Large Eddy Simulation of Thermal Turbulent Mixing in T-Junction

Melouka Benyamina [1*], Pavel Knyazkov [2], Omar. Imine [1]

[1]Institute of Mechanical, University of science and Technology Oran (USTO) BP 1505 El Mnaouer, Algeria

[2] J.V. AL CONTRACTING, Algiers, Algeria

* corresponding author : benyaminamelouka@yahoo.fr

Résumé - Cet article présente les résultats numériques de mélange thermique dans un T-jonction. Les champs d'écoulement ont été prédits en utilisant la simulation de la grande échelle (LES) sur le code Fluent avec la supposition de profils de vitesse complètement développés en aval du pipe principale et le pipe de branchement. Les données numériques ont été comparées à celles de l'étude expérimentale effectuée par d'autres auteurs. Les résultats obtenus se trouvent dans un accord satisfaisant avec les données expérimentales disponibles. En outre, les paramètres de l'écoulement calculé pour T-jonction, comme la vitesse, la vorticité, les fluctuations de température ainsi que leurs densités de spectre de puissance (PSD), ont été étudiés. A partir l'analyse de ces résultats, il est constaté que la gamme de fréquence est de 3-5 Hz contient la plupart de l'énergie pour ce T-jonction.

Abstract - This paper presents the numerical results of thermal mixing in a T-junction. The flow fields have been predicted by using Large Eddies Simulation (LES) on the Fluent code with the assumption of fully-developed velocity profiles at both main and branch pipe inlet. The numerical data were compared to those of the experimental study carried out on this one by other authors. The obtained results were to be found in a satisfactory agreement with the available experimental data. Furthermore, the calculated flow parameters for T-junction, as velocity, vorticity, temperature fluctuations as well as their power spectrum densities (PSD), have been carried out. From the analysis of these results, it's found that the frequency range is 3-5 Hz contains most of the energy for this T-junction.

Keywords: T-junction, Thermal mixing, Turbulence, Large-Eddy Simulations, Temperature fluctuations.

Nomenclature

RMS	Root Mean Square	*Greek Symbols*	
LES	Large Eddies Simulation	ρ	density
DES	Detached Eddy Simulation	ρ_0	reference density
RANS	Reynolds Averaged Navier Stokes	β	thermal expansion coefficient
URANS	Unsteady Reynolds Averaged Navier Stokes	μ	molecular dynamic viscosity
CFD	Computational Fluid Dynamics	λ	thermal conductivity
PSD	Power Spectrum Densities	$\overline{S}_{ij}$	rate-of-strain tensor
SGS	Sub-Grid Scale	τ_{ij}	Eddy viscosity
$\overline{u}$	velocity implicit filtered variable	μ_t	turbulent viscosity
$\overline{p}$	pressure implicit filtered variable	Ω	vorticity
$\overline{T}$	temperature implicit filtered variable	*Indices*	
$\overline{u}''$	velocity sub-grid part	c	Cold
$\overline{T}''$	temperature sub-grid part	h	Hot
C_p	specific heat capacity		
L_s	mixing length for the sub-grid scales		
k	von Karman constant		
d	distance to the closest wall		
C_s	Smagorinsky constant		

1. Introduction

The mixture of two hot and cold fluids downstream a T-junction generates thermal fluctuations which can cause thermal fatigue and consequently cracks in pipes. To understand thermal stripping phenomena, encountered in pipe systems of nuclear plants, several experimental and numerical researches were carried out by analyzing cyclic stresses in the pipes induced by fluid temperature fluctuations. To suggest adequate solutions aiming to attenuate thermal stresses, the exact assessment of temperature fluctuations magnitude is important. Many authors have investigated experimentally thermal mixing in T-junctions (Faidy, 2003; Hu and Kazimi, 2006; Metzner and Wilke, 2005; Westin et al.; 2008 Zboray et al., 2007). It is mentioned, in their studies, that thermal fatigue depends on temperature signals near the pipe wall. In particular, (Walker et al., 2009) have noted, in their experimental study, the occurrence of four flow regions near the mixing zone. The first region is characterized by low values of (RMS) temperature. The second is a strong mixing zone with high values of temperature RMS. The third region is also characterized by low values of the temperature RMS as the first. The last region is a separation zone which contains two vortices. To complete experimental research in mixing tees, the numerical studies became very important to simulate thermal stripping phenomena using (CFD) codes. Among the numerical methods, (RANS) and Unsteady RANS (URANS) models which are applied to calculate essentially the mean flow field. The results obtained from these methods cannot be directly used to identify the local fluctuations associated with thermal mixing. Therefore, in most of numerical studies, (LES/DES) turbulence models were chosen for the study of thermal mixing in T-junction. Many authors compare between the (LES/DES) and (RANS/URANS) approaches (Addad et al., 2009; Coste et al., 2008; Frank et al., 2008, 2010; Höhne, 2014; Hu and Kazimi, 2006; Kuczaj and Komen, 2008; Kuczaj et al., 2010; Kuhn et al., 2010; Manera et al., 2009; Niceno et al., 2008; Smith et al., 2013; Westin, 2007, Westin et al., 2008). They noted that LES and DES approaches are the appropriate tools to predict thermal mixing in piping systems. To evaluate accurately thermal fatigue in pipe, (Hannink and Blom, 2011) have suggested an adequate method for the thermal stresses calculation, called sinusoidal method. By using LES with a dynamic Smagorinsky sub-grid scale model, (Ndombo and Howard, 2011) have investigated the effect of the turbulent inlet conditions in a mixing tee junction. The authors stipulated that the turbulence at the inlet influences the flow parameters near the pipe wall. Finding solutions to prevent and diminish thermal fatigue in the pipes has become a very important issue in the nuclear power field. It is known that the maximum of temperature fluctuations is proportional to the thermal stresses. In this context, many authors have committed in the study of new configurations aiming to reduce temperature fluctuations in piping systems. (Lu et al., 2013) have studied, numerically, the influence of the elbow upstream of the main branch pipe in T-junction by using LES model. They have found the geometrical conditions leading to the attenuation of temperature and velocity fluctuations. (Passuto et al., 2007) have investigated the effects of the upstream elbows on thermal fatigue using LES. The results show that the upstream elbows have little influence on the flow dynamic. As expected, the mean and RMS temperature field are twisted when elbows are taken into account. (Lu et al., 2015) find a way to reduce temperature fluctuations and thermal fatigue. Numerical simulations are modeled by LES on the FLUENT code. The obtained results show that temperature fluctuations in the elbow pipe can be reduced by fixing a vortex breaker in the upper straight pipe.

In the present work, thermal mixing is numerically investigated on a mixing T-junction, in order to avoid the contact of the hot fluid with the wall. This investigation has been carried out by using LES approach with Smagorinsky Lilly sub-grid scale model (SGS) on the Fluent code. The numerical method has been applied to Study thermal mixture in T-junction and Calculate thermo-fluid parameters, the results have been compared with the available experimental data.

2. Large Eddy simulation (LES) turbulence model

2.1 Governing equations

The large eddies are solved by the filtered Navier–Stokes equations, and the small eddies are modeled using Smagorinsky Lilly sub-grid scale (SGS) model. For incompressible flow, the filtered Navier–Stokes and energy equations can be found in literature about turbulence (Lu et al., 2013; Ndombo and Howard, 2011):

$$\frac{\partial \rho}{\partial t}+\frac{\partial \rho \bar{u}_i}{\partial x_i}=0 \quad (1)$$

$$\frac{\partial \rho \bar{u}_i}{\partial t}+\frac{\partial \rho \bar{u}_i \bar{u}_j}{\partial x_j}=-\frac{\partial \bar{p}}{\partial x_i}-\rho_0 \beta\left(T-T_0\right) g+\frac{\partial}{\partial x_j}\left(2\mu \bar{S}_{ij}-\tau_{ij}\right) \quad (2)$$

$$\frac{\partial \rho \bar{T}}{\partial t}+\frac{\partial \rho \bar{T} \bar{u}_j}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\frac{\lambda}{C_P}\frac{\partial \bar{T}}{\partial x_j}-\rho \overline{T'' u_j''}\right) \quad (3)$$

Where $\bar{S}_{ij}$ is the rate-of-strain tensor for the resolved scale defined by

$$\bar{S}_{ij}=\frac{1}{2}\left(\frac{\partial \bar{u}_i}{\partial x_j}+\frac{\partial \bar{u}_j}{\partial x_i}\right) \quad (4)$$

2.2 Sub-Grid Scale (SGS) Modeling

The effect of the unresolved scale on the resolved scale in the above equations is represented by the sub-grid scale (SGS) stress, which is modeled by eddy viscosity hypothesis. The Smagorinsky SGS model was firstly proposed by (Smagorinsky, 1963) and further developed by (Lilly, 1966). In the Smagorinsky–Lilly model, the eddy-viscosity is modeled by

$$\tau_{ij} - \frac{1}{3}\tau_{kk}\delta_{ij} = -2\mu_t \bar{S}_{ij} \quad (5)$$

Where μ_t is the turbulent viscosity, which is written as

$$\mu_t = \rho L_s^2 \left|\bar{S}\right| \quad (6)$$

L_s and $\left|\bar{S}\right|$ are computed using

$$L_s = \min(\mathrm{kd}, \mathrm{C}_s V^{1/3}) \quad (7)$$

$$\left|\bar{S}\right| = \sqrt{2\bar{S}_{ij}\bar{S}_{ji}} \quad (8)$$

Where k is the von Karman constant equal to 0.42, d is the distance to the closest wall, C_s is the Smagorinsky constant for which FLUENT recommends a value of 0.1, and V is the volume of the computational cell.

3. Geometrical models

In the present paper, computational domain is based on the experimental setup described by (Andersson et al.; 2006), mentioned as Standard T-junction presented in Figure 1.

For tested configuration, the system of piping is composed of a main straight branch pipe (primary pipe) to which is connected another lateral branch pipe (secondary pipe). The cold fluid flows out in the main pipe whereas the hot fluid flows out in the secondary pipe before mixing themselves in the T-junction. The origin of the axis system is placed in the center of the mixing tee. The coordinate system showing the x-axis is directed along the axis of the main pipe's centerline. The z-axis is along the centerline of the branch pipe, and the y-axis spans the main pipe perpendicular to both main and branch centerlines, therefore the velocity components (u, v, w) reflect these axes of coordinate.

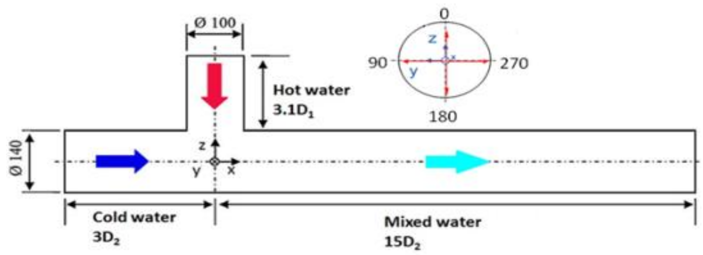

Figure 1 Computational domain for standard T-junction.

The inner diameters of both primary and secondary pipes are respectively D_2 =140 mm and D_1 =100 mm. The upstream lengths of the cold and hot pipes are $3D_2$ and $3.1D_1$ respectively, while the down-stream length of the main pipe from the origin of the axis to the outlet is 15 D_2 shown in figure 1.

4. Boundary conditions

Using the LES in thermal mixing requires the generation of boundary conditions, turbulent and unsteady for T-junction. The boundary conditions at the hot and cold inlets are determined by assuming fully-developed velocity profiles at these locations. Therefore, the velocity, turbulent kinetic energy and turbulent dissipation profiles are calculated using a $(k-w)$ SST model in both pipes. The output solutions were used as inlet conditions for both inlets junction. A zero static pressure has been adopted for the outlets main pipes and no-slip boundary conditions at all the walls. The volumetric flow rate in the connecting tube (Q1, hot water) is 6 l/s, and in the main tube (Q2, cold water) is equal to 9 l/s with rate aspect ratio equal to 1.5. The temperature of the cold and hot water are respectively 19° C and 36°C whereas the mean velocity for both fluids are respectively 0.585 m/s and 0.764 m/s, which corresponds to a Reynolds number of $(0.8–0.95)\times10^5$ respectively.

The physical properties of the cold and hot water were kept constant at the values indicated in Table 1.

Table 1.Physical properties of water used as constants in the simulations.

Density [kg/m3]	Specific heat [$m^2/(s^2.K)$]	Conductivity[$kg.m/(s^3.K)$]	Viscosity [m^2/s]
1000	$4.18*10^3$	0.6	$1.005*10^{-6}$

5. Numerical schemes and Mesh

In the present work, the physical domains were meshed with hexahedral elements for the studied configuration by using GAMBIT, a pre-processor for the FLUENT software. All computations were performed with a mesh including two central regions 1 and 2 corresponding to a grid spacing of 3 mm and 3.9 mm respectively as shown in Figure 2. The total number of mush is 2917183 hexahedral cells were obtained with a refinement near the wall of the pipe, to resolve the small-scale turbulent motions in this region.

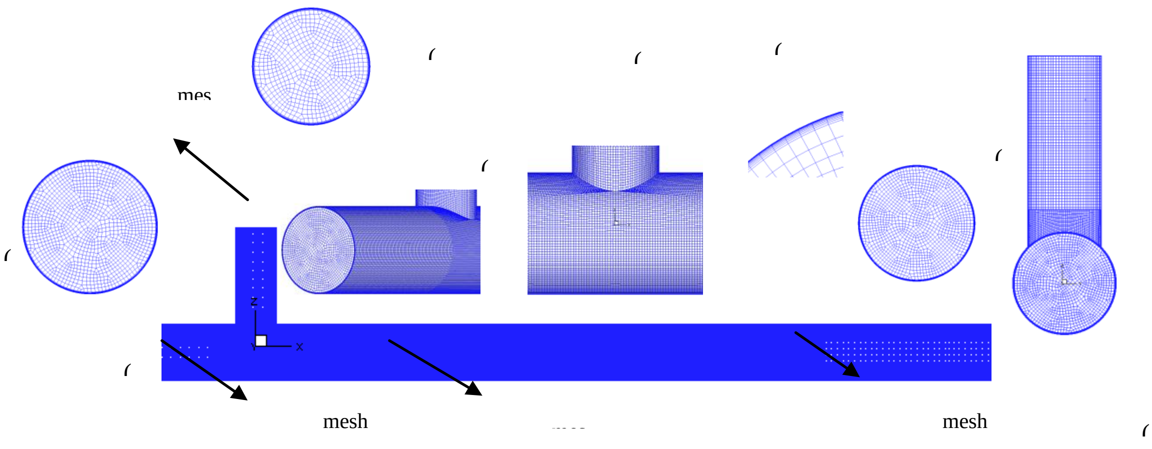

Figure 2 : The computational grid from different views of T- junction: Full domain (a), Cold inlet (b), Hot inlet (c), Outlet (d), Cross section of T- junction (e,f,g), and (d) Boundary layer.

The first element thickness near the wall was $1.25*10^{-5}$ mm and a growth factor of 1.3 is adopted for the subsequent 15 layers. The corresponding y+ values are lower than 1 (y+ < 1) and the CFL number is equal to 0.6.

The spatial discretization scheme for solving the momentum and energy equations was the central-differencing scheme. Except for the convection term in the momentum equation, the second-order upwind scheme was used. The Navier Stokes equations are solved using the SIMPLE algorithm. The equations were considered to be converged when the absolute values of the residuals were below $1\ 10^{-6}$. The total simulation time for the mixing process was about 12 s.

6. Results

The LES was initiated at T=0.0s using the previously converged solution as the initial condition. A constant step time Δt= 0.001s was used for the LES simulation for real-time 12s. The establishment of statistically reliable averaged values was launched after 5s.

6.1. Average velocities profiles and velocities fluctuations RMS

The objective of this section is the assessment of the LES approach used by Fluent code in the present work. For that, a comparison between the numerical data and the already published experimental data by (Smith et al., 2011) has been made.

The velocity profiles were normalized with the bulk velocity defined as $u_{bulk} = Q / \left(\pi r_c^2 \right)$ where Q is the mean flow rate equal to 15 l/s.

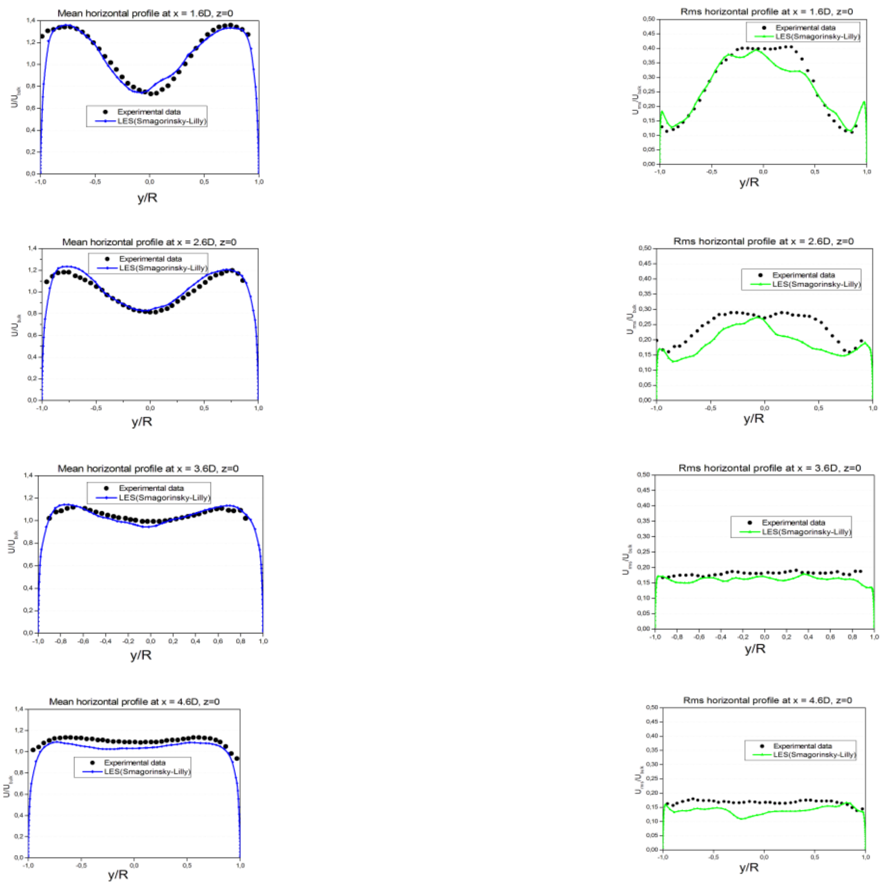

Figure 3 : Time averaged U velocity and U velocity fluctuations at z=0;x=(1.6,2.6,3.6,4.6)D of standard T-junction

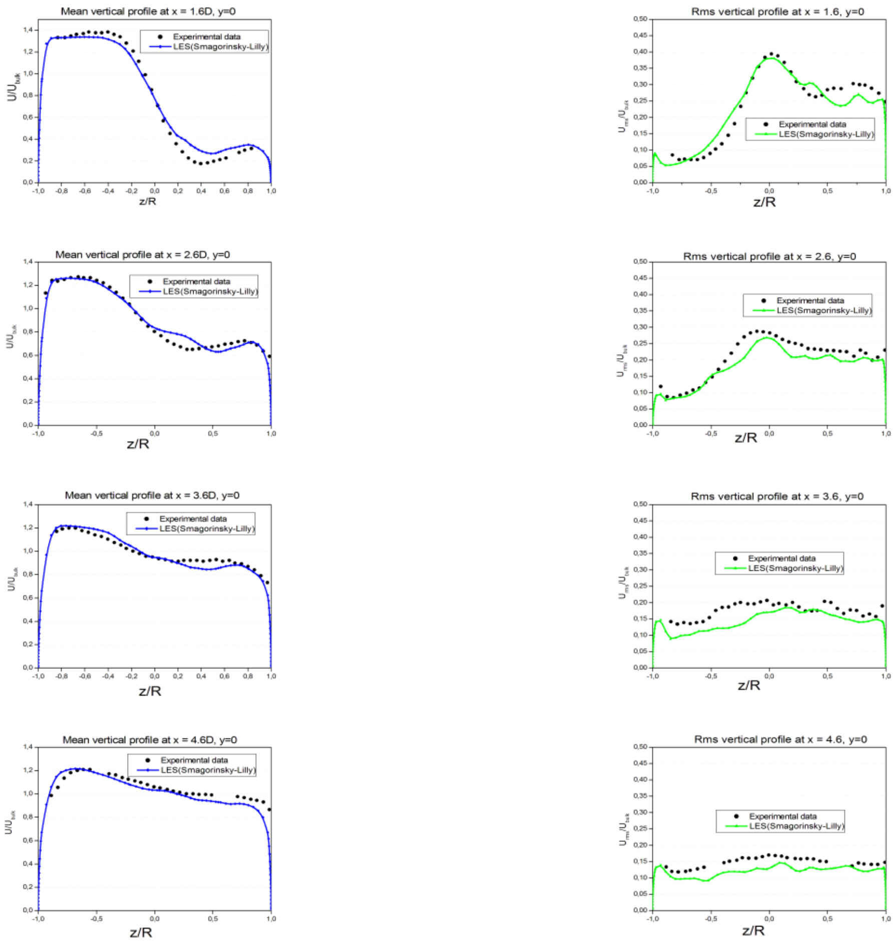

Figure 4 : Time averaged U velocity and U velocity fluctuations at y=0;x=(1.6,2.6,3.6,4.6)D of standard T-junction

Figure 3 and 4 shows the profiles of the mean axial U velocity and the root mean square velocity fluctuations (Urms) at z=0 and y=0 for x=1.6D,2.6D,3.6D and 4.6D downstream the standard T-junction along the horizontal and vertical direction respectively.

The comparisons between experimental and numerical solutions of axial velocity (U) as well as their fluctuations (Urms), show a good agreement. It could be an indication that the LES approach is reliable for good predictions of thermal mixing.

6.2. Analysis of the thermal and dynamic field

To obtain a global impression on the predicted flow in the T-junction, a survey of thermal and dynamic fields has been carried out respectively on geometry. The distribution of the static temperature drawn in the central plane, at y=0, are shown on the Figure 5 where the contours correspond to the time 12s.

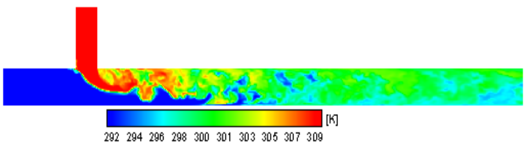

Figure 5 : Contour of Static temperature distributions at y=0, represented at 12s

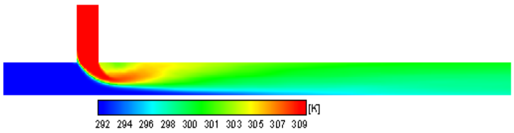

Figure 6 : Contour of Time averaged temperature at y=0, represented at 12s

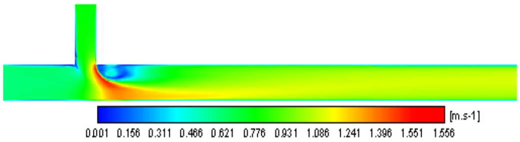

Figure 7 : Contour Time averaged velocities distributions at y=0, represented at 12s

Figure 6 and 7 show respectively the contours of time averaged temperature and velocity magnitude distributions in the central plane of the studied configuration. Figure 7 shows a zone of recirculation close to the T junction at the top side which leads to a delay of hot and cold water mixture in this region for the T-junction as it is well illustrated in Figure 6.

a) x=2D **b) x=6D**

Figure 8: Contour of mean Temperature shows cross section [2D-(a), 6D-(b)] for standard T-junction.

Figure 8 show the distributions of the average temperature in the T-junction, at x=2D and x=6D. The hot water occupies the top of pipe and the cold water gets at the bottom of pipe as it can be seen in the section x=2D. The separation of the two fluids just downstream of the T junction is due to the effect of gravity. The gradient of density which is a consequence of the difference of temperature in the fluid has a meaningful influence on the water distribution. Figure 8.b show that the mixture of the cold and hot fluids is well advanced in the section x=6D where a homogeneous flow covers almost all area of this section.

6.3. Analysis of vortex structures

The relationship between the vortices movement of large scale and the temperature distribution in the T-junction is treated in this section. Figure 9 shows the visualization of vortices generated by the turbulent mixing for studied configuration at the time 12 s.

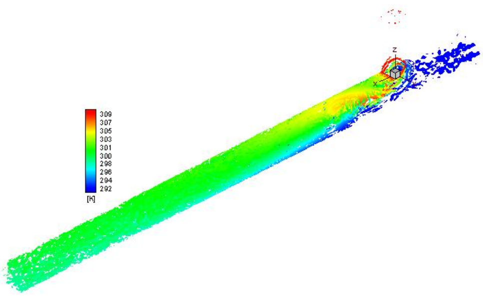

Figure 9 : Vortex structure developing downstream of the Standard T-junction as visualized by iso-surfaces of the Q-criteria colored by mean temperature (mesh 1, Q=5 1/s^2).

at time 12s

The visualization of the vortex structure was based on the iso-surfaces of the Q-criteria which is the second invariant of the velocity gradient, defined by the following equation (Chakraborty et al. 2005; Kim et al. 2013; Tanaka et al.2010):

$$Q = \frac{1}{2}\left(\|\Omega\|^2 - \|S\|^2\right) = \frac{1}{2}\left(\Omega_{ij}\Omega_{ij} - S_{ij}S_{ij}\right) \tag{9}$$

Where S is the strain rate of the flow field defined by Eq. (4).

Ω being the vorticity defined as:

$$\overline{\Omega}_{ij} = \frac{1}{2}\left(\frac{\partial \overline{u}_i}{\partial x_j} - \frac{\partial \overline{u}_j}{\partial x_i}\right) \tag{10}$$

The formation of a horseshoe vortex is clearly visible upstream the hot water jet for studied configuration. Immediately downstream the T-junction, irregular structures of vortex appear. Downstream, the length scale of these structures progressively decreases with the turbulent dissipation conducting to a good mixing of the hot and cold fluids.

6.4. Spectral Analysis

This section presents the results of numerical simulation of the mixing flow turbulent in the pipes with a standard T junction. The LES method is able to predict the instantaneous turbulent variables everywhere in the flow.

To understand the effect of temperature fluctuations, it is appeared very interesting to analyze the temperature signal behavior of hot spots (4D-270°) that reflect high temperature fluctuations. Then, the coordinates of this hot spot has been noted and entered in the Fluent code as point where virtual thermometer sensors are introduced to measure and record the instantaneous temperature signal during about 7s. It is well known that the fluctuations of temperature in the flow near the wall are transmitted to this wall and consequently cause thermal fatigue of the pipes. These fluctuations increase when the hot spot nears the wall and decrease when it moves away. Figure 10 indicates the recorded fluctuations of temperature of hot spot for T junction. The temporary change of the fluctuations magnitude which is a consequence of the instantaneous position of the hot spot from the wall is clearly noticed.

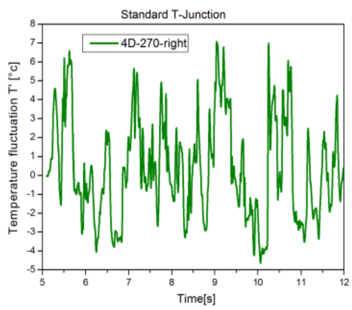

Figure10 : Temperature fluctuations T' as a function of time .plotted at data location (4D-270-right) near the pipe wall

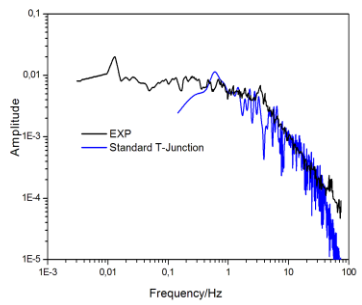

Figure11 : Power spectrum densities of temperature fluctuation at data location (4D-270-right) near the pipe wall compared with (Thermocouple Experiment, (Brain Smith et al., 2009, Höhne, 2014))

Figure 11 presents power spectrum densities (PSD) of the temperature fluctuations recorded in the hot spots close to the wall respectively for the standard configuration. The power spectrum density exhibits the repartition by frequency of the temperature fluctuation signal energy obtained by the Fourier transformation compared with experimental data location thermocouple (4D-270) the spectral peak is near 3–5 Hz.

The frequency characteristic of the temperature fluctuations is an important factor for the thermal fatigue evaluation. As it is reported in the work of (Ayhan et al., 2012), only the fluctuations of dominant amplitudes which have frequencies in the range of several hertz (between 1 and 10 Hz) are converted to the thermal stress. In the figure 11, the main frequency range is between 3-5 Hz for the standard T junction.

7. Conclusion

In the present work, thermal mixing in standard T-junction, have been numerically simulated by using LES approach based on the Smagorinsky Lilly model.

These simulations have permitted to evaluate the risk of temperature fluctuations, delimit the flow regions of high temperature fluctuations near the pipe wall and finally determine the characteristic frequencies of turbulent signals.

For the standard T-junction, comparison shows that the mean velocity profiles and velocity fluctuations RMS are in a good agreement with the experimental data. These results clearly indicate that this approach is reliable for the prediction of temperature fluctuations in thermal mixing which is the origin of thermal fatigue in piping systems.

From the analysis of PSD results, it's found that the Spectral peaks in both CFD and experimental data were found near 3-5 Hz which contains most of the energy for this T-junction studied throw the article.

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