EXPERIMENTS AT THE MIXING TEST FACILITY ROCOM FOR BENCHMARKING OF CFD-CODES

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Abstract

For the validation of Computational Fluid Dynamics (CFD) codes experimental data on fluid flow parameters with high resolution in time and space are needed.

ROCOM (Rossendorf Coolant Mixing Model) is a test facility for the investigation of coolant mixing in the primary circuit of pressurized water reactors. This facility describes the primary circuit of a German KONVOI type reactor. All important details of the reactor pressure vessel are modelled in a linear scale of 1:5. The facility is characterized by flexible possibilities of operation in a wide variety of flow regimes and boundary conditions. The flow path of the coolant from the cold legs through the downcomer until the inlet into the core is equipped with high resolution measurement technique. Especially, wire mesh sensors in the downcomer of the vessel with a mesh of 64 x 32 measurement positions and in the core inlet plane with one measurement position for the entry into each fuel assembly allow to carry out high-level CFD code validation. Two different types of experiments at the ROCOM test facility are proposed to be used for this purpose. The first proposal concerns the transport of a slug of hot, under-borated condensate, which has formed in the cold leg after a small break LOCA, towards the reactor core with natural circulation flow rate. The propagation of the emergency core cooling water in the test facility under natural circulation or even stagnant flow conditions should be investigated in the second experiment. The measured data can contribute significantly to the validation of the CFD-codes.

Introduction

Mixing of coolant with different boron content and/or different temperature in the primary system of pressurized water reactors (PWR) plays an important role during normal operation and under accident conditions.

Slugs of low borated coolant can form in the cold legs of the primary circuit due to different mechanisms, e.g. in the course of reflux-condenser mode after a small break loss of coolant accident (LOCA). If the inadvertent start of the first main coolant pump is performed or the natural circulation re-starts, the low borated slug will be transported to the reactor core. In that case, the slug mixing is the only mechanism mitigating the reactivity insertion into the core. The same mechanism is responsible for the mitigation of a reactivity insertion due to a temperature perturbation created in one of the loops during an overcooling transient. The mixing of slugs of water of different temperature is also very important for pre-stressed thermal shock (PTS) situations. In emergency core cooling (ECC) situations after a LOCA, cold ECC water is injected into the hot water in the cold leg and downcomer. Due to the large temperature differences, thermal shocks are induced at the reactor pressure vessel (RPV) wall. Temperature distributions near the wall and temperature gradients in time are important to be known for the assessment of thermal stresses.

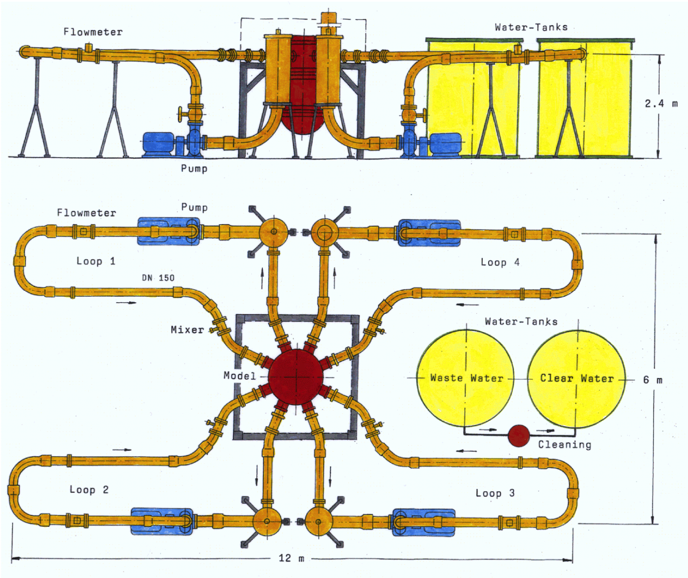
The application of Computational Fluid Dynamics (CFD) simulation methods to model these single-phase flow phenomena is underway. In the near future, these codes are expected to be used for assessing the nuclear reactor safety. This objective requests a comprehensive validation work. This validation should be performed again dedicated experiments at test facilities providing the necessary detail of modelling all structures important for the coolant mixing. This concerns the loop and vessel geometry and especially the internals of the RPV. Further, the measurement data should be provided with high resolution in space and time to enable a detailed comparison with the calculation results.

ROCOM is a test facility, which fulfils the aforementioned preconditions to perform integral single phase mixing experiments aimed at the investigation of turbulent mixing of the coolant in the downcomer and lower plenum of a PWR.

The ROCOM test facility

ROCOM (Rossendorf Coolant Mixing Model) is a four-loop test facility (Fig. 1) with a RPV mock up made of Perspex for the investigation of coolant mixing operated with water at room temperature [1]. The facility models a KONVOI type reactor with all details important for the coolant mixing along the flow path from the cold leg nozzles until the core inlet in a linear scale of 1:5. Special attention was given to components, which significantly influence the velocity field such as the core barrel with lower core support plate and core simulator, perforated drum in the lower plenum, inlet and outlet nozzles. The geometry of the inlet nozzles with their diffuser segments and the curvature radius of the inner wall at the junction with the RPV was modelled in detail (Fig. 1). The core and the upper plenum are modelled in a very simplified manner. Individually controllable pumps in each loop give the possibility to perform tests in a wide range of flow conditions, from natural circulation to nominal flow rate including flow ramps (pump and natural circulation start up). The water inventory of the loops is kept in the scale of 1:125 and the travelling time of the coolant is identical to the original reactor.

The test facility is operated with de-mineralized water. Two loops are equipped with a pair of fast acting gate valves. The water between the valves in one or two loops (in dependence on the scenario) is tracered by salt to establish a conductivity level of about 100 µS/cm, characterizing the maximum under-boration. The valves are opened just before starting the pump according to the required scenario. Further, the loop N°1 is equipped with a tracer injection system, what can be used instead of the valves. By means of this injection system it is possible to create perturbations of different length and initial position.



a) Scheme of the ROCOM test facility

b) Vessel of the ROCOM test facility

Fig. 1 ROCOM test facility

Measurement technique

The test facility is equipped with measurement devices, which allow a high resolution measurement of the transient tracer concentration in space and time. For that purpose, special wire-mesh sensors, based on the measurement of the electrical conductivity have been developed [2]. They consist of two orthogonal electrode grids put into the measuring cross section. The electrodes are electrically insulated wires. The wires of the first grid (transmitter electrodes) are supplied with short voltage pulses in a successive order. When a voltage pulse is given to a certain wire of the first grid, the individual currents, arriving at each of the wires of the second plane (receiver electrodes) are proportional to the local conductivity of the water at the crossing points between the corresponding transmitter and receiver electrodes.

The measured conductivity values are transformed into a dimensionless mixing scalar $\Theta_{x,y,z}(t)$. It is calculated by relating the local instantaneous conductivity $\sigma_{x,y,z}(t)$ to the amplitude of the conductivity change in the cold leg of the loops with the slug(s).

$$\Theta_{x,y,z}(t) = \frac{\sigma_{x,y,z}(t) - \sigma_0}{\sigma_1 - \sigma_0} \qquad \text{Equ. 1}$$

3

Θ represents the contribution of the coolant from the initial slugs to the mixture at the given position x,y,z. The upper reference value σ_1 in Equ. 1 is the conductivity in the initial slugs between the gate valves or the conductivity of the injected water. The lower reference value σ_0 is the initial conductivity of the water in the test facility before the valves are opened.

All inlet nozzles are equipped with sensors. Further, sensors can be installed at important positions along the flow path in the primary coolant loops (e.g. at the position of the ECC water injection). One sensor is integrated into the lower core support plate providing one measurement position at the entry into each fuel assembly. Two different types of sensors can be installed in the downcomer. The first one measures the tracer concentration in one radial plane. Two of such sensors can be implemented into the upper and the lower part of the downcomer, respectively (Fig. 2). They represent 4 x 64 measuring positions, i.e. the azimuthal distribution of the tracer concentration is measured at 64 angular positions with a pitch of 5.625 deg. Over the radius there are 4 measuring positions with a radial pitch of 13 mm.

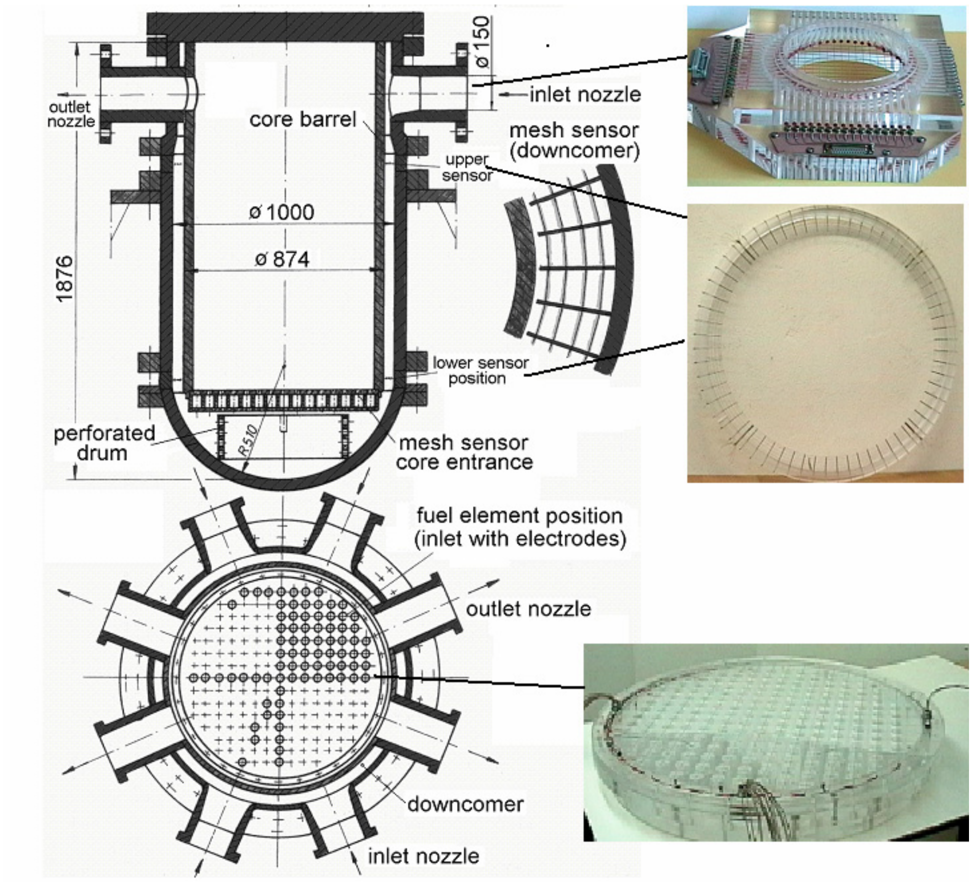


Fig. 2 Scheme of the vessel with positions of the sensors

Recently, a sensor was developed for an improved visualisation and quantification of the coolant mixing in the downcomer which can be installed instead of the two radial sensors described above. This new sensor spans a measuring grid of 64 azimuthal and 32 positions over the height of the downcomer (Fig. 3). For that purpose, 64 fixing bolts were installed at the inlet and the outlet of the downcomer. Between them, 64 wires (detail on Fig. 3) are spanned. These wires are the transmitter electrodes. The receiver electrodes are flat bar steels with a width of 3 mm, which are glued onto the inner side of the vessel in a distance of 31 mm between each other. The vertical wires are located nearby the core barrel wall. In this way, the measuring signal is the conductivity averaged over the width of the downcomer.

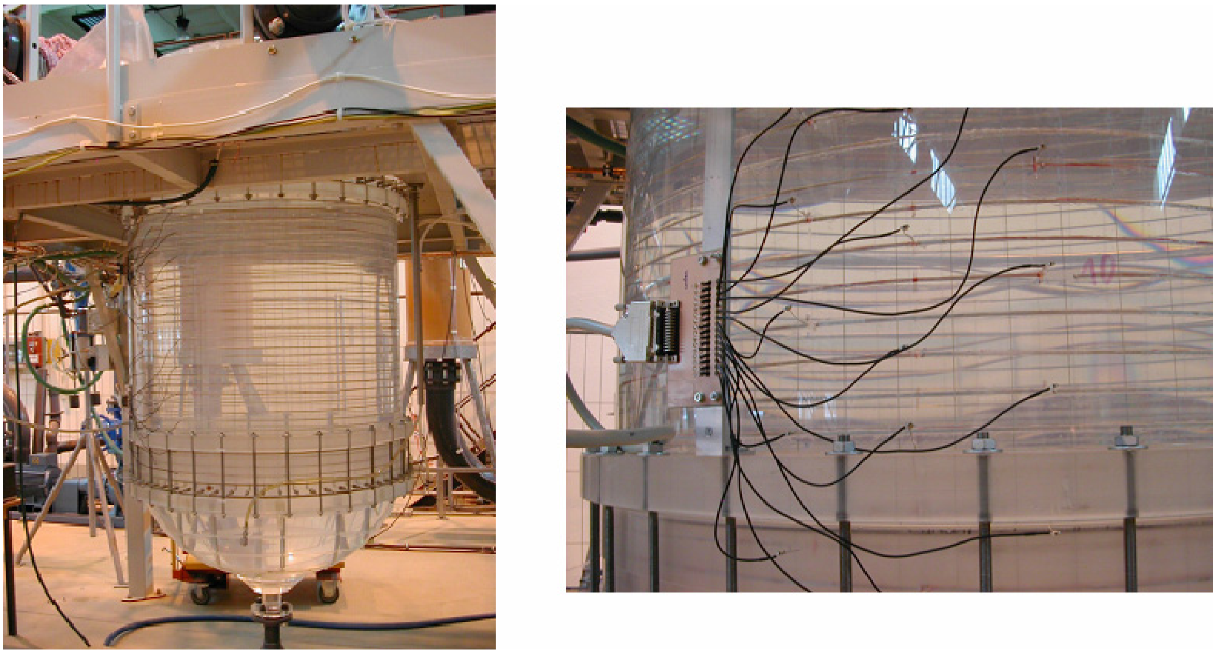


Fig. 3 View of the test facility with the new downcomer sensor

More details about the facility, the measurement devices, and the experiments performed earlier can be found in [3].

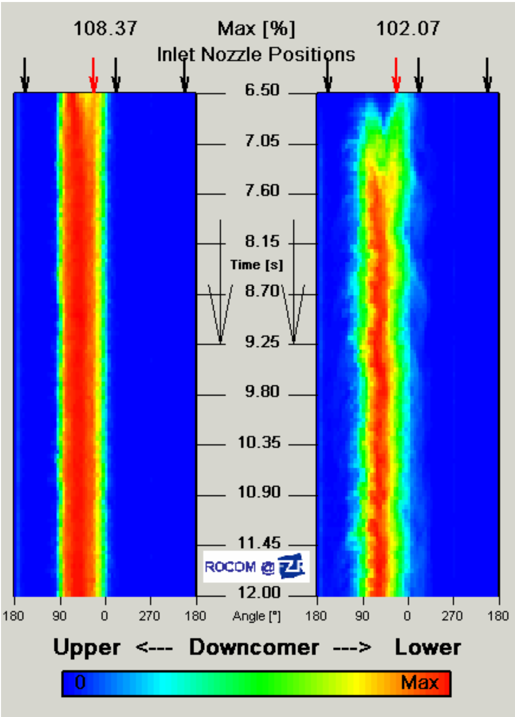
Overview on stationary and transient experiments

In the past, series of stationary and transient experiments have been performed [3, 4]. Here, an example of one stationary, one transient and one experiment with density differences are shown to demonstrate the capabilities of the test facility. In the steady-state test, all four loops are in operation, while a tracer solution is injected in one of them. In the transient test, the start-up of the first main coolant pump is simulated, and in the third presented experiment water with higher density is injected into the primary circuit of the test facility.

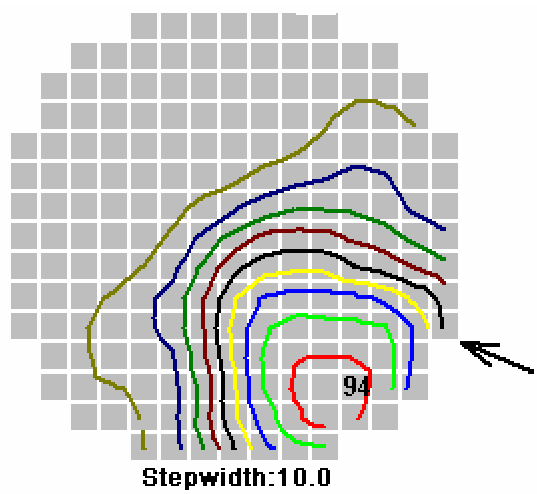
Stationary experiments

In a stationary experiment, the pumps in all loops are driven with constant frequency. The facility is operated over a certain time interval until the flow regime reached stable conditions. In the shown experiment (Fig. 4), the flow rates in all four loops correspond to the nominal values. Tracer injection is performed by means of a set of computer controlled pneumatic and magnetic valves. Usually five seconds after starting the measurement, the tracer injection valves are opened starting a continuous injection of salted water into the flow of loop N° 1. The time point for closing the valves is selected in such a way, that the tracer distribution reaches a saturation level at the core inlet. Time dependent mixing scalar data are obtained using Equ. 1.

The left part of Fig. 4 shows the time evolution of the mixing scalar at both radial sensors in the downcomer (shown in an unwrapped view). Already at the upper sensor, a redistribution of the flow is observed. The sector with the tracer shifted from the inlet position (22.5°) to the sector corresponding to the share of the total flow (middle position now is 45°). The sector covered by the tracer is 90°, what confirms the quality of the boundary conditions (equal flow rates in all loops). At the lower sensor, the tracer remains in the indicated sector, but fluctuations of the whole flow field are observed. Mixing with the ambient coolant takes places at the outer edges of the sector. At the core inlet, the tracer arrives at two positions at the border of the sector belonging to the corresponding loop at the same time. Only with growing time, the part in the middle of the sector is filled with tracer. After several seconds, the quasi-stationary concentration level establishes with a maximum in the middle of the sector (shown on Fig. 4 b). The shown distribution is obtained by a so-called plateau-averaging. All data at the quasi-stationary concentration level, which establishes several seconds after injection of the tracer are used for this averaging. Fig. 5 shows the time course of the average mixing scalar in the core inlet plane in the single realizations of one experiment. The time interval for the plateau-averaging is indicated, too. The above mentioned fluctuations of the whole flow field are clearly to be seen in the lower part of Fig. 5, where the time course of the mixing scalar at one single measurement position is shown. The assessment of the uncertainty arising from these fluctuations is described below.



a) Time evolution of the mixing scalar in the downcomer of the test facility



b) Plateau-averaged distribution of the mixing scalar in the core inlet plane
perturbation in loop 1 (arrow)
maximum: bold number in %
Stepwidth: difference between two isolines

Fig. 4 Distribution of the mixing scalar at different sensors in the vessel of the test facility

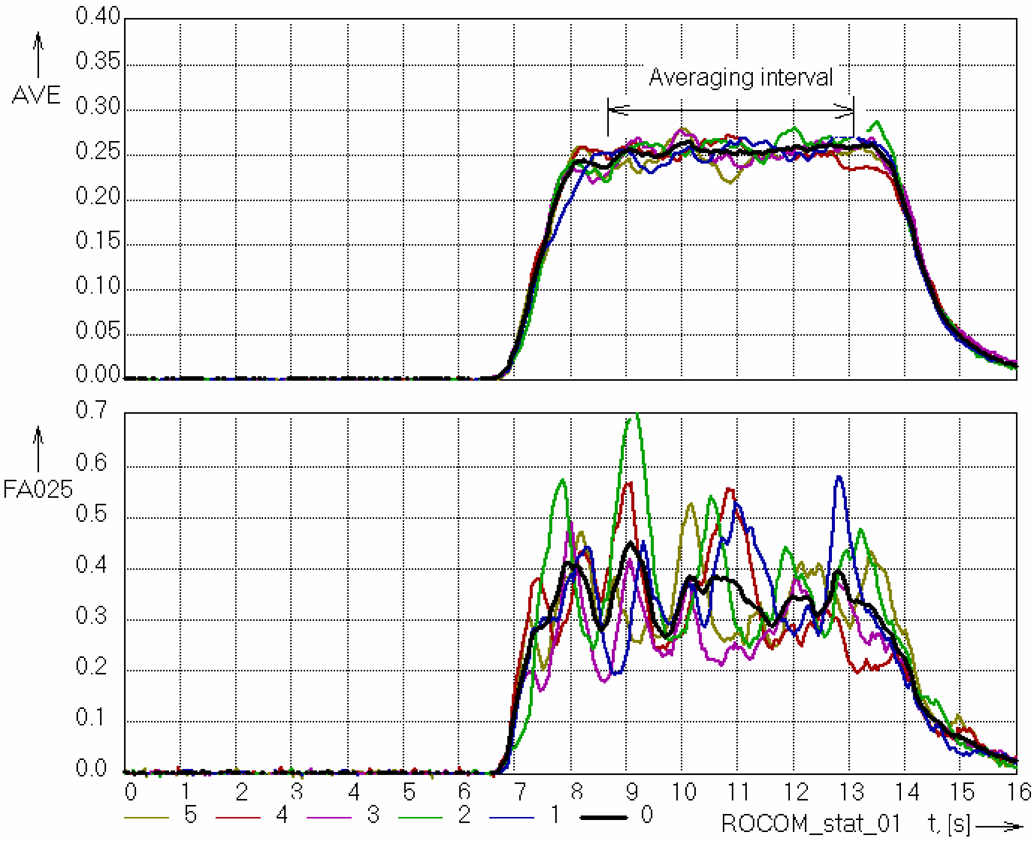


Fig. 5 Time evolution of the average mixing scalar (upper part) and at one certain position (lower part) in the single realizations of the stationary experiment

Transient experiments (start-up of the first main coolant pump)

Loop N°1 of the test facility is equipped with two valves between them a deborated slug has been prepared. These valves include a water volume of about 58 l, what corresponds to the volume of the loop seal and a part of the steam generator outlet chamber at the real plant. The distance of the front valve from the inlet into the vessel corresponds to the distance of the loop seal to the reactor pressure vessel at the plant, too. In the initial state, the coolant is stagnant in the whole test facility. At t = -3 s, the experiment is started with the opening of the valves, At t = 0 s the pump in loop N°1 is started, the pump rotation is controlled by a linear frequency ramp. The duration of the frequency ramp is the same as at the original reactor: 14 s. The final value of the frequency ramp corresponds to the nominal flow rate for one loop (185.0 m^3/h corresponding to a velocity of 2.91 m/s). As can be seen on Fig. 6, the movement of the coolant in loop N°1 starts with a small delay due to the inertia of the pump and the water column. Than, the velocity increases more or less linearly until the plateau value. In the passive loops, a reverse flow of about 5 % of the nominal value establishes.

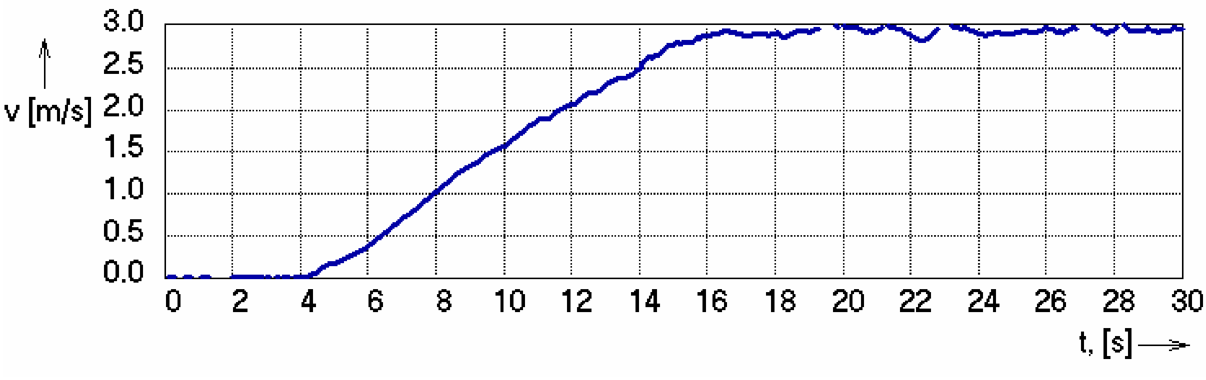


Fig. 6 Velocity in the starting up loop

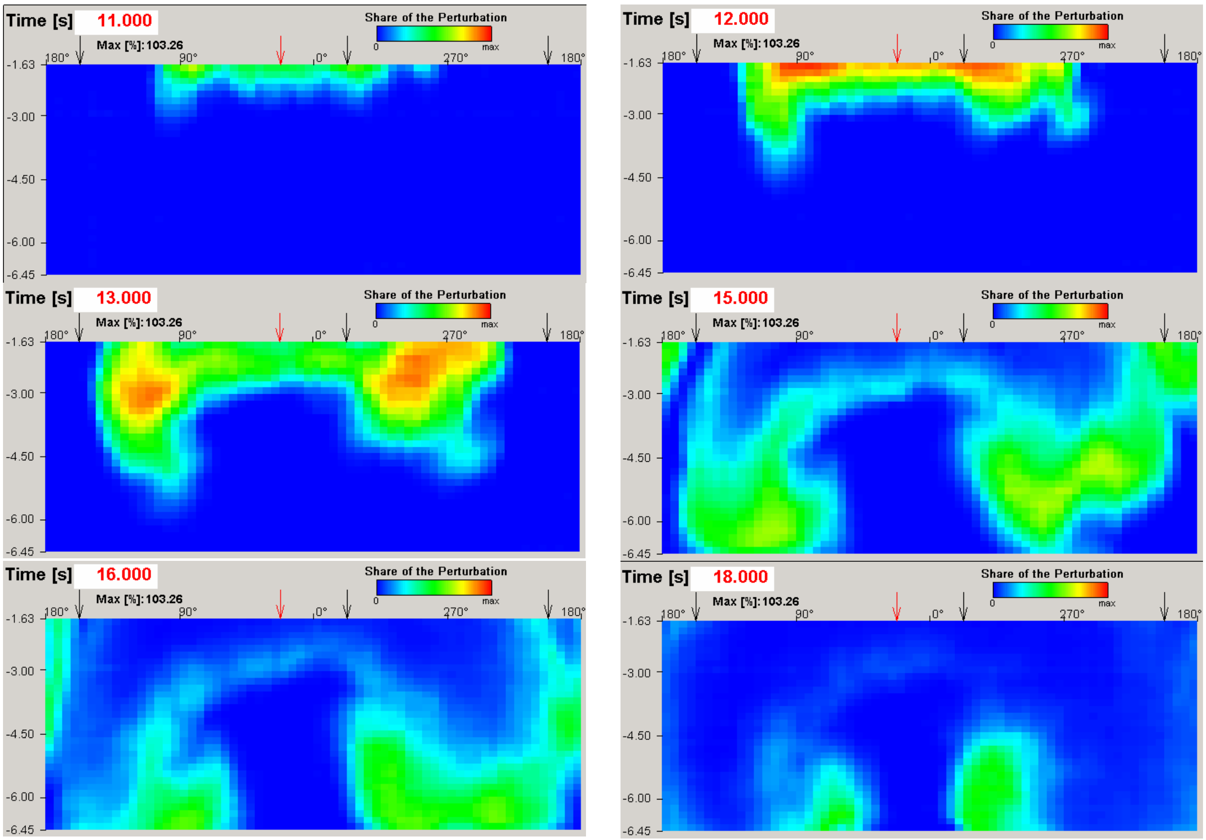


Fig. 7 Time sequences of the perturbation in the axial downcomer sensor

In the presented experiment, the axial downcomer sensor was installed. Fig. 7 shows sequences of the movement of the deborated water through the downcomer at different time points in an unwrapped view. The position of the loops are shown by arrows, the red one indicates the loop with the starting-up pump. The numbers of the left side are elevations counted from the middle of the cold leg in real reactor geometry.

Different from the time evolution shown in Fig. 4a, now information about the mixing in the whole downcomer is available due to the new sensor. The measurements of the new sensor add a lot of information, how the deborated water flows in the downcomer. From the visualization is clearly to be seen, that the deborated coolant passes around the core barrel instead of flowing directly downstream. It arrives below the affected inlet nozzle. With growing time, the tracer spreads in the azimuthal direction. Even recirculation areas found in velocity measurements and earlier CFD calculations can be visualized (especially to be seen at t = 15.0 s and t = 16.0 s).

At the core inlet, the tracer appears at the side nearly opposite to the affected inlet nozzle (Fig. 8). The maximum value of the mixing scalar (equal to under-boration) reached 58 % in this test. It strongly depends on the volume of the initial slug of deborated coolant, i.e. the amplitude of the deboration of the core decreases, if the slug is smaller.

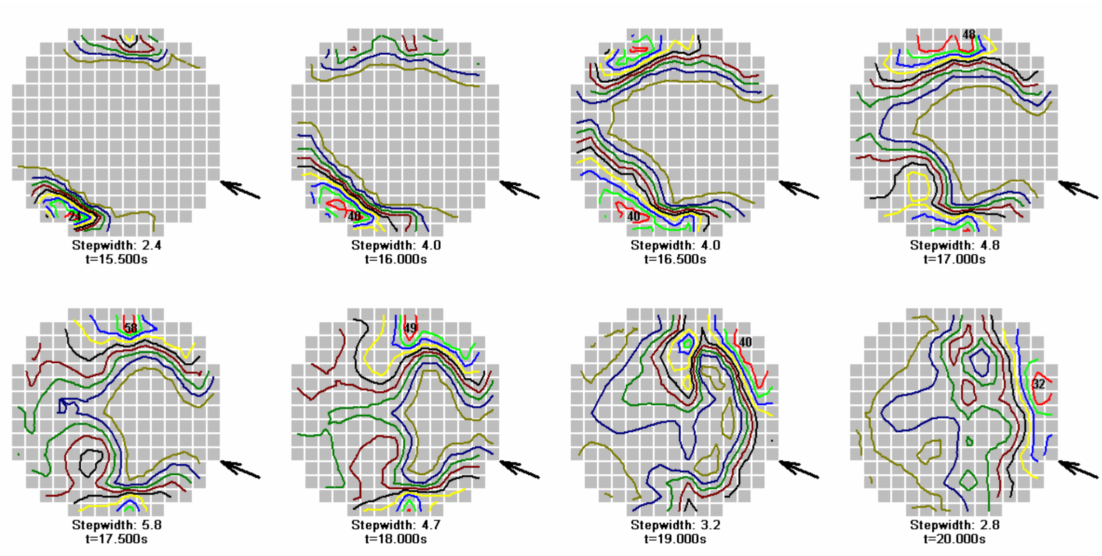


Fig. 8 Time sequences of instantaneous mixing scalars at the core inlet
perturbation in loop 1 (arrow)
maximum: bold number in %
Stepwidth: difference between two isolines

Experiments with density differences (Mixing of ECC-water)

For the investigation of the influence of density effects, generic experiments have been carried out at the ROCOM test facility [4]. It is expected, that density differences can be neglected, if the flow rates are sufficiently high, that means, if mixing is momentum controlled. To find the conditions for transition between momentum controlled and buoyancy driven mixing, experiments with variation of density differences between the mixing fluids were performed. To simulate the mixing of colder ECC water, an accurately modeled ECC injection nozzle has been connected to one of the cold legs of ROCOM. Due to the fact, that the test facility cannot be heated up, the necessary density differences were simulated by adding sugar (glucose) to the water that is injected into the cold leg. To observe the mixing of the ECC water, this water was tracered by small amounts of sodium chloride, as in previous experiments. In the experiments of this series, the two radial downcomer sensors were installed in the test facility.

The experiment without density effects serves as reference experiment for the comparison. Fig. 9 (left) visualizes in an unwrapped view the time evolution of the tracer concentration measured at the two downcomer sensors. The downwards directed arrow indicates the position of the loop with the running pump, in that case delivering 10 % of the nominal flow rate. At the upper radial downcomer sensor, the ECC water (injected in each experiment from t = 5 to t = 15 s) appears directly below the inlet nozzle. Due to the momentum created by the pump, the flow entering the downcomer is divided into two streams flowing right and left in a downwards directed helix around the core barrel. At the opposite side of the downcomer, the two streaks of the flow fuse together and move down through the measuring plane of the lower downcomer sensor into the lower plenum. Almost the whole quantity of ECC water passes the measuring plane of the lower downcomer sensor at the side opposite to the azimuthal position of the affected loop. Such a velocity field is typical for single-loop operation (see Fig. 7). It has its maximum at the opposite side of the downcomer and a minimum at the azimuthal position of the running loop, which has been found in velocity measurements by means of a laser-Doppler anemometer at the ROCOM test facility, too. The maximum tracer concentration of the ECC water in the downcomer is 20.0 % of the injected water concentration at the upper sensor and 8.0 % at the lower sensor.

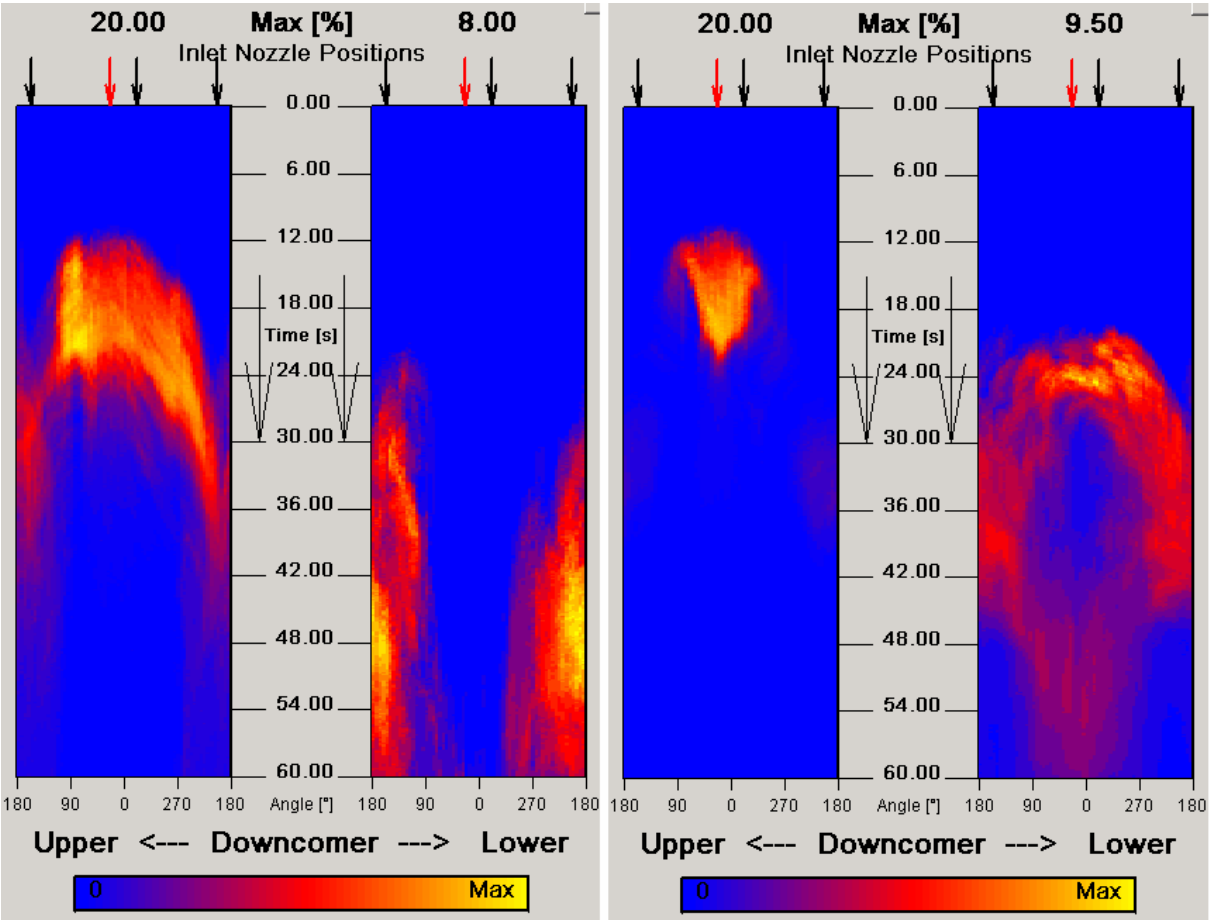


Fig. 9 Time evolution of the mixing scalar in the experiment with 10 % flow rate and 0 % density difference (left) and 10 % flow rate and 10 % density difference (right)

Fig. 9 (right) shows the experiment, carried out at the same flow conditions, but the density difference between the injected ECC water and the primary loop coolant is now 10 %. In that case a streak formation of the water with higher density is observed. At the upper sensor, the ECC water covers a much smaller azimuthal sector. The density difference partly suppresses the propagation of the ECC water in horizontal direction. The ECC water falls down in an almost straight streamline and reaches the lower downcomer sensor directly below the affected inlet nozzle. Only later, coolant containing ECC water appears at the opposite side of the downcomer. The maximum concentration values observed at the two downcomer sensors are in the same region as in the case without density differences, i.e. 20.0 % and 9.5 % from the initial concentration in the ECC water tank. The visualizations of the behavior of the ECC water in the downcomer reveals that in case of momentum driven flow, the ECC water covers nearly the whole perimeter of the upper sensor and passes the measuring plane of the lower sensor mainly at the opposite side of the downcomer. When the density effects are dominating, the sector at the upper measuring device covered by the ECC water is very small. The ECC water falls down straightly and passes the sensor in the lower part of the downcomer below the inlet nozzle of the working loop.

Uncertainty analysis of the measurement results

It was found in the experiments, that the time behavior of the resulting mixing scalar at identical positions in the pressure vessel differs in each single realization of an experiment with identical boundary conditions. Fluctuations of the flow field in the reactor pressure vessel are the reason for these deviations between single realizations of one experiment. These fluctuations are due to the turbulent nature of the flow, and therefore they appear by chance to a certain degree. Usually, the experiments are repeated five or more times. The results of these single realizations were averaged. These averaged data are documented and can be used for further analysis. That was done to damp the statistical fluctuations mentioned above.

It is possible to use the data of the single realizations to carry out an uncertainty analysis of the obtained results: In the first step, the minimum error amount $FS_{\min,\Theta}$ for each local value of the mixing scalar at each time point is calculated according to Equ. 2 using the averaged values and the n single realizations.

$$FS_{\min,\Theta}(x,y,z,t) = \sum_{k=1}^{n} (\theta_{ROCOM,k}(x,y,z,t) - \bar{\theta}_{ROCOM}(x,y,z,t))^2 \quad \text{Equ. 2}$$

The standard deviation is calculated according to

$$s_{\Theta}(x,y,z,t) = \sqrt{\frac{FS_{\min,\Theta}(x,y,z,t)}{n-1}} \quad \text{Equ. 3}$$

In the last step, the confidence intervals can be calculated using:

$$u_{z,\Theta}(x,y,z,t) = \pm t_P . \frac{s_{\Theta}(x,y,z,t)}{\sqrt{n}} \quad \text{Equ. 4}$$

This confidence interval characterizes the interval around the average value in which the measured value can be found with a given probability of the statistical confidence. Hereby, t_p is the value of the Student-factor. This factor varies with the selected statistical confidence. Usually, the confidence intervals for 68.4 % (corresponds to 1 σ), for 95.4 % (2 σ) and 99.5 % (3 σ) are calculated and included into the documentation, whereby σ is the square root of the variance of the distribution.

Using Equ. 2 to Equ. 4, the time curves for the confidence intervals are calculated for each measurement position of all wire mesh sensors inside the reactor pressure vessel. An example is shown on Fig. 10.

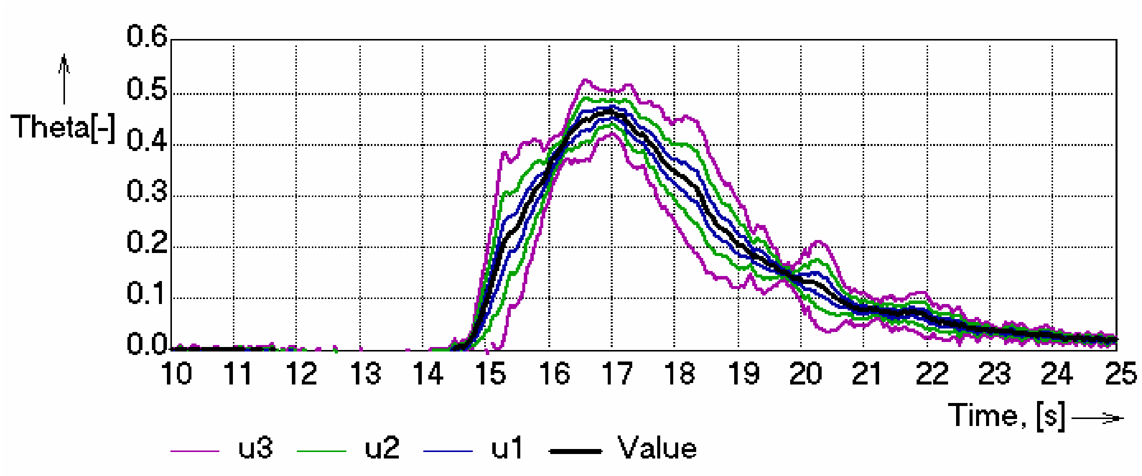


Fig. 10 Confidence intervals for one certain measurement position in the start-up experiment (average value over all realizations, confidence interval for 1 σ, 2 σ and 3 σ)

Error analysis of the measurement results

An error analysis of the measured conductivity values has been performed to assess the quality of the obtained results [3]. In this analysis, the following three different sources of errors are included:

A linear calibration curve is used to transfer the measured current at each position into a conductivity value. This curve is based on the sampling points, determined in the actual measurement series. The deviation of the real measurement value from the calibration curve is a possible source of error.

A 11 bit digital number is the primary measurement value, representing the current at the corresponding crossing point of two wires. This current is proportional to the local conductivity at the measurement position. Each measurement position has its individual characteristic (dependence of the conductivity from the measured current). The steepness of this dependence determines the value of the discretisation error. It corresponds to the change of the conductivity caused by a change of the primary measured value by 0.5.

Electrical noise acting on the sensors from outside, fluctuations of conductivity or temperature of the water in the facility as well as the noise of the used electronic devices lead to statistical fluctuations of the signals. They are present in the measured conductivity values as a statistical error. This error can be determined by analyzing the measurement values at the single wire mesh sensors before the injected tracer reaches the measuring cross section. The analysis revealed a clear statistical nature of these fluctuations.

The single contributions to the total error were determined as absolute errors with a given statistical confidence P. The absolute total error of a directly measured value is given as the sum of the contributions together with the smallest statistical confidence. That means for a instantaneous measured conductivity value:

$$\Delta\sigma_P = \Delta\sigma_{calib} + \Delta\sigma_{Diskr} + \Delta\sigma_{fluct} \qquad \text{Equ. 5}$$

where $\Delta\sigma_P$ is the total error of a conductivity value, $\Delta\sigma_{calib}$ is the calibration error, $\Delta\sigma_{Diskr}$ the discretisation error and $\Delta\sigma_{fluct}$ the error introduced by statistical fluctuations.

The mixing scalar (Equ. 1) is an indirectly determined quantity. Three different conductivity values contribute to this mixing scalar. Therefore, the absolute maximum error is calculated with:

$$\Delta\Theta(t,x,y,z) = \pm\left(\left|\frac{\partial\Theta}{\partial\sigma(t,x,y,z)}\right|\cdot\Delta\sigma + \left|\frac{\partial\Theta}{\partial\sigma_0(x,y,z)}\right|\cdot\Delta\sigma_0 + \left|\frac{\partial\Theta}{\partial\sigma_1}\right|\cdot\Delta\sigma_1\right) \qquad \text{Equ.6}$$

The contributors are the instantaneous conductivity at the measurement position ($\sigma(t,x,y,z)$), the averaged conductivity at the measurement position before the tracer reaches the position ($\sigma_0(x,y,z)$) and the reference conductivity (σ_1) at the inlet into the reactor, each of them with their own deviations.

As outlined above, the single measurement positions in the test facility have their individual error characteristics. An assessment of the data of a typical experiment showed, that the mixing scalar can be determined with an error band of less than ± 3 %.

Conclusions and outlook

ROCOM (Rossendorf Coolant Mixing Model) is a test facility for the investigation of coolant mixing in the primary circuit of pressurized water reactors. The installed measurement technique together with the flexibility in operation virtually predestine the facility for the validation of CFD-codes.

Data from already conducted measurements can be provided for CFD-code validation. An overview on the available data base has been presented.

Based on the broad experience gained in performing mixing experiments, FZR proposes two different types of new experiments for the validation of CFD-codes. The first proposal concerns the transport of a slug with reduced density from the cold leg of one loop to the core inlet. This experiment refers to generic boron dilution transient (BDT) conditions, when a slug of hot, under-borated condensate, which has formed in the cold leg after a small break LOCA, is moved towards the reactor core with natural circulation flow rate in one loop. In the second experiment the propagation of the emergency core cooling water in the test facility under natural circulation or even stagnant flow conditions is proposed to be investigated. In this experiment, the density of the injected water will be higher than the ambient coolant (relevant for PTS scenarios). Such an experiment would be an extension of the already available measurement data on mixing of ECC water. It is also possible to perform other experiments with momentum or buoyancy driven mixing processes.

The experiments will be accompanied by velocity measurements in the downcomer.

The information from the about 2000 single measurement positions of the new sensor allows a detailed 2D visualization of the mixing processes in the downcomer. By means of these data it is possible to carry out validation of CFD-codes at a qualitative new level.

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