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URANS STUDY OF THERMAL TRANSIENTS IN A T-JUNCTION PIPE

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1. ABSTRACT

High cycle thermal fatigue (HCTF) induced cracking in the turbulent thermal mixing areas of T-junction piping systems is a vital safety concern in the nuclear power plants. We present a URANS study (with conjugate heat transfer) of hot thermal transients (linear ramp over a short period, for different Froude numbers 0.4 to 0.9, at the branch pipe inlet) through a T-junction configuration (working fluid is water), having constant ratio of mass flow rate (main / branch, 5:1). The analysis indicates that small Froude number transients lead to potential risk of thermal fatigue. Additionally, complex physical phenomena in these flows are also explored.

2. INTRODUCTION

This work is related to nuclear applications. The aim to understand the thermal fatigue due to mixing flows of significant temperature differences, in and around T-junctions. Early identification and safeguarding of nuclear plant components from such incidents are possible with the help of CFD simulations. Building on their earlier work on the prediction of thermal transients in U-bends [1], here the authors extend their study of thermal transients using URANS to T-Junctions. The URANS approach is first validated for steady flows through T-Junctions, and it is then used to explore the effect of thermal transients through mixed convection and conjugate heat transfer analysis.

3. METHODOLOGY

3.1 Turbulence modelling and meshing

In the URANS approach to the simulation of T-junction flows, we employ eddy-viscosity-based Low Re k-ε (Launder Sharma) to model turbulent stresses and eddy-diffusivity approach for turbulent heat fluxes, extended with the suitable buoyancy generation terms. Transient computations are carried out using open-source software OpenFOAM (v1912), employing the finite volume method. This incorporates the PIMPLE algorithm for the pressure field, and the QUICK convective discretization scheme. Meshes comprising structured hexahedral control volumes are utilized, with fine near-wall grid. The y+ values of near-wall nodes are maintained less than 1 in all cases. Grid independence study was performed, and 2.3 million cells have been adopted. To account for conjugate heat transfer, meshing is extended to the solid wall regions as well. Fig. 2 shows a representative image of mesh resolution and refinement in the yz-plane and symmetry plane.

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3.2 Case Set-up

The experimental setup used by Cenk Evrim [2] is considered for this study, shown schematically in Fig. 1. The configuration tested is a 3D T-junction shaped pipe with smooth walls, a circular cross-section throughout, having an inner diameter of 0.0718 and 0.0389 m for main and branch pipe respectively. Transient simulations for hot thermal transient propagating through the isothermal T-junction are performed by selecting the hot shock case with a Reynolds number (the flow Re is based on bulk velocity) of 8877 and 3300 for main and branch pipe respectively. The working fluid for the simulation is taken as water, at an initial inlet temperature of 293 K, Prandtl number (Pr) of 7. At the inlet of branch pipe, the temperature linearly increases to a fixed value (358, 390 and 460 for case 1 2 and 3 respectively) over the transient period (6.9 seconds) and then remains constant. The cases considered are Froude number (Fr), 0.40 - 0.80.

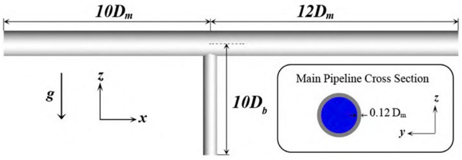

Figure 1: Schematic of the T-junction pipe used by [2]. Blue (fluid) and ash (solid).

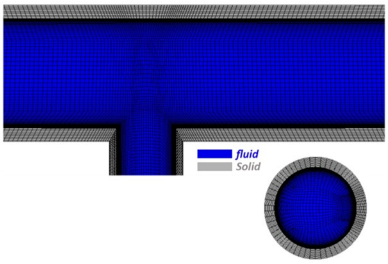

Figure 2: The mesh (mixing zone, xz-plane above and cross-section below).

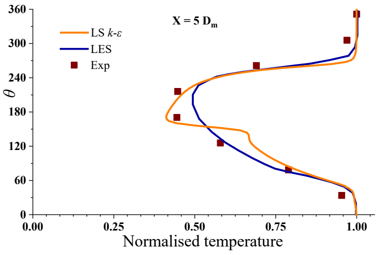

Figure 3: Normalised temperature comparison [2] ($5D_m$ downstream).

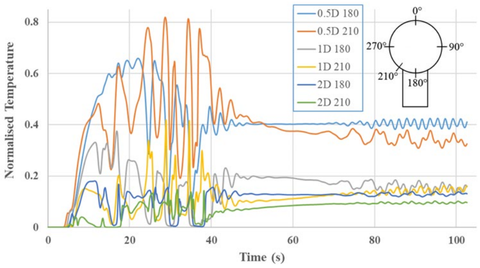

Figure 4: Normalised temperature ($T-T_0 / \Delta T$, T_0 initial temperature, ΔT temperature of ramp) predictions (2 mm below fluid boundary) at different locations (looking towards downstream direction). Fr is 0.6 and D represents D_m.

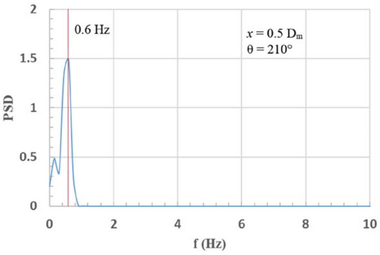

Figure 5: Power spectral density of temperature fluctuations, downstream of the T-junction (the reader is referred to Fig. 4 for probe locations). Fr is 0.6 for this case.

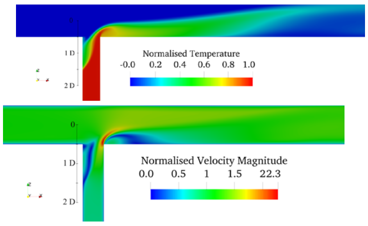

Figure 6: Top, contours of normalised temperature and bottom contours of normalised velocity (U/Um) at time 66 second (xz-plane). Fr is 0.6.

4. RESULTS

Circumferential distribution of normalised temperature at the location $x = 5D_m$ (validating against experimental and LES results [2]), is shown in Fig. 3. We can see that near wall temperature is predicted with good accuracy by the LS $k - \varepsilon$ model, with only a small quantitative difference (shows some wiggles compared to the LES data) in the region $90^0 < \theta < 150^0$ (lowest temperature region, where cold fluid from branch pipe is mixing with the hot fluid). This might be due to the inability of the model to better predict anisotropy related to turbulence induced by buoyancy.

Fig. 4 shows the normalised temperature history (near-wall) predictions in the main pipe at different downstream locations. As the hot transients penetrate into the main pipe, high amplitude fluctuations are noticed near the bottom region ($\theta = 150^0$ - 210^0, till $1D_m$), inside the turbulent shear layer (see Fig. 6), for the initial 40 seconds. These fluctuations, dampen and the flow reaches thermally steady state over the subsequent 20 seconds. As it progresses, temperatures in these regions slowly start showing oscillatory behaviour. Additionally, from the T-junction to position $x = 1\ D_m$, a strong temperature gradient is noticed along the axis of the main pipe. These temperature fluctuations can cause cyclic thermal stresses, which results in fatigue crack. This is further investigated through power spectral density analysis of the temperature fluctuations at 0.5D, $\theta = 150^0$ (see Fig. 5). The resulting dominant frequency of 0.6 Hz is low enough (less than 10 Hz) to cause thermal fatigue issues to the thermal hydraulic system [3].

Fig. 6 shows the normalized temperature and velocity field distribution in the xz-plane (x and z directions defined in Fig. 1). An acceleration area enclosing the recirculation zone (main pipe) is evident. A portion of the main pipe cold flow penetrates into the branch pipe (nearly $1D_m$) developing a recirculation zone, this is because of the higher density of the cold fluid. Main characteristics of the secondary flow development at a section $2D_m$ downstream are highlighted in Fig. 7. As the hot transient reaches the section (time = 15sec), buoyancy driven secondary flow develop two counter rotating vortices like Dean vortices. Temperature contours of Fig. 6 show that, downstream of the recirculation zone, hot transients from the branch pipe move towards the upper wall, resulting in the vortex-pair. Interestingly, by time = 28.5 s, the flow destabilises leading to one of the two vortices to expand and dominate and the other to shrink at the same time. This phenomenon continues till 36 s and finally a mono-vortex structure is observed before it finally returns to a stable symmetrical vortex pair confined to pipes lower half.

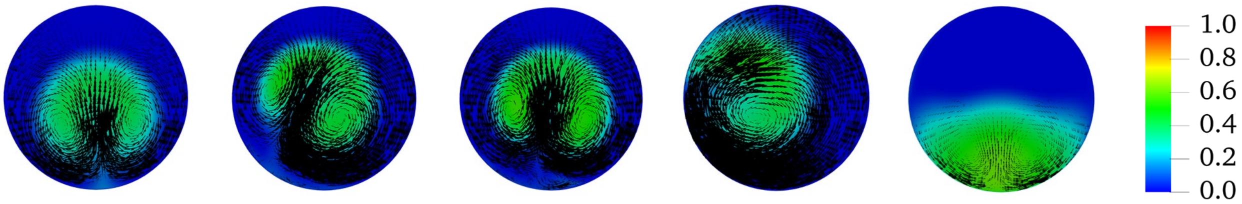

Figure 7: Evolution of secondary flow for Fr 0.6 , coloured by normalised temperature, 2D downstream of the junction at different time (frrom left to right 15, 28.5, 30, 36 and 66 seconds respectively).

5. CONCLUSIONS

The URANS simulations of thermal transients through the branch pipe of a T-junction have led to the conclusion that as the Froude number of thermal transient decreases thermal fatigue risk increases. Due to space restrictions only few results of case 2 have been included here. The remaining wide range of comparison (case 1 and 3) results, including animations will be presented in the conference.

REFERENCES

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