Effects of inlet velocity profiles for thermal stripping phenomena in T-junctions

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Abstract. This paper investigates the effects of different inlet velocities on thermal stripping phenomena within a T-junction. The computational flow domain is modelled using the Improved Delayed Detached Eddy Simulation (IDDES) turbulence model implemented within the commercial CFD code STAR-CCM+ 12.04. The computational model is validated against the OECD-NEA-Vattenfall T-junction Benchmark data. The influence of flat and fully developed inlet velocity profiles is then assessed. The results are in good agreement with the experimental data. The different inlet velocity profiles have a non-negligible effect on the mean wall temperature. The mean velocity shows lower sensitivity to changes in inlet velocity profiles, whose influence is confined mainly to the recirculation zone near the T-junction.

1. Introduction

Thermal stripping is defined as the turbulent mixing of fluid streams with different temperatures. The incomplete mixing of the fluid streams causes temperature fluctuations on the pipe wall which can lead to thermal fatigue and as a consequence this may lead to pipe failure. In Nuclear Power Plants (NPPs), thermal stripping and fatigue phenomena were observed in the secondary loop of the PHENIX and SUPERPHENIX French sodium cooled fast reactors (SFRs) [1]. In Civaux in France a PWR, experienced a leak within the reactor heat removal system. This was subsequently found to have been initiated by high-cycle thermal fatigue [2].

A benchmark study was organized by OECD/NEA to assess the ability of state-of-the-art CFD codes to represent the turbulent mixing in T-junctions against the Vattenfall experimental data [3]. This study concluded that the less time-consuming Reynolds-Averaged Navier-Stokes (RANS) models did not perform well, whereas the high-cost Large Eddy Simulation (LES) and hybrid LES-RANS, such as Detached Eddy Simulation (DES), produced results consistent with the experimental data [3][4].

In this paper the Improved Delayed Detached Eddy Simulation (IDDES, [5]) model is used to study the effects of different inlet velocity profiles on thermal stripping phenomena in T-junctions. The flow domain is modelled using the commercial CFD solver STAR-CCM+ 14.02 [6] and the computational model is validated using the OECD-NEA-Vattenfall T-junction Benchmark study [3].

2. Methodology

The schematic of the computational domain is presented in Figure 1. A polyhedral mesh was used in the main T-junction area with a base cell size of 0.002 m, and a volume extruder mesh was used for the
outlet pipe. The total number of cells is around 5 million. The flow domain is modelled with the IDDES turbulence model, a hybrid bounded central difference spatial discretization scheme is used and the time step size is $5 \times 10^{-4}$ s. The mean flow quantities were averaged for a total simulation time of 20 s. The length of the inlet pipes used to calculate the boundary conditions (BCs) is equivalent to 100D. For these inlet pipes the volume extruder mesh was used and the flow domain was modelled using a steady $k$-$\omega$-SST [7] turbulence model together with a second order upwind spatial discretization scheme.

The experimental conditions were firstly replicated to validate the computational model. Volumetric flow rates of 9 l/s and 6 l/s were used for the main and branch inlet pipes, respectively. The BCs were extracted at 100$D_{\text{main}}$ for the main inlet pipe and 20$D_{\text{branch}}$ for the branch inlet pipe and applied to the T-junction inlets. The effects of flat and fully developed inlet velocity profiles were then assessed. The BCs related to the fully developed inlet profiles were extracted at 60$D_{\text{main}}$ and 60$D_{\text{branch}}$ for the inlet pipes. A total of four simulations were performed, each of them used a different combination of BCs, namely flat or fully developed profiles at both inlets, and flat profile for the main/branch inlet and fully developed profile for branch/main inlet.

![Figure 1. Schematic of the computational model.](image)

3. Findings

The results for the model validation are presented in Figure 2 and Figure 3. The IDDES model performed quite well, especially for the mean velocity profile downstream the T-junction. Minor discrepancies were found in the upper part of the pipe at $x=1.6D_{\text{main}}$, $y=0$, and close to the pipe wall at $x=4.6D_{\text{main}}$, $z=0$. The mean temperature along the pipe is correctly predicted at the pipe sides, 90° and 270°. The mean temperature mostly agrees with the measurements at the top and the bottom of the pipe wall (0° and 180°, respectively) though the values predicted at $x=6D_{\text{main}}$, 180° and $x=2D_{\text{main}}$, 0° and 90°, are slightly lower than the one measured by the thermocouple. Overall, the results obtained are in good agreement with the experimental data and are mostly within the error tolerance.

![Figure 2. Time-averaged $U/U_{\text{bulk}}$ at $x=1.6D_{\text{main}}$ on a vertical line, $y=0$, and a horizontal line, $z=0$. Time-averaged velocity at $x=4.6D_{\text{main}}$ on $y=0$, ad $z=0$.](image)
The mean temperature and x-component of the velocity obtained with different inlet velocity profiles are presented in Figure 4, Figure 5 and Figure 6. The different inlet profiles showed non-negligible effects on the temperature distribution on the pipe wall and on the mean velocity in the recirculation zone downstream the T-junction. The fully developed profile produces stronger mixing of fluids at different temperature near the T-junction compared to the flat profile.

When both profiles are flat, the mean temperature at the top wall downstream the T-junction ranges from 32-33°C, for x<3D_{main}, to 29°C, for x<6D_{main} (Figure 4(a)). However, a fully developed velocity profile for the main flow improves the mixing in the central part of the pipe and produces a higher mean temperature with a peak of 34°C, at x=2D_{main} (Figure 4(c)). When the branch flow velocity profile is fully developed and the main flow is flat, the fluid with a higher temperature is confined to the centre of the pipe (Figure 4(b)). The maximum value of the mean temperature at the top wall is reached near the T-junction and is, in this case, around 29°C. If both profiles are fully developed, the top wall temperature is still 29°C near the T-junction and it remains the same further downstream (Figure 4(d)).

The x-component of the mean velocity is presented in Figure 5 for the whole computational model and in Figure 6 for the T-junction area. The mean value of the velocity remains almost constant for x>4D_{main} for all four cases but changes appreciably near the T-junction (see Figure 5). The fully developed profile in the branch pipe (Figure 6(b)(d)), produces a higher velocity in the lower half of the pipe. In this case, the mean velocity peak in the center of the pipe is around 1.53 m/s, whereas it reaches a value of around 1.3 m/s with flat profile applied at the branch side.

![Figure 3](image1.png)

**Figure 3.** Non-dimensional temperature, $T^*=(T-T_{main})/(T_{branch}-T_{main})$, along the x-axis for pipe top, pipe bottom, and pipe sides.

![Figure 4](image2.png)

**Figure 4.** Contours of $T^*$ on XZ plane for flat BCs (a), flat-fully developed BCs (b), fully developed-flat BCs (c), and fully developed BCs (d).
4. Conclusions

IDDES turbulence modelling of thermal stripping phenomena in a T-junction was performed and validated against the OECD/NEA-Vattenfall T-junction Benchmark. The influence of flat and fully developed inlet profiles was also assessed. Four simulations were performed, each of which used different combinations of flat and fully developed velocity profiles at both main and branch inlets. It was found that the inlet velocity profile has a considerable impact on the temperature on the wall, due to a stronger mixing near the T-junction in the case of fully developed flow. For flat inlet profile in the branch side, the hot fluid at the top of the pipe ranges from 33 to 34°C, whereas for fully developed profiles the maximum temperature is around 29°C. The mean velocity changes mainly in the area near the T-junction and it remains almost unchanged further downstream. These results will be used in future works to evaluate the thermal loads in the pipe wall and the heat transfer in the solid domain using the conjugate heat transfer analysis.

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