DENSITY EFFECTS ON COOLANT MIXING IN PRESSURIZED WATER REACTORS

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1. Introduction

During emergency core cooling (ECC) injection into the cold leg of a PWR, an incomplete mixing with the natural circulation flow in the loop takes place. Due to the higher density of the ECC water, a streak of cold water is flowing downwards the downcomer. This causes thermal loads on the reactor pressure vessel (RPV). Furthermore, in the case of inadvertent injection of low borated ECC water, a boron dilution transient would be initiated. The transient is determined by the resulting boron concentration distribution at the core inlet. For the investigation of the influence of density effects, generic experiments have been carried out at the ROCOM (Rossendorf Coolant Mixing Model) [1-3] test facility. ROCOM is a 1:5 scaled model of a German KONVOI type 1300 MW PWR with controllable pumps in all loops, so that a wide range of flow conditions between natural circulation and nominal flow can be simulated. Previous investigations have been done on coolant mixing with operating pumps and during the start-up of coolant circulation in the primary circuit without density differences in the fluid [1-3]. 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 to buoyancy controlled mixing, generic experiments with density differences were performed. To investigate the mixing of the ECC water, an exactly modelled ECC injection nozzle has been connected to one of the cold legs of ROCOM.

Investigations on density effects in coolant mixing have been performed earlier at different experimental facilities (i.e. HDR [4], UPTF [5], University of Maryland [6, 7]). However, in the experiments presented in this paper, a significantly higher spatial resolution of the tracer concentration measurements is achieved.

2. Boundary conditions of the experiments

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, enhancing the conductivity. Generating density differences by high salt concentrations is not possible, because the measurement system is very sensitive and would be saturated at high salt concentrations.

The test facility is equipped with wire mesh sensors for high resolution measurement of the transient concentration of the tracer in space and time. They are based on the measurement of the electrical conductivity. One sensor is located in the cold leg inlet nozzle of the loop with the ECC injection nozzle, two in the downcomer just below the inlet nozzles and before the entrance into the lower plenum, respectively. Each of the downcomer sensors has a measurement grid consisting of 64 angular and 4 radial points. The fourth sensor is integrated into the lower core support plate and has one measurement position at each fuel element inlet [2]. Dimensionless mixing scalars were derived from the data provided by the sensors with a time resolution of 0.05 s. These scalars are defined as follows:
where $i$ is the current measurement position; $\sigma_i$ the conductivity at that position, $\sigma_0$ the conductivity of the water before the experiment and $\sigma_P$ the conductivity of the injected ECC water.

The goal of the experiments presented in the current work was the generic investigation of the influence of density differences between the primary loop inventory and the ECC water on the mixing in the downcomer. To separate the density effects from the influence of other parameters, a constant flow in the loop with the ECC injection nozzle was assumed in this study. The mass flow rate was varied in the different experiments between 0 and 15 % of the nominal flow rate, i.e. it was kept in the magnitude of natural circulation. The other pumps were switched off.

The density difference between ECC and loop water has been varied between 0 and 10 %. Fig. 1 summarises the boundary conditions of the experiments. Altogether 20 experiments have been carried out (dots in Fig. 1). In all experiments, the volume flow rate of the ECC injection system was kept constant at 1.0 l/s. The normalised density is defined as the ratio between ECC water density and density of fluid in the primary circuit. All other boundary conditions are identical. Due to the fluctuations of the flow field in the RPV [2] observed earlier, each experiment was repeated five times to average over these fluctuations.

3. Experimental results and interpretation

3.1. Reference experiment

The experiments without density effects serve as reference experiments for the comparison. Fig. 2 visualises the time evolution of the tracer concentration in an unwrapped view measured at the two downcomer sensors. The downwards directed red arrow indicates the position of the loop with the running pump, in that case delivering 10 % of the nominal flow rate. At the upper 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.

The maximum tracer concentration of the ECC water in the downcomer is 20% of the injected water concentration at the upper sensor and 8% at the lower sensor. This concentration profile results from the velocity field typical for single-loop operation. 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 [8].

3.2 Experiment with 10% density difference

Fig. 3 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 impedes the horizontal propagation of the ECC water. The ECC water falls down in an almost straight streamline and reaches the lower downcomer sensor directly below the affected inlet nozzle. Later only, coolant containing ECC water appears at the opposite side of the downcomer.

The maximum concentration values observed at the two downcomer sensors are significantly higher than in the case without density differences, i.e. 37.5% and 20.0% from the initial concentration in the ECC water tank. The visualisations of the behaviour 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. Furthermore, variations of the density were carried out to identify the transition region between momentum driven and density driven flow.

### 3.3 Experiment with 4 % density difference

Fig. 4 shows an experiment with a density difference of 4 %, while the flow rate was again 10 % of the nominal. At the upper sensor, the width of the azimuthal sector covered by the ECC water is in-between the two cases with 0 % respectively 10 % density difference. Near the lower sensor, the ECC water reaches the opposite side of the downcomer and the region below the inlet nozzle position almost at the same time. That means, that one part of the ECC water follows the stream lines of the external momentum driven flow field and another part directly falls down due to the internal momentum created by density differences. We consider this as an intermediate state between momentum and density driven flow. The experiment in Fig. 4 was therefore assigned to the transition region between the two flow regimes.

Based on these observations, the set of experiments conducted according to the matrix in Fig. 1, was divided into three groups: density dominated flow (◊), momentum dominated flow (∆) and the transition region (*). The conditions at the inlet into the downcomer were used to calculate Froude-numbers of the experiments according to the following formula [3]:

\[
Fr = \frac{v_{in}}{\sqrt{g \cdot s \cdot \frac{\rho_{in} - \rho_{a}}{\rho_{in}}}}
\]

(2)

where \(v_{in}\) is the velocity at the reactor inlet (combined loop and ECC flow), \(g\) is the gravitational acceleration, \(s\) is the width of the downcomer, \(\rho_{in}\) the density of the incoming flow, calculated with the assumption of homogeneous mixing between ECC and loop flow, and \(\rho_{a}\) the density of the ambient water in the downcomer. Lines of constant Froude-numbers calculated by means of this formula are shown in Fig. 1. All experiments identified as density dominated are located in the region left of the isoline \(Fr = 4.0\) and all momentum dominated points are found right of the isoline \(Fr = 7.0\). These two numbers are critical...
Froude numbers separating the two flow regimes for the ROCOM test facility. A transition region is located between the two critical values.

Density effects are extremely developed in an experiment with no flow in the primary loop (Fig. 5), where the fluid circulation is initiated only by starting the ECC injection (injection time was 40 s). At the upper sensor, the ECC water appears unmixed and covers a sector of only about 15°. The data from the lower downcomer sensor show clearly buoyancy induced turbulent structures. As can be concluded from these data, the water with higher density accumulates in the lower plenum.

4. Core inlet distribution

The conclusions concerning the influence of the density on the mixing processes in the RPV are confirmed by the experimental data obtained from the measuring device at the inlet into the core. Fig. 6 shows the distribution of the tracer at the core inlet sensor at the time point of the first maximum in the three above described experiments. The different mixing mechanisms responsible for the distribution of the tracer in the downcomer determine the distribution at the core inlet, too. Thus, in the experiment without density differences, the ECC water goes preferred to the side opposite to the azimuthal position of the loop with the working pump. The experiment with 4 % density difference shows the transition character of the flow regime and in the experiment with 10 % density difference the first tracer appears directly below the position of the loop with the working pump.

![Core inlet distribution diagram](image)

Fig. 5: Time evolution of the mixing scalar at the two downcomer sensors in the experiment with 0 % loop flow rate and 10 % density difference

![Core inlet distribution diagram](image)

Fig. 6: Core inlet distribution of the mixing scalar at the time point of maximum in the experiments with 10 % loop flow rate and varied density difference
5. Outlook

The goal of further investigations should be to clarify the possibility of generalisation of the transition criterion between density controlled and momentum controlled mixing and the dependence on geometry and other parameter constellations. This should include the analysis of experiments from other test facilities. The data of the experiments will be used for the validation of computational fluid dynamics codes to density driven flow regimes in reactor geometry.

References


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