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Numerical Analysis Of Thermal Mixing In T-Junctions: A Comprehensive Exploration Of Flow Dynamics And Heat Transfer

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Abstract

This research utilizes two- and three-dimensional simulations to investigate the thermal mixing in a T-junction. Changes in the size of the inlet, the inclusion of two hot inlets, variations in inlet speeds, and a comparison of different turbulence models help to explain the notable impacts on temperature distribution and flow properties. Selecting the turbulence models and geometric features plays a role, in shaping the thermal performance. The research provides information, on how to improve T junction designs, for dynamics and heat transfer purposes, merging simulations seamlessly, with thorough graphical analysis.

Keywords: T-junction, Thermal Mixing, Computational Fluid Dynamics (CFD), Turbulent Flow, Heat Transfer, ANSYS

1. Introduction

In nuclear power plant cooling systems when fluids at varying temperatures blend it can lead to temperature fluctuations, events like the pipe crack at the Civaux facility have shown how High Cycle Thermal Fatigue (HCTF) can lead to damage [1]. Many studies have delved into this matter. Adeosun and Lawals [2] study, on the mixing dynamics in microchannel T junctions, confirmed the significance of fluid dynamics (CFD), in system design. Zughbi et al. [3] validated their temperature and velocity predictions through mixing experiments. Msaad et al. [4] conducted a study, on mixing in rotating mixers highlighting the impact of rotation speeds, on heat dissipation. Cao et al. [5] studied the temperature variances in triple jet setups observing a frequency of temperature fluctuations with differing amplitudes. Hosseini et al. [6] classified jets, in T junctions according to their velocity ratios. Lu et al. [7] investigated how temperature variances behave in mixing tees when porous materials are introduced emphasizing the decrease in gradients observed with the inclusion of mediums. Rhakasywi et al. [8] studied the heat dissipation abilities of jets hitting heat sinks showcasing their cooling performance. The combined research efforts improve our knowledge and fine-tune the mixing procedures to ensure the safety of nuclear power plants.

Hu and Kazimi et al. [9] showed a correlation, between the coolant temperature variances, in a T junction as simulated and as measured. Huang et al. [10] the effectiveness of impellers in minimizing temperature variations in T junctions was emphasized. Lin and Ferng [11] have studied that higher velocity in the main pipe diminishes backflow in a T-junction. Shao et al. [12] investigated that solute mixing dynamics in a T junction highly depend on momentum ratios between the branch and main pipe. Investigation of the effect on thermal mixing behavior in a T junction due to fluid momentum and rupture and fatigue occurring in a pipe due to mixing of hot and cold water is studied by Zhou et al. [13]. Sakowitz et al. [14] explored flow characteristics and mixing degrees in a T junction. Two researchers Wang and Mujumdar [15] worked on multi-set opposing jets and they found strong agreement between experimental and simulation estimates. Investigation has been done on flow and mixing in a T-junction. Above all these investigations will add to the knowledge of thermal mixing behavior in a T- junction, which is necessary for safe nuclear power plants, so that no fatigue or breaking in pipes occurs due to thermal fatigue and thermal fluctuations.

Evrim and Maurya et al. [16,17] inquired about the significance of Reynolds number (Re) in inlet flows. Frank et al. [18] investigated that the SST turbulence model is good for predicting turbulent flow. Many researchers worked on thermal mixing and flow dynamics in a T-junction which is important for analyzing high-cycle thermal fatigue (HCFT). Dahlberg et al. study [19] explored the working of T-junction in light water reactors and forecasting the anticipated temperature change that arises from turbulence in a T-junction. Three-dimensional turbulent flow analysis is very important for understanding high-cycle thermal fatigue (HCFT) in a T-junction using computational fluid dynamics (CFD).

Brückner [20] investigated cold and hot fluids mixing in a T-junction using particle image Velocimetry (PIV) and found an anti-parallel whirlwind in a horizontal rectangular T-junction. Kamide et al. [21] explored thermal mixing in a vertical T-junction configuration and investigated three different flow patterns in it. When fluids of different velocities and densities mixed together inside T-junction so it causes fluctuations and instabilities that results change in temperature near pipe wall [22]. Large-scale turbulence was found possible cause of temperature fluctuations which result in pipe cracking while small-scale turbulence has no such effect on pipe material. These highlight the need for the reduction of temperature fluctuations for safety purposes.

Smith et al. [23] used thermocouples to monitor temperature and Particle Image Velocimetry (PIV) and Laser Doppler Anemometry (LDA) to find velocities. It was noticed that thermal mixing inside the T-junction when the temperature difference between hot and cold fluids is 17k. Experiments were performed on the Vattenfall T-junction experiment [24–26] and it was concluded that the Reynolds-Averaged Navier-Stokes Equations (RANS) turbulence model is not able to predict realistic behavior inside the T-junction. On the other hand, large eddy simulation (LES) is able and has the power to predict precisely modeling velocity and temperature fields, even if the mesh is coarse grids and has a high Reynolds number.

2. Methodology

To generate geometry Space Claim and Design Modeler are used, which is necessary for simulations. In Space Claim sketching, meshing, and modeling can be done which is important for perfect design. While on the other hand, Design Modular allowed us to make 3D and 2D geometry in a methodological manner.

In research, branch pipe diameter, orientation around the main pipe, and velocity change in the branch pipe are the main geometric variables to examine thermal behavior in a T-junction. To find temperature distribution along the diameter of the main pipe of the T-junction, both 2D and 3D models are used. In 2D simulations, geometry is made as a reference for comparison with other 2D geometry. 2D geometry which was made as a reference has main and branch pipes. The main pipe has a length of 50cm and a diameter of 5cm while the branch pipe has a length of 15cm and a diameter is 2cm. Water is used as a working fluid with a velocity of

30m/s. Velocity is the same in both pipes. Changes have been made in these above specifications to compare it with the T-junction which was selected as a reference, such as changes in velocities of branch pipe, changes in diameters of branch pipe, installed two branch pipes, and changes in turbulence model. The 3D study had also been done to do comparison between rectangular and circular 3D T-junctions.

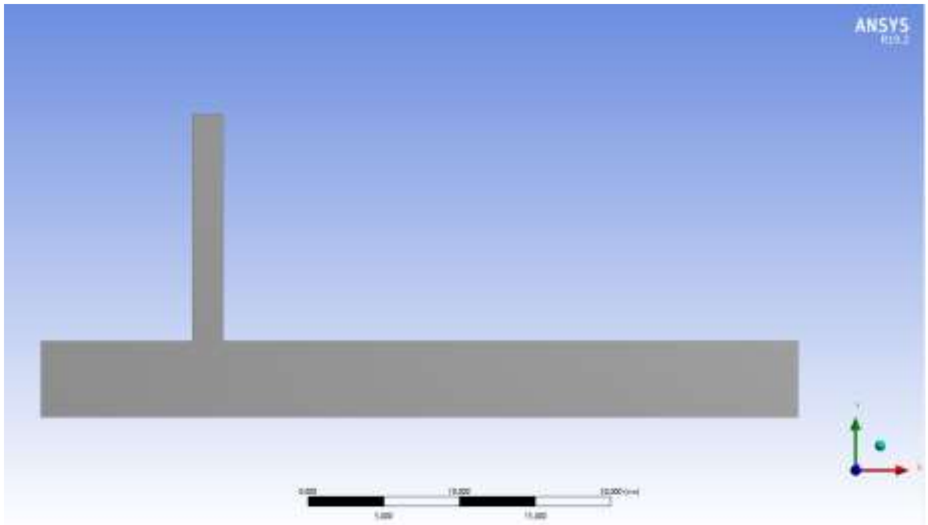

Figure 1: Geometry of basic T-junction (2D)

2.1 Numerical methodology and empirical formula

The study employs ANSYS Fluent 19.2 R1 for thermal mixing and flow dynamics at T-junctions, using the SIMPLE algorithm to resolve pressure-velocity coupling. The SST k-omega turbulence model is chosen for its accurate prediction of complex turbulent flows, including rotation, mixing behavior, separation, and recirculation under challenging conditions. Boundary conditions include adiabatic and no-slip conditions, with convective and diffusive fluxes combined using a second-order upwind approach. Convergence criteria for momentum and continuity equations are set at less than 10^-4, and for the energy equation, less than 10^-7, with an additional criterion based on residual decay trends. The governing equations for thermal mixing and fluid flow dynamics at steady state in the T-junction are specified [27].

For material transfer across T-junction, the equation used is the continuity equation as mentioned in the Ansys Fluent users guide v19.2 by Ansys. The turbulence models used are the k-omega and k-epsilon models mentioned in the v19.2 user guide by Ansys.

2.2 Grid Independence Analysis and Mesh Resolution Selection

Grid independence for a 2D T-junction was explored using mesh sizes from 1mm to 3mm to ensure result correctness and minimize mesh-related influence. The study maintained consistency despite varying mesh resolutions, with both main and branch pipes at a constant velocity of 30 m/s. Focus lay on fluid temperature and pipe diameter, particularly along a vertical line at 48cm along the main pipe. ANSYS Fluent simulations confirmed mesh independence, enabling reliable use of any selected mesh size. Consequently, a 2mm mesh size was chosen for continuity in the study.

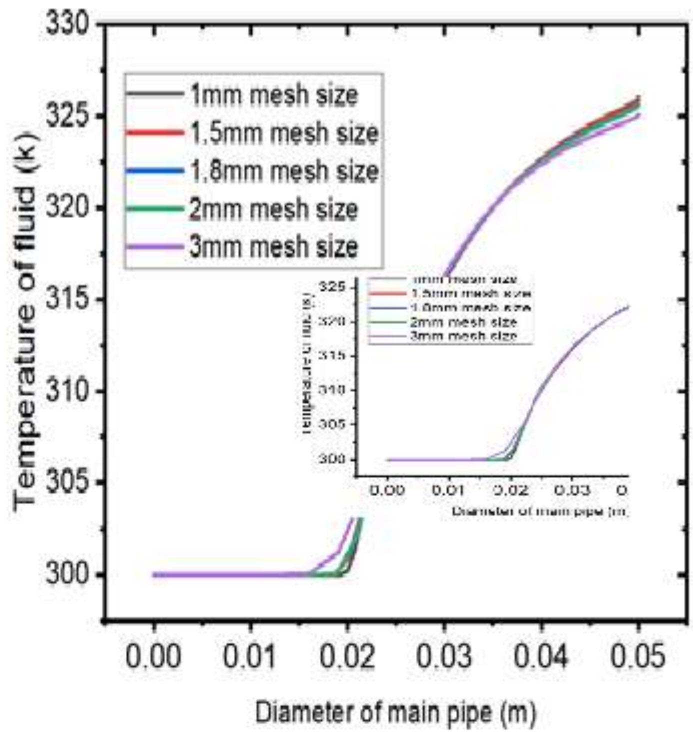

Figure 2: Graph for GIT

If the graph is fully examined in detail and if on horizontal axis at 0.02m the image is fully zoomed, all mesh sizes lines were closed except purple line (3mm). Remaining 4 lines were very closed so 2mm mesh size was selected because if 1mm, 1.5mm and 1.8mm mesh sizes were selected so it will take more simulation time as compared to 2mm mesh size and there will no effect on result because mesh size become independent.

3. Results and discussion

By studying the temperature and velocity data obtained from the thermal mixing process involving hot and cold fluids, this part explores the temperature and velocity distribution within the flow field. A comparative analysis is carried out to investigate the effects of Mass Ratio (Mr) on the T-junction's thermal mixing and flow properties. The Thermal Mixing Degree (TMD) metric is used to measure the degree of thermal mixing to thoroughly examine the impact of the mixing jet and flow rate ratio on thermal mixing and mixing length.

3.1 Exploring Turbulent Flow Dynamics: Differential Inlet Velocities and Temperature Distribution in T-Junction Cases

In T-junction analysis, with hot inlet velocity at 40 m/s and cold inlet at 30 m/s, the k-omega turbulence model illustrates diverse temperature and velocity contours, demonstrating the effects of varying inlet velocities (Figure 3). Higher velocity at the hot inlet expands temperature distribution due to enhanced turbulence, unlike equal velocities. When hot inlet velocity is reduced to 20 m/s while cold remains at 30 m/s, temperature distribution diminish (Figure 3). At 20 m/s, the main pipe's outlet temperature drops to 223.382 K compared to 325.975 K at 30 m/s, highlighting the sensitivity of temperature distribution to velocity changes. This analysis underscores the critical role of inlet velocities in system dynamics.
The comparison reveals the complex link between inlet velocities and temperature distribution in our T-junction study. Detailed contour plots and temperature graphs highlight the importance of variable inlet velocities for understanding thermal dynamics. Visualization illustrates how velocity adjustments affect temperature distribution.

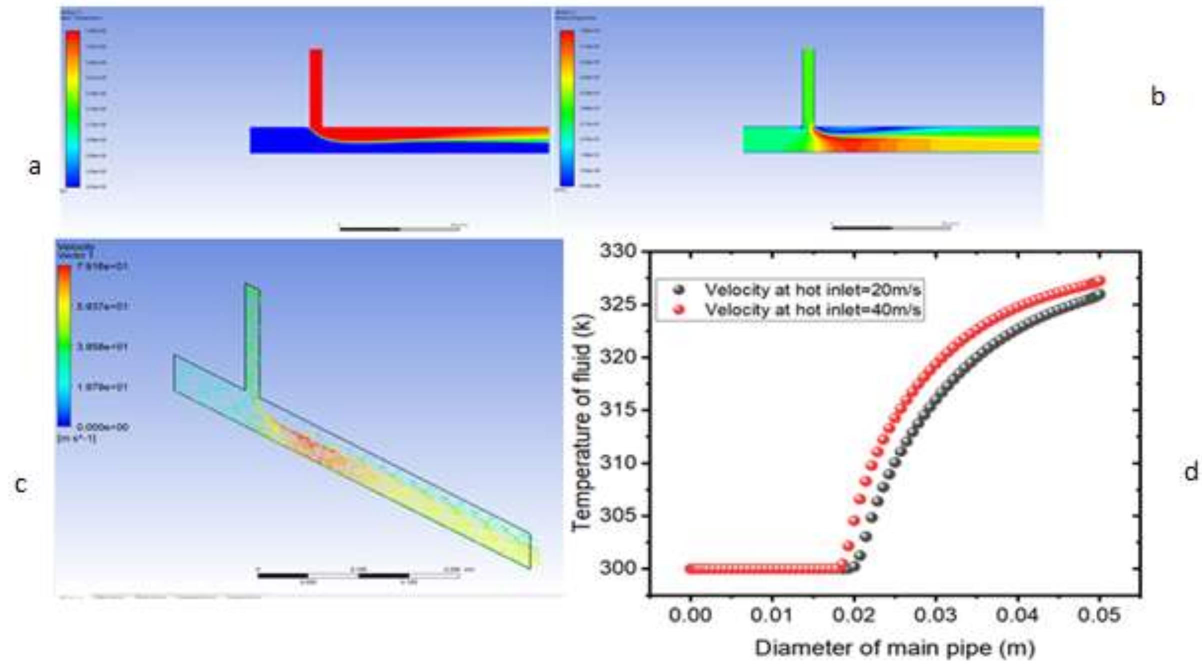

Figure 3: Results for case 1

a. Temperature Distribution contour
b. Velocity Distribution contour
c. Velocity Vector
d. Temperature Distribution graph

Figure 4: Results for case 2

a. Temperature Distribution contour
b. Velocity Distribution contour
c. Velocity Vector
d. Temperature Distribution graph

3.2 Exploring Thermal Effects: Impact of Hot Inlet Diameter Variation on Temperature Distribution in T-Junction Flow

In investigation, we've enlarged the hot inlet diameter from 2cm to 4cm while maintaining a steady velocity of 30m/s in both hot and cold inlets, aiming to analyze its impact on temperature distribution at the main pipe's outlet. Figure 4 depicts temperature and velocity contours, revealing notable changes due to the modification. The temperature distribution graph demonstrates a substantial rise along the main pipe's outlet vertical line with the increase in diameter, from 325.95 K to 329.797 K, attributed to improved mixing and heat transfer in larger diameter pipes. This exploration underscores the direct relationship between inlet diameter adjustments and temperature variations, emphasizing the significance of geometric parameters in shaping T-junction system thermal characteristics.

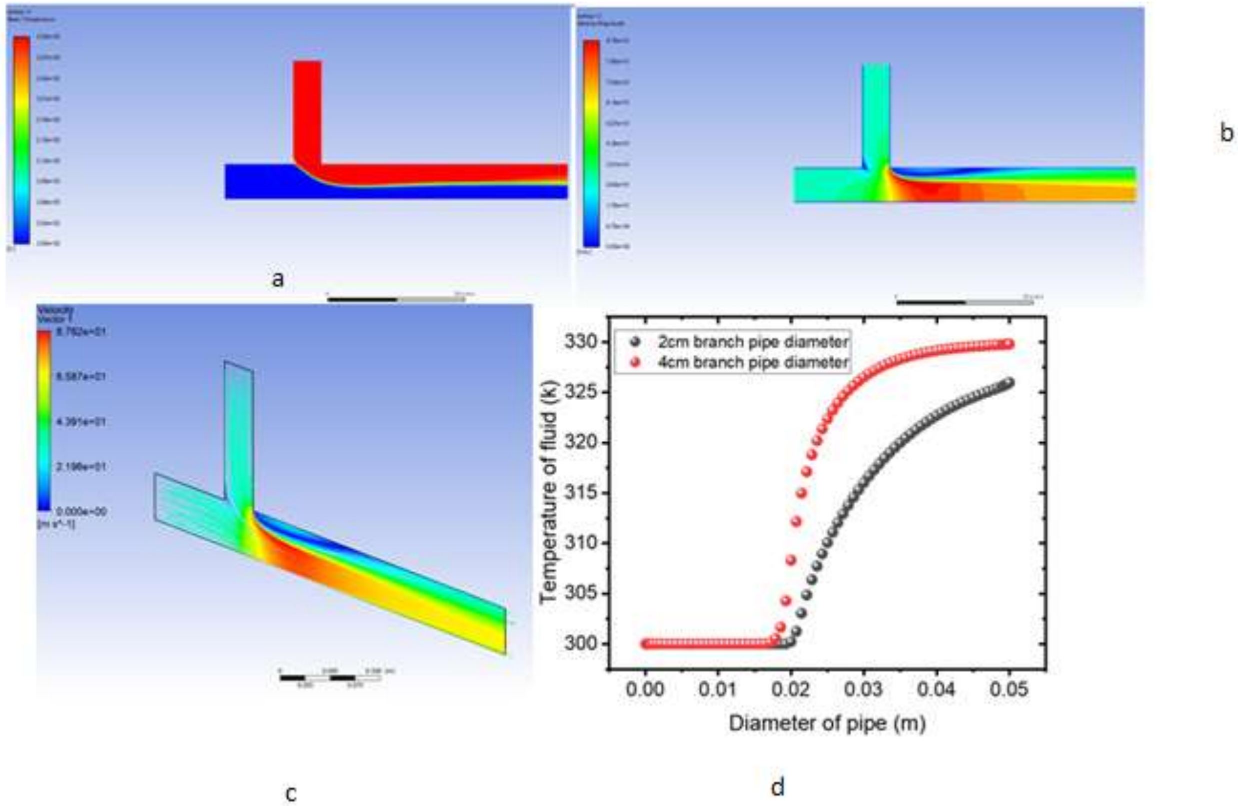

Figure 5: Results for case 3

a. Temperature Distribution contour
b. Velocity Distribution contour
c. Velocity Vector
d. Temperature Distribution graph

3.3 Enhancing Heat Transfer: Impact of Dual Hot Inlets on Temperature Distribution in T-Junction Flow

In study of heat transfer enhancement in T-junction flows, a critical adjustment involves installing two hot inlets, departing from the previous single inlet configuration. Figure 5 compare temperature and velocity contours, highlighting the distinctive characteristics introduced by dual hot inlets. The temperature distribution graph compellingly contrasts T-junctions with two hot inlets to those with a single inlet, showing a notable increase in outlet temperature from 325.975 K to 329.797 K with dual inlets. This enhancement stems from the augmented heat input, emphasizing the significant impact of dual hot inlets on temperature dynamics and the potential for improved heat transfer in our research endeavors.

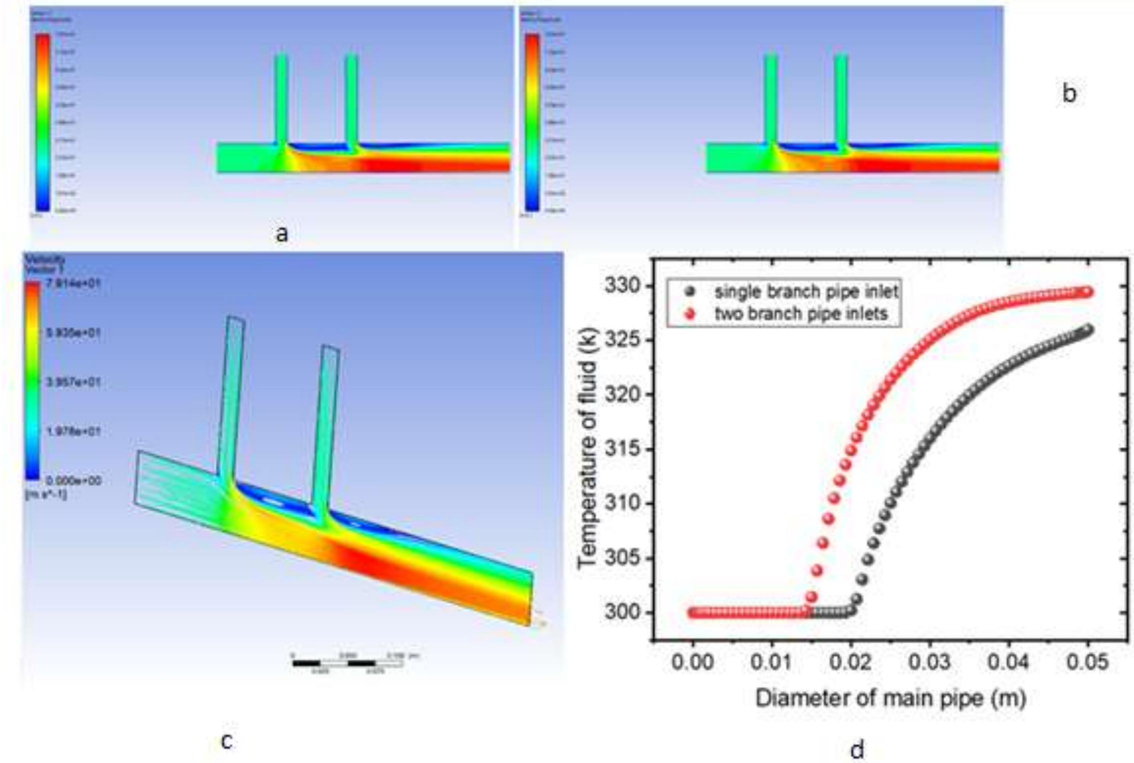

Figure 6: Results for case 4

a. Temperature Distribution contour
b. Velocity Distribution contour
c. Velocity Vector
d. Temperature Distribution graph

3.4 Unveiling Turbulence Dynamics: Comparative Analysis of Temperature Distribution with k-epsilon and k-omega Models in T-Junction Flow

In extensive examination of turbulence dynamics in T-junction flows, the fourth phase introduces a pivotal shift from the k-omega to the k-epsilon turbulence model. This deliberate alteration aims to unveil the impact on temperature distribution at the main pipe's outlet, specifically along the vertical direction within the T-junction configuration. Figure 6 visually capture temperature and velocity contours under the influence of the k-epsilon model, offering a comparative analysis with the k-omega model. The graph starkly reveals a more uniform temperature distribution with the k-omega model, emphasizing its effectiveness in capturing turbulence when hot and cold fluids mix in a T-junction. This observation underscores the significant role of the chosen turbulence model in shaping temperature dynamics, providing profound insights into the intricate behaviors of the system.

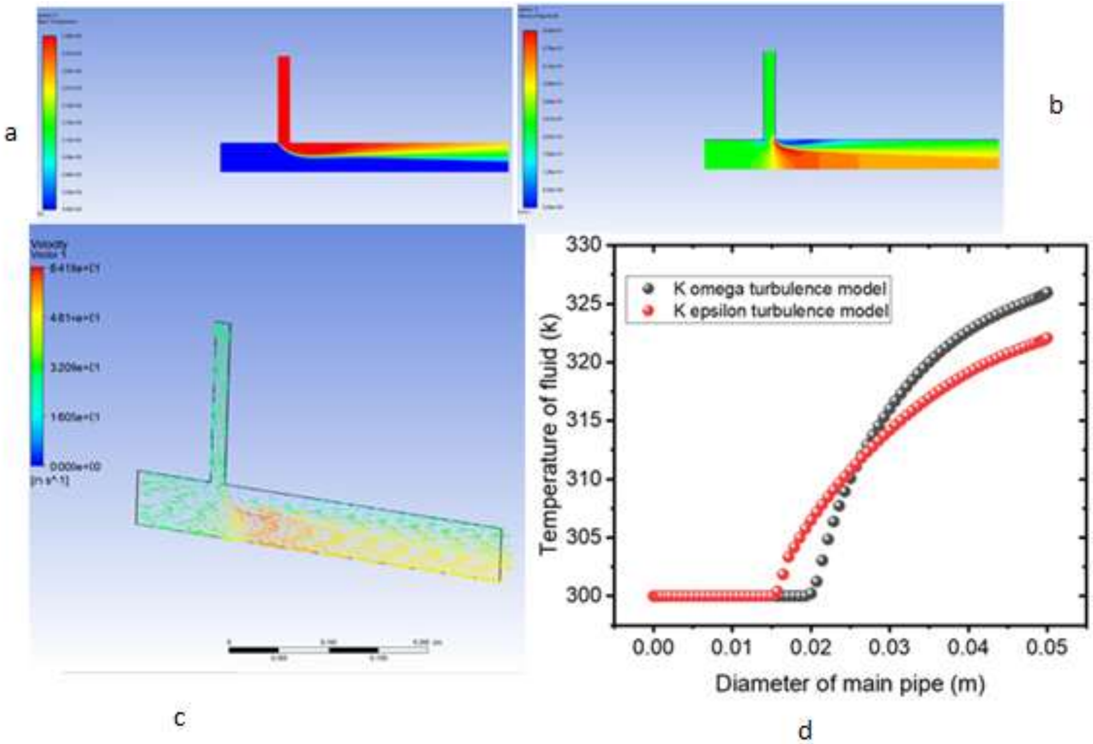

Figure 7: Results for case 5

a. Temperature Distribution contour
b. Velocity Distribution contour
c. Velocity Vector
d. Temperature Distribution graph

3.5 Dimensional Dynamics: Comparative Analysis of Circular and Rectangular T-Junctions for Temperature Distribution, Heat Transfer, and Fluid Mixing in 3D Configurations

3D exploration compares circular and rectangular T-junction configurations to unravel dimensional dynamics in temperature distribution, heat transfer, and fluid mixing. Identical analysis settings enable direct comparison of their properties. Figures 8 and 9 display temperature and velocity contours for the circular T-junction, facilitating comparison. Attention then shifts to the rectangular T-junction with Figure 10 illustrating temperature contours.

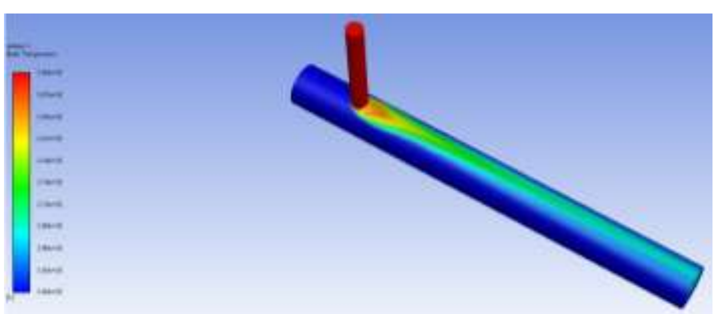

Figure 8: Temperature contour of circular T junction 3D analysis

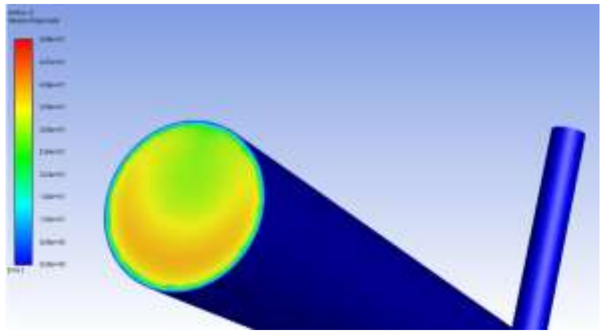

Figure 9: Velocity contour of the circular T junction

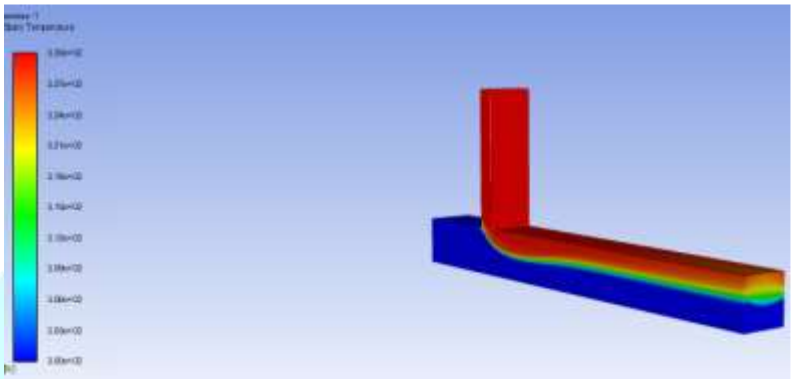

Figure 10: Temperature contour of basics (rectangular) T junction 3D analysis

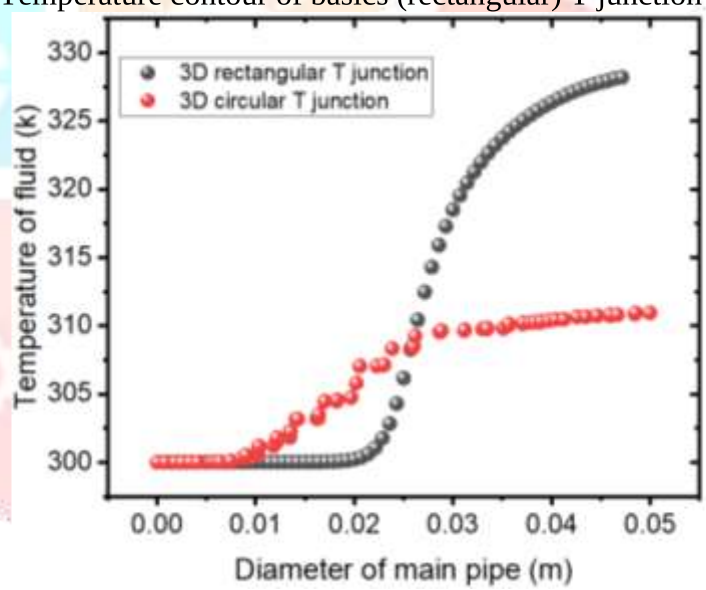

Figure 11: Temperature distributions for 3D rectangular and 3D circular T junction

4. Conclusion:

Research has delved into a multifaceted exploration of the intricate factors influencing thermal mixing within T-junctions. This comprehensive investigation provides a nuanced understanding that is imperative for the optimization of systems relying on such configurations. Temperature distribution is examined in different cases; when velocity in branch pipe is increase from 30m/s to 40 m/s, increased in temperature distribution in case of 40m/s has been noticed. In another case, when velocity has been decrease from 30m/s to 20m/s in branch, decrease in temperature along the diameter of main pipe has been examined. In 3rd case when branch pipe diameter changed from 2cm to 4cm we saw increase in temperature distribution because more fluid is allowed to through branch pipe. In 4th case when two branch pipes were installed so noticeably increase in temperature distribution had been examined. When k-omega turbulence model is used instead of k-epsilon turbulence so increase in temperature distribution has been noticed because k-omega model is best suited to capture turbulence flow. In case of 3D analysis, when circular and rectangular T-junction had been compared so we saw increase in temperature distribution in case of rectangular T-junction because rectangular T-junction offered large surface area as compared to circular T-junction and also rectangular T-junction encounters more abrupt changes and hence more turbulence in case of rectangular T-junction.

Finally, this work fill the gap between theoretical and practical findings that gives us new direction for research in future that will improve understanding of thermal mixing in a T-junction.

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