A NUMERICAL STUDY OF THERMAL MIXING IN BIFURCATED Y-SHAPED PIPES

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Thermal mixing is an important avenue of research in power plant engineering sector and finds widespread applications in the fields of nuclear engineering, evaporators and condensers, micro and Nanofluidics, engine dynamics and hemodynamics. The present study deals with the thermal mixing of hot and cold fluids in bifurcated Y- shaped pipes. Dependence of mixing on process parameters such as velocity ratio of the cold and hot inlet, the angle of bifurcation, and diameter ratio of pipes are the main highlights. Commercially available Fluent software is used to simulate and analyze the pipe shapes and configurations. Temperature profile at different cross-sections for different non-dimensional longitudinal lengths and pressure drop coefficient are taken as the decisive factors to determine the effectiveness of mixing. Results show that the effectiveness of mixing varies inversely with Diameter ratio and relative velocity of hot and cold fluids, whereas Pressure drop coefficient (Cp) varies directly with Diameter ratio and Angle of Bifurcation.

Keywords: - Y-pipes, Fluent, Angle of Bifurcation, Pressure Drop Coefficient, Velocity ratio

1. Introduction

Thermal mixing is an important phenomenon in the energy sector as it is the genesis of thermal stripping which primarily arises due to the amalgamation of hot and cold fluids near the piping walls of reactors. Thermal stripping causes damage to pipes in the power plant grid through temperature fluctuations and the occurrence of cyclic thermal stresses followed by fatigue cracking (Lee, I.J. et.al, 2009). Thus, from a reactor safety point of view, studying the implications of thermal leakage in a piping system is summed prioritate. So far, there has been a report of several leakage accidents eventuating in various light water and sodium-cooled reactors owing to thermal fatigue. In an incident of 1998, early onset degradation was reported in a reactor in Civaux, France, the reason being a crack developing in a mixing tee which was the confluence of hot and cold water flowing from a branched pipe into the main pipe in a residual heat removal (RHR) system. Studies conducted by Blondet and Faidy (2002) concluded that the crack was caused by an unwanted degree of cyclic thermal stresses. As the failure of the piping system in a nuclear reactor carries serious environmental hazard, more careful and stringent monitoring policies were implemented. The easiest way to implement these monitoring policies is to estimate the residual thermal stresses at various potential failure points due to the inner wall temperatures. But as the literature review of numerous cases suggests, it is fruitful to estimate the outer wall temperatures rather than inner temperatures for the sake of maintaining the integrity of the nuclear power plant. Guo et al. (2017) solved an IHCP to evaluate the damages incurred from thermal fatigue from estimated outer wall temperatures.

A T-junction is an indispensable part of a nuclear reactor and heavy damages may occur to it over time due to thermal and cyclic stresses. Thus, by carefully analyzing the thermal profile in a T-junction can help in mitigating damages to a great extent and also save huge investments in the process.

Erstwhile, many researchers have studied a fair share about T-junctions in efforts to mitigate the damages in case a failure of the staple system. Water tests were carried out by McFarland and Landy (2017) with three delineations of a T-junction, discussing the implications of transient and steady-state data for pressure and temperature profile of the fluid, and juxtaposing it with visual observations of the mixing processes. Their findings implicated that similar fluids show good mixing beyond L/D < 10 without incurring considerable pressure losses.

Maruyama et al. (1982) divested their resources into the experimental investigation of two fluids mixing at a T-joint. They developed several empirical correlations from their rigorous experimental procedures which are valid for a wide range of velocity ratios and pipe diameters. They also devised various analytical procedures for finding the optimum mixing conditions based on entrainment of fluid when mixed.

Maruyama et al. (1981) have also carried out experimental investigations into the mixing conditions for fluids as a function of branch angle and cross-referencing results with the cross-sectional temperature distribution in the main pipe. They also evaluated the experimental cases for optimal velocity ratio for a correlation between the degree of mixing and the jet angle. By solving the equations of the tee-joint, it was evident that the oblique branch should be at an angle of 450 with the main pipe for efficient rapid mixing.

Ogawa et al. (2005) have elucidated the influence of an upstream elbow on velocity and temperature distributions in a T-junction system. Particle Image Velocimetry (PIV) stringed with a movable system of thermostats was incorporated to obtain the experimental findings. Coupled with a near wall frequency analysis (1 mm from the inner side of the wall), the reports indicate that the elbow in the T-junction biases the velocity distribution and an unsteadily decaying secondary flow. The findings indicate that a vortex forming behind the branched pipe jet is the major source of temperature fluctuations. They concluded that the elbow case has a higher value of power density in the low-frequency region (f<1 Hz) as suggested by the power spectrum density (PSD) plots.

Kamaya and Nakamura (2011) evaluated the damages incurred due to thermal fatigue when cold fluid flowed into the main pipe by estimating transient temperatures.

Lee et al. (2009) obtained experimental data to validate the fluctuations in coolant temperatures and superimposed those to analyze the thermal fatigue with the aid of LES. According to their studies, it is evident that thermal fatigue is accelerated by the temperature contrast between the hot and cold fluids. Therefore, accurate analysis for mitigation of thermal fatigue can only be mitigated when instantaneous temperature estimations are obtained either through experimentation or devise numerical analysis.

Meanwhile, much research has been put into ways to minimize the effects of thermal fluctuations. Wu et al. (2003) conducted various experimental assays on a tee-joint modified with a sleeve tube fitted in it. Velocity ratio between the main pipe and the branched pipe is used as the parameter to create three types of jets. Evidently, the sleeve tube was an efficient mean to mitigate the thermal shock experienced by the tube due to a sudden injection of cold fluid.

Lu et al. (2010), have aided LES to estimate the thermal stripping phenomenon in a tee-joint with the periodic injection of a porous media. Like other accessory additions such as the sleeve tube (Wu et al. (2003)), the introduction of a porous media works wonderfully to eliminate the temperature and velocity fluctuations. Review of previous research pertinent to the topic provides a good benchmark for this work which uses a benchmark such as a porous medium to reduce the fluctuations in the system.

Over the years various official and freelance experiments were carried out around the world to validate the numerical results. The Organization for Economic Co-operation and Development(OECD) and Nuclear Energy Agency (NEA) developed a benchmark tee known as the Vattenfall tee-junction through a coordinated efforts in order to test the ability of state-of-the-art CFD codes to compare and contrast the decisive factors affecting the thermal fatigue in mixing tees (Smith et al. (2011)). The results obtained from the LES analysis of the benchmark model clearly indicated the superiority of LES over DES and RANS models.

Kimura et al. (2007) performed a sodium flow experiment, as a method to quantify the thermal stripping parameter in order to assess the integrity of nuclear reactors. The experiment was equipped with a parallel triple-jet configuration to ease up the process of analyzing the transfer of fluctuations to reactor structures.

Hosseini et al. (2008) performed experiments on a tee-joint with an upstream 900 bend replicating the operating conditions as in The Phoenix reactor in Arizona; A unique feature of their theoretical analysis included a constant convective heat transfer coefficient. Their study was evident that a 900 bend had a profound effect on the mixing phenomenon of fluid, also, the momentum ratio (MR) can be a decisive factor in minimizing the fluctuations in temperature and velocity near the piping walls.

Kamide et al. (2009) carried out experimental and numerical studies on water flow to analyze the thermal and hydraulic aspects of stripping in a vertical tee-joint with a straight pipe in the upstream direction. Three flow patterns emerged in the tee based on the momentum ratio between the main and branch pipes vis-a-vis wall jet, deflecting jet, and impinging jet. The division of jets into various types shows an increase in the precision of measurement and diversification the number of cases to be studied which increases the accuracy of obtained results.

Kimura et al. (2010) studied experimental methods involving horizontal mixing and the effects of the presence of an upstream elbow in the main pipe. Their studies revealed that the mixing tee-joint accessorized with an upstream elbow had a larger value of low-frequency component as compared to a straight tee-joint.

In the present study, the dependence of mixing on governing parameters like Reynolds Number, Angle of bifurcation and diameter ratio of pipes is carefully analyzed by obtaining temperature profiles and pressure drop coefficient at different Length-to-Diameter ratios (4 to 32) along the length of the pipe

2. Mathematical Modelling

A Y-shaped bifurcated pipe is used to demonstrate the mixing process using water as working fluid and at different temperatures. One branch of the Y-pipe is an inlet for cold water and another branch is an inlet for hot water, both branches having a length of 20D. The hot and cold streams are allowed to mix in a mixing tube of length 33D in the downstream direction. Two diameter ratios (1 and 2) are used to define the diameter relation of the two branches of the Y-pipe and three angles of bifurcation (600, 900, and 1200) are used to govern the shape of the pipe. A schematic diagram of the model is given in Fig. 1..

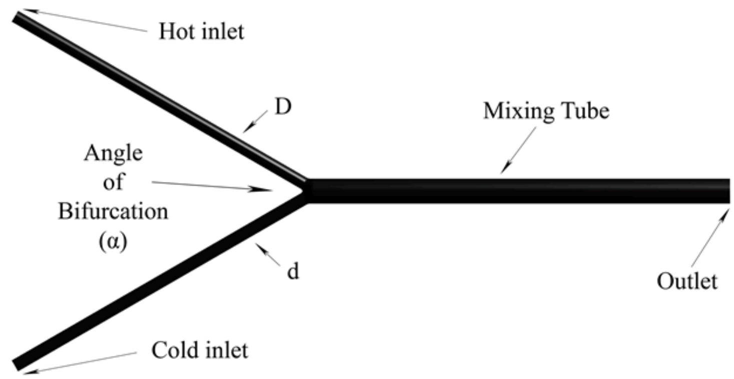


Figure.1. Schematic diagram of the pipe

The schematic used for analysis of the cases is a Y-shaped pipe with two inlets (hot and cold) and one outlet. The outlet diameter is greater than both the inlet stream diameters to allow proper mixing of fluids. All cases are simulated with combining set partial differential equations based on Reynolds Averaged Navier-Stokes (RANS) equation amalgamated with k-ε turbulence model in commercially viable Ansys Fluent (2009). The governing equations of continuity, momentum and energy for the 3-D Cartesian coordinate system are shown below

(a) Continuity Equation

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \vec{V}) = 0$$

(b) Momentum Equations

$$\rho \frac{Du}{Dt} = -\frac{\partial p}{\partial x} + \nabla.(\mu \nabla u)$$

$$\rho \frac{Dv}{Dt} = -\frac{\partial p}{\partial y} + \nabla.(\mu \nabla v)$$

$$\rho \frac{Dw}{Dt} = -\frac{\partial p}{\partial z} + \nabla.(\mu \nabla w)$$

(c) Energy Equations

$$\rho \frac{Di}{Dt} = \nabla.(k \nabla T) - p \nabla.(V) + \phi$$

The following Shear stress transport (SST) turbulence model is used in characterising the fluid flow.

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial}{\partial x_j}(\rho u_j k)=\frac{\partial}{\partial x_j}\,[(\mu+\mu_t/\sigma_k)\frac{\partial k}{\partial x_j}]+P_k-\beta^{'}\rho k\omega+P_{kb}$$

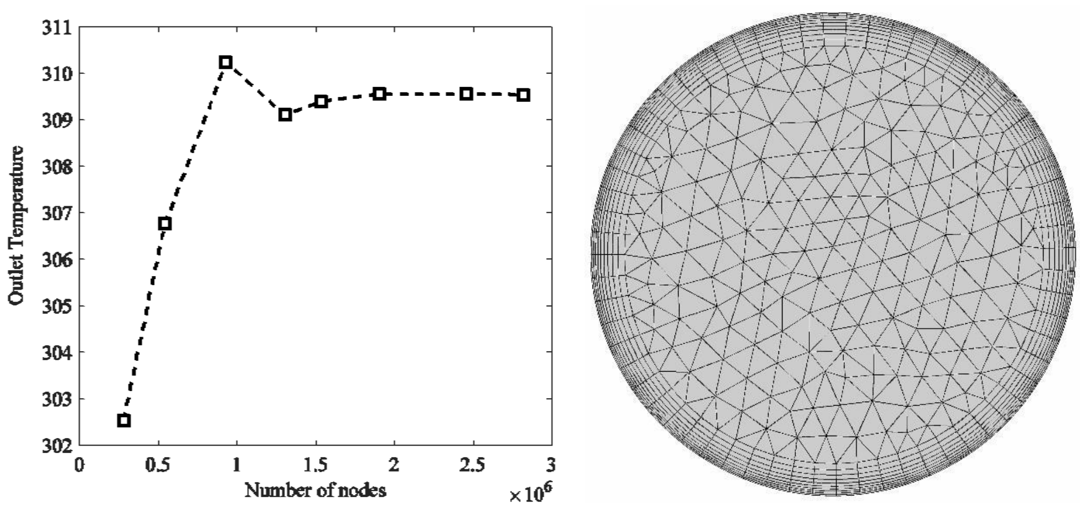
$$\frac{\partial(\rho\omega)}{\partial t}+\frac{\partial}{\partial x_j}(\rho u_j \omega)=\frac{\partial}{\partial x_j}[(\mu+\frac{\mu_t}{\sigma_k})\frac{\partial\omega}{\partial x_j}]+\alpha\frac{\omega}{k}P_k-\beta\rho\omega^2+P_{ab}$$

The coefficients used in the above SST equations are

$$\beta^{'}=0.09;\alpha=5/9;\beta=0.075;\sigma_k=2;\sigma_w=2$$

3. Numerical Analysis and Validation

Grid independence test is a viable method to validate mesh settings used for simulation and optimum results are obtained by using a mesh having an ideal number of nodes and elements. In the present work, grid independence was conducted on the Y-pipe having an angle of bifurcation of 1200, the diameter ratio of 2 and a velocity ratio of 0.5. The plot of outlet temperature with the increasing number of nodes is shown in Fig 2(a).



(a) (b)

Figure 2. (a) Plot of outlet temperature with the increasing number of nodes (b) Grid cross-section

To validate the grid, domain with the first case was solved for Ri = 1 with Ø = 3 %. The average Nusselt number (Nu) was plotted for various grid sizes. The average Nu showed a significant variation for mesh count varying from coarse to a refined one with 20,984 nodes. Nu showed a fluctuation less than 0.005% beyond 20,984 nodes which can be accepted. Fig.3. represents the variation of Average Nu versus the number of nodes after computational study.

The present numerical model is validated with the results of G.De Vahl Davis (1983) and Talebi et al. (2010) and the analysis showed satisfactory results with a good agreement which are shown in Fig.4.
K-ε turbulence model with enhanced wall treatment is employed to compute the turbulent mixing phenomenon occurring in the mixing tube. Water is used as the working fluid having a temperature of 293 K at the cold inlet and a temperature of 343 K at the hot inlet. The turbulent intensity is taken as 2% at both inlets and the hydraulic diameter is taken equal to the diameter of the pipe. The velocity ratio of hot inlet to the cold inlet is taken as a governing variable and five ratios vis-à-vis 0.5, 0.75, 1, 1.25, and 1.5 are used as velocity inlet boundary condition.
Simple solution scheme is adopted for obtaining a solution and setting the convergence criterion for continuity as 10-5. The solution is initialized using a standard initialization method and having a reference frame relative to cell zones.

4. Results and Discussions

Figure 3 and 4 represent the plot of the variation of Non-dimensional temperature (Θ) with Non-dimensional longitudinal length (χ) in the downstream direction for different diameter ratios (ψ) and velocity ratios (Φ) at an angle of bifurcation (α) 600 and 900 respectively. From figure 3 it is evidently clear that the value of Θ decreases at higher velocity ratios which is an important parameter governed by the mixing phenomenon. Dependence of Θ with diameter ratio also follows a similar trend as far as the plots are concerned. The increase in velocity ratio results in a higher relative velocity between hot and cold fluid. As the streams do not get ample amount of time to interact with each other, there is insufficient mixing resulting in a fall in Θ. Furthermore, the increase in diameter ratio allows a higher mass flow rate of cold fluid with respect to hot fluid, causing a decrease in bulk temperature of the fluid and subsequent fall in Θ.

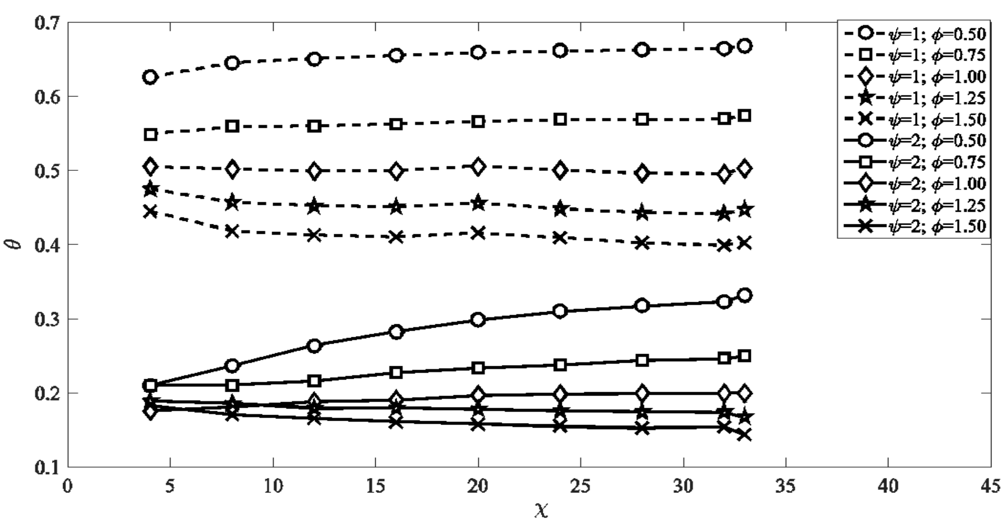


Figure 3. The plot of Non-dimensional Temperature (Θ) with Non-dimensional Length (χ) for Angle of Bifurcation (α) = 60^0

Figure 4 also follows a similar trend at Angle of Bifurcation (α) = 900. At lower χ the plots of Θ for ψ = 2 are closer to each other as compared to ψ = 1 for all velocity ratios. For ψ = 2 and Φ = 0.5, a gentle rise in Θ can be observed for both angles of bifurcation.

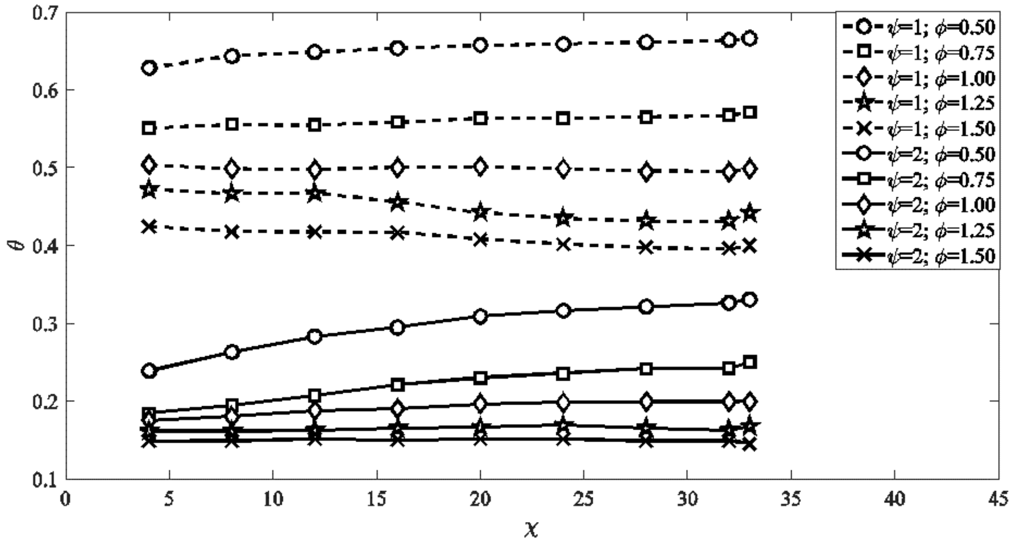


Figure 4. The plot of Non-dimensional Temperature (Θ) with Non-dimensional Length (χ) for Angle of Bifurcation (α) = 90^0

Pressure drop is an important governing parameter in predicting the pumping efficiency of any system. It is highly sensitive to change in Velocity of fluid, Surface roughness, Fluid properties and Temperature. Figure 5 represents the plot for variation of pressure drop coefficient (Cp) with Velocity ratio (Φ) for different α and ψ. It can be stated without clarification that increase in Angle of Bifurcation produces a transverse component of velocity which opposes the flow creating more flow impedance inside the pipe, resulting in an increase of Cp. It is evident that Cp decreases with increase in Velocity ratio with a gradual reduction in slope. Cp increases with an increase in both Diameter ratio and Angle of Bifurcation. For ψ = 2 the difference in Cp reduces gradually at higher velocity ratios.

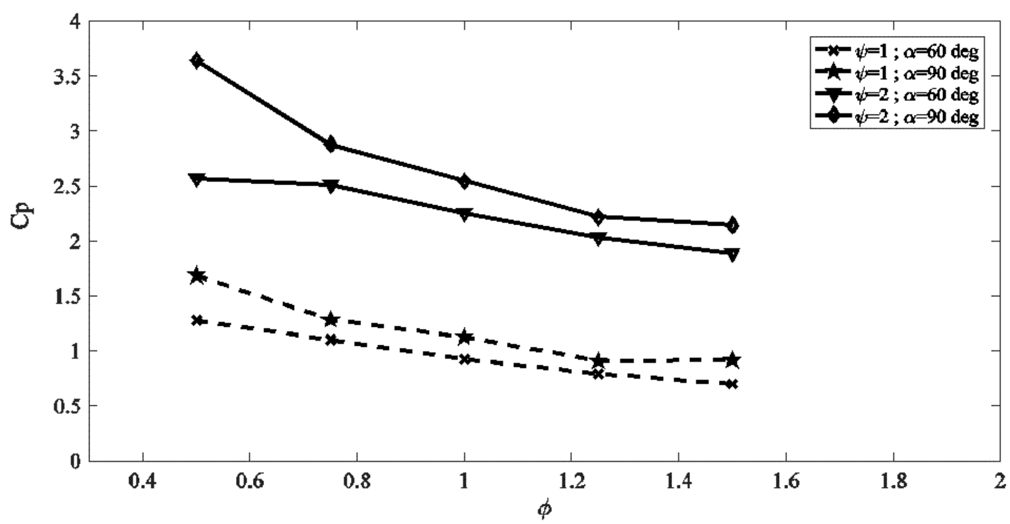


Figure 5. The plot of Pressure drop Coefficient (Cp) with Velocity ratio (Φ)

The increase in Diameter ratio causes an increase in Reynolds number of flow and causes flow transition to turbulent regimen inside the pipe. Turbulence caused by higher Reynolds number of flow causes a loss in pressure head and subsequent reduction in Cp.

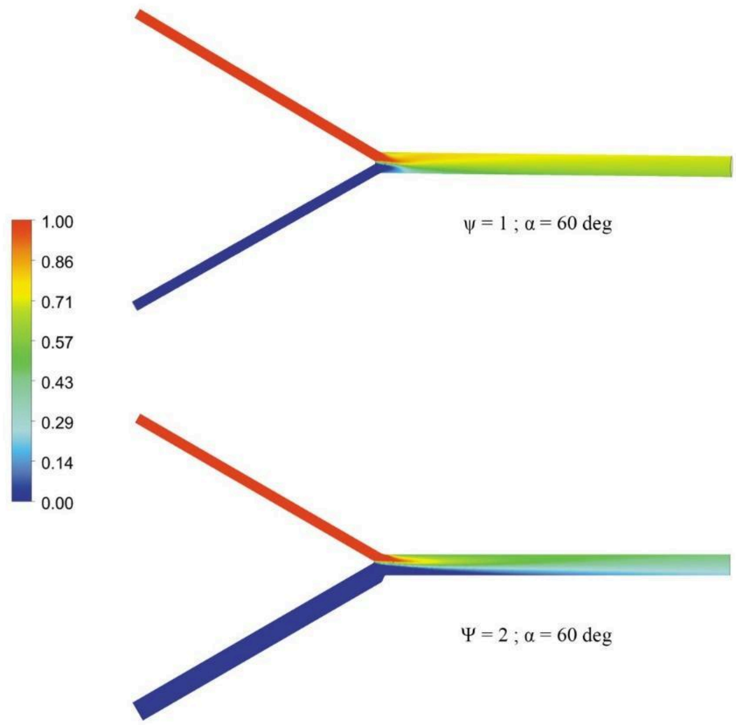


Figure 6. Distribution of Non-Dimensional Temperature (Θ) along the Longitudinal Cross-section of pipe

Figure 6 depicts the distribution of Non-dimensional Temperature at an axisymmetric plane for two diameter ratios. It can be clearly observed that the increase in Diameter ratio causes an increase in the proportion of cold fluid in the total mass flow rate inside the pipe. Contour for ψ=1 shows better mixing of hot and cold fluid as compared to ψ=2 and it is noteworthy to mention that even at higher diameter ratio a very long mixing tube allows proper mixing at the low-velocity ratio.

5. Conclusion

Various factors affecting thermal mixing in bifurcated Y-shaped pipe have been exhausted and scrutinized in the present study. As thermal mixing is a crucial phenomenon in power plant engineering and other important facets of engineering, it cannot be overlooked during the safety inspection of a reactor. Mixing is also responsible for thermal and cyclic stresses which cause damage to parts and fragments of machinery which will prove to be fatal if disregarded. It is evident that the geometry and configuration of pipe, the velocity of fluids, the temperature of fluids are the paramount factors affecting mixing. The effectiveness of mixing and efficiency of the pumping system are characterized by Non-dimensional Temperature (Θ) and Pressure drop coefficient (C_P) respectively. A few concluding remarks for the present study can be stated as follows:

1) Non-dimensional temperature (Θ) bears an inverse relation with both diameter ratio (ψ) and relative velocity of hot and cold fluids (ψ) for both angles of bifurcation (60^0 and 90^0) as is evident from Fig. 4 and 5

2) Pressure Drop (C_P) bears a positive relationship with both the diameter ratio (ψ) and angle of bifurcation (α).

3) From the contours shown in Fig.7, it can be concluded that relatively better mixing is observed for the lower value of diameter ratio (ψ).

Thus the effectiveness of mixing is affected in ways similar to non-dimensional temperature (Θ) and the efficiency of the pumping system decreases with increasing pressure drop coefficient (C_P).

Future scope of the present work can include experimentation on various shapes and configurations of ducts and cross-referencing them with the proper relative velocity between fluid streams to get optimal mixing parameters.

Conflict of Interest

All authors have equal contribution to this work and declare that there is no conflict of interest for this publication.

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