Influence of upstream pipe bends on the turbulent heat and mass transfer in T-junctions

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Abstract. An influence of upstream pipe bends on the thermal mixing in T-junctions has been investigated with the use of Improved Delayed Detached Eddy Simulation, which accuracy for such flows has been justified by a comparison against the experiment. The parametrical study of T-junctions with various upstream pipe bends has shown that the most dangerous in terms of the thermal fatigue are configurations with the branch pipe and upstream bend pointing in different directions, especially in case when the bend is located relatively close to the junction.

1. Introduction

In order to increase the efficiency and safety of nuclear power plants, it is important to obtain a detailed information about the turbulent mixing of fluids of different temperatures in T-junctions since it can lead to highly transient, low frequency temperature fluctuations known as the “thermal striping”, which could result in the high cycle thermal fatigue and failure of the piping (such incidents are known for both light water [1,2] and sodium cooled [3] reactors). It should be pointed out, that the thermal striping noticeably depends on the flow upstream of T-junctions, which could be affected by various bends and turns [4–6]. However, a systematic study of the aforementioned effect is not available from the literature and, therefore, the goal of the current work is to investigate the sensitivity of the thermal mixing in T-junctions to the upstream flow inhomogeneity.

For that purpose several T-junctions with both straight and bended upstream pipes are simulated in the framework of Improved Delayed Detached Eddy Simulation (IDDES) [7], which is acknowledged to be very effective for the prediction of the turbulent heat and mass transfer at high Reynolds numbers typical for industrial applications [8,9].

The paper is organized as follows. Firstly, the accuracy of IDDES simulations is justified by a comparison against the experimental data for the T-junction [5] and, then, several configurations of the upstream pipe bends are parametrically investigated. All the simulations within the paper are performed with the use of the general purpose CFD code ANSYS-FLUENT [10].

2. Test case description and numerical setup

The considered experimental rig [5] corresponds to the T-junction configuration for which the leakage due to the thermal fatigue has been observed during the operation of the light water reactor [1]. The rig consists of the branch and main pipes with the inner diameters of D/3 and D. Two configurations of the main pipe are considered, namely the “straight” and “elbow” (Figure 1). For the “straight” case the length of the upstream pipe is 2·D, whereas for the “elbow” the bended pipe with the radius of 1.5·D and with the additional straight segment of 1·D is located 2·D upstream of the junction. The bulk velocity is kept constant throughout the experiment and is equal to 0.68·U₀ and U₀ in the branch and
main pipes respectively. The temperature of the water is \( T_0 \) in the branch pipe and \( T_0 + \Delta T \) in the main one with the adiabatic condition preserved on both pipes. These parameters correspond to \( Re = \rho U_0 D / \mu = 390000 \) (\( \rho \) is the density and \( \mu \) is the dynamic viscosity) and to \( Pr = \mu C_p / \lambda = 3.7 \) (\( C_p \) is the specific heat capacity and \( \lambda \) is the thermal conductivity).

The computational grid consists of about 4.4 \( \times \) 10\(^6\) and 6.6 \( \times \) 10\(^6\) hexahedral cells for the “straight” and “elbow” configurations respectively. The grid satisfies the recommendations for IDDES calculations [11] and utilizes the steps of 10\% and 5\% of the boundary layer thickness in the streamwise and spanwise directions. The wall-normal step is changing from its minimum value corresponding to \( \Delta y^+ < 1 \) up to 5\% of the boundary layer thickness in the core-flow. The used time step of \( \Delta t = 0.004 D / U_0 \) corresponds to the maximum CFL number less than one in most part of the domain.

The boundary conditions are specified as follows (Figure 1). The no-slip adiabatic condition is applied on the pipe walls. The constant pressure is specified at the outlet boundary, whereas the other transported quantities are extrapolated from the domain. Vortex Method (VM) [12] is used at the inlet boundaries in order to generate the unsteady turbulent fluctuations based on the mean profiles of the velocity, temperature, and turbulence quantities extracted from the precursor simulation of the developing pipe flow up to the experimental boundary layer thickness.

Finally, it is worth mentioning, that the meshes and boundary conditions employed for the parametrical study in Section 4 are similar to those for the experimental rig [5].

3. Comparison of IDDES results with the experimental data

In order to justify the applicability of IDDES for prediction of the thermal mixing in T-junctions with upstream bends, a comparison against the experimental data [5] is firstly performed. As seen from the mean and RMS profiles of the velocity and temperature at \( x/D = 0.5 \) (the definition of the section is shown in Figure 1), relatively good agreement between the IDDES and experimental profiles is obtained for both “straight” (Figure 2) and “elbow” (Figure 3) cases with the maximum deviation from the experimental data of about 20\%.

Particularly, for the “straight” case the mean velocity as well as the mean and RMS temperature is slightly overestimated in the mixing zone (Figure 2-a, c, d). At the same time, the RMS velocity is correctly predicted within the mixing zone (Figure 2-b), whereas a noticeable under-prediction is observed in the core-flow, which origin is likely in the inconsistent with the experiment representation of the turbulence intensity upstream of the junction (similar results are obtained in [6]).
With regards to the “elbow” case, the size of the mixing zone is slightly over-predicted comparing to those of the experiment (Figure 3-a) resulting in a shift of the RMS velocity and temperature peak (Figure 3-b, d) away from the junction (similarly to the “straight” case, the RMS velocity is under-predicted in the core-flow). As a result, the minimum of the mean and RMS temperature (Figure 3-c, d) in the mixing zone is lower than in the experiment, whereas near the wall a noticeably better agreement is observed.

Summing up, it is shown, that IDDES is capable to predict the thermal mixing in T-Junctions with a reasonable accuracy (within 20%) for both “straight” and “elbow” cases, which justifies its usage for further investigations.

4. Influence of upstream pipe bends on the thermal mixing in T-junctions

In order to estimate the effect of the upstream flow inhomogeneity totally 9 configurations (Figure 4) with various angles ($\phi$=0°, 90°, 180°) and distances ($L/D$=1, 2, 4) between the branch pipe and
upstream bend are considered (the configuration with $\phi=0^\circ$ and $L/D=2$ corresponds to the experimental rig [5] investigated in the previous section).

![Computational setup for the considered distances ($L$) and angles ($\phi$) between the branch pipe and upstream bend](image)

**Figure 4.** Computational setup for the considered distances ($L$) and angles ($\phi$) between the branch pipe and upstream bend

As seen from the instantaneous vorticity contours with the time averaged streamlines (Figure 5), the increase of $\phi$ results in a noticeable shift of the oncoming mixing layer emanating from the upstream bend from the adjacent to the junction side ($\phi=0^\circ$) towards the opposite one ($\phi=180^\circ$), which is accompanied with a pronounced decrease of the size of the mixing zone downstream of the junction. At the same time, the increase of $L/D$ results in larger thickness of the oncoming mixing layer and smaller recirculation zone downstream of the junction. Finally, it is worth mentioning that, for the “straight” case the flow structure is similar to the “elbow” case with $L/D=2$ and $\phi=180^\circ$ and $\phi=90^\circ$.

![Influence of the angle ($\phi$) and distance ($L/D$) between the branch pipe and bend on the instantaneous vorticity contours and time averaged streamlines](image)

**Figure 5.** Influence of the angle ($\phi$) and distance ($L/D$) between the branch pipe and bend on the instantaneous vorticity contours and time averaged streamlines

For all the considered configurations the effect of $\phi$ and $L/D$ on the thermal mixing is the most pronounced in the vicinity of the junction ($\theta=0^\circ$). As seen from the mean temperature distributions, the increase of $\phi$ results in the noticeably lower mean temperature near the junction (Figure 6-a, b). Particularly, for $\phi=90^\circ$ and $\phi=180^\circ$ the mean temperature profiles are close to the “straight” case (Figure 6-a, b) and noticeably lower than those for $\phi=0^\circ$ (however, the effect of $\phi$ is diminishing with the increase of $L/D$). At the same time, the increase of $L/D$ results in almost monotonic decrease of the mean temperature with the asymptotic profile corresponding to the “straight” case (Figure 6-c).
Figure 6. Distributions of the mean temperature along the wall at $\theta=0^\circ$

With regards to the RMS temperature (Figure 7), the effect of the angle between the branch pipe and upstream bend ($\phi$) is more pronounced than those of the distance ($L/D$). Particularly, the difference between the RMS temperature peaks for the considered $L/D$ values is less than 25% (Figure 7-c), whereas the change of $\phi$ results in up to 40% variation of the maximum RMS temperature (Figure 7-a, b). It should be noted, however, that the effect of $\phi$ is decaying with the increase of $L/D$ (Figure 7-a, b) and the “elbow” configuration tends to the “straight” one (although, for $\phi=180^\circ$ and $L/D=4$ the RMS temperature peak is still about 40% higher than those of the “straight”), which indicates that the configurations with relatively small $L/D$ ratio are the most dangerous in terms of the thermal fatigue.

Figure 7. Distributions of the RMS temperature along the wall at $\theta=0^\circ$

Finally, in order to indicate the areas of high thermal loads, the maximum RMS temperature is plotted for various circumferential directions ($\theta$) in Figure 8. As expected, for all the considered configurations the most loaded region is observed near the junction ($\theta=0^\circ$), whereas the minimum value of the RMS temperature peak is located at the opposite side ($\theta=180^\circ$) for $\phi=0^\circ$ and $\phi=180^\circ$ and is shifted to higher $\theta$ values for $\phi=90^\circ$.

Figure 8. The maximum RMS temperature for various circumferential angles ($\theta$)

Summing up, the performed analysis outlined that the configurations with $\phi=90^\circ$ and $\phi=180^\circ$ are potentially more dangerous in terms of the thermal fatigue than those of $\phi=0^\circ$ (especially in case of relatively small $L/D$ ratios) and, thus, should be avoided when the pipelines are designed.
5. Conclusions
An influence of the upstream flow inhomogeneity on the thermal mixing in T-junction with straight and bended upstream pipes has been investigated with the use of IDDES, which accuracy for such flow has been justified by a comparison against the experimental data.

The parametrical study of T-junctions with various upstream pipe bends has outlined that the angle between the branch pipe and upstream bend noticeably influences the wall RMS temperature. Particularly, for the branch pipe and upstream bend pointing in different directions the maximum of the RMS wall temperature is noticeably higher in the vicinity of the junction comparing to the aligned case (up to 40%), indicating that such configurations are potentially more dangerous in term of the thermal fatigue. In contrast, the distance between the branch pipe and upstream bend has relatively smaller effect (less than 25%) on the RMS wall temperature, but noticeably affects the thermal mixing downstream of the junction, which efficiency is increasing with the increase of the distance to the bend.

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