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Simulation Analysis of Thermal Mixing Characteristics of Fluids Flowing Through a Converging T-junction

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ABSTRACT

Temperature fluctuation occurs while mixing of hot and cold fluids in a T-junction due to incomplete thermal mixing. This temperature fluctuation can produce thermal fatigue at the weld area of the T-junction. The present study aims to numerically investigate the thermal mixing characteristics of hot and cold fluids in a T-junction. The realizable k-ε turbulence model is used with natural gas as the working fluid. Temperature distribution, mixing quality, and intensity of temperature fluctuation are evaluated and compared along with the mixing outlet. The inlet temperature difference and branch to main pipe flowrate ratio have a direct influence on thermal mixing. The higher temperature difference can reduce the thermal mixing performance. Thermal mixing increases with the increase of branch to main pipe flowrate. The intensity of temperature fluctuation is found within a short distance from the intersecting point of the two inlets. With the increase of distance along with the mixing outlet, the frequency of temperature fluctuation decreases, and thermal mixing increases.

1. Introduction

T-junction is a significant component of pipe network which is mainly used for combining, dividing, and mixing fluid flowing through the pipeline. Mixing of hot and cold fluid can be found in the cooling system in nuclear power plants, production, and distribution of oils and gases, and many other industries [1,2].

When mixing of hot and cold fluid, temperature fluctuation occurred due to incomplete mixing of fluids. The rapid temperature fluctuation causes high cycle thermal fatigue or thermal stress at the mixing tee [3,4]. This thermal fatigue can eventually cause the failure of the pipelines such as leakage, crack, breakdown of the weld joint, leading to safety issues. A better thermal mixing performance is required to reduce the rapid temperature fluctuations in the mixing region of pipelines. If complete thermal mixing of two inlet fluids of different temperatures takes place at the shortest distance along

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the mixing region and shortest time, then the mixing temperature will be uniform and there will be less fluctuation of temperature [5,6].

Many experimental [7-9], numerical [10-13], and combinations of both [14-17] research have been conducted by many researchers all over the world to investigate the thermal mixing characteristics and mixing performance of T-junction. There are some identified factors such as T-junction's geometry, inclination angle between a branch and main pipe, diameter ratio, inlet temperature difference, velocity ratio, mass flow rate, etc. which have a direct influence on thermal mixing characteristics.

Zughbi *et al.,* [18] found that thermal mixing is achieved faster over a shorter mixing length for the inclination angles of the branch pipe 45° and 60° and slower mixing at 30° or 90° inclination angle of mixing tee. It is also found that for 45° and 60° inclination angles, the mean temperature becomes a straight line which means no fluctuation at the shortest distance along the centerline of the main pipe. Chuang and Ferng [19] found from their investigation that the mixing temperature is about uniform, very less temperature fluctuation for 45° mixing tee for both downward injection (DI) and the horizontal injection (HI), and the temperature fluctuation is many getters for 90° mixing tee than 45° tee.

Inlet temperature difference is a function of temperature fluctuation and thermal mixing quality. If the temperature difference is lower, the thermal mixing quality will be higher, and mixing performance decreases with the increase of inlet fluid temperature difference [7,20]. Chen *et al.,* [7] found that the influence of branch and main pipe inlet flow rate ratio on thermal mixing quality experimentally and concluded that if the flow rate ratio is getter than 0.16, then the thermal mixing quality will be good.

The thermal mixing performance is therefore proportional to the flow rate ratio [21-25]. Mixing quality increases with the increase of branch to main pipe velocity ratio [7]. If the velocity ratio is more than 13.6, then the mixing quality will be good. The pipe length required to achieve 95% mixing is a strong function of branch and main pipe inlet velocity ratio. The mixing length decreases with the increase of velocity ratio [18]. If the velocity ratio is higher, then reverse flow is observed which causes good thermal mixing and less temperature fluctuations [26]. The inlet velocity ratio also affects the mean temperature of the mixing fluid. If the branch and main pipe velocity ratio are higher, then the mean temperature will be lower [16,17,21]. The mean temperature decreases and the thermal mixing increases with the increase of the distance of the location from the intersecting point of the two inlets [10,27].

The intensity of temperature fluctuation is reduced with the increase of Reynolds number [28]. From the research of B. Kok *et al.,* [29], it is found that thermal mixing performance increases in the first half of the channel (x/L = 0 – 0.5) with an increase in Reynolds number and decreased in the second half (x/L = 0.5 – 1) of the channel with higher values of Reynolds number. The best mixing performance is found at Re = 200 near the exit of the fluid mixer.

Hoh *et al.,* [30] concluded that the mixing degree can be affected by the chosen time-step size significantly. They also attribute their result to the chosen mesh resolution. Recently, a new modified k-ε turbulence model had been studied by Pujowidodor *et al.,* [31] to predict compressible fluids flow in a converging-diverging supersonic nozzle and found that the expanded cross-sectional area affected the turbulence behavior and fluid properties. Heat transfer performance for steady one-directional and oscillatory flow conditions with and without vortex generators had been studied numerically by Lin *et al.,* [32]. They found that the use of a vortex generator enhanced the heat transfer for both one-directional and oscillatory flows, but the heat transfer behavior of both flow conditions is quite different.

For solving fluid flow problems numerically different turbulence models are used to solving different governing equations. Reynolds-Averaged Navier-Stokes (RANS) is the most common model and is used to simulate different fluid flow problems. The low Reynold number (LRN) k-ε turbulence model is more accurate than the standard k-ε turbulence model among all the RANS models [33].

Almost all the previous numerical and experimental research was conducted using water as a working fluid to evaluate thermal mixing characteristics in a T-junction. So, the temperature fluctuations and thermal mixing efficiency of natural gas having high temperature differences in a mixing tee are not known yet. The temperature fluctuations and thermal mixing efficiency of natural gas in a converging T-junction have been calculated where hot and cold natural gas were mixing. The findings of this research can provide industrial guidelines to reduce temperature fluctuations and high cycle thermal fatigue in mixing tee of the pipelines of different liquified natural gas (LNG) manufacturing industries like Malaysian Liquified Natural Gas (MLNG) TIGA plant located in Bintulu, Sarawak, Malaysia.

In the present study, thermal mixing characteristics of hot and cold fluids in a T-junction have been investigated numerically using a computational fluid dynamics (CFD) software called ANSYS FLUENT. The realizable k-ε turbulence model with standard wall functions and along with the Energy equation model was used for simulation. SIMPLE scheme pressure-velocity coupling method was used as solution methods. The effect of inlet temperature difference and mass flow rate ratio on temperature fluctuation has been observed. This study can provide industrial guidelines to observe and increase thermal mixing performance which can help to reduce temperature fluctuations and thermal fatigue. This study can help to prevent crack, leakage, and sudden accident in the pipelines.

2. Methodology

When hot and cold fluids combine in a mixing tee, thermal mixing and temperature fluctuation take place at the mixing region which later causes thermal fatigue, crack, or leakage. In this numerical study, thermal mixing efficiency at different time steps and different planes along the mixing outlet in a 90° T-junction has been calculated using Ansys FLUENT software. Temperature fluctuations at different locations also have been found out. The numerical simulation consisted of three main steps: namely pre-processing, solution procedures, and post-processing. The pre-processing included geometry modeling, mesh generation, boundaries/surfaces definition, mesh independence test, etc. The solution procedure included selecting appropriate CFD model, material, prescribing boundary conditions, solver, etc. In post-processing, calculated numerical solutions were extracted and subjected to further manipulation to obtain the desired outcome.

2.1 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 solved fluid flow problems numerically and run a simulation for data analysis.

2.1.1 Continuity equation

The continuity equation describes the transport of some quantities like fluid or gas. The continuity equation is sometimes referred to as conservation of mass. This equation is used for conservation of mass, which means the total mass of fluids entering through the two inlets will be the same as the total mass of fluid leaving from the mixing out. The equation explains how a fluid conserves mass in its motion. Many physical phenomena like energy, mass, momentum, natural quantities, and electric charge are conserved using the continuity equations. The continuity equation for compressible fluid flow is given below [34]

$$\boldsymbol{\nabla}.(\rho\vec{v}) = 0 \tag{1}$$

ρ = Density of the fluid, v = fluid velocity

2.1.2 Momentum equation

Momentum equations are also referred to as Navier-Stokes equations. The momentum equation is used to determine the resultant force exerted on the boundaries of a flow passage by a stream of flowing fluid as the flow changes its direction or the magnitude of velocity or both. The momentum equation for gas is given below [34]

$$\boldsymbol{\nabla}.(\rho\vec{v}\vec{v}) = -\boldsymbol{\nabla}p + \boldsymbol{\nabla}.(\mu^{*}\boldsymbol{\nabla}\vec{v}) \tag{2}$$

where, μ^{*}= effective viscosity = $\mu + \mu_t$

2.1.3 Energy equation model

This equation is used for the conservation of energy. The application of steady flow energy equation can be used to study the performance of many engineering devices such as boiler, turbine, compressor, throttling process, nozzle, condenser, etc. that undergo thermodynamic processes, as these devices closely satisfy the conditions for steady flow processes. The conservation of energy equation is given below

$$\boldsymbol{\nabla}.\left(\rho c_p\vec{v}T\right) = \boldsymbol{\nabla}.(\lambda^{*}\boldsymbol{\nabla}T) \tag{3}$$

λ^{*} = effective conductivity= $\lambda + \lambda_t$
μ_t and λ_t are the turbulence-induced viscosity and conductivity respectively.

2.2 T-Junction Geometry

For this computational fluid dynamics study, a simple convergent 90° T-junction of the same diameter has been chosen. This T-junction is kept at a horizontal position so that the influence due to gravity can be neglected. Though it is connected to a long and complex piping system, a small portion is taken under consideration for a calculation to reduce difficulties and calculation time. In this mixing tee hot fluid enter with one end of the main pipe and cold fluid from the branch pipe. These two inlet fluids having temperature differences are mixed thermally and heat is transferred from hot to cold fluid. After mixing, the mixer gas leaves through another end of the main pipe called outlet. The schematic and 3D design of the mixing tee and its parameters are given in Figure 1.

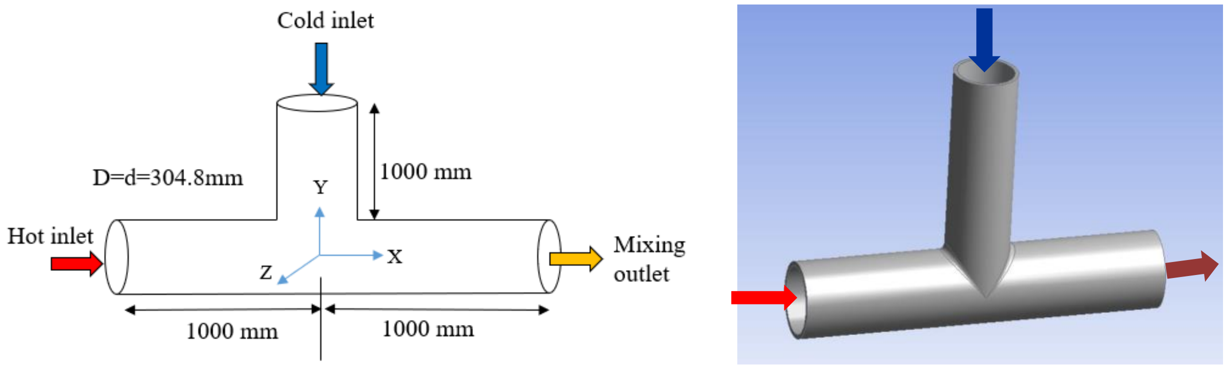


Fig. 1. T-junction geometry and its parameters

2.3 Mesh Generation

In this numerical study, the hexahedral mesh is generated for the T-junction geometry, and these meshes are distributed more uniformly throughout the whole mixing tee. A uniform distribution of mesh can produce more accurate results during numerical analysis. A fine mesh that is used for this study is shown in Figure 2.

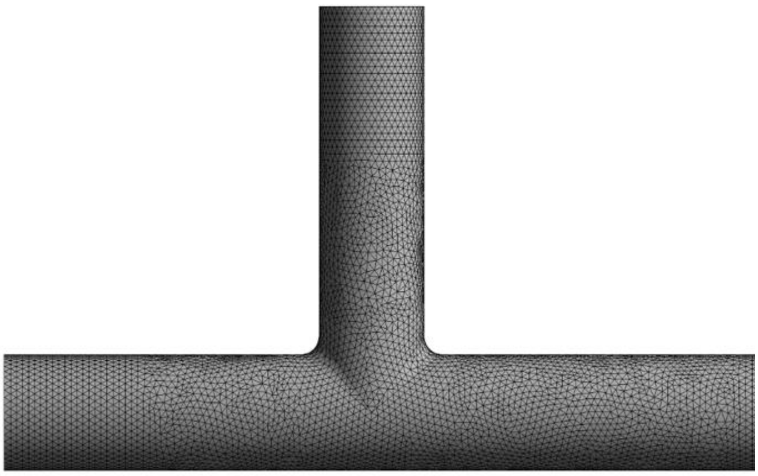


Fig. 2. Front view of the generated mesh

2.4 Mesh Convergence Test

The mesh convergence test or mesh independency test is an important prerequisite for any numerical analysis. This exercise is used to study the accuracy of numerical solutions in relation to the mesh degrees of freedom. For this study, 5 different cases with different element numbers are taken to check the mesh independence. Figure 3 shows the relationship between maximum element size, numbers of elements, and the mesh outlook in increasing order of mesh density.

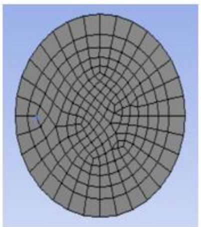
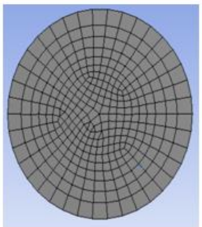
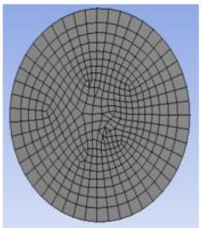
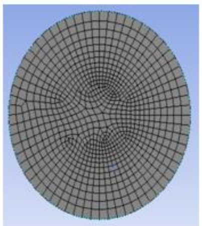
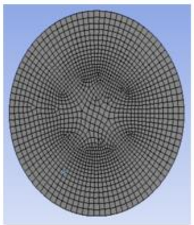
Mesh	1	2	3	4	5
Element Size (m)	0.03	0.025	0.02	0.015	0.01
Number of Elements	48428	75651	115739	272062	454805
Mesh Visualization on Outlet					

Fig. 3. Mesh generation and visualization for different mesh sizes

The average temperature at the mixing outlet has been collected to check the mesh dependency. In Figure 4, the value (1/*N*) x 10^{-6} has been plotted as X-axis where *N* is the total element number, and the outlet temperature has been plotted along Y-axis. From point 'a' to 'b' and 'b' to 'c', the change in average temperature is high which indicates coarse mesh. These coarse meshes are not acceptable for numerical calculation. The temperature difference is about 0.7 K between point 'c' and 'd'. As the temperature difference is not much high it represents intermediate mesh. This intermediate mesh is also not accepted due to less accuracy. From point 'd' to 'e' the temperature difference is very less, about 0.1 K. So, fine mesh is found at point 'd' for total element number 272062. But for more precise accuracy element number 458005 shown at point 'e' in Figure 4 is accepted for numerical analysis in this current study. Further increase of element number will not change the temperature difference much but it will increase a lot of computational time.

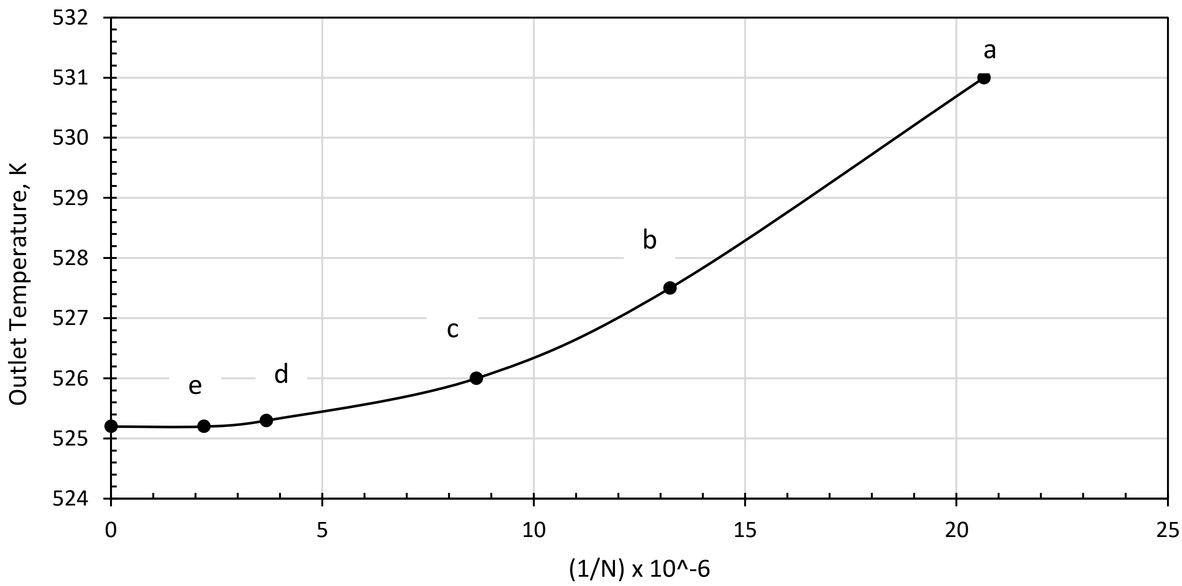


Fig. 4. Mesh convergence test

2.5 Boundary Conditions

Natural gas of 633 K temperature enters through the hot inlet of the T-junction shown in Figure 5 and cold gas of 294 K enters through the cold inlet. The hot and cold inlet mass flow rate is 3.33 and 1.67 K respectively. These boundary conditions along with fluid flow direction are shown in Figure 5. Transient simulation with no-slip boundary conditions has been done in this study.

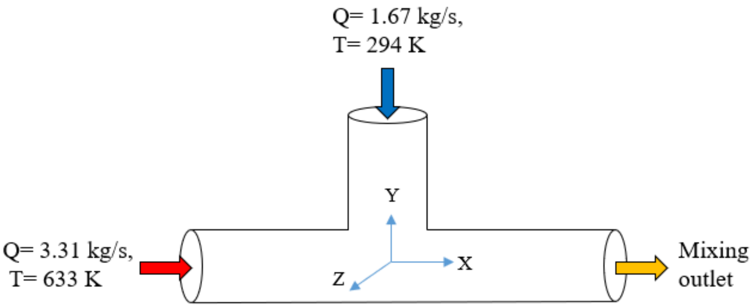


Fig. 5. Different inlet parameters for boundary conditions

2.6 Numerical Assumptions

A pressure-based solver was chosen for numerical prediction. No slip boundary condition was assumed at the inner wall of the solid and fluid contact surface. The process was considered as an isothermal process, heat transfer from solid structure to surrounding was neglected.

2.7 Thermophysical Properties of the Natural Gas

In this study natural gas at different temperatures has been used as a working fluid. This is a compressible flow and different fluid properties dependent on temperature. Different fluid properties, at low and high temperatures, are listed in Table 1.

Table 1
Fluid properties of natural gas

Property	At 21°C	At 320°C
Density	50.4 kg/m^3	20.9 kg/m^3
Viscosity	0.000013 Pa.S	0.00002 Pa.S
Specific heat	2.63 kJ/kg/K	3.22 kJ/kg/K
Thermal conductivity	0.031 W/m/K	0.081 W/m/K

3. Results and Discussion

3.1 Temperature Distribution

When the fluids from two inlets of different temperatures mix at the T-junction heat transfer from hot fluid to the cold fluid. Due to incomplete thermal mixing of fluid temperature fluctuations occur at the mixing region. Figure 6 showed the temperature distribution at the longitudinal plane of the T-junction. It shows that thermal mixing quality increases with the increase of mixing length along the outlet pipe. But still, a high temperature difference is found at the mixing outlet.

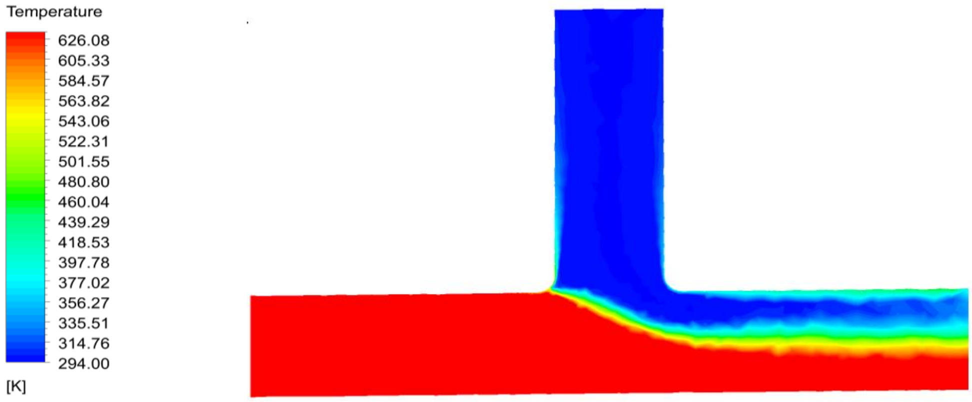


Fig. 6. Temperature contour at the T-junction

Figure 7 showed the locations of different planes at the mixing outlet. Here *d* is the diameter of the main pipe, and it equals 304.8 mm or 12 inches. These planes are used to show the cross-sectional view of temperature contour at the mixing region.

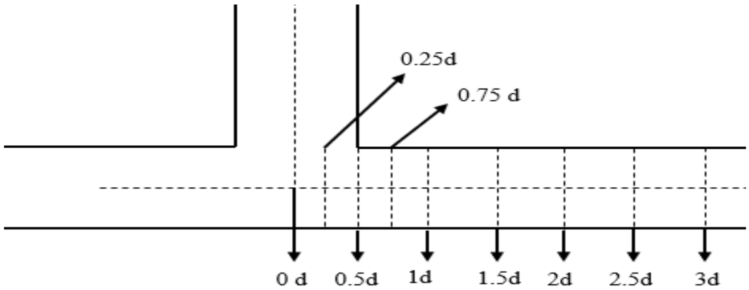


Fig. 7. Position of different planes for cross-section along with the mixing outlet

While passing through the mixing outlet, rapid collisions take place between hot and cold fluids. As a result, thermal mixing and heat transfer occurs. Figure 8 shows the cross-sectional view of temperature contour at different planes along with the outlet. In these sampling plans, temperature ranges from 294 K to 626 K. At the 0d plane, the temperature difference is maximum as the hot and cold stream just met. It can be observed in Figure 8 that thermal mixing is increasing with the increase of distance.

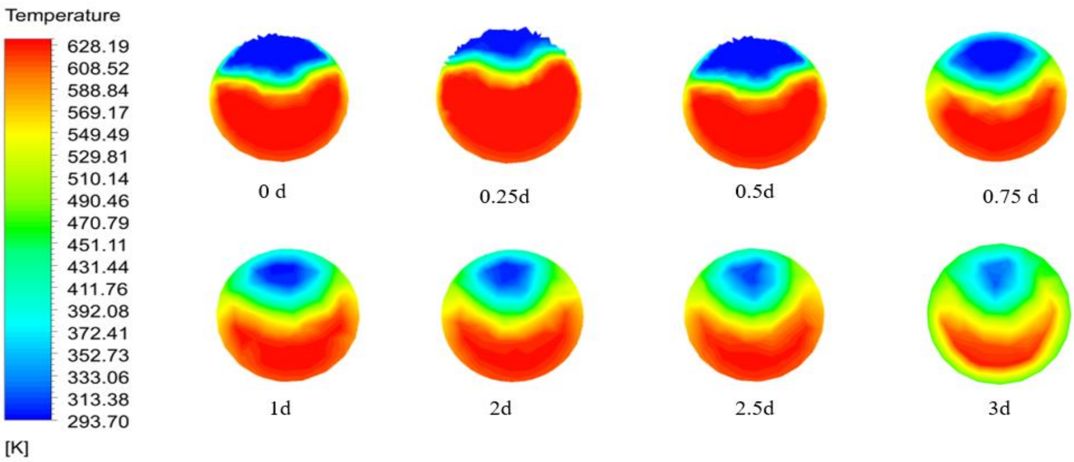


Fig. 8. Temperature contour cross-sectional view at different locations along with the mixing outlet

3.2 Temperature Fluctuations at Mixing Region

Temperature fluctuations mainly occur due to incomplete mixing fluids having a certain temperature difference. It was found from Figure 9 that at a short mixing length the intensity of temperature difference is high. Temperature fluctuation decreases with the increase of distance. Within 1d distance, the temperature difference is found maximum and with the increase of distance, the temperature difference decreases. After 2.5d, the fluctuation in temperature becomes less significant.

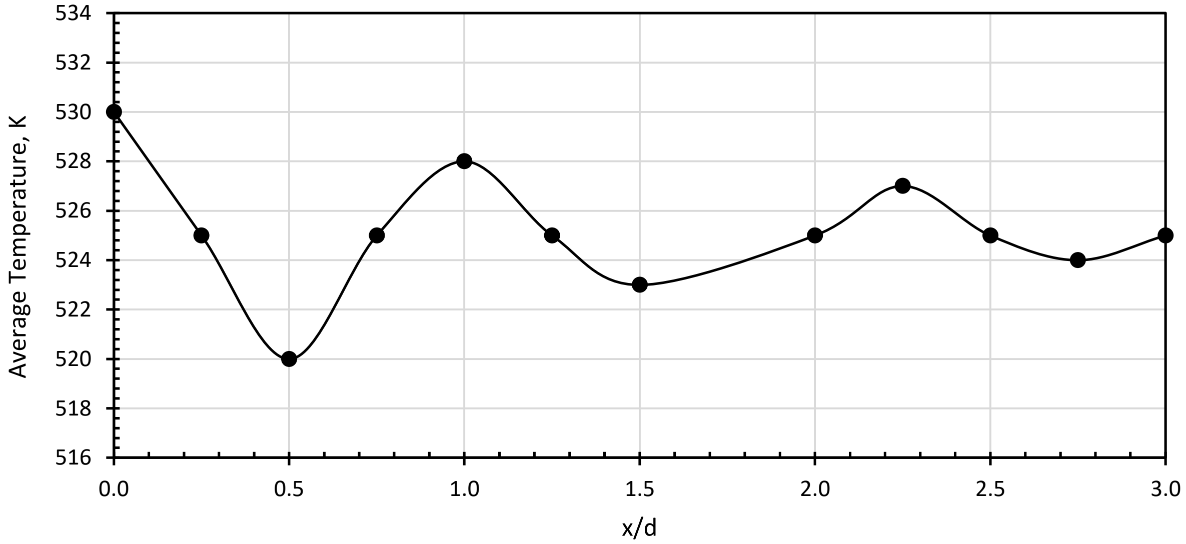


Fig. 9. Temperature distribution at different planes along the mixing region

3.3 Temperature Distribution at Different Timesteps

In this study, the thermal mixing has been simulated using the transient model. This can help to observe the change of thermal mixing characteristics with passing of time. Averaged temperature fluctuation at different time steps is shown in Figure 10. The curve showed high temperature fluctuation in the beginning, but the temperature oscillation died down quickly after 3 seconds. At the 5th-second, the average temperature becomes plateau indicating a state of equilibrium has been reached.

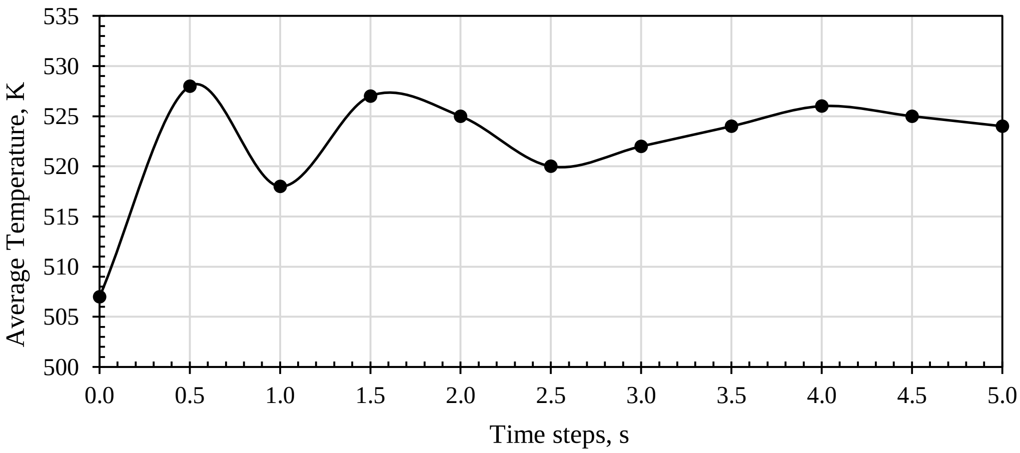


Fig. 10. Temperature distribution at different time steps

3.4 Thermal Mixing Performance

The thermal mixing performance of hot and cold fluids can be defined by Temperature Mixing Degree (TMD). This TMD can be expressed as [35],

$$TMD = 1 - \frac{\Delta T_{max}}{\Delta T_{in}} \tag{4}$$

where, ΔT_{max} is the maximum temperature difference at 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. TMD = 1 indicates complete mixing or 100% thermal mixing efficiency which indicates 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. In this study, the inlet fluid temperature difference is 339°C and ΔT_{max} is a variable that depends on the locations of different planes.

Thermal mixing performance at different planes along the mixing outlet is shown in Figure 11. Mixing efficiency is found very low near the mixing outlet. It increases with the increase of distance. At 3d, the mixing efficiency is around 50%. The high inlet temperature difference is the main cause for less TMD.

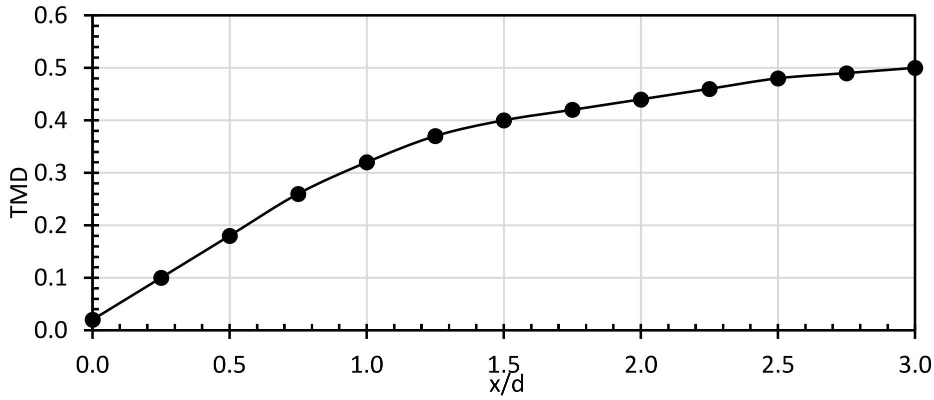


Fig. 11. Temperature mixing degree at different planes

Figure 12 showed the thermal mixing performance at different time steps. Mixing performance is low at the start. The temperature mixing degree increases with the passing of time. After 5s, about 50% efficiency is achieved and the change thereafter is insignificant.

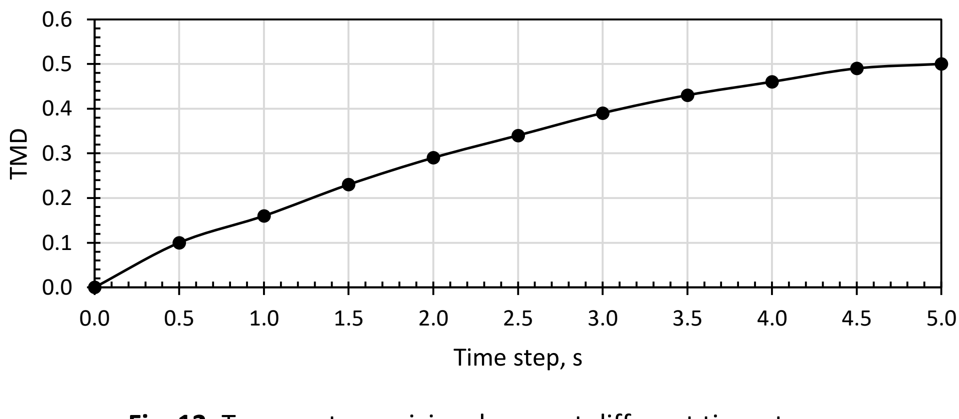


Fig. 12. Temperature mixing degree at different time steps

3.5 Velocity Distribution

Velocity distribution inside the T-junction is shown in Figure 13. 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 the adhesive force between fluids and structure.

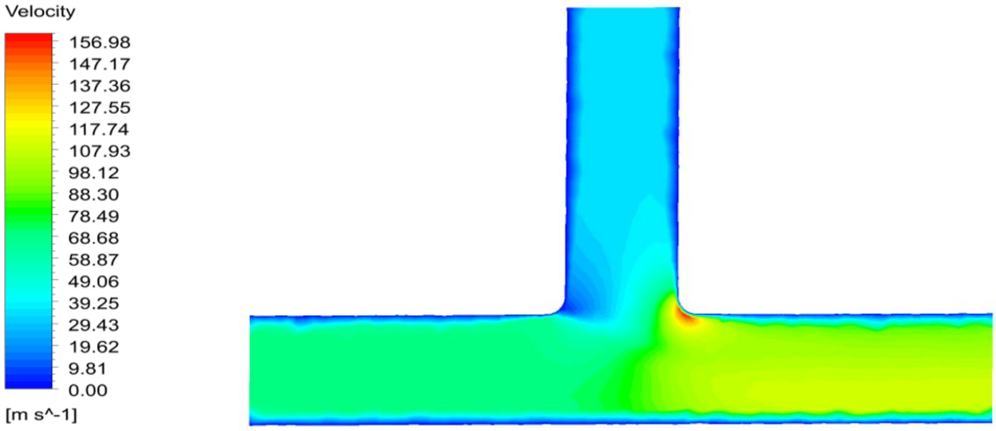


Fig. 13. Velocity contour at the T-junction

3.6 Pressure Distribution

Pressure distribution along the hot and cold inlet and mixing outlet is shown in Figure 14. It was found that 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. At the cold inlet of the branch pipe, the pressure was maximum and medium pressure was found at the hot inlet of the main pipe. The lowest pressure was found at the weld or fillet area between the cold inlet branch pipe and the mixing outlet. This area is also called the 'wake region'. The wake is the region of disturbed flow (often turbulent) downstream of a solid body moving through a fluid, caused by the flow of the fluid around the body. Consequently, the flow separates from the surface and creating a highly turbulent region behind the cylinder called the wake. The pressure inside the wake region remains low as the flow separates and a net pressure force (pressure drag) is produced.

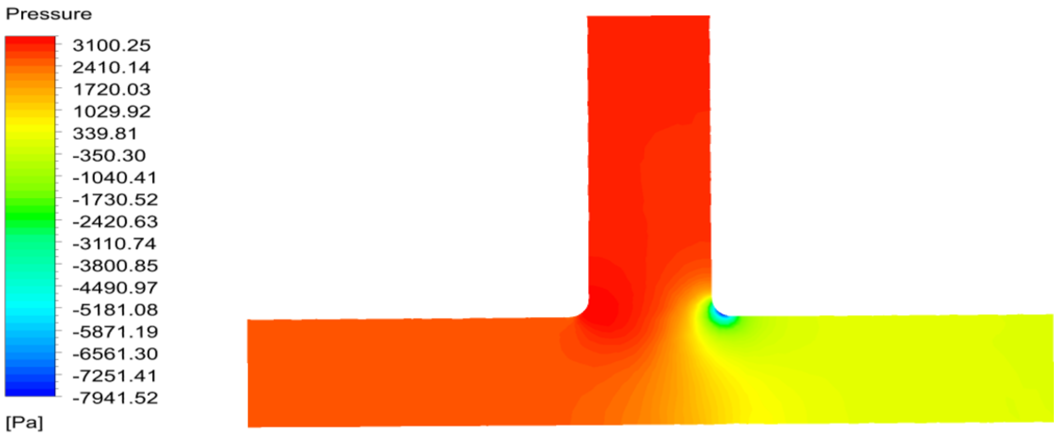


Fig. 14. Pressure contour at the T-junction

4. Conclusions

Thermal mixing characteristics at different positions along the mixing region in a T-junction have been investigated numerically in this study. Realizable k-ε turbulence model has been used for calculation. The summary of findings from this numerical study are given below

i. It is found from this study that high intensity of temperature fluctuation is found at a short distance as the thermal mixing just starts.
ii. Thermal mixing performance depends on mixing length and time. After 5s, at 2.75d, about 50% mixing is achieved.
iii. In this study, the inlet temperature difference was very high (339°C), so the thermal mixing process seems slow enough and the mixing performance is not high.

This study provides an idea about the thermal mixing characteristics of fluids in a T-junction. As the T-junction is in a horizontal position in this current study, the effect of gravity force has been neglected while doing simulation. In the future, thermal mixing characteristics can be investigated by using more variable parameters and a wide range of values of these parameters. Different turbulence models can also be used for conducting numerical calculations.

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