Simulation of pool scrubbing experiments performed in the large-scale SAAB facility

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Abstract

In the late stages of a postulated severe accident scenario, the pressure inside the containment building might rise beyond the design limit of the containment, thereby challenging its structural integrity. Hence, the containment atmosphere might have to be vented to prevent a containment pressure failure. A large amount of fission products is released from the primary circuit in form of airborne particles (aerosols) and has to be filtered to avoid environmental risks, such as land contamination. Pool scrubbing is considered as a suitable aerosol filtering method. Therefore, knowledge of pool scrubbing behavior is a key to optimize severe accident management (SAM) measures.
Within the framework of the government funded national projects (SAAB-II, 2017-2022 and APVOR, 2021-2024), pool scrubbing investigations are carried out in the large-scale SAAB facility at Research Centre Juelich, Germany.
The paper deals with a review of the experimental facility including a description of a specific experiment and its simulation with the Containment Code System COCOSYS, which is part of the software package AC². The considered experiment investigates the retention of CsI by Pool Scrubbing in a 2.25 m water layer with a submergence of 1.5 m of the nozzle outlet. The Pool Scrubbing model SPARC-B/98 is used to calculate the aerosol depletion efficiency and the decontamination factor. For a more detailed validation the depletion efficiencies for nine aerosol size classes are analyzed. Contrary to the simulation, the depletion efficiency decreases for larger aerosols in the experiment what is explained by a coursing of the aerosols and a shift in the size distribution. It becomes obvious that the discrepancy in the decontamination factor can not only be explained by hydrodynamic parameters.

Introduction

In case of a postulated severe accident scenario in a nuclear power plant with boiling water reactor (BWR), the pressure in the reactor pressure vessel (RPV) might increase and has to be reduced to maintain the cooling circuits' integrity and to avoid fuel rod uncovering. Therefore, the pressure in the RPV is controlled by Safety Relief Valves (SRVs). Gases can be released via these SRVs into the suppression pool, with the intention to scrub fission products from the gas flow before it is released to the containment atmosphere. The most known code for the simulation of such pool scrubbing

phenomena is the code SPARC, which is implemented in different versions in codes like MELCOR, ASTEC and COCOSYS and is also available as stand-alone versions such as SPARC-90. The code considers many injection types and phenomena. The models in the code are derived from assumptions, computer code simulations and experiments.
In the frame of the joint project IPRESCA, running under the auspices of NUGENIA/SARNET, a code benchmark is conducted, in which five participants of a total of nine contributions used a version of SPARC for their simulations [1]. The outcomes are limited to the hydrodynamic parameters of the considered experiment and codes. In addition, this paper deals with the analysis of the depletion efficiency of different aerosol size classes in an experiment, conducted in the SAAB test facility at Research Centre Juelich (FZJ), Germany, to analyse the influence of the aerosol behaviour on the total decontamination factor and depletion efficiency.

SAAB test facility

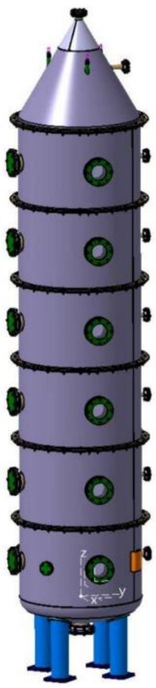


Figure 1 SAAB test vessel [8]

In the SAAB test facility aerosol is generated, conditioned and injected through a water reservoir [2]. The test vessel, that contains the water pool is shown in Fig. 1. The vessel consists of a bottom part, a conical top and five identical one-meter high segments, which can be removed to vary the test vessels total height. The inner diameter of the test vessel is 1.5 m and the maximum possible water volume is 10 m³ [2]. The generated aerosol is fed into a mixing chamber, where different aerosol streams are combined and mixed with the carrier gas [2]. The gas stream is injected into the test vessels' water reservoir by an upward directed nozzle, 0.75 m above the vessels' floor. The inner diameter of the orifice is 21 mm. Before this injection into the water pool, the aerosol in the gas stream is measured by an Electrical Low Pressure Impactor (ELPI+), which determines the aerosol concentration for fourteen size classes. The second aerosol measurement is performed 0.625 m above the pool surface in the conical part of the test vessel.

Experiment

In the considered experiment, four of the one-meter segments are removed. A pool height of 2.25 m is realized, i.e. the submergence of the injection nozzle is 1.5 m. Nitrogen is used as carrier gas and is injected with 22 m³/h. Thus, the Weber number is approximately 90,000. The pool temperature is 22°C and the test is conducted with Caesium Iodine (CsI). The inlet gas temperature is 30°C and to keep the humidity on a constant level, the sampling temperature of the ELPI+ is at 60°C. This experiment was repeated more than once, to obtain the accurate measurements results.

Modelling in AC² COCOSYS

The Containment Code System COCOSYS, which is part of the software package AC² is validated regarding the simulation of pool scrubbing phenomena by calculation of the considered test, conducted in the SAAB test facility at FZJ.
The software package AC² consists of the system codes ATHLET, ATHLET-CD and COCOSYS as well as the simulator software ATLAS and the Numerical Toolkit [3] and is developed by the *Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH* to simulate design basis and beyond design basis accidents in light water reactors and light water reactor containments [4, 5]. Furthermore, ATHLET has been extended to cover also working fluids like helium, liquid metals or molten salt [5].
COCOSYS simulates the pool scrubbing respectively the aerosol retention in water pools by the model SPARC-B/98, which is an extension of the code SPARC especially for the coupling with COCOSYS [6]. SPARC-B/98 divides the liquid pool according to Fig. 2 in an injection zone and a bubble rise zone. The injection zone is characterised by the gas injection via quencher, downcomer, horizontal opening or via

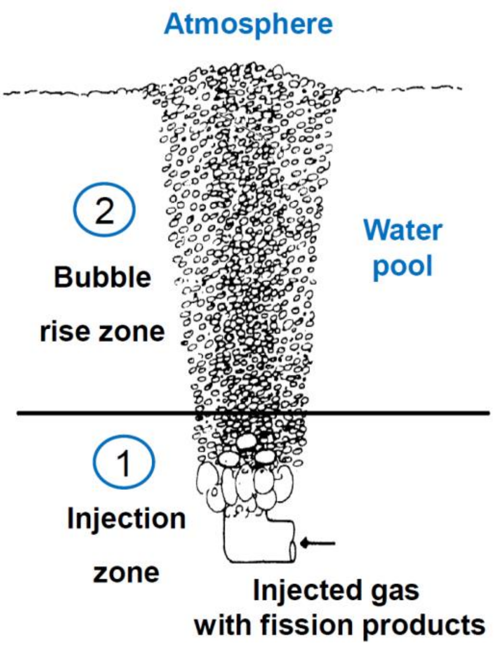


Figure 2 Subdivision of the water pool in the code SPARC-B/98 [7]

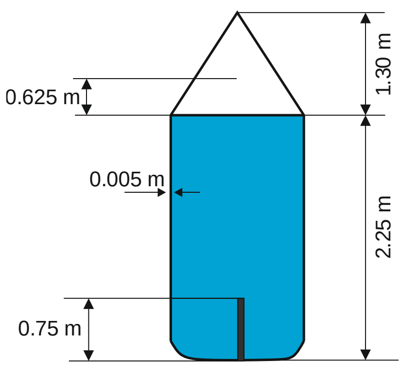
a single small orifice and the formation of the big bubble. After big bubble detachment and disintegration, the bubble rise zone starts, which is characterised by bubbles of different size and shape that flow to the pool surface in form of a bubble swarm. For the gas injection via a single orifice, SPARC-B/98 calculates the Entrainment-Velocity u_E by Eq. 1, where σ is the surface tension, ρ_w the water density and ρ_g the gas density.

$$u_E = 3.1 \cdot \sqrt[4]{\sigma \cdot g \cdot \rho_w / \rho_g^2} \qquad (1)$$

If the Entrainment-Velocity is above 16 m/s, a jet is calculated at whose end, the big bubble is situated. As in the considered test the nitrogen injection leads to an Entrainment-Velocity of approximately 9.37 m/s, no jet is simulated and the big bubble is considered to be situated at the nozzle outlet. The big bubble diameter d_B is calculated in dependence of the inlet opening diameter D_0:

$$d_B = \left(1.5 \cdot (3.45 \cdot We^{0.46}) \cdot D_0^2 \cdot \sqrt{\frac{\sigma}{\rho_w \cdot g}} \right)^{1/3} \qquad (2)$$

In this injection zone aerosol depletion is considered by the processes of steam condensation and diffusiophoresis, Brownian diffusion, thermophoresis, bubble circulation, sedimentation and impaction [6].
In the bubble rise region, the bubble size distribution is given by eleven size classes with a logarithmical equidistant separation [6]. The decontamination factors (DF) are calculated for each size class and are summarized based on their volumetric fraction. It is assumed, that the bubbles, which result from bubble detachment, are in thermic equilibrium with the water layer. The necessary steam condensation for this assumption leads to an aerosol depletion, which is considered as well as the effect of diffusiophoresis [6].
For the simulation with AC² COCOSYS, the SAAB test vessel is modelled by one zone “Vessel”, which consists of a liquid pool and a gas phase above (cf. Fig. 3).



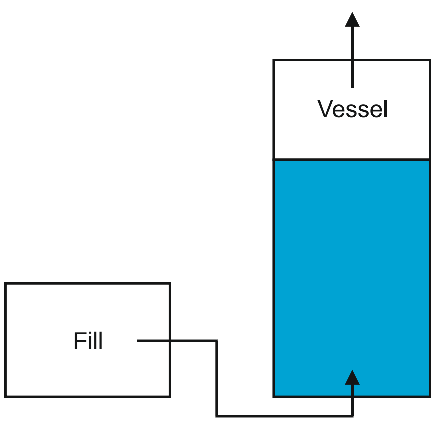


Figure 3 l.: Sketch of the SAAB test vessel; r.: Nodalisation of the SAAB test vessel for the simulation with AC² COCOSYS

In the considered test, the gas injection nozzle is submerged by 1.5 m water. The whole water pool has a height of 2.25 m. The aerosol measurement is conducted by an ELPI+ System, whose sensor is situated 0.625 m above the pool surface, as shown in Fig. 3 on the left. In the experiment, the aerosol is generated, mixed with the nitrogen flow and then injected into the water pool by the injection nozzle. In the simulation, the generation and mixing are modelled by the zone “Fill” (cf. Fig. 3 on the right). The given aerosol concentration and thermodynamic boundary conditions of the gas are achieved by aerosol and nitrogen injections into the zone “Fill”. Thus, the aspired nitrogen and aerosol mass flow through the junction from the zone “Fill” into the water layer in the zone “Vessel”, simulating the injection in the experiment. As in the experiment, the test vessel is connected to the atmosphere by an atmospheric junction.

Simulation results

As the aim of the considered SAAB experiment is the measurement of the initial aerosol concentration in mg/m³ as well as the aerosol concentration 0.625 m above the pool surface and to determine the decontamination factor and the depletion efficiency from these values for each size class of the used measurement device (ELPI+), the depletion efficiency derived from the experiment as well as from the AC² simulation are shown in Fig. 4 in dependence of the aerosol diameter.

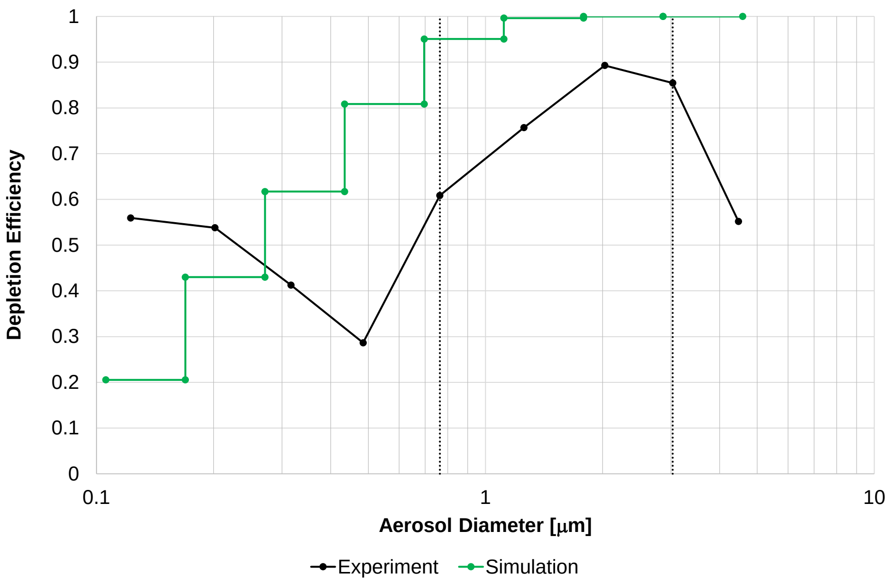


Figure 4 Depletion Efficiency measured in the experiment and calculated with AC²

Two dotted black lines can be seen in Fig. 4, that subdivide the aerosol diameter in three categories. In the first category, the depletion efficiency decreases from 0.122 µm till 0.485 µm aerosol diameter and increases after this local depletion efficiency minimum again. In the second category the depletion efficiency increases with increasing aerosol diameter and slightly decreases after the depletion efficiency maximum at 2.027 µm. In the third category, the depletion efficiency decreases to approximately 55 %. The simulation results are given by a step function (cf. Fig. 4) as AC² calculates the depletion efficiency for each size class, which is defined from a minimum to a maximum aerosol diameter. The depletion efficiency derived from the simulation, increases with each size class and reaches a maximum of 100 % at the last size class. Compared to the measurements, the depletion efficiency decreases in the first as well as in the third category in Fig. 4 are not simulated by AC². Beyond an aerosol diameter of 0.3 µm, the depletion efficiency of the experiment is overestimated in the simulation.
The decrease in the first category can be explained by a filter gap, that has already been reported by the experimenters in other experiments [8]. The decrease in the third category can be attributed to several mechanisms. For a more detailed analysis, the depletion efficiency achieved only in the injection zone in the simulation as well as the part of this injection-zone-efficiency, which results from the inertial impaction, is shown in Fig. 5.

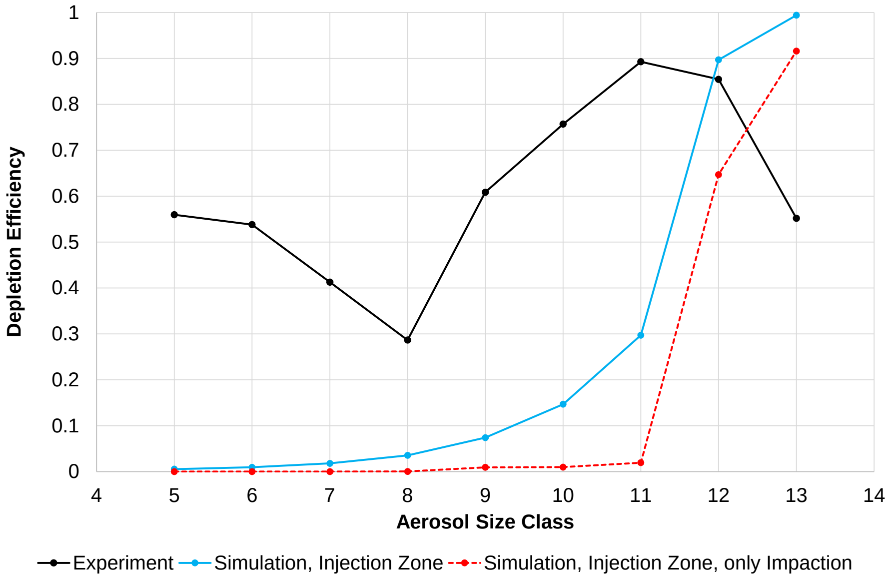


Figure 5 Depletion efficiency achieved in the injection zone in the simulation as well as the depletion efficiency in the injection zone due to inertial impaction

It becomes obvious, that a huge amount of the larger particles (> 3 μm) is separated in the injection zone in the simulation, whereby a huge depletion efficiency of > 90 % is already achieved by the inertial impaction (cf. Fig. 5, dashed red line). These findings fit qualitatively with the experimental results of *Dehbi et al.* [9], who conducted experiments with insoluble SnO_2 particles and measured for particles larger than 0.1 μm a clear increase of the DF for increasing particle sizes due to inertial removal mechanisms, which "become increasingly dominant" [9].
The most likely explanation for the decreased depletion efficiency for larger particles in the experiment is a shift in the aerosol size spectrum. This shift is underlined by the findings in Fig. 6, which shows the CsI mass fraction of each size class, measured at 0.625 m above the pool surface with the ELPI+ in the experiment and in the control volume above the pool in the simulation. It becomes obvious that in the simulation the largest mass fraction of CsI is situated in the size classes eight to ten, while in the experiment the amount in these size classes is decreased compared to the simulation and seems to be shifted to the higher size classes eleven to thirteen.

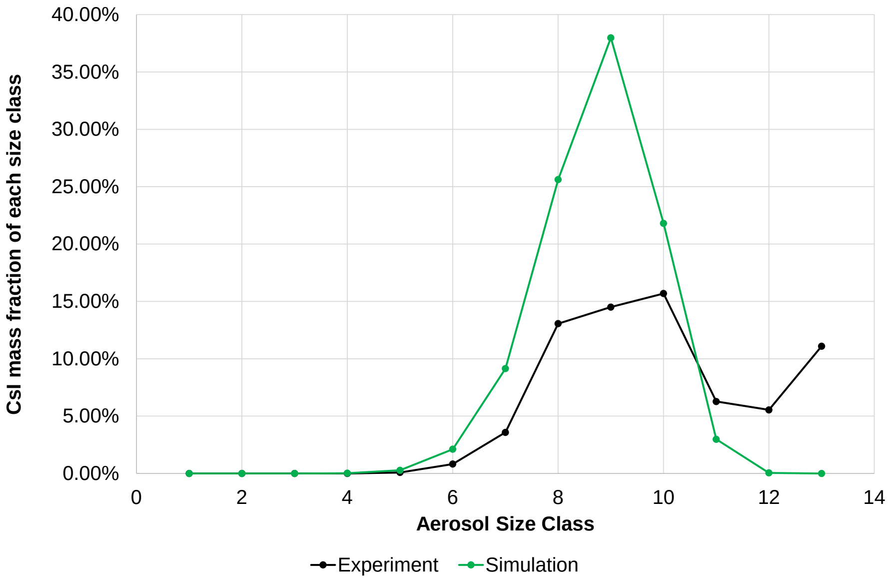


Figure 6 CsI mass fraction of each size class in the gas space above the pool surface

This size-class-shift might be attributed to agglomeration processes of smaller particles, but also to the water affinity of the CsI, what might lead to a coarsening of the aerosol detected by the ELPI+ system. This shift would lead to an even higher difference in the depletion efficiency in the size classes below 3 μm between the experiment and the simulation.

Conclusion and Outlook

The comparison between the measurements from the SAAB test facility and the simulation results show an overestimation of the depletion efficiency in the simulation for most of the considered size classes. Furthermore, the filter gap, measured at 0.4848 μm aerosol diameter, is not reproduced in the simulation. The largest discrepancy between experiment and simulation occurs for particles larger than 3 μm, where a huge depletion efficiency of more than 90 % is already achieved by inertial impaction in the injection zone in the simulation. It is shown that the decreased depletion efficiency for larger particles in the experiment is most likely due to a coursing of aerosol particles. A coursing due to the water affinity of the CsI would cause an error in the overall-DF calculation, that could not be explained only by hydrodynamics. Furthermore, only a DF for several size classes is able to identify the potential risk by smaller particles, which might become airborne for a long time.
It has to be clarified in further investigations, if the depletion efficiency overestimation in the simulation can be attributed to soluble particles respectively if the SPARC-B/98 code might only be applicable to insoluble particles. Furthermore, a measurement strategy is required, that ensures a detection of the dry aerosol mass above the pool surface to determine the effect of aerosol coursing due to the water affinity of the CsI.

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The results were obtained using the GRS software package AC² 2021.0.

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