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Severe accident related activities of the research center Jülich/Germany

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ABSTRACT

In Germany, the Helmholtz Association's program NUSAFE (Nuclear Waste Management, Safety and Radiation Research) tackles the scientific challenges for the safety of nuclear reactors in the key areas of design basis (DBA) and beyond design basis accidents (BDBA). As one of the three research centers in NUSAFE, the R&D activities at Forschungszentrum Jülich (FZJ) focus on containment phenomena and processes during severe accidents. FZJ supports international efforts to further develop computational methods and tools by providing worldwide unique facilities in the field of wall condensation, aerosol behavior and hydrogen mitigation for advanced code development and validation. Development of computational fluid dynamics (CFD) tools for containment application aims at the integration of existing knowledge and the transfer of research results into application. All research activities are integrated into international collaborations and projects.

1. Introduction

The significant release of radioactivity into the environment as a consequence of a severe accident in a nuclear power plant can cause severe consequences for population health, the environment, and the national economy. Consequently, nuclear safety is in the focus of considerable research efforts worldwide. In Germany, the Helmholtz Association is the leading national institution to provide the scientific background for the development and evaluation of highest safety standards and acceptance criteria regarding the operation of nuclear power plants worldwide. The Helmholtz program NUSAFE (Nuclear Waste Management, Safety and Radiation Research) tackles the scientific challenges for the safety of nuclear reactors in the key areas of design basis (DBA) and beyond design basis accidents (BDBA). Three Helmholtz centers, Forschungszentrum Jülich (FZJ), Helmholtz-Zentrum Dresden-Rossendorf (HZDR), and Karlsruhe Institute of Technology (KIT) are providing strong competencies in nuclear technologies with the focus on safety aspects for existing and future reactor concepts (Fig. 1). The Helmholtz Association supports current trends in advanced accident analyses by operating unique experimental facilities and further developing computational methods and simulation tools. Although the activities focus on PWRs currently operated in Europe, the research also addresses future concepts of small modular reactors (SMR) as well as gas-cooled reactors of GenIV. The assessment and improvement of the safety of nuclear reactors together with the protection of the population against radiation exposure constitute strategic long-term goals of the Helmholtz provident research even after termination of nuclear electricity generation in Germany in 2022 [1].

The focus of R&D at FZJ is on severe accidents and containment behavior. Considerable efforts are required to protect the integrity of the containment as the last barrier against the release of radioactive substances into the environment. In this context, the formation and distribution of flammable hydrogen/air mixtures and the fission product behavior are among the most relevant phenomena. While hydrogen combustion may challenge the containment integrity, the transport and deposition processes of fission products in the form of aerosols define the radiological source term. Both phenomena are governed by thermal hydraulic processes inside the containment. Hence, the further development and validation of accident simulation tools – lumped-parameter-codes as well as computational fluid dynamics (CFD) – with the inclusion of passive safety systems plays a key role in supporting accident and emergency management. FZJ supports the international efforts focusing on the further development of computational methods

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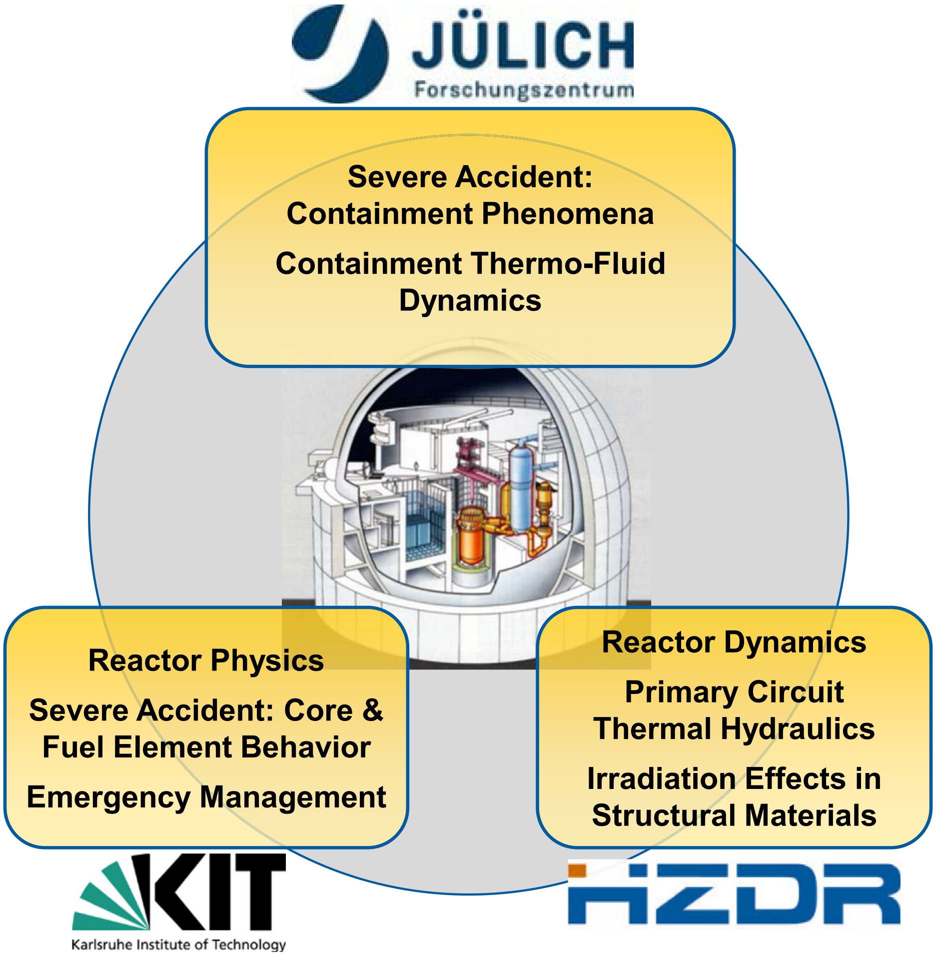


Fig. 1. Research topics covered in the Helmholtz centers.

and tools in these fields providing advanced experimental facilities with high quality data bases for advanced code development and validation (Fig. 2).

2. Analytical work on containment thermo-fluid dynamics

The Fukushima Daiichi accidents highlighted the need to understand the transport and mixing phenomena inside the containment and connected buildings. Knowledge of the spatial distribution of gases and the atmospheric conditions is essential,

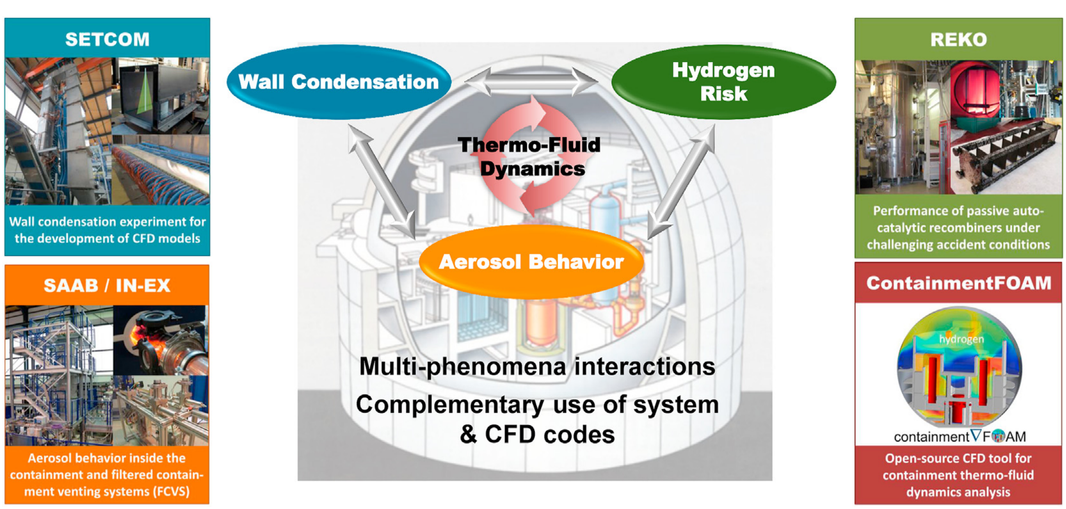


Fig. 2. Thematic structure of reactor safety research at FZJ.

e.g. for the design of safety systems and accident management and provides relevant information for subsequent analyses of possible hydrogen combustion loads and the radiological source term. Today, safety assessments are based on established 1D-System Codes, which include a broad variety of physical models and are comprehensively validated, e.g. COCOSYS [2]. Nevertheless, here are several safety relevant phenomena, e.g. H_2 distribution, mitigation or combustion, that cannot be assessed reliably on basis of a 1D model. Thus, computational fluid dynamics (CFD) models are developed to complement safety assessment, support quantification of safety margins and provide detailed insight into the phenomenology. Today, CFD is already applied in support of the design and evaluation of dedicated reactor safety experiments as well as part of safety demonstration, where experimental evidence can hardly by obtained. By means of upscaling experimental findings via validated models and assessing interactions of multiple phenomena on relevant scales, CFD represents a crucial element of bringing research into application.

At FZJ, the model development and validation aim at CFD application for full-scale containment analysis. This implies on the one hand a thorough trade-off between model efficiency and accuracy. On the other hand, the completeness of the physical and system model is mandatory to obtain a representative analysis. This requires a wide scope of efforts, ranging from modeling various physical phenomena (e.g. mixing in buoyant flows, aerosol transport, thermal radiation heat transport or wall/bulk condensation) to the operational behavior and efficiency of technical systems (e.g. burst discs, passive auto-catalytic recombiners, containment condensers). The R&D work is tightly coupled with the experimental programs conducted at FZJ (see chapter 3) and within German, e.g. THAI [3], European, e.g. ERCOSAM [4] and international research projects, e.g. OECD/NEA THAI or HYMERES projects [5–7], and in scientific collaboration with other research groups [8–10].

The model development cycle involves a four-step methodology:

1. Assessment and transfer of fundamental models from other fields of research e.g. turbulence in buoyant flows or thermal radiation heat transfer into the baseline model
2. If required, new or further development towards the application range
3. PIRT (phenomena identification and ranking table)-based systematic and continuous validation involving experiments on all scales
4. State-of-the-Art model application to involve application experience in the development and validation

An example is given on basis of heat and mass transport in buoyant flows. The effect on density gradients on the production and dissipation of turbulence is extensively discussed by Ref. [11] under the background of fire safety engineering. On this basis, the model was transferred, and additional source terms were included in the transport equations for turbulent kinetic energy and eddy frequency. The impact of the models' 'dissipation coefficient' was assessed for containment relevant unstably stratified plume flows and stably stratified conditions. On this basis, comprehensive validation was carried out against experiments, ranging from momentum driven mixing processes at different scales to free convection mixing. A typical test scenario to asses for turbulent mixing in a density gradient is the erosion of a stably stratified helium layer due to a vertical jet with different momentum impinging from below. Experimental database collected at the MiniPanda facility (~2 m^3, ETH Zurich, Switzerland), PANDA (100 m^3, PSI, Switzerland) or THAI (60 m^3, Becker Technologies, Germany) allowed to confirm good predictive capabilities of Helium-Air mixing processes, e.g. Ref. [12]. Natural convection driven Air-Helium mixing processes in the THAI and MISTRA (100 m^3, CEA, France) were analyzed and further substantiated the reliability of the model, but also revealed the sensitivity to the defined thermal initial and boundary conditions [13]. On this basis, the model was applied to comparable processes in gas mixtures containing steam and significant deviation to the experimental mixing behavior and gas temperature distribution was observed if radiative heat transport in the humid atmosphere is neglected, see Figs. 3 and 4 [14].

This finding again confirms the fundamental requirement of a complete physical model and thus opened a new branch in the development cycle. Currently, a dedicated weighted sum of gray gases (WSGG) model for containment relevant conditions ($T < 500$ K, high humidity) is developed [15].

The validation work is continued along with the international progress e.g. within the OECD/NEA HYMERES2 project [16]. In parallel, the state of the baseline model was applied to integral containment flows, such as the THAI International Standard Problem (ISP) 47 [17,18] or a prototypic full-scale containment analysis (Fig. 5) of a small break loss of coolant (SB-LOCA) transient. From this application, it can be concluded that the developed model and methodology is already representative of containment mixing processes and applicable to full-scale analysis.

Even more, the achieved level of detail complements the existing system code analysis and reveals safety relevant 3D effects, such as local hydrogen accumulation or the heat and mass exchange with dead-end compartments.

Nevertheless, these applications also identified several gaps e.g. the need to consider fog formation and transport, decay heat that is transported by aerosols [19], the reduction of prohibitive mesh requirements for wall condensation or simply the possibility to address the potential model and input uncertainties. These aspects are subject of ongoing R&D and will be implemented within the new 'containmentFOAM' package [20], developed at FZJ on basis of the widely used open source CFD toolbox OpenFOAM® (currently, version 6). The systematic further development and validation of the baseline CFD model for containment analysis will be continued alongside with the experimental programs in NUSAFE as well as national and international projects and thus transfer the experimental insights to application scale. The state-of-the-art models will be applied to address current research issues for operating European nuclear power plants, e.g. support development of PAR concepts, containment-venting strategies or analyze passive cooling systems. Furthermore, an application to the assessment of passive safety features in innovative SMR concepts is intended.

3. Experiments on containment phenomena

The experimental research program on containment phenomena aims at studying the complex interaction between hydrogen and aerosol behavior driven by containment thermal-fluid dynamics. The current SETCOM program includes a comprehensive investigation on wall condensation under mixed convection conditions. The SAAB facility serves to investigate aerosol retention in water pools, such as reactor sumps, condensation chambers and wet filters, e.g. in the context of filtered containment-venting systems (FCVS). Aerosol interaction and effects on containment instrumentation is investigated in the IN-EX facility. Finally, the REKO platform allows studying the operational behavior of passive autocatalytic recombiners under challenging boundary conditions.

3.1. Wall condensation (SETCOM facility)

Heat transfer between the containment atmosphere and structures determines its pressurization as well as the transport and

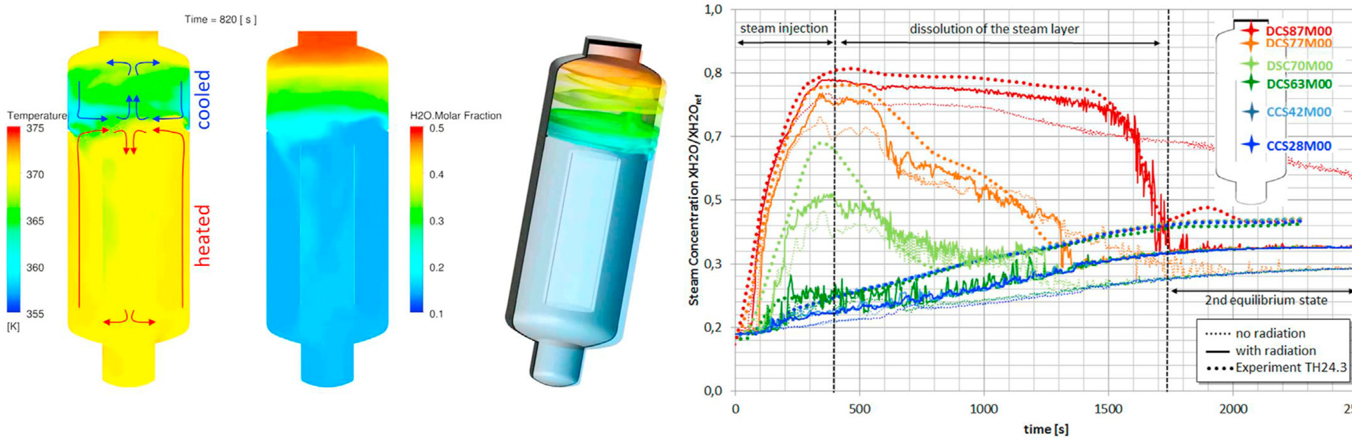


Fig. 3. Natural convection driven mixing: scenario (left), predicted mixing processes, steam stratification build-up and erosion mixing with and without gas radiation (right) [14].

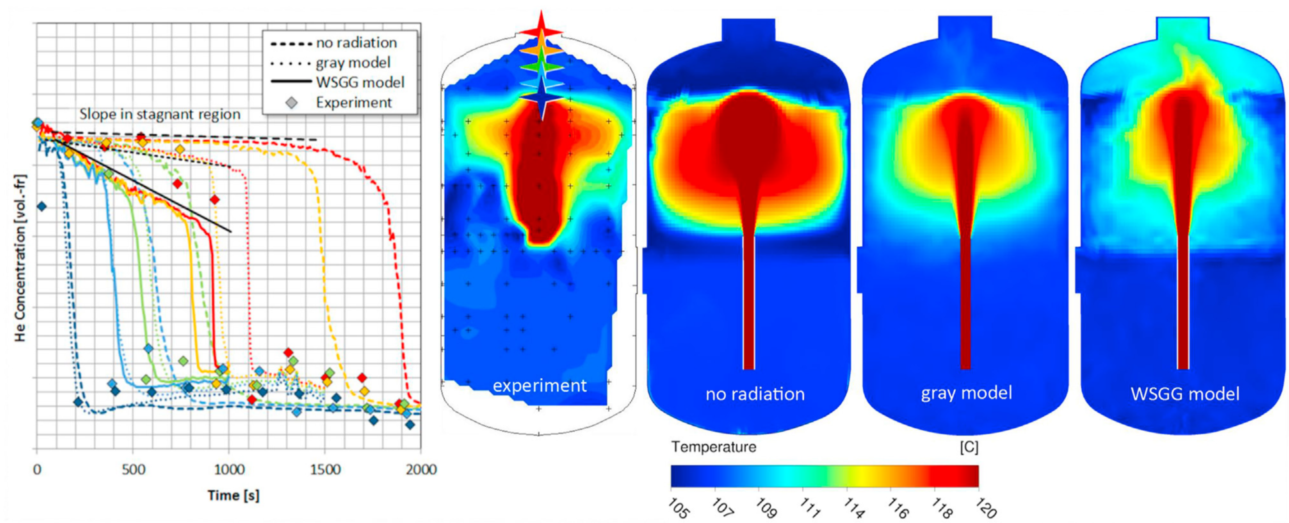


Fig. 4. Momentum driven mixing scenario: predicted mixing process (left) and gas temperature field (right) for different spectral models [14].

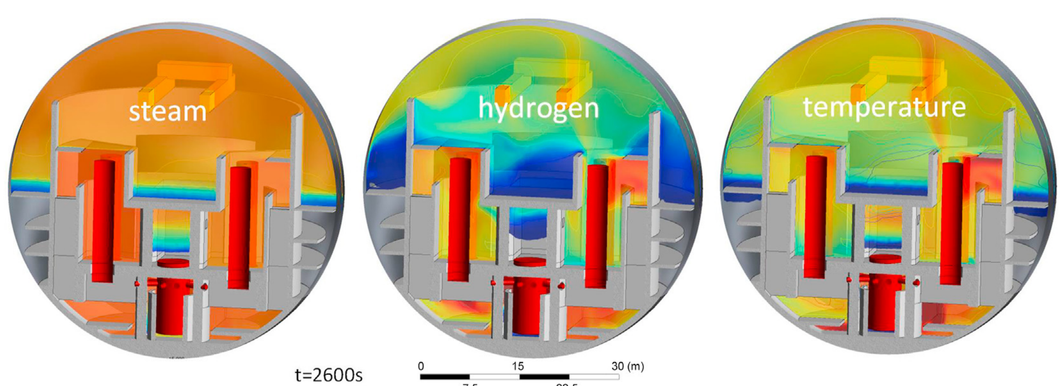


Fig. 5. Prototypic application of the baseline CFD model for analysis of the gas distribution and pressurization inside the containment during an SB-LOCA.

mixing processes, which are mostly driven by density differences due to temperature and/or concentration gradients. It is obvious that a reliable modeling of wall condensation is a crucial element for CFD analysis of containment atmosphere flow and mixing processes. In order to reduce the numerical effort, available models neglect the liquid film and prescribe the condensation rate by means of the mass transfer through the transpiring boundary layer [21]. This approach however requires a resolved boundary layer, to consider the near wall effects such as buoyancy and suction, which is however prohibitively demanding on containment scale.

As a basis of a further development of a wall-function approach, the SETCOM (Separate Effect test for Condensation Modeling) facility at FZJ is operated to gain an insight into the turbulent heat and mass transfer in the boundary layer during wall condensation. The facility is essentially a closed loop, which allows steady state operation with reproducible boundary conditions. In order to ensure optimal use for CFD model development and validation, comprehensive efforts have been made to design the facility components in order to realize well-known boundary conditions that can be directly transferred to the CFD model without (major) further assumptions. The facility concept is flexible and can be adapted to a broad bandwidth of flow configurations. The SETCOM test section consists of a rectangular flow channel (0,44 m x 0,44 m) with three adiabatic walls, which are electrically heated to balance heat losses (see Fig. 6 top).

The 6 m long cooling plate, is designed as a water cooled counter current cross-flow heat exchanger, which allows for a nearly uniform wall temperature ($\Delta T < 2$ K) along the entire cooling plate. The SETCOM facility can be inclined between a horizontal to a vertical position (see Fig. 6 top) in order to allow for a detailed investigation of buoyancy effects in mixed convection flows. The facility periphery allows to specify gas temperatures up to 100 °C, wall temperatures between 10 and 40 °C, a gas humidity up to 99% and flow velocities between 0.5 m/s and 5 m/s. The test section is equipped with two optical modules that can be placed flexibly along the channel to allow assessment of the boundary layer development. A schematic of the main optical module placed first in the middle and later near the end of the test section is given in Fig. 6 (bottom). Currently, a 2D-PIV (Particle Image Velocimetry) system and a 2D-LDV (Laser Doppler Velocimetry) probe, both from ILA GmbH (Jülich, Germany), are implemented to characterize the convective and turbulent transport processes within down to the viscous sub layer ($y+ \geq 4$) [22]. A typical measurement data set contains inlet and wall boundary conditions, measurements of the local heat flux and integral condensation rate and detailed information on the momentum boundary layer, i.e. velocity profiles as well as turbulent kinetic energy obtained from a statistic evaluation.

A systematic measurement campaign focused on mixed convection heat and mass transfer on a vertical wall. The effect of buoyancy (increasing Richardson number) on the local mass transfer (Sherwood number) and its link to the momentum boundary layer (dimensionless velocity profile) is depicted in Fig. 7. The near wall acceleration of the fluid due to buoyancy leads to increase of the mass transfer of up to one order of magnitude with regard to forced convection.

The data also reveals the error that appears if standard wall functions, developed for forced convection heat and mass transfer are used: The condensation rates are under predicted, which leads in a containment application to a non-conservative result regarding the steam inertization on the atmosphere.

Due to the strongly coupled nature of the governing equations, an analytical solution, which can be provided as boundary condition on under-resolved meshes cannot be obtained. Thus, at FZJ, data-driven models are developed on basis of SETCOM and validated analytical models [23,24] to include the effects of buoyancy and suction into the wall treatment. To describe the above-mentioned effects two additional dimensionless parameters, namely the dimensionless buoyancy force and the dimensionless heat flux are used to parametrize the data sets. A multi-dimensional approximation via radial basis function is used to efficiently included the information into existing wall-functions by

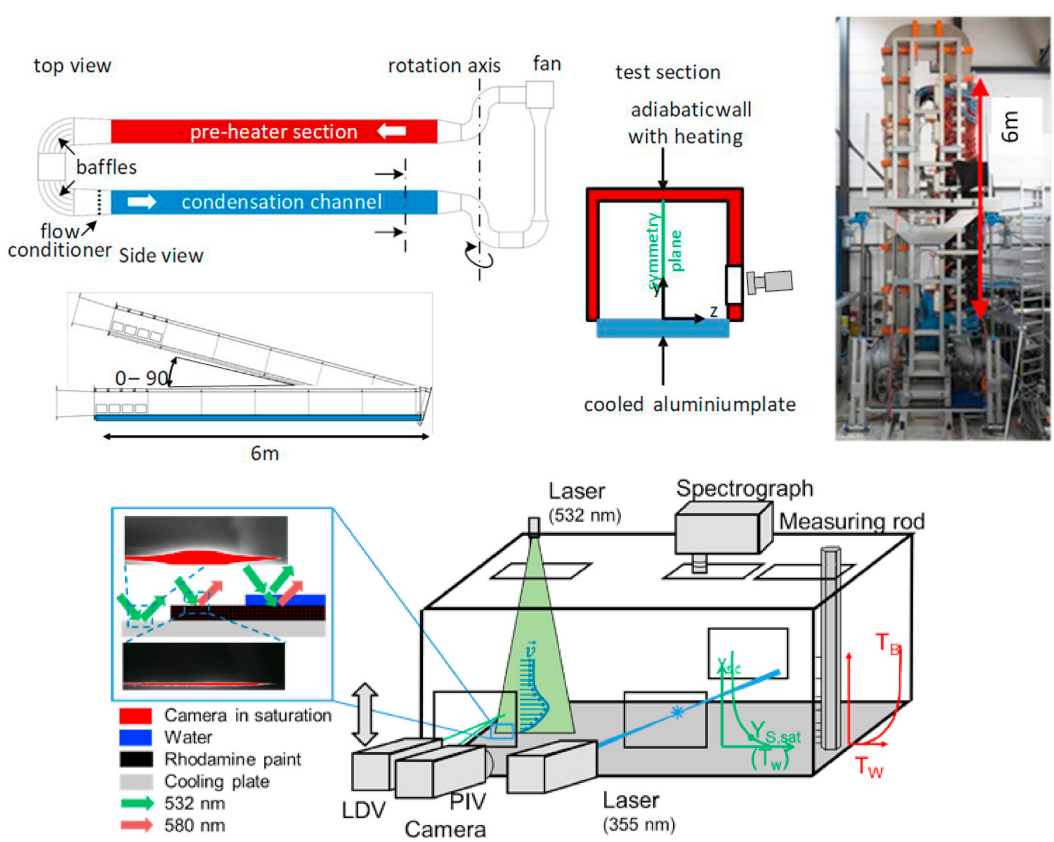


Fig. 6. SETCOM facility: Principal setup (top), Measurement concept for assessing the transport inside the boundary layer (bottom).

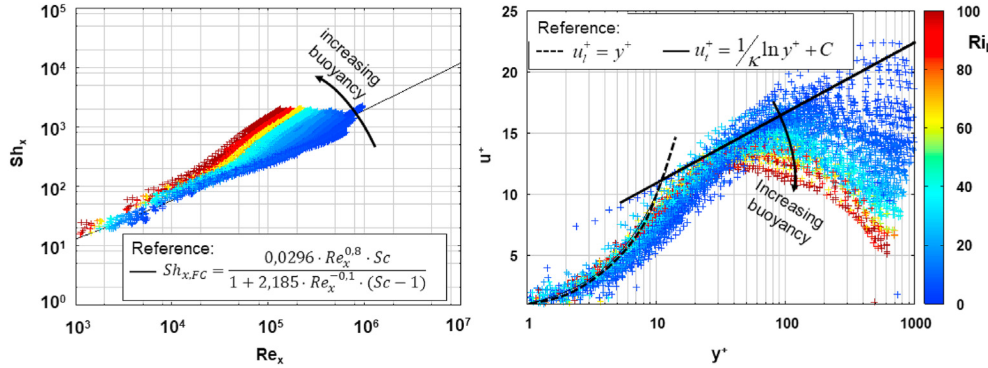


Fig. 7. Effect of near wall buoyancy on mass transfer (left) and transport in the boundary layer (right).

means of a non-equilibrium factor. Thus, a consistent boundary condition can be provided for all governing equations (Fig. 8).

The derivation and procedure are described in detail in Ref. [24]. Ongoing work aims at the extension of the model towards inclined walls and realistic surface characteristics.

3.2. Aerosol behavior (SAAB and IN-EX facilities)

A significant part of the fission products released in the process of a loss of coolant accident enter the containment in the form of airborne particles. Once leaked into the atmosphere, aerosols accumulate over time and might lead to long-term land contamination. Consequently, reliable prediction of aerosol behavior inside the containment during severe accidents is the key to optimizing Severe Accident Management (SAM) procedures, e.g. Filtered Containment Venting (FCV). Main focus in the context of source term mitigation investigations at FZJ is 'pool scrubbing', the particle retention in water pools. In addition, the following research objectives addressing aerosol-related issues are pursued:

- Development of enhanced models for source term assessment with regard to both reactor sumps and wet filters
- Investigation of distribution and depletion behavior of nuclear aerosols inside the containment
- Interaction of core melt aerosols with particles generated by combustion
- Qualification of measurement devices under challenging sever accident boundary conditions including the mechanical influence of aerosols

For this purpose, the SAAB and IN-EX facilities (Fig. 9) provide a unique aerosol research infrastructure.

3.2.1. SAAB facility

The SAAB ("Severe Accident Aerosol Behavior") test facility aims at providing a new database for validation and optimization of pool scrubbing models by performing systematic experimental research of decontamination factors and on the influence of different parameters on aerosol retention [25,26]. The facility is designed in order to be able to carry out single effect investigations, which, from a modeler's point of view, helps to isolate the sole influence of one single physical parameter on the overall retention behavior. The test vessel's modular set-up consists of up to seven segments with an inner diameter of 1.5 m (Fig. 9, left). The aerosol can be injected into the lowermost segment in three different ways: upward, sideward and downward. Five identical segments with 1 m height each can be installed above the injection segment and filled with water, which leads to a maximum pool height above the injection of approx. 5.5 m. Each segment includes three inspection glasses (0°, 90°, 180°) enabling the observation of bubble formation and bubble rise velocities for the investigation of hydrodynamics with a high speed camera. The topmost segment is a hood to collect the remaining particles with minimized particle losses for taking samples with various particle measurement devices, including filters to determine particle number concentration and particle mass concentration.

Before entering the test vessel, the particles are mixed with carrier gas inside a mixing chamber to generate aerosols consisting of different gas mixtures (nitrogen, helium, steam and air) and different particles (e.g. SnO_2, CsI, CsOH and Ag). Right after the

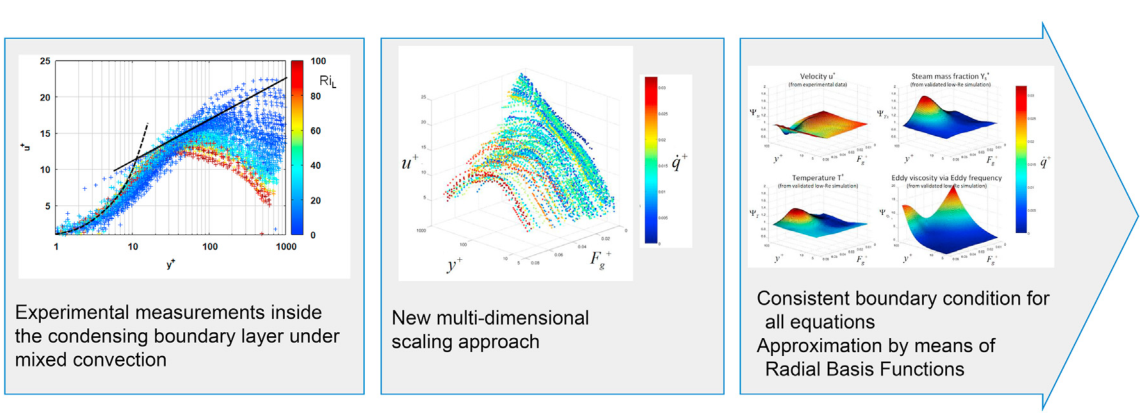


Fig. 8. Exemplary result: new multi-dimensional wall function for mixed convection heat and mass transfer.

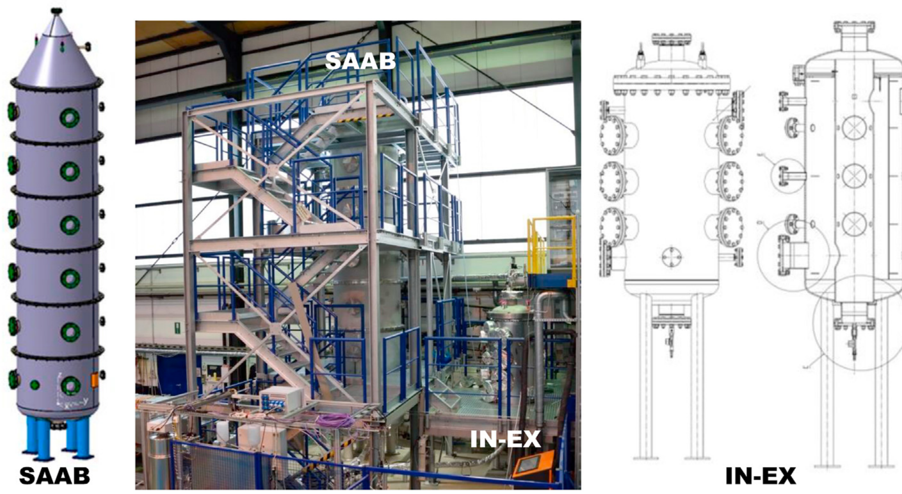


Fig. 9. SAAB and IN-EX facilities: a unique aerosol research infrastructure.

aerosols leave the mixing chamber, isokinetic sampling is conducted to determine the injected aerosol mass and size distribution. By this, differences in retention of soluble and insoluble particles with condensable and non-condensable gases can be investigated. Furthermore, the effect of particle size and size distribution as well as different fluid dynamics conditions can be studied. These activities are part of the national research project SAAB II ("Severe Accident Aerosol Behavior") and also are embedded in the European network IPRESCA ("Integration of Pool Scrubbing Research to Enhance Source Term Calculations").

3.2.2. IN-EX facility

The IN-EX facility allows pre-qualification of measuring instruments under thermophysical boundary conditions inside a LWR containment under severe accident conditions, including the presence of nuclear (but non-radioactive) aerosols, including fire aerosols. This is regarded as a first step in a qualification process in order to preselect devices to be proceeded to further – more expensive – tests, e.g. under relevant dose rates.

Specific generators for a wide variety of aerosols enable a continuous injection with constant particle size distribution and mass flow. Based on the experience of the PHÉBUS-FP tests [27], e.g. a mixture of SnO_2, Ag, CsI, CsOH and Cs_2MoO_4 can be used as largely representative core melt aerosol mixture. This makes it possible to prove the resistance under these environmental conditions for any newly developed accident-resistant measurement technology such as particle measurement technology or humidity measurement technology. The results of investigations in IN-EX show, among other things, the suitability to simulate severe accident containment atmosphere conditions with typical parameters to be produced stationary for hours in the test facility [28].

The main component of the test facility is the IN-EX pressure vessel (Fig. 9, right). The vessel has a free internal volume of 1.08 m^3 (80 cm inner diameter, 2 m height). The cylindrical part of the vessel is closed with two dished heads, the lower one being welded directly to the cylinder and the upper one being detachable and bolted on via a flange connection. Vessel inlet (at the bottom) and outlet (at the top) consist of flanges. A further eleven flanges for the measurement devices to be qualified and eight flanges for the vessel instrumentation are welded to the shell on five height levels. The vessel instrumentation includes sensors to determine the thermo-hydraulic atmosphere properties (pressure, temperature and humidity).

For the qualification of aerosol measurement devices, the particle number distribution and the particle density are additionally determined inside the vessel. For this purpose, aerosol sampling is performed at characteristic points.

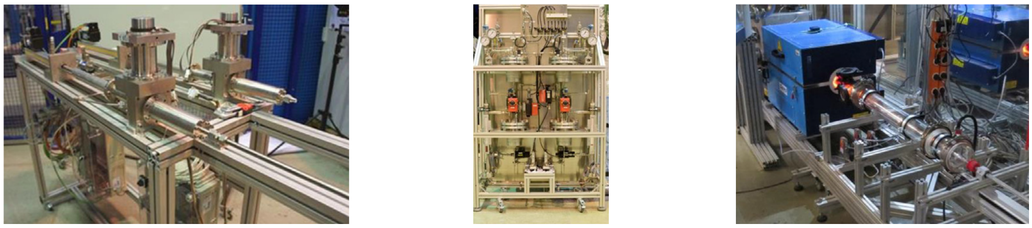
3.2.3. Aerosol generation and characterization

The selection of particles used in the investigations was made on the basis of earlier test programs and general considerations on accident sequences. In principle, the facilities are designed for both water-insoluble (e.g. SnO_2, Ag) and water-soluble (e.g. NaCl, CsI) particles and are capable of injecting mixtures as well. Furthermore, fire aerosols (e.g. soot, pyrolysis products) can be generated and injected to study the interaction with nuclear aerosols.

Key to maintaining comparability within individual test series, even at the same test facility, is the generation of aerosols in a reproducible manner. Several different generation strategies depending on the aerosol species of interest are used (Fig. 10): a brush generator (PDB) is available for the generation of water-insoluble particles and an atomizing spraying system (ASNS) for water-soluble particles. Fire aerosols are generated by means of a specially designed cable fire generator (CFG).

Two PDBs [29] were designed and manufactured for operating pressures of 8 bar(g) and operating temperatures of up to 200 °C. Operation over a long period of time is ensured by the alternating operation of both PDBs, each with a linear actuator driven by a servo motor and a reduction gear. The linear actuators achieve accuracies in the travel speed of 1 μm per second. Particle discharge efficiencies of up to 80% were achieved by the system. For the generation of airborne silver particles, the PDB was modified so that uncompressed silver powder can be applied [29].

For the production of aerosols with water-soluble particles, e.g. cesium iodide (CsI) and cesium hydroxide (CsOH), an air atomizing spray nozzle system (ASNS) is used [29]. In this process, a liquid mass flow is atomized by supplying a gas mass flow within an air atomizing nozzle. Due to high pressure losses through the nozzles, up to 25 bar(g) must be applied to the solution as an inlet pressure. Liquid supply between 6 g/h and 300 g/h is possible. Due to the high operating pressure in the liquid supply area, helium is used for the necessary pressure build-up. The liquid supply consists of a lock system so that a constant aerosol mass flow of liquid particles can be produced with the system. CsI is used in aqueous solution at the saturation limit in order to minimize the water input into the process. CsOH is produced in a quite similar way.



Powder dispersing unit with a brush (PDB)
- Insoluble particles, e.g. SnO_2, Ag
- Mechanical particle abrasion of pellets
- Carrier gas: N_2 or He
- max. gas flow: 12 m³/h
- Linear actuator for controlling particle release (7 g/h – 2 kg/h)

Air Atomizing Spray Nozzle System (ASNS)
- Water-soluble particles, e.g. CsI, CsOH, Cs_2MoO_4
- Two-component jet system

Fire Aerosol Generator (CFG)
- Cable fire aerosols from different stages (e.g. pyrolysis, open fire)
- Temperature-controlled tube furnace with constant cable feed (all components)
- Setting of defined combustion boundary conditions (temperature, fuel/air ratio) possible

Fig. 10. Use of different concepts for reproducible, constant aerosol supply.

The Fire Aerosol Generator (CFG) consists of an actuator system driving a specimen boat through a quartz glass reactor channel into a tube furnace. During operation, adjustment of furnace temperature, gas inlet composition and feed rate allows defining the combustion boundary conditions of interest [30].

Various complementary measuring systems are applied for aerosol characterization. Particle masses are measured most easily by weighing. For this purpose, a representative aerosol sample stream is passed through a filter paper, which is weighed before and after. The particle concentration can be calculated by the mass difference divided by the gas flow and the measurement duration. Filter measurements offer a simple procedure, which makes it less likely that procedural errors in the measurement will be overlooked. Therefore, despite their inability to measure size-resolved or online, they are an indispensable measurement principle for a comprehensive analysis. Even though mass balances are preferably carried out using filter measurements, the derivation of masses from the data gained from particle spectrometer measurements is also possible.

Another common principle in aerosol measurements is impaction. At FZJ, an electrical low-pressure cascade impactor (ELPI) is used, in which a stream of gas is directed through a defined geometry and thereby deflected several times. Large and thus inert particles cannot follow the flow as well as smaller ones and are deposited on a surface provided for this purpose. The main advantage of this device, besides the possibility for online measurements, is the resolution of the whole range relevant for this field of research (approx. 6 nm up to 10 μm).

In order to supplement filter and ELPI measurements, also different spectrometer systems (Scanning Mobility Particle Sizer, SMPS and Aerodynamic Particle Sizer, APS) are available. The aim of these additional systems is to obtain a finer resolution in the size range of particular interest. While the SMPS system covers the lowest range of particle sizes from 3 nm to 1 μm, the APS is used to cover the range from approx. 500 nm to 20 μm. That way, the combination of SMPS and APS offers an alternative measuring method to the ELPI system.

3.2.4. Exemplary results

Regarding pool scrubbing, the influence of various parameters on the particle retention efficiency for both, in-soluble and soluble particles were investigated in the recent past at the SAAB facility [25,26,31], e.g.:

- Pool height
- Injection velocity
- Inlet particle concentration
- Carrier gas density

Fig. 11 exemplarily show the results of a test series with variation of the pool height for soluble particles. It depicts the integral particle retention at different pool heights (left) and the size-class dependent in and outlet concentrations (right, same color coding, inlet size distribution in blue), showing that the water level above the injection is one of the most dominant factors for pool scrubbing. While for 1.5 m the retention efficiency is slightly below 90%, it increases significantly with the pool height leading to an overall efficiency of approx. 99% at 5.5 m. Nevertheless, when comparing particle size distributions at inlet and outlet, it reveals that even if the integral mass-based retention efficiency is very high, there are major differences between the different size classes. Small particles (<0.1 μm) as well as big particles (>1 μm) are held back very efficiently, but especially respirable sizes (~0.5 μm) are showing distinct filter gaps with efficiencies dropping to approx. 60% at 1.5 m and 90% at 5.5 m pool height. These results show that the integral retention efficiency has only limited informative value, because it is too much dominated by large, mass-bearing particles and cannot give information about e.g. filter gaps.

In the IN-EX facility, pre-qualification test series have been performed for an optical aerosol measurement device (OAMD) as well as for two optical humidity sensors [28,32].

The qualification program of the optical aerosol sensor included long-term investigation of the measurement performance under accidental conditions. The test matrix included humid atmospheres up to 95% at 6 bar and 433.15 K. Multi-component aerosols containing SnO_2, CsI and CsOH were applied with particle densities of up to 1 g/m^3. The post-test inspections revealed massive impact of the corrosive aerosol CsOH (Fig. 12). Being considered as exclusion criterion, this result led to a failure of the qualification goals of the tested OAMD. This example illustrates the usefulness of pre-qualification in the IN-EX facility before more expensive tests under relevant dose rates.

3.3. Hydrogen mitigation (REKO facilities)

Passive auto-catalytic recombiners (PARs) are installed inside the containments of nuclear power plants worldwide in order to remove hydrogen that may be released during a loss-of-coolant accident and to avoid possible threats related to fast hydrogen deflagration [33]. Besides the removal of hydrogen, PARs contribute to the containment thermal hydraulics by inducing heat and flow patterns promoting atmosphere mixing. In order to further

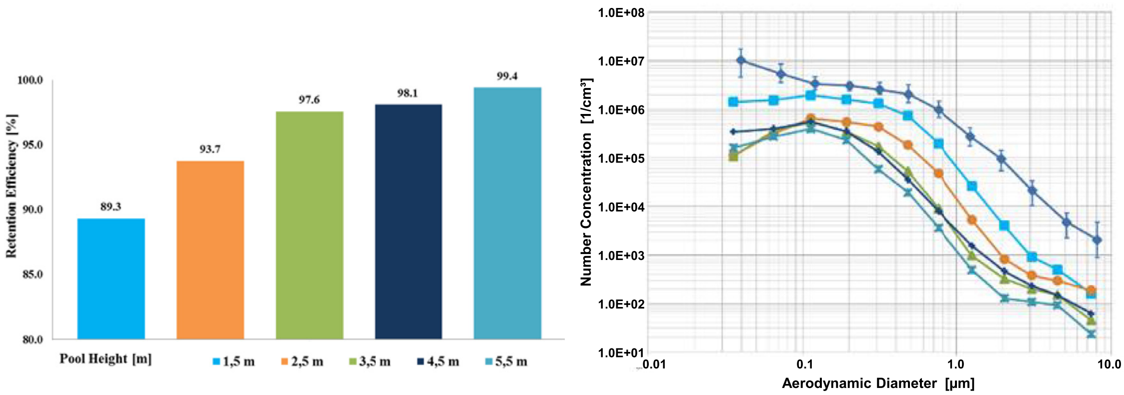


Fig. 11. Exemplary results: effect of different pool heights on the particle retention efficiency.

Fig. 12. Example of pre-qualification tests.

enhance the assessment of hydrogen mitigation efficiency, current research projects are focusing on PAR operation under challenging boundary conditions of severe accidents, e.g. the effect of carbon monoxide in the ex-vessel phase or the interaction with cable fire products. The aim of the research work is to enable reliable simulation of PAR operation under severe accident conditions. The work contributes to PAR implementation strategy and performance assessment, and supports new applications of PARs e.g. for filtered containment venting systems.

Fig. 13 gives a schematic overview of challenges on PAR operation during both normal rector operation and severe accidents. While permanent effects during normal reactor operation are usually detected during periodic PAR testing with the possibility of regenerating the catalysts, effects of fires or earthquakes may become initiating events for an accident scenario, and the corresponding effects on PARs will probably reduce the following performance. In the course of a severe accident, condensate formation on the catalyst surface, gaseous fission products, fire product deposition as well as adverse flow conditions might delay or slow down especially the PAR start-up. During hydrogen release and in the late phase of an accident, core melt aerosols and gaseous products (especially carbon monoxide) released during the molten core-concrete interaction (MCCI) represent the most relevant stresses for the mitigation efficiency of a PAR [34].

The research strategy at FZJ for enabling advanced PAR simulation tools (Fig. 14) involves the operation of several test facilities at different scales in order to study the processes inside PARs to provide a database for the validation of detailed mechanistic PAR models. The REKO-3 facility represents a full-scale segment of a PAR catalyst section to be investigated under forced flow conditions. The tests allow to determine steady-state conversion rates and catalyst temperatures in the catalyst section for various gas mixtures and flow velocities. In order to study the interaction of the catalyst section with the PAR chimney in detail, the REKO-4 facility consists of a 5.5 m^3 vessel. The facility may be operated at a pressure of up to 2.3 bar at 280 °C. The REKO-1 facility enables performance tests, e.g. start-up tests of catalyst samples contaminated with aerosols like cable fire soot. Furthermore, homogeneous gas phase ignition on hot catalyst sheets is investigated. The GRART facility enables the investigation of the effect of humidity on the start-up delay of catalyst sheets by determining the adsorption isotherms of water condensate on the catalyst surface. The most recent facility, REKO-Fire, combines a vertical cylindrical flow channel with a cable fire aerosol generator to allow studying the impact of cable fire products released under different fire conditions on start-up and hydrogen conversion behavior of catalyst sheets.

While the development of the in-house REKO-DIREKT code has been supported by these experiments, the experimental program performed in the frame of the OECD/NEA projects THAI and THAI2 [35] offers a comprehensive database which is especially suited for the validation of numerical PAR codes. In the framework of the validation of the PAR code REKO-DIREKT, a total of 32 experiments of both test programs including two different PAR types (from suppliers Areva/France and Atomic Energy of Canada Ltd.) have been simulated. In the light of the broad parameter field including

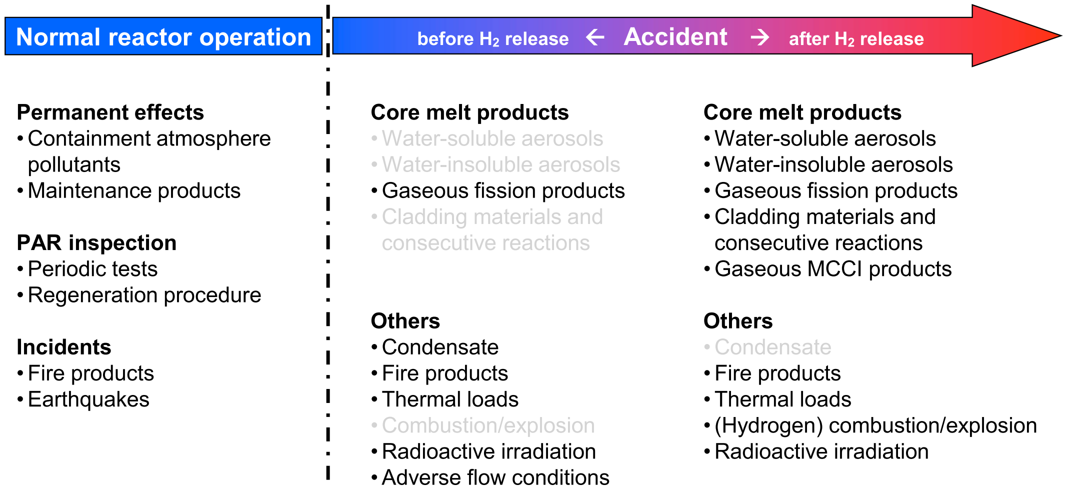


Fig. 13. Challenges for PAR operation during normal reactor operation and accidents [34].

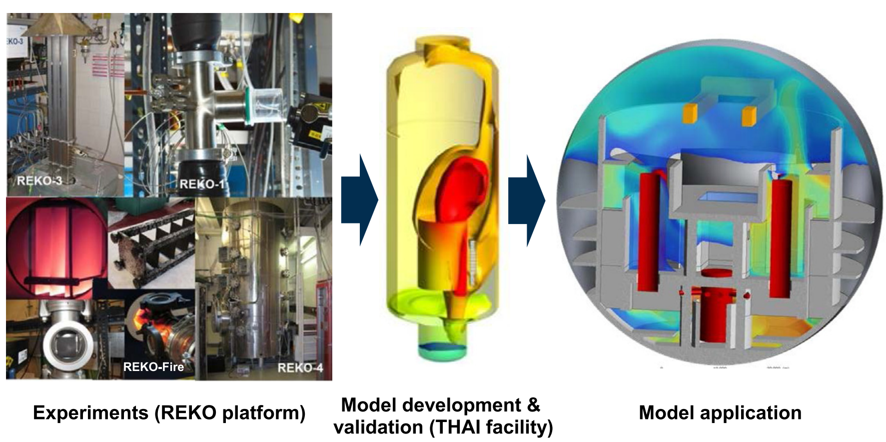


Fig. 14. PAR simulation research strategy.

pressures between 1 and 3 bar, steam concentrations up to 60 vol%, and low-oxygen conditions as well as the significant differences of both PAR types of geometries, the results achieved are highly convincing and confirm the suitability of the code for the simulation of the operational behavior of full-scale PARs [36,37].

In order to use REKO-DIREKT for numerical scenario analyses, the code has been successfully coupled to the lumped-parameter code COCOSYS [38] and the CFD codes ANSYS-CFX [39] and containmentFOAM. Especially the implementation of REKO-DIREKT in ANSYS-CFX has demonstrated to allow consistent simulation of experimental transients regarding all available measurements as well as derived quantities like the recombination rate [36,37].

The recent experimental program at FZJ aimed at solving open issues related to PAR modeling [40], including PAR ignition [41], carbon monoxide conversion and poisoning [42,43], and the impact of cable fire aerosols [30,36,37]. Furthermore, the influence of adverse flow conditions (counterflow) on the start-up behavior of PARs has been investigated [44].

Recent comprehensive test series include start-up behavior under adverse flow conditions, in the presence of carbon monoxide, cable fire products and high humidity [45]. Fig. 15 shows exemplarily start-up characteristics of catalyst sheets covered with soot from cable fire burns at high temperatures (blue lines) and with pyrolysis products from low temperature burns (green lines). While the soot covered sheets reveal only minor start-up delay compared to the reference sheets, the pyrolysis products cause significant more delay. The outcome of the tests demonstrates the relevance of the burning conditions on the effect of cable fires. Corresponding considerations have been taken when designing the new REKO-Fire facility.

Fig. 16 gives another exemplary result on the effect of water condensate on the catalyst surface on PAR start-up. Catalyst sheets have been exposed to different humid and wet conditions in the GRART facility with alternating phases of application of humid or wet atmosphere to catalyst samples and injection of hydrogen/air mixtures [46]. The measurement results reveal the dependence of the amount of water deposited on the catalyst surface from relative humidity and the sample surface characteristics. The start-up delay caused by water adsorption was found to increase linearly with the condensate mass.

Recently, two studies of PAR application outside the field of severe accidents in LWRs have been performed in the REKO-4

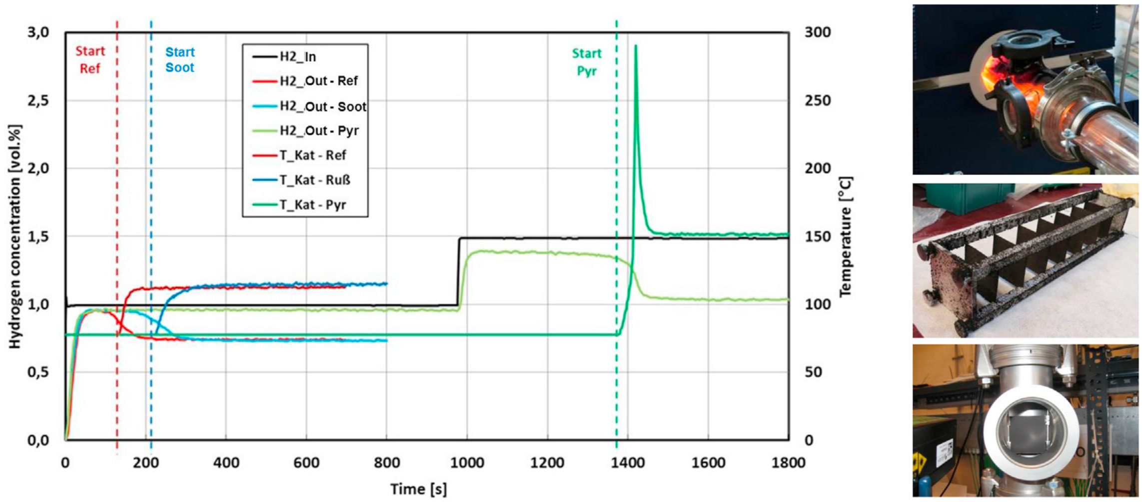


Fig. 15. Exemplary results: start-up delay in the presence of cable fire products.

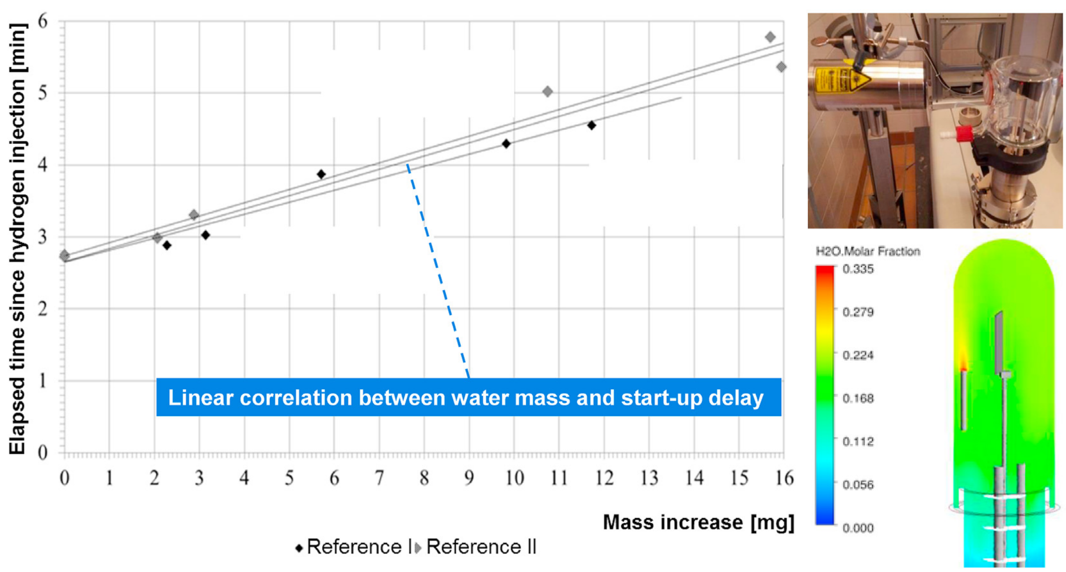


Fig. 16. Exemplary results: start-up delay in humid atmosphere.

facility. For the ITER Fusion project, the application of PARs inside the suppression tank has been studied, involving experiments under sub-atmospheric pressures and oxygen-lean conditions. The study reveals several scenario-typical limitations of PAR performance. Most significant is the prolonged start-up of the PAR chimney flow at sub-atmospheric pressures which will cause a significantly delayed start-up after the air ingress. Furthermore, the chimney flow velocity is decreasing at lower pressure causing a reduction of the hydrogen conversion rate [47]. In the framework of a national Japanese project, the potential application of PARs inside containers for long-term storage of high-concentration radioactive waste in Fukushima Daiichi has been investigated. In order to obtain fundamental data for catalyst design, basic operational characteristics as a function of the cell density, the catalyst thickness and the chimney height were investigated [48].

4. Conclusions and outlook

During a severe accident, the formation and distribution of flammable hydrogen/air mixtures and the fission product behavior are among the most relevant phenomena inside the containment. While fast combustion processes may challenge the containment integrity, the aerosol behavior defines the radiological source term. Reactor safety research activities at FZJ support the international efforts focusing on the further development of computational methods and tools providing advanced experimental facilities with high quality data bases for advanced code development and validation. The further development and validation of accident simulations with the inclusion of passive safety systems plays a key role in supporting accident and emergency management.

The development of 'containmentFOAM' aims at integrating existing knowledge and thus transferring the research into application. Recent developments target gas radiation heat transfer, mixed convection heat and mass transfer, uncertainty quantification and aerosol transport. Its development comprises a strong link to experimental work at FZJ as well as international R&D activities in the field. The experimental programs involving worldwide unique facilities in the field of wall condensation, aerosol behavior and hydrogen mitigation, serve as data bases for corresponding model development.

The focus of the on-going activities in the SETCOM facility is to systematically characterize wall condensation under mixed convection along an arbitrarily inclined wall with various surface characteristics relevant to reactor containments. In the framework of the SAAB II project, systematic investigations of particle retention in a water pool are currently being performed. The foreseen test matrix includes the experimental investigation of single effects and the validation of reliable correlations for the assessment of particle retention. The activities in the REKO platform currently focus on advanced investigations on the effect of cable fire products on the operational behavior of passive autocatalytic recombiners.

At FZJ, international collaboration is regarded as integral part for successful research. All activities are closely linked to the international networks SAMHYCO-NET ("Severe Accident Management for Hydrogen and Carbon Monoxide") and IPRESCA ("Integration of Pool Scrubbing Research to Enhance Source Term Calculations"), as well as to the European AMHYCO ("Towards an enhanced accident management of the Hydrogen/CO combustion risk") project under the auspices of the European Sustainable Nuclear Energy Technology Platform (SNE-TP). We are always open for new cooperations and projects.

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