1. Introduction

During emergency core cooling the higher density of the Emergency Core Cooling (ECC) water forms a plume of cold water flowing downwards the downcomer. This can cause thermal loads on the reactor pressure vessel (RPV). Additionally, in the case of inadvertent injection of low borated ECC water, a boron dilution transient would be initiated.

To make realistic predictions about the consequences it is necessary to study the coolant mixing, which is a complicated three-dimensional fluid dynamic problem. Modern CFD codes running on powerful computers became available to model the coolant flow in the complex geometry of a PWR a couple of years ago. Due to the high safety relevance of the coolant mixing phenomenon it is necessary to validate computer codes and to verify computational results using experimental data.

In order to study coolant mixing under these conditions inside the RPV of a German type PWR the test facility ROCOM (Rossendorf Coolant Mixing Model) was used. Within a cooperation with CEA Grenoble the TRIO_U code was applied for a Large Eddy Simulation (LES) of density driven flow and mixing phenomena.

2. The ROCOM Test Facility

ROCOM is a 1:5 scaled 4-loop model of a German Konvoi pressurized water reactor. There are controllable pumps (Fig. 1) in each of the loops so that flow regimes can be simulated from natural coolant circulation to nominal flow conditions [1]. Beginning from the bends in the cold legs, which are close to the reactor inlet, the geometrical similarity between model and original reactor is respected until the core inlet. The RPV model is manufactured from Plexiglas®. In case of the experiments on ECC injection, an injection nozzle was used, which was geometrically similar to the original Konvoi reactor. The higher density of the cold ECC water was simulated by adding sugar (glucose), since density gradients cannot be created by temperature differences, because the facility cannot be heated up. Fortunately, the viscosity of glucose solution becomes large only at concentrations, where the relative density increase is well above the 10% necessary for the experiments. A sugar solu-
tion with the corresponding density of 1100 kg/m³ has a viscosity, which is still just by factor of about 3 higher than that of pure water. The tracer can therefore still be envisaged as a low-viscous fluid.

The test facility is equipped with advanced instrumentation [2], which delivers high-resolution information characterizing either temperature or boron concentration fields in the investigated pressurized water reactor.

3. The Buoyancy Driven Experiment

The goal of the experiment 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 volume flow rate of the ECC injection system was kept constant at 1.0 l/s. For the comparison with Trio_U an experiment with constant flow rate of 5% of nominal flow in one loop (magnitude of natural circulation) and 10% density difference between ECC and loop water was taken (Table 2). According to the classification of mixing provided in [1] based on the Froude number, it was identified as density dominated mixing.

Table 1: Experiment chosen for code validation

<table>
<thead>
<tr>
<th>( \dot{V} ) (ECCS) / ( [m^3/h] )</th>
<th>( \dot{V} ) (Cold Leg) / ( [m^3/h] )</th>
<th>Density difference Loop Inventory / ECC water ( [kg/m^3]/[kg/m^3] )</th>
<th>Fr (Downcomer) [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6</td>
<td>9.25</td>
<td>1:1.1</td>
<td>1.62</td>
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</table>

4. The Trio_U Code

Within the Trio_U project, a thermal hydraulic code for strongly unsteady low Mach number, single phase turbulent flows is under development at the CEA-Grenoble, which is especially designed for industrial LES on structured and non-structured grids of several tens of millions of nodes [3]. The platform independent code is based on an object oriented, intrinsically parallel approach and is coded in C++. The flexible code structure allows the user to choose a suitable discretization method and to combine various appropriate physical models. Several convection and time marching schemes as well as a wide range of boundary conditions are available. This flexibility is implemented without a reduction of the overall performance of the code.

For unstructured grids, the hybrid « Finite Volume based Finite Element » method (VEF) is applied. This method consists in determining for a continuous problem a discrete solution in the space of the finite element by maintaining the balance notation of finite volumes. The space discretization is performed with triangles in 2-dimensional case and with tetrahedral cells in 3-dimensional case. In Trio_U, the main unknowns velocity and temperature are located in the center of the faces of an element (triangle or tetrahedron) whereas the pressure is discretized in the center and in the vertices of the element (staggered mesh) in order to improve the velocity/pressure coupling for LES applications.
5. Grid Generation and Boundary Conditions

This meshing has been generated from the CAD model using the mesh generator ICEM-CFD TETRA. For this study, a LES approach was used for mesh sizes between 1–2 million control volumes.

Solid walls bound the fluid domain, an outlet boundary was put at the position above the core support plate. The cold leg CL1 (see Fig. 2) including the ECC injection line was modeled. Inlet boundary conditions were put at the ECC line and at the area after the bend of the cold leg CL1. At the outlet, a free outflow condition with a constant pressure was used. For the solid walls, standard wall functions were applied for both momentum and temperature transport equation. The velocities in the idle loops were defined as zero. The ECC injection lasts 10 s. A uniform velocity profile was defined at the injection line during this period. The tracer injection was simulated by the help of a scalar field, which was defined to be unity in the cold leg CL1 and zero at the ECC injection line.

The Boussinesq approximation (1) was used to model the effect of density differences.

\[ \frac{\rho}{\rho_0} = 1 - \beta(T - T_0) \] (1)

6. Results

Both, the experiment and the Trio_U calculation show qualitatively the same flow and mixing behavior.

In the cold leg the ECC water only partly mixes with the loop inventory. A clear stratified flow is developing during the injection. At the upper downcomer sensor position, the ECC water appears directly below the inlet nozzle.

At the beginning, the covered area in the downcomer is bigger, because the momentum driven flow field of CL1 (mass flow rate of 5% of nominal flow rate) is still present. After this, the density difference partly suppresses the propagation of the ECC water in circumferential direction. The ECC water falls down in an almost straight streamline (Fig. 2) and reaches the lower downcomer sensor directly below the affected inlet nozzle (Fig. 3). The well mixed ECC water in the lower plenum is directed upwards towards the core by the impact of the perforated drum. As a result, the well mixed ECC water at the core inlet arrives also in the sector below the inlet nozzle CL1 (Fig. 4).

Only later, coolant containing ECC water appears at the opposite side of the lower downcomer area and occurs also at the opposite part of the core inlet.
7. Conclusion

A generic investigation of the influence of density differences between the primary loop inventory and the ECC water on the mixing in the downcomer was made at the ROCOM Mixing Test Facility at Forschungszentrum Rossendorf (FZR). For the validation of the Trio_U code an experiment with 5% constant flow rate in one loop (magnitude of natural circulation) and 10% density difference between ECC and loop inventory was taken. The study showed, that density effects play an important role during natural convection with ECC injection in pressurized water reactors. Furthermore it was important to point out, that Trio_U is able to cope the main flow and mixing phenomena.

References