Numerical Evaluation of Thermal Striping in MLNG Tiga Regenerative Piping

by

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With Honours

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32610 Sri Iskandar

Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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BACHELOR OF ENGINEERING (Hons)

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Approved by:

____

(Dr. William Pao)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

JANUARY 2020

CERTIFICATION OF ORIGINALITY

This is to certify that I am liable for the research submitted in this venture, that the original work is mine, except as stated in the references and acknowledgments, and that the original work found therein was not carried out or carried out by unspecified sources or individuals.

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MUHAMMAD AFIQ IKHWAN BIN ZULKIFLI

ABSTRACT

Temperature fluctuations or known as thermal striping able to develop cyclic thermal stresses resulting in thermal fatigue. This can lead to unexpected failure of pipe material. New design of the T-junction has been made due to the raising concern regarding the current MLNG Tiga regenerative piping mixing tee design, which may degrade further as operations continue. However, there is no guarantee at the moment that the new colliding T-Junction design will improve in terms of magnitude and frequency of temperature fluctuations and temperature distribution along the mixing tee. This paper will discuss the behaviour of thermal striping at two different T-junction configuration which is the intersecting T-junction and colliding T-junction in MLNG Tiga regenerative piping. The numerical evaluation is conducted using Ansys 19 with the approach of Reynold Averaged Navier-Stokes (RANS), $k - \varepsilon$ turbulence model is employed with water as a working fluid. The end of simulations found out that the colliding mixing tee provides a better thermal mixing than intersecting mixing tee. However, in terms of temperature fluctuations intensity and energy content in the temperature fluctuations shows that the intersecting mixing tee is much better when comparing to the colliding mixing tee. Thus, thermal striping will most likely to occur faster in the colliding mixing tee.

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CHAPTER 1

INTRODUCTION

1.1 Background Study

Regenerative gas is one of the system available in MLNG Tiga to ensure uniform heating of the fluid flow. The piping system is designed in a way where the main pipe transport hot fluids, and a branch pipe injects a cold fluid which eventually resulting in thermal fatigue. Thermal fatigue is a degradation of the pipe structure caused by the thermal loading as a result of stress that been induced by the thermal striping. Since piping system consist of various of pipe fitting, which include tees, elbows, bends, and etc, there will be a risk for the thermal striping to occur at each of the pipe fitting mention above. However, the main concern is at the T-junction as this pipe fitting is used to mix the natural gas with two different temperature which most likely for the thermal striping to occur. In addition, based on previous incident that been reported, which is the occurrence of cracks on weldment areas of T-junction section is the main reason for the investigation of thermal behaviour should be conducted.

Thermal fatigue occurred when the material surfaces being exposed to a cycle of thermal stress that been induced by the random temperature fluctuation and turbulent mixing. Temperature fluctuation can generate crack network that cause component failure with enough fluctuation’s frequencies and magnitude at the walls. Due to the adequate frequencies and amplitude of wall fluctuations, these temperature fluctuations alone can create crack networks that cause component failure.

A further evaluation and research will be conducted as an effort to mitigate the problem occur at the mixing region in the T-junction especially regarding the thermal behaviour. The importance of knowing the behaviour of the flow is to ensure that the incident occur in the previous year could not repeated and ensuring plant operability.

1.2 Problem Statement

In order to solve issue involving thermal striping, MLNG Tiga's engineers has took a proactive countermeasure by replacing the intersecting T-junction with colliding T-junction which has a different flow pattern. The new design is comparatively different from the initial design as the natural gas of different temperatures will not be mixed by flowing from a branch pipe into a main flowline, but rather designed as a colliding T-Junction. Hot and cold natural gas will flow from the opposite ends of the T-Junction and flow into a branch pipe, containing mixed fluids of different temperatures.

The flow patterns of the T-junction configurations are one of the contributors to the thermal striping phenomenon. This flow configurations are assumed to be the main problem as the mixed temperature creates magnitude of temperature fluctuations and temperature distribution in some critical regions at both fluid and solid domain in which later will cause structural damage to the T-junction wall. Both intersecting tee and colliding tee will differ in terms of temperature oscillations, temperature distribution and the overall mixing quality.

It is well understood that the mixing of fluid in two differing temperature would produce a thermal flux but the behaviour of the thermal after the changes of the design is still inconclusive. Since the behaviour of the thermal is unknown, an intensive evaluation by using computational fluid dynamics (CFD) needs to be carried out as a prognostication steps in reducing the risk for MLNG Tiga operation.

1.3 Objective

The objective for this research is to evaluate and conduct a comparative analysis for thermal striping between two different T-junction configuration designs, the intersecting and colliding mixing tee, for MLNG Tiga regenerative gas piping.

1.4 Scope of Work

Scope of work will be focusing on the creation of simulation of flow and thermal behaviour along the T-junction geometry which is the intersecting tees and the colliding tees. Both tees will have a mixing of working fluids with two different temperatures, which are 320^{o}C for the hot inlet and 21^{o}C for the cold inlet. The analysis will be done based on the frequencies and magnitude of the fluctuation. Both colliding and intersecting mixing tee will have the same geometry modelled as the dimensions were given by the MLNG Tiga engineers. The fixed parameter throughout this project is the diameter of the T-junction, working fluid which is water and the transient flow in the T-junction. While the variable parameter would be the T-junction flow configurations, pressure and the temperature of the working fluids. The result of this study will only include the fluid domain. This research is only focusing at the T-junction and not the whole piping system of the Regenerative Gas and further studies on the thermal cyclic stress would not been conducted.

CHAPTER 2

LITERATURE REV1EW

Many theories of thermal mixing and thermal striping begins with the flow configuration inside the T-junction. Flows in T-junction can be classified as combining or dividing flow whereas the combining flow will accumulate flows from many pipes to a single pipe, while dividing will diverge the fluids from the main pipe to several branches pipe [21]. The T-junction can also be used to mix two liquids, gas and liquid or two gases. By referring to the figure 2.1, various pattern of fluid flow toward the mixing region and exiting toward the T-junction can be observed.

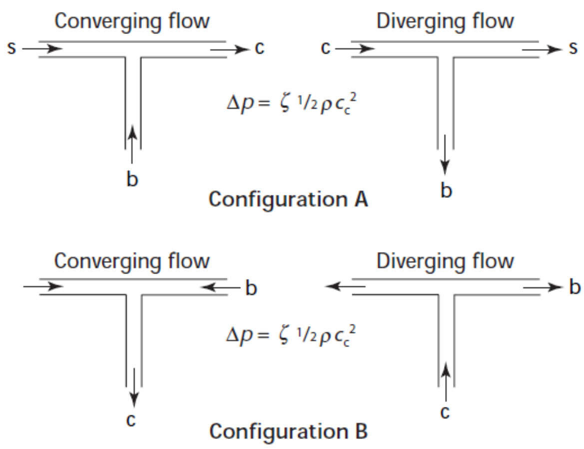


Figure 2.1: Flow type in T-junction [21]

Depending on the fluid properties and the direction of the flow, the behaviour of flow in the T-junction can varies accordingly. [15] conducted a CFD analysis for 90^o and 180^o bend angle of T-junction, suggest that velocity and pressure is varies by changing the angle of the T-junction. The pressure loss can be at minimum by reducing the angle of the T-joint of the pipe. An experimental investigation was carried out by [27] to observe the effects of system pressure and pipe diameter on the phase redistribution of the impacting T-junction. As a result, the diameter has a little effect on the phase redistribution while the pressure will affect the density and eventually effected the momentum rate of the fluids.

It can be argued that the T-junction will suffer a loss in pressure under certain circumferences that might affect the thermal mixing behaviour. A pressure drops happen when the existence of frictional forces exerted on the fluid that will cause a resistance to flow with the same fluid properties. This fluid flow resistance is affected by mainly fluid velocity and viscosity through the pipeline [20]. The pressure loss in the piping network increases proportionally to the frictional shear forces. [29] conducted a numerical experiment to investigate the pressure profile and velocity profile for two different T-junction configurations in the turbulent flow. The results from their experiments which has an agreement with [15] and [27], showed the pressure in the impacting T-junction begins to drop at the centre of the mixing region and the flow becomes fully developed further downstream while colliding T-junction shows the decreasing in pressure at the corner flow of the T-junction and the velocity stable much earlier compare to the impacting tee.

Bernoulli equation is used in order to describe the fundamental relationship between the fluid velocity and pressure which states that the total energy is conserved in the moving fluid. Therefore, energy from the pressure and kinetic remains constant throughout the process even the volume of the flow changes. However, pressure can reduce when the fluid is flowing through a constriction and this pressure reduction can be demonstrated by applying Bernoulli equation to the pressure and the area of the pipeline [2]. Velocity of the fluid needs to increase in the constricted area. Thus, kinetic energy will increase and will result in loss of pressure in order to balance the total energy.

Various temperature in a turbulent mixing especially in the mixing region of the T-junction has become priority concern in the area of plant safety in terms of pipe fitting reliability. This different temperature turbulent mixing can lead to temperature fluctuation in the pipe wall thus induced a thermal stress cycles which eventually produce a thermal fatigue and pipeline failure. Thermal mixing characterizes the process of merging hot and cold flow channels, mixing and resulting in variations in temperature.

One of the examples of thermal mixing experiments in T-junctions were conducted in Vattenfall test facility as shown in Figure 2.2. The objective of the experiment conducted is to describe the flow inside the T-Junction, temperature measurement and velocity measurement. The most common CFD solver used in industry is the Reynold-Averaged Navier Stoke (RANS) which tends to provide inaccurate result especially in this flow situation. Recent researches applying the advanced scale-resolving methods such as Large Eddy Simulation (LES) and Detached Eddy Simulation (DES) have shown a great agreement with the experiment results [13]. Similar to [13], [6] conducted numerical evaluation based on the Vattenfall T-junction experiment. The simulations result describes that RANS (k-ω SST model) based simulations unsuccessfully in predicting an accurate mixing between the fluids. While Large Eddy Simulations (LES) shows differently where the average temperature and field of velocity is predicted with a good accuracy. The numerical studies and experiment both have good agreement in finding the spectral peaks which both were found in the range of 3 – 5 Hz.

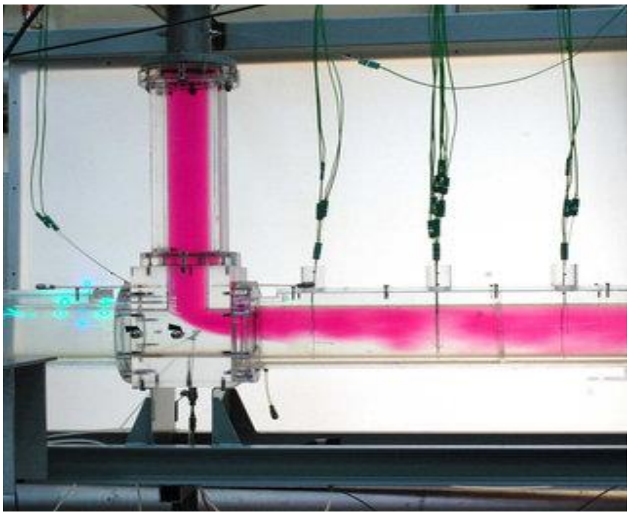


Figure 2.2: Vattenfall T-junction experimental set up (Angele, 2009)

[19] investigated the characteristics of thermal mixing flows in horizontal T-junctions using computational fluid dynamics (CFD), turbulence model named Large Eddy Simulations (LES). In the investigation, he has obtained results that the strong turbulence penetration of hot fluids entering the branch pipe was observed at $\Delta T > 140$ °C. A stable thermal stratified able to gives strong temperature gradients between the top and bottom of pipe that shows the fluid is not mixing well. These showed that the temperature differences in the mixing region play a vital role in determining the longevity of the T-junction.

[8] focus on investigating the promotion and control of turbulent thermal mixing of hot and cold airflows in a rectangular cross-section of a T-junction. By blowing jets into the main pipe of the T-junction in the direction of 45^o against the main flow to promote turbulent thermal mixing, they claim that the jet velocity able to control the degree of thermal mixing. In addition, they mention that a lower velocity ratio has a higher effectiveness of promoting jets compare to the high velocity ratio.

Thermal striping is a phenomenon that results in random temperature gradient in the jet instability interface between two streamlines. Since the fluid and pipe material contained a heat transfer coefficient, the thermal fluxes are exerted to pipe surface structures with minimal attenuation, resulting in high cycle fatigue and crack initiation in the pipe surface structures [14].

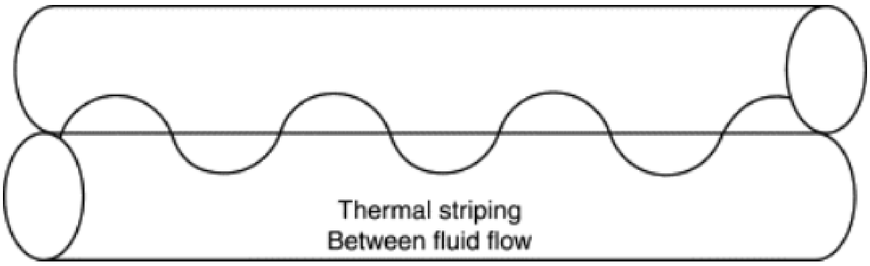


Figure 2.3: Thermal Stripping Between Fluid Flow [16]

The characteristics of thermal striping are important to be studied especially after few major incidents involving thermal fatigue crack at the weldment area. Material fatigue can occur when there is sufficiently strain cycles and high amplitude temperature oscillations. The mixing jets that influence the structures result in variations in temperature at the inner surface. In order to know the number of temperature cycles over a component lifetime and temperature oscillations in propagating from fluid to structure, a frequency analysis need to be done [23]. The frequency behaviour of thermal striping was explored by [16] and the effect of thermal striping frequency to surrounding structure of mixing tee is by [8]. [8] and [16] comes to a conclusion that the high frequency thermal oscillations from fluid to pipe inner wall is due to the relatively slow transient thermal response.

[20] performed T-junction flow mixing experiments to investigate the temperature fluctuations as a result of turbulence mixing by using numerical simulation code "MUGTHES". The authors conclude that the existing of wavy boundary at the mixing region located at $0.5D_m$ and $1.0D_m$ generate the highest temperature fluctuation with intensity of 30% from the temperature difference. The wavy boundary caused by the vortex is one of the thermal mixing phenomena that leads to the thermal striping [17] and [20] which eventually causing thermal fatigue. An experiment by [17] come out with a result where the vortex-shedding frequency is

evaluated at 5.84Hz where the frequency of the dominant peak of PSD is at 5.80Hz. This can conclude that the frequency of the temperature fluctuations is correspond to the vortex-shedding frequency of the branch jet.

An experiment to study the thermal mixing and thermal striping in a T-junction with the consideration of using different injection direction and different flowrate at both main pipe and branch pipe has been conducted by [4]. The authors used Power Spectral Density (PSD) and Strouhal number for Fast Fourier Transformation (FFT) analysis in order to quantitatively describe the thermal striping. At the end of the experiment, the result is nearly identical to the value of 10 Hz in the [9] investigation where the distinguishing frequency of thermal striping occur in between 9.2 Hz and 9.4 Hz.

[1] studied the temperature fluctuations by using computational fluids dynamics (CFD) with the turbulence model of Reynold's Averaged Navier-Stokes (RANS) and Large Eddy Simulation (LES). The results from the investigation agreed that the frequency of fluctuation at 2-5 Hz consists the highest energy which is the contribution to the thermal fatigue. [3] set up a numerical simulation by using turbulence model of Large Eddy Simulation (LES) mentioned that the thermal striping most likely to occur at frequency range of 1 to 50 Hz. As the frequency range reached below 10 Hz, the high cyclic thermal stress will occur at the point of interest. [5] has a good agreement with [1] and [3] whereas the greatest energy lies at the frequency range between 0.5 Hz and 20 Hz whereby the thermal striping took place. [5] also conducted an experiment and achieved fairly similar result to the numerical evaluation. From the past researches [1], [3], [4], [5] and [9], it can conclude that the highest energy to stimulate the thermal striping will exist in the mixing region at frequency range between 0.5 Hz to 10 Hz.

Reynolds-averaged Navier-Stokes (RANS) models suitable to use in evaluating the flow of a steady state, but unfit for unsteady flow simulations which include temperature fluctuation with time-variable function. Both the RANS and LES methods were implemented in the existing study to model thermal striping in the upper plenum of the experimental generation-IV sodium-cooled rapid reactor (PGSFR), currently being developed at KAERl [3]. As mentioned in the paper of [13] and [6], experiment in [3] has a good understanding that LES is much more fitting to examine the thermal behaviour and thermal striping for a transient condition but with the drawbacks of longer simulation period.

For the researcher to overcome or study the behaviour of the thermal striping, it is crucial to first predict the location of the temperature oscillations at the flow junctions. This is because, certain region is significantly sensitive to a rapid temperature cycles than others. Classifications of flow patterns at 90o intersection tee can be made by finding the momentum rate by using equations (1) and (2) for both hot and cold streams [23]:

$$M_H = \frac{\pi}{4} D_H^2 V_H^2 \rho_H \qquad (1)$$

$$M_C = \frac{\pi}{4} D_C^2 V_C^2 \rho_C \qquad (2)$$

where V, D, and ρ are defined as the velocity, hydraulics diameter, and density of the cold and hot inlet streams. The momentum flow ratio of hot to cold flow at the junction can be calculated by using following equation:

$$M_R = \frac{M_H}{M_C} = \frac{V_H^2 \rho_H}{V_C^2 \rho_C} \qquad (3)$$

These flow equations were found in a report of Japan Society of Mechanical Engineers for the characteristic equations to only be used in solving problem involving T-junction intersections [17]. Note that the momentum ratio for a T-junction is defined as the main tube flow divided by a branch flow. Table 2.1 provides categorization of T-junction flow, with categories for wall jet, re-attached jet, turn jet, and impinging jet as a function of momentum ratio [9].

Table 2.1: Flow category with the respect to momentum ratio

Flow Category	M_R
Wall Jet	>4
Reattached Jet	1.35 - 4
Turn Jet	0.35 – 1.35
Impinging Jet	<0.35

Table 2.2: Critical Analysis of the literature review

No.	**Author/Date**	**Dimension of T-junction**	**Remark**	**Result**
1	Ferrara &Di Marco (2017)	d/D = 0.068/0.494 D = 0.1377 m	1. The range of frequency of oscillations under thermal striping is found to be 0.1-10 Hz. 2. Conduction inside pipe wall (near-mixed region) is needed to achieve accuracy.	1. Mixing zone- Highest RMS temperature. 2. Effective thermal stripping 0.5 – 20 Hz
2	Tanaka, Ohshima & Moniji (2010)	d/D = 0.05/0.15 D = 0.3333 m	1. The existence of wavy temperature boundary cause high temperature fluctuation intensity. 2. Wall surface is affected by significant temperature fluctuation.	1. Interaction between Karman's vortex and large-scale hairpin vortex, dominated temperature fluctuation in the thermal striping in the T-junction.
3	Nakamura, Utanohara, Miyoshi & Kasahara (2014)	d/D = 0.05/0.15 D=0.3333 m	1. Vortices generate temperature fluctuation in main flow. 2. Fluctuations propagates to the boundary layer of flow.	1. The maximum fluctuation amplitude: centre of the main pipe. 2. Averaged fluctuating frequency was about 5-7Hz.

4	Selvam (2016)	d/D = 0.0389/0.0718 D = 0.5418 m	1. Induced thermal stress related to its temperature fluctuation frequency.	1. Highest temperature fluctuation amplitude occurs along the stratification layer. 2. Peak temperature amplitude range between 36-43% of temperature difference.
5	Qian, Kanamaru & Kasahara (2015)	d/D = 0.05/0.15 D = 0.3333m	1. The prediction of the temperature fluctuation frequency of interest was around 6.0 Hz (below 10.0 Hz).	1. Temperature fluctuations take place at mixing streams and attenuated after 2.0D m from the center of the branch pipe.

CHAPTER 3

METHODOLOGY

Computational fluid dynamic (CFD) is used to simulate this project and the proposed methodology is as presented. For the flow of cold and hot water along the intersecting T-Junction and colliding T-junction, the results will be predicted using ANSYS along with analysis of effected areas on the T-Junction.

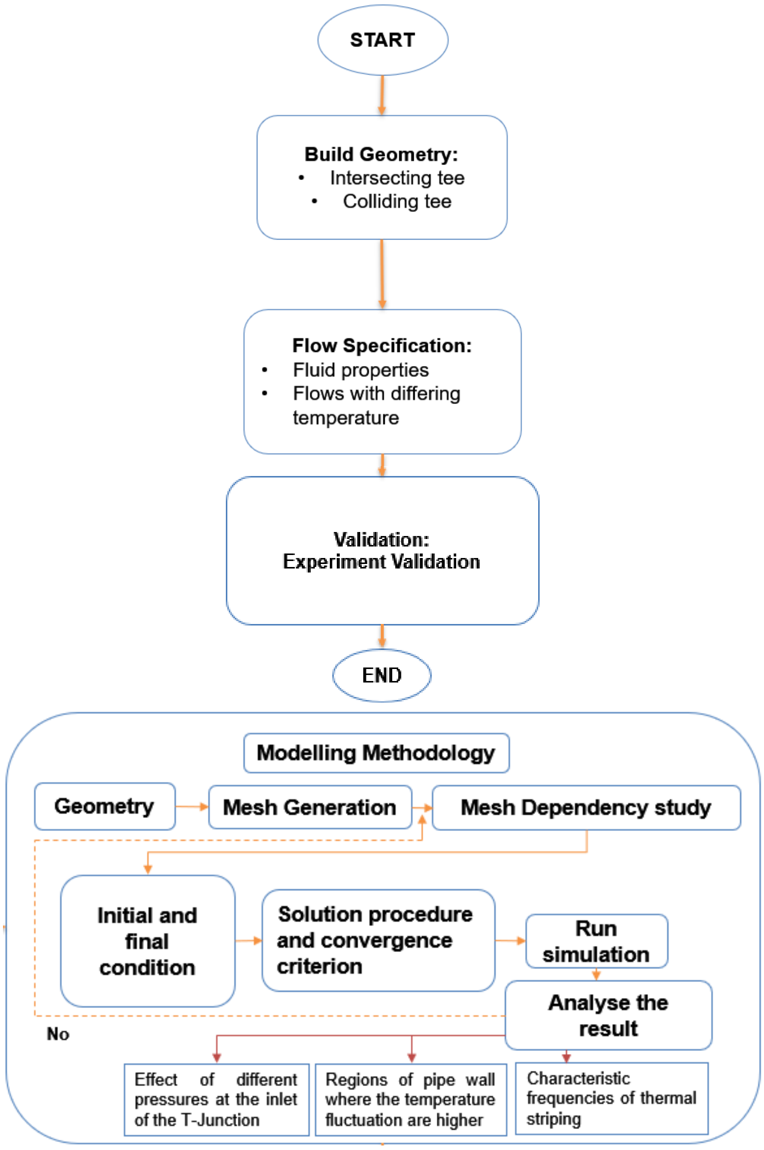


Figure 3.1: Flow chart of research methodology

3.1 Modelling Methodology

3.1.1 T-Junction Geometry

The intersecting T-Junction and colliding T-junction will use the same geometry configuration as shown in the figure below but with different flow configuration. The dimension of the mixing tee is given by the engineers of MLNG Tiga and can be seen in the table provided below.

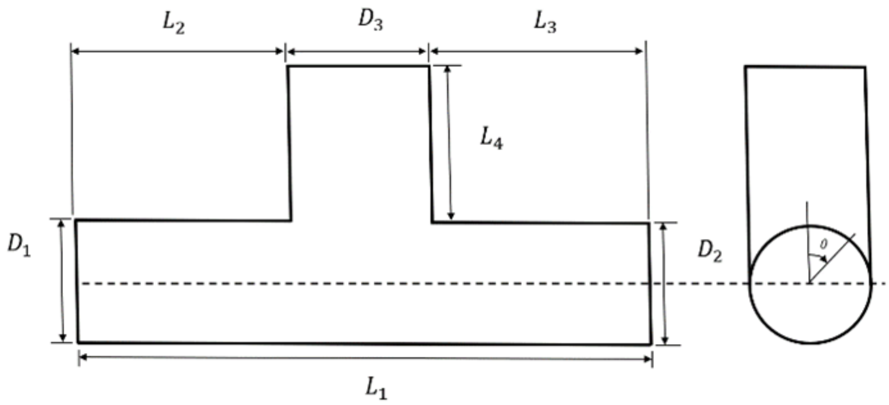


Figure 3.2: Schematic of Mixing Tee

Table 3.1: Dimensions of Colliding and Intersecting Mixing Tee

Geometric Parameter	Intersecting Mixing Tee	Flow Configuration	Colliding Mixing Tee	Flow Configuration
Diameter, $\boldsymbol{D_1}$(mm)	304.8	Mixing Outlet	304.8	Cold Flow Inlet
Diameter, $\boldsymbol{D_2}$(mm)	304.8	Hot Flow Inlet	304.8	Hot Flow Inlet
Diameter, $\boldsymbol{D_3}$(mm)	304.8	Cold Flow Inlet	304.8	Mixing Outlet
Length, $\boldsymbol{L_1}$(mm)	2400.0	-	2400.0	-
Length, $\boldsymbol{L_2}$(mm)	1047.6	-	1047.6	-
Length, $\boldsymbol{L_3}$(mm)	1047.6	-	1047.6	-
Length, $\boldsymbol{L_4}$(mm)	1500.0	-	1500.0	-

3.1.2 Computational Mesh Generation

Mesh to be applied to the geometry in finite element solvers can be categorize into several types such as hexahedral, tetrahedral and ply meshes [27]. For this current study, the combination of tetrahedral and hexahedral is used in the numerical setup for the fluid domain.

The wall domain which covers the inlet branch and outlet branch of the geometry are using hexahedral mesh type to give much stable and reducing the numerical diffusion error when solving the numerical model [28]. Since the mixing region or the intersecting area between the main pipe and branch pipe consists of curvature surfaces, tetrahedral mesh is assigned to achieve good and acceptable mesh for the simulation. The usage of tetrahedral mesh in these areas provide much finer mesh volume comparing to hexahedral type. The reasons for combine both hexahedral and tetrahedral is to ensure the overall quality of this mesh through the skewness which range between 0 and 0.8 and the orthogonal quality is at range of 0.3 to 1.0. It is important to achieve this value in the meshing in order to get an accurate result and to avoid unnecessary range of error during the simulation activities.

Mesh dependency study was conducted as a step in ensuring a quality result based on the generated mesh and the results are presented in the mesh independency study section of this paper.

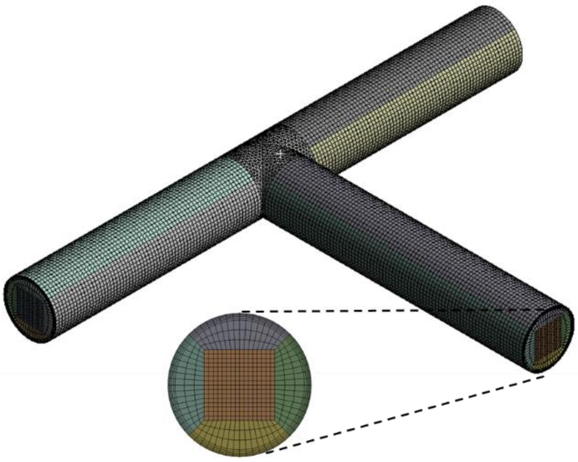
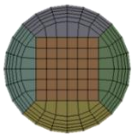
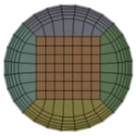
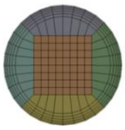
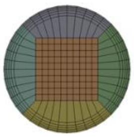
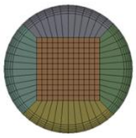
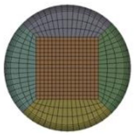
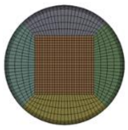


Figure 3.3: Mesh Generated on Mixing Tee

3.1.3 Mesh Dependency Study

In order to study the mesh convergence behaviour, numerous simulations need to be run with different number of tetrahedral cells. Stable calculation and result are achievable by applying this method and identify the mesh number elements through relevance meshing of model. Increasing the meshing relevance will increase the size of the mesh element thus produce a greater number of mesh element. In other words, the error on the mesh is highly depend on the number and size of the mesh element. A poor-quality meshing will only produce inaccurate result and inadequate solution convergence. The requirement for the optimum mesh from ICEM is the minimum determinant should be greater than 0.2 and the minimum angle required greater than 18 degrees. Table 3.2 details out the parameter used in order to conduct the mesh dependency study.

Table 3.2: Mesh Generated with Number of Elements

Mesh	Element Size (mm)	Number of Elements	Mesh Visualization on outlet
1	40	26063	
2	35	39924	
3	30	48428	
4	25	75713	
5	20	181066	
6	15	272237	
7	10	392844	

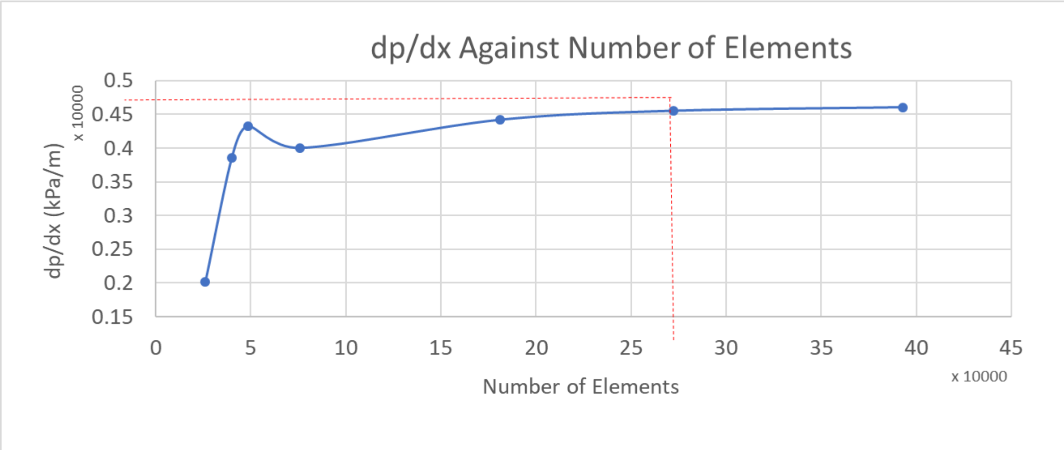


Figure 3.4: dp/dx Convergence vs Number of Elements

From the mesh dependency test obtained above, the longitudinal pressure gradient convergence slightly increases in value when the number of elements increases from 181066 to 392844. For this research, the element size of the meshing used is 15 mm whereby the differences in total pressure in mesh 6 and 7 was less than 1%. It is not necessary to use a greater number of elements as it can take a longer time to run the simulation.

3.2 Numerical Model

Navier-Stokes equations is used to characterize fluid behaviour in flow. In the LES system, sub-grid models are used to model the small-scale eddies and large-scale eddies are solved directly using filtered equations from Navier-Stokes. Equation (4) is the conservation of mass:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}\left(\rho \bar{u}_i\right) = 0 \qquad (4)$$

where ρ and $\bar{u}_i$ represent filtered density of fluid and velocity component, respectively. The conservation of momentum, equation (5):

$$\frac{\partial}{\partial t}(\rho \bar{u}_i) + \frac{\partial}{\partial x_j}\left(\rho \bar{u}_i \bar{u}_j\right) = \frac{\partial \sigma_{ij}}{\partial x_j} - \frac{\partial \bar{p}}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} + S_{M,i} \qquad (5)$$

where $S_{M,I}$ and $\bar{p}$, represent gravitational body force with temperature function and filtered pressure, respectively. For small density variations, the gravitational force of the body can be approximated using the Boussinesq approximation: $S_{M,i} = (\rho - \rho_o)g_i$. Where ρ_o is the initial density and g_i is the gravitational acceleration in the *i* direction. Equation (6) define the effect of molecular viscosity (μ) to stress tensor, σ_{ij}:

$$\sigma_{ij} = \mu\left(\frac{\partial \bar{u}_i}{\partial x_j} - \frac{\partial \bar{u}_j}{\partial x_i}\right) - \frac{2}{3}\mu \frac{\partial \bar{u}_l}{\partial x_l}\delta_{ij} \qquad (6)$$

Equation (7) describe the sub grid-scale stress, τ_{ij} :

$$\tau_{ij} = \rho \overline{u_i u_j} - \rho \bar{u}_i \bar{u}_j \qquad (7)$$

The Conservation of Energy is described in equation (8):

$$\frac{\partial}{\partial t}(\rho\bar{h}) + \frac{\partial}{\partial x_j}(\rho\bar{h}\bar{u}_j) = \frac{\partial}{\partial x_j}\left(k_{eff}\frac{\partial\bar{T}}{\partial x_j}\right) \tag{8}$$

where $\bar{T}$ and $\bar{h}$ represent filtered temperature and enthalpy, respectively. k_{eff} is a coefficient of effectiveness, in addition to molecular conduction, a turbulent mixing involvement and the equation of k_{eff}, as stated below:

$$k_{eff} = k + \frac{\mu_t c_p}{Pr_t} \tag{9}$$

where k, c_p and μ_t represent the thermal conductivity, constant pressure of the specific heat coefficient of the fluid and the sub-grid viscosity (eddy-viscosity) turbulent, respectively. Pr_t is a sub grid Prandt1 number.

3.3 Design of Experiment (DOE) Modelling

A design of experiment (DOE) was conducted for the current study to enhance the method of evaluations that depends on several factors in respond to the simulations. DOE able to identify important input factors by manipulating multiple inputs at the same time. This can reduce the time when doing the computational evaluation by analysing the important factors only. DOE is used to evaluate the thermal behaviour based on temperature and pressure, which are the interest of this project. The interaction between both temperature and pressure will also be an interest of study as their might influences the response of the thermal behaviour.

A^B is the expression to represent the total simulation number that will be conducted, where A is the number of factor level and B is number of factors. Despite many DOE types were available, Factorial design will be adopted in this research by running a subset of a full factorials. The method neglects three factor and higher interactions resulting in a smaller number of runs required to assess the same number of factors.

A 3-level design compromising of low, medium and high values has been selected. These three levels are selected based on 1 factor while the other factor will use two level factors. Table 3.3 shows the list of factors and values represented from low, medium and high levels of each respective factors. Table 3.4 shows the computed DOE using the software Minitab. The results will be taken from these simulation runs.

Table 3.3: Factors table

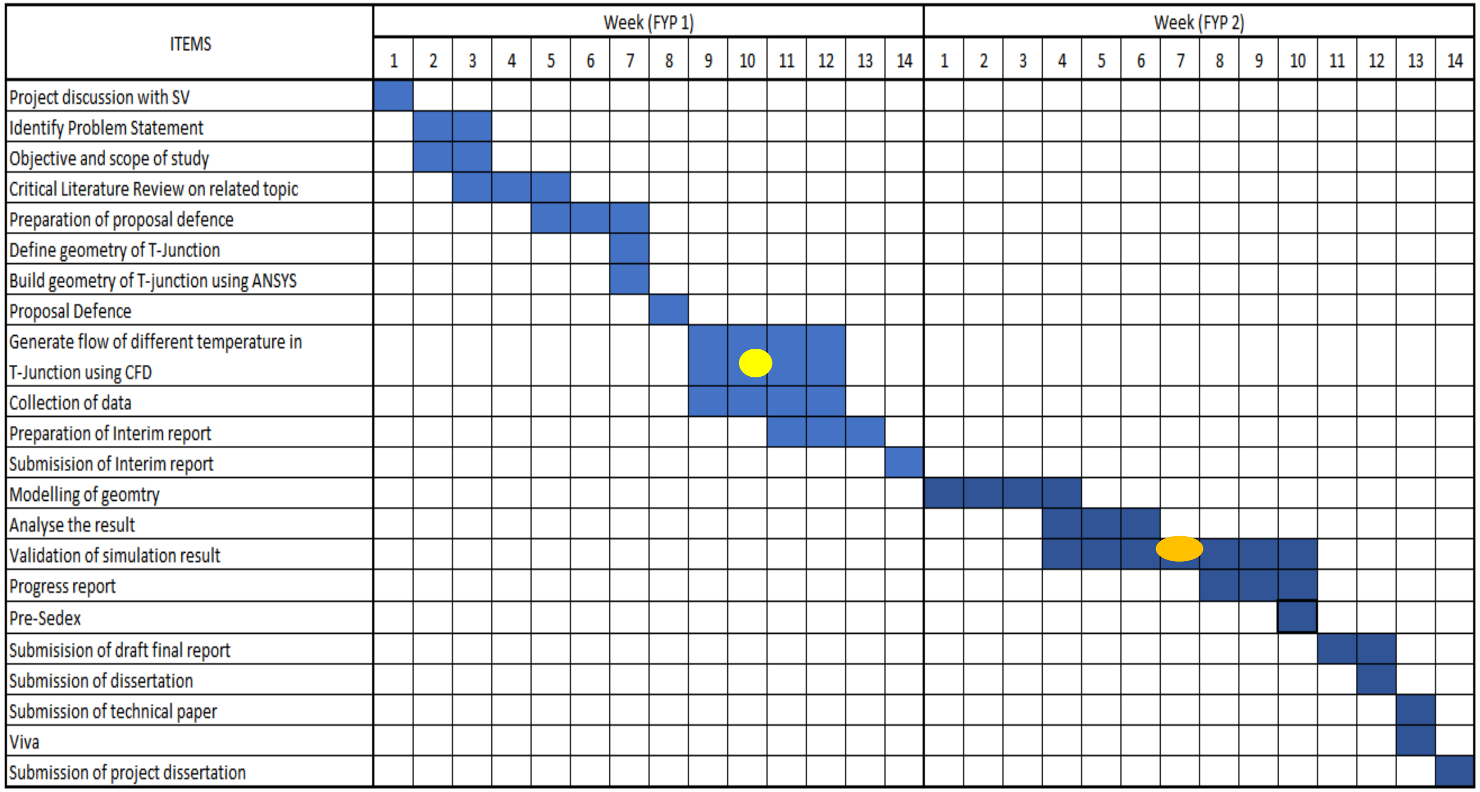
Factor	Level	Cold Flow	Hot Flow
Pressure (Bar)	Low	26.3	26.3
	Medium	52.6	52.6
	High	78.9	78.9
Temperature	Low	21	120
	High	120	320

Table 3.4: Design of experiment

Pressure at Cold Inlet (Bar)	Pressure at Hot Inlet (Bar)	Temperature Cold Inlet	Temperature Hot Inlet
78.9	52.6	21	320
52.6	26.3	21	360
26.3	78.9	120	360
78.9	52.6	21	360
78.9	26.3	120	360
26.3	78.9	21	360
78.9	26.3	21	320
26.3	52.6	21	360
26.3	52.6	21	320
52.6	52.6	120	360
52.6	26.3	120	320
52.6	78.9	120	320
78.9	52.6	120	360
26.3	52.6	120	360
52.6	52.6	21	360
78.9	26.3	120	320
52.6	26.3	21	320
78.9	78.9	21	360
52.6	78.9	21	320
52.6	78.9	120	360
78.9	78.9	21	320
26.3	26.3	21	320
52.6	26.3	120	360
26.3	26.3	120	360
52.6	52.6	120	320
78.9	78.9	120	360
52.6	78.9	21	360

3.4 Project Gantt Chart and Key Milestones

Table 3.5: Gantt Chart for FYP1 and FYP2



CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Model Validation

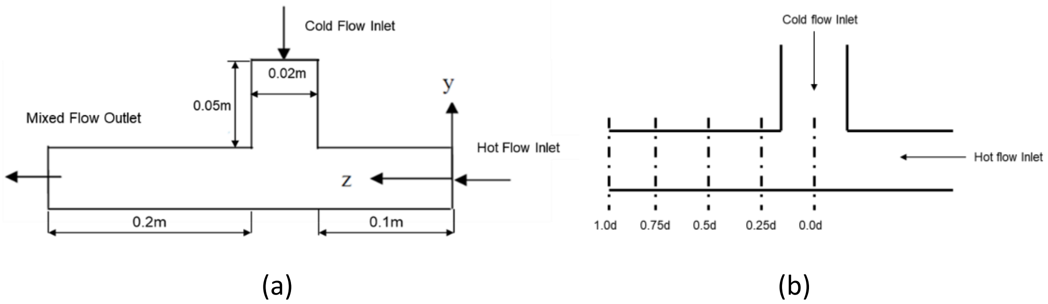


Figure 4.1: (a) Schematic Diagram of Intersecting Mixing Tees. (b) Sampling Point of Interest for Intersecting Mixing Tee

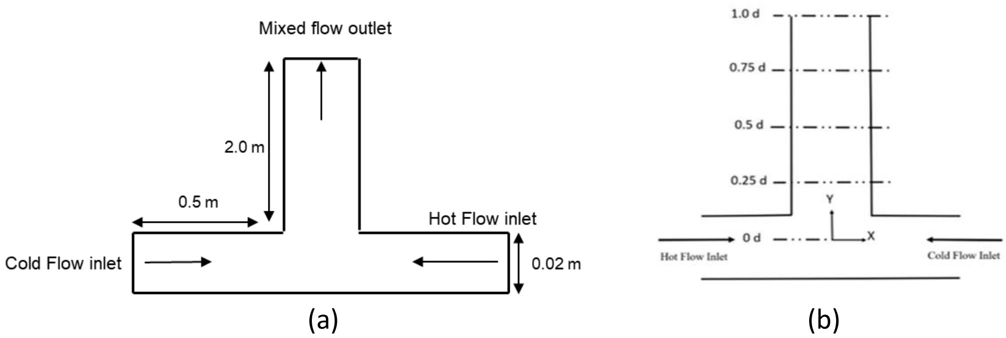


Figure 4.2: (a) Schematic Diagram of Colliding Mixing Tees. (b) Sampling Point of Interest for Colliding Mixing Tee

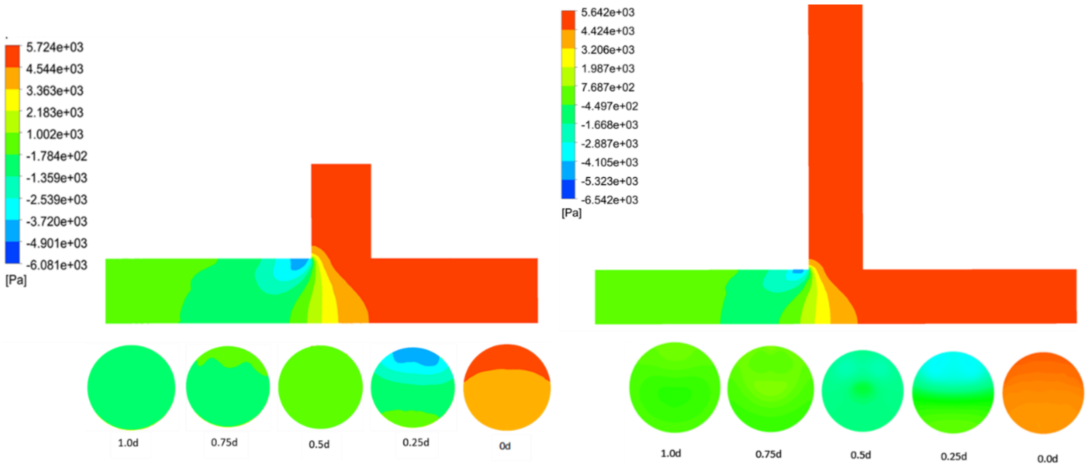
Intersecting and colliding T-junction junction geometry is modelled to use as model validation as describe in Figure 4.1 and Figure 4.2 with the pressure contour obtained in the research of [7]. As of the geometry of the T-Junction, different dimensions were used for the different T-Junction whereas the diameter can be observed from the Figure 4.1 (a) and Figure 4.2 (a)

Both of the mixing tees are using the same simulation setup, as mention in the Table 4.1, for the pressure and velocity coupling is SIMPLE with second order bounded differencing scheme to be used as the diffusive and convective parts of the equation discretization for the model. The result obtained in their studies was computed using the commercial package of Ansys Fluent and utilize the turbulence model of Realizable K-Epsilon.

Table 4.1: Simulation Setup for Validation based on [7]

Parameter	Value
Scheme	Simple
Discretization	Second order upwind
Convergence criteria	1×10^{-6}
Wall conditions	Adiabatic and no slip
Turbulence Model	K-ε
Cold flow inlet	15 Deg C
Hot Flow inlet	70 Deg C
Inlet velocity	0.5 m/s

By referring to the Table 4.1, the inlet boundary conditions for the cold fluid flows into the pipe with the temperature of 15℃ and velocity of 0.5 m/s. While the hot fluid flows with the same value of velocity but with 70°C of temperature. The temperature difference for this research is 55°C and using water as the operating fluid. [7] results were validated by the experimental conducted by Kuczaj A.K et al (2010). Based on the simulation result, the pressure contour profile at mixing region of the colliding and intersecting T-junction were compared to observe the flow pattern of the fluid.



(a) (b)

Figure 4.3: (a) Pressure Contour Profile of Intersecting Mixing Tee [7]. (b) Pressure Contour Profile of Intersecting Mixing Tee for Current Study

As describe in the Figure 4.3 (b), the current study shows the pressure profile contour and were compared to the Figure 4.3 (a), [7], and it was clearly seen that the profile obtained were identical. In the present study, some limitation is involved while conducting this numerical evaluation and that is the computational capability and the academic version of the Ansys Fluent. However, since the flow pattern is within the acceptable range to [7], the model is applicable to be used for further evaluation in this study. This model will be used for the intersecting mixing tee.

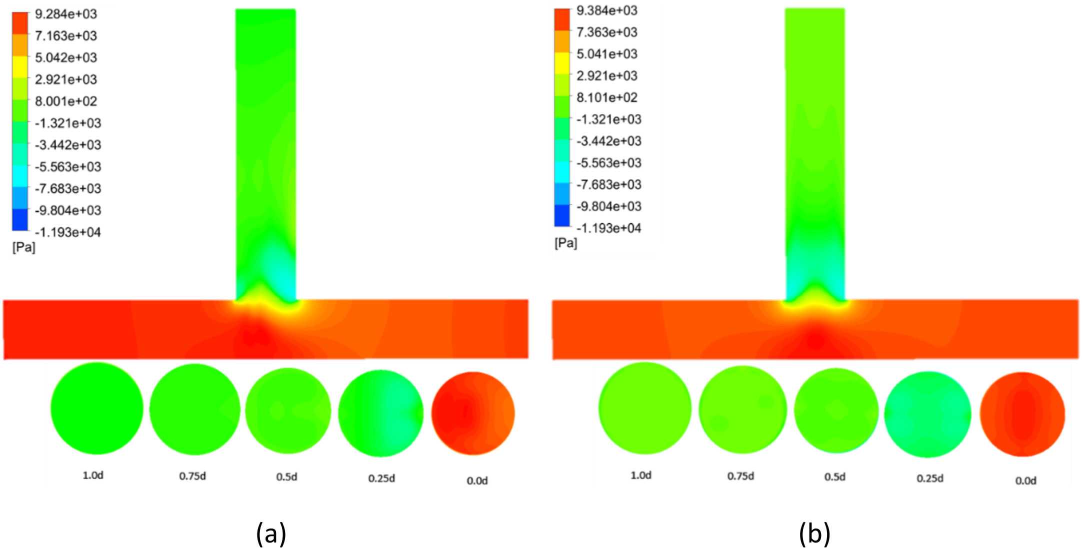


Figure 4.4: (a) Pressure Contour Profile of Colliding Mixing Tee [7]. (b) Pressure Contour Profile of Colliding Mixing Tee for Current Study

Similar to the validation result of intersecting mixing tee. colliding mixing tee from the current study is having fairly identical pressure contour profile when in comparing to the [7] researches. By referring to Figure 4.4 (b), each one of the cross sections of the sampling point for the current study shows slightly different from the [7]. However, the differences are acceptable, and this model of colliding mixing tee is applicable to be use in further analysis.

4.2 Temperature Distribution

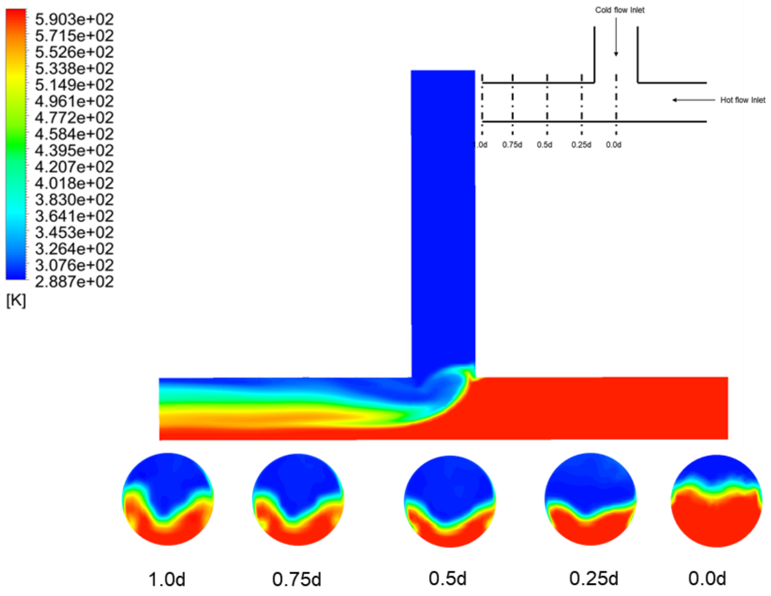


Figure 4.5: Temperature Profile Contour with the Cross Section of the Intersecting Mixing Tee

Figure 4.5 is the temperature contour schematic diagram of the intersecting mixing tee with location of sampling points along the mixing tee. The sampling point begin at the centre line of the schematic diagram with an increment of 0.25 for each of the sampling point. The length of the mixing branch of the tee is denoted as *d*. The higher temperature variance can be observed at the 0.0d as this sampling point is the mixing regions for both fluids. As the fluids flow through the outlet, the mean temperature become lower with the variant temperature remains notable. This indicate that the flows remain thermally stratified even at the length of 1.0d. It can be clearly observed from the cross-sectional temperature contour that the fluid was not fully mixed as each one of the sampling points shows a stratified flow. Based on the temperature contour profile obtained, intersecting mixing tee does not provide a great quality thermal mixing.

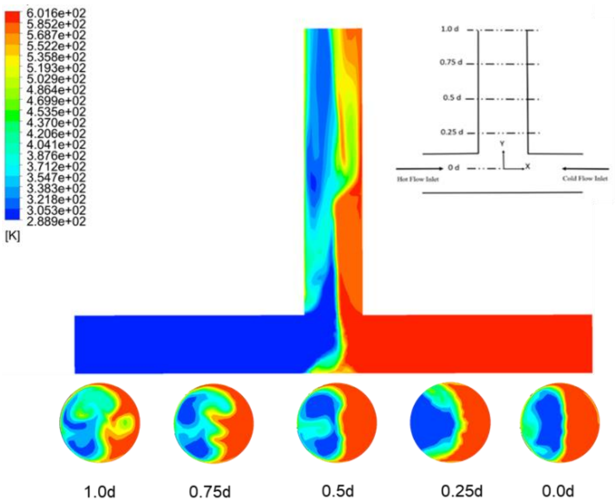


Figure 4.6: Temperature Profile Contour with the Cross Section of the Colliding Mixing Tee

Figure 4.6 shows a temperature profile with a cross section of the sampling point for the colliding mixing tee. Similar to intersecting mixing tee, the centre line of the schematic diagram is represented as 0.0d with an increment of 0.25 for each of the sampling point throughout the mixing outlet. Figure 4.6 describe the prediction of the mean temperature along the colliding mixing tee together with the range of bulk temperature of the fluid flow. The mean temperature recorded from 601K to 289K as the hot and cold flow are branched to flow perpendicularly of each other. At 0.0d, the temperature profile and the mean temperature variation indicate that this region is the mixing region. As the fluids flow toward the outlet, the mean temperature decreasing, and the mixing can be seen getting more intense as the flow becoming less stratified when approaching the outlet.

Unlike the intersecting mixing tee, the cross section of the colliding mixing tee shows that the flow is thermally stratified from point 0.0d to the 0.5d only and begin to mix from 0.75d onwards. The cross section of the temperature contour provided show that the flow is better at thermal mixing when compared to the intersecting mixing tee.

4.3 Circumferential Temperature Distribution

The measurement for this section were taken at an angle perpendicular to the cross section of the mixing branch sampling points at an angle from 0° to 360° with an increment of 45°. In order to validate the sampling point, the work of [17] was taken as reference as they stated to take the angular sampling point at 1 mm from the pipe wall where the thermocouple was installed.

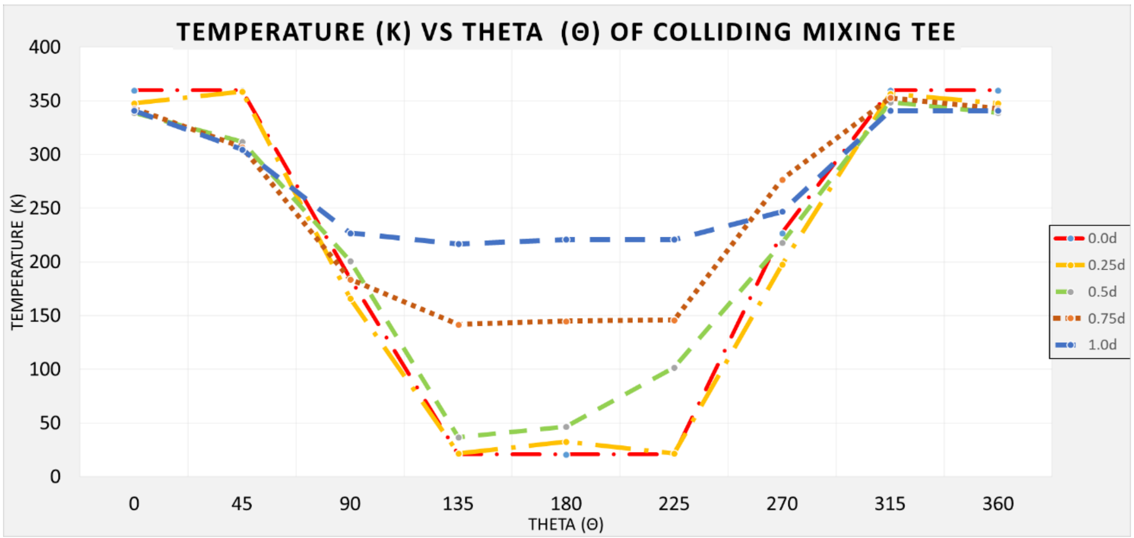


Figure 4.7: Circumferential Temperature Distribution of Colliding Mixing Tee

Circumferential temperature distribution along near wall for the colliding mixing tee is shown in Figure 4.7. Each line representing the sampling point from the centre of mixing region which is 0.0d until the outlet which represent by 1.0d. Higher temperature is notable at every sampling point at angles of 0° to 45° and 315° to 360°. However, the trends start to drop after 45° up to 135° and it is recorded that at 180°, the temperature achieve the lowest for every sampling point. At point 0d, the lowest temperature remains constant from the angle 135° to 225° unlike others point, where the temperature gradually increases from 180° onwards. The variation in temperature difference along the circumferential sampling point indicate that the thermal mixing is taking place in each sampling point. In justification, the temperature difference from 0^o to 360^o keep decreasing as the sampling point increase from 0d to 1.0d. At 0d till 0.5d, very decent fluid mixing takes place in these regions of the mixing branch as the temperature difference is ranging between 339K to 302K. But after the flow progress to the point of 0.75d to 1.0d, the temperature difference remarkably lower in comparison. This lower temperature difference indicate that the fluids is mixed well and mostly occur in this region.

In order to evaluate the thermal mixing quality, [3] has create a benchmark based on the temperature difference between maximum and minimum temperature for each sampling point. By observing Table 4.2, a good quality mixing will result in less than 278K, medium quality in between 279K and 281K, and a bad mixing is larger than 282K.

Table 4.2: Thermal Mixing Quality Benchmark for Colliding Tee

Sampling Points	Temperature Difference (K)	Mixing Quality
0.25 d	337	BAD
0.5 d	302	BAD
0.75 d	201	GOOD
1.0 d	124	GOOD

For the present study of colliding mixing tee, the bad mixing quality was noticeable at sampling point of 0.25d and 0.5d only with the value of 337K and 302K respectively. While 0.75d and 1.0d produce a good mixing quality as temperature differences resulted in 201K and 124K respectively. With all this mixing quality, it can confirm that as the flow moves towards the mixing outlet, the mixing quality improves, and thermal mixing section occurs from sampling point 0.25d.

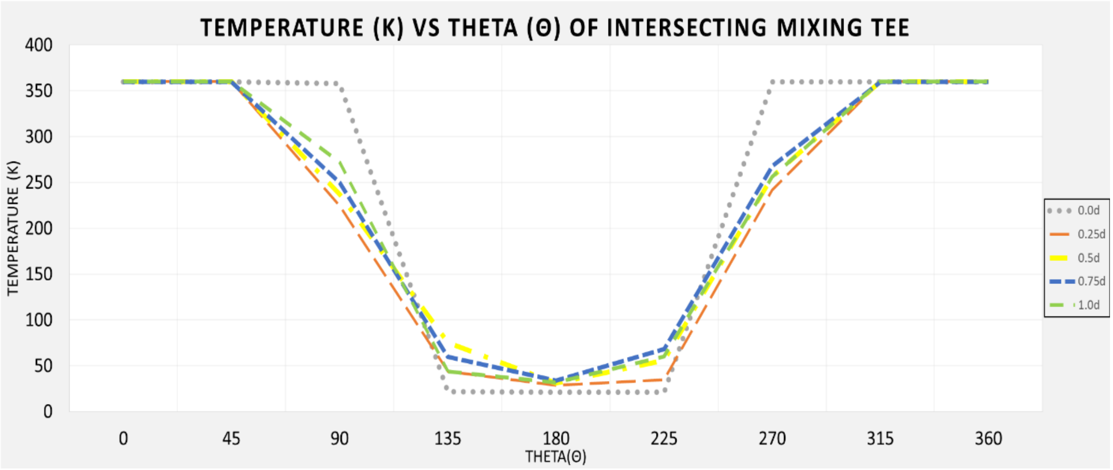


Figure 4.8: Circumferential Temperature Distribution of Intersecting Mixing Tee

Figure 4.8 is the circumferential temperature distribution along the near wall for intersecting mixing tee. Compare to the colliding mixing tee, the trends for all sampling point are quite similar in terms of circumferential temperature distribution where the temperature remain constant from angle 0^o to 45^o, reach minimum reading at 180^o and continue to increase to the high temperature. However, for sampling point 0d, the temperature gradually drops at angle 90^o and remains at lowest temperature from 135^o to 225^o. At 0.25d, the temperature begins to drop at angle 45^o indicate that the degree of mixing start to take place.

Table 4.3: Thermal Mixing Quality Benchmark for Intersecting Tee

Sampling Points	Temperature Difference (K)	Mixing Quality
0.25 d	331	BAD
0.5 d	329	BAD
0.75 d	326	BAD
1.0 d	328	BAD

Unlike colliding mixing tee, intersecting mixing tee tend to have high temperature differences even at the point of 1.0d. In other words, as the sampling increases from 0d to 1.0d, the differences in temperature remain significant. As a result, the flow inside the intersecting mixing tee maintain to be thermally stratified till the mixing outlet and this shows that intersecting mixing tee is having a bad mixing quality. To justify, with the same benchmarking method as colliding tee, point 0d, 0.25d, 0.5d, 0.75d and 1.0d have temperature difference at 339K, 331K, 329K, 326K and 328K respectively. These temperature differences indeed resulting a bad mixing quality that makes intersecting mixing tee flow configuration is not as good as the colliding mixing tee.

4.4 Temperature Fluctuations

A transient simulation was done with both cases of mixing tees with a total flow time of 100 seconds and a timestep of 0.05 seconds. According to figure 4.10 and 4.12, there are 3 regions highly notable to have high turbulent mixing and the regions are at 0.25d, 0.5d and 0.75d. Only these three sampling points are presented in the temperature fluctuation section for both colliding and intersecting mixing tee.

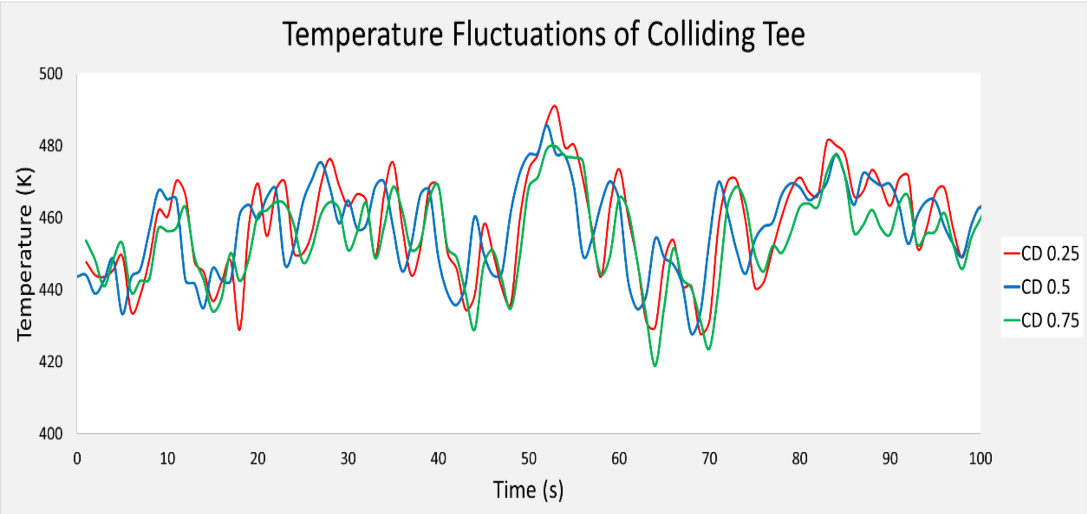


Figure 4.9: Temperature Fluctuations of Colliding Mixing Tee

Temperature and fluctuation profiles of 0.25d, 0.5d and 0.75d sections of the colliding mixing tee are presented in Figure 4.9. It can be observed from the graph that the temperature fluctuation is dominant at point 0.25d whereas the temperature dramatically fluctuated throughout the total flow time. The intensity of the temperature fluctuation is also the highest as the maximum temperature at this point read at 490K which later drops to the lower temperature of the 423K.

At 0.5d, the temperature fluctuation occurs at a range of 427 K to 486K with notable fluctuations at the time frames of 10s to 20s and 50s to 70s. The temperature fluctuation in this section is quite intense like other sampling point but however, in term of temperature difference shows that 0.5d is at the middle ranked. At 0.75d, the temperature fluctuations are the lowest compare to the other points as the maximum temperature is at 479k and the minimum temperature is at 420K. The intensity can clearly see as the poorest especially at time flow of 50s to 60s.

By referring to Figure 4.9 and comparing between point 0.25d, 0.5d and 0.75d, the lowest turbulence intensity is located at point 0.75d which is the reason why the temperature fluctuations is lower. This indicate that the mixed flow with two temperature starts to provide a quality thermal mixing. This can conclude that at 0.25d, the fluctuations due to the turbulent mixing occur the most in the colliding mixing tee and therefore, thermal crack are likely to occur at this region.

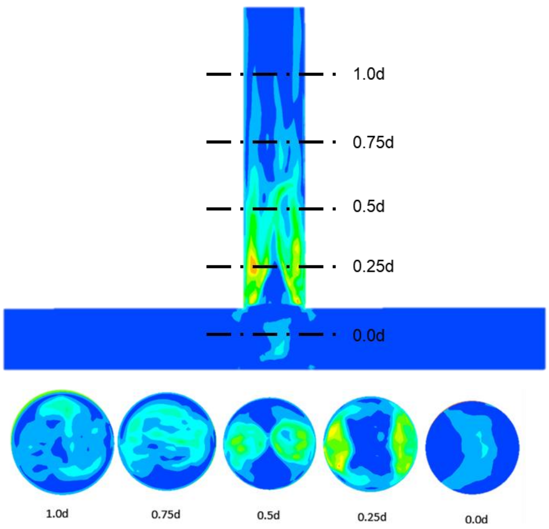


Figure 4.10: Turbulent Regions of Colliding Mixing Tee

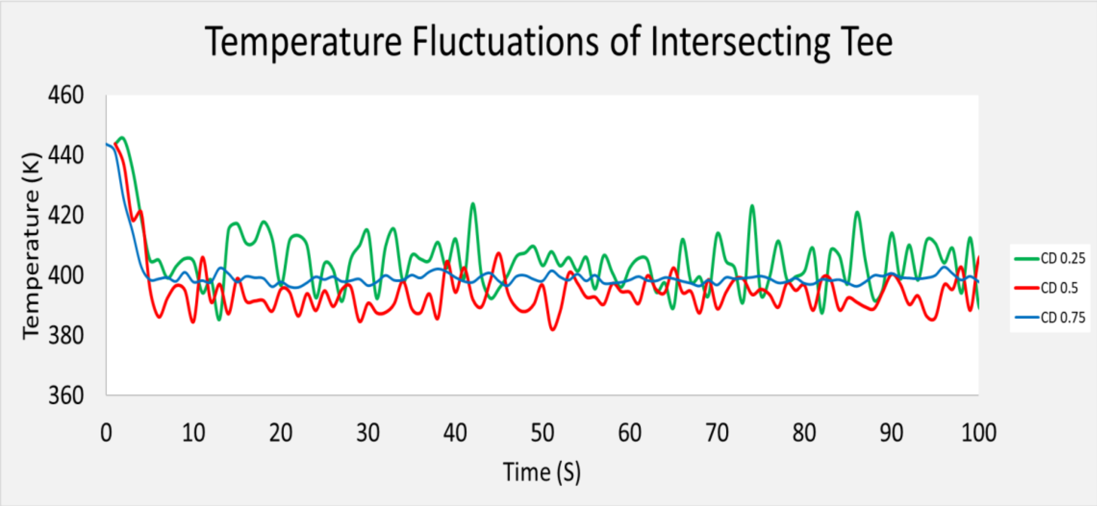


Figure 4.11: Temperature Fluctuations of Intersecting Mixing Tee

Temperature and fluctuation profiles of 0.25d, 0.5d and 0.75d sections of the intersecting mixing tee are presented in Figure 4.11. In comparison to the colliding mixing tee, the fluctuation occurred in the intersecting mixing tee is at the range 445K to 382K whereas much lower to the colliding tee. For the first sampling point, 0.25d, it can clearly see that the highest fluctuation intensity occurred in this region by observing the graph in Figure 4.11 and the turbulence contour in Figure 4.12. The high fluctuations can be seen to occur along the flow time and the most notable fluctuations is occur at the time flow of 15s to 40s and 75s to 90s. The maximum average temperature at this region is at 445K and the minimum temperature is at 387K. The reason why this region is the highest is due to mixed point of fluid with two different temperature which cause a high turbulence flow.

Temperature fluctuations at the 0.5d section is significantly less compared to sampling point 0.25d. At this rate, the temperature fluctuations begin to drop as the fluid begin to thermally mixed. From Figure 4.11, the average of the fluctuation is the lowest in compare to the point 0.25d and 0.75d. The maximum temperature for 0.5d occur at the beginning of the time flow which is at 443K and the minimum temperature is at 382K which is the lowest temperature among the three sampling points. Despite having low temperature fluctuations, the intensity of the fluctuations is at the middle ranked and that make point 0.75d is having the lowest intensity.

The reason why 0.7d is having lowest intensity is because of the flow begin to become stratified and thus, there is no turbulence occurring here. By looking the graph in the Figure 4.11, the fluctuation line of 0.75d is almost flat throughout the flow time. Similar to other sampling points, the maximum temperature for 0.75d is at 443K while the minimum temperature is at 396K. This can conclude that at 0.25d, the fluctuations due to the turbulent mixing occur the most in the intersecting mixing tee and therefore, thermal crack are likely to occur at this region.

Based on the results of the colliding and intersecting mixing tee shown in Figures 4.9 and 4.11, the data of temperature fluctuation was then further analysis by applying the Fast Fourier Transform (FFT) function in the ansys FLUENT. However, only the data at sampling point 0.25d was further processed due to the highest turbulence and temperature fluctuation intensity occurred at this region. Fast Fourier transform is used to evaluate the temperature fluctuation frequency and magnitude.

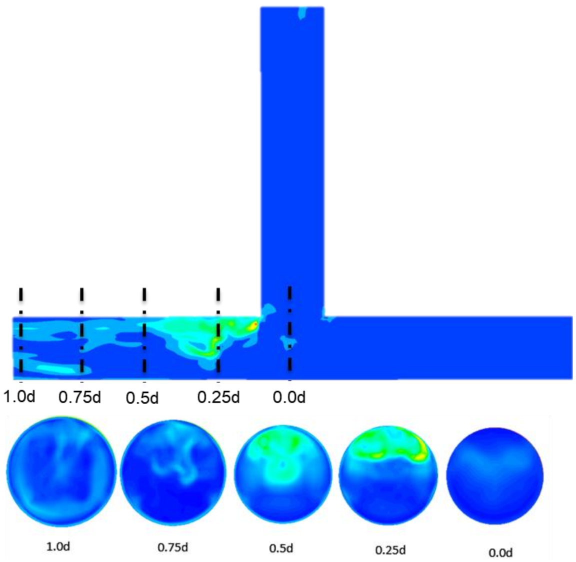


Figure 4.12: Turbulent Regions of Intersecting Mixing Tee

4.5 Magnitude Against Frequency

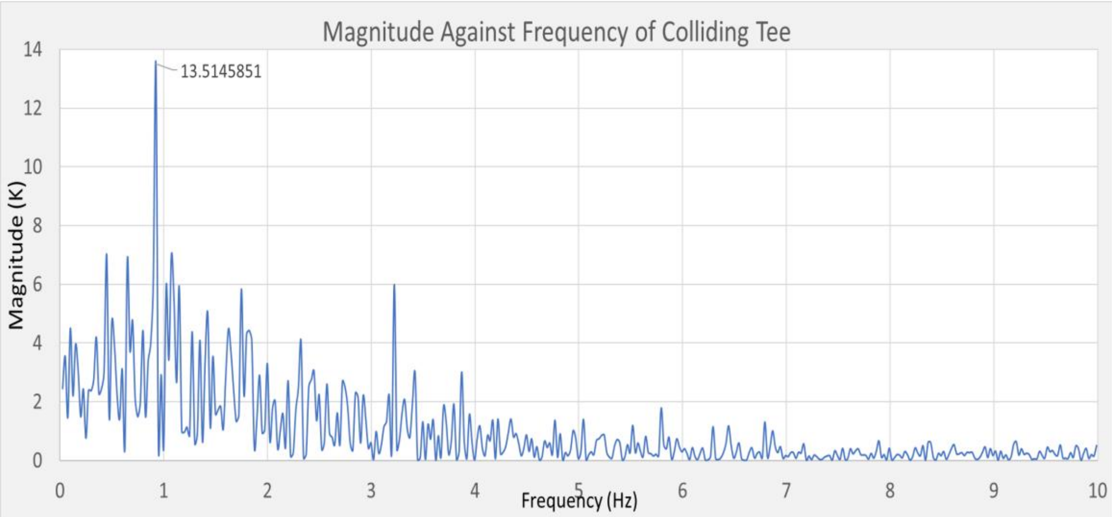


Figure 4.13: Magnitude vs Frequency of Colliding Mixing Tee

Sampling point 0.25d is used in this analysis section as this region is where is the highest temperature fluctuation intensity and turbulent kinetic energy occurred. Magnitude is the function of temperature fluctuation while the frequency is the intensity thermal load [1]. As describe in Figure 4.13, the peak magnitude of the fluctuation was recorded at a value of 13.51K and occurring at a low frequency of 0.92 Hz. Throughout the frequency axis, the magnitude begins to decrease rapidly from 0.92 Hz to 3.22 Hz and continue to fluctuate steadily up to the maximum frequency range in this study which is 10 Hz.

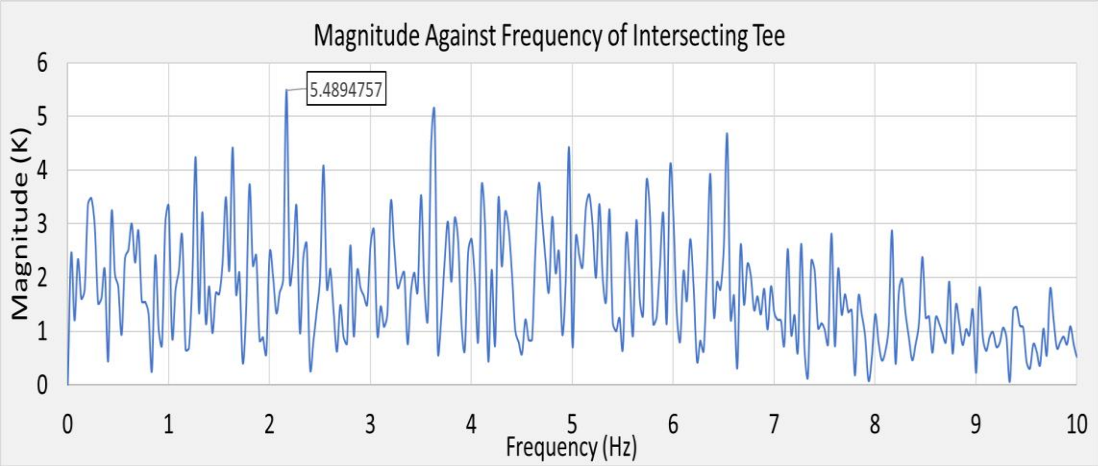


Figure 4.14:Magnitude vs Frequency of Intersecting Mixing Tee

As shown in Figure 4.14, the peak magnitude of the fluctuation occurs at a value of 5.49 K and occurring at a low frequency of 2.17 Hz. Along the frequency axis, it can be observed that the magnitude does not decreases rapidly in the range of 2.17 Hz and 6.53 Hz. The pattern then continues to show slightly decreasing in the range of 6.53 Hz to 10 Hz.

Based on Figure 4.13 and Figure 4.14, the results obtained are in good agreement with the past results made in the numerical evaluation of [1], where the peak magnitude is in the range of 2-5Hz. However, according to the work of [19], he found out that the peak magnitude occurs in the range of 0.1-10Hz, which make the present result for colliding is having a similar agreement to his research. To conclude the finding in this analysis, colliding mixing tee is having much higher magnitude of temperature fluctuation at lower frequency in comparisons to the intersecting mixing tee. Based on MLNG report, the intersecting mixing tee had pipe structural failure happened before and since colliding mixing tee is having higher magnitude, the lifespan of the colliding mixing tee would be much lower compare to the intersecting tee.

4.6 Power Spectral Density

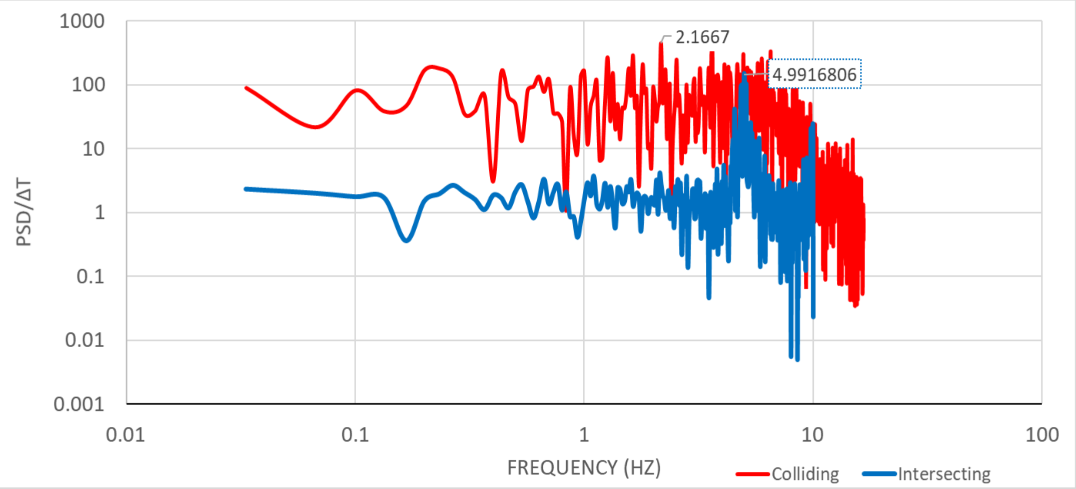


Figure 4.15: Power Spectral Density of temperature fluctuations for Colliding and Intersecting Mixing Tee at sampling point 0.25d

According to Figure 4.15, Power Spectral Density of temperature fluctuations is presented for both intersecting and colliding mixing tee. Sampling point at 0.25d was taken for both mixing tee in order to complete this analysis due to the turbulence and intensity of the temperature fluctuations as mention before. It is distinguished that both mixing tees obtained a different value as the PSD is the power that content inside the temperature fluctuation itself. The colliding mixing tee show dominant in terms of overall spectral peak which immediately shows that the colliding has higher potential in inducing high cycle thermal fatigue. The dominant frequency or the spectral peak of the fluctuation for colliding mixing tee is at 2.17 Hz that might indicate the present of high thermal stress in the pipe structure. After the power content of temperature fluctuation reach the dominant frequency, the spectral begin to slightly decrease until it reaches frequency of 6.33 Hz. Beyond 6.33 Hz, a waterfall-type drop was noticed in the power content of fluctuations This result has a good agreement with [5] as they stated that the highest energy lies between 0.5 Hz and 20 Hz, where the frequency interval that thermal striping might took place.

As for intersecting mixing tee, the spectral peak of the fluctuation occurs at frequency of 4.99 Hz which the result obtained is similar to the work of [1]. Unlike colliding mixing tee, the decreasing in the spectral is not showing any sign of waterfall-type drop whereas the power content of fluctuations starts to increase from range 7.62 Hz to 9.77 Hz. Since the spectral peak of intersecting mixing tee is much lower compare to the colliding mixing tee, the probability for it to have a high thermal stress in pipe structure is lower. Even though thermal striping was bound to happen if the dominant frequency is below 20 Hz [5], the lifespan of the intersecting mixing tee is expected to be much longer compare to the colliding mixing tee.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

A numerical simulation of turbulent flow of two streams at different temperatures was conducted to analyse the differentiations in the intersecting and colliding mixing tee. Turbulence model of Realizable K-epsilon was used in this project and comparison was made with previous work which state that the current project's results are sufficiently accurate. Even though most of the literature reviews are using similar turbulence model in conducting their researches, it is widely recommended that Large Eddy Simulation simulations is much preferable in simulating a turbulence flow model.

The different flow configurations in the mixing tee resulting different thermal mixing behaviour whereas the colliding mixing tee provided a better mixing quality compare to the intersecting mixing tee. Despite the quality of the thermal mixing, colliding mixing tee prove to have higher intensity in term of temperature fluctuations when in comparison to the intersecting mixing tee. Since the temperature fluctuations intensity is much higher, the magnitude of the fluctuations tends to become high. Moreover, all the results achieved were equivalent to the researches of [1], [3], [5] and [9] whereas the dominant frequency will occur at the range of 0.1 Hz to 10 Hz. Therefore, thermal striping and high-cycle thermal fatigue tends to occur at colliding mixing tee more often with shorter period compare to the intersecting mixing tee. Hence, the objective of this project is achieved.

5.2 Recommendation

1. Future works for improvement that could be done later is by expanding the studies to focus on the attenuation of the temperature fluctuations and vortex shedding.

2. Conduct a numerical simulation considering different physical properties of the mixing tee (angle of the branch pipe, diameter ratio etc) to study its relation to the thermal striping.

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