CFD MODELING OF MIXING PHENOMENA FOR PRESSURIZED THERMAL SHOCK ANALYSIS ON THE DOWNCOMER OF WWER-440

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ABSTRACT

Pressurized thermal shock (PTS) due to mixing of hot and cold coolant during certain accident conditions can lead to the rupture of the reactor pressure vessel (RPV), evaluation of which is therefore one of the crucial tasks of nuclear safety. In the current investigation, three dimensional computational fluid dynamics (CFD) analysis was carried out in the context of PTS study for the WWER-440 type reactor of the Armenian Nuclear Power Plant Unit 2 using the ANSYS CFX commercial code. The objective of the analysis is to assess coolant mixing phenomena in the cold leg and the downcomer of the WWER vessel.

Calculations were performed for normal operation and after the emergency core cooling system (ECCS) injection begins. Different turbulence models were investigated with the objective of assessing their impact on the results of the analysis. Cold coolant tongues inside the downcomer were observed and their location and minimum temperature at these spots were determined. Sensitivity analysis of the pipeline geometry was performed to study its influence on the velocity profile at the downcomer inlet and the coolant velocity streamlines in the downcomer. Results also showed thermal stratification of the coolant inside the pipes and the downcomer.

KEYWORDS
Reactor pressure vessel, CFD, ANSYS CFX, Pressurized thermal shock, WWER-440

1. INTRODUCTION

One of the most important problems considered in safety assessment of some PWR’s including WWER reactors is PTS which can be a reactor vessel lifetime limiting factor as the replacement of the vessel is not feasible and it is a barrier against fission product release. PTS can occur during emergency core cooling (ECC) injection, when coolant at a much lower temperature than the coolant inside the primary circuit is injected, the turbulent mixing of which can cause temperature fluctuations with large gradients inside the cold leg and downcomer of the reactor. These temperature gradients on the structure surfaces of the primary circuit create thermal stresses while they are still loaded with high pressure. PTS in the case of a small-break loss-of-coolant accident (SB-LOCA) can lead to propagation of cracks bringing about a structural failure of the primary pipelines or of the vessel, leading to a severe accident.

Lumped-parameter codes use conservative methods to predict thermal-hydraulic processes with results that are averaged within a reactor to estimate safety margins and are acceptable by regulatory authorities, but do not take local 3D flow phenomena such as those that can lead to PTS into account. While the history of CFD usage in nuclear safety assessment is relatively recent, its capability to assess the 3D conditions of fluid mixing and other phenomena allow it to predict fluid stratification and temperature distribution throughout the reactor vessel to be able to predict possible locations where PTS can occur.

While its use has not been integrally validated for a WWER-440 pressure vessel, coupled with RELAP or other 1D lumped-parameter codes to supply its boundary conditions, it can provide additional analysis for safety assessment purposes [1-2].

In this paper, the case of coolant mixing during emergency injection of an 18 mm LOCA was considered. An 18 mm break in one of the cold legs will lead to actuation of ECCS and injection of cold water in the cold legs of the primary circuit, which in half of the cold legs is injected after and in half before the reactor coolant pump (RCP).

2. DESCRIPTION OF THE MODEL

2.1. ANPP Unit 2 Reactor

The Armenian Nuclear Power Plant (ANPP) Unit 2 is equipped with a WWER-440-V270 reactor, which is an antiseismic modification of V230. It is a first generation reactor designed in the late 1960’s, and is clad with stainless steel.

Armenia-2 reactor pressure vessel (RPV), as shown in Fig. 1, consists of two concentric cylinders that form the downcomer, the water flowing down from which then rises through the inner cylinder as it cools the reactor core. The diameters of the cylinders are variable, with the inner diameter at its thinnest point about 3.5015 m and at its thickest point reaching 3.840 m. The lower plenum curve can be estimated to be elliptical, with the major inner diameter equal to 3.501 m and the minor inner diameter equal to 0.861 m. The six hot and six cold legs are arranged on two planes with mirror symmetry. The horizontal angles between every two nearest pipes are 50 or 80 degrees, depending on the location with respect to the mirror symmetry. The hot leg plane is located 64 cm above the cold leg plane. The cold legs enter the downcomer, while the hot legs leave the central cylinder above the reactor core.

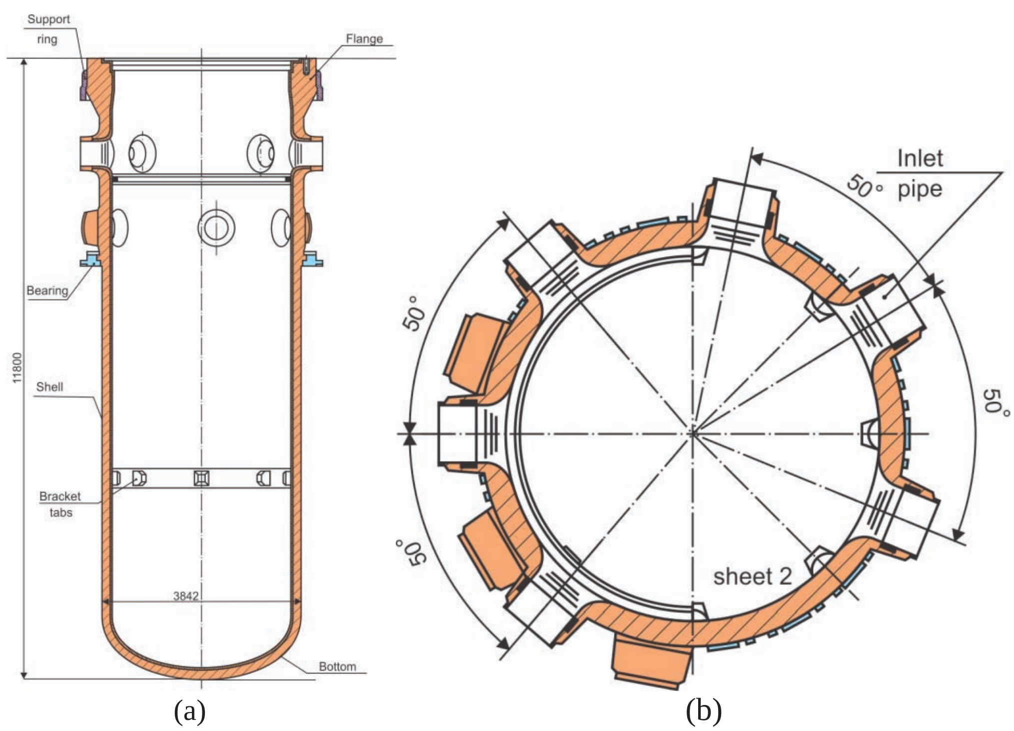


Fig. 1. Sketch of ANPP reactor vessel side view (a) and overhead view where horizontal cut on the left half is through the hot legs and on the right half is through the cold legs (b) [3].

The cold leg piping of the reactor can be seen in Fig. 2. The inner diameter of the pipe in ANPP unit 2 is 496 mm, while the wall thickness is 32 mm. High pressure injection (HPI) nozzles connect to the cold legs of the reactor. The location of connection varies in different WWER-440 reactors; in case of ANPP unit 2 the HPI is connected before the RCP on loops 1, 3, 5 and after the RCP on loops 2, 4, and 6. Originally, this was based on a design solution for WWER-440's which was later determined to be a deficiency and in later WWER-440's the locations were changed to be closer to the vessel. Locations for HPI connection on a cold legs are shown in Fig. 2.

The second unit of ANPP includes a stainless steel cladding, and the inner shaft of the vessel is also made from the cladding material. The vessel itself and the pipes are from the same type of steel used in WWER-440 construction. The thermal properties of the vessel, cladding, and pipe material were assigned based on IAEA guidelines on PTS analysis for WWER's [4].

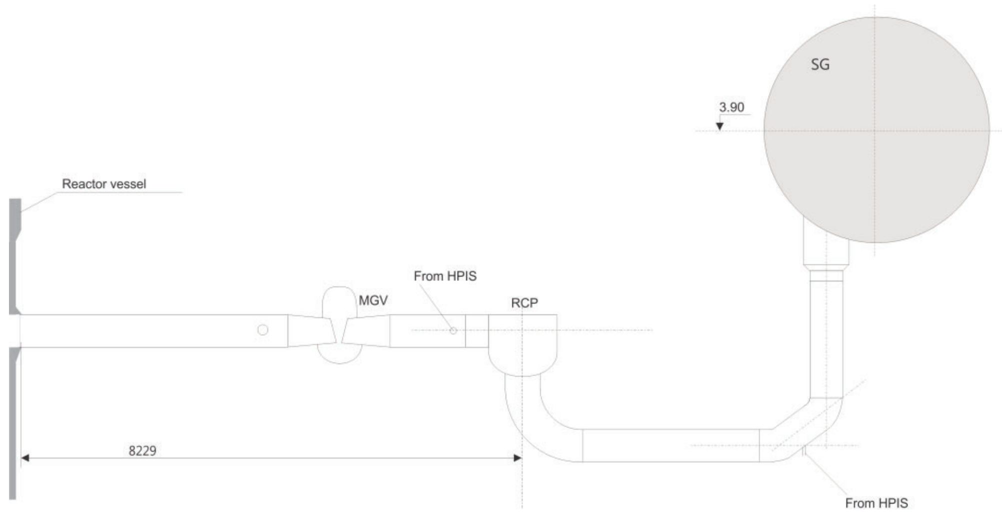


Fig. 2. Sketch of the cold leg piping of WWER-440 [3].

2.2. ANSYS model of ANPP Unit 2

A model of the cold leg and downcomer of ANPP Unit 2 was created according to the specifications in the ANPP documentation [3] using ANSYS DesignModeler in order to study the fluid mixing phenomenology during ECC injection through the cold leg, which can be seen in Fig. 3.

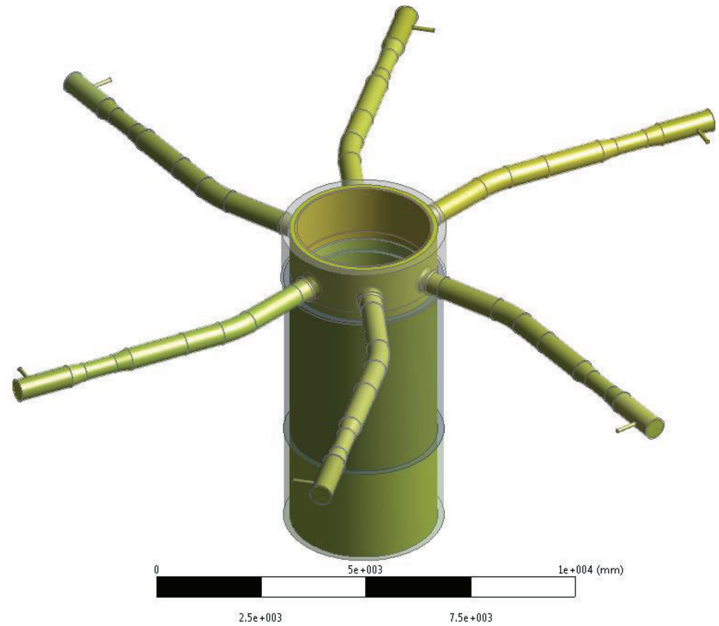


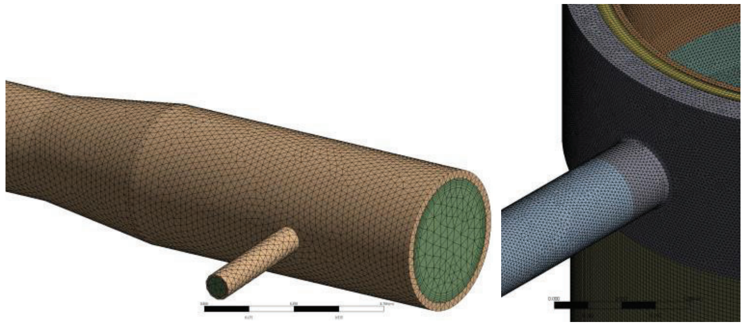
Fig. 3. Geometry of the model. Green areas signify downcomer and pipe coolant.

The model was meshed mainly using sweep and tetrahedral meshes, and the fluid interfaces were inflated in order to capture flow phenomenology near the wall, where flow is much more viscous due to domination of shear stress forces and boundary layer theory applies. The thickness of the first layer of inflation was chosen to be 5 mm, and a total of five layers were applied with a growth rate of 1.2. The fluid in the HPI nozzle was the only fluid section not inflated. The meshed components can be viewed in Fig. 4.

Various mesh size combinations were attempted; however, the orthogonal quality of the mesh proved to be extremely sensitive to these combinations. Solutions were not attempted for meshes with minimum orthogonal quality less than 0.05. Tetrahedral mesh was used for the entirety of the solid regions. The mesh parameter details for the best orthogonal quality achieved can be viewed in Table I. The minimum orthogonal quality of the mesh was 0.10.

Table I. Mesh parameters of the ANPP Unit 2 model.

Parameters		**Value**
Sizing	Min Size (m)	0.01
	Max Face Size (m)	0.03
	Max Size (m)	0.05
Orthogonal quality	Min	0.10
	Max	1.00
	Average	0.90
Nodes		3,433,235
Elements		6,707,878



(a) (b)

(c)

Fig. 4. Meshing of the pipe head (a) and pipe-vessel (b).

The case of an 18 mm LOCA before the RCP of cold leg number 2 was considered. The initial and boundary conditions for the ANSYS CFX solution were taken from the calculation of the corresponding RELAP model of ANPP Unit 2 [5]. To obtain the steady state solutions, the absolute pressure at the outlet at 0 s was set to 12.799 MPa; this was accomplished by setting the reference pressure to 12.7 MPa and the relative pressure at the outlet to 0.99 MPa. At 1000 s, this value was changed to 13.472 MPa. The coolant in the vessel was assigned an initial static pressure of 13.54 MPA (135.4 bar) and a temperature of 277 °C.

3. ANALYSIS

The fluid in the primary circuit can be in single phase or multiphase condition, depending on the diameter and location of the break and the operating conditions of the plant [2]. In current analysis, single phase flow inside the primary circuit in case of an 18 mm LOCA of the cold leg was considered. For each solution, the time-appropriate vertical heat flux distribution at the inner shaft of the vessel was assigned based on solutions of the RELAP analysis [5].

3.1. Steady State Solution at Normal Operation

The boundary conditions were taken from the ANPP Unit 2 RELAP calculations. The inlet coolant mass flow rate was set to 1494 kg/s and the inlet coolant temperature at 266 °C. Single-phase steady state solution at normal operation was obtained using two different turbulence models, k-ε and shear stress transport (the SST model is based on the k-ω model and is appropriate for predicting flow separation and performing high accuracy boundary layer simulations). The results, as shown in Fig. 5, show the coolant to pour down at a unique angle through the downcomer.

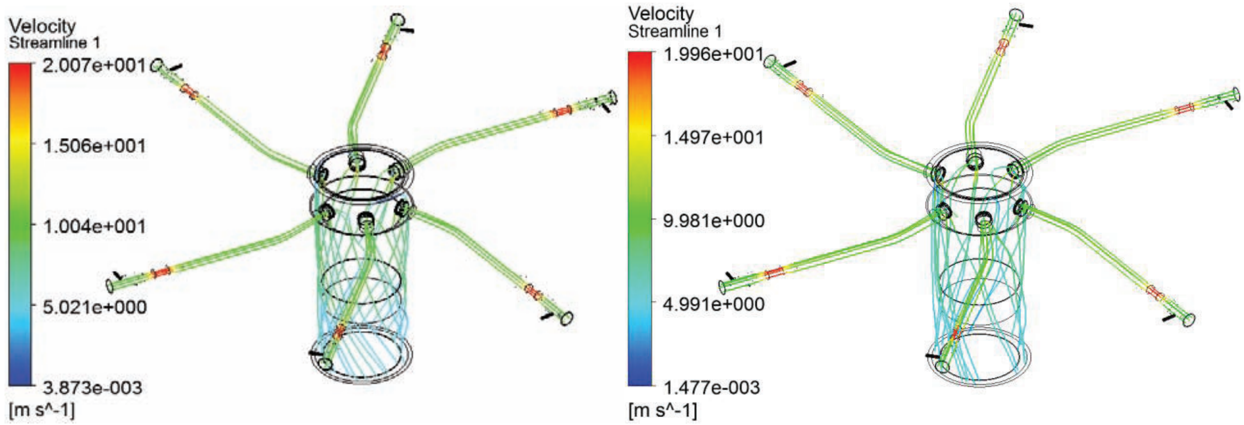


Fig. 5. Water velocity streamlines at normal operation with k-ε (left) and SST (right) turbulence models.

The reason for water leaning sideways as it enters the downcomer and pouring down at an angle seems to be the velocity differences across the cross section of the pipe introduced because of the bends in cold legs that bring out pressure differences across the cross section of the pipe. The velocity and pressure contours are shown in Fig. 6. The entrance length to achieve fully developed flow in the case of the high Reynolds flow in the pipe ($Re = 3.78 \times 10^7$) is $L_{turbulent} = 1.359 \times 0.496\, m \times (3.78 \times 10^7)^{1/4} = 53\, m$ which is much greater than the distance between the bend and the downcomer, which causes the underdeveloped flow to continue with its velocity vectors leaning to one side of the pipe when entering the downcomer, which in turn causes the angular flow down the downcomer.

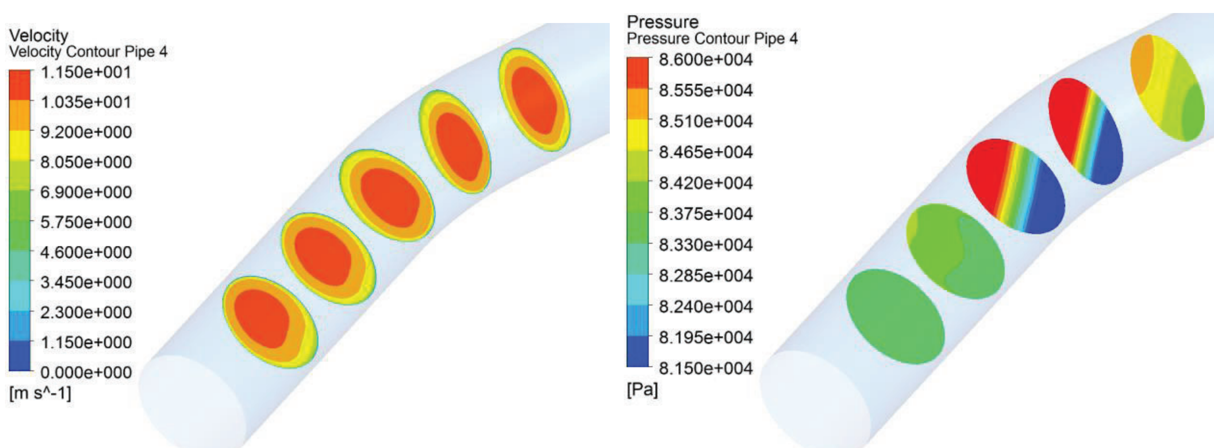


Fig. 6. Coolant velocity (left) and pressure (right) contours at the cold leg bend

To verify this effect, two further models of the vessel were created lacking the HPI nozzle, one with straight and the other bent pipes. As seen in Fig. 7, the results show that it is indeed the bend that causes the semi-circular flow down the downcomer. This can in turn provide the possibility of further mixing when cold coolant is injected in case of a LOCA.

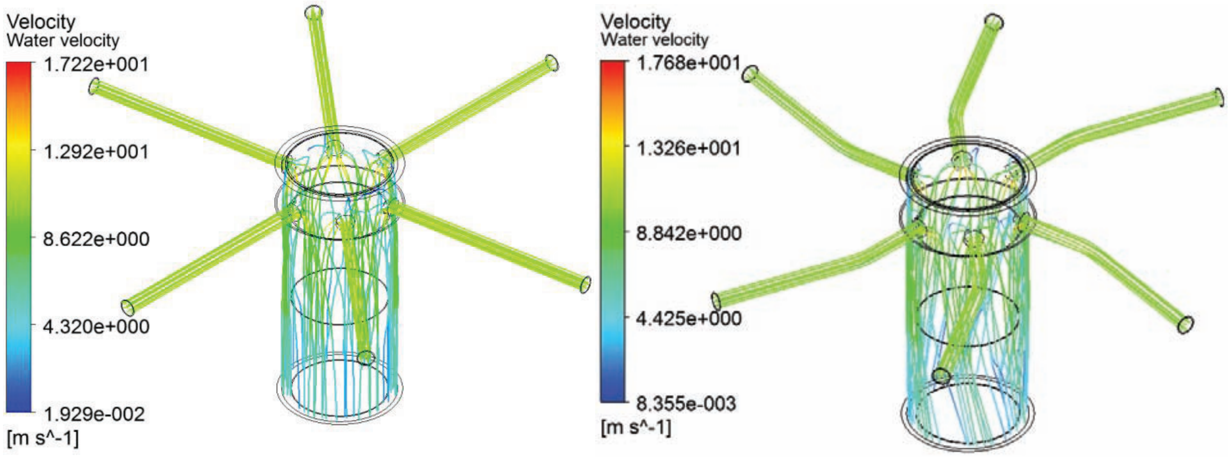


Fig. 7. Straight cold legs (left) and bent cold legs (right) determining the direction of the flow inside the downcomer.

3.2. Steady state solution for conditions at 1000 s after LOCA

In the scenario that was considered, an 18 mm LOCA occurs at t=0. It takes 200 s for the ECC injection to start, after which it takes a few thousand seconds for the mixed flow to stabilize. The mass flow rate through these legs coming into the downcomer calculated by RELAP is shown in Fig. 8 [5]. The mass flow rate drops much more significantly in three of the loops than the rest of them. The reason is that HPI is injected after the reactor coolant pump (RCP) in the cold legs in loops 2, 4, and 6, and is injected before the RCP in the rest of the loops (Fig. 2). Coolant injected after the RCP is injected inside the straight segment of the cold leg and continues flowing in stratified manner with the primary coolant. The coolant injected before the RCP, however, mixes with the primary coolant causing an increased density inside the bottom of the U-bend before the RCP (Fig. 2) which stops the natural convection inside the primary circuit.

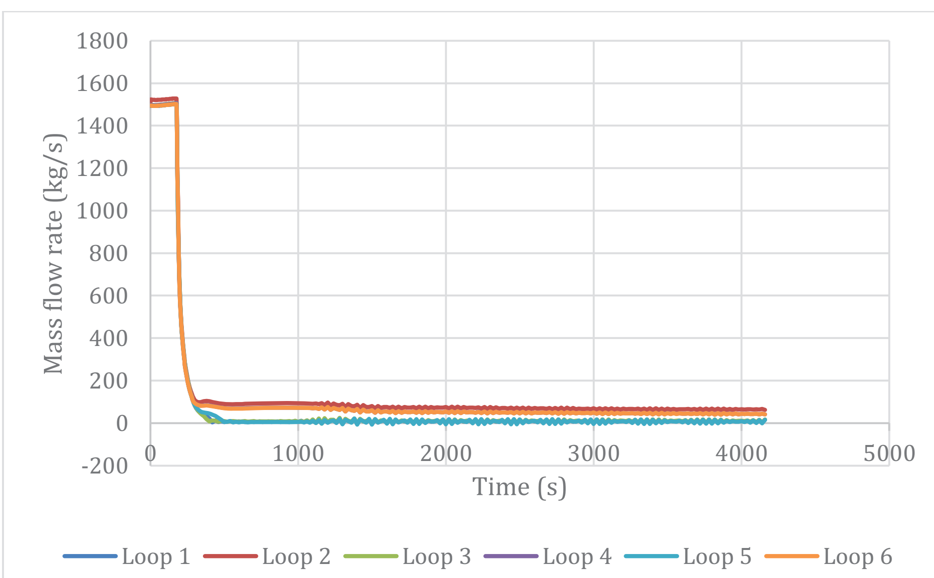


Fig. 8. Inlet mass flow rate for various loops [5].

The location of HPI was different for the different loops due to a design solution that results in HPI being injected before the RCP in three of the loops, and after the RCP in the rest. Since the model only includes the section of the pipes after the RCP, various HPI locations were taken into account in the symmetric model by introducing appropriate boundary conditions from the corresponding RELAP analysis. Therefore, the HPI mass flow rate in loops 1, 3, and 5 were introduced as combined mass flow rates and temperatures at inlets 1, 3, 5 of the model and the mass flow rates from the HPI nozzles themselves were set to zero in these loops. The mass flow rates and temperatures of HPI at loops 2, 4, 6 were set accordingly.

The steady state solution was obtained at boundary conditions present at 1000 s after LOCA occurred. The heat transfer from the core to the inner shaft of the downcomer is kept at the level present at 1000 s, and so are the boundary conditions. The problem is of transient nature, and the steady state solution is a primary step in determining phenomenology that might be present, rather than a quantitatively accurate account. The results are presented below. Fig. 9 shows the cold plumes on the inner shaft underneath the loops and leaning sideways, caused by lower temperature of the water pouring in from the pipes into the downcomer.

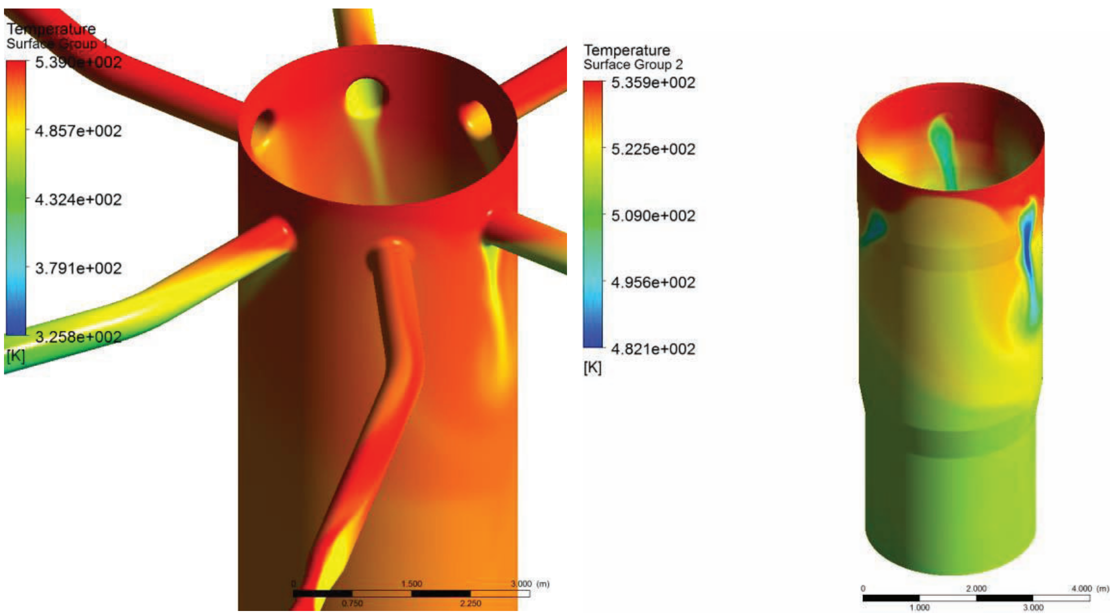


Fig. 9. Temperature of water on the surface of the downcomer outer surface (left) and shaft (right).

Fig. 10 shows the velocity streamlines of water flowing through the HPI nozzle of the second loop. As can be seen, water touches the opposite surface of the pipe and moves forward while touching it, after which it spirals around while still moving close to the surface of the pipe until it pours down the downcomer. The tendency of the cold water, which is injected at higher velocity relative to the hot water to stay close to the surfaces may be explained by Coandă effect, which causes the faster flowing stream to tend and adhere to the surfaces nearby.

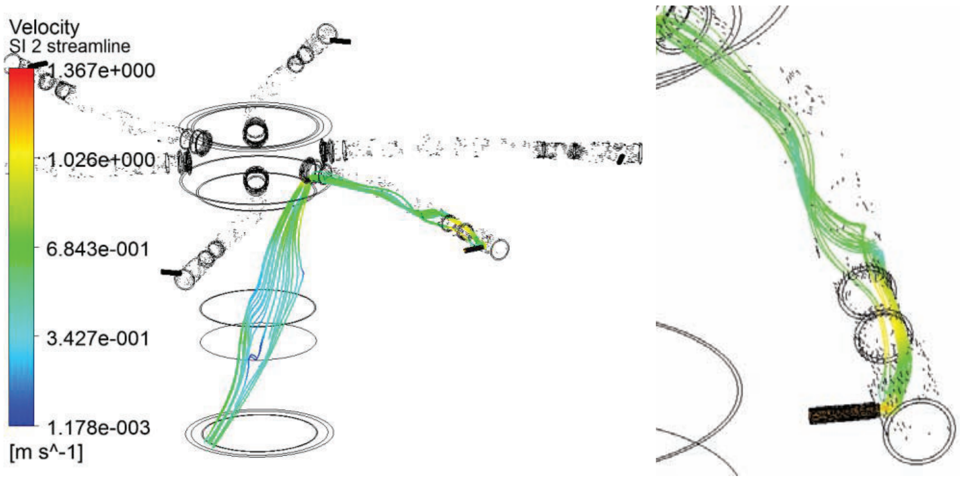


Fig. 10. HPI water velocity streamlines from second leg (left) and close-up of flow in the pipe (right).

Water velocity streamlines coming from the inlets of the model are shown in Fig. 11. Stagnation can be seen in loops 1, 3, 5, where water is fed before the RCP, as expected. The mass flow rate through them is in the range of 4-7 kg/s, while the mass flow rate through loops 2, 4, 6 are two orders of magnitude higher, causing some of the downcomer coolant to backflow into pipes 1, 3, 5. Vertical eddies can also be spotted inside the downcomer in the current simulation as well, which cannot be explained in detail as of this point, though the downcomer does change in width a few times.

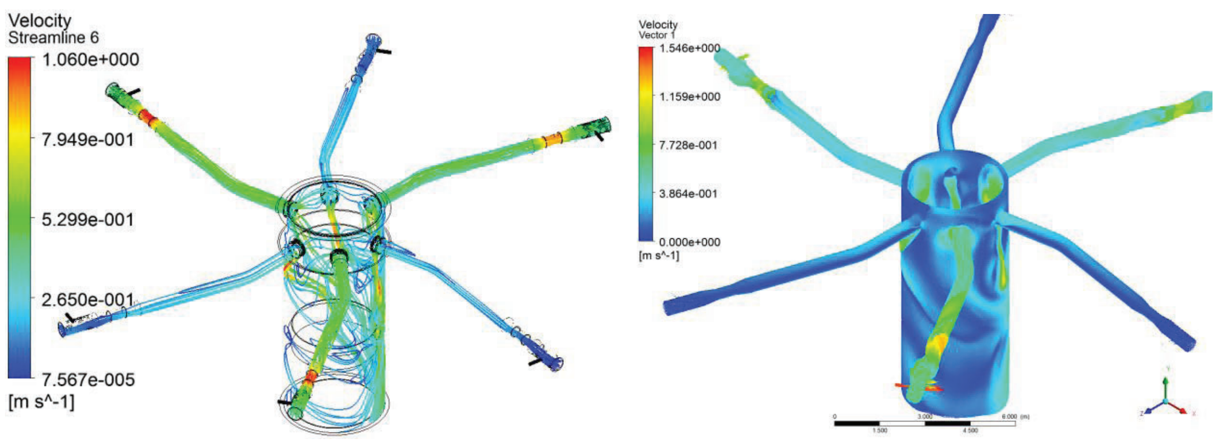


Fig. 11. Water velocity streamlines (left) and velocity vectors (right) coming from the inlets.

Flow stratification takes place inside the legs as colder water has higher density. The effect on the temperature changes of downcomer and pipes at the downcomer inlet can be seen in Fig. 12. Stratification occurs in all the pipes, regardless of whether the water is injected before or after the RCP.

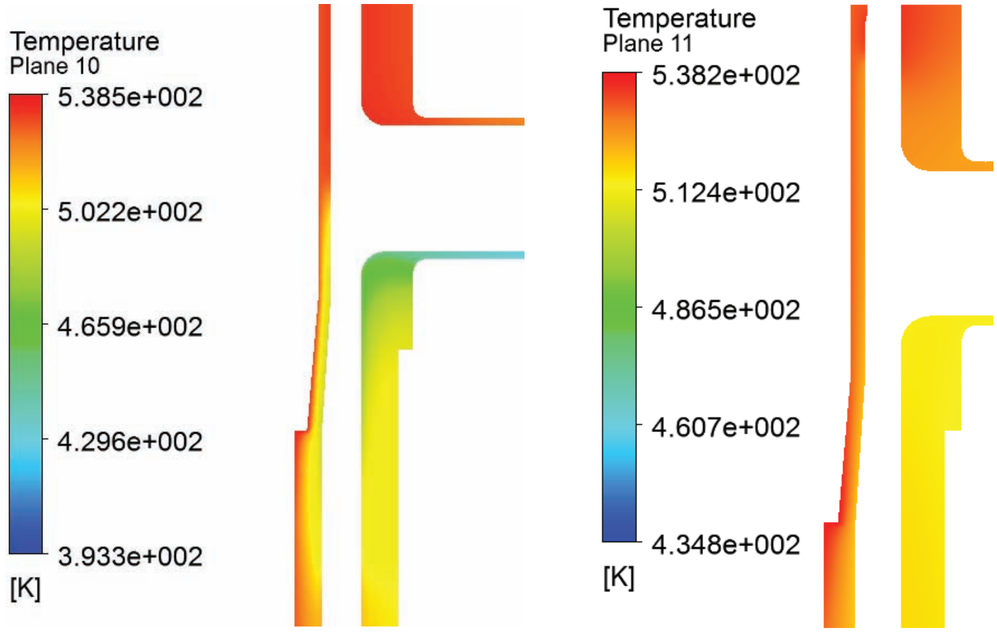


Fig. 12. Temperature profile at the two solid mediums of the downcomer inlet showing stratification with HPI injection before (left) and after (right) the RCP.

4. CONCLUSIONS

Various scenarios were modeled to be able to compare them together and separate certain phenomena and their causes. Firstly, steady state normal operation was modeled, which resulted in mildly circulating water velocity profiles inside the downcomer. Sensitivity analysis was then performed with two models of the vessel without the safety injection pipes, one with straight and the other with bent pipes. The results showed that it is the short length of the pipe after the bend that prevents the flow from achieving full development before entering the downcomer, hence the bend causes the flow to lean sideways while pouring down the downcomer.

Convergence of 10^{-4} was achieved for the steady state solution at 0 s (or normal operation), when the values of the mass flow rate and temperature of coolant coming in from the cold legs is close; however, as the mass flow rate and temperature in three of the legs diverge from the rest of them (as a result of HPI during LOCA), the order of convergence becomes closer to 10^{-3}, and vertical eddies start to appear as a result of mixing in the reactor vessel, which will require extended work to be explained. Furthermore, the sensitivity of convergence to the mesh size should be further explored.

Results also showed thermal stratification in both the cold legs and the downcomer of the vessel. Cold plumes were observed underneath the cold legs, especially those where the HPI is injected before the RCP and therefore displays stagnation through pipes 1, 3, 5. Results showed that the minimal temperature at the vessel wall is 188 °C.

It was also observed that the injected water with lower temperature tended to spiral around the cold legs leaning towards the walls, which could be explained by the Coandă effect, which implies that a fluid jet with a momentum higher than the medium it travels in will be attracted to a nearby surface.

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