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# Large-eddy simulation in a mixing tee junction: High-order turbulent statistics analysis

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ABSTRACT

This study analyses the mixing and thermal fluctuations induced in a mixing tee junction with circular cross-sections when cold water flowing in a pipe is joined by hot water from a branch pipe. This configuration is representative of industrial piping systems in which temperature fluctuations in the fluid may cause thermal fatigue damage on the walls. Implicit large-eddy simulations (LES) are performed for equal inflow rates corresponding to a bulk Reynolds number $Re = 39{,}080$. Two different thermal boundary conditions are studied for the pipe walls; an insulating adiabatic boundary and a conducting steel wall boundary. The predicted flow structures show a satisfactory agreement with the literature. The velocity and thermal fields (including high-order statistics) are not affected by the heat transfer with the steel walls. However, predicted thermal fluctuations at the boundary are not the same between the flow and the solid, showing that solid thermal fluctuations cannot be predicted by the knowledge of the fluid thermal fluctuations alone. The analysis of high-order turbulent statistics provides a better understanding of the turbulence features. In particular, the budgets of the turbulent kinetic energy and temperature variance allows a comparative analysis of dissipation, production and transport terms. It is found that the turbulent transport term is an important term that acts to balance the production. We therefore use *a priori* tests to evaluate three different models for the triple correlation.

## 1. Introduction

Flows in mixing tee junctions occur in a wide variety of industrial applications such as boilers, pumps and cooling devices. The thermal fluctuations developed by the flow generate mechanical stresses on the pipe walls. These stresses are generally quite small however the effect over a long period of time can lead to weaknesses in the structure. If the material properties of the pipe structure and the thermal forcing from the fluid create the right conditions then cracks can form in the pipe structure. This phenomenon is known as thermal striping. The prediction of thermal fatigue in mixing tees is needed for life management of nuclear power reactor piping systems. Therefore research efforts have been concentrated to improve the understanding on the thermal striping phenomenon. However, such a flow is very challenging for experiments and numerical modelling. The mixing between the hot and the cold fluid flowing from the two branches produces a turbulent mixing layer interacting with multiple turbulent boundary layers. The curved geometry at the junction leads to local separation and flow reattachment. In addition to this the heat transfer between the flow and the tee junction walls must be taken into account.

Several experimental investigations have been made to understand the physics of this flow. Using Particle Image Velocimetry (PIV) in an apparatus with circular cross-sections at small Reynolds numbers (<3000), Brücker (1997) measured the mean and instantaneous flow and described some of the vortical structures including the counter-rotating vortices directly downstream of the junction. Walker et al. (2009) investigated mixing phenomena. They studied the distribution of the scalar mixing between pure tap water and coloured tap water for four different velocity ratios ($V_r = V_{branch}/V_{main}$). They showed that downstream of the tee junction, the mixing between the two fluids is increased for higher velocity ratios $V_r$. They identified four characteristic regions in the vicinity of the tee junction. Two regions are characterised by a small rms value of temperature whereas the third one consists of mixture with very high rms values of temperature. The last region is located on the edge of the side branch pipe. It contains two contra-rotating vortices which dominate the recirculation region. Walker et al. (2009) also provided useful data that can be used to check the accuracy of CFD simulations. Other experiments

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**Nomenclature**

| | |
|---|---|
| $R$ | radius of the branches |
| $\lambda$ | heat conductivity |
| $\mu$ | viscosity |
| $\rho$ | density |

*Superscripts*

| | |
|---|---|
| $f$ | fluid property |
| $s$ | solid property |

| | |
|---|---|
| $\bar{~}$ | implicit filter |
| $\langle \cdot \rangle$ | time average |
| $k_{sgs}$ | sub-grid scale kinetic energy |
| $\varepsilon_{sgs}$ | sub-grid scale dissipation |

were performed by Andersson et al. (2006) using Laser Dopper Velocimetry (LDV) and thermocouples in the Vattenfall R&D experiment with water (Westin, 2006). They measured statistics of the velocity and temperature at Reynolds numbers up to 100,000. Further experiments in the same group were carried out by Westin et al. (2008) in order to assess the performance of computational fluid dynamics for modelling such a problem. Although the near wall region is a critical region to assess the thermal transfer between the flow and pipe walls it is also notoriously difficult to conduct accurate measurements. In this case the experiment had limited data near the walls (temperatures measured up to 1 mm from the walls and velocities up to 5 mm from the walls). It was therefore not possible to do a full comparison of the numerical solution with data near the walls. The experiment was carried out using a Plexiglas model (which acts as an insulating, adiabatic, boundary) while reactor tee junctions are made of steel.

On the computational side, a large number of studies have been performed mostly motivated by thermal fatigue (see a rather exhaustive list of references in Ming and Zhao (2012)). Although thermal fluctuations from the fluid cause mechanical stresses in the solid, not all the fluid fluctuations have an effect on it. The thermal transfer in the solid involves only conduction while thermal transfer in the fluid involves convection and conduction (if we ignore radiation). Thus the solid tends to be insensitive to rapid high-frequency fluctuations associated with small scale turbulent mixing. Larger scale turbulent fluctuations can however lead to corresponding fluctuations in the solid. This means that the RMS temperature fluctuation in the fluid is not a viable indicator of the thermal forcing on the solid. Thus turbulence modelling methods based on Reynolds Averaged Navier Stokes methods (RANS) need to be used with care because the Reynolds averaging process does not explicitly make is possible to identify the scales from which the total rms fluctuations are evaluated. Steady and unsteady RANS have been applied by Walker et al. (2010) and Frank et al. (2009), respectively. In these studies it was concluded that an *ad hoc* adjustment of the model parameters is necessary in order to obtain a reasonable agreement with experimental data. Walker et al. (2010) performed calculations with ANSYS-CFX-10 and found that both turbulent mixing and turbulent momentum transport down-stream of the side-branch connection were under-estimated. As expected, unsteady RANS results gave more quantitative information about the large-scale turbulence structure development and the transient behaviour of the scalar fluctuations.

On the other hand large-eddy simulation methods (LES) deal with turbulence on a local scale. A large eddy simulation therefore does not model the larger scales of motion and the three dimensional time dependent nature of the flow is captured explicitly. This means the thermal forcing of the solid is also modelled explicitly and those fluctuations that are too rapid to be transferred to the solid will not have an effect. It is for this reason that the majority of studies of thermal striping make use of LES. LES has shown reasonable agreement with experimental data. Hu and Kazimi (2006) and Kuczaj et al. (2010) obtained a reasonable agreement when the mesh is fine enough, typically when Taylor micro-scales of the flow were resolved. Ming and Zhao (2012) and Kim and Jeong (2012) analysed the temperature fluctuations in tee junctions with diameter ratios of about unity and found large fluctuations with dominant frequencies of Strouhal numbers in the order of 0.5. Galpin and Simoneau (2011) investigated thermal fatigue phenomenon using both the Smagorinsky and the structure–function models, the latter providing slightly better predictions.

Despite the existing literature, the flow description remains incomplete and information on high-order turbulent statistics are missing. Large eddy simulation can generate sufficient data to provide high-order turbulent statistics such as budgets of the turbulent kinetic energy and temperature variance. Such statistics can provide a wealth of detail about a given flow. There are three primary uses for such information: (i) an assessment of the resolution of a simulation – if the budgets balance then that shows the given turbulent quantity is conserved, (ii) an evaluation of assumptions used for RANS of the relevant budget, and (iii) an extra source of information about the physics of the flow. High-order statistics are therefore included in this paper. We begin by introducing the geometrical and mathematical model followed by the numerical model and details. The resulting flow characteristics and statistics are presented and the paper finishes with some concluding remarks.

## 2. Geometrical and mathematical model

The flow conditions and geometrical model are based on the (MOTHER) project. This project aimed to model tee junction heat transfer and was initiated in the framework of NULIFE (Nuclear Plant Life Prediction) network of excellence under EURATOM FP6. Here the round corner geometry is slightly different from that used in the (MOTHER) project due to a slightly different filleting operation used to map the curvature of the corner. The domain in Fig. 1 consists of a tee junction created when a horizontal and a vertical pipe are joined. The coordinate system is chosen such that the horizontal direction is taken as the $x$-direction, the vertical direction is taken as the $z$-direction and the spanwise direction is taken as the $y$-direction. The origin is the centre of the tee. The hot and cold branches are given the same diameter ($D = 0.054$ m) and the inlets are placed $10D$ upstream of the junction (to allow each inlet flow to become fully developed) and the outlet is placed $15D$ further downstream. For the coupled fluid–solid simulations the structure is made of steel 0.01 m thick.

### 2.1. Governing equations of the fluid

The fluid flow is governed by the incompressible Navier–Stokes and energy equations. Effects due to changes in density are of secondary importance and have therefore been neglected in this

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