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Large Eddy Simulation of a T-Junction with Upstream Elbow: The Role of Dean Vortices in Thermal Fatigue

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Abstract

Turbulent mixing of fluids in a T-Junction can generate oscillating thermal stresses in pipe walls, which may lead to high cycle thermal fatigue. This thermal stripping problem is an important safety issue in nuclear plant thermal-hydraulic systems, since it can lead to unexpected failure of the pipe material. Here, we carry out a large eddy simulation (LES) of a T-Junction with an upstream bend and use proper orthogonal decomposition (POD) to identify the dominant structures in the flow. The bend generates an unsteady secondary flow about the pipe axis, known as Dean vortex swirl-switching. This provides an additional mechanism for low-frequency near-wall temperature fluctuations downstream of the T-Junction, over those that would be produced by mixing in the same T-Junction with straight inlets. The paper highlights the important role of neighbouring pipe bends in T-Junction thermal fatigue problems and the need to include them when using CFD as a predictive tool.

Keywords:
Thermal Fatigue, T-Junction with Upstream Bend, Dean Vortices, LES, POD

1. Introduction

Thermal stripping in cooling system pipework is a major safety challenge in the nuclear power industry. The phenomenon occurs via fluctuating temperatures in turbulent coolant flow causing fluctuating thermal stresses in pipe walls, which can lead to high cycle thermal fatigue [1]. In the last 20 years there have been several safety incidents caused by this problem, most notably at the French Civaux PWR plant in 1998 [2] and the Japanese Tsuruga-2 and Tomari-2 PWR plants in 1999 and 2003 [3].

T-Junctions are particularly susceptible to this problem and this has prompted many studies of the mixing that occurs within them; an extensive list of references is available in Ming and Zhao [4]. The geometries considered typically consist of a 90°
junction between two near-fully developed flows through straight pipes. Experimental studies of the turbulent mixing that occurs in such T-Junctions have been performed by Brucker [5], Walker et al. [6], Kamide et al. [7] and by numerous workers at the Vattenfall R&D facility [8, 9, 10]. These studies describe how temperature fluctuations are generated downstream of the junction by the turbulent mixing of the two fluid streams.

Many studies have used experimental data to validate CFD techniques for this application. In an international blind benchmarking exercise by Smith et al. [11], CFD results from 29 research groups were compared against experimental data for the Vattenfall T-Junction. The exercise concluded that wall-resolved LES is able to provide predictions that are in reasonable agreement with experimental data. Examples of other works that have demonstrated the suitability of LES for predicting the flow field in T-Junctions with straight inlets include Hu & Kazimi [12] and Kuczaj et al. [13].

However, practical T-Junctions in real-world plants typically have nearby upstream pipe bends. In a bend, the pressure gradient balancing the centrifugal force acts to sweep low inertia near-wall fluid around the pipe diameter towards the centre of curvature. This fluid subsequently returns along the symmetry plane, resulting in the formation of counter-rotating Dean vortices [14, 15].

Tunstall & Harvey [16] experimentally studied turbulent flows through a mitred and sharp 90° pipe bend and were the first to observe a phenomenon which is now widely referred to as swirl-switching. In both cases, the flow downstream of the bend was found to switch between two bi-stable states where the vortex in one half of the pipe dominates that in the other.

A number of experimental [17, 18, 19, 20] and LES [21, 22] investigations into the physics of swirl-switching have been carried out in recent years and for a thorough review the reader is referred to Kalpakli Vester et al. [23]. The applicability of LES to flows in pipe bends has been demonstrated by Carlsson et al. [22] and Rohrig et al. [24], where numerical predictions were found to be in good agreement with experimental data. Throughout these recent studies the phenomenon is reported as a smooth transition rather than a sudden switching between bi-stable states.

A wide range of time-scales have been associated with swirl-switching, which is typically reported as having more than one characteristic Strouhal number. Hellstrom et al. [19] reported the flow as being governed by two characteristic Strouhal numbers of 0.16 and 0.33 (based on the bulk velocity and pipe diameter). Other studies [17, 20, 21, 22, 23] report a low frequency mode with $S_T \approx 0.01 - 0.04$ and a higher frequency mode with $S_T \approx 0.12 - 0.3$. Carlsson et al. [22] suggest that the lower frequency is related to very large scale motions in the upstream pipe while the higher frequency is caused by structures originating in the bend. Tunstall & Harvey [16] found the Strouhal number to be Reynolds number dependant and it should also be emphasised that the flow conditions and measurement techniques vary significantly between these existing studies.

Though swirl-switching is not yet fully understood, it is clear that turbulent flow through a pipe bend generates Dean vortices which oscillate about the pipe axis and
vary in strength. Few workers have discussed this phenomenon in the context of flows in T-junctions. Sakowitz et al. [25] identified how structures similar to Dean vortices can be formed by the branch flow being turned through 90° as it enters the main pipe of a T-Junction with straight inlets. Examples of studies of T-Junctions with an upstream bend include those by Hosseini et al. [26], Kimura et al. [27], Nematollahi & Khonsha [28], Aulery et al. [29] and Lu et al. [30]; although none make a connection to Dean vortices or to the swirl-switching phenomenon.

We have previously demonstrated that the presence of an upstream bend strongly influences the mean thermal boundary layer development downstream of a T-Junction, through the effect of Dean vortices enhancing mean thermal mixing [31]. Here, we report findings from a high fidelity LES study of a T-Junction with an upstream bend and subsequent POD analysis. The bend generates Dean vortices and an unsteady secondary flow that interacts with the relatively low momentum hot fluid injected at the downstream T-Junction. This causes the hot fluid to be displaced about the pipe axis in alternating directions. Swirl-switching of the Dean vortices therefore leads to low-frequency near-wall temperature fluctuations downstream of the T-Junction, providing a further mechanism for thermal stripping in addition to that which would occur in the same T-Junction with a straight inlet.

To the author’s knowledge, this is the first detailed investigation into the role of Dean vortices in thermal mixing in a T-Junction. Although in the present work we focus on nuclear plant thermal-hydraulics systems, Dean vortex swirl-switching may also be of relevance to mixing problems in a wide range of other applications, such as oil and gas pipelines, internal combustion engines and process plants.

2. Methodology of Numerical Simulations

We study a 90° T-Junction between a cold main pipe flow and hot branch pipe flow. Parameters relating to the two pipe flows are given in Table 1 and the configuration is illustrated in Figure 1. The horizontal main pipe has a 90° bend 2D_m upstream of the junction which has a radius of curvature R_c = 1.4D_m, corresponding to a curvature ratio γ = D_m/(2R_c) = 0.357. We assume fully-developed turbulent inlet conditions, adiabatic walls and that the intersection between the pipes is sharp. The working fluid is water with constant fluid properties; the Prandtl number is taken as Pr = 6 and turbulent Prandtl number as Pr_t = 0.9. The ratio between main and branch pipe diameters is 5.14 and the branch flow is of considerably lower Reynolds number. The test case is representative of configurations found in nuclear plant thermal-hydraulics systems and matches the experimental setup of Hosseini et al. [26].

| Diameter       | Main        | Branch     |
|----------------|-------------|------------|
| Diameter       | D_m = 108 mm| D_b = 21 mm|
| Bulk Velocity  | U_m = 0.89 ms\(^{-1}\) | U_b = 0.23 ms\(^{-1}\) |
| Reynolds number| R_e_m = 107893 | R_e_b = 5422 |

Table 1: Characteristics of the T-Junction.
2.1. Large Eddy Simulations

For an incompressible flow the filtered mass and momentum conservation equations can be written as

\[
\frac{\partial \Pi_i}{\partial x_i} = 0 \quad (1)
\]

\[
\frac{\partial \Pi_i}{\partial t} + \frac{\partial \Pi_j}{\partial x_j} = - \frac{1}{\rho} \frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 \Pi_i}{\partial x_j \partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j} \quad (2)
\]

Here \( \tau_{ij} = u_i u_j - u_i u_j \) represent the stresses due to subgrid scale motions, which can be modelled using the Boussinesq approximation

\[
\tau_{ij} = \frac{1}{3} \delta_{ij} \tau_{kk} - 2 \nu_{SGS} \overline{S_{ij}} \quad (3)
\]

where \( \delta_{ij} \) is the Kronecker delta, \( \nu_{SGS} \) is the subgrid viscosity and \( \overline{S_{ij}} = \frac{1}{2} \left( \frac{\partial \Pi_i}{\partial x_j} + \frac{\partial \Pi_j}{\partial x_i} \right) \) is the filtered rate of strain tensor. For an incompressible flow, the isotropic term can be incorporated into the pressure. The dynamic Smagorinsky subgrid scale model [32, 33] is used to evaluate the subgrid viscosity:

\[
\nu_{SGS} = C_D \Delta^2 \sqrt{2 \overline{S_{ij}} \overline{S_{ij}}} \quad (4)
\]

where \( \Delta \) is the filter width (computed as the cube root of the cell volume) and \( C_D \) is calculated using the dynamic method proposed by Lilly [33]. In the implementation of the model used here, the cell centred values of the coefficient \( C_D \) are evaluated as the local average of face values and the effective viscosity \( (\nu + \nu_t) \) is clipped to zero, in order to avoid numerical instabilities [34].

Temperature is considered as a passive scalar, for which the wall boundary conditions are adiabatic. Using a simple gradient-diffusion hypothesis, the temperature transport equation can be written as

\[
\frac{\partial \overline{T}}{\partial t} + \overline{u_j} \frac{\partial \overline{T}}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \nu \frac{\partial \overline{T}}{Pr \, \partial x_j} + \nu_{SGS} \frac{\partial \overline{T}}{Pr_t \, \partial x_j} \right) \quad (5)
\]
We also define a non-dimensional temperature, for use in subsequent analysis

\[ T^* = \frac{T - T_m}{T_b - T_m} \]  

(6)

The LES simulation is carried out using the open source CFD toolbox foam-extend-3.1 [35]. The coupled momentum and pressure equations are solved using the PISO algorithm [36]. A second order backwards differencing scheme is used for time integration and second order schemes are used for the spatial discretisation.

The multi-block structured mesh contains 80 million hexahedral cells and is designed to resolve the viscous sublayer. Near-wall grid spacings of \( \Delta y^+ \leq 15 \) and \( \Delta x^+ \leq 60 \) are used in the circumferential and stream-wise directions, respectively, with the wall adjacent cell centres located at \( y^+ < 1 \); these spacings are in line with the recommendations of Piomelli and Chasnov [37] for wall-resolved LES. However, due to the geometric constraints of a structured mesh and the need for small cell growth rates in LES, the mesh is much finer in many areas of the domain, particularly around the pipe junction. A mesh with half the number of cells produced very similar results, indicating that the discretisation errors are not significant and that the mesh is of sufficient resolution.

Frohlich et al. [38] suggest that a grid with \( \Delta/\eta \leq 12 \) (where \( \eta = (\nu^3/\epsilon)^{1/4} \) is a conservative estimate for the Kolmogorov length scale) has sufficient resolution to resolve a significant portion of the dissipative range. Post-processing of the simulation reveals that on average there are 4 Kolmogorov micro-scales per filter width and that \( \Delta/\eta \leq 12 \) is satisfied throughout.

Variable time-stepping is used to enforce a maximum Courant number of unity. The mesh results in a highly localised maximum Courant number near to the junction, while in the remainder of the domain it is at least an order of magnitude lower. The time-step is typically \( \Delta t \approx 2.5 \times 10^{-5} \) s. Post-processing suggests that the Kolmogorov time-scale is larger than \( \tau_\eta = 7 \times 10^{-5} \) s throughout the entire domain; the time-stepping employed should therefore be more than adequate to resolve the large scale turbulence in the LES.

The divergence free synthetic eddy method (SEM) [39, 40] is used to generate fluctuating inflow conditions for the main and branch pipe inlets. Statistics for the SEM were obtained from precursor RANS simulations of the fully-developed main and branch pipe inflows. The main pipe SEM inlet is 10\( D_m \) upstream of the bend and the branch SEM inlet is 10\( D_b \) upstream of the junction, to provide sufficient development length. After initial transients were discarded, results were averaged over 12.57 seconds, corresponding to 103 convective time units based on the main pipe’s parameters.

3. Results

The mean velocity field is shown on the geometric symmetry plane in Figure 2. Immediately downstream of the bend the flow on the upper wall is separated, whilst fluid in the lower half of the pipe is accelerated. The flow does not recover before the T-Junction. A recirculating region spanning approximately 1\( D_b \) is visible downstream.
of the junction and the branch flow does not appear to have sufficient momentum to deeply penetrate into the main pipe. Although it was not possible to obtain detailed experimental data to fully validate the LES results, simulations using similar approaches have previously been validated for flows in T-Junctions and pipe bends elsewhere, see for example [11, 24].

![Figure 2: Contours of mean velocity normalised by $U_m$ on the geometric symmetry plane, note that full inlet and outlet pipes are cropped.](image)

Selected mean stream-wise velocity profiles are shown in Figure 3. The velocity profiles upstream of the junction are typical of those near to the outlet of a 90° bend, see for example [20]. 7$D_b$ upstream of the junction, the flow near the upper wall is decelerated and that near the lower wall is accelerated, leading to an asymmetric vertical velocity profile. Though its effect weakens, the bend still has an influence on the mean velocity profiles at the junction. The profiles highlight that 1$D_b$ downstream of the junction there is a recirculation region in the mixing layer which reattaches by 2$D_b$ downstream.

In the upstream elbow the pressure gradient, balancing the centrifugal force, acts to transport low inertia near-wall fluid towards the centre of curvature. This fluid subsequently returns along the symmetry plane, leading to the formation of the Dean vortices visualised in Figure 4. The bend results in the formation of two pairs of counter-rotating vortices. The larger of these vortices forms part way around the bend, whilst a smaller vortex separates from the upper wall near to the symmetry plane at the bend exit. The injection of fluid at the junction causes the smaller vortex to be displaced towards the centre of the pipe where it eventually coalesces with its larger neighbour. The overall picture is that Dean vortices are formed by the bend, interact with the fluid injected at the T-Junction and remain a significant feature of the flow further downstream.

The mean non-dimensional temperature field downstream of the junction is visualised on the geometric symmetry plane in Figure 5. The region of elevated temperature is largely confined to the region immediately downstream of the junction, though it can be seen that the penetration depth of hot fluid into the main pipe increases as it is convected downstream. The branch pipe flow has insufficient momentum to cause the hot fluid to penetrate so deeply; the high degree of mixing observed is a consequence of the Dean vortices originating at the upstream bend.
Figure 3: Mean stream-wise velocity profiles at various locations in the main pipe downstream of the bend. The length of \( U_m \) in the figure indicates a velocity equal to \( U_m \).

Figure 4: Mean streamlines coloured by mean velocity (normalised by \( U_m \)) to show the spatial evolution of the Dean vortices in one half of the pipe.
3.1. Unsteady Swirling Secondary Flows

To investigate whether the Dean vortices give rise to an unsteady secondary flow about the pipe axis, we first compute the instantaneous swirl number on cross-sectional planes $7D_b$ upstream and $1 & 2D_b$ downstream of the junction. The swirl number physically represents the ratio of circumferential momentum fluxes in the axial direction to axial momentum fluxes in the axial direction, and therefore gives an indication of the strength of any secondary flows about the pipe axis. Here we follow the definition of Gupta et al. [41]:

$$S_w = \frac{\int_0^R \int_0^{2\pi} UV \, dr \, d\theta}{\int_0^R \int_0^{2\pi} U^2 \, dr \, d\theta}$$

(7)

where $U$ is the axial velocity, $V$ is the circumferential velocity, $r$ & $\theta$ are respectively radial and angular coordinates relative to the centre of the cross-sectional plane.

The time-series of the swirl number is shown over a selected interval in Figure 6(a). The swirl number alternates between positive and negative values, indicating that there is an unsteady secondary flow about the pipe axis which alternates in circumferential direction. This secondary flow is a feature both upstream and downstream of the junction.

The power spectral density of the swirl number at each of the measurement planes is shown in Figure 6(b). At each of the locations considered the most prominent peak is at a Strouhal number of $S_t = 0.21$, suggesting a strong correlation of the frequency of the unsteadiness downstream of the junction with that at the upstream bend. This peak occurs within a range of Strouhal numbers commensurate with the literature for swirl-switching in pipe bends ($\approx 0.12 - 0.33$). Several lesser peaks in the swirl-number are also apparent (e.g. $S_t = 0.33$ and $S_t = 0.65$) suggesting that the unsteady motion about the pipe axis is quasi-periodic, as reported by Kalpakli and Orlu [20]. Consistent with the study of Hellstrom et al. [19], no peaks at low frequencies ($S_t \approx O(10^{-2})$) were observed. Tunstall and Harvey [16] demonstrated that the swirl-switching frequency is sensitive to Reynolds number, and it should also be noted that the Reynolds number of the present study is significantly larger than the recent studies of pipe bends discussed in Section 1.
3.2. Proper Orthogonal Decomposition

A snapshot proper orthogonal decomposition (POD) [42] of the velocity field is used as a post-processing tool to investigate the unsteady secondary flows present downstream of the bend and T-Junction. POD decomposes the turbulent flow field into orthogonal modes of decreasing energy content and each mode is accompanied by a coefficient which describes its temporal evolution. The mean field and any large scale structures in the flow are therefore represented in the first POD modes [43]. Snapshots of the instantaneous velocity field on cross-sectional planes $7D_b$ upstream and 1 & $2D_b$ downstream of the junction were collected. For each of these cross-sectional planes, 2514 snapshots spanning a total of 12.57 seconds were analysed using POD; this was found to be satisfactory by repeating the analysis using lower sampling rates and sizes.

Mode zero, corresponding to the mean flow, is illustrated for each cross-sectional plane in Figure 7. At all locations, mode zero features a pair of large counter rotating Dean vortices, which have their origin at the pipe bend. The T-Junction injects low momentum fluid, which does not impinge on the lower wall, through a relatively small branch pipe and would not in itself cause the formation of such large vortices downstream of the junction.

At the location upstream of the junction a smaller pair of vortices are also present in mode zero. $1D_b$ downstream of the junction there is also a four vortex structure, however it is quite different in nature. At the junction, the main flow is deflected around the injected fluid causing the now weakened second pair of vortices that were present at the upstream plane to coalesce with the larger vortices; evidenced by the

Figure 6: Time series (plotted for an arbitrary time interval) and power spectral density of the swirl number: $S_{sw}$

Here $t_0 = \frac{D_m}{U_m}$ and $S_t = ft_0$ is the Strouhal number.
Figure 7: In-plane components of POD mode zero, representing the mean velocity, at three cross-sectional planes in the main pipe. The colouring indicates the magnitude of the in-plane components of the POD mode normalised by the maximum at that downstream location.

enlargement of these vortices. The fluid injected by the branch pipe is turned through 90° as it rounds the junction, causing a smaller pair of counter-rotating vortices to be generated within it; leading to the four vortex structure at the plane 1Dₜ downstream of the junction. 2Dₜ downstream of the junction mode zero is characterised by a two vortex structure; the smaller pair of vortices originating from the branch flow weaken as they are convected downstream. The fluid injection therefore has an impact on the precise form of the Dean vortices downstream of the junction, though they have their origins at the upstream pipe bend.

The relative energy of the turbulent fluctuations contained in each of POD modes 1 to 20, along with the integrated energy of these modes, is shown in Figure 8. The first 20 modes contain approximately 20% of the total fluctuating energy at all downstream locations. The relative energy of the first mode is greater downstream of the junction than upstream; since any structures generated at the bend can be expected to weaken as they are convected downstream, this suggests that the presence of the branch pipe has a role in increasing its relative energy.

Mode one is visualised on each of the planes considered in Figure 9. A large vortex in the upper half of the pipe is the most prominent feature in each. The POD coefficient of this mode is plotted over a selected time interval in Figure 10(a). The time-coefficient alternates in sign, indicating that the direction of rotation of this vortex will alternate. This mode is responsible for the swirl-switching, and causes the Dean vortices in mode zero to rotate about the pipe axis in alternating directions.

There are also smaller structures present in mode one. Upstream of the junction there is a single large vortex in the lower half of the pipe, whereas downstream there
Figure 8: Scaled mode energy (bars) and integrated energy (lines) of the first 20 fluctuating POD modes computed at cross-sectional planes $7D_b$ upstream and $1D_b$ & $2D_b$ downstream of the junction.

Figure 9: In-plane components of POD mode one at three cross-sectional planes in the main pipe. Colouring as Figure 7.

are two. This is likely a result of the main pipe’s flow being deflected downwards due to fluid injected by the branch pipe. Smaller vortices are present in the upper half of the pipe $1D_b$ downstream of the junction that are not present $2D_b$ downstream. There is a vortex on the centreline between the larger vortex and the upper wall, and two vortices near the wall approximately $0.5D_b$ from the centreline. These vortices are within the recirculating region of fluid injected by the branch pipe and weaken as they are convected downstream.

The power spectral densities for the first POD mode’s coefficient are shown in Figure 10(b). At all locations the most prominent peak is associated with $S_t = 0.21$, corresponding to that of the swirl-number. There are several other peaks, again reflecting the quasi-periodic nature of the unsteadiness. $7D_b$ upstream of the junction a further peak can be seen at $S_t = 0.33$, corresponding to a peak observed in the swirl number. The planes downstream of the junction do not show a peak at $S_t = 0.33$ while they did display a peak in the swirl number at this Strouhal number, though it was
much less prominent than that for the plane $7D_b$ upstream of the junction. Both planes downstream of the junction exhibit a peak at $S_t = 0.88$; though this does not correspond to a definitive peak in the swirl number, its PSD was elevated in this frequency range. These results show that the unsteady secondary flow about the main pipe’s axis has its origins at the upstream bend, and is essentially Dean vortex swirl-switching, though the injected fluid influences its precise behaviour downstream of the T-Junction.

![Figure 10: Time series (plotted for an arbitrary time interval) and power spectral density of the POD coefficients for mode one: $7D_b$ upstream, $1D_b$ and $2D_b$ downstream of the junction.](image)

3.3. Risk of Thermal Fatigue due to Secondary Flows

LES predictions for the mean and RMS fluctuations of wall temperature in the area immediately downstream of the T-Junction are shown in Figure 11. Downstream of the T-Junction, the most intense temperature fluctuations occur approximately $0.5 – 1D_b$ either side of the geometric symmetry plane. There is also a region of intense temperature fluctuations around the upstream half of the interface between the two pipes. These areas of the component are therefore most susceptible to thermal fatigue damage.

The time-averaged temperature field with superimposed vectors of in-plane mean velocity is shown on the cross-sectional plane $1D_b$ downstream of the junction in Figure 12. This location is within the recirculation zone just downstream of the junction, shown in Figure 2, and as a result the fluid with the most elevated temperature does not impinge on the wall in the mean.

Two instantaneous snapshots of the flow $1D_b$ downstream of the junction are shown in Figures 12(b) and 12(c). In the first snapshot the Dean vortices are rotated about the pipe axis in the clockwise direction, whilst in the second snapshot they are rotated...
Figure 11: Mean and RMS wall temperature, $0.5D_m$ upstream to $2D_m$ downstream of the T-Junction.

Figure 12: Mean and two instantaneous snapshots of the temperature field with vectors of in-plane velocity on a plane $1D_b$ downstream of the T-Junction. Colour bar as Figure 11(a).

in the opposite direction. The time elapsed between the two snapshots is $2.38D_m/U_m$, corresponding to half a period of the dominant $S_t = 0.21$ peak in the swirl-number and first POD mode. At this downstream location, it appears that the turbulence within the shear layer has a significant influence on the wall temperature, in addition to Dean vortex swirl-switching. Turbulence within the shear layer provides mixing within the region of elevated fluid temperature, causing localised hot spots to form in this region which can impinge on the wall. Furthermore the small vortices present near the upper-wall of the pipe in POD mode 1 at this downstream location may damp the effect of swirl-switching on near-wall temperature.

The time-averaged temperature field with superimposed vectors of in-plane mean velocity is shown on the cross-sectional plane $2D_b$ downstream of the junction in Fig-
Figure 13. At this downstream location, in the mean, the hot fluid is confined to a narrow region penetrating approximately $1D_b$ into the main pipe.

Figure 13: Mean and two instantaneous snapshots of the temperature field with vectors of in-plane velocity on a plane $2D_b$ downstream of the T-Junction. Colour bar as Figure 11(a).

Instantaneous snapshots demonstrate that $2D_b$ downstream of the junction, the unsteady secondary motions of the Dean vortices cause the region of hot fluid to be convected about the pipe axis in alternating directions. In Figure 13(b) the unsteadiness has caused the Dean vortices to be rotated about the geometric symmetry plane in the clockwise direction, resulting in the fluid of elevated fluid temperature being displaced about the pipe axis in the same direction. In Figure 13(c) the Dean vortices are rotated in the opposite direction and the hot fluid is displaced circumferentially in the anticlockwise direction. The elapsed time between the snapshots again corresponds to half the time period period of the dominant $S_t = 0.21$ peak in the swirl-number and first POD mode. This swirl-switching of the Dean vortices causes large fluctuations in wall temperature, particularly at locations greater than $0.5D_b$ from the centreline. For example, at a point on the wall in the right half of the pipe $0.5D_b$ from the centreline, in Figure 13(b) the wall temperature is elevated whereas in Figure 13(c) it is comparable to the cold inlet temperature. The difference in wall temperature between these two time instants at this location is around 50% of the difference between the hot and cold inlet temperatures.

POD mode 1 demonstrated that there are differences in the turbulent structures that are prevalent $1D_b$ and $2D_b$ downstream of the T-Junction. Inspection of instantaneous snapshots has demonstrated the consequences of this on the instantaneous temperature field. Near to the junction there is a recirculating shear layer which arises as a consequence of the injection of hot fluid by the branch pipe. The turbulence in this shear layer promotes mixing and appears to reduce the effect of the unsteady secondary circulations about the pipe axis on the temperature field. Further downstream from the junction there is reattachment and the effect of the unsteady secondary circulations on
the temperature field is far more pronounced. They cause large displacements of the hot fluid about the pipe axis in alternating directions, causing large fluctuations in wall temperature and providing a mechanism for thermal stripping that would not occur if the T-Junction had a straight inlet pipe.

3.4. Temperature Spectra

We now investigate the power spectral density of the temperature fluctuations measured using probes 0.1\,mm from the pipe wall at the locations shown in Figure 14.

![Figure 14: Locations of probes on the main pipe cross-section, looking in the downstream direction. We consider these probes at sections 1\,D_b and 2\,D_b downstream of the junction.](image)

Figure 15: Power spectral density of temperature fluctuations at the probes shown in Figure 14, at two locations downstream of the junction. --- indicates a $-5/3$ slope.

![Figure 15: Power spectral density of temperature fluctuations at the probes shown in Figure 14, at two locations downstream of the junction. --- indicates a $-5/3$ slope.](image)

Results from probes 1\,D_b and 2\,D_b downstream are shown in Figure 15. The spectra indicate that at both downstream locations, a significant portion of the energy of the temperature fluctuations is associated with $S_t < 1$, corresponding to frequencies
< 8.25Hz. Temperature fluctuations below 10Hz are associated with an increased risk of thermal fatigue problems in nuclear plant thermal-hydraulics systems [1]; the T-Junction considered could therefore be susceptible to this safety issue. The correspondence of the spectra with a −5/3 slope is a further indication that the LES is well-resolved.

4. Conclusions

Dean vortices generated by the turbulent flow through a pipe bend can exhibit a swirl-switching phenomenon, whereby vortices in one half of the pipe alternately dominate those in the other. The existing literature has yet to make a strong connection between Dean vortices generated by a pipe bend and the thermal mixing that occurs in downstream T-Junctions. In the present study, the role of swirl-switching in the thermal mixing that occurs in a T-Junction with an upstream bend has been investigated using wall-resolved LES.

The flow in the industrial T-Junction considered is highly complex. Dean vortices are generated by the upstream bend which give rise to a swirling flow about the pipe axis, alternating in direction and extending beyond the junction. This unsteadiness of the swirling is associated with a dominant Strouhal number of $S_t = 0.21$, though multiple peaks in the PSD of the swirl-number suggest that it is quasi-periodic. POD analysis reveals that though the secondary flow has its origins at the pipe bend, its behaviour is influenced by the injection of fluid at the junction.

A recirculating turbulent shear layer is present just downstream of the junction. The turbulence in this shear layer provides mixing within the region of elevated temperature, providing a mechanism for thermal stripping. Further downstream, there is reattachment and the effect of Dean vortex swirl-switching on the temperature field is far more pronounced; it acts to convect the region of hot fluid about the pipe axis in alternating directions, resulting in large wall-temperature fluctuations. The time-scale of these motions corresponds to that of the dominant Strouhal number associated with the unsteadiness of the swirl-number and the first POD mode. Dean vortex swirl-switching can therefore provide an additional mechanism for thermal stripping in T-Junctions with an upstream bend.

At both downstream locations considered, the PSD of near-wall temperature fluctuations reveal that a significant portion of the energy is contained in frequencies which correspond to the range known to cause thermal fatigue damage in pipe walls [1]. Dean vortices generated by a pipe bend can therefore have a crucial role in T-Junction thermal fatigue problems.

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Highlights: ‘Large Eddy Simulation of a T-Junction with Upstream Elbow: The Role of Dean Vortices in Thermal Fatigue’

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- A T-Junction with an upstream bend is studied using wall-resolved LES and POD
- The bend generates Dean vortices which remain prominent downstream of the junction
- Dean vortex swirl-switching results in an unsteady secondary flow about the pipe axis
- This provides a further mechanism for near-wall temperature fluctuations
- Upstream bends can have a crucial role in T-Junction thermal fatigue problems