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NUMERICAL EVALUATION OF THERMAL MIXING EFFICIENCY OF NATURAL GAS IN TWO DIFFERENT CONVERGING MIXING T-JUNCTIONS

by

MD NURUZZAMAN

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NUMERICAL EVALUATION OF THERMAL MIXING EFFICIENCY OF NATURAL GAS IN TWO DIFFERENT CONVERGING MIXING T-JUNCTIONS

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MD NURUZZAMAN

A Thesis

Submitted to the Postgraduate Studies Programme

as a Requirement for the Degree of

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BANDAR SERI ISKANDAR,

PERAK

DECLARATION OF THESIS

Title of thesis	NUMERICAL EVALUATION OF THERMAL MIXING EFFICIENCY OF NATURAL GAS IN TWO DIFFERENT CONVERGING MIXING T-JUNCTIONS

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hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTP or other institutions.

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DEDICATION

This thesis is dedicated to my beloved mother Mst. Nurun Nahar, my father Md Zaynal Abedin and my grandmother Mst. Maleka Khatun for their never-ending love, support, and motivation. Though my journey was very difficult and full of barriers, but their endless support made it possible. Thank you!

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ABSTRACT

Rapid temperature fluctuations and thermal fatigue occur at the weld area of T-junction due to incomplete thermal mixing of hot and cold fluids in the mixing region. Crack or leakage in pipelines or sudden accident can happen in cooling system of nuclear reactor due to this high cycle thermal fatigue. Higher thermal mixing performance can help prevent this phenomenon. So, it is essential to find out and compare thermal mixing performance for different flow configurations and flow parameters. The present study aims to compare thermal mixing characteristics and efficiency of two different converging mixing tees, namely colliding, and intersecting T-junction with intention to produce working correlation(s) for thermal mixing efficiency, inlet temperature ratio and mass flow rate ratio. Numerical simulations were conducted by utilizing k-ε turbulence model and natural gas as working fluids. Thermal mixing efficiency for both intersecting and colliding tees at different planes along the mixing outlet and at different time steps were recorded. Experimental design methodology was used with inlet temperature and mass flow rate ratios as two variable factors. Results indicated that for same boundary conditions, thermal mixing efficiency of colliding mixing tee is 9 to 13% higher than intersecting tee. In the intersecting tee, there is an irreducible thermal stratification layer, but such layer was not observed in the colliding mixing tee. It is discovered that thermal mixing for both mixing tees increased with the increase of distance and time. Thermal mixing efficiency is found to be higher when the cold and hot inlet temperature ratio is higher which shows a direct proportionality relation. Moreover, higher thermal mixing was found to be achieved for much lower or much higher flow rate ratio than unity as the higher flow rate difference produce more turbulent mixing. This study provides clear guidelines to reduce thermal fatigue and temperature fluctuation in thermal mixing T-junction used in pipeline of different industries.

ABSTRAK

Turun naik suhu yang cepat dan kelesuan terma berlaku di kawasan kimpalan T-junction disebabkan oleh pencampuran haba yang tidak lengkap bagi cecair panas dan sejuk di kawasan pencampuran. Keretakan atau kebocoran dalam saluran paip atau kemalangan mengejut boleh berlaku dalam sistem penyejukan reaktor nuklear disebabkan oleh kelesuan haba kitaran tinggi ini. Prestasi pencampuran haba yang lebih tinggi boleh membantu mencegah fenomena ini. Jadi, adalah penting untuk mengetahui dan membandingkan prestasi pencampuran terma untuk konfigurasi aliran dan parameter aliran yang berbeza. Kajian ini bertujuan untuk membandingkan ciri-ciri pencampuran terma dan kecekapan dua tee bancuhan tumpu yang berbeza, iaitu perlanggaran, dan persilangan T-junction dengan niat untuk menghasilkan korelasi kerja untuk kecekapan pencampuran terma, nisbah suhu masukan dan nisbah kadar aliran jisim. Simulasi berangka telah dijalankan dengan menggunakan model pergolakan k-ε dan gas asli sebagai cecair kerja. Kecekapan pencampuran terma untuk kedua-dua tee bersilang dan berlanggar pada satah berbeza di sepanjang saluran keluar adunan dan pada langkah masa yang berbeza telah direkodkan. Metodologi reka bentuk eksperimen digunakan dengan suhu masukan dan nisbah kadar aliran jisim sebagai dua faktor pembolehubah. Keputusan menunjukkan bahawa untuk keadaan sempadan yang sama, kecekapan bancuhan haba tee bancuhan berlanggar adalah 9 hingga 13% lebih tinggi daripada tee bersilang. Dalam tee bersilang, terdapat lapisan stratifikasi terma yang tidak dapat dikurangkan, tetapi lapisan tersebut tidak diperhatikan dalam tee campuran yang berlanggar. Didapati bahawa pencampuran terma untuk kedua-dua tee pencampuran meningkat dengan pertambahan jarak dan masa. Kecekapan pencampuran terma didapati lebih tinggi apabila nisbah suhu masukan sejuk dan panas lebih tinggi yang menunjukkan hubungan perkadaran langsung. Selain itu, percampuran terma yang lebih tinggi didapati dapat dicapai untuk nisbah kadar aliran yang jauh lebih rendah atau lebih tinggi daripada perpaduan kerana perbezaan kadar aliran yang lebih tinggi menghasilkan percampuran yang lebih bergelora. Kajian ini menyediakan garis panduan yang jelas untuk mengurangkan keletihan haba dan turun naik suhu dalam persimpangan T pencampuran haba yang digunakan dalam saluran paip industri yang berbeza.

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LIST OF ABBREVIATIONS

CFD	Computational Fluid Dynamics
LES	Large Eddy Simulation
LNG	Liquified Natural Gas
MLNG	Malaysia Liquified Natural Gas
RANS	Reynolds-Averaged Navier-Stokes
RSM-EB	Reynolds Stress Model-Elliptic Blending
TMD	Temperature Mixing Degree
URANS	Unsteady Reynolds-Averaged Navier-Stokes

NOMENCLATURE

C_p	specific heat at constant pressure ($Jkg^{-1} K^{-1}$)
D	diameter of main pipe (m)
d	diameter of branch pipe (m)
g	gravitational acceleration (ms^{-2})
k	Turbulent kinetic energy ($J/kg = m^2s^{-2}$)
N	Total number of mesh elements
Q	Mass flow rate (kgs^{-1})
ΔT_{max}	maximum temperature difference at different plane (K)
ΔT_{in}	inlet temperature difference (K)

Greek symbols

ε	Turbulent kinetic energy dissipation rate ($Jkg^{-1}s^{-1} = m^2s^{-3}$)
ω	specific dissipation (s^{-1})
ρ	Density (kgm^{-3})
τ	2^{nd}-order deviatoric stress tensor
Φ	dissipation function

Subscripts

b	branch
m	main
max	maximum
in	inlet
x	Cartesian x coordinate

y	Cartesian y coordinate
z	Cartesian z coordinate

CHAPTER 1

INTRODUCTION

This chapter introduces the problem statement and objectives of this numerical research. Different scopes and significance of this study are also discussed in this chapter.

1.1 Background

Pipe networks are considered very useful for transportation and supply of fluids such as water, oil, and natural gases. Pipe networks consist of elbow, T-junction, bends, expansion valve, pump, turbine etc. All these parts are interconnected in a network to carry fluids. Among them T-junction is an important part of piping system. There are three main purposes of a T-junction: (a) dividing the flow, (b) combining or mixing of same or different fluids (c) partial phase separation in multiphase flow. Fluids flowing through T-junction may be same or different in temperature, pressure, flowrate, velocity, and density.

T-junction is a significant part of a piping network for combining and dividing the flow. Under certain favourable circumstances, it can be used for partial phase separation for multiphase flow. Each T-junction has three arms, two arms in main pipe and one arm in branch pipe. T-junction is also a piping feature that is commonly seen in industries, e.g., for the cooling system in nuclear industry, LNG production or transportation, oil, and gas refining businesses. A simple T-junction is shown in Figure 1.1.

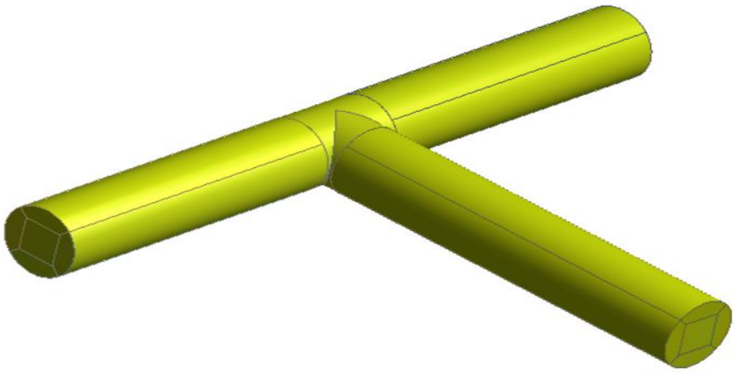


Figure 1.1: Simple T-junction

Though a T-junction is a simple geometry with one main pipe and one branch pipe, it can be different types for different parameters. For inclination angle between branch and main pipe it can be different type tee [3] such as 30°, 45°, 60°, 90°, 120° etc. Among all these the 90° T-junction is the most common tee. For the diameter ratio of branch and main pipe it can be also classified. If the branch pipe diameter is smaller than the main pipe diameter, then it is called reduced T-junction and when the diameter is same it is called regular T-junction. But most important classification of T-junction is according to the flow configuration of fluids flowing through it. Firstly, a simple T-junction can be classified as two types namely ‘Converging’ and ‘Diverging’ tee. In ‘Converging’ T-junction fluid from two inlets get mixed and leave through the outlet as shown in Figure 1.2(a). This type of T-junction is used for thermal mixing mainly in cooling system in industries. On the other hand, fluid from the inlet is divided into two flow and leave through two outlets in ‘Diverging’ tee. For partial phase separation this diverging tee is used.

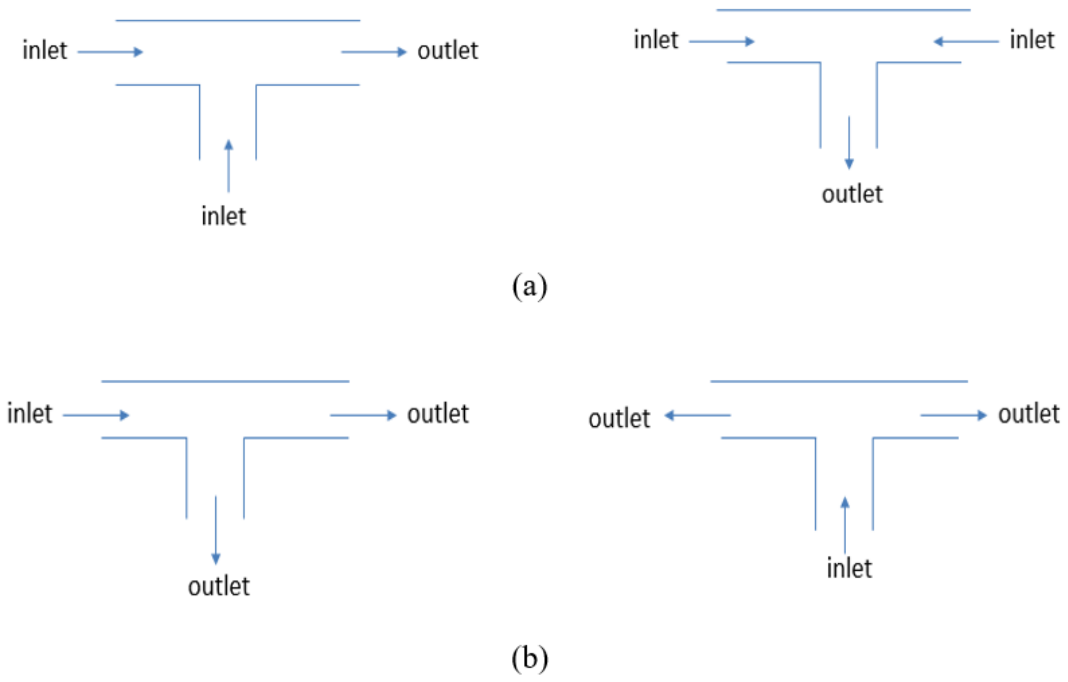


Figure 1.2: Possible flow direction of (a) converging and (b) diverging T-junction

Converging T-junction is used for mixing of fluids mainly for cooling purpose. In a converging type T-junction fluid from two inlets are mixed in the mixing region and leaves through the outlet. This converging type mixing tee can be classified as two types: intersecting and colliding T-junction.

The conventional T-junction that is mostly used in pipelines is intersecting converging T-junction where the branch pipe and one end of the main pipe are considerate as inlet port for fluid. In this flow orientation fluid from two inlet intersect each other perpendicularly. Two possible flow directions of intersecting converging T-junction have been shown in Figure 1.3.

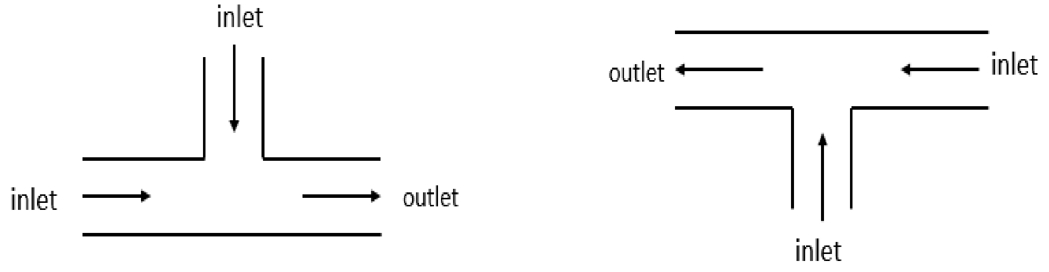


Figure 1.3: Intersecting converging mixing T-junction

In colliding T-junction, fluid entered through the two ends of the main pipe from opposite directions and mix at the center of the joint and leave through the branch pipe. Figure 1.4 shows the possible flow configurations of colliding T-junction.

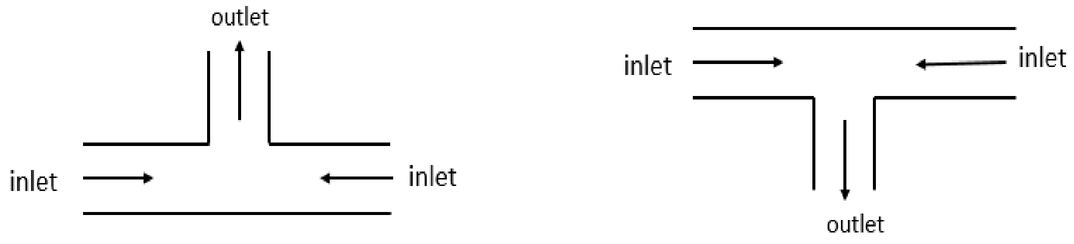


Figure 1.4: Colliding converging mixing T-junction

The structural geometry of both T-junction looks similar, but the fluid flow configuration is quite different. Some basic differences between these two T-junction are mentioned in table 1.1.

Table 1.1: Difference between Intersecting and Colliding T-junction

Intersecting T-junction	**Colliding T-junction**
Two inlets are at 90° angle	Angle between two inlets is 180°
One inlet is at main pipe and another inlet is at the branch pipe	Both inlets are at the main pipe
The outlet for mixed fluids is at the main pipe	Outlet is at branch pipe

Malaysia Liquified Natural Gas (MLNG) plant located in Bintulu; Sarawak produces Liquified Natural Gas (LNG). All the stages and processes of production and transportation of LNG are interconnected by a vast piping system. Drier vessels in ‘Dehydration Unit’ are used to remove water or moisture from treated natural gas (NG) to prevent freezing out in ‘Liquefaction Unit’. Drier vessels contain molsieve beds which are used to absorb the moisture. Once molsieve bed reaches to saturation, need to regenerate by using hot NG (at temperature 310°C), called ‘Regen gas’ which is from

Regenerator heater with high temperature (~ 380°C). To meet required temperature specification (310°C) to regenerate the bed, needs to mix with cold NG at T-junction called 'Mixing Tee'.

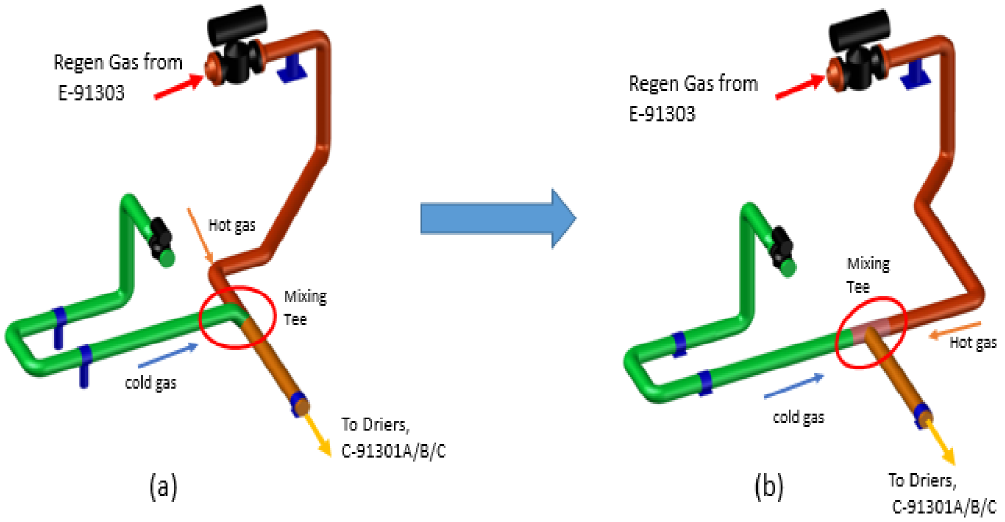


Figure 1.5: (a) conventional intersecting mixing tee and (b) proposed colliding mixing tee in MLNG plant.

In a mixing tee, when the flows of hot and cold natural gas combine thermal mixing and temperature fluctuations occur due to temperature difference. This phenomenon can produce thermal fatigue which later causes the occurrence of cracks on weldment areas of the T-junction. For this reason, MLNG TIGA has decided to replace their conventional intersecting mixing T-junction as shown in Figure1.5(a). A new flow configuration called colliding mixing tee as shown in Figure1.5(b) is proposed. This study will be focused on the evaluation of relative thermal mixing characteristics of both mixing T-junctions to find out the better thermal mixing performance. A correlation for the thermal mixing efficiency with T-junction's geometry, inlet and outlet temperatures, velocities and mass flow rates will be performed.

1.2 Problem Statement

T-junction is a significant parts of piping system for distributing, combining, or dividing the flow and partial phase separation in case of multiphase flow. It can be classified as two types: converging and diverging tee. Again, converging T-junction can be two types according to flow configuration: intersecting and colliding mixing tee. In a converging T-junction, when hot and cold fluids from two inlets combine at the mixing region and leave through the outlet, thermal mixing of fluids takes place due to temperature difference [3]. Rapid temperature fluctuations occur due to incomplete mixing of fluids [4, 5]. This rapid temperature fluctuation can create high cycle thermal fatigue and cyclic thermal stress at the weld area of the T-joint [6-8]. Thermal fatigue cracking generally initiates at mixing tee where low and high temperature fluid flow [9-11]. This can shorten the service life of the pipelines [12].

A comparative study and analysis is required to find out thermal mixing efficiency to evaluate the relative performance of the two mixing T-junctions, namely intersecting and colliding mixing tee to find out which one have better thermal mixing performance. A correlation is also required for thermal mixing efficiency in relation to T-junction's geometry, inlet and outlet temperatures, velocities, and mass flow rates.

1.3 Research Objectives

The present research intends to achieve the following two objectives:

a) To compare the thermal mixing efficiency of two flow configuration T-junction for better thermal mixing performance.

b) To correlate thermal mixing efficiency in relation to hot and cold inlets temperatures, and mass flow rates.

1.4 Scope of the Study

A new geometry of the T-junctions called colliding mixing tee has been proposed in the regenerative system to remove moisture from treated natural gas to replace the conventional intersecting mixing tee for better thermal mixing performance. In this study, the thermal mixing efficiency for both mixing tees have been calculated numerically and compared. For this calculation, required fixed and variable parameters and their values or ranges are discussed below:

I. A comparative study to evaluate thermal mixing characteristics between an intersecting T-junction and colliding mixing T-junction has been performed numerically using ANSYS fluent software and k-ε turbulence model.

II. The main and branch pipe diameter was kept constant at 304.8 mm (12 inch), the same as the MLNG TIGA regenerative piping's dimension.

III. Thermal mixing quality and temperature fluctuations mainly depend on temperature difference of the hot and cold fluids inlet temperature[1, 2]. In this study, the cold inlet temperature was varied from 21 to 120°C while the hot inlet temperature varied from 120 to 360°C.

IV. The cold inlet flow rate was varied from 1.67 to 9.07 kg/s and the hot inlet will be ranging from 3.31 to 10.71 kg/s because these ranges are found in the pipelines of MLNG plant.

V. As the working fluid was natural gas, the flow is considered as compressible flow.

1.5 Research Contribution

Thermal mixing and rapid temperature fluctuations when hot and cold fluids are mixed in the mixing region of the pipelines are great problem for different industries. To reduce this problem a new flow orientation has been proposed which is called colliding mixing converging T-junction to replace the conventional intersecting mixing tee for better mixing quality. In this study the thermal mixing characteristics and efficiency have been found numerically using k-ε turbulence models and computational fluid dynamic (CFD) software ANSYS fluent. The effect of inlet temperature ratio and mass flow rate ratio on thermal mixing efficiency have been found out by changing those ratios in different cases. Later, a comparative study was done to observe the relative performance between intersecting and colliding mixing tee to find out a better flow orientation for high thermal mixing performance. This study can provide a clear guideline to any industries about how to improve the thermal mixing performance to reduce the thermal stripping and high cycle thermal fatigue. This guideline can also help to prevent sudden accident in the pipeline such as crack, leakage and increase the longevity of T-junction in pipeline system.

1.6 Thesis Outline

This thesis consists of total five chapters and each chapter have elaborate discussions with figures and tables of relevant objectives as follows.

Chapter 1 provides basic background, introduction, problem statement, objectives, scope of the study, research significance and contributions in industrial sector.

Chapter 2 mainly provides the literature review of published papers related to thermal mixing in T-junction. As this research is focused on the effect of inlet temperature and mass flow rate ratio on thermal mixing performance in T-junction, these areas were reviewed thoroughly. The effect of different parameters such as inlet temperature, inlet velocity, mass flow rate, flow direction, T-junction geometry, inclination angles between branch and main pipe etc. were discussed based on the obtained results of previous published papers.

Chapter 3 provides detailed description of different methods, material, technique, and conditions for numerical prediction of this research. This chapter consists of geometry design, mesh generation, mesh independence test, initial boundary conditions, numerical model validation etc. Input parameters and design of experiment (DOE) with different value of variable parameters are discussed in this chapter.

Chapter 4 represents all the results of this research obtained from numerical simulations. These results are also analysed and discussed elaborately in this chapter. Thermal mixing efficiency of both intersecting and colliding T-junctions were compared to find out the flow configuration which have better performance. At last correlations between thermal mixing efficiency and input parameters were found out to improve efficiency.

Chapter 5 summarizes all the results presented in this thesis and concludes this numerical study. Limitations of this study and recommendations for future research were also provided in this chapter.

CHAPTER 2

LITERATURE REVIEW

Thermal mixing of hot and cold fluid inside T-junction can be found in cooling system in nuclear power plant and many other industries. While mixing of hot and cold fluid, temperature fluctuation is occurred due to incomplete mixing of fluids. Due to temperature fluctuation leakage, cracks, and failure of T- junction of pipelines take place. A better thermal mixing performance is required to reduce the rapid temperature fluctuations in the mixing region of pipelines. Many experimental and numerical research have been conducted by many researchers all over the world to investigate the thermal mixing characteristics of T-junction using different turbulence models. There are some factors such as T-junction's geometry, branch and main pipe diameter ratio, inlet temperature difference, velocity ratio, mass flow rate etc. which have influence on thermal mixing characteristics.

2.1 Thermal Mixing of Fluid in a T-junction

When hot and cold fluid from two inlet combine in the mixing region, thermal mixing and heat transfer occur due to temperature difference [4]. Incomplete thermal mixing can cause rapid temperature fluctuation in fluid and structure [5, 6]. Thermal mixing performance plays an important role in the structure like T-junction through which fluid having temperature difference flows. In a converging T-junction, when hot and cold fluids from two inlets combine at the mixing region and leave through the outlet, thermal mixing of fluids takes place due to temperature difference [4]. Rapid temperature fluctuations occur due to incomplete mixing of fluids [5, 6]. This rapid temperature fluctuation can create high cycle thermal fatigue and cyclic thermal stress at the weld area of the T-joint [7-10]. Thermal fatigue cracking generally initiates at mixing tee where low and high temperature fluid flow [11-14]. This can shorten the service life of the pipelines [14]. This temperature fluctuation and thermal fatigue is dependent on thermal mixing performance.

2.2 Factors Affecting Thermal Mixing

There are some important factors that affect the thermal mixing process. Inlet temperature difference, mass flow rate ratio, velocity ratio, branch and main pipe inclination angle, Reynolds number etc. are the key factors which have a great influence on thermal mixing performance.

2.2.1 Effect of Inlet Temperature

Thermal mixing characteristics mostly depend on inlet temperature difference when fluids of different temperatures mix in a T-junction. When hot and cold water mix, heat transfer occur from hot water to cold water due to temperature difference. This can create rapid temperature fluctuations due to incomplete mixing of fluids. This temperature fluctuations depend on the thermal mixing performance of fluids at the mixing region. An experimental observation had been performed by Chen et al. [1] to evaluate thermal mixing quality in T-junction. If the temperature difference is lower, the thermal mixing quality will be higher.

- If, $\Delta T \leq 5$ then mixing quality is Good
- If, $6 \leq \Delta T \leq 8$ then mixing quality is Medium
- If, $\Delta T \geq 9$ then mixing quality is Bad

Where, ΔT is the temperature difference of the hot and cold water.

Inlet temperature difference is function of temperature fluctuation and thermal mixing quality. Zughbi et al. [3] carried out an experimental and numerical study to quantify the degree of mixing in a T-junction by measuring the temperature. By analyzing the temperature contours that they had found numerically from their study they got the result that 95% mixing was achieved at distance of 9 times of main pipe diameter. In that study they used a side tee with temperature difference 40k, branch and main pipe diameter ratio 0.25, standard k-ε turbulence model, velocity ratio 17.1.

An experimental investigation on the influence of the temperature difference on the thermal mixing phenomena at a 90 T-junction had been carried out by Zhou et al. [2, 15]. The experiments were performed with temperature differences of 140 K, 180K and 220K between the inlet flows of fluids at the T-junction. In the mixing region of the T-junction, various temperature differences between the two inlets create thermal stratifications with different stabilities. In that experiment, it was found that an increased temperature difference can stabilize the thermal stratification in the mixing region. From that experiment it was found that the stable thermal stratification can reduce the temperature fluctuations in the entire mixing region and in the unstable stratified mixing flow, high temperature fluctuations can be created during the mixing processes.

The effect of temperature difference on thermal mixing characteristics was investigated numerically by Bo Su et al. [16, 17]. Fluids having temperature difference 15 K, 30 K and 45 K were used as working medium. They found that due to inertia force, the reverse flow is observed in the unsteady thermal mixing process. This area of reverse flow decreases with the increase in temperature difference.

2.2.2 Effect of Inlet Mass Flow Rate Ratio

Chen et al. [1] found out the Influence of branch and main pipe inlet flow rate ratio on thermal mixing quality experimentally. The result shows that if the flow rate ratio is higher, then the mixing quality will be higher and if the flow rate ratio is lower, then the mixing quality will be lower [18-20]. This result can be expressed by a bar chart shown in Figure 2.1.

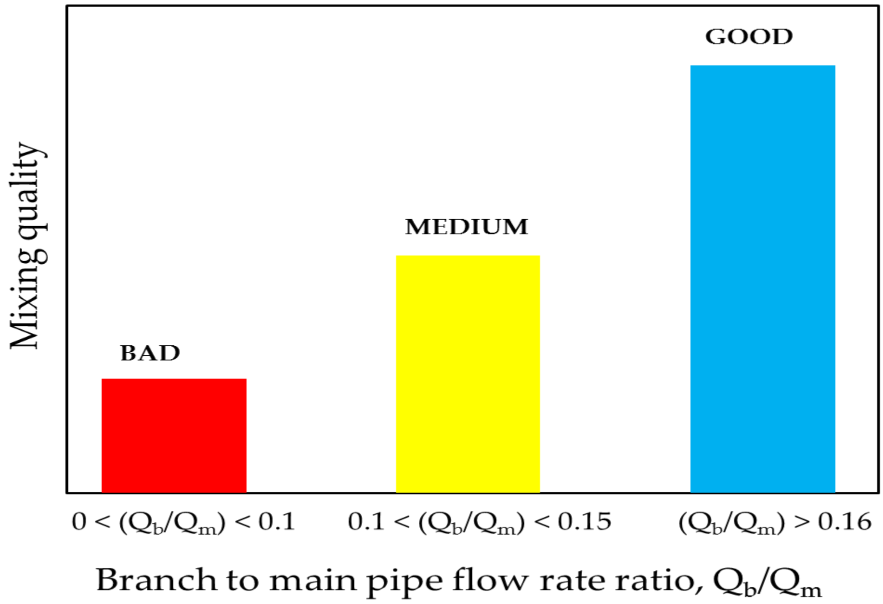


Figure 2.1: Relation between mixing quality and inlet flow rate ratio of branch and main pipe

The distributions of normalized mean temperature and normalized root mean square temperature shown in Figure 2.2 for three different flux ratios with a fixed temperature difference and Reynolds number had been found by Wang et al. [21]. They found that the temperature curve moves up and to the right with increasing flux ratio.

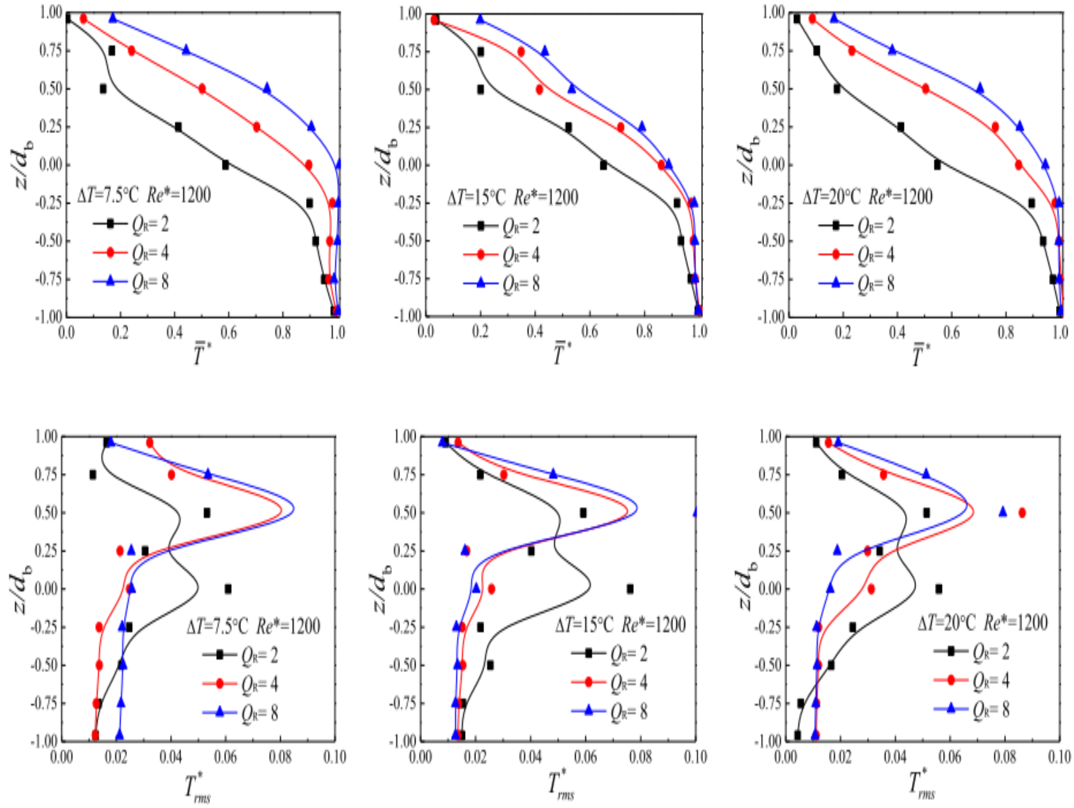


Figure 2.2: Distributions of normalized mean temperature and root mean square temperature for three different three flux ratios [21]

Chen et al. [1] had found that the thermal mixing performance increases with the increase of branch and main pipe flowrate ratio. Their experimental data and results are given below in table 2.1. This table shows that if the branch pipe flowrate is kept constant and the main pipe flowrate increases then good thermal mixing will be at lower main pipe flowrate where the flowrate ratio is higher. Again, it shows that if the main pipe flowrate is kept constant and the branch flowrate varies from a lower value to a higher value then thermal mixing is good at a higher branch pipe flowrate. It is found from this experiment that the reverse flows have the potential to produce good thermal mixing.

Table 2.1: Thermal mixing and reverse flow test for different flowrate ratios, temperature difference and velocity ratios [1].

Q_b/Q_m	300/100	300/200	30/300	20/300	40/300	50/300
T_{avg} (°C)	78.12	81.54	83.21	85.83	81.22	78.93

T_{max}-T_{min}	5	9	9	9	8	5
V_b/V_m	29.43	14.72	9.81	6.54	13.06	16.35
Good thermal mixing	Yes	No	No	No	No	Yes
Reverse flow	Yes	Yes	No	No	No	Yes

2.2.3 Effect of Inlet Velocity Ratio

Branch and main pipe inlet velocity ratio has direct effect on mixing quality. Mixing quality increases with the increase of velocity ratio [1]. If the velocity ratio V_r is more than 13.6, then the mixing quality will be good.

- If, $V_r < 9$ then mixing quality is Bad
- If, $9 < V_r < 13.6$ then mixing quality is Medium
- If, $V_r > 13.6$ then mixing quality is Good

The pipe length required to achieve 95% mixing is a strong function of branch and main pipe inlet velocity ratio. If a fluid stream from branch pipe is centered along the axis of the main pipe gives the shortest mixing length [3]. The mixing length for 95% mixing decreases when the velocity ratio increases. The rate of change becomes slower at velocity ratios higher than 30. For certain velocity ratios, the 95% mixing length may start to increase if the velocity ratio is increased over a threshold value.

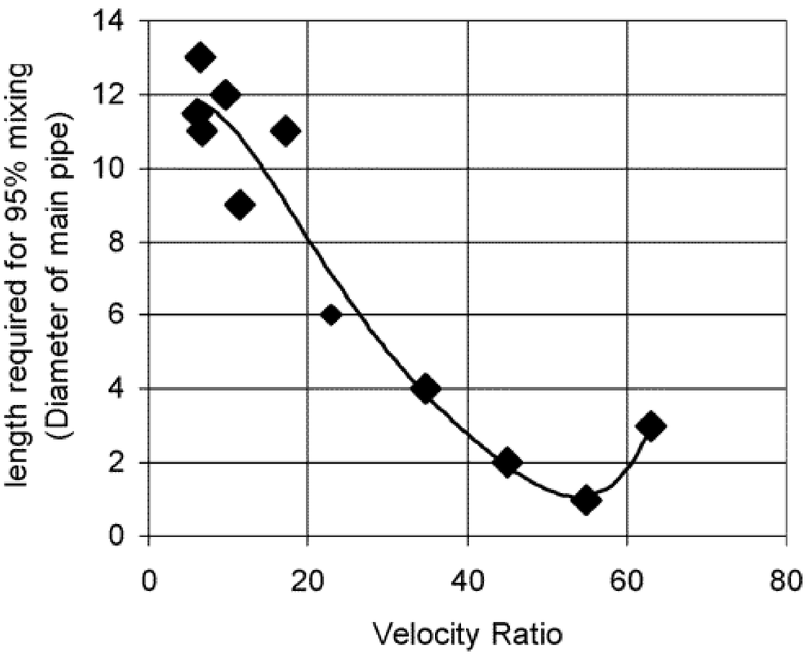


Figure 2.3: 95% mixing length in term of diameters of the main pipe for different velocity ratio (U_j/U_m) in a 0.25-inch right-angled side tee [3].

These results are plotted in Figure 2.3. The data show a certain amount of scatter especially for velocity ratios of less than 20. Similar data for the same main pipe and a side-tee diameter of 1/8 inch are plotted in Figure 2.4. A much clearer trend and significantly less data scatter are observed. Figure 2.3 shows how the 95% mixing length changes with an increase in the velocity ratio. At low velocity ratio, the jet impinges on the opposite wall and connects with that wall. This means that the jet is not centered, and 95% mixing requires a long distance. As the velocity increases, the jet starts to bounce back off the opposite wall and at a ratio of about 55, the jet becomes centered after its impingement. The 95% mixing length starts to increase as the velocity ratio is further increased. This is because the jet starts to move further away from the center.

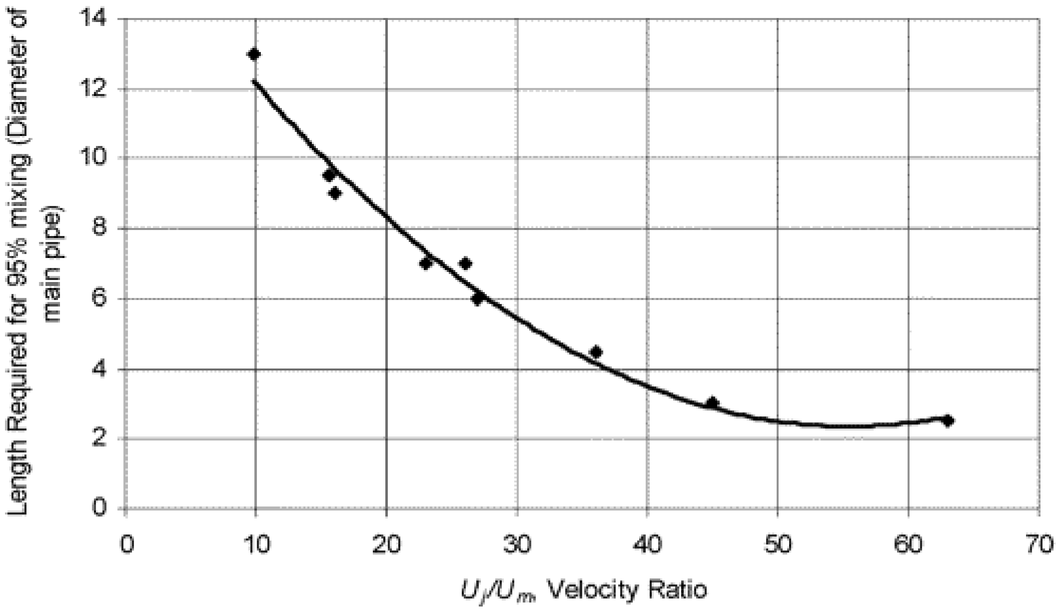


Figure 2.4: 95% mixing length for different velocity ratio (U_j / U_m) for all cases for a 0.125-inch right-angled side tee [3].

Branch and main pipe velocity ratio, V_r is an appropriate parameter to indicate the thermal mixing characteristics for a T-junction [5]. Thermal mixing and reverse flow of inlets fluid mostly depend on velocity ratio. If the velocity ratio is higher, then reverse flow is observed which causes good thermal mixing and less temperature fluctuations. Relation between velocity ratio and reverse flow using water as working fluid was found out experimentally by Chuang and Ferng [5], and their result is shown by some snapshots in Figure 2.5.

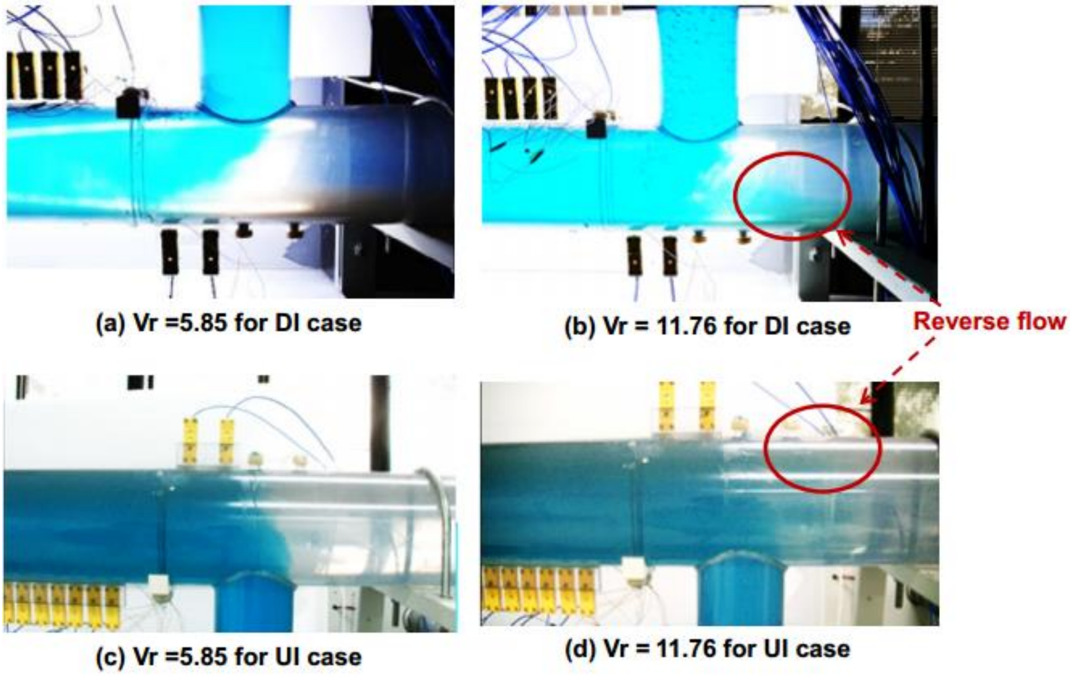


Figure 2.5: Snapshots of the mixing characteristics around a T-junction intersection for both downward injection (DI) and upward injection (UI) cases with V_r = 5.85 and 11.76. [5]

Figure 2.5 shows snapshots of the mixing characteristics around a T-junction intersection for both downward injection (DI) and upward injection (UI) cases with V_r = 5.85 and 11.76. Plots (a) and (c) in this figure are the snapshots for the mixing characteristics without the reverse flow for both DI and UI cases; plots (b) and (d) are those with the reverse flow. Using the blue dye injected from the branch, the flow pattern in the mixing region of the T-junction can be clearly observed. The fluid injected from the branch can mix with the fluid from the main pipe and then the mixing fluid flows downstream along the main pipe. However, the velocity of branch fluid is high enough that the branch fluid can impinge onto the bottom of the main pipe and some of fluid would flow reversely upstream a T-junction, resulting that the blue dye may appear upstream a T-junction. Figure 2.9 (b) and (d) can shows this characteristic for V_r = 11.76. However, this reverse characteristic is not shown in the cases of V_r = 5.85 since the velocity ratio is lower.

2.2.4 Effect of Inclination Angles Between Branch and Main Pipe

T-junction's geometry can be changed with variation of angles inclination between the main and branch pipe [3]. These inclination angles may be 30°, 45°, 60°, 90°, 120°, 150° etc. Different T-junctions with different inclination angle have been shown in Figure 2.6.

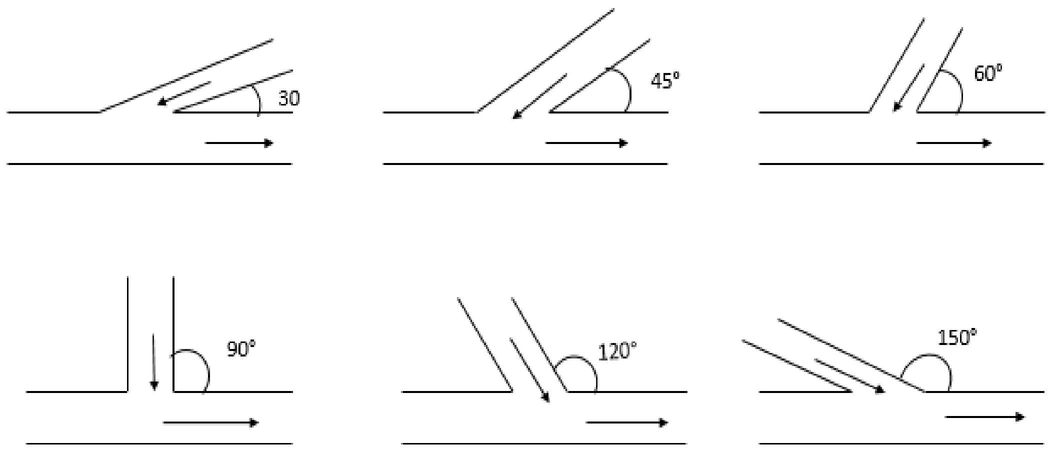


Figure 2.6: Different angles of inclination for different geometry of T-junctions.

Thermal mixing of hot and cold fluids depends on the distance along the mixing region. Thermal mixing is achieved faster over a shorter distance and slower if fluids mix over a long distance. This mixing distance which is also called as mixing length depends on the angle of inclination of branch pipe of T-junction. Zughbi et al. [3] found that thermal mixing is achieved faster over a shorter length for the angle of the branch pipe 45° and 60°. They found slower mixing at 30° or 90° inclination angle of mixing tee. In their study, 95% mixing was achieved at distance of 3*D* (*D* is the main-pipe diameters) for an inclination angle of 45°, at distance of 3.5*D* for an angle of 165°.

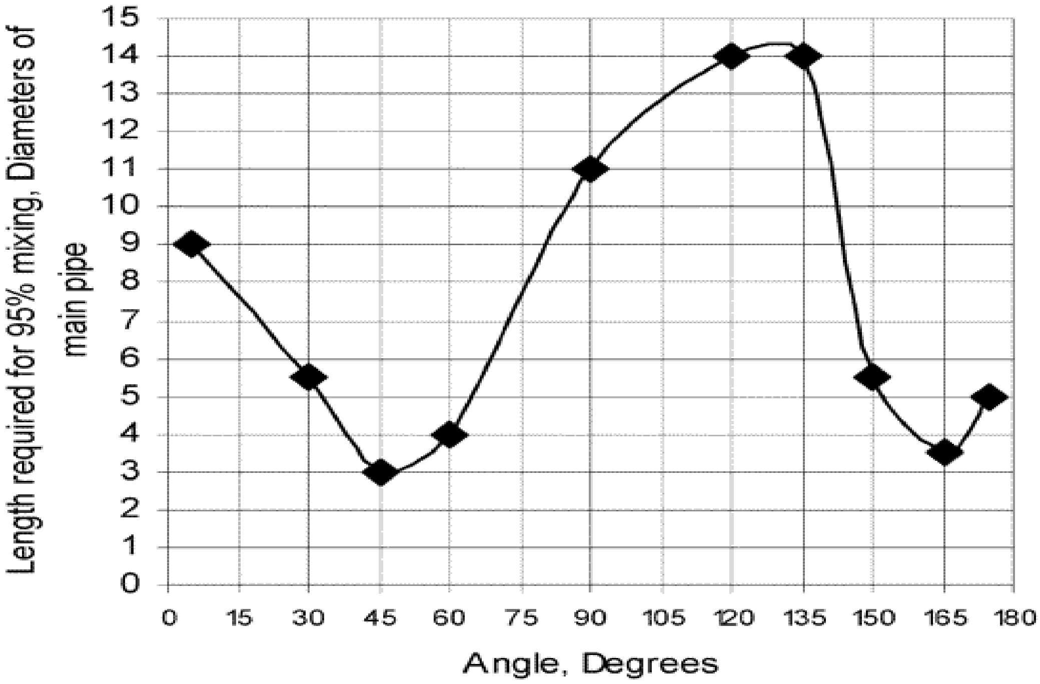


Figure 2.7: Plot of the distance required to achieve 95% mixing versus the angle of the side tee. [3]

Figure 2.7 shows a plot of the length of the pipe needed to achieve 95% mixing as a function of the angle of the tee. These results show that the angle of the tee will determine whether the jet impinges on the opposite wall and will also affect the length needed to achieve mixing.

This same experimental and numerical study was done by using an opposed tee (flow of fluids of two inlets are from opposite direction) for same diameter ratio and velocity ratio for a 90° T-junction. The result showed that 95% mixing take place faster at distance of 5.5D while it was slower at 11D for side tee. It indicates that 90° opposed tee has better thermal mixing performance than 90° side tee.

It is also found from this experiment that the inclination angle of the branch pipe can affect the temperature profile in the mixing region. Fluctuations of temperature in the mixing region change with the change of inclination angles. It is found that for 45° and 60° inclination angles, the mean temperature become a straight line which means no fluctuation at a shortest distance along the centerline of main pipe.

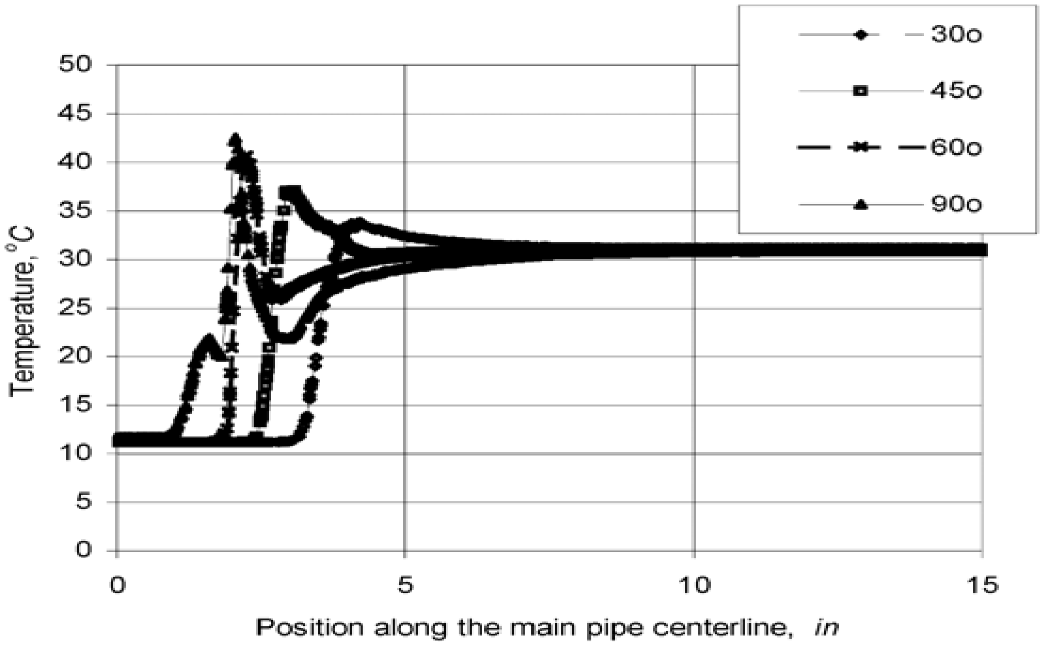


Figure 2.8: Temperature profile along the axis of the main pipe for tee angles of 30, 45, 60, and 90° [3]

Figure 2.8 shows the temperature profile along the center of the main pipe for a selected number of inclination angles between the branch and main pipe, namely, 30°, 45°, 60°, and 90°. After the distance of 5*D* (where D is the main pipe diameter = 1 inch) along the main pipe centerline, the temperature profile starts to stabilize.

Hirota et al. [22] investigated the influence of the jet angle on the turbulence promotion in the upper part of the mixing layer and found that the jet works most effectively with an angle of 45° against the main flow. The results of root mean square velocity distributions suggest that the most efficient promotion of the turbulent thermal mixing of hot and cold airflows is expected at jet to main velocity ratio equal to 3. Their work confirmed the conclusion by Zughbi et al. [3] that 45^o and 60^o has the shortest mixing length.

2.2.5 Effect of Reynolds Number

The effect of inertia on the mixing of the hot and cold fluids in the porous medium zone increases with increasing Reynolds number [21]. This means the turbulent mixing of hot and cold fluids in the porous medium zone is intensified.

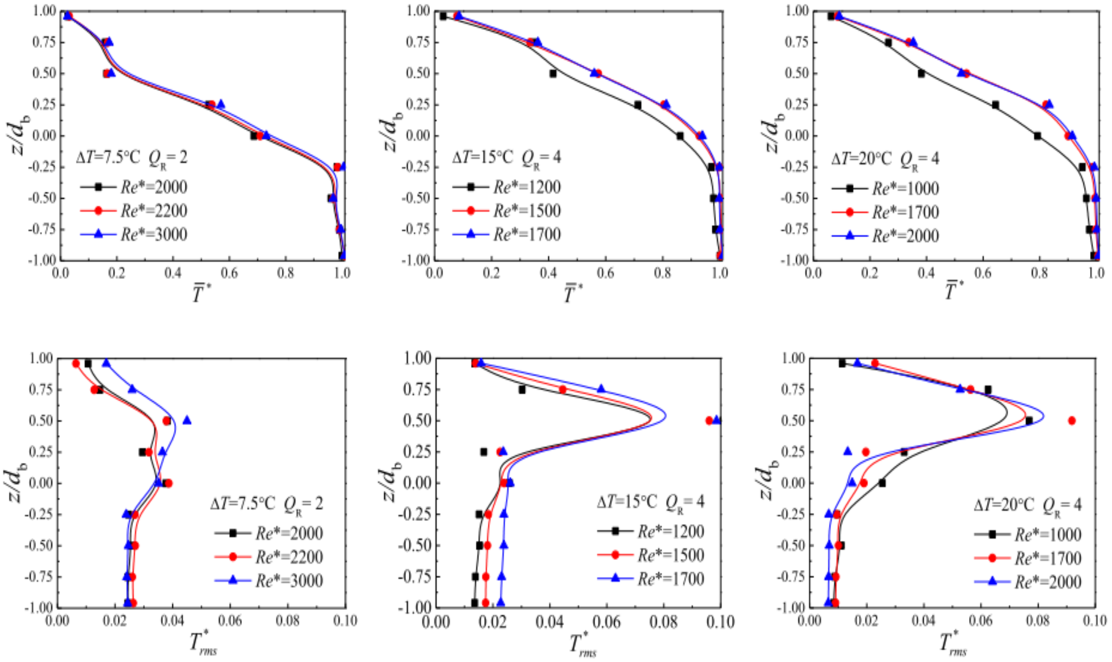


Figure 2.9: Figure 2.13: Distributions of normalized mean temperature and root mean square temperature for three different Reynolds numbers [21].

In Figure 2.9, the normalized mean temperature and normalized root mean square temperature tend to increase because of the enhanced turbulent mixing for larger Reynolds number at a fixed temperature difference and flux ratio, but the increase is limited. The main reason for this limited change is that the distribution patterns of hot and cold fluid in the T-junction do not change significantly with increasing Reynolds number, but rather with increasing flux ratio.

A numerical investigation was performed by Cao et al. [23] on temperature fluctuation of parallel jet. They found that the inception of the mixing of hot and cold fluid was delayed with increasing Reynolds number because the large fluid inertia which caused large inlet velocity needs to decay after a period before intense mixing. Meanwhile the role of inertia blocked the mixing of hot and cold fluids at forced convective mixing region to get larger. It was also found from their research the intensity of temperature fluctuation is reduced with the increasing of Re number.

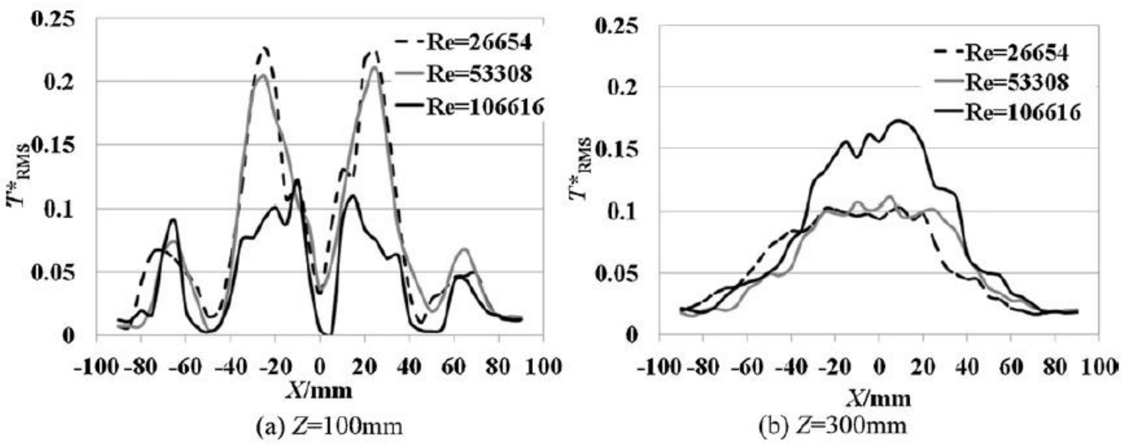


Figure 2.10: The normalized RMS temperature with different Reynolds numbers, case3, case4 and case6. (a) Z = 100 mm, (b) Z = 300 mm. [23]

Figure 2.10 shows normalized RMS temperature with different Re numbers of conditions at temperature difference of 10°C. The normalized RMS temperature at Z = 100 mm (where Z is the height direction) is presented in Fig. 10(a). We can find from this figure that the main mixing region is located between hot and cold fluid, −40 mm < X < −10 mm and 10 mm < X < 40 mm (where X is the horizontal direction). Near the exit jet of the hot fluids, the intensity of temperature fluctuation is seen increased small. In the main mixing region with the increase of Re number, the intensity of temperature fluctuation is decreased. Fig. 10(b) is showing the normalized RMS temperature at Z = 300 mm. The main fluctuation region is around the cold jet at −40 mm < X < 40 mm. In this region, with the increasing of Reynolds number, the temperature fluctuation intensity in the main fluctuation region is gradually enhanced.

The influence of the jet Reynolds number, aspect ratio and different locations of the passive element on flow and thermal mixing performance in a rectangular cross-section channel was investigated numerically by Kok et al. [24, 25]. From their research, it is found that mixing performance increases in the first half of the channel (x/L = 0 – 0.5) with an increase in Reynolds number and it is decreased in the second half (x/L = 0.5 – 1) of the channel with higher values of Reynolds number. The best mixing performance is formed at Re = 200 near the exit of fluids mixer.

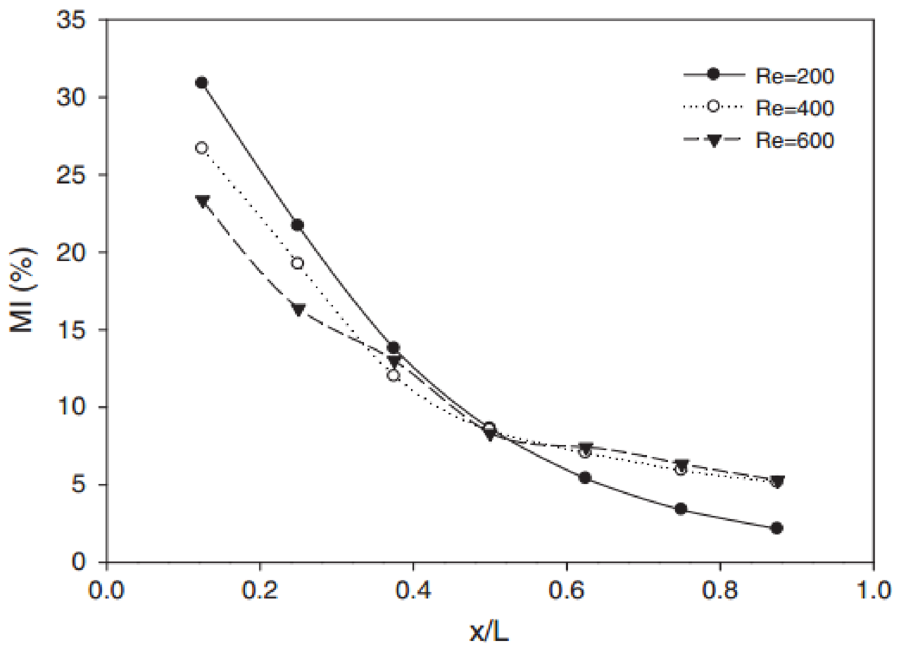


Figure 2.11: Variation of mixing index along the channel (L) without any PE inserted [24]

Figure 2.11 presents the mixing index (MI) along the channel with no passive element (PE) inserted. Mixing Index (MI) starts from 100% at x/L = 0 and decreases along the channel (L) when the thermal mixing efficiency of the cold and hot fluid gets better. The values of MI decrease at the middle part of the channel (x/L = 0.5) with increasing jet Reynolds number. After those higher values of mixing index are formed for higher values of Reynolds number.

2.3 Influence of Velocity Ratio on Mean Temperature

The another influencing factor is inlet velocity ratio which directly affect the mean temperature of the mixing fluid. If the branch and main pipe velocity ratio is higher, then the mean temperature will be lower [26-29]. To investigate thermal mixing and thermal stripping characteristics, experimental research was carried out by Chang and Ferng [5]. Different flowrates in the branch and main pipe and different branch injection directions, named, downward injection (DI) and upward injection were considered as variable. Figure 2.12 shows the temperature distribution of the mixing fluids in the mixing region at various location along the pipe. This temperature distribution is important to measure the temperature fluctuations. It shows that mean temperature fluctuates with the change of branch and main pipe velocity ratio at different location at downward injection (DI) and upward injection (UI). Mean temperature decreases gradually when velocity ratio is between 6 to 8 for both downward and upward directions. For other velocity ratio the change in mean temperature is not so high.

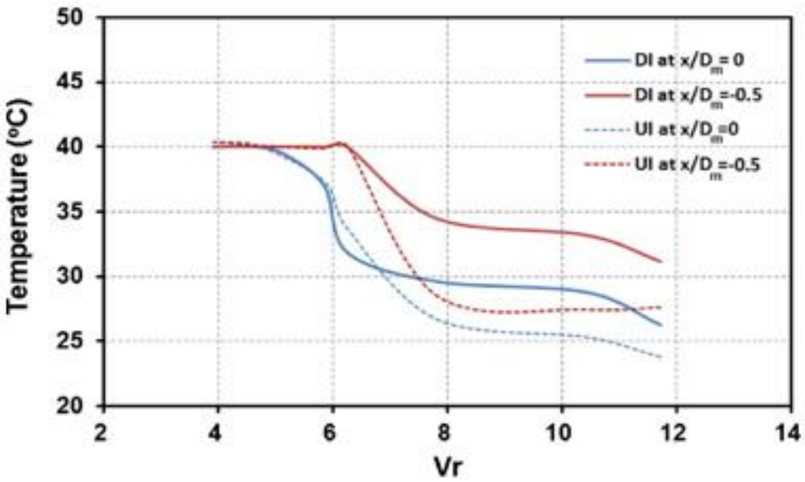


Figure 2.12: Mixing temperature distribution with respect to velocity ratio at x/Dm = 0 and 0.5 cold inlet temp=20°C and hot inlet=40°C [5]

2.4 Influence of Flow Region Along Mixing Outlet on Mean Temperature

The mean temperature is found in the mixing region where hot and cold fluids are mixed. This mean temperature is not same everywhere in the mixing region. It depends on the locations at the top, bottom, left and right sides along the pipe as shown in Figure 2.13. The mean temperature decreases with the increase of distance of location from the intersecting point of the two inlets [14, 30, 31]. This mean temperature is used to measure the temperature fluctuations. Figure 2.14 shows the temperature distribution near wall along mixing region at top, bottom, left and right side of the pipe. This mean temperature is required to measure the temperature fluctuations. It shows that normalized mean temperature increases with the increase of distance along the pipe.

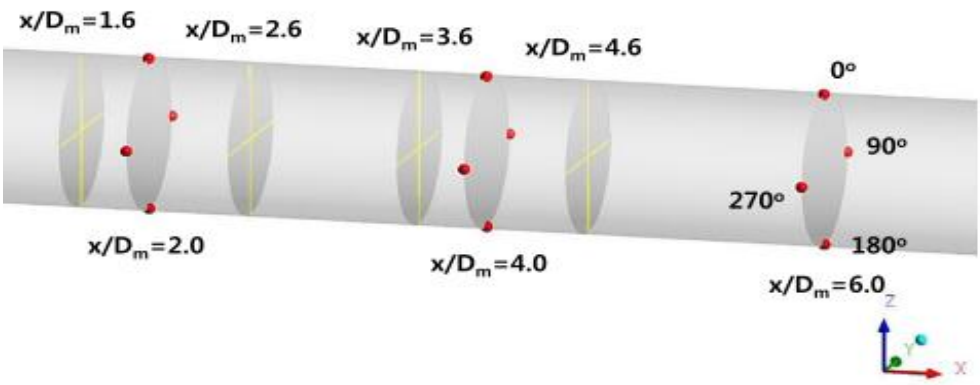


Figure 2.13: Different position along the mixing outlet (0° = top, 90° = right, 180° = bottom, 270° = left side of the pipe) [26]

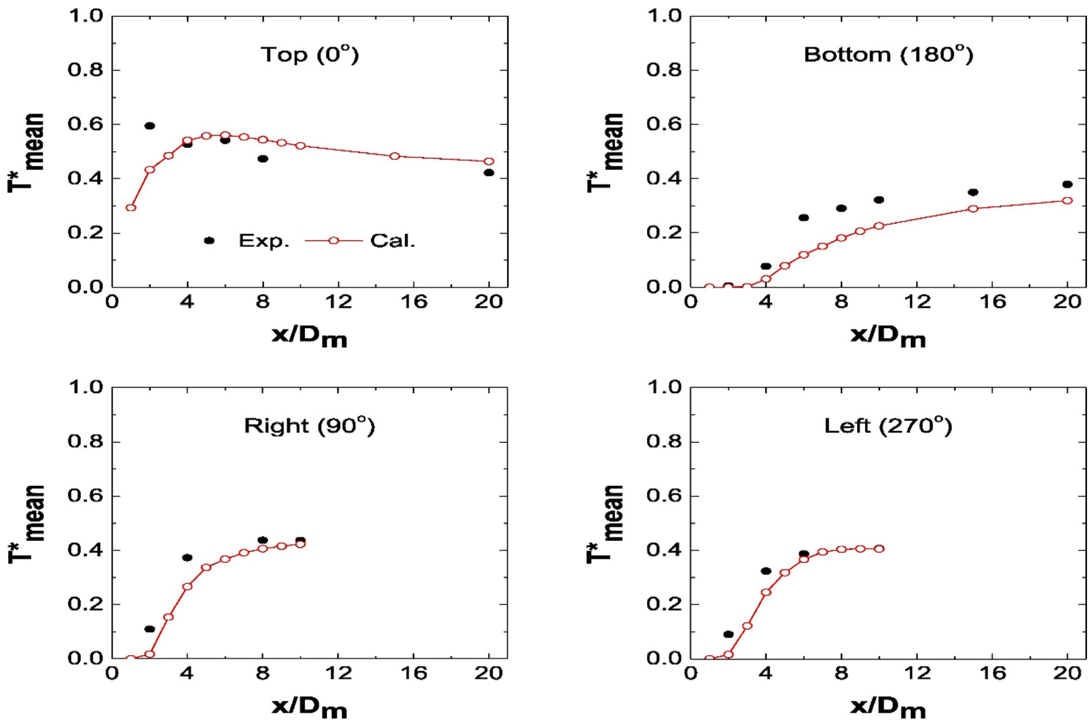


Figure 2.14: non-dimensional normalized mean temperature near wall at different positions [26].

2.5 Influence of Frequency of Temperature Fluctuation

There are some attenuation factors in the process of fluid thermal fluctuations converting to thermal stresses in the structure [18, 32]. Figure 2.15 shows the factors and their effect on thermal stress along with attenuation mechanism.

- At high frequencies, fluid thermal fluctuations are transferred to the structure with attenuation due to heat transfer loss resulting in low amplitude thermal stresses.

- On the other hand, low frequency thermal fluctuations result in low thermal stress due to thermal diffusivity homogenizing the structure.

- The medium frequency fluctuations have the potential to induce high amplitude thermal stresses in the structure.

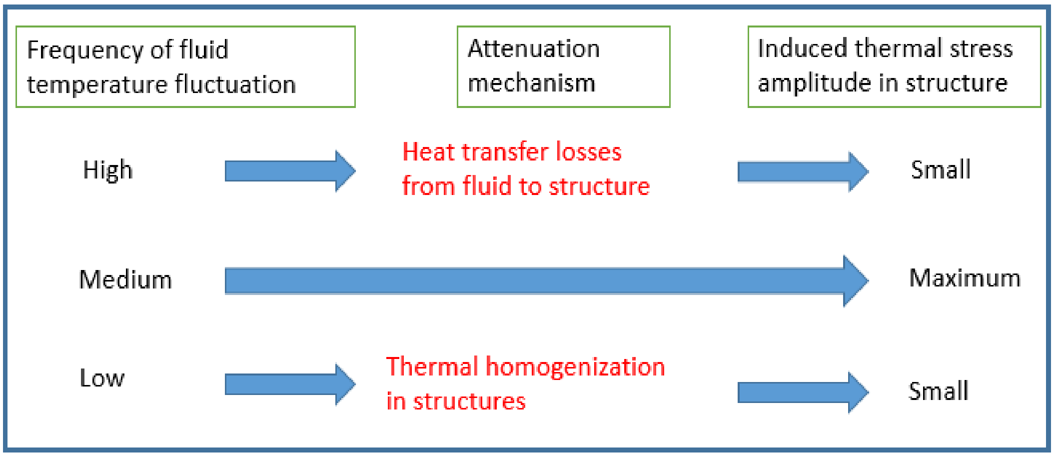
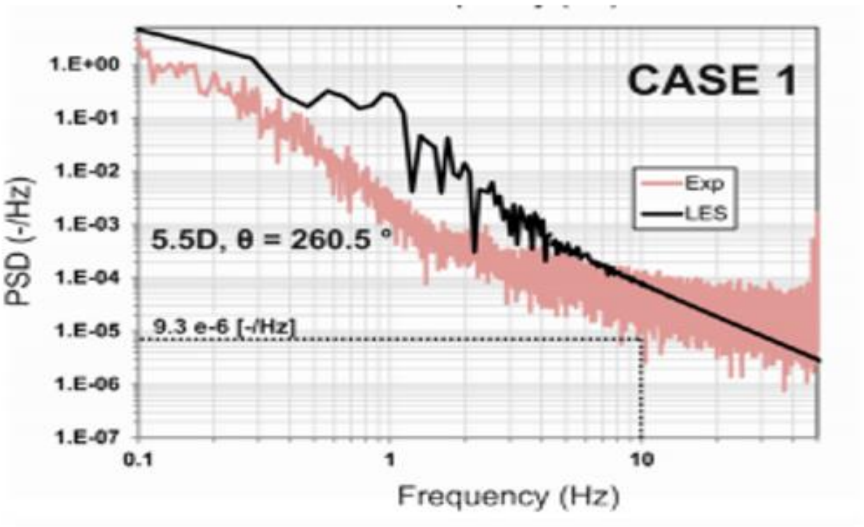


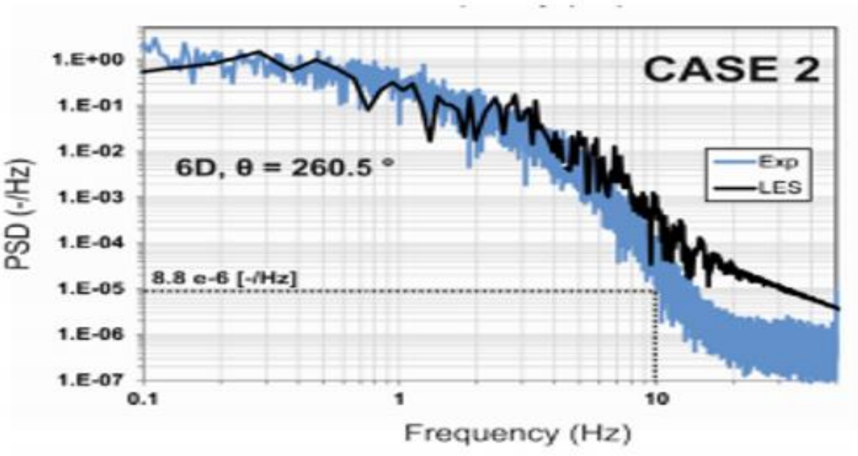
Figure 2.15: Thermal stress response to frequency of temperature fluctuations [18, 32]

2.6 Spectral analysis of Temperature Fluctuation

The frequency characteristics of temperature fluctuation in a T-junction can be expressed in the PSD versus frequency graph that are obtained from the transfer of time history data using the fast Fourier transform (FFT) analysis [18, 33]. Power spectrum density analysis gives an information about dominant frequencies of temperature fluctuations. Peak value of PSD can be found at the dominant frequency in the PSD vs frequency graph in Figure 2.16. Higher peak value of PSD can produce high cycle thermal fatigue which reduce the lifespan of the structures. So, the primary objective of power spectral density (PSD) analyses in this figure is to look for thermal fluctuations exhibiting dominant frequency in 0.1–10 Hz range.



(a)

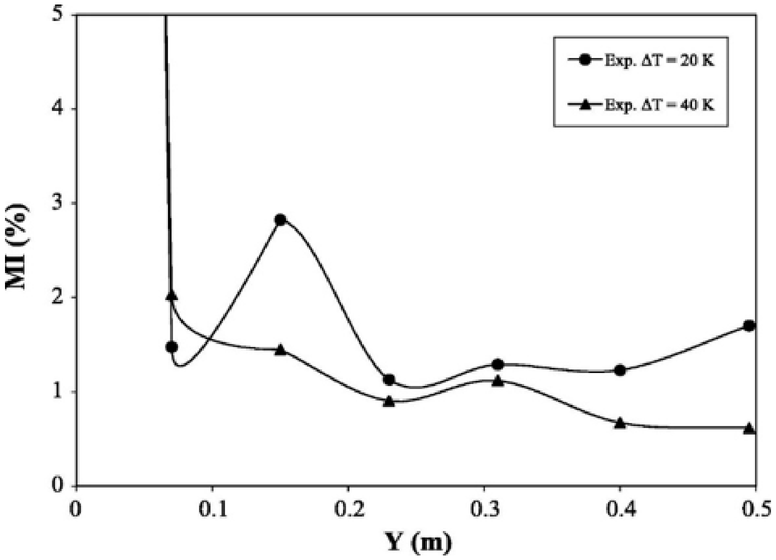


(b)

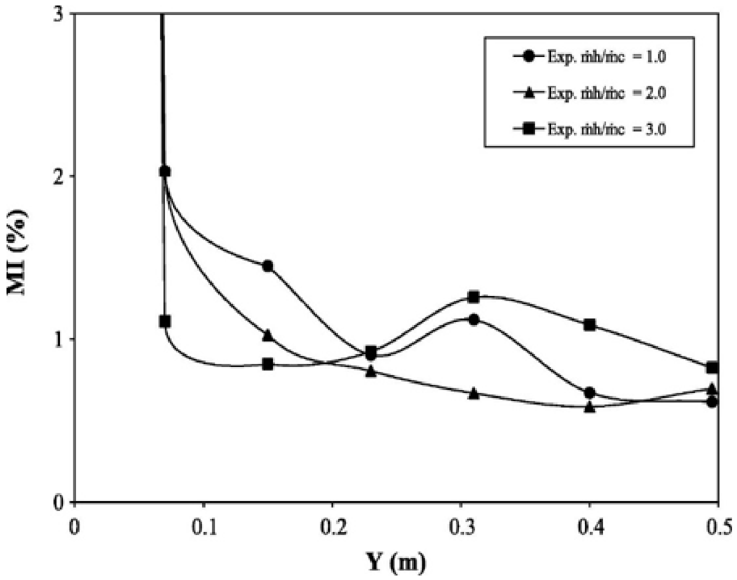
Figure 2.16: Comparison of PSD of thermal fluctuation between near-wall thermocouple data and LES predictions in (a) cases 1 and (b) case 2 between x = 5D till 6D [18]

2.7 Influence of Mass Flow Rate and Temperature Difference on Mixing Index

Devahastin and Mujumdar [34] first proposed Mixing Index (MI) and then [35-38] used this mixing index to measure the thermal mixing performance of fluids having different temperature. If the mixing index is lower, then the thermal mixing performance will be higher. Mass flow rate ratio and temperature difference has influence on mixing index (MI) at various location of mixing region along the pipe. Figure 2.17(a) shows that if temperature difference is higher, the mixing index will be lower and figure 2.17(b) shows that for mass flow rate ratio 2, the fluctuation of MI is lower. Both graphs show that the mixing index fluctuates with the increase of distance along the pipe, and it has a higher value near the intersecting point of the inlets.



(a)



(b)

Figure 2.17: Variation of mixing index along the channel for (a) hot and cold fluid mass flow rate ratio=1 and (b) temperature difference ΔT = 40 [36]

2.8 Use of Different Turbulence Models

For numerical analysis using computational fluid dynamics (CFD) software, different turbulence models, such as LES, RANS, URANS, DES, k-ε, k-ω are used. Numerically, Large Eddy Simulation (LES) is preferred [39] because it could predict turbulent mixing with high accuracy and precision. Accompanying the high accuracy is an equally high computational cost and time. The Reynolds-Averaged Navier-Stokes (RANS) and Unsteady Reynolds-Averaged Navier-Stokes (URANS) turbulent models, which were less expensive than LES, were also highly recommended [40, 41]. Kang et al. [26] performed a transient numerical analysis for the Vattenfall T-junction test by using Detached Eddy Simulation (DES) turbulence model. They evaluated the applicability of the DES turbulent model for turbulent thermal mixing by comparing the numerical results with experimental data. To visualize the temperature fluctuation in T-junction, temperature measurement experiments in a pipe wall [42] and temperature distribution visualization experiments [43] have been conducted using FATHER and FATHERINO facilities. The temperature distribution was calculated by Kuhn et al. [44] using CFD code to compare temperature which had been measured by infrared rays via a thin brass pipe in FATHERINO. The effect of modelling on temperature fluctuation had been investigated by Howard and Pasutto [45] using code Saturne and some models such as LES Dynamic, LES Smagorinsky, and WALE.

The k-ε model is a commonly used turbulence model to describe the characteristics of turbulent flows. This model was first proposed by Kolmogorov in 1942, then modified by Harlow and Nakayama [46]. Standard, RNG and Realizable k-ε models are some other variants of the k-ε model. In general, the k-ε model relied on two transport variables, namely the transported kinetic energy and dissipation, to represent the effects of convection and diffusion of turbulent energy. In the present study, the realizable k-ε model was adopted for simulation due to its short turnover time and ease of deployment.

In this study, ANSYS FLUENT 2020R1 had been chosen for fluid dynamics simulation of thermal mixing in T-junctions. It was considered as state-of-the-art CFD software for numerical investigation of fluid flow problems, and for heat transfer in different complex geometries [47]. FLUENT had different turbulent models for both single-phase and multiphase flow. The subject of turbulent flow is extremely complex and difficult. To summarize, turbulent flows were classified by the length and time scales of eddies. The large eddies could be solved directly, and the small eddies were modelled with the Large Eddies Simulation model which is time dependent. The entire continuum of turbulent scales can be resolved directly using a method called Direct Numerical Simulation (DNS). Even though the high accuracy and precision of these models were desirable, it is not always practical due to cost and time constrain.

2.9 Chapter Summery

This chapter described many previous works on thermal mixing at T-junction. Different researchers focused on different parameters which have effect on thermal mixing at T-junction such as inlet temperature, velocity, mass flow rate inclination angles, branch and main pipe diameter ratio etc. Most of them worked on conventional intersecting T-junction. Comparative study for thermal mixing performance between intersecting (90^{o}) and colliding (180^{o}) haven’t done yet. This current study deals with the comparison of thermal mixing efficiency between these two flow configurations.

CHAPTER 3

METHODOLOGY

This chapter describe sequential methods for the numerical solution procedure to conduct the research to evaluate characteristics of fluids flowing through the T-junction. Elaborate information about geometry drawing, mesh generation, mesh quality checking, different mesh element number, mesh independence test, selection of boundary surface, turbulence model selection, different boundary conditions model validation etc. are provided in this chapter. The geometry was built by design modeler of Ansys fluent software. Hexahedral meshes were generated throughout the geometry. Mesh convergence and mesh independence were checked to select fine mesh. For numerical solution k-ε turbulence model was chosen. The numerical model was successfully validated with published experimental and numerical data.

3.1 Research Outline

To improve the thermal mixing efficiency in T-junction of the regenerative system of the pipeline of MLNG plant, they proposed a new design of T-junction. This proposed new design is called “Colliding T-junction” where hot and cold flows from both inlet at 180° apart. On the other hand, the angle between hot and cold inlet was 90° in the conventional “Intersecting T-junction”. Both kinds of T-junction were considered as regular type converging T-junction where the branch and main pipe diameter was same, or diameter ratio was 1 to avoid complexity. The inclination angle between branch and main pipe was 90°. Although the thermal mixing performance can be affected by numerous factors, only hot and cold inlet temperature and mass flow rate were taken into consideration in this research. These two factors have the most influence on thermal mixing efficiency which was the reason for choosing these two factors as variable. This research investigated the effect of inlets temperature and mass flow rate on thermal mixing performance of hot and cold fluids in term of efficiency and temperature fluctuation. Figure 3.1 illustrated the flow chart of numerical solution of the research methodology adopted for this study.

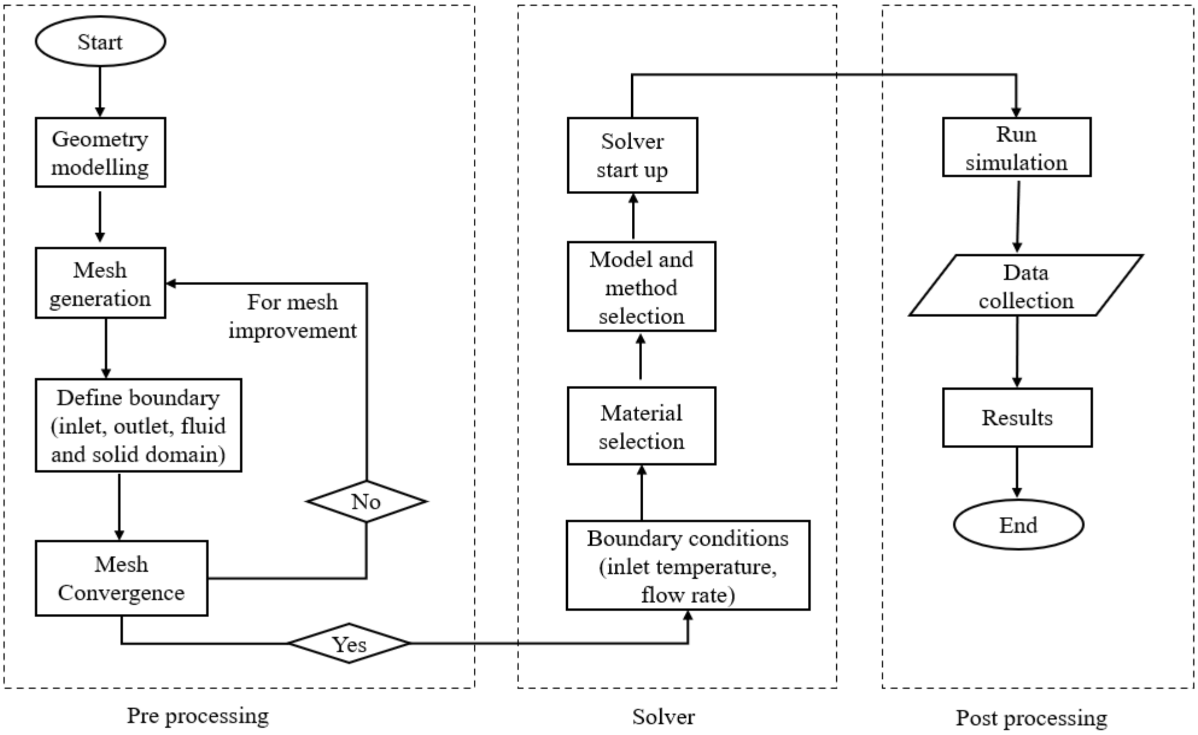


Figure 3.1: Numerical modelling flow chart

3.2 Description of Problem

Elaborate description of converging T-junction of two different flow configuration, working fluid properties, flow specification etc. are described one by one in different subsection under this section. Ansys Fluent software which is considered as the most common CFD tool was used in this study for numerical investigation of thermal mixing characteristics.

3.2.1 T-junction Geometry

The conventional T-junction that is commonly used is the intersecting mixing tee in which the two inlets are perpendicular to each other. This flow orientation has less thermal mixing performance. To increase the performance of thermal mixing and to reduce the thermal fatigue a new T-junction called colliding mixing tee is proposed in this study. The geometry of the intersecting and colliding mixing tee is almost same, but the inlets flow orientation of the hot and cold fluid is quite different. In colliding mixing T-junction, two opposite ends of the main pipe are considered as the inlets port for hot and cold fluids and the branch pipe is considered as the outlet of the mixer fluid. Figure 3.2 shows the T-junction geometry for both intersecting and colliding T-junction that has been used in this research. On the other hand, measurements all the parameters of the T-junction such lengths and diameters of two inlets and the outlet are shown in table 3.1.

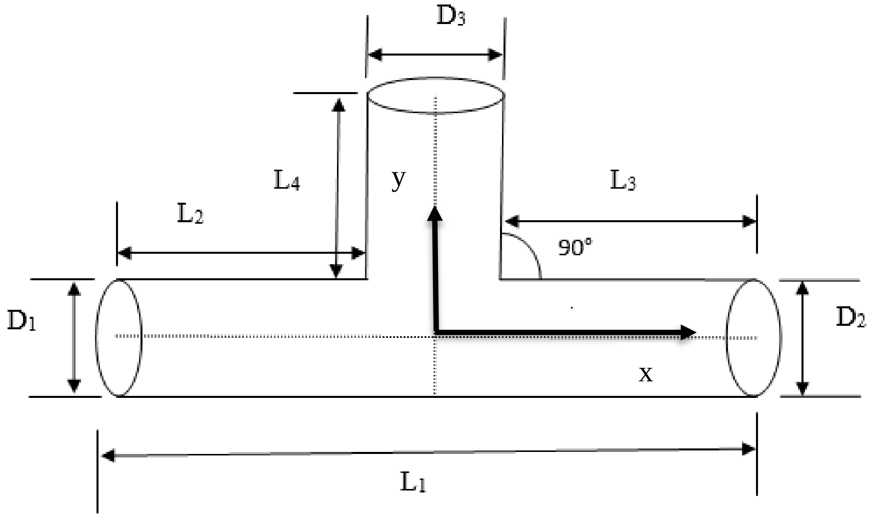


Figure 3.2: T-junction geometry

Table 3.1: Dimensions of intersecting and colliding mixing tee

Geometric parameters	Intersecting mixing tee		Colliding mixing tee	
	Dimensions (mm)	Flow configuration	Dimensions (mm)	Flow configuration

Diameter, D_1	304.8	Mixing outlet	304.8	Cold flow inlet
Diameter, D_2	304.8	Hot flow inlet	304.8	Hot flow inlet
Diameter, D_3	304.8	Cold flow inlet	304.8	Mixing outlet
Length, L_1	2200.0	_	2400.0	_
Length, L_2	1047.6	_	1047.6	_
Length, L_3	847.6	_	1047.6	_
Length, L_4	444.0	_	1500.0	_

3.2.2 Flow Specification

This study worked with the investigation of thermal mixing phenomenon for cold and hot fluid flowing through two inlets in a T-junction. For this purpose, hot and cold fluid at different temperature and mass flow rate were mixed at the mixing region of T-junction for two different flow configurations. In intersecting mixing tee, the cold inlet flow was along the -y axis direction and hot inlet flow was along the +x axis direction. The mixing fluid was flowing along +x axis through the mixing outlet. On the other hand, in colliding mixing tee, cold and hot inlet flow directions were -x axis and +x axis respectively. The mixing outlet direction was along +y axis. Gravity was applied along downward direction (-y axis) to meet the real-life scenario.

3.2.3 Data Range

The numerical investigation was performed for two flow configurations in two converging T-junctions. Inlet temperature and mass flow rate were taken into consideration as variable parameters for both intersecting and colliding T-junctions. Each T-junction was tested for three inlet temperature ratios and three inlet mass flow rate ratios. The design of experiment (DOE) adopted for this numerical research was shown in table 3.2. The inlets temperature ratios were 0.087, 0.34 and 0.59. The cold inlet temperature varied from 21 to 95°C and hot inlet temperature ranged from 120 to 300°C. On the other hand, three mass flow rate ratios were 0.24, 0.93 and 1.6. The cold inlet mass flow rate was from 1.67 to 7.5 Kg/s and for hot inlet flow it ranged from 3.31 to 8 kg/s. Several simulations were performed using different inlets temperature and mass flow rate. The pressure was assumed atmospheric pressure for all simulations.

Table 3.2: Inlet temperature and mass flow rate for different case

Case No	Cold inlet temp, T_c (°C)	Hot inlet temp, T_h (°C)	Cold mass rate, M_c (Kg/s)	Hot mass rate, M_h (Kg/s)	Inlet temp ratio, T_r (T_c/T_h)	Inlet mass flow rate ratio, M_r (M_c/M_h)
1	70	120	5.37	3.31	0.59	1.6
2	70	120	7.5	8	0.59	0.93
3	70	120	1.67	7	0.59	0.24
4	95	300	5.37	3.31	0.34	1.6
5	95	300	7.5	8	0.34	0.93
6	95	300	1.67	7	0.34	0.24
7	21	240	5.37	3.31	0.087	1.6
8	21	240	7.5	8	0.087	0.93
9	21	240	1.67	7	0.087	0.24

3.3 Governing Equations

The flow of most fluids can be mathematically described by some equations which are called governing equations. The governing equations are used to simultaneously solve fluid flow problems, numerically. In this study, Navier-Stokes equations such as continuity equation and momentum equation are used.

The continuity equation is sometimes referred to as conservation of mass. According to the continuity equation, the total amount of fluids entering through the inlet is equal to the total amount of fluid leaving through the outlet. The continuity equation for compressible flow is given in equation 3.1.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \tag{3.1}$$

where ρ is the density of the fluid, **u** is the fluid velocity vector.

Momentum equations are also referred to as Navier-Stokes equations. Momentum equations are used for the conservation of momentum at the inlet and outlet of fluid flow through pipelines. The momentum equation for gas is given in equation 3.2.

$$\frac{\partial}{\partial t}(\rho \mathbf{u}) \nabla \cdot (\rho \mathbf{u} \otimes \mathbf{u}) = -\nabla p + \nabla \cdot \boldsymbol{\tau} + \rho \mathbf{g} \tag{3.2}$$

where p is the pressure, $\boldsymbol{\tau}$ is the 2nd-order deviatoric stress tensor, and $\mathbf{g}$ is the gravity acceleration vector.

This equation is used for the conservation of energy. Total energy at the inlet and outlet of the mixing tee will always remain same when fluids flow through it. The conservation of energy equation is given in equation 3.3.

$$\rho C_p \left[\frac{\partial T}{\partial t} + (\mathbf{u} \cdot \nabla) T \right] = k \nabla^2 T + \Phi \tag{3.3}$$

where C_p is the specific heat at constant pressure, k is the thermal conductivity of the working fluid, Φ is the dissipation function representing the work done against viscous forces, which is irreversibly converted into internal energy. It is defined as,

$$\Phi = (\boldsymbol{\tau} \cdot \nabla) \mathbf{u} \tag{3.4}$$

3.4 Realizable k-ε Turbulence Model

In this study, realizable k-ε (k-epsilon) turbulence model has been used for simulation. Lin and Ferng [7] found from their study that the realizable k-ε model can provide a good performance for flows that possess strong gradients in temperature, pressure, and recirculation due to turbulence. The k-ε model is a commonly used turbulence model to describe the characteristics of turbulent flows. This model was first proposed by Kolmogorov in 1942, then modified by Harlow and Nakayama [50]. Standard, RNG and Realizable k-ε models are some other variants of the k-ε model. In general, the k-ε model relied on two transport variables, namely the transported kinetic energy and dissipation, to represent the effects of convection and diffusion of turbulent energy. So, the realizable k-ε model was adopted for simulation due to its short turnover time and ease of deployment. Two variables, namely, turbulent kinetic energy, K, and turbulent dissipation, ε are solved by Computational Fluid Dynamics (CFD) software ANSYS fluent (ANSYS 2020R1 Academic version). The transportation equations for turbulent kinetic energy and turbulent dissipation rate are given in equation 3.5 and 3.6.

Turbulent kinetic energy, K

$$\frac{\partial(\rho\kappa)}{\partial t}+\frac{\partial(\rho\kappa u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left(\frac{\mu_t}{\sigma_x}\frac{\partial\kappa}{\partial x_j}\right)+2\mu_t E_{ij}E_{ij}-\rho\varepsilon \tag{3.5}$$

Turbulent dissipation, ε

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial(\rho\varepsilon u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left(\frac{\mu_t}{\sigma_\varepsilon}\frac{\partial\varepsilon}{\partial x_j}\right)+C_{1\varepsilon}\frac{\varepsilon}{\kappa}2\mu_t E_{ij}E_{ij}-C_{2\varepsilon}\frac{\varepsilon^2}{\kappa}$$

(3.6)

3.5 Solution Methodology

This section describes different procedures of methodology for numerical solution such as model tessellation, mesh quality control, mesh dependency test, initial boundary conditions, solution procedure, convergence criterion etc. Accuracy of numerical prediction greatly depends on those procedure.

3.5.1 Modal Tessellation

Mesh tessellation can affect the solution accuracy for numerical prediction. Mesh applied to the geometry in finite volume solver can be categorized into several types such as hexahedral, tetrahedral and ply meshes [51]. For this current study, the tetrahedral mesh was used in the numerical setup for the fluid domain. This tetrahedral mesh can provide better performance for different joints, T-junction, and sudden change in direction of flow domain [52]. Since the mixing region or the intersecting and colliding area between the main and branch pipe consist of curvature surface, tetrahedral mesh is considered to provide good and acceptable mesh for the numerical solution. The usage of tetrahedral mesh in those areas can produce finer mesh volume comparing to hexahedral type [53]. Moreover, it is much easier to fill an arbitrary volume with tetrahedral cells as compared to hexahedral cells. A regular T-junction was tessellated using tetrahedral mesh as shown in Figure 3.3 where the grid density can be controlled in axial and radial directions.

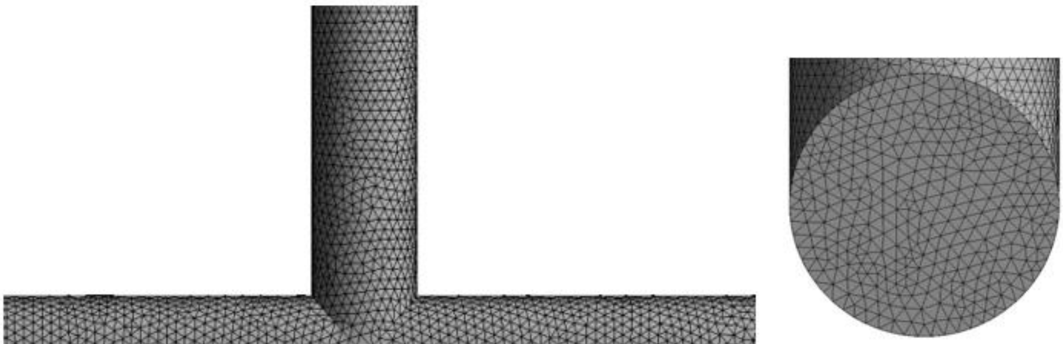


Figure 3.3: Generated mesh at different positions

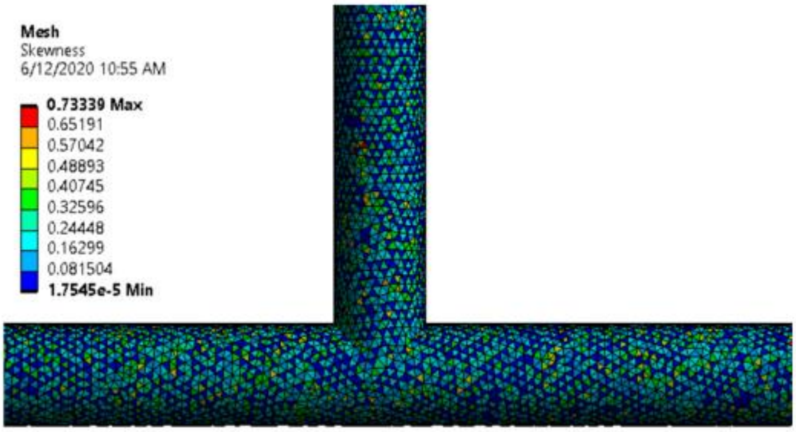
3.5.2 Mesh Quality control

In this numerical study, tetrahedral mesh was generated for the whole geometry, and these meshes are distributed more uniformly throughout the whole mixing tee. A uniform distribution of mesh was chosen to produce more accurate results during numerical analysis. A fine mesh that was used for this study is shown in Figure 3.3. Mesh skewness and orthogonal quality were performed for quality assurance purposes to ensure that the generated meshes were not overly distorted. The value ranges for skewness and orthogonal quality are listed in table 3.4. For skewness quality lowest value provide excellent mesh quality. The skewness quality decreases gradually with the increase of number value. But orthogonal quality shows a proportional relation with the number value with is quite opposite relation with the skewness quality.

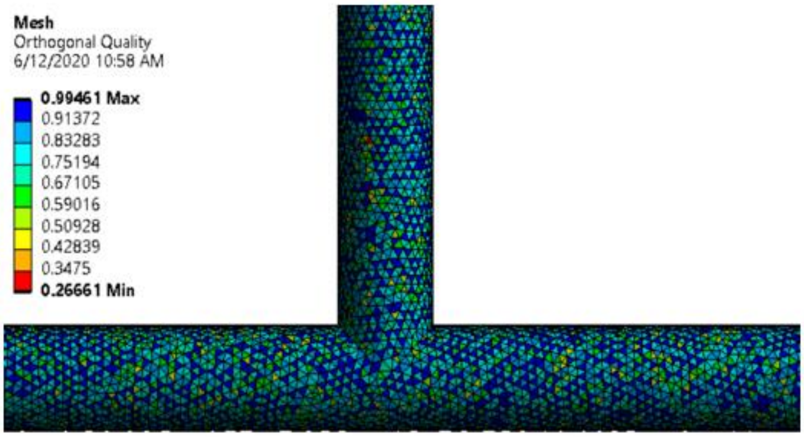
Table 3.3: Mesh quality value range

Mesh quality	Value range for Skewness mesh metrics	Value range for Orthogonal metrics
Excellent	0-0.25	0.98-1.00
Very good	0.25-0.50	0.95-0.97
Good	0.50-0.80	0.80-0.94
Acceptable	0.80-0.94	0.50-0.80
Bad	0.95-0.97	0.25-0.50
Unacceptable	0.98-1.00	0-0.25

The quality assurance of mesh has been shown in Figure 3.4, showing very little distortion or unacceptable tessellation. The values for skewness and orthogonal quality in all regions i.e., inlet, outlet and mixing zone of the T-junction are found good to excellent quality. Acceptable quality is also found in small portion of the whole mixing tee. Unacceptable mesh quality is hardly found in this Figure 3.4.



(a) Skewness mesh metrics



(b) Orthogonal quality

Figure 3.4: Mesh quality assurance check using (a) skewness and (b) orthogonality

3.5.3 Initial and Boundary Conditions

In this current research, cold and hot inlet temperature ratio and mass flow rate ratio were taken as two variable parameters. On the other hand, other parameters like branch and main pipe diameter ratio and inclination angle were considered as constant. Cold and hot inlet temperature ratios and mass flow rate ratios were prescribed as the inlet boundary conditions. Inlet temperature and mass flow rate conditions were applied at each inlet of the T-junction. The temperature and mass flow rate ratios used in this study were listed in table 3.5.

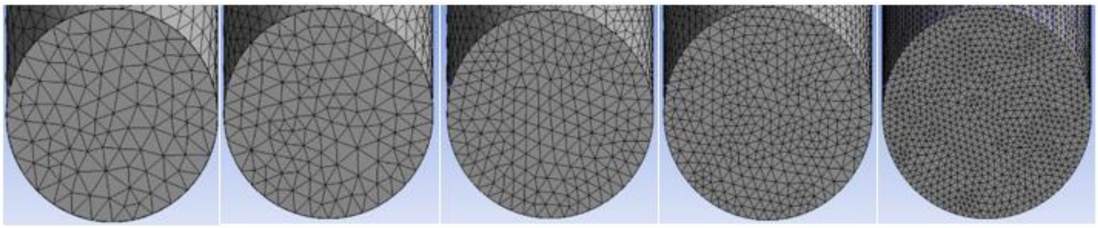
Table 3.4: Inlet temperature and mass flow rate for different case

Case No	Cold inlet temp, T_c (°C)	Hot inlet temp, T_h (°C)	Cold mass rate, M_c (Kg/s)	Hot mass rate, M_h (Kg/s)	Inlet temp ratio, T_r (T_c/T_h)	Inlet mass flow rate ratio, M_r (M_c/M_h)
1	70	120	5.37	3.31	0.59	1.6
2	70	120	7.5	8	0.59	0.93
3	70	120	1.67	7	0.59	0.24
4	95	300	5.37	3.31	0.34	1.6
5	95	300	7.5	8	0.34	0.93
6	95	300	1.67	7	0.34	0.24
7	21	240	5.37	3.31	0.087	1.6
8	21	240	7.5	8	0.087	0.93
9	21	240	1.67	7	0.087	0.24

The cold and hot inlet temperature were varied from 21-70°C and 120-300°C respectively. Inlet temperature ratios used in this study were 0.087, 0.34 and 0.59. On the other hand, the cold and hot mass flow rate varied in the range 1.67-7.5ms^{-1} and 3.31-8ms^{-1} respectively. The mass flow rate ratios were 1.6, 0.93 and 0.24. Throughout the simulation, pressure at the outlet was kept constant at atmospheric pressure. Near the wall, standard wall function was used. No slip shear condition was applied at the contact surface of solid and fluid.

3.5.4 Mesh Dependency Study

Mesh dependency test can ensure that the output results are not depending on mesh size or the total number of mesh elements. For this purpose, five samples of different mesh element numbers have been chosen and corresponding output temperatures at the outlet for each mesh element number are calculated. The mesh visualizations at the mixing outlet for different element numbers are shown in Figure 3.5.



a) Coarse mesh (112043) b) Coarse mesh (127030) c) Intermediate mesh (231567) d) Fine mesh (375870) e) Fine mesh (540347)

Figure 3.5: Five level of tessellation refinement for mesh sensitivity check

Average temperature at mixing outlet has been calculated for different element numbers to check the mesh dependency on increase of element number. Figure 3.6 shows that for first three cases, where the element numbers are less, outlet temperature is changing at high magnitude and error is much higher which indicates coarse mesh. From point “d” to “e”, the change of temperature is very less with the change of element number which. This indicates that the output parameters are not depending much on mesh element numbers which provide fine mesh and satisfy the mesh dependency test. So, mesh element number 540347 is accepted for simulation in this study.

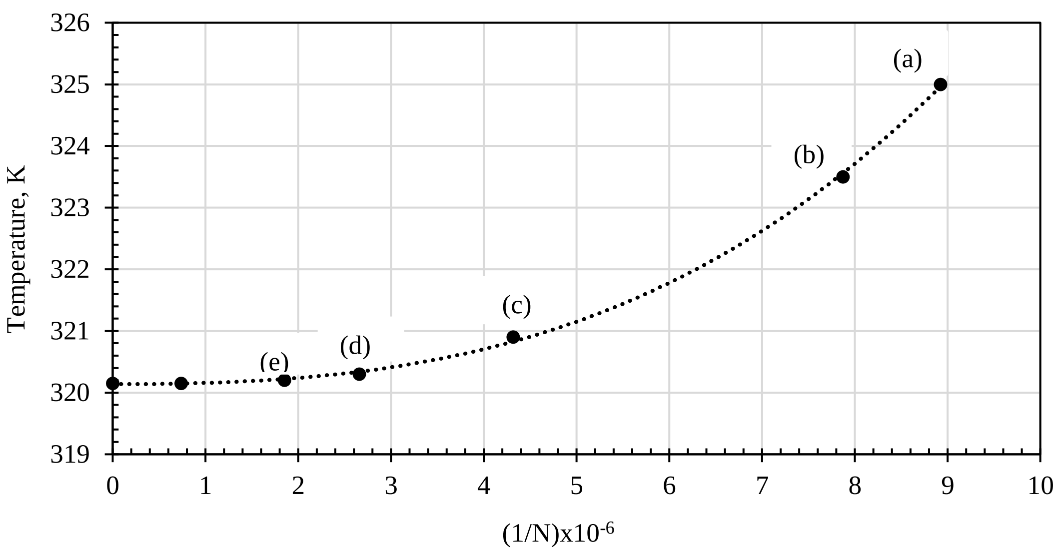


Figure 3.6: Mesh dependency test

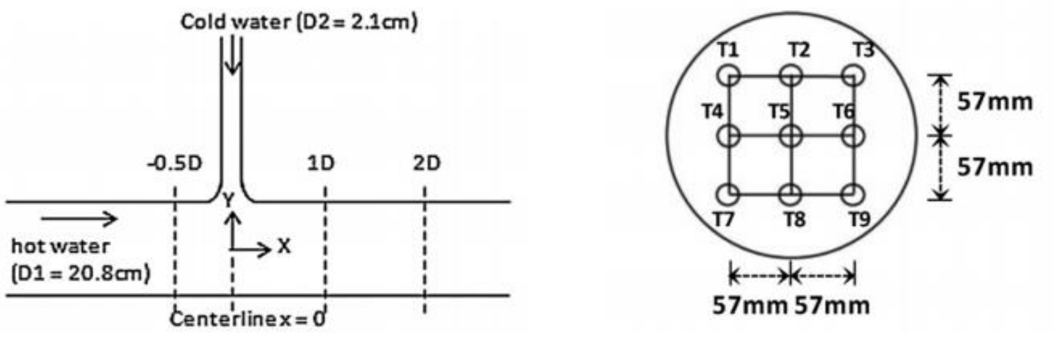
3.5.5 Solution Procedure and Convergence Criterion

Pressure based transient simulations were performed in this current research. SIMPLE scheme was used for the pressure-velocity coupling method. Standard discretization scheme was used for spatial discretization. For momentum, turbulent kinetic energy, turbulent dissipation rate and energy equations, the second order upwind discretization was applied for solution. Residual values of continuity, fluid velocity in each axis, energy, k and ε were selected as the solution convergence criteria. When the absolute values of a particular variable drop below 10^{-4}, the solution was considered converged.

3.6 Numerical Model Validation

In this study realizable k-ε turbulence model has been used as this can predict thermal mixing more accurately [7]. But at first, to check the turbulence model and other parameters k-ε turbulence model has been validated with previous experimental work. Same boundary conditions of previous work have been followed using realizable k-ε turbulence model.

For validation purpose, an experimental work of Chen et al. [1] has been used to compare with the numerical data. A 90° T-junction having main pipe diameter of 20.8 cm and branch pipe diameter of 2.1 cm has been used. The boundary conditions were the same as in Chen et al. [1] where hot and cold inlet temperature is set at 90°C and 20°C, respectively. Hot and cold inlet mass flow rates were different for different test conditions. Figure 3.7(a) shows the locations of different cross-sectional planes. While doing this experiment, 9 thermocouples had been used at different circumferential locations of each plane as shown in Figure 3.7(b) to measure the temperature.



(a) (b)

Figure 3.7: (a) positions of different planes and (b) positions of different thermocouples at cross-section [1]

In the experimental study for Test Condition 1, the branch pipe inlet flow rate was kept constant at 30 L/min and the main pipe flow rate was varying in the range of 100 L/min to 400 L/min. But for simplicity and easier to compare, only main pipe flowrate 100 L/min is chosen for numerical study. Figure 3.8 and Figure 3.9 shows the temperature found from experimental and numerical results at different thermocouple positions at 0D and 2D planes respectively. It is found from these two figures that the output temperature at different locations for both experimental and simulation results are very close and have very low temperature difference.

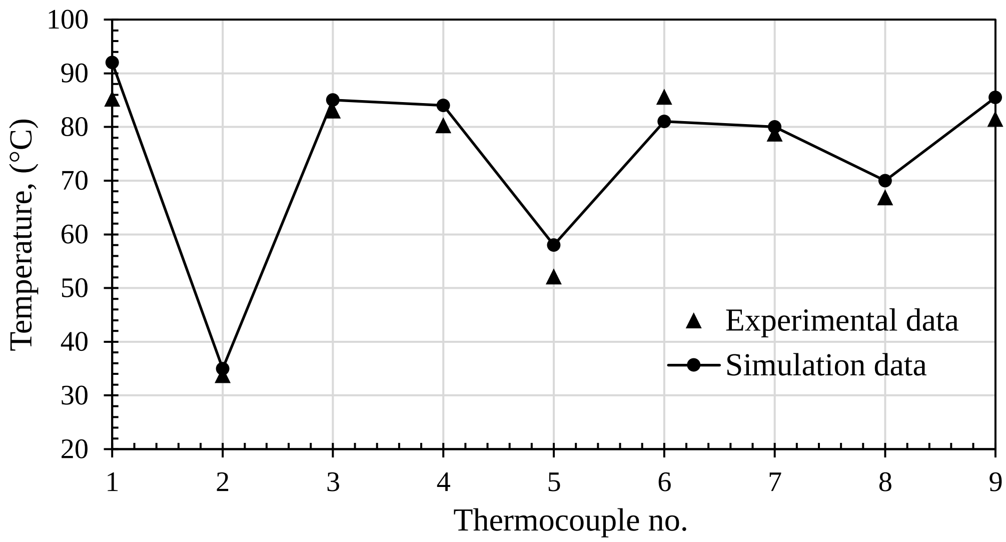


Figure 3.8: Temperature profile of experimental and simulation data at 0D plane for Test Condition 1. [1]

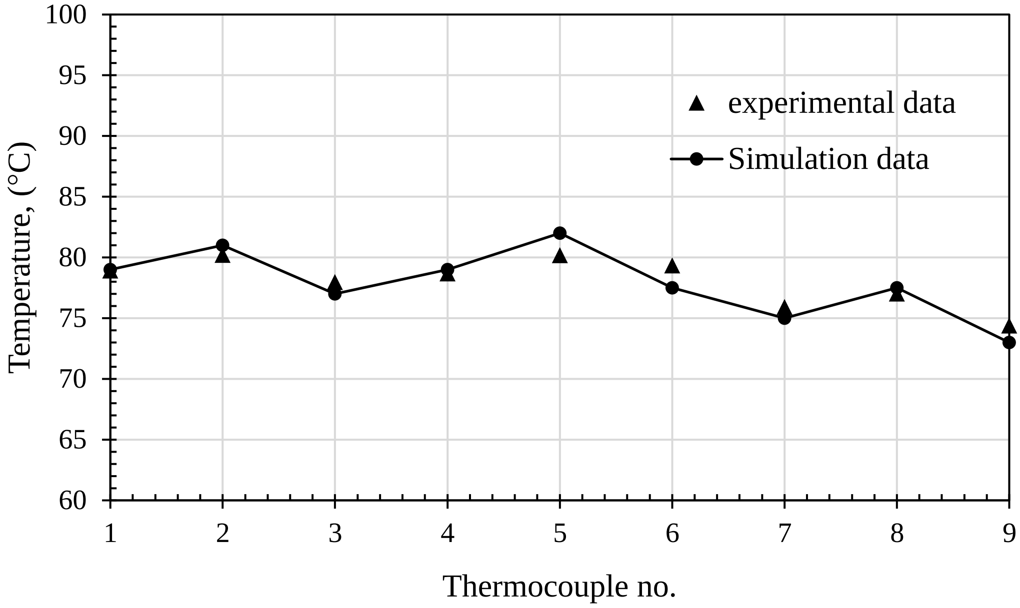


Figure 3.9: Temperature profile of experimental and simulation data at 2D plane for Test Condition 1. [1]

For test condition 2, the main pipe flow rate was kept constant at 300 L/min, and branch pipe flowrate was changing from 20 L/min to 50 L/min. For this numerical validation, main pipe flow rate 30 l/min is chosen. Figure 3.10 and Figure 3.11 shows the temperature at 0D and 2D planes respectively. It is found that the output temperature at different locations both experimental and simulation results are in good agreement.

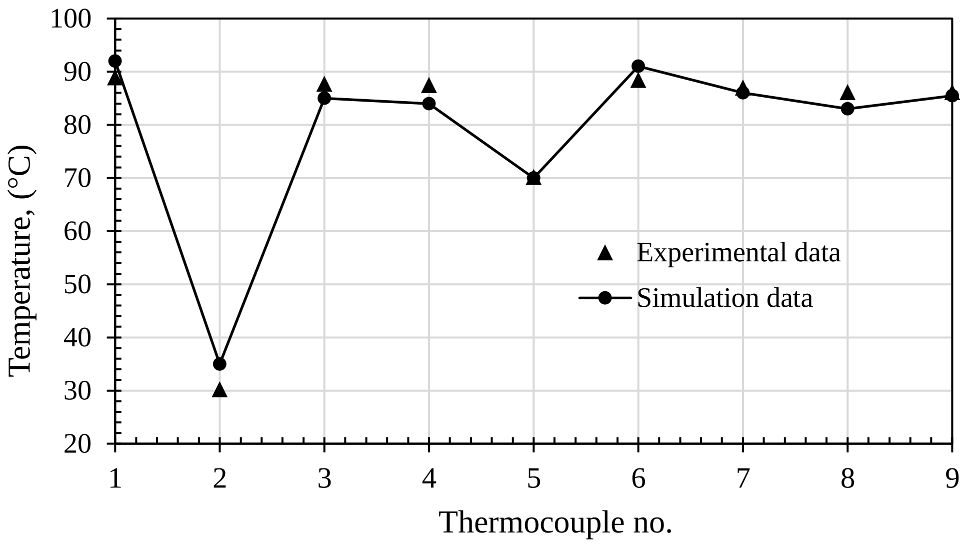


Figure 3.10: Temperature profile of experimental and simulation data at 0D plane for Test Condition 2. [1]

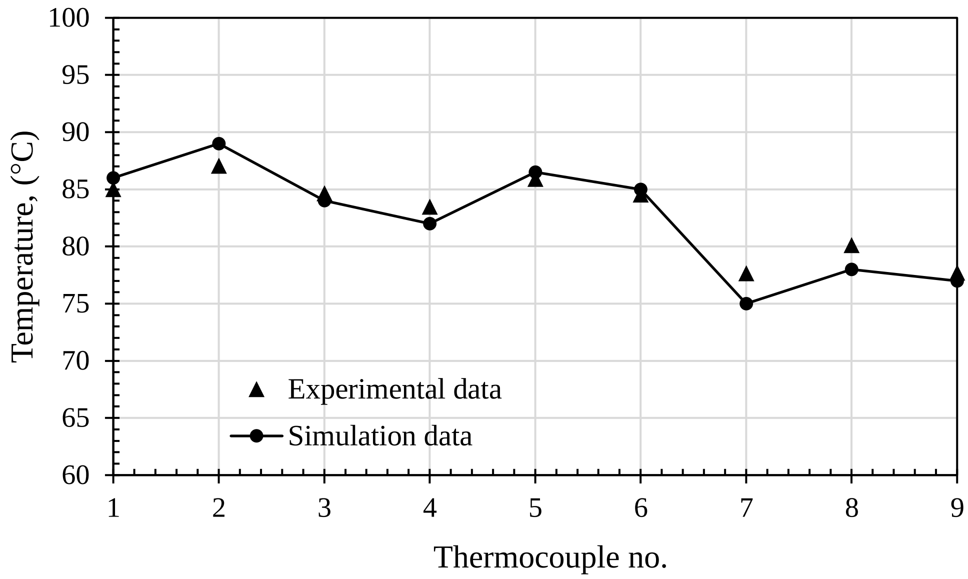


Figure 3.11: Temperature profile of experimental and simulation data at 2D plane for Test Condition 2. [1]

Another validation was done with the work of Ming and Zhao [47]. RANS turbulence was used for numerical calculation in their research. Water was used as working fluid. It was an intersecting mixing tee with similar diameter of the branch and main pipe. It was placed at horizontal position. It is found that realizable k- turbulence model can provide almost same results as RANS model. Figure 3.12 shows the T-junction geometry and boundary conditions.

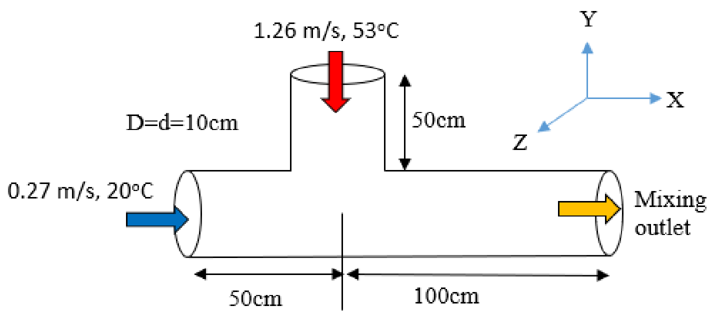
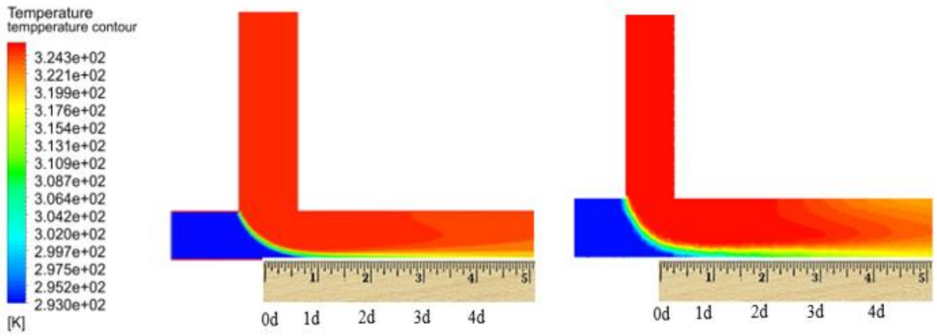


Figure 3.12: Geometry and its parameters for validation [47]

Figure 3.13 shows the temperature contour of both previous and current study. In this study, a transient simulation has been done using k-ε turbulence model. From Figure 3.13, it is found that temperature at different mixing region is almost same as it was found by Ming and Zhao [47] using RANS turbulence model. As the branch to main pipe velocity ratio is much higher, high temperature is found in most locations at mixing outlet.



RANS model　　　　k-ε turbulence model (current study)

Figure 3.13: Temperature contour of work of Ming and Zhao [47] and current study

Figure 3.14 shows the velocity contour at different positions for the previous work of Ming and Zhao [47] and for current study. At both hot and cold inlets, velocity is uniform, with no significant change because of no mixing of different flow streams. But at the mixing region, the velocity is found different from one location to another. At the main pipe outlet near the joint, the velocity is significantly low as there is no fillet at weld of T-joint branch and main pipe. On the other hand, on the opposite side of joint, at 0.5d to 3d distance of mixing outlet, the highest velocity is found as the hot and cold fluids flow intersect at 90° angle mostly in this region. So, from 0d to 4d distance at the outlet, three layers of region for low, medium, and high velocity are found. But after 4d distance, the velocity is found uniform as mixing of two fluids of different velocities and temperatures take place. One more noticeable matter is that there is low velocity at the region adjacent to wall due to the viscous effect and adhesive force between fluids and structure.

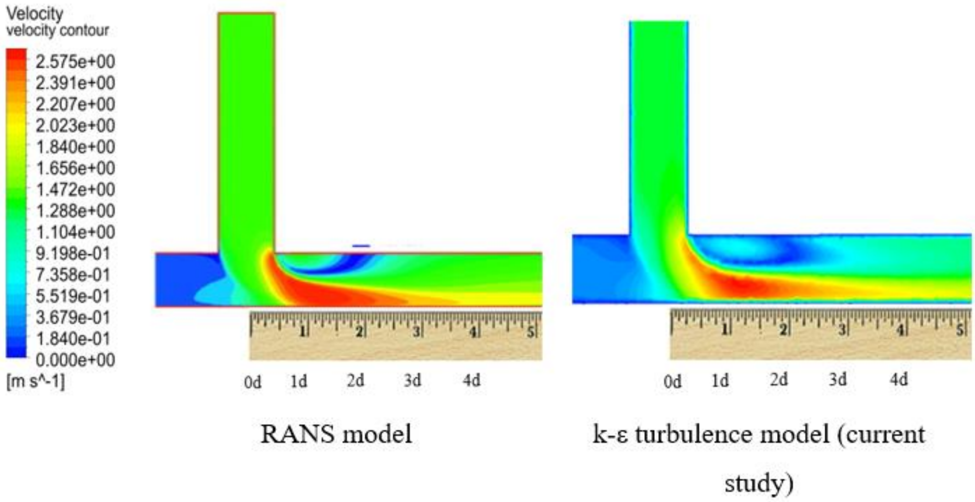


Figure 3.14: Velocity contour of work of Ming and Zhao [47] and current study

3.7 Chapter Summery

This chapter provided elaborate information about numerical methods and solution techniques used to find out thermal mixing characteristics of hot and cold fluid in T-junction. For design of geometry and to run simulations Ansys FLUENT 2020R1 was used as CFD software. Single phase natural gas was used as the working fluid. The flow chart for numerical modelling was given and described in this chapter. The T-junction geometry and its parameters like diameter and length were described as well as flow configuration. Fluid properties of natural gas were provided including fluid flow parameters with flow directions. Detailed description about k-ε turbulence model along with the equations of two transport variables, namely, turbulent kinetic energy and turbulent dissipation rate were given in this chapter. Mesh generation, mesh quality, mesh convergence, mesh dependency test etc. were also discussed. Finally, the numerical model adopted for this research was validated with previous experimental and numerical research.

CHAPTER 4

RESULTS AND DISCUSSIONS

This chapter presents all the results obtained from numerical simulations. Qualitative results were presented as temperature contours for different locations and different time-steps. These contours were described elaborately. Fluctuations of temperature at the mixing outlet were represented in graphs and discussed to show the mixing characteristics. Thermal mixing performances were investigated and discussed in term of “Temperature Mixing Degree (TMD)” which refer to thermal mixing efficiency. All the results were calculated for both flow configurations at the same boundary conditions to compare the thermal mixing performance of intersecting and colliding T-junctions.

4.1 Qualitative Analysis of Thermal Mixing

In a converging intersecting mixing tee, hot water enters through the main pipe inlet and cold water enters through the branch pipe inlet. Fluids from two inlets intersect at the right angle (90°) and a mixer of fluids leaves through another end of the main pipe. In colliding mixing tee, hot water enters through one end of the main pipe and cold gas through another end of the same pipe. Fluids from two inlets collide from the opposite directions (180°). Fluids after mixing leave through the branch pipe. For qualitative analysis temperature contours at longitudinal plane were shown in Figure 4.1 to observe the temperature distribution for both mixing for tees case no 7 where the inlet temperature difference was 205℃, and the branch to main pipe mass flow rate ratio is 1.6. A No-slip boundary condition has been used at the wall of the T-junction.

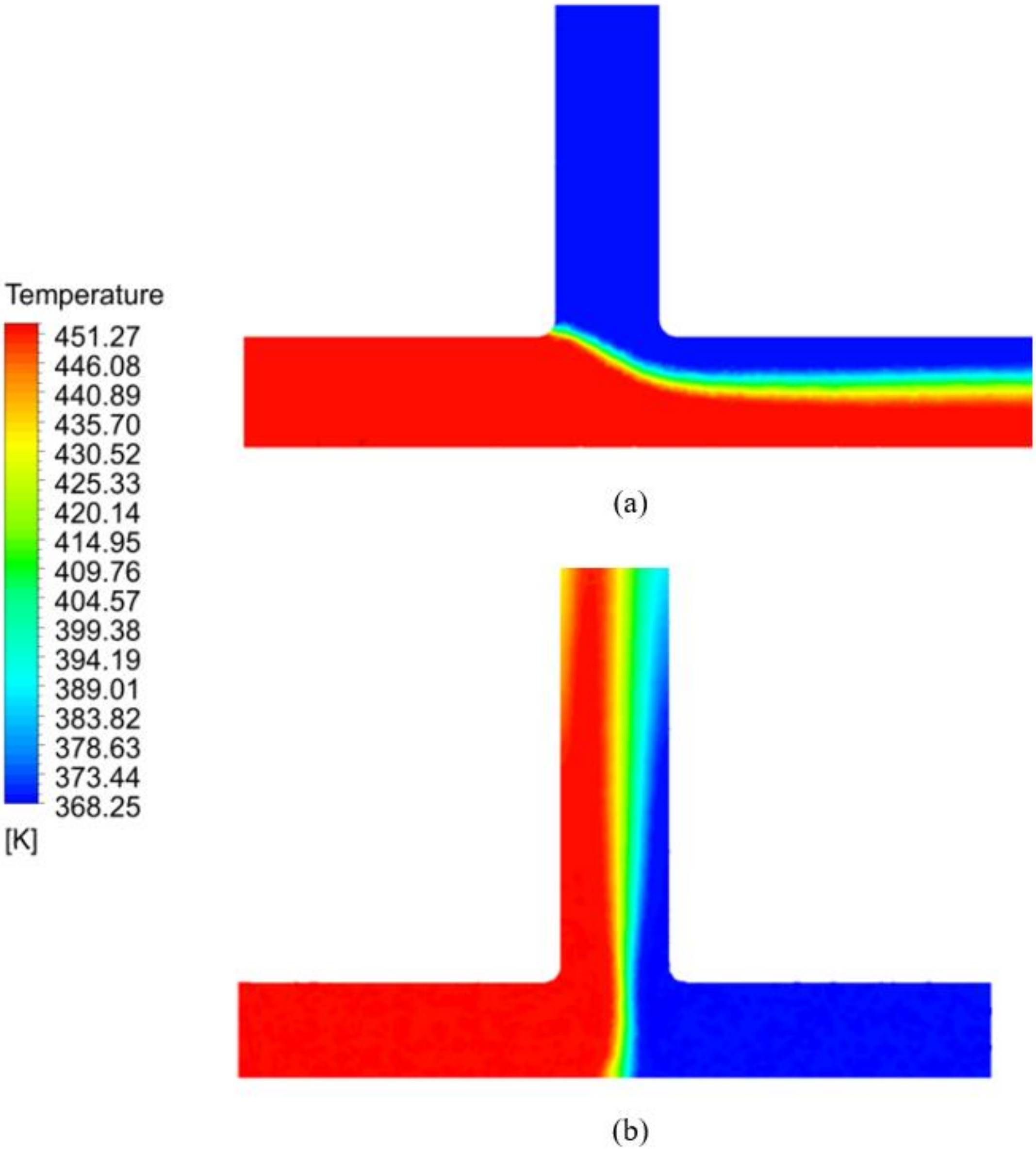
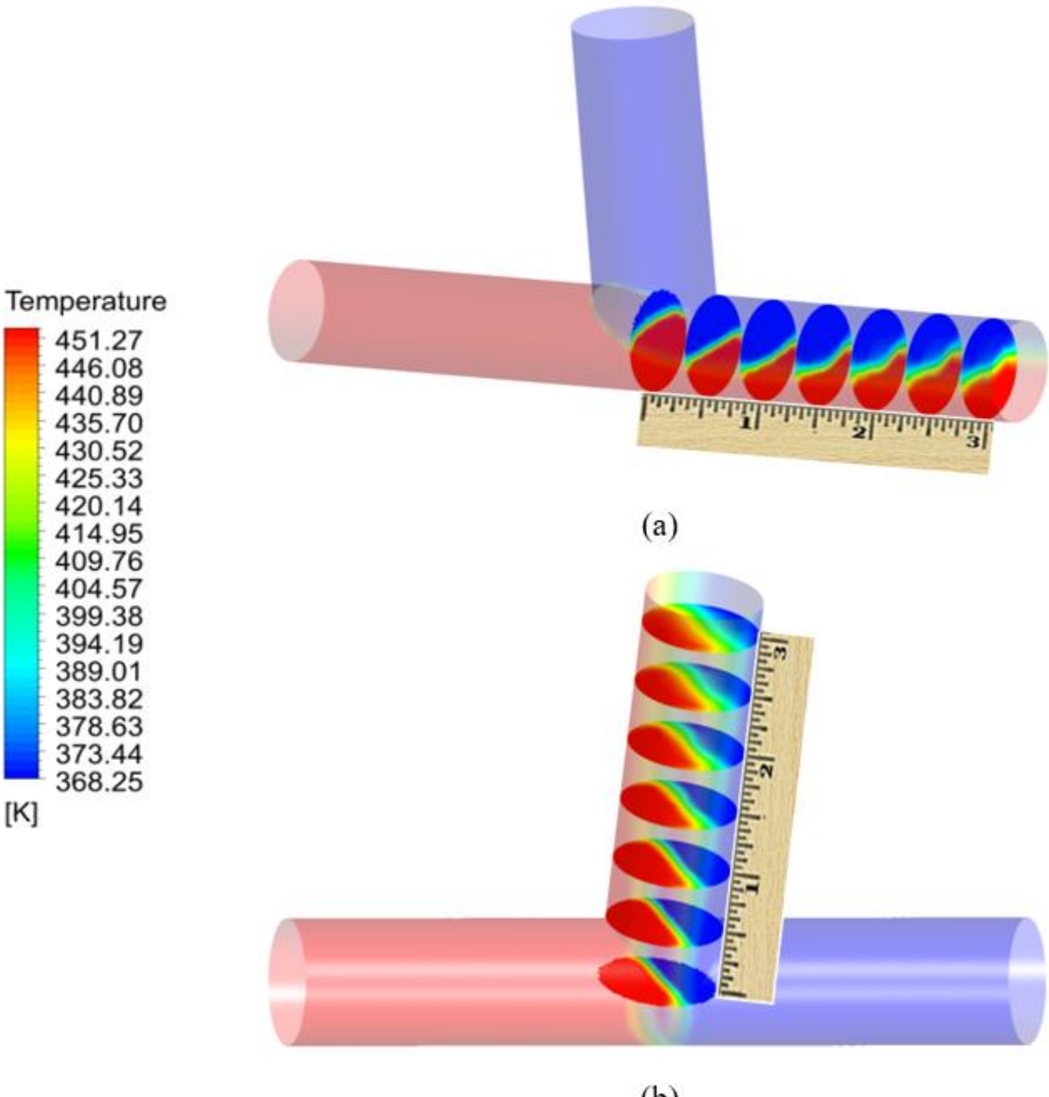


Figure 4.1: Temperature contour of (a) intersecting and (b) colliding T-junction

Figure 4.1(a) shows the temperature contour of intersecting mixing tee, and three distinct regions of a high, medium, and low temperature are found. Even after 3d distance, a high temperature difference is found, and thermal mixing just takes place in the middle of the mixing outlet. There is a clear hot stagnation layer that cannot be penetrated by the cold fluid. The temperature contour of colliding mixing tee is shown in Figure 4.1(b). At the branch pipe, which is considered here as a mixing outlet, three regions of temperature are found, similarly, to intersecting tee. Thermal mixing performance increases with the increase of mixing length. Temperature contour at longitudinal plane for more cases are shown in 'Appendix A' at the end of this thesis.

4.1.1 Temperature Contour at Different Locations

To observe a better one-to-one comparison, Figures 4.2 and 4.3 show the cross-sectional view of temperature at different planes of mixing outlets. These contours are also from case 7 of table 4.1. The scale attached with the mixing outlet of the T-junction indicates the distance of different cross-sections in terms of main pipe diameter (1, 2, 3 means 1d, 2d, 3d distance). As expected, thermal mixing quality for both T-junctions increases with the increase of distance, but the colliding tee is seen to perform slightly better than intersecting tee. At 0d, thermal mixing quality is low as hot and cold fluids just begin to meet at that point. Temperature contour at cross-sectional planes at different locations for more cases are shown in 'Appendix A' at the end of this thesis.



(a)

(b)

Figure 4.2: Temperature contour of (a) intersecting and (b) colliding mixing tee at different locations

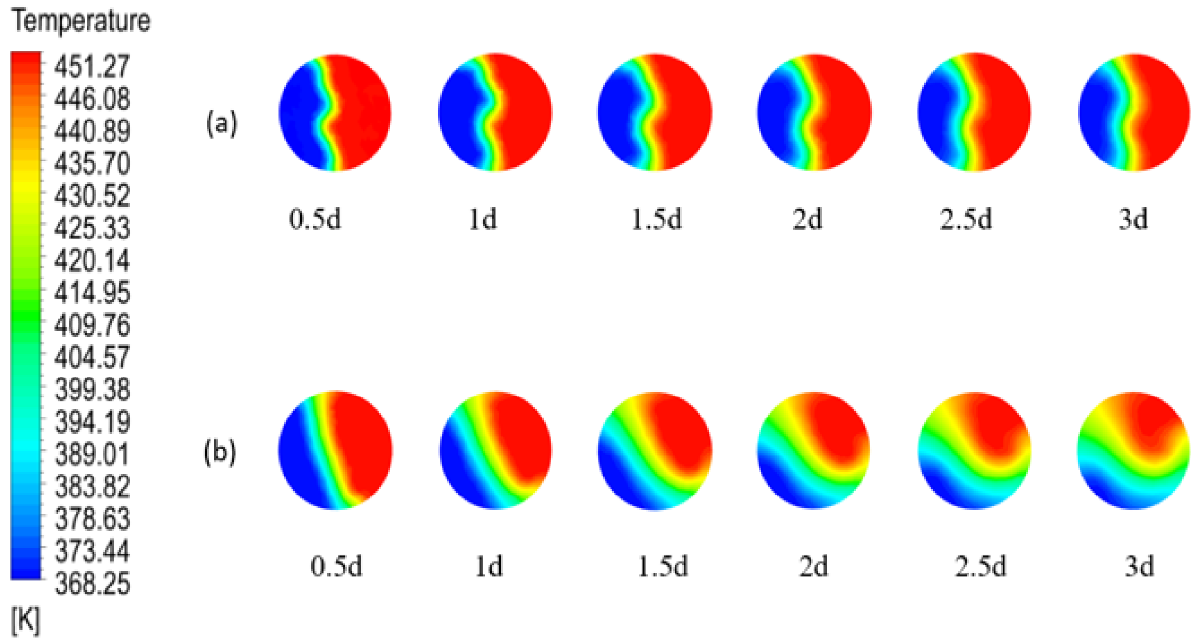


Figure 4.3: Cross-sectional temperature contour at of (a) intersecting and (b) colliding mixing tee at different locations

4.1.2 Temperature Contour at Different Time

The thermal mixing process of fluids having higher temperature differences also depends on the time taken for mixing. In this study, a transient simulation of 10 seconds has been performed for more accurate analysis. Temperature variation after 10 seconds is neglected because there is no change in temperature profile after that. Figure 4.4 compares the cross-sectional temperature contours at the plane 3d distance from the mixing point for both intersecting and colliding mixing tee at different time steps. This contour was selected from case 7. It is found there is little change in temperature contours for different time steps in both mixing tees. However, the colliding tee shows a significant and noticeable mixed layer in comparison to intersecting tee. Temperature contour at cross-sectional planes at different times for more cases are shown in 'Appendix A' at the end of this thesis.

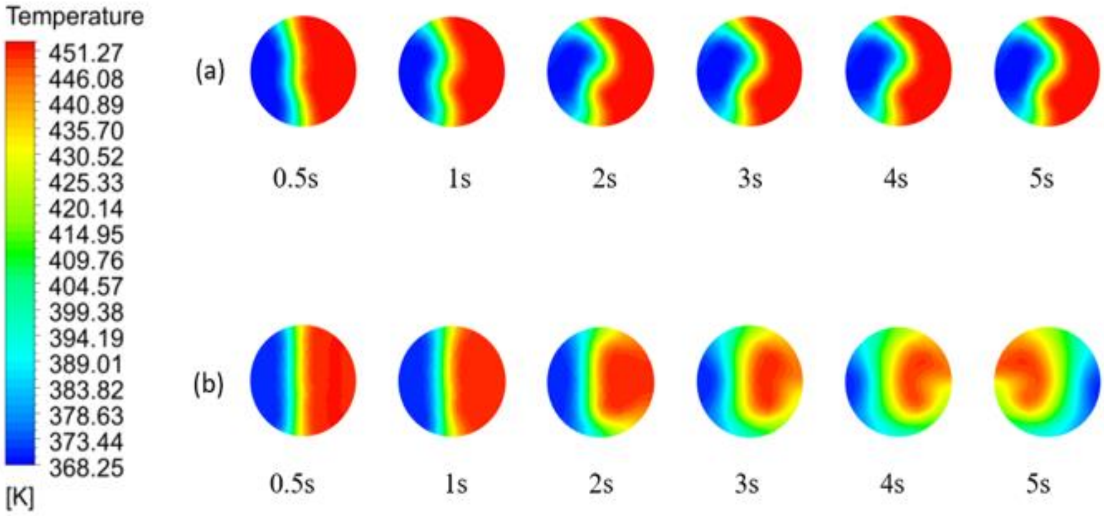


Figure 4.4: Cross-sectional temperature contour at 3d distance of (a) intersecting and (b) colliding mixing tee at different times

4.2 Temperature Fluctuation at Mixing Outlet

While mixing of hot and cold fluids in a T-junction heat is transferred from hot fluid to cold fluid. The temperature of hot fluid decreases gradually as it releases heat. On the other hand, cold fluid's temperature increases gradually by receiving heat after mixing at the outlet. For releasing and receiving of heat by hot and cold fluid respectively, the average temperature at the mixing outlet fluctuates rapidly. This rapid temperature fluctuation causes thermal stress at the weld area of T-junction, and it can be varied with the locations and time of mixing.

4.2.1 Temperature Fluctuation at Different Locations

To analyze the data in detail, Figure 4.5 shows the average temperature fluctuation at different locations of mixing outlets for both intersecting and colliding mixing tee. The highest average temperature in intersecting T-junction is found at the plane of 0d distance as the thermal mixing is just started at this plane. From Figure 4.5, it is found that for intersecting mixing tee, the intensity of temperature fluctuation is much higher as it fluctuates from 472.5k to 547k and the fluctuation range is 74.5°C. This means intersecting mixing tee has lower thermal mixing quality as the temperature difference is high. But in colliding mixing tee, temperature fluctuation is much lower as it fluctuates between the temperature 501k to 507k, and the difference is only 6°C. This indicates that colliding mixing tee has higher thermal mixing performance than intersecting mixing tee. Temperature fluctuations at different locations and times for more cases have been shown in ‘Appendix B’ at the end of this thesis.

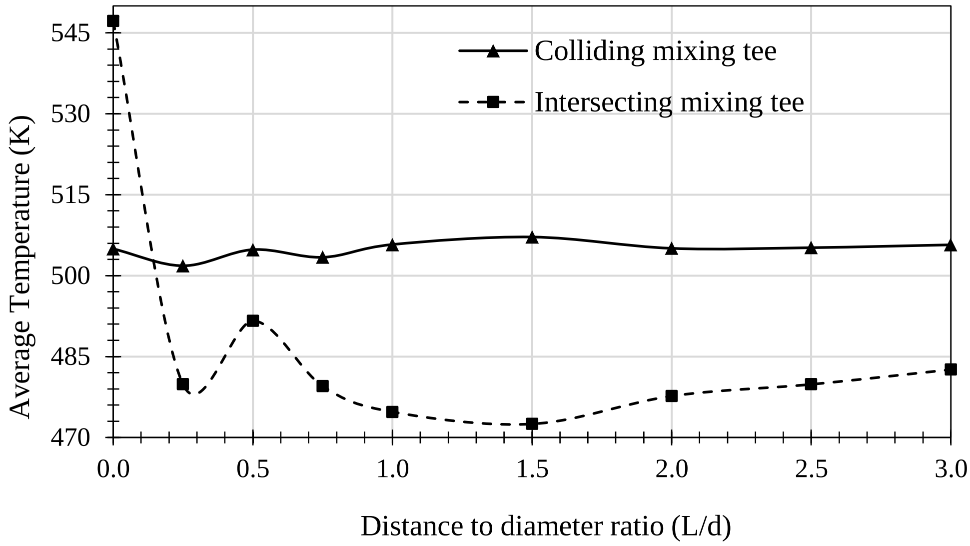


Figure 4.5: Comparison of average temperature fluctuations between Colliding and Intersecting mixing tee at temperature ratio 0.087 and mass flow rate ratio 1.6

4.2.2 Temperature Fluctuation at Different Times

In this current study, transient simulations were performed with time step 0.1 seconds and total flow time of 10 seconds for both intersecting and colliding T-junctions. Average temperature at different planes for every timestep was calculated to check the temperature fluctuations at the thermal mixing region of fluids inside the T-junctions. A comparison of temperature fluctuation is also found out between two different flow configurations called intersecting and colliding mixing tee. Figure 4.6 shows the temperature fluctuations at 3d plane of mixing outlet of both flow configurations where cold and hot inlet temperature ratio is 0.087 and mass flow rate ratio is 1.6. It is found that that temperature change is much higher until first 3s, medium in between 3s to 5s and after 5s the fluctuation is not much significant. From this Figure

4.6, it is found that Intersecting mixing tee provides higher temperature fluctuation than colliding mixing tee.

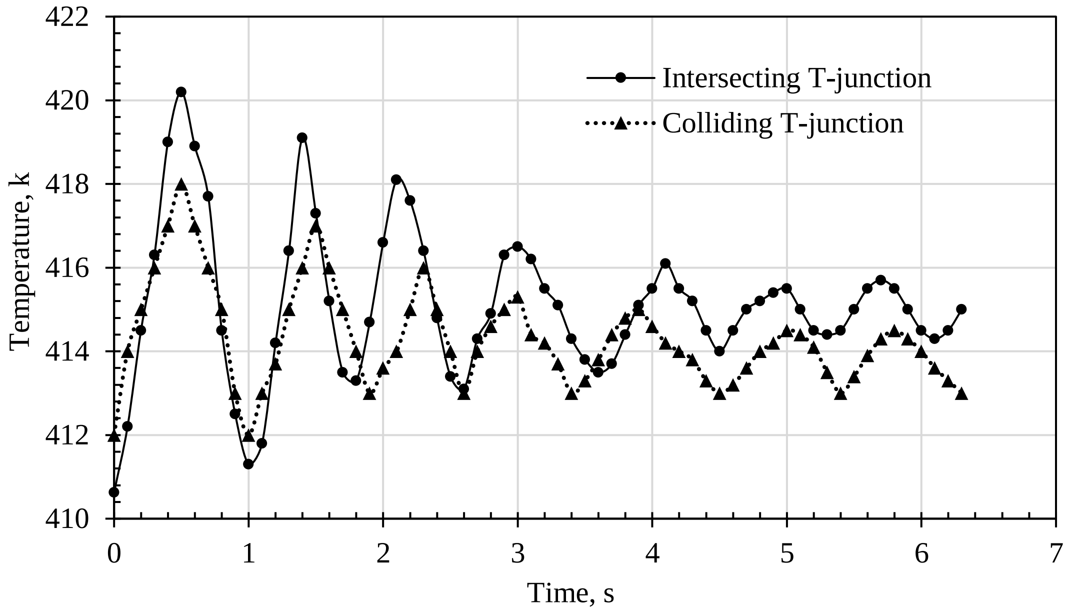


Figure 4.6: Temperature fluctuations at intersecting mixing tee at temperature ratio 0.087 and mass flow rate ratio 1.6.

Magnitude of temperature fluctuations have been calculated using "Fourier Analysis" in Microsoft excel. Figure 4.7 shows magnitude of temperature fluctuations at mixing outlet for different time steps with their frequency. For both flow configurations the pick value of magnitude is found within 2Hz. But for intersecting higher pick value of magnitude is found than colliding mixing tee.

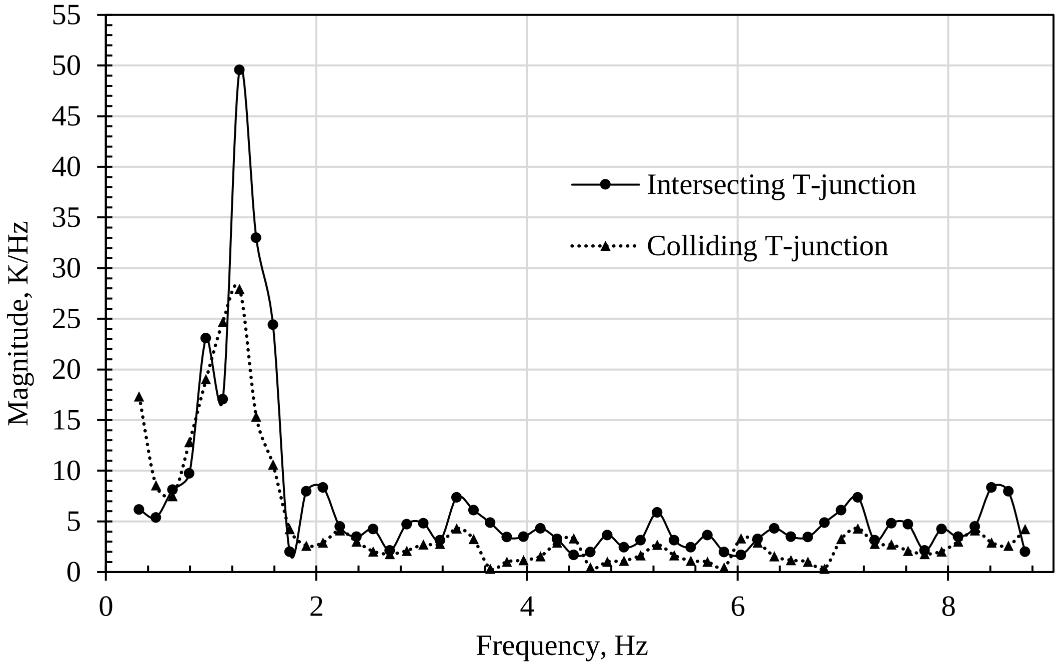


Figure 4.7: Magnitude of temperature fluctuations with frequency at intersecting mixing tee at temperature ratio 0.087 and mass flow rate ratio 1.6.

4.3 Thermal Mixing Efficiency

Thermal mixing performance or thermal mixing efficiency can be expressed by Temperature Mixing Degree, TMD, defined as [29, 54]:

$$\mathrm{TMD} = 1 - \frac{\Delta T_{\max}}{\Delta T_{in}} \quad (4.1)$$

where, ΔT_{max} is the maximum temperature difference at any desired cross-section and ΔT_{in} is the inlet temperature difference between hot and cold fluids. TMD is a dimensionless parameter that can be expressed by fraction or percentage. The value of TMD equal to 1 indicates complete mixing or 100% thermal mixing efficiency when there is no temperature difference of fluids in the mixing regions. In that case, the temperature distribution is uniform, no fluctuation of temperature is found. TMD = 0 refers to no temperature mixing of the fluid.

4.3.1 Thermal Mixing Efficiency at Different Locations

Figure 4.8 shows the temperature mixing degree or thermal mixing efficiency at different planes along the mixing outlet of both intersecting and colliding mixing tee. It shows that TMD increases gradually from 0d to 5d for both T-junctions. After 5d to 6d, the increase in TMD is less, not much significant but still increasing slowly. For same inlet boundary conditions, at 6d plane, the TMD is found around 59% for intersecting tee and it is about 68% for colliding tee which is higher than intersecting tee.

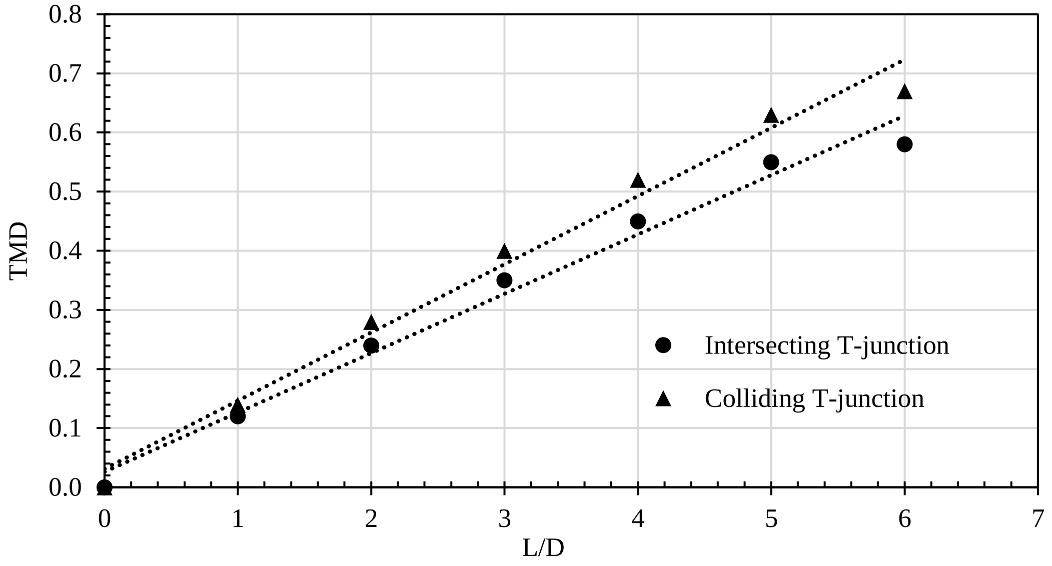


Figure 4.8: TMD at different planes along mixing outlet at temperature ratio 0.087 and mass flow rate ratio 1.6.

4.3.2 Thermal Mixing Efficiency at Different Time-steps

As transient simulations have been done for this current study to observe thermal mixing performance at different time steps from initial time 0 second, TMD is shown in Figure 4.9 for different time steps at 6d plane along mixing outlet for both T-junctions. Result shows that TMD increases with a high magnitude from 0 to 5 seconds and after 5s the change in TMD is not much significant. After 10s, TMD for intersecting tee is 59% and 68% for colliding tee. So, colliding T-junction has higher efficiency than intersecting tee.

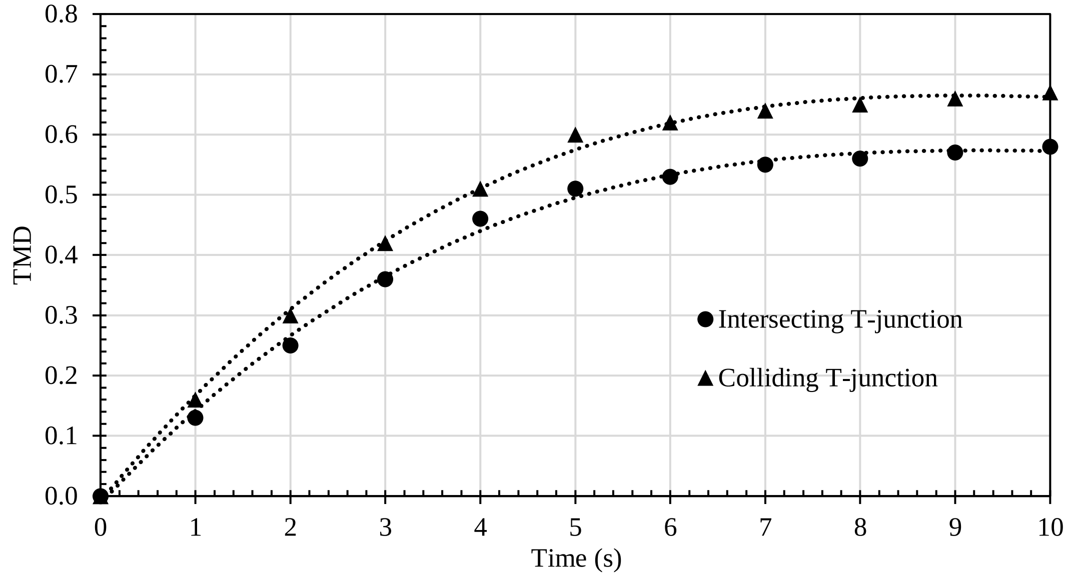


Figure 4.9: TMD at 6d plane along mixing outlet for different time steps at temperature ratio 0.087 and mass flow rate ratio 1.6.

4.4 Pressure and Velocity Distribution

Pressure distribution along the hot and cold inlet and mixing outlet is shown in Figure 4.10. It is found that at the inlet pressure is higher where the velocity is lower. At the mixing outlet pressure is much lower as the mixing fluids are passed out from the mixing region.

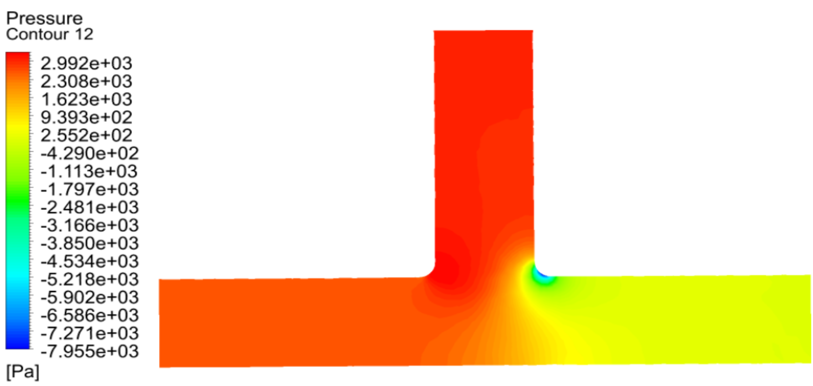


Figure 4.10: Pressure distribution at the T-junction for case 7

Velocity distribution inside the T-junction is shown in Figure 4.11. Main pipe inlet velocity is shown larger than branch pipe as the main pipe flowrate is larger. Maximum velocity is found at the mixing region as the fluids from two inlets are combined. Near the pipe wall, velocity is much lower because of kinetic friction and adhesive force between fluids and structure.

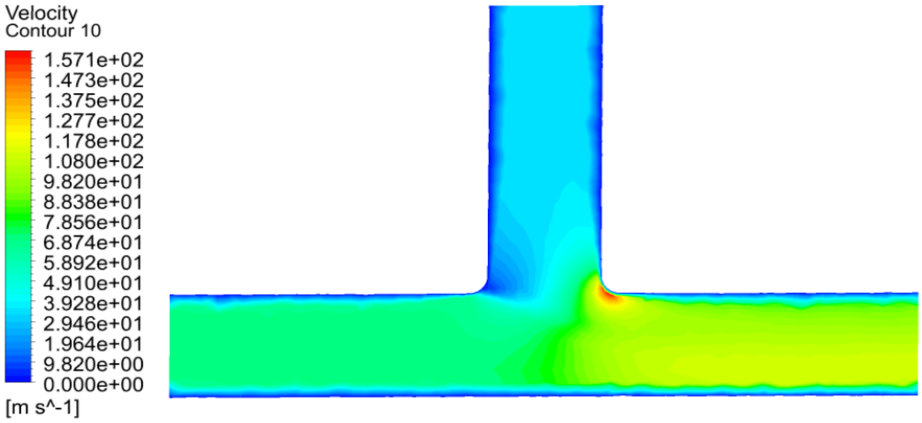


Figure 4.11: Velocity distribution at the T-junction case 7

4.5 Empirical Correlations

In this study two input parameters were inlet temperature ratio (Tr), and mass flow rate ratio (Mr). Thermal mixing efficiency was taken as output parameter. Altogether, two empirical correlations were developed for two different type T-junction.

The coefficient of determination "R^2" was used as the criteria check the accuracy of the prediction. The value of R^2 shows how accurate the prediction data points are from the actual numerical results. No transformation of the output response was required for these reported empirical correlations. General form of a polynomial is given below.

$$Y = A_0 + A_1X + A_2X^2 + \cdots + A_nX^n + \varepsilon \tag{4.1}$$

Here, Y, A_0, X, n and ε represents the predicted output, intercept, independent parameter, order of polynomial and relative error respectively. "A" refers the coefficient of estimate which measure the expected change in the output variable if the value of an independent variable is changed.

An empirical equation for prediction of thermal mixing efficiency for conventional intersecting T-junction is presented in Equation 4.2. the presented correlation is a reduced quadratic with all significant factor eliminated. Figure 4.12 shows the important factor related with the correlation for intersecting T-junction. The value of R^2 in this correlation is 0.99 which indicates a high accuracy.

$$TMDi = 0.579 - 0.484Tr - 0.340Mr + 0.363Tr^2 + 0.225Mr^2 \tag{4.2}$$

Coefficients | Coded Equation | Actual Equation

Final Equation in Terms of Actual Factors

TMDi	=
+0.579308	
-0.484488	* Tr
-0.340674	* Mr
+0.363249	* Tr²
+0.225111	* Mr²

Std. Dev.	0.0078	**R^2**	0.9959
Mean	0.4189	**Adjusted R^2**	0.9918
C.V. %	1.87	**Predicted R^2**	0.9791
		Adeq Precision	46.9104

Figure 4.12: Important factors for correlation for intersecting T-junction

Equation 4.3 represents the coded correlation for the prediction of thermal mixing efficiency for colliding T-junction. The correlation is also a reduced quadratic model. All the important factors are presented in Figure 4.13. the R2 value was found 0.9941 that refers 99% prediction accuracy of numerical results.

$$TMDc = 0.699 - 0.460Tr - 0.393Mr + 0.337Tr^2 + 0.254Mr^2 \tag{4.3}$$

Coefficients | Coded Equation | Actual Equation

Final Equation in Terms of Actual Factors

TMDc	=
+0.699573	
-0.460128	* Tr
-0.393742	* Mr
+0.337055	* Tr²
+0.253952	* Mr²

Std. Dev.	0.0097	**R^2**	0.9941
Mean	0.5278	**Adjusted R^2**	0.9882
C.V. %	1.84	**Predicted R^2**	0.9701
		Adeq Precision	39.1152

Figure 4.13: Important factors for correlation for colliding T-junction

4.6 Chapter Summary

This chapter provided all the results found from numerical prediction. Qualitative and quantitative analysis of thermal mixing of performance were described in this chapter. For qualitative analysis, temperature contours at different planes, locations and time steps were shown in figures with descriptions. For quantitative analysis, firstly, temperature fluctuations at different locations were presented in graphs and described. Later, Temperature Mixing Degree (TMD) which refer the thermal mixing performance or efficiency were found out and shown in figure at different locations and time steps. To provide clear guidelines for industrial application of T-junction, correlations were found out using Minitab software. These correlations can provide ideas to describe the effect of inlet temperature and mass flow rate ratio on thermal mixing efficiency.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

This chapter concludes the present research and recommends different research gaps and scopes for further study. Results obtained from this research are described briefly and summarised in conclusion part of this chapter. Later limitations of this present study and recommendations for future research has been discussed.

5.1 Conclusion

This research aimed to evaluate thermal mixing characteristics, mainly, thermal mixing performance or efficiency in T-junction. This was a comparative study to compare thermal mixing performance between two flow configurations in converging T-junction named as intersecting and colliding T-junction. Inlet temperature and mass flow rate ratios were taken into consideration as variable parameters since these two parameters have most influence on thermal mixing in a T-junction. Different inlet temperature and mass flow rate ratios were used for both T-junctions to compare the results for same boundary conditions. A design of experiment (DOE) was adopted for simulation combining inlet temperature ratios and mass flow rate ratios. For numerical prediction, transient simulations were performed using Ansys FLUENT 2020R1 software which is the most common CFD tool. K-ε turbulence model was used as turbulent model to solve transport equations. The selected turbulence model was validated with previous experimental and numerical work. Inlet temperature ratios 0.087, 0.34 and 0.59 were selected whereas inlet mass flow rate ratios were 0.24, 0.93 and 1.6. Total 9 combinations of temperature and mass flow rate ratios were chosen for numerical investigation to find out thermal mixing efficiency, temperature fluctuation and correlation.

Thermal mixing efficiency of both intersecting and colliding mixing tee was investigated at different boundary conditions, locations along mixing outlet, and time steps. Efficiency was compared and it was found that colliding mixing tee showed higher efficiency than intersecting mixing tee. In some cases, it was 13% higher than intersecting T-junction. At 6d plane, after 10s, thermal mixing efficiency for intersecting mixing tee was found 59% and 68% for colliding mixing tee. Colliding mixing T-junction showed higher efficiency than intersecting tee. So, the first objective of this research was fulfilled successfully.

The correlations among thermal mixing efficiency, inlet temperature and mass flow rate ratio were found out for both intersecting and colliding T-junctions. Thermal mixing efficiency was found increasing with the increase of cold and hot inlet temperature ratio. TMD and mass flowrate ratio between cold and hot inlet mass flowrate showed a quadratic relation. If the mass flow rate ratio is either higher or lower than 1, the thermal mixing efficiency stayed higher. So, the second objective of this research was also fulfilled successfully.

Temperature fluctuation along the mixing outlet was also observed for both T-junctions at different locations and time steps. It was found that Intersecting mixing tee had higher temperature fluctuation than colliding tee. The magnitude of temperature fluctuations was calculated using “Fast Fourier Transform (FFT)” and found that the peak value of magnitude for intersecting T-junction was higher than colliding tee at a lower frequency. Realizable k-ε turbulence model was validated successfully with previous experimental and numerical work as all the simulations for this study have been done using realizable k-ε turbulence model.

5.2 Recommendations

This research introduces comparison thermal mixing performance in different type T-junction to improve the thermal mixing efficiency. Followings are the future recommendations for research in this field.

- This research was totally numerical study. In future, fabrication of the setup for this research and experimentation can be done.

- Inclination angle between branch and main pipe has effect on thermal mixing performance. Experimental and numerical research using different inclination angles such as 30°, 45°, 60°, 120° etc. can be performed.

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LIST OF PULICATIONS

1. **Md Nuruzzaman**, William Pao, Faheem Ejaz, Hamdan Ya. (2021). "A preliminary numerical investigation of thermal mixing efficiency in T-junctions with different flow configurations". *International Journal of Heat and Technology*, Vol. 39, No. 5, pp. 1590-1600. https://doi.org/10.18280/ijht.390522
(Scopus Indexed)

2. **Md Nuruzzaman**, William Pao, Hamdan Ya, Md Ragibul Islam, Mohammad Ayub Adar, & Faheem Ejaz. (2021). "Simulation Analysis of Thermal Mixing Characteristics of Fluids Flowing Through a Converging T-junction". *CFD Letters*, *13*(9), 28–41. https://doi.org/10.37934/cfdl.13.9.2841
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3. Faheem Ejaz, William Pao, Mohammad Shakir Nasif, Ahmed Saieed, Zeeshan Q. Memon, and **Md Nuruzzaman**. "A review: Evolution of branching T-junction geometry in terms of diameter ratio, to improve phase separation." *Engineering Science and Technology, an International Journal* 24, no. 5 (2021): 1211-1223. https://doi.org/10.1016/j.jestch.2021.02.003
(Scopus Indexed, Q1, IF: 4.36)

APPENDIX A

QUALITATIVE ANALYSIS

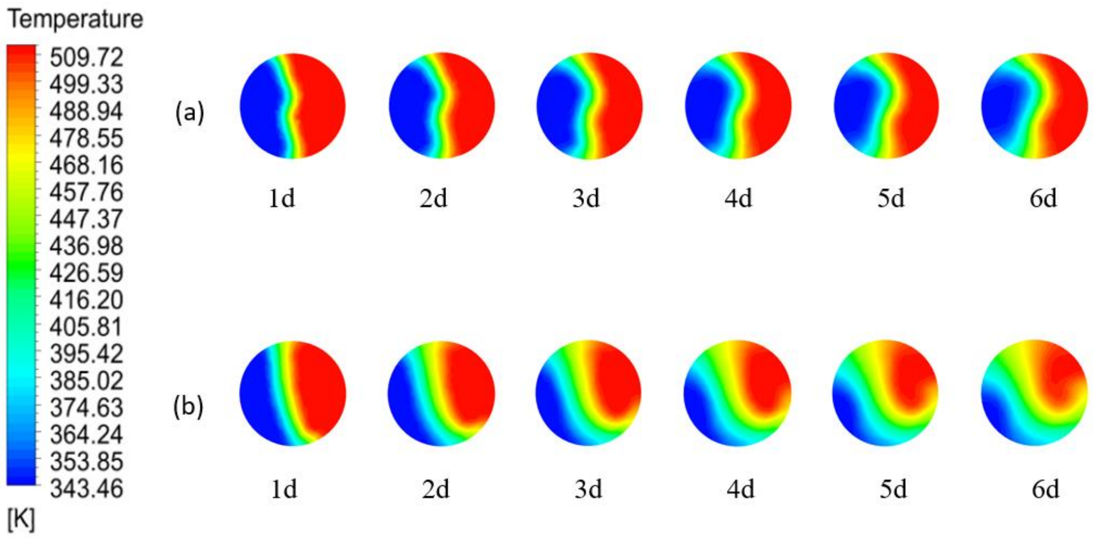

Figure A.5.1: Temperature contour at different planes for case 2

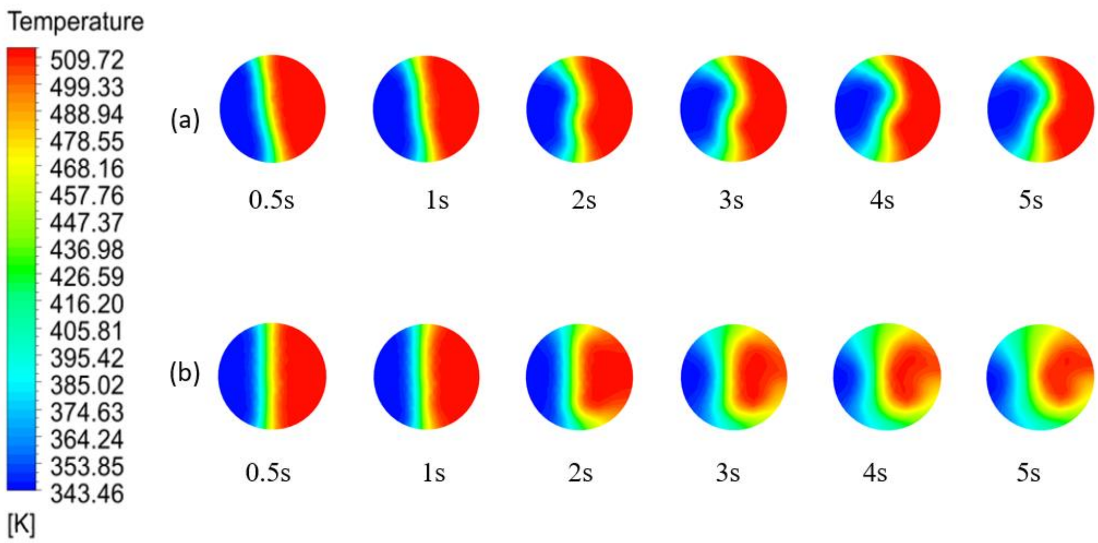

Figure A.5.2: Temperature contour at different timesteps for case 2

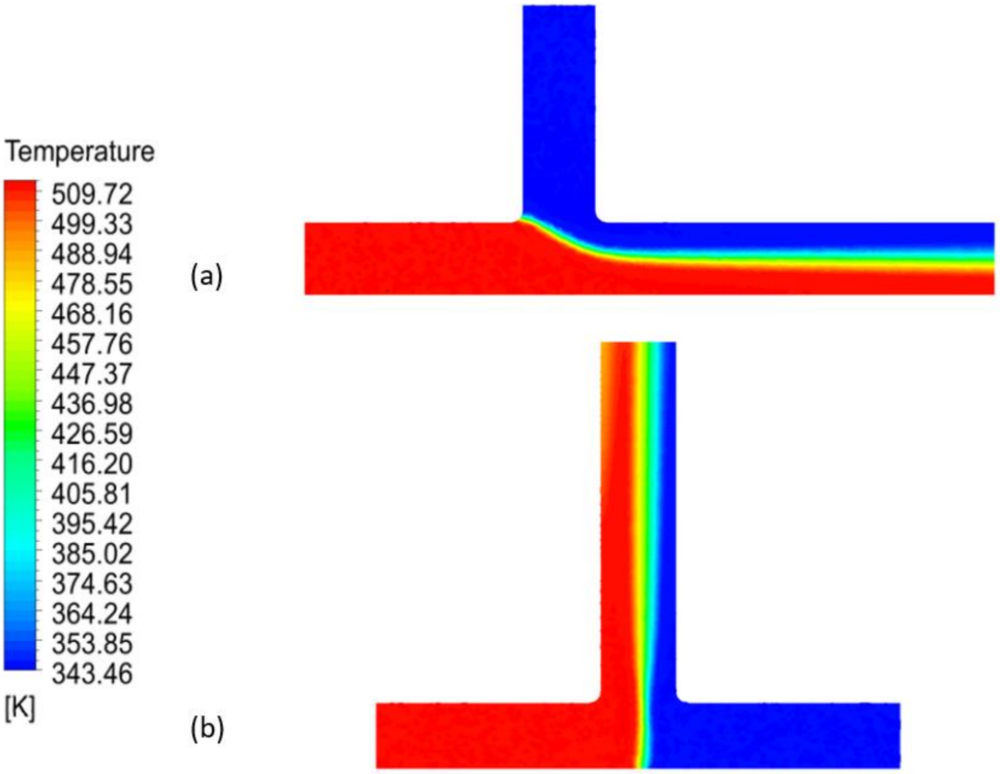

Figure A.5.3: Temperature contour at longitudinal planes for case 2

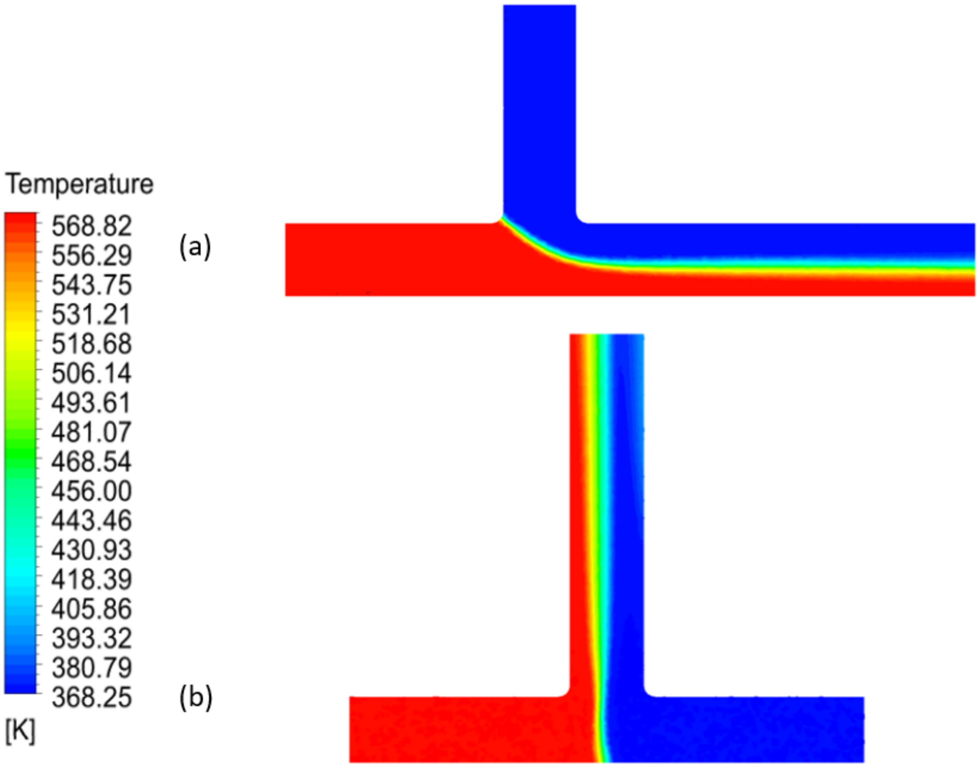

Figure A.5.4: Temperature contour at longitudinal planes for case 3

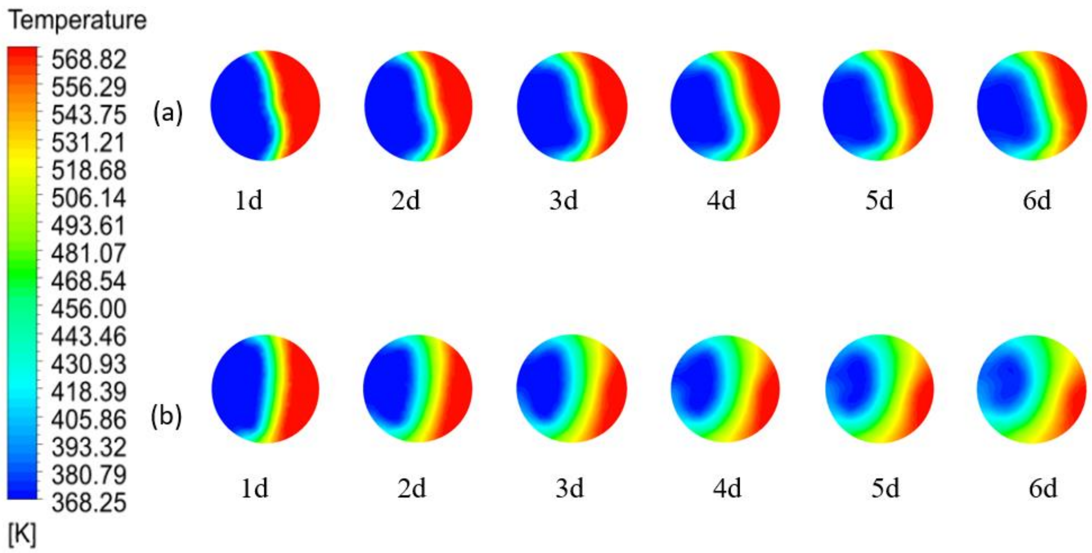

Figure A.5.5: Temperature contour at different planes for case 3

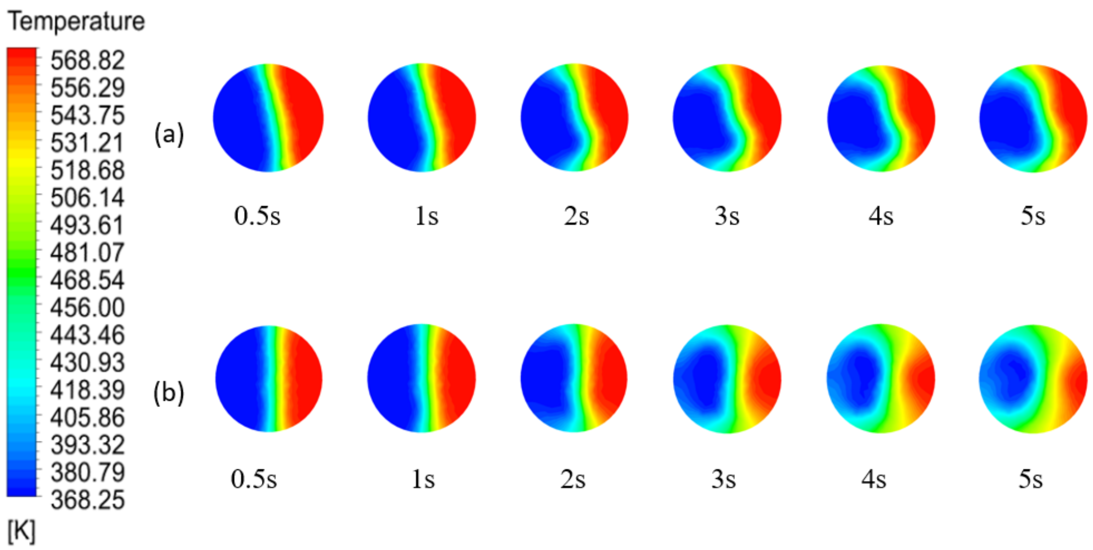

Figure A.5.6: Temperature contour at different timesteps for case 2

APPENDIX B

QUANTITIVE ANALYSIS

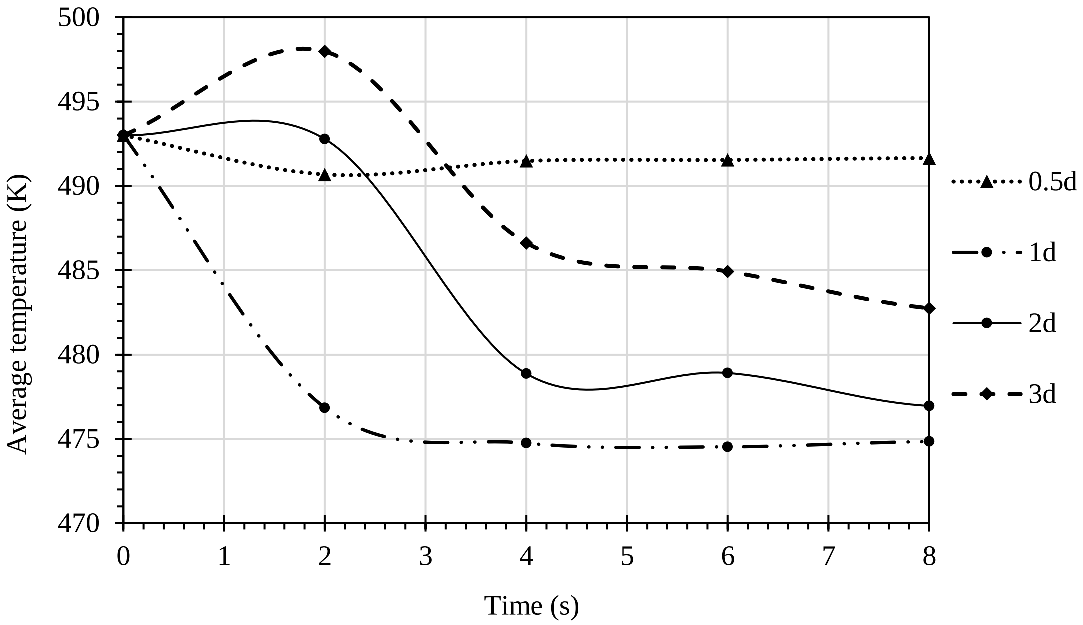

Figure B.1: Temperature distribution at the different cross-section for different time steps of intersecting tee for case 3

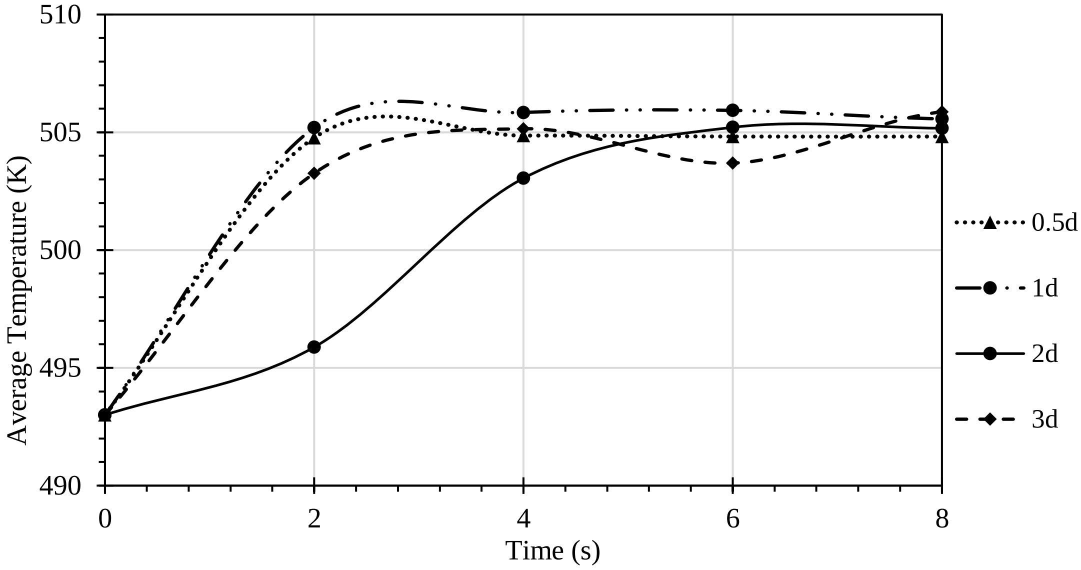

Figure B.2: Temperature distribution at the different cross-section for different time steps of colliding tee for case 3

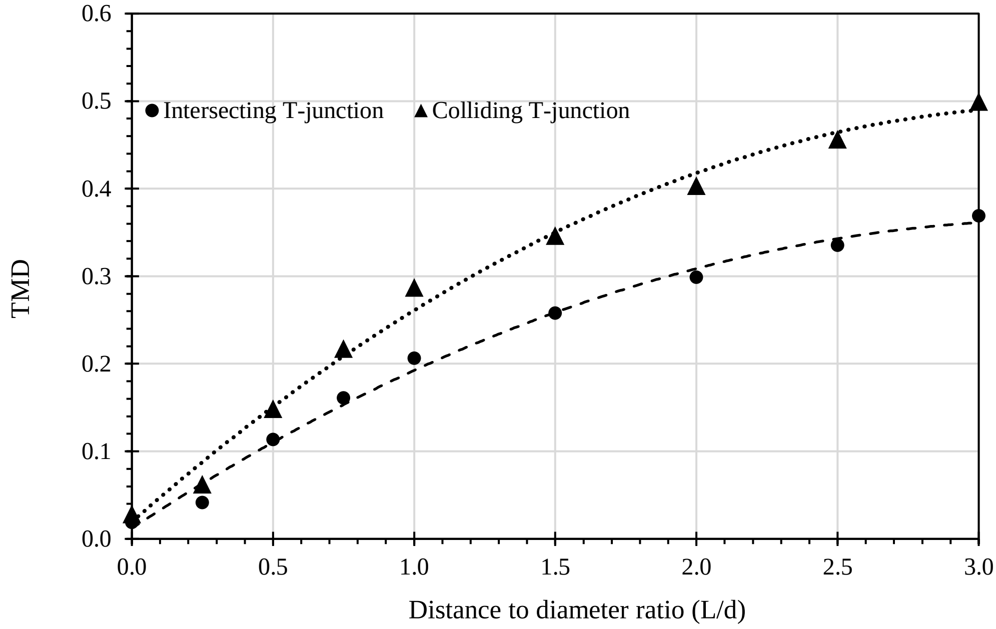

Figure B.3: Variation in TMD for intersecting and colliding mixing tees at various planes of different locations for case 3

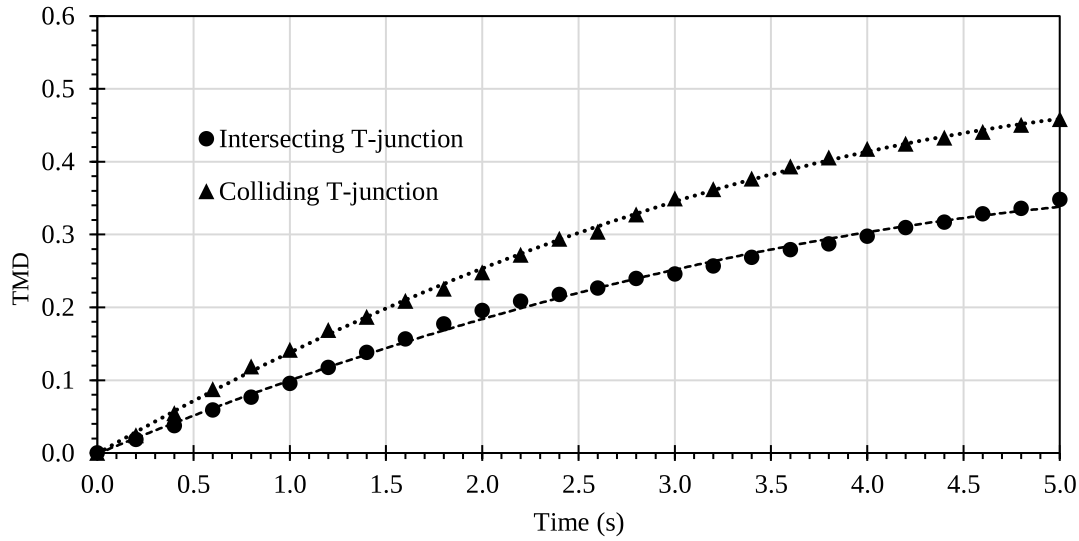

Figure B.4: Variation in TMD for intersecting and colliding mixing tees at 3d plane for different time steps for case 3