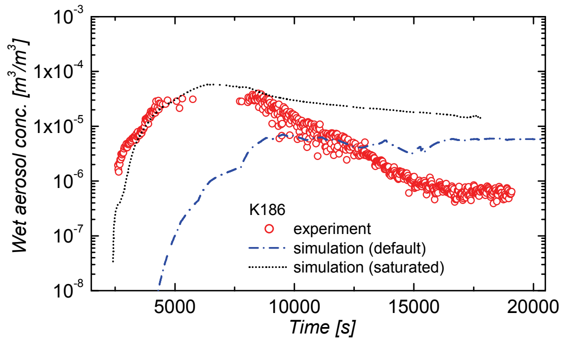

Figure 17: Test K186 - Total wet aerosol volumetric concentration in test vessel

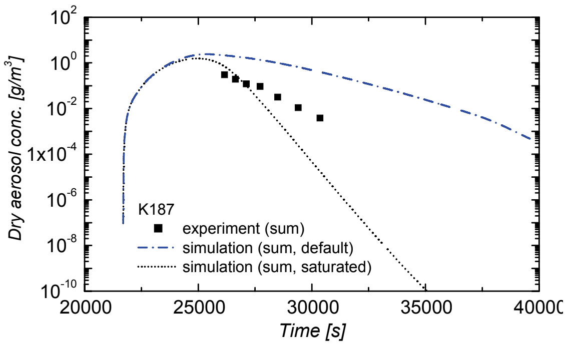

Figure 18: Test K187 - Total dry aerosol mass concentration in test vessel

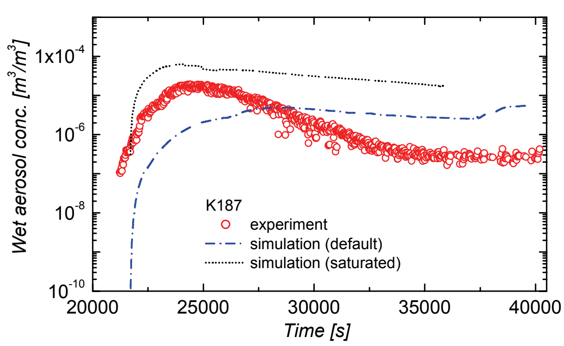

Figure 19: Test K187 - Total wet aerosol volumetric concentration in test vessel

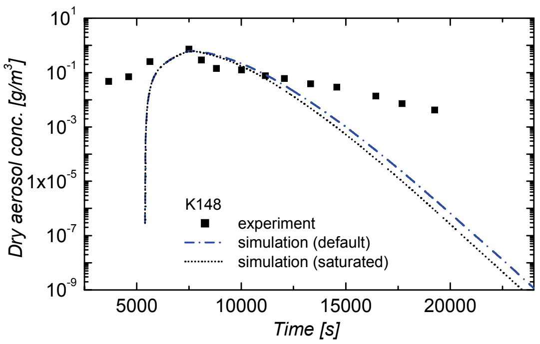

Figure 20: Test K148 - Total dry aerosol mass concentration in test vessel

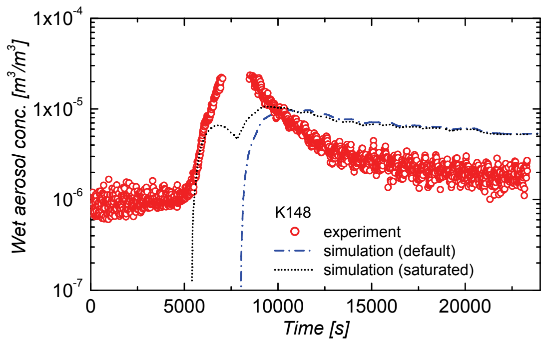

Figure 21: Test K148 - Total wet aerosol volumetric concentration in test vessel

5 CONCLUSIONS

Five experiments on aerosol behaviour in a light-water-reactor nuclear power plant containment atmosphere at accident conditions, which were performed in the KAEVER facility, were simulated with the ASTEC CPA V1.2 code. Simulations were carried out with the prescribed boundary conditions, obtained from the experiments, and with modified boundary conditions to simulate a saturated atmosphere which allegedly occurred in four of the five tests. The results obtained with the correctly simulated saturation (non-saturated for test K123, saturated for all other tests) are considered as relevant for the validation of the ASTEC CPA code.

In general, the simulated maximum dry aerosol concentration agrees well with the measured value. After reaching a maximum, the simulated dry aerosol concentration decreases very fast. Except in the simulation of tests K123 and K188, the concentration in the simulation decreases much faster than in the experiment.

The timing of the start of the increase of wet aerosol concentration agrees well with experimental data. In general, the maximum value of the wet aerosol concentration agrees well with the measured value in tests with at least one soluble component in a saturated atmosphere. In comparison to experimental data, the decrease of wet aerosol concentration after the maximum is reached is too slow.

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