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Assessment of different URANS models for the prediction of the unsteady thermal mixing in a T-junction

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ABSTRACT

Turbulent thermal mixing of fluids at different temperature in T-junctions represents a major concern for the safety of nuclear reactors. This is due to the significant thermal fluctuations that can arise under such circumstances, consequently leading to cyclic thermal stress and thermal fatigue within the pipe wall. Computational Fluid Dynamics (CFD) can be employed in order to obtain useful insights on the characteristics of the transient behaviour of the turbulent heat transfer in T-junctions. Although LES has been found to be the most accurate approach to turbulence modelling for this type of flow, its application at high Reynolds numbers is limited by its considerable computational costs. In this respect, the Unsteady Reynolds-Averaged Navier-Stokes (URANS) approach can be considered as a less computationally demanding option. In the present work, different URANS models are applied for the simulation of the thermal mixing in a T-junction at high Reynolds numbers. The numerical results are thoroughly assessed against the available experimental data. It is shown that, despite its limitations, a proper use of the URANS approach can give reasonable results for the considered flow configuration; in particular, a good prediction of the temperature fluctuations near the wall has been obtained, which is important for the evaluation of the cyclic thermal stress induced within the pipe wall. Therefore, it is concluded that URANS models can be regarded a pragmatic approach for the evaluation of temperature fluctuations in T-junction pipes. Finally, general guidelines for the application of the URANS approach for the simulation of such configurations are given.

1. Introduction

The structural material in T-junction pipes is subjected to thermal fatigue degradation due to the temperature fluctuations generated by the mixing of fluids at different temperature at the junction (Braillard et al., 2018; Miyoshi et al., 2016; Kamaya et al., 2017). An accurate prediction of the transient behaviour of the fluid temperature close to the wall is necessary in order to evaluate the stresses within the pipe wall (Westin et al., 2008; Shams et al., 2018). Computational Fluid Dynamics (CFD) can be considered as a valuable tool to evaluate the transient turbulent heat transfer taking place in a T-junction. As a consequence, a considerable effort has been put into evaluating the performance of different turbulence modelling approaches for the prediction of the transient thermal behaviour in T-junctions (Frank et al., 2010). In general, it was observed that the classical steady-state Reynolds-averaged Navier-Stokes (RANS) approach, which represents the most common modelling technique for complex industrial problems, is not adequate for an accurate prediction of the inherently unsteady thermal mixing phenomenon observed in T-junctions (Ayhan et al., 2012). More sound approaches that have been assessed in the literature include: Unsteady RANS (URANS), Large Eddy Simulation (LES) and hybrid LES/RANS models (Shams et al., 2018; Ayhan et al., 2012). The OECD/NEA benchmark exercise, which has seen the participation of 29 institutions from several countries (Smith et al., 2013), was devised in order to assess the performance of different CFD models in this context. The case considered in the benchmark was the Vattenfall T-junction configuration; only the fluid domain was considered in the modelling exercise, i.e. the solid walls were not considered in the CFD calculations. It was observed that, in general, the LES approach gave the most accurate prediction of the fluctuating behaviour of the thermal field. Nevertheless, in the conclusive remarks, it was highlighted that this approach is extremely computationally demanding, especially at high Reynolds numbers; therefore, it is far from a widespread industrial use (Smith et al., 2013).

Subsequently, the MOTHER (MOdelling T-junction HEat Transfer) (Shams et al., 2018) was devised in order to extend the assessment of the different turbulence modelling approaches for the

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prediction of the transient temperature behaviour in T-junctions including heat transfer to the wall. The evaluation of the models was performed against novel CFD-grade experimental data obtained in the FATHERINO facility at the Commissariat l'Energie Atomique et aux Energies Alternatives (CEA) (Braillard et al., 2018). Both sharp-corner and round-corner configurations were considered within the project, at two different Reynolds numbers i.e. 40,000 and 60,000. A total of 29 different CFD simulations (including LES, hybrid LES/RANS, and (U)-RANS approaches) were performed by the six participants in the benchmarking exercise, i.e.: Électricité de France S.A, France; Forsmark Kraftgrupp AB, Sweden; Nuclear Research and Consultancy Group, The Netherlands; Onsala IngenjörsbyråAB, Sweden; Technische Universität Dresden, Germany and Vattenfall Research and Development AB, Sweden. Also in this case, LES was observed to be the most accurate approach. Nevertheless, it was pointed out that long physical times need to be simulated in order to obtain converged statistics within the solid wall, and this is extremely costly from a computational point of view. From the aforementioned two benchmarking exercises it appears evident that LES is the most suitable turbulence modelling technique for this flow configuration, but its application is seriously hampered by its elevated computational costs. At the high Reynolds numbers usually encountered in industrial applications, this represents a major bottleneck which prevents the use of LES in many cases. It is also worth to observe that the use of the classical wall functions, usually employed in wall-modelled LES (WM-LES) in order to reduce the computational costs (Jayaraju et al., 2010), is questionable in this flow configurations; this is to due to local non-equilibrium conditions observed at the junction (Jayaraju et al., 2010). Theoretically, a wall-resolved LES would represent the ideal approach, but this results in an even higher computational burden compared to the more commonly employed wall-modelled LES. Therefore, as one of the outcomes of the MOTHER project, it was highlighted that there is a need to develop more advanced wall functions for the application of LES to non-equilibrium flows as the one observed in T-junctions (Shams et al., 2018; Jayaraju et al., 2010). Furthermore, it is interesting to observe that the wall-resolved URANS approach considered in the same project gave reasonable results for the transient temperature behaviour close to the wall, especially compared to the LES computations performed on under-resolved meshes (Shams et al., 2018). Therefore, despite their intrinsic limitations, the URANS models can be regarded as an attractive and pragmatic option for the modelling of T-junction configurations. Lastly, an advanced algebraic turbulent heat flux model, named AHFM-NRG (Shams et al., 2014), was also assessed within the MOTHER project and resulted in encouraging results in steady-state RANS calculations (Shams et al., 2018), showing the potential benefits of employing such a model in the simulation of thermal mixing in T-junctions. Nevertheless, it should be pointed out that such benefits would not result in any useful input data for the evaluation of the cyclic thermal stress in the solid pipe since, by definition, the steady-state RANS approach is not able to resolve any unsteadiness in both the flow and the thermal fields.

More recently, the EU project ATLAS+ has been devised with a particular focus, in one sub-work packages, on the use of advanced structural codes based on fracture mechanics to assess the effects of thermal fatigue in T-junction pipes. The case considered in the ATLAS+ project is based on the geometry of the WATLON experimental facility (Kamide et al., 2009), and is characterised by a Reynolds number of $\approx 4.5 \cdot 10^5$ and a particularly high temperature difference between the main and the branch flows, which was deliberately chosen in order to obtain significant cyclic thermal stresses within the pipe. Within this project, it is foreseen to employ CFD simulations including conjugate heat transfer in order to evaluate the transient temperature behaviour at the solid wall, which is required as a boundary condition for the structural codes. Due to the high value of the Reynolds number and to the long physical time that needs to be simulated, LES does not represent a feasible option for this case; hence, the URANS approach has been selected here. In order to evaluate the performance of the selected approach for such a case, different URANS models have been tested for the prediction of the unsteady thermal mixing in the same T-junction geometry considered in the ATLAS+ project and for a similar value of the Reynolds number.

Therefore, in the present work, wall-resolved URANS simulations of a sharp-corner T-junction flow at a high Reynolds number have been performed; only the fluid domain is considered in the present CFD calculations and the presence of the solid walls is not accounted for. The results are compared against the experimental data reported in Kamide et al. (2009) for a thorough assessment of the different models. More in detail, four different low-Reynolds RANS models have been considered for the calculations, i.e.: a linear and a cubic $k-\varepsilon$ models, a differential Reynolds Stress Model based on the Elliptic Blending concept (RSM-EB) and an algebraic heat flux model (AHFM-NRG) including a transport equation for the modelled (i.e. non-resolved) temperature variance.

The paper is organised as follows: a description of the flow configuration and of the numerical techniques is given in Section 2, followed by a discussion of the results in Section 3. Finally, concluding remarks and future perspectives are given in Section 4.

2. Flow configuration and numerical strategies

2.1. Reference experimental case

The case considered in the present work is taken from the extensive experimental campaign carried out at the WATLON facility, which employs water as a working fluid (Kamide et al., 2009). The WATLON experimental facility has been devised with the aim of obtaining further insights into the thermal fatigue phenomenon observed in PWR nuclear reactors. A Particle Image Velocimetry (PIV) system has been used for the measurement of the velocity field, with a sampling frequency of 15 Hz over a measurement time period of about 17 s. The temperature measurements have been performed by means of a thermocouple tree at a sampling frequency of 100 Hz over a measurement time period of 100 s (Kamide et al., 2009). A sketch of the T-junction configuration is given in Fig. 1. The inner diameter of the main (D_m) and the branch (D_b) pipes are equal to 0.15 m and 0.05 m, respectively.

For the main pipe, the average inlet velocity V_m and temperature T_m are equal to 1.46 m/s and 321.15 K (48.0 °C), respectively. With respect to the branch pipe, the inlet velocity V_b and temperature T_b are 1.0 m/s and 306.15 K (33.0 °C), respectively, resulting in a characteristic temperature difference $\Delta T = T_m - T_b$ equal to 15.0 K, which is equal to the one considered in the Vattenfall experiments. The momentum ratio M_r is a parameter commonly employed to identify the flow pattern expected downstream of the junction (Miyoshi et al., 2016). It is defined as the ratio between the momentum associated with the flows in the main (M_m) and the branch pipe (M_b) as

$$M_r = \frac{M_m}{M_b} \tag{1}$$

$$M_m = D_m D_b \rho_m V_m^2 \tag{2}$$

$$M_b = \frac{\pi}{4} D_b^2 \rho_b V_b^2 \tag{3}$$