CANDIDATE'S DECLARATION

I hereby that the work presented in this dissertation entitled "S**imulation of thermal mixing in multi tee junction geometry using LES and RANS model**" submitted in partial fulfillment of the requirement for award of degree of **Master of Technology** in Chemical Engineering with specialization in Industrial safety and Hazard Management (ISHM), in an authentic record of my own work carried out under the supervision of **Dr. V.K.Agrawal Professor and Head**, Department of Chemical Engineering, Indian institute of Technology Roorkee.

Place- Roorkee VERONICA

Date- Enrol. No.-12516013

CERTIFICATE

This is certifying that the above statement made by the candidate is correct to the best of my knowledge.

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Dated: (Veronica)

Place: Roorkee

ABSTRACT

In the T-junction, when two fluids mix at different temperatures, then generation of cyclical stresses takes place, and these stresses are responsible for the failure of pipe material because these stresses cause thermal fatigue. This difference in temperature causes frequent changes in temperature, which further results in unpredicted breakdown of material of pipe. As a result, with the purpose of knowing the lifetime of material of pipe, a precise prediction of alteration in temperature is mandatory. When fluids at different temperature mix then fatigue cracks develop at mixing tees. These failures are the reason that there is an increase in the investigation of thermal mixing problems in piping networks, because safety is a major issue in nuclear power plant. The flow in the T-junction is a demanding investigation for, the CFD techniques based on RANS, and Computational Fluid Dynamics(CFD)which are in general employed in industrial application have complications in giving precise results for this flow state.

In case of thermal mixing in T-junction, hydraulic design (i.e dimensions and momentum ratios) of tee components is important. The magnitude and intensity of the thermal load are directly affected by the momentum ratio of hot and cold streams. Momentum ratios of streams can be controlled by pipe diameters or mass flow rates.

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NOMENCLATURE

ρ	Density of fluid
ρ_o	Reference density
Ps	Pressure (Pa)
ε	Dissipation rate of turbulent kinetic energy
D	diameter, (m)
t	Time, (s)
u	Velocity component in radial direction, (m/s)
T	Temperature (^{o}c)
x	length of the pipe (m)
v	Velocity component in axial direction, (m/s)
μ	Dynamic viscosity, (kg/ms)
τ_i	Viscous stress tensors, (Pa)
C	Instantaneous velocity vector of phase
K_s	Diffusion coefficient of granular temperature
Re	Reynolds number
Pr_t	Prandtl number
C_D	Drag coefficient
g	Vector representation of acceleration due to gravity, 9.81 m/s2
g_o	Radial distribution function between particles belonging to a solid phase s
&	And

Greek Letters

μ	Shear viscosity (Pa.s)
ξ	Bulk viscosity (Pa.s)
ρ	Density (kg/m3)
τ	Shear stress tensor (N/m^2)

Subscripts

fr	Frictional
g	Gas or fluid phase
i	x- direction

CHAPTER 1
INTRODUCTION

1.1 Introduction

Cracks due to the stress generated in the pipe material because of the mixing of fluids at different temperatures are a major issue of problem in a nuclear power plant. These occurs when two fluids at different temperatures meet in a pipe network. Due to this mixing turbulence occurs in the pipe and then it causes alteration in temperature. These alterations in temperature, causes thermal exhaustion and stir up cyclical thermal stresses and can lead to unpredicted collapse of pipe material. Therefore, a precise classification of alteration in temperature is mandatory in order to guess the existence of matter of pipe. Such thermal exhaustion related breakdowns happen in a variety of nuclear power plants. Therefore, for the safety in nuclear power plants, a precise classification of circumstances which can lead to collapse due to thermal exhaustion is vital. Failure caused due to these alterations in temperature is the reason for the increase in exploration of thermal mixing problems in these piping systems. A number of experimental and computational studies have been performed for the prediction of these reasons causing a failure in pipe.

The place which is more prone to these thermal stresses is the place where hot and cold fluids are mingled. This fact is mandatory for structural reliability and protection of the plant

High-cycle thermal fatigue in the vicinity of T-junctions (mixing Tees) is a major cause of structural damages, which in some cases have resulted in leaks and power plant shut downs ([1],[2]). Structural failures can be avoided by using static mixers or by regular replacement of components.The T-junctions must be identified that are at risk. For a detailed structural analysis, both the amplitudes and spectral distribution of the temperature fluctuations near the walls are needed which requires detailed knowledge of the flow field.

The flow in the T-junction is a most promising case for Comptational Fluid Dynamcs (CFD). The CFD techniques that are based on RANS (Reynolds Averaged Navier-Stokes equations), which are on average used in industrial purposes include drawback to grant precise consequences for the flow in T-junction. Studies which uses highly developed scale resolving techniques such as DES and LES have given promising outcomes ([3]-[6]). Though, thorough confirmation of the techniques and tools is still needed in order to conclude their probable precision and range of validity and.

In the case of thermal blending in T-junction, hydraulic design (i.e. dimensions and momentum ratios) of tee components is important. The magnitude and intensity of the thermal load due to mixing of hot and cold fluids is directly affected by the momentum ratio of hot and cold streams. Momentum ratio of streams at T-junction can be controlled by various parameters like pipe diameters or mass flow rate. In thermal mixing problem, there are two important parameters which are responsible for the supply of information about thermal stress. These parameters are the frequency and magnitude of temperature fluctuations. The magnitude of temperature fluctuations can be defined as the difference of maximum and minimum temperatures at a given location.

Magnitude of fluctuations is dependent on the distance from the wall where thermal mixing takes place and whether the streams are in thermal equilibrium or not when they reach the wall. These magnitude of fluctuations are important because thermal fatigue damage may occur when incompletely mixed hot and cold fluid streams reach the wall.

In some studies [6-9], momentum ratio of streams is changed while keeping the diameter of branch pipe (D_b) constant. So, mass flow rate values are changed for each case. In some cases, mass flow rate value cannot be changed. For example in nuclear reactors, Emergency Core Cooling System (ECCS) or Residual Heat Removal System (RHRS) water must be supplied at a high flow rate which is independent of the pipe diameter. In this study, hot branch hydraulic diameter is changed keeping mass flow rate and cold branch hydraulic diameter constant. For all these cases, the magnitude of fluctuations and intensity of thermal load is investigated and then compared with each other.

In T-junction geometry which has been considered in this study, main pipe is located in horizontal plane and cold water is flowing through it while branch pipe is located in vertical plane through which hot water is flowing.

Previous [1] and similar studies [10, 11] regarding the flow in T-junction have shown that Large Eddy Simulation calculations with an eddy-viscosity kind of Subgrid-scale Stress model resulted in satisfactorily more precise prognosis of alterations in temperature and velocity rather than additional computational models which are imperative with the purpose of concluding thermal exhaustion. In this study LES turbulence model is adopted in order to calculate the turbulence.

The consequences of geometric factors like operating conditions of turbulent mingling occurrence and ratio of diameters of the branch pipe and main pipe have been examined.

Dissimilar velocity ratios in the branchpipes and mainpipe were scrutinized by Kamide et al. (2009) to notice what makes the changes in temperature circulations.

Study illustrates that the ratio momentum b/w the branch and main pipe is responsible for the intensity of temperature fluctuations in a T-junction. Turbulent mingling of flows with dissimilar temperatures and isothermal flows were scrutinized by Frank et al. (2010) who find out that for the correct and more precise analysis of the turbulent mingling LES model gives better results than the RANS model. This is due to the fact that LES model resolves all small scale eddies while RANS model fails at this point.

CHAPTER 2

Literature Review

Kamide et al. 2008 had studied the blending behaviour of fluids in a tee junction piping system and also done the numerical analysis for the assessment of thermal stripping. In this paper water experiments were performed for thermal hydraulic features of thermal stripping in a tee junction where mixing takes place, which consists of two pipes in which main to branch diameter ratio is of 3. Detailed temperature and velocity fields were also studied by the author in this paper. Temperature was measured by movable thermocouple tree whereas velocity fields were measured by a particle image velocimetry. In this paper author performed a water experiment of mixing phenomenon in a tee junction piping systems to find out the temperature fluctuation characteristics at a point of thermal stripping phenomenona. Experiment was performed, in which a branch pipe of 50 mm in diameter was connected to a main pipe which is of 150 mm diameter. The code used for numerical simulation of the mixing tee experiments was AQUA code. The calculated temperature and fluctuation intensity fields were found in good conformity with the measured statistics.

Lee et al. 2008 had studied about the numerical examination of thermal striping provoked high cycle thermal exhaustion in a tee junction. Thermal striping occurs due to the turbulent blending of two flow streams at dissimilar temperatures, then the consequence of this is alteration in temperature of coolant close to the pipe wall. This is the chief cause for the thermal fatigue breakdown. Coolant temperature alterations are caused due to thermal striping are measured in Hz. The main focus of this learning is on mathematical analysis of the alteration in structural reaction of coolant piping and temperature and in a tee. The alterations in temperature of coolant are found using LES model which are further confirmed by experimental statistics. For the thermal stress exhaustion examination, a model is found to know out comparative significance of different limitations that causes fatigue breakdown. This study illustrates that the factors that are responsible for thermal fatigue failure are temperature difference between the two fluids i.e cold and hot fluids in a pipe junction and the coefficient of transfer of heat which elevated because of turbulent mingling. Author found that the calculated normalized mean temperatures were in good conformity by means of the experimental statistics. The unsteady coefficient of transfer of heat in a tee junction system of piping was found equal to three times more than that of fully developed flow, as a result it needs additional study to conclude its dependency on geometry and ratio of velocity so that improved thermal stress calculation can be performed.

Kamaya et al. 2011 had studied about the thermal stress examination for fatigue breakdown assessment at a mixing tee. When fluids at different temperatures meet at a tee junction fatigue cracks are found. In this study, author calculated thermal stress with the help of finite element method in a mixing tee. This method is employed for temperature transients which are acquired by a simulation of fluid dynamics. The intention of the simulation was to conduct test for a blending in a T-junction, in which cold water is flowing into the mainpipe with the help of a branchpipe. The cold spot is generated due to the cold water which flowing along the main pipe, at this spot the stress of membrane was found to be reasonably big. Based on the simulations following conclusions were obtained:

1) Due to the membrane constraint huge axial stress was detected along the line.

2) Because of the low alteration in frequency of the cold spot, the dissimilarity range and resulting fatigue break became comparatively huge near the location at θ= +-40^{o}.

4) The membrane limit result on the fatigue harm was negligible.

Ayhan et al. 2012 had studied about the modeling of thermal blending in a T-junction geometry using CFD by means of Large Eddy Simulation model. Alterations in Temperature at the pipe stuff were caused by turbulent mingling of fluids at dissimilar temperatures. These alterations in temperature, stir up cyclical thermal stresses and causes thermal fatigue and can lead to unpredicted collapse of pipe material. Therefore, a precise classification of alteration in temperature is mandatory in order to guess the existence of pipe material. Therefore, an precise prediction of alteration in temperature is significant in order to find out the life span of pipe stuff. This paper focuses on the estimation of the frequency of alteration in velocity and temperature in the blending section of a tee junction using Computational Fluid Dynamics(CFD). Turbulence characteristics were simulated using Large Eddy Simulation and Reynolds Averaged Navier Stokes and then CFD end results were equated with the obtainable investigational statistics. LES outcome with the use of coarse mesh were in good accord with the obtainable experimental consequences in terms of frequency of alteration in velocity and temperature and amplitude. Region having the strongest alteration in temperature showed that the frequency range of 2-5 Hz consists of the the most energy with the help of the examination of the alteration in temperature and the power spectrum densities(PSD). This collection of frequency is important parameter for thermal exhaustion breakdown analysis.

Aulery et al. 2012 had studied about the simulations of sodium blending in a tee junction numerically. For liquid metals, chief crisis is thermal fatigue in reactors because of the rise in temperature dissimilarity in the circuits of the coolant. Liquid metals causes more alteration in temperature to walls. In this paper the author had studied about the thermal hydraulic explorations in detail to get out the amplitudes and frequencies of the alteration in temperature in the phenix pool type fast reactor. Large Eddy Simulation or Rans equations were used for the CFD calculations. In this paper a zone where constant wetting of hot sodium was occurring, a high thermal fluctuation plume was calculated; and this was in good agreement with the black as well as white spots which were observed experimentally. Moreover, the site of the breaks due to thermal exhaustion of the tee junction was accurately found with the help of simulations. In this paper, to find out a precise calculation of the thermal heat transfer and also the exhaustion zone regions in a junction, conjugate calculations of transfer of heat are suggested.

Jian-lei et al. 2012 had studied about the simulation of water & oil two phase flow and thier behaviour of segregation in T- junctions which are combined together. The combined T-junction used for the water & oil segregation have many benefits like firmness in structure, uniformity in effects and also cost efficeint. For simulation of flow and phase distribution, the Eulrian multi fluid model and k-ϵ model for turbulence were employed in the combined T-junction. The consequences of various restrictions like height on the division of flow, distance of branched pipe, and the segregation behaviours were also examined. The consequences showed that, tee junctions which are combined together at a fixed outlet & inlet boundary conditions, form a single system of hydraulic equilibrium in which the fluid energy allocates itself without restraint until a balance is attained. The separation of the immiscible water & the oil was enhanced by split-flow. With the slight changes in the rise of the branch pipe & rise in the interval of branched pipe, separation efficiency increases. The path of flow in the branch pipes can be changed by modifying change in the structure of the tee junctions which are combined together. The consequences showed that, tee junctions which are combined together at a fixed outlet & inlet boundary conditions, form a single system of hydraulic equilibrium in which the fluid energy allocates itself without restraint until a balance is attained.

Sakowitz et al. 2013 had studied about the turbulent flow mechanisms in mixing T-junctions region using Large Eddy Simulation model. In this paper, the author has considered the mixing process due to turbulence different types of tee junction geometries. These two different types of junctions have square and circular cross-sections, respectively. The turbulent structures of flow and modes are examined with the help of large eddy simulation model. A sensitivity of grid study was also executed and the field of velocity and scalar mixing were compared with available statistics of experiments. The conformity was found excellent for high enough resolutions of mesh. Moreover, the unsteady Reynolds averaged Navier-Stokes results were compared with Large Eddy Simulation results, to get the better perceptive of the weakness which are linked with URans model. The mixing quality was studied using a uniformity index which showed more consistent and quicker mingling in the junction having circular cross section. Moreover, phenomena of vortex shedding were noticed in the case of circular cross section at S1~0.5. The author found out that the mean flow structures were analogous in different junctions.

Ashrafizadeh et al. 2013 had studied about the examination of breakdown of a high pressure natural gas pipe under split tee with the help of computer simulations. In this study, a crack of 36 inch in a high pressure gas pipe was noticed throughout usual examination of station, then that was examined. The crack, which was around one meter in length, was started from a notch which was inside the hole in line of pipe which was fitted approximately 30 years ago. The study was carried out by evaluating the data of construction & history of design , visual examination, classification of the material of pipe, with the help of finite element method. With the help of Investigations the author found out that the valve, which was in a straight line linked to the split tee, experienced huge dynamic periodic forces because of the pressure drop b/w two pipelines. Based on scrutiny of dynamics, it was originate that the first mode shape, the utmost stress were precisely located within the zone of crack beginning. The ancient study showed no signal of stress corrosion cracking or associated matters accountable for this breakdown. Conversely, dynamic investigation validated that the syatem had comparitively small natural frequencies for a system of pipe line of gas. Since a enormous level of energy was concerned, the ball valve was harshly shaked with a frequency range under 100 Hz.

Lu et al. 2013 had studied about the Large eddy simulations of structure effects of an upstream elbow main pipe on hot and cold fluids mingling in a vertical tee junction. The main cause for the thermal fatigue is thermal stripping in the system of pipes which is employed in nuclear plants. In this current work, the mingling of streams of cold and hot liquids in a vertical T-junction with an upstream elbow main pipe is studied numerically with Les model. The parameters which are changed for the study are: the proportion of the diameter of the main pipe to the curvature of the elbow pipe, and the dimensionless horizontal distance b/w the branch pipe and the elbow pipe. The RMS temperature, normalized mean temperature and velocity were studied numerically to find out how the two parameters stated above effects the mixing. The numerical results showed that the increase in the elbow curvature ratio and dimensionless distance would weaken the temperature and velocity fluctuations,due to the reductionin the secondary flow in the elbow pipe. It was found that with increase in the elbow curvature ratio and dimensionless horizontal distance, RMS temperature and velocity decreases, although those parameter selected in this present work do not significantly affect the normalized mean temperature and velocity. Therefore it is found that the parameters taken, only affects the RMS temperature and velocity and do not effects the normalized temperature and velocity.

CHAPTER 3

Motivation

Thermal mixing is a well-known root cause of thermal fatigue break in nuclear power plants. Thermal mixing is an occurrence where cold and hot streams join, mix and which further result in alteration in temperature inside the pipe. In the T-junction, when two fluids mix at different temperatures, then generation of cyclical stresses takes place, and these stresses are responsible for the failure of pipe material because these stresses cause thermal fatigue. This difference in temperature causes frequent changes in temperature, which further results in unpredicted breakdown of material of pipe. Thus, with the purpose of knowing the lifetime of pipe matter, a precise prediction of alteration in temperature is mandatory. When fluids at different temperature mix then fatigue cracks develop at mixing tees. These failures are the reason that there is an increase in the investigation of thermal mixing problems in piping networks, because safety is a major issue in nuclear power plant. To find out the power of structure, steadiness and existence these T-junctions, it is necessary to know the following:

1) Magnitude of the alterations in temperature
2) Distinguishing frequencies of alteration in temperature
3) Area of the pipe wall that bears the most alteration in temperature
4) Reduction in temperature alteration in boundary layer close to wall of pipe

CHAPTER 4

Objectives

Keeping the above literature review in mind, the present investigation has been planned with following objectives:-

1) To compare the Large Eddy and RANS (steady and unsteady) simulation of velocity and temperature fluctuation in a T-junction.

2) To compare the Large Eddy and URANS simulation of velocity and temperature fluctuations in hot and cold fluids mixing in:

Case a) ForT-junction geometry in which two junctions are parallel to each other.

Case b) Formulti T-junction geometry in which two junctions are opposite to each other.

CHAPTER 5
Modeling approach

5.1. COMPUTATIONAL MODEL

5.1.1. CONSERVATION EQUATIONS

The leading equations which are used for LES model, found by filtering the time-dependent Navir Stkes equations. In order to divide the large scales and small scales which are filtered and sub filtered respectively, filtering process is helpful in Navier-Stokes equations. The huge scale turbulence is represented by filtered eddies. Les is a 3-D, approach of unsteady turbulence commence which can be used to model the small scale edies. It solves the large scale edies straight. The big scale edies are resolved explicitly with the help of filtered Navir Stokes equations whereas the small scale edies are modeled with the help of a subgrid scale stress model.

The conservation of mass and momentum equations can be expressed as following:

$$\frac{\delta \rho}{\delta t} + \frac{\delta}{\delta x i}(\rho \bar{v}_i) = 0 \qquad (1)$$

and

$$\frac{\delta}{\delta t}(\rho \bar{v}_i) + \frac{\delta}{\delta x j}(\rho \bar{v}_i \bar{v}_j) = \frac{\delta \sigma i j}{\delta x j} - \frac{\delta \bar{P}}{\delta x j} - \frac{\delta \tau i j}{\delta x j} + S_{G,i} (2)$$

where $\bar{v}$ and $\bar{P}$ stand for filtered velocity component and pressure. $S_{G,i}$ stand for force of gravitational body. This force is found with the help of Boussinesq approximation so that $S_{G,i}$= $(\rho-\rho_o)g_i$ where ρ_o stand for reference density and g_i stand for componnt of gravtational aceleration in the ith direction.

In eqn. (2) σ_{ij} stand for tensor of stress because of molecular viscosity (μ), given by

$$\sigma_{ij} = [\ \mu(\frac{\delta \bar{v_i}}{\delta x j} + \frac{\delta \bar{v_j}}{\delta x j})\ ] - \frac{2}{3}\mu\frac{\delta \bar{v_l}}{\delta x l}\ \delta_{ij} (3)$$

The subgrid-scale stress, τ_{ij}, is defined by

$$\tau_{ij} = \rho\overline{v v} - \rho v_i \bar{v}_j \qquad (4)$$

and it needs extra modelling.

The energy conservation equation can be demonstrate as:

$$\frac{\delta}{\delta t}(\rho\overline{H}) + \frac{\delta}{\delta xj}(\rho\overline{h\bar{v}}_j) = \frac{\delta}{\delta xj}(K_{eff}\frac{\delta\bar{T}}{\delta xj}) \qquad (5)$$

In equation (5) $\overline{H}$ and $\overline{T}$ stand for filtered enthalpy and temperature, in that order. K_{eff} is valuable coefficient which consits of turbulent blending involvement in calculation of conduction of molecules and can be demonstarted like

$$k_{eff} = k + \frac{\mu_t c_p}{Pr_t} \qquad (6)$$

where K and c_p stand for the thermal conductivity and constant pressure specific heat in that order of the liquid and μ_t is the turbulent subgrid viscosity. Pr_t stands for the subgrid Prandtl number which has the value of 0.85, which is the value suggested in ANSYS(2009).

5.2 MODELS

5.2.1.*Sub grid scale stress models*

Sub grid-scale stresses consequence of the filtering process, are unidentified as well as involve modelling. The majority of models of sub grid scale stress depend on an eddy viscosity postulation, that deduce linear relation b/w SGS tensor and filtered rate-of-strain tensor.

The subgrid scale stress expression, τ_{ij}, known by eq. (4), possibly will demonstrated like

$$\tau_{ij} - \frac{1}{3}\tau_{kk}\delta_{ij} = -2\mu_t\bar{S}_{ij} \qquad (7)$$

whereμ_t stands for the eddy viscosity that desires to be modelled. The common mechanism of the SGS(τ_{kk}) are not modelled, other than further to the filtered static pressure term $\bar{p}$.$\bar{S}_{ij}$ stand for rate-of-strain tensor for the resolved scale, demonstrated by

$$\bar{S}_{ij} = \frac{1}{2}\left(\frac{\delta\bar{v}_i}{\delta x_j} + \frac{\delta\bar{v}_j}{\delta x_i}\right) \qquad (8)$$

Smgorinsky Lily and Wall Adapting Local Edy Viscosity models are the models used for sub grid scale stress. In Smagorinsky Lily model, the edy viscosity is modelled by

$$\mu_t = \rho L_s^2|\bar{S}| \qquad (9)$$

whereL_s stand for the mingling length of SGS and $|\bar{S}| = \sqrt{2\bar{S}_{ij}\bar{S}_{ij}}$ is a guess for the quality velocity scale of turbulence.

In FLUENT, L_s is calculated using

$L_S = MIN(\kappa d, C_s V^{1/3})$ (10)

where κ stand for constant of von Karman, d is the distance of the wall which is closest, *V* stand for computational cell volume and value of C_s of around 0.1 has been establish to give up the most excellent results for the broad range of flows. This value is a default value in FLUENT.

5.2.2.*Large-Eddy Simulation Model*

Large Eddy Simulation is a mathematical model which is employed for turbulence in computational fluid dynamics. For the simulation of atmospheric air cureents it was found by Joseph in the year 1963. Low pass filtering is the the key action in large eddy simulation. This procedure when employed with the Navier Stokes equations, helps in the elimination of small scales of the solution. This helps in diminishing the cost of computations. The leading equations are thus altered, and the solution is a filtered velocity field.

5.2.3.*Reynolds-AveragedNavier-StokesModel*

The main goal of the models for turbulence which are used for the Rans equations is to figure out the Reynolds Stresses, these could be completed by 3 foremost categories of Rans-based models of turbulence:

1. Linear Eddy viscosity models
2. Nonlinear eddy viscosity models
3. Reynolds stress model (RSM)

5.2.4.*Linear eddy viscosity models*

These models are the models for turbulence. In this the reynolds stresses are obtained by RANS equations and are modeled by a linear constitutive relationship with the mean flow straining field as :

$-\rho(u_i u_j) = 2\mu_t S_{ij} - \frac{2}{3}\rho\kappa\delta_{ij}$

where

- μ_t is the coefficient term turbulence viscosity
- $\kappa = \frac{1}{2}[\ (u_1u_1) + (u_2u_2) + (u_3u_3)\ ]$ is the mean turbulent kinetic energy
- $S_{ij} = \frac{1}{2}[\ \frac{\delta \bar{u}_i}{\delta x_j} + \frac{\delta \bar{u}_j}{\delta x_i}\ ] - \frac{1}{3}\frac{\delta U_k}{\delta x_k}\delta_{ij}$is the mean strain rate

5.2.5.*Non Linear Eddy Viscosity Models*

This is class of turbulence models for the Rans equations in which an coefficient of eddy viscosity is employed for relating the mean turbulence field with mean velocity field, however in a non-linear relationship

$-\rho(u_i u_j) = 2\mu_t F_{nl}(S_{ij}, \Omega_{ij}, ...)$

where

- $F_{nl}$is a nonlinear function perhaps depends on the mean strain and vorticity fields or even other variables of turbulence.
- μ_t stands for turbulent viscosity
- $S_{ij} = \frac{1}{2}[\frac{\delta v_i}{\delta x_j} + \frac{\delta v}{\delta x_i}] - \frac{1}{3}\frac{\delta v_k}{\delta x_k}\delta_{ij}$ is the mean strain rate
- $\Omega_{ij} = \frac{1}{2}[\frac{\delta v_i}{\delta x_j} - \frac{\delta v}{\delta x_i}]$ is the mean vorticity

5.2.6.*Reynolds Stress Models*

The Reynolds stress model include estimation of the individual Reynolds stresses, $\rho\bar{u}_i\bar{u}_j$, using unlike transport equations. Then conclusion of the Reynolds averaged momentum equation van be acquired by individual Reynolds stresses.

CHAPTER 6

Numerical Methodology

6.1 Computational Procedures

The length of the main pipe used in this modeling is 140 mm and the length of the vertical pipe connected to top of the main pipe is taken as 100 mm.The total distance is taken to be approximately 20 pipe diameters with invariable diameter of 100 mm which joined vertically.

The horizontal cold branch has a temperature of 19^{o}c and vertical hot branch has a temperature of 36^{o}c. The total flow rate of the hot and cold stream coming out of the pipe is 15 l s^{-1} and the proportion of hot to total flow rate is 0.4.

6.2 Boundary Conditions

The horizontal cold branch has a temperature of 19^{o}c and vertical hot branch has a temperature of 36^{o}c. The total flow rate of the hot and cold stream coming out of the pipe is 15 l s^{-1} and the proportion of hot to total flow rate is 0.4.

Table 6.1

	Temperature(^{o}c)	Pipe dia(mm)	Flow rate(l s^{-1})
Branch pipe 1	36	100	6.0
Main pipe 2	19	140	9.0

6.3 Mesh

For creating mesh structure of domain, GAMBIT, which is code for geometry and structure of mesh has been used. In order to get suitable and good results for the Les model, it is proposed that the elements of grid should have the shape of hexahedral arrangement. The elements should be minute to diminish the involvement of the SGS because small edies are modelled by Les model. Computation time required by the LES model increases as the resolution of grid elevated by employing a finer mesh. A suitable size of grid be supposed to be chosen because if dimension of grid is excessively coarse then model will not perform accurately.

6.4 Computational procedures used in two different cases of multi tee junction geometries

6.4.1 Case a)

Multi tee junction (parallel)

The dimension of the length of the horizontal pipe used is 2 m and the diameter used is 140 mm. The length of the two branch pipes used is 0.4 m and diameter is 0.1 m. The distance between the branch pipes used is 0.6 m. The pipe which is horizontal is having a cold fluid flowing through it and the temperature of the fluid is 19^{o}c and the two pipes which are vertically attached to the main pipe is having a hot fluid flowing through it and the temperature of the fluid is 36^{o}c. The total flow rate of the fluids flowing through the pipe is 21 l s^{-1} and the proportion of flow rate of hot liquid to total flow rate of all the liquids is 0.58 approximately.

Boundary Conditions

The pipe which is horizontal is having a cold fluid flowing through it and the temperature of the fluid is 19^{o}c and the two pipes which are vertically attached to the main pipe is having a hot fluid flowing through it and the temperature of the fluid is 36^{o}c. The total flow rate of the fluids flowing through the pipe is 21 l s^{-1} and the proportion of flow rate of hot liquid to total flow rate of all the liquids is 0.58 approximately.

Table 6.2

	Temperature(^{o}c)	Pipe diameter(m)	Flow rate(l s^{-1})
Branch pipe 1	36	0.1	6
Branch pipe 2	36	0.1	6
Main pipe 3	19	0.14	9

Mesh

For creating mesh structure of domain, GAMBIT, which is code for geometry and structure of mesh has been used. In order to get suitable and good results for the Les model, it is proposed that the elements of grid should have the shape of hexahedral arrangement. The elements should be minute to diminish the involvement of the SGS because small edies are modelled by Les model. Computation time required by the LES model increases as the resolution of grid elevated by employing a finer mesh. A suitable size of grid be supposed to be chosen because if dimension of grid is excessively coarse then model will not perform accurately.

6.4.2 Case b)

Multi tee junctions (opposite to each other)

The dimension of the length of the horizontal pipe used is 1.2 m and the diameter used is 140 mm. The length of the two branch pipes used is 0.4 m and diameter is 0.1 m. The pipe which is horizontal is having a cold fluid flowing through it and the temperature of the fluid is 19^{o}c and the two pipes which are vertically attached to the main pipe is having a hot fluid flowing through it and the temperature of the fluid is 36^{o}c. The total flow rate of the fluids flowing through the pipe is 21 litre per second and the proportion of total flow rate of hot liquid to total flow rate of all the liquids is 0.58 approximately.

Boundary Conditions

The pipe which is horizontal is having a cold fluid flowing through it and the temperature of the fluid is 19^{o}c and the two pipes which are vertically attached to the main pipe is having a hot fluid flowing through it and the temperature of the fluid is 36^{o}c. The total flow rate of the fluids flowing through the pipe is 21 l s^{-1} and the proportion of total flow rate of hot liquid to total flow rate of all the liquids is 0.58 approximately.

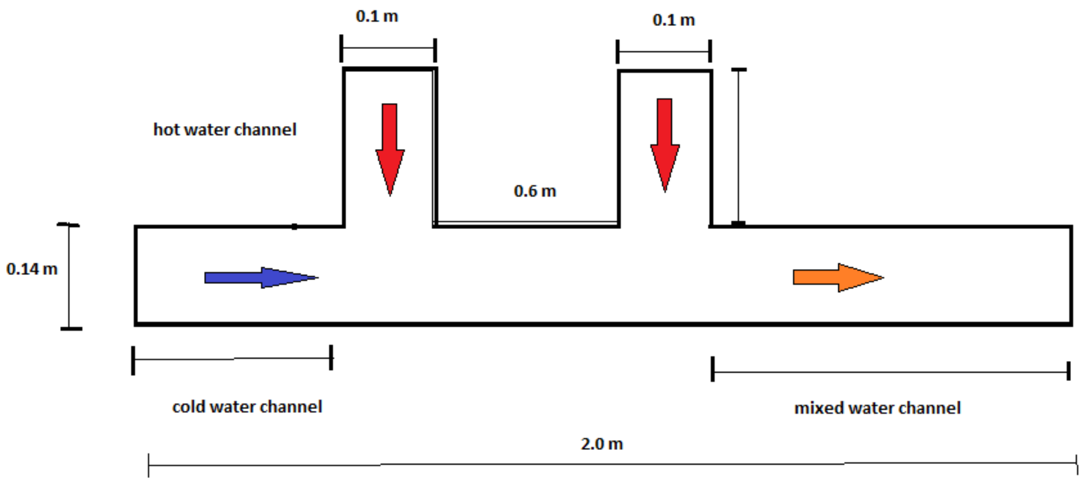
Table 6.3

	Temperature(^{o}c)	Pipe diameter(m)	Flow rate(l s^{-1})
Branch pipe 1	36	0.1	6
Branch pipe 2	36	0.1	6
Main pipe 3	19	0.14	9

Mesh

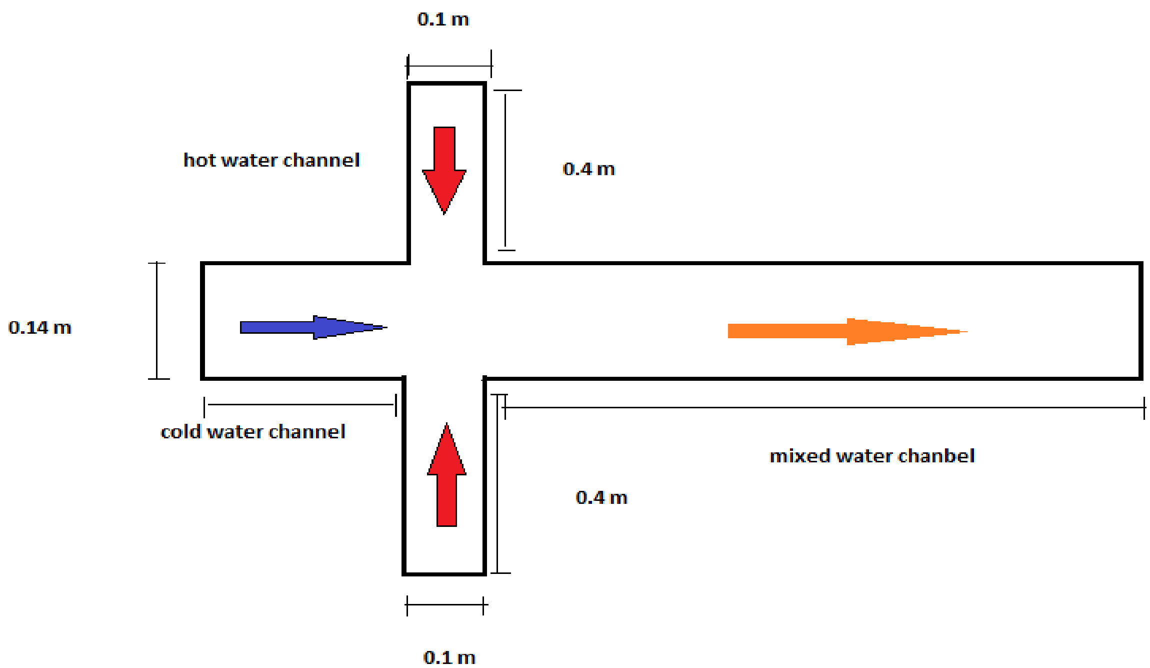
For creating mesh structure of domain, GAMBIT, which is code for geometry and structure of mesh has been used. In order to get suitable and good results for the LES model, it is proposed that the elements of grid should have the shape of hexahedral arrangement. The elements should be minute to diminish the involvement of the SGS because small edies are modelled by Les model. Computation time required by the LES model increases as the resolution of grid elevated by employing a finer mesh. A suitable size of grid be supposed to be chosen because if dimension of grid is excessively coarse then model will not perform accurately.

CASE a)



0.1 m
0.1 m
hot water channel
0.6 m
0.14 m
cold water channel
mixed water channel
2.0 m

CASE b)



0.1 m
hot water channel
0.4 m
0.14 m
cold water channel
mixed water chanbel
0.4 m
0.1 m

CHAPTER 7
Results and Discussion

7.1 Model validation

Table 7.1 and 7.2 shows the contours for circulation temperature and velocity respectively at center segment of the pipe by RANS (a1 and a2), URANS (b1 and b2) and LES (c1 and c2) models by comparing the results obtained from simulation and result obtained from Ayhanet al.2012.

It is observed that the results obtained from simulation are same as computed by Ayhan et al.2012.

The Realizable k-ϵ turbulence model has been employed for unsteady as well as steady URANS and RANS assessment and then equated with LES model in current study. It can be undoubtedly seen in the figure 7.1 and 7.2 that employing LES model provides superior results than URANS or RANS models in scrutinizing the distinctiveness of turbulence which is caused due to mingling. Models of turbulence, which solves equations of Navier Stokes employing reynolds average technique, are not proficient in scrutinizing alterations in velocity and temperature, it can be used only for the average distribution (fig.7.1(a1-b2)). LES model resolves all the small scale eddies that is why it gives more accurate results than the RANS model. RANS model don not resloves small scale eddies, it on ly gives the average distribution of the velocity. However, average circulation wont be able to describe evidently uncertainty of the turbulence. It can be seen in the fig. 7.1(c2) that the degree of velocity gradient is far better and more reasonable than those in fig.7.1(b2) in T-region.

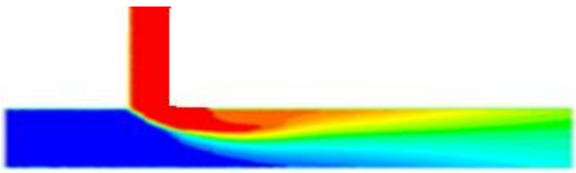
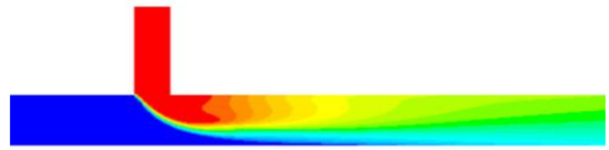
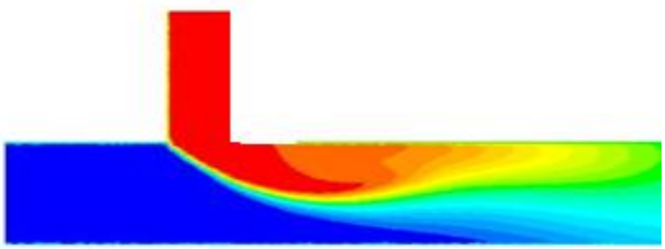
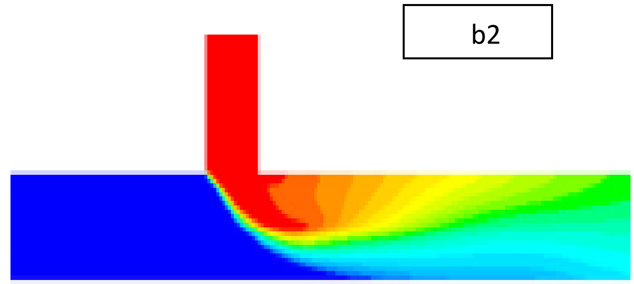
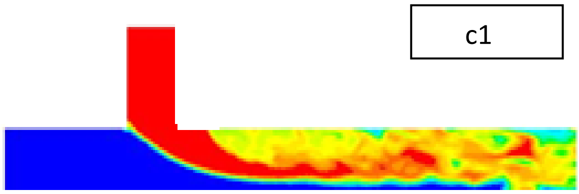
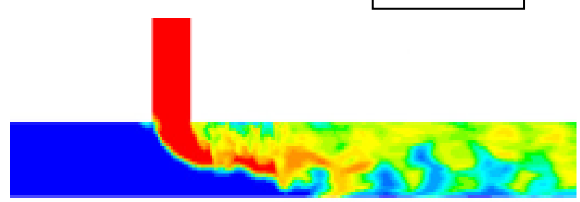
Validation Results	Paper Results
a1 	a2 
b1 	b2 
c1 	c2 

Figure 7.1 contours for distribution of temperature at central section of pipe using different models: RANS(a1 and a2), URANS(b1 and b2) and LES(c1 and c2)

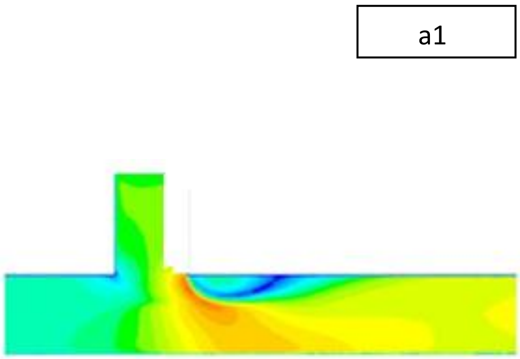
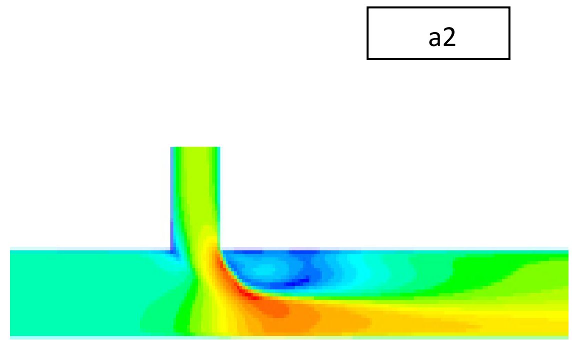
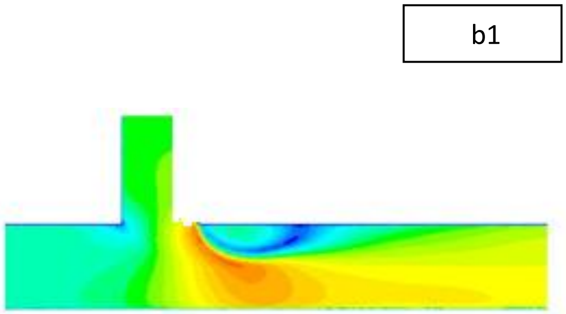
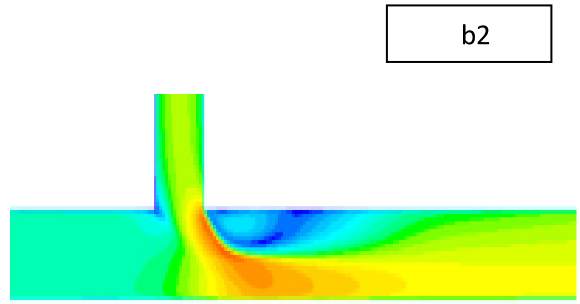
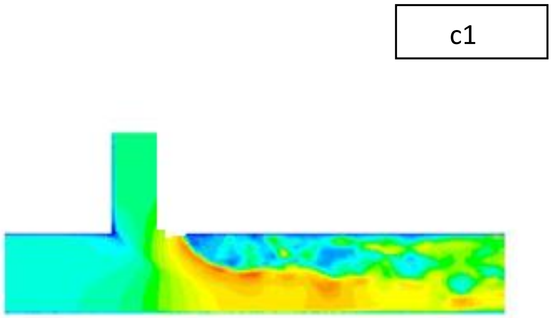
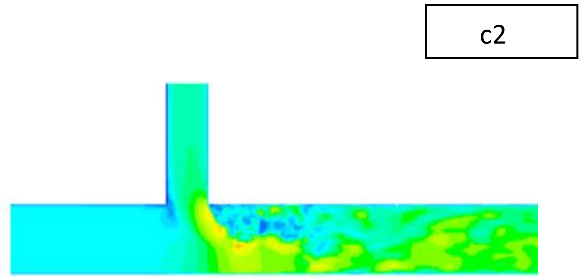
Validation Results	Paper Results
	
	
	

Figure 7.2 contours for distribution of velocity at center section of the pipe using different models: RANS(a1 and a2), URANS(b1 and b2) and LES(c1 and c2)

7.2 Contours of temperatures and velocities for continues two junctions

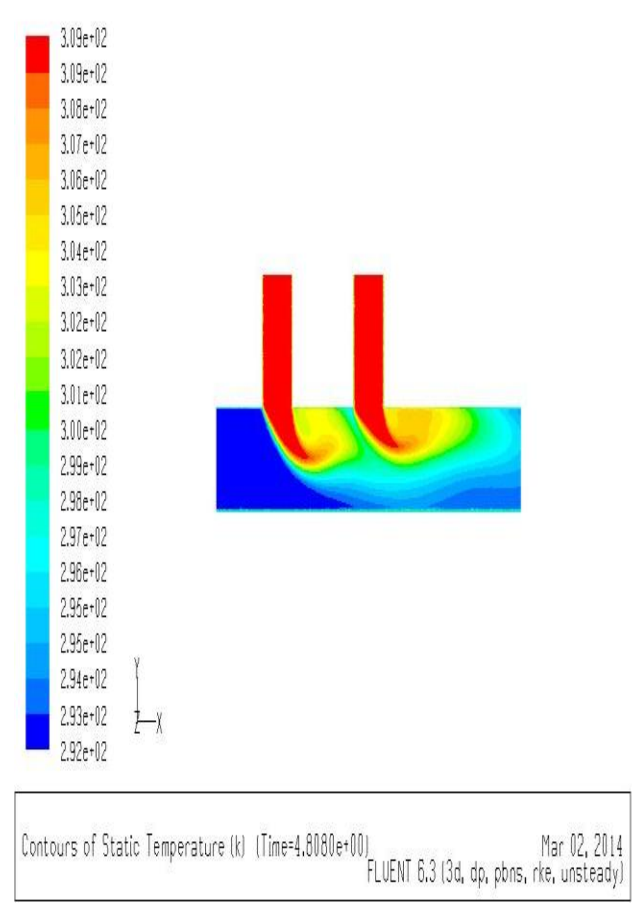
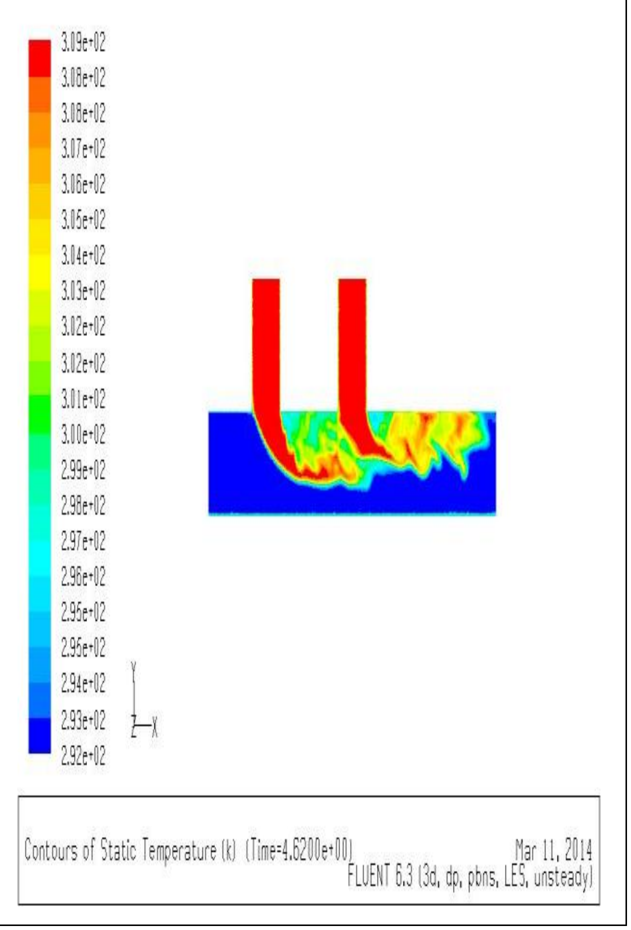
RANS	LES
	

Figure 7.3 Contours of temperature distribution at centeral part of the pipe using RANS(left) and LES(right)

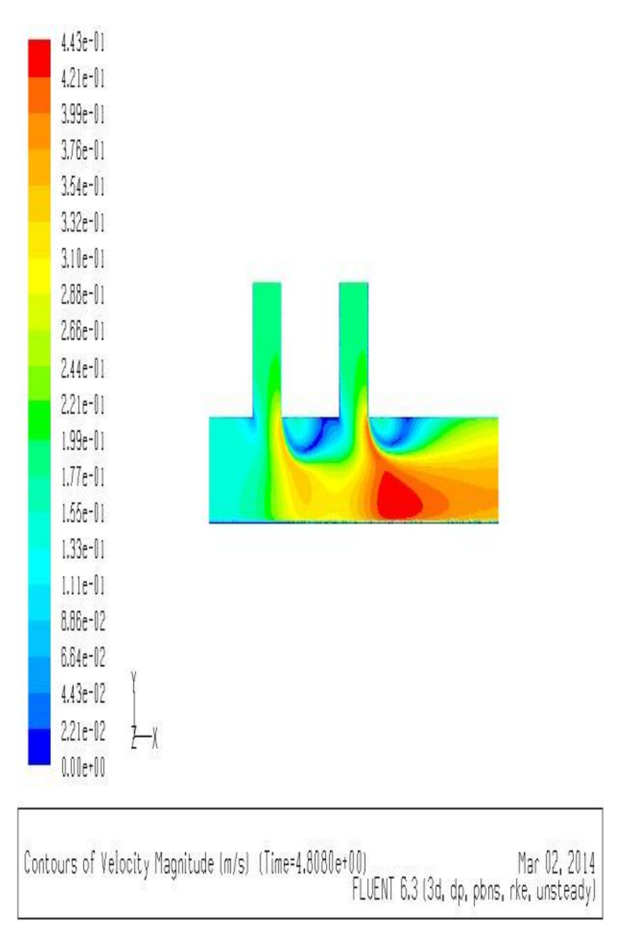
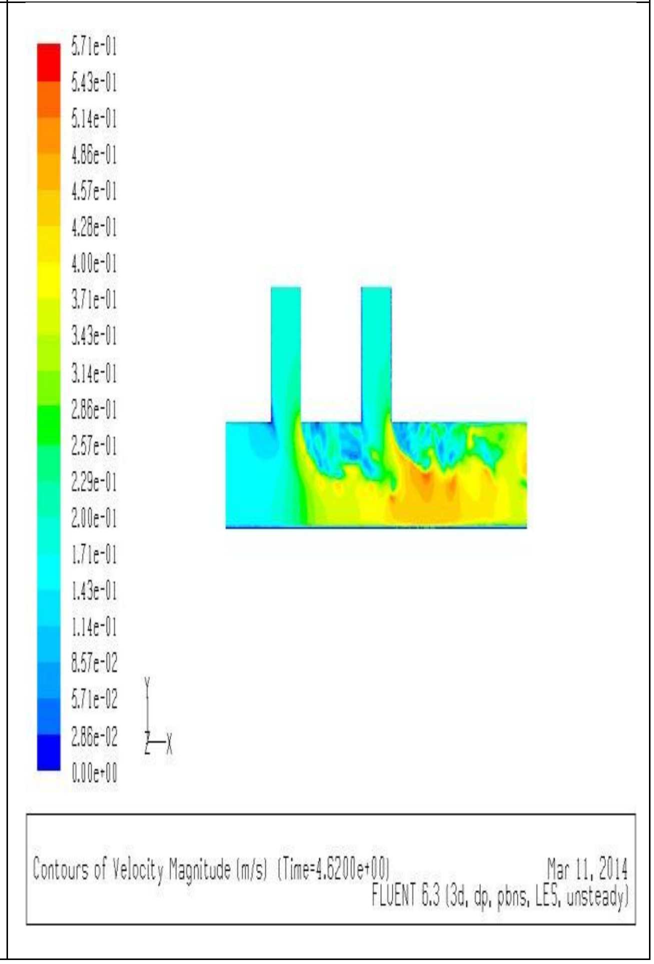
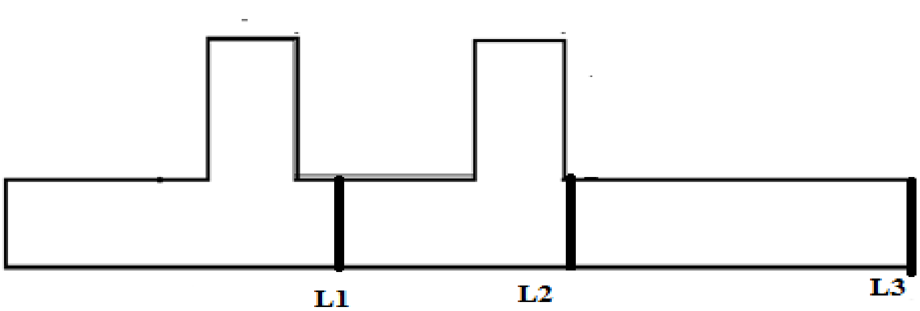
RANS	LES
	

Figure 7.4 Contours of velocity distribution at central plane section of the pipe using RANS(left) and LES(right)

Study of cross section contours are at three locations L1 = 0.7 m, L2= 1.2 m, L3 = 2 m from inlet



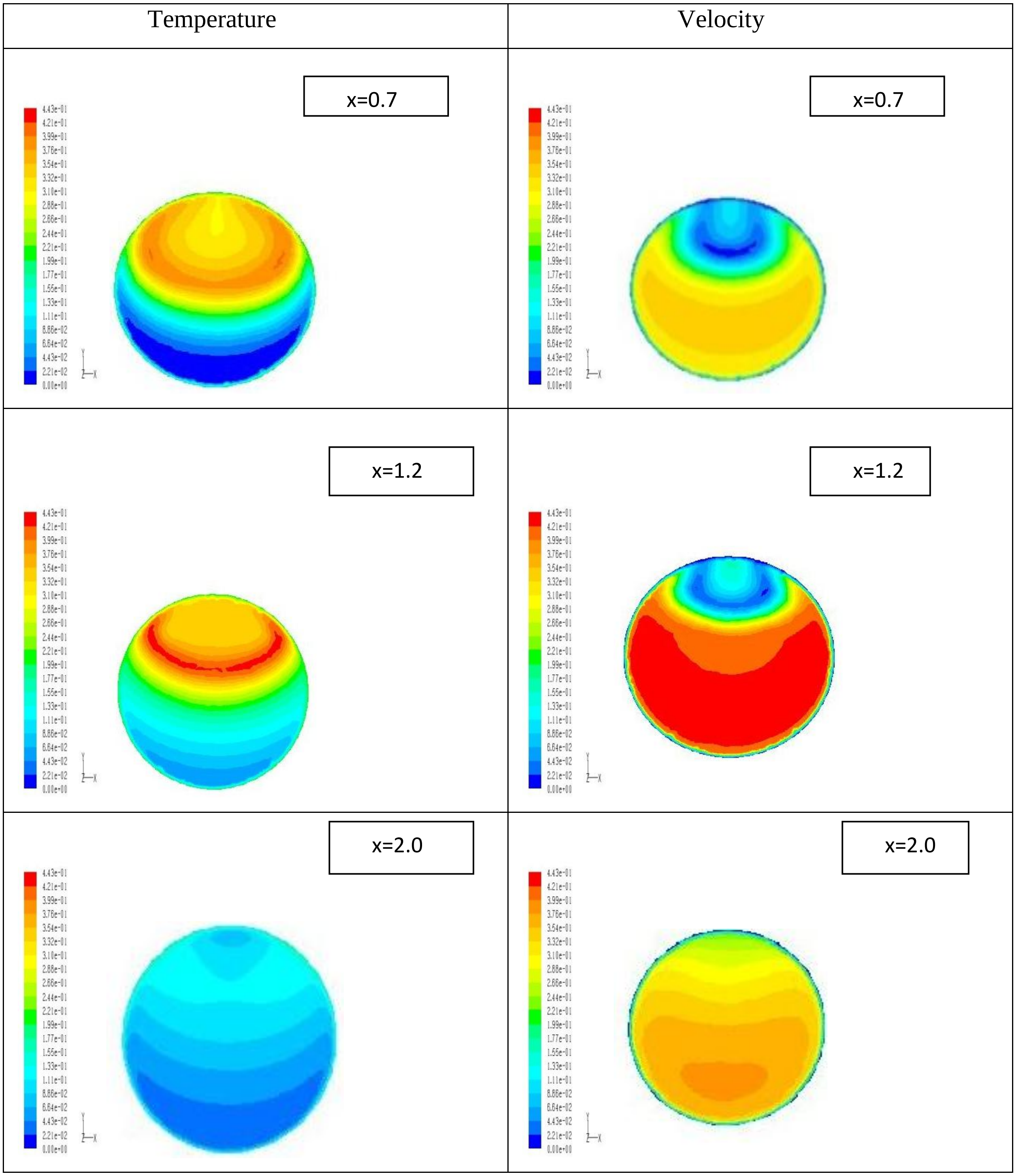


Figure 7.5 Cross Section contours of distribution of temperature on the left side and velocity on the right side at different locations along the length of pipe using RANS(unsteady) model.

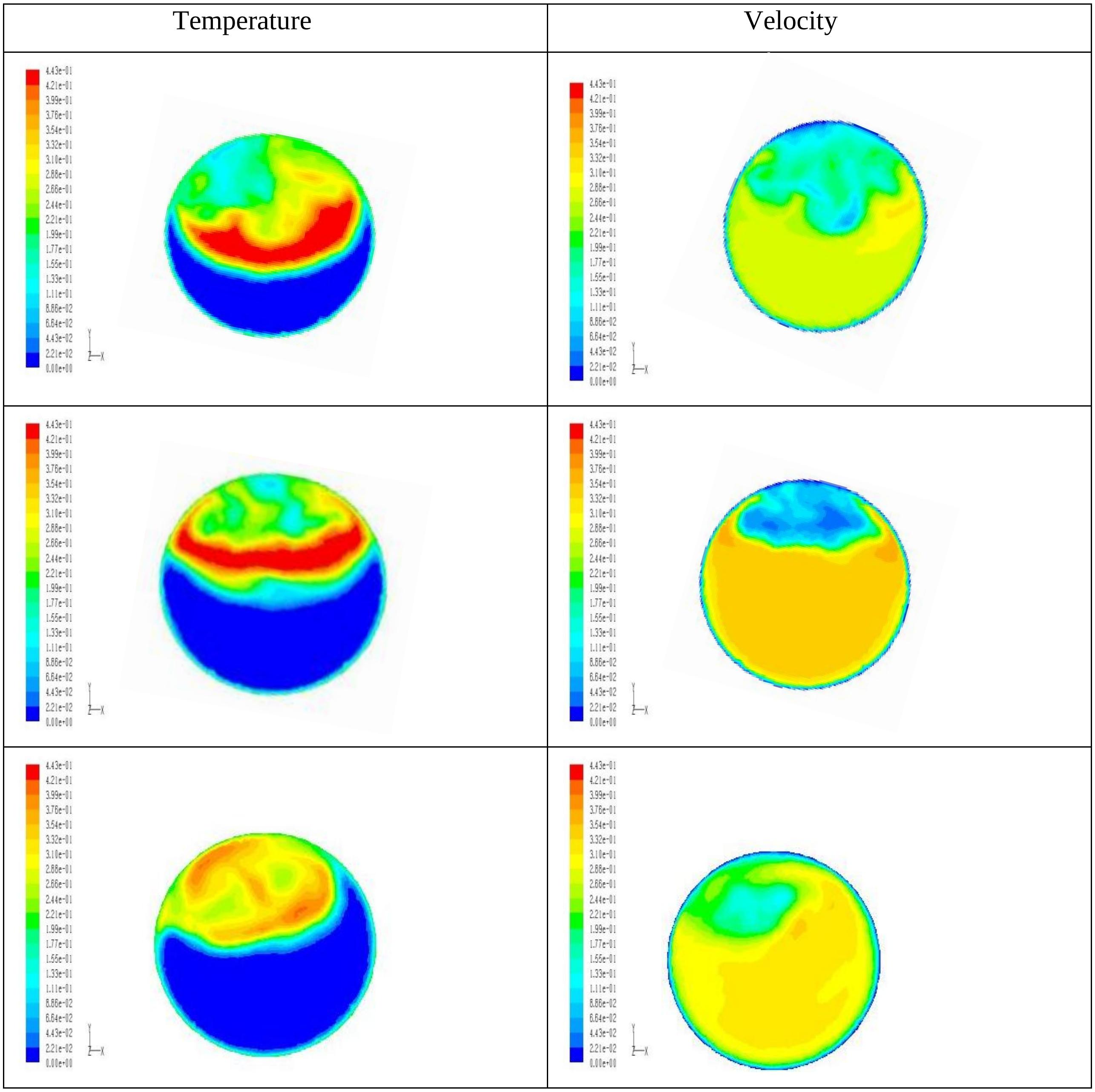
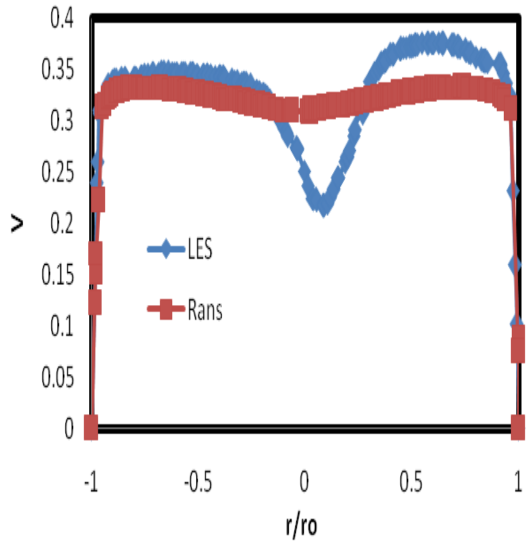


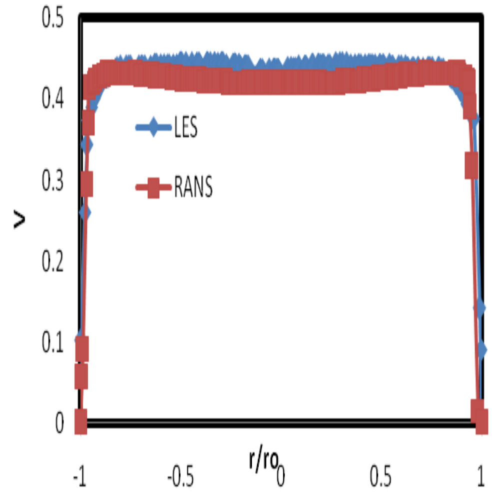
Figure 7.6cross section Contours of distribution of temperature on the left and velocity on the right at different locations along the length of pipe using LES model

7.3 Velocity profiles at differnet loaction for continoues two T junctions

AT X=0.7 m



AT X=1.2 m



AT X=1.7 m

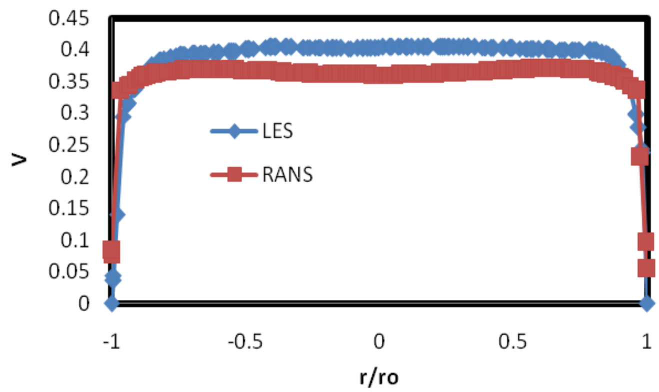


Figure 7.7Comparison of velocity distribution along horizontal direction at different locations using LESand RANS model.

Velocity profiles shown in figure 7.7 that near the junction (x = 0.7) LES model gives different velocity profiles than RANS models, this is because LES model consider the small eddies, near the junction when one fluid enters in other pipes its create turbulence in main pipe because of momentum transfer from one fluid to another fluid. But with time eddies dissipate and along length. So at location far from junction, RANS's and LES's velocity profiles are approximately same.

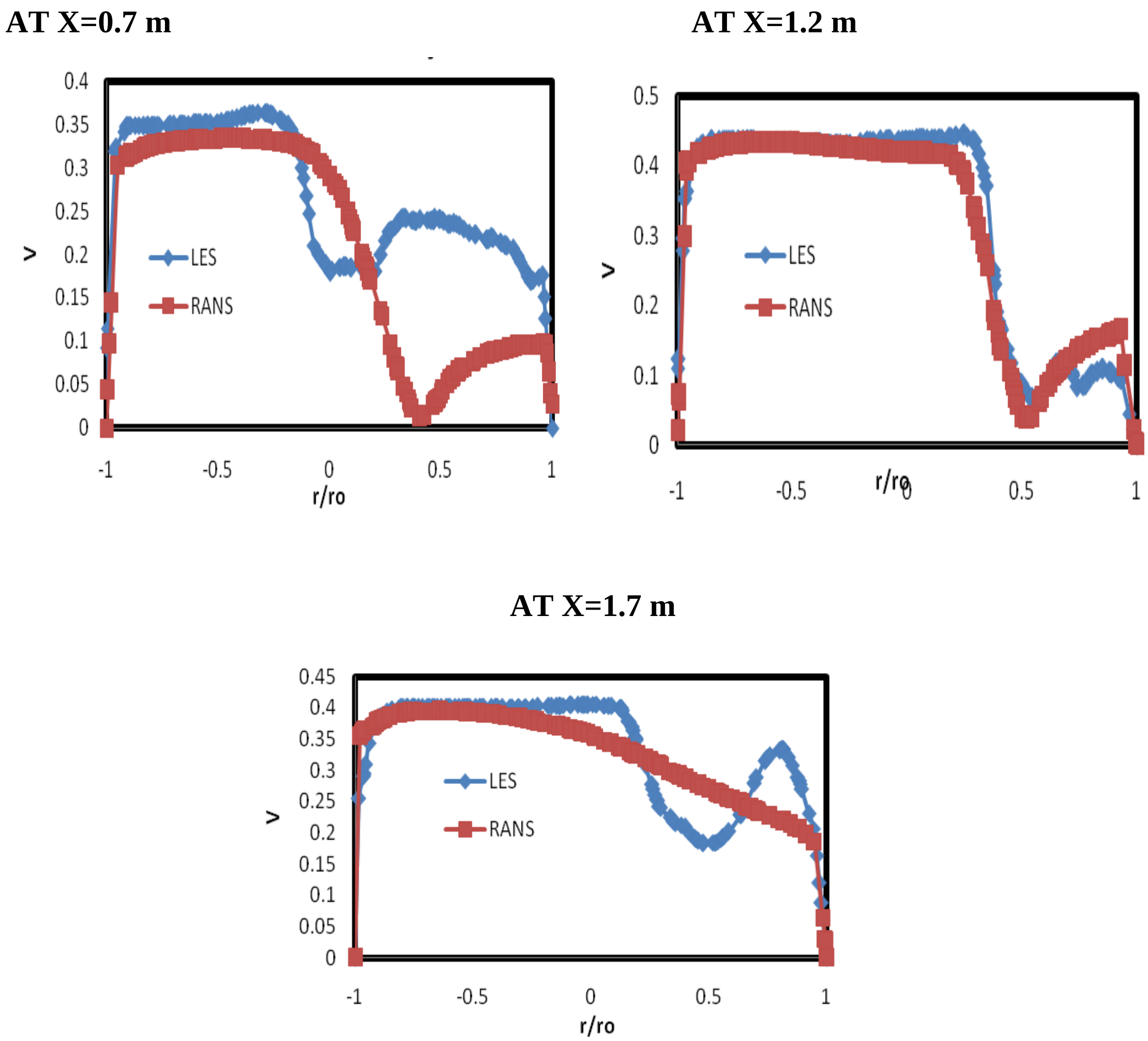


Figure 7.8 Comparison of velocity distribution along vertical direction at different locations using LES and RANS model.

Velocity profiles shown in figure 7.8 that near the junction (x = 0.7) LES model gives different velocity profiles than RANS models, this is because LES model consider the small eddies, near the junction when one fluid enters in other pipes its create turbulence in main pipe because of momentum transfer from one fluid to another fluid. But with time eddies dissipate and along length. So at location far from junction, RANS's and LES's velocity profiles are approximately same.

7.5 Contours of temperature and velocities for T-junction opposite to each other

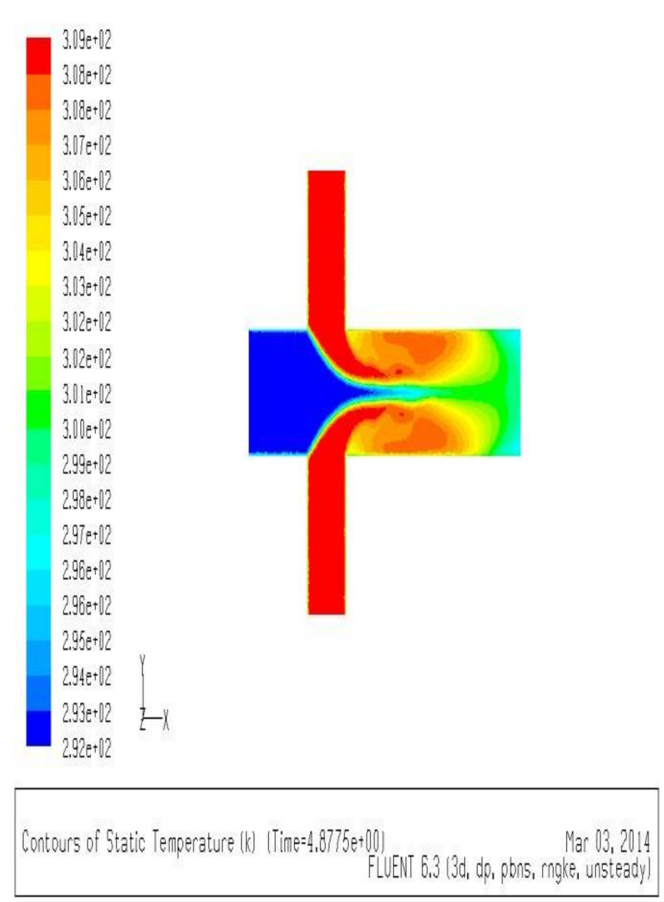
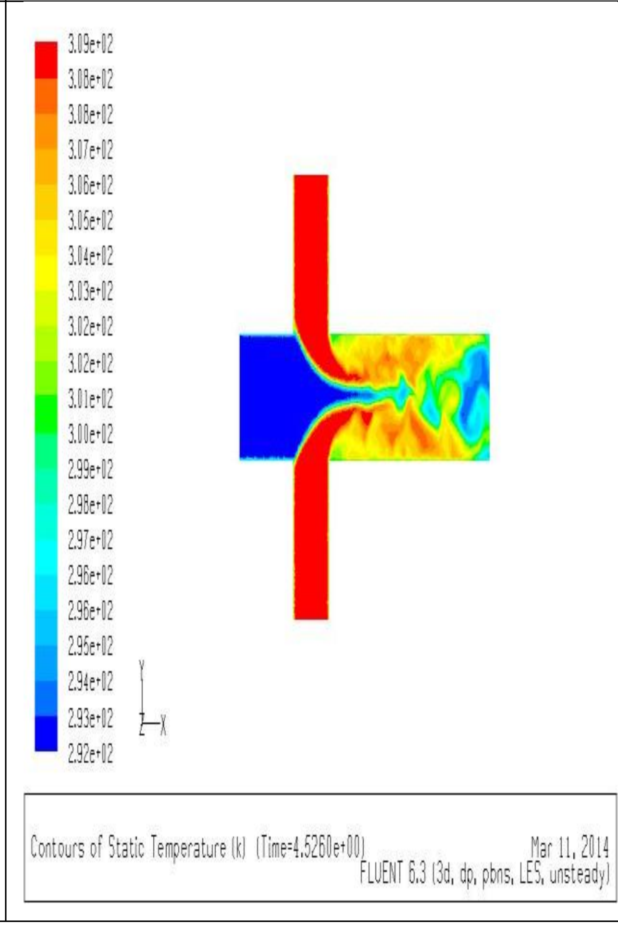
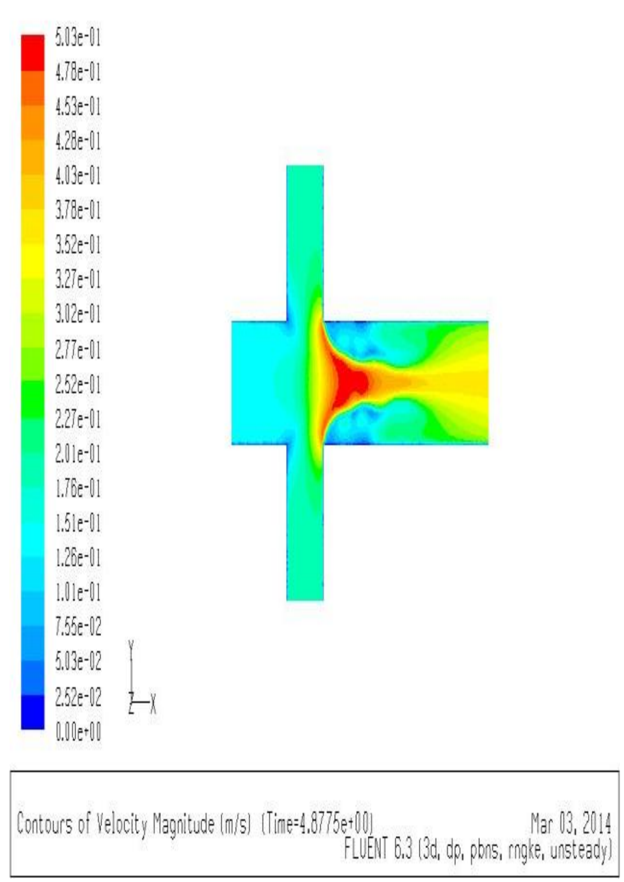
RANS	LES
	

Figure 7.9 Contours of temperature distribution at central plane section of the pipe using URANS(unsteady(left)) and LES(right) model**.**

RANS



LES

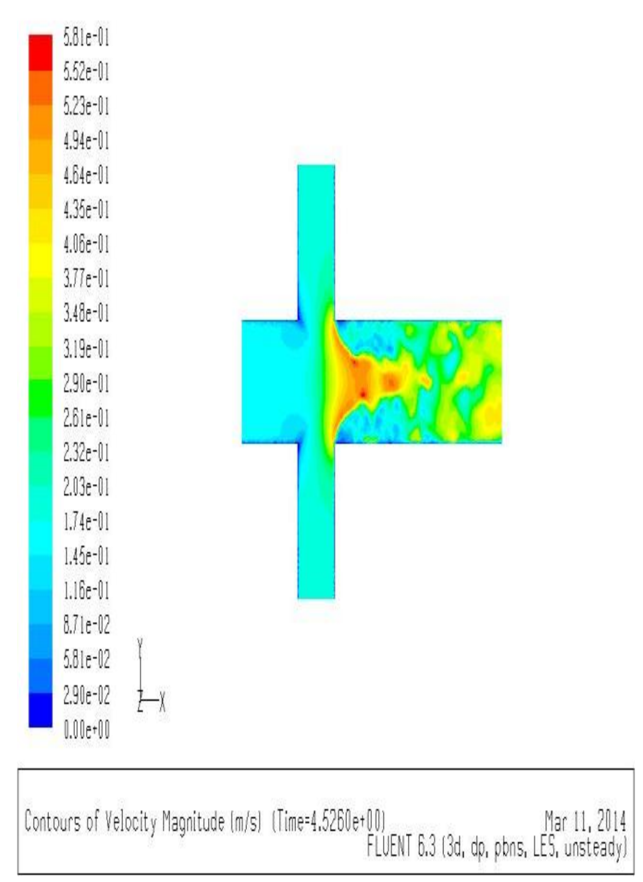
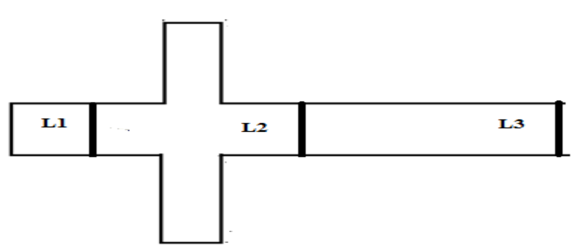


Figure 7.10 shows the comparison of contours velocity distribution at center part of the pipe using RANS(left) and LES(right)

Study of contours at different locations L1 = 0.2 m, L2 = 0.7 m, L3 = 1.2 m from inlet



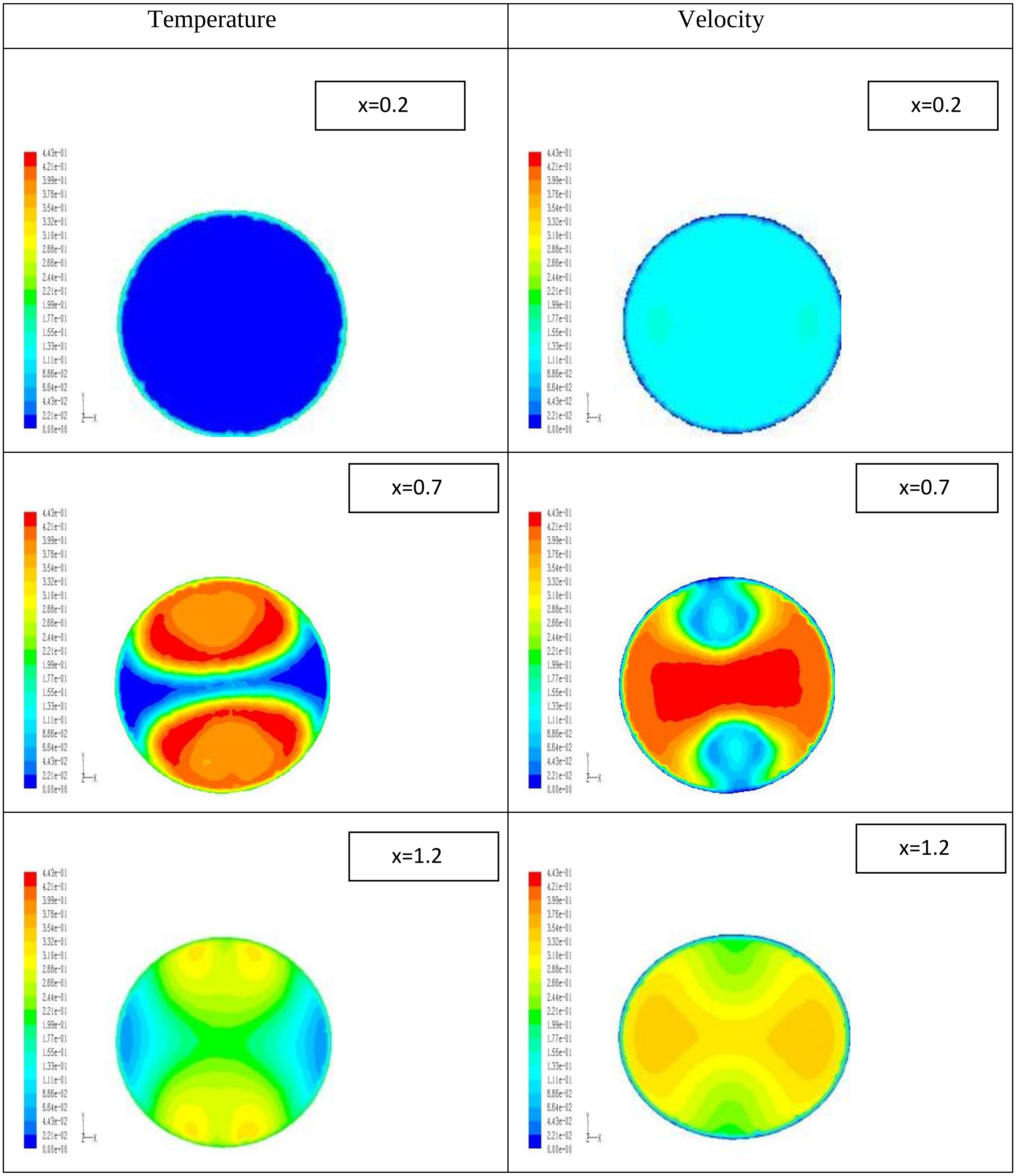


Figure 7.11 Cross section contours of distribution of temperature on the left and velocity on the right at different locations along the length of the pipe using RANS(unsteady) model

Temperature	Velocity

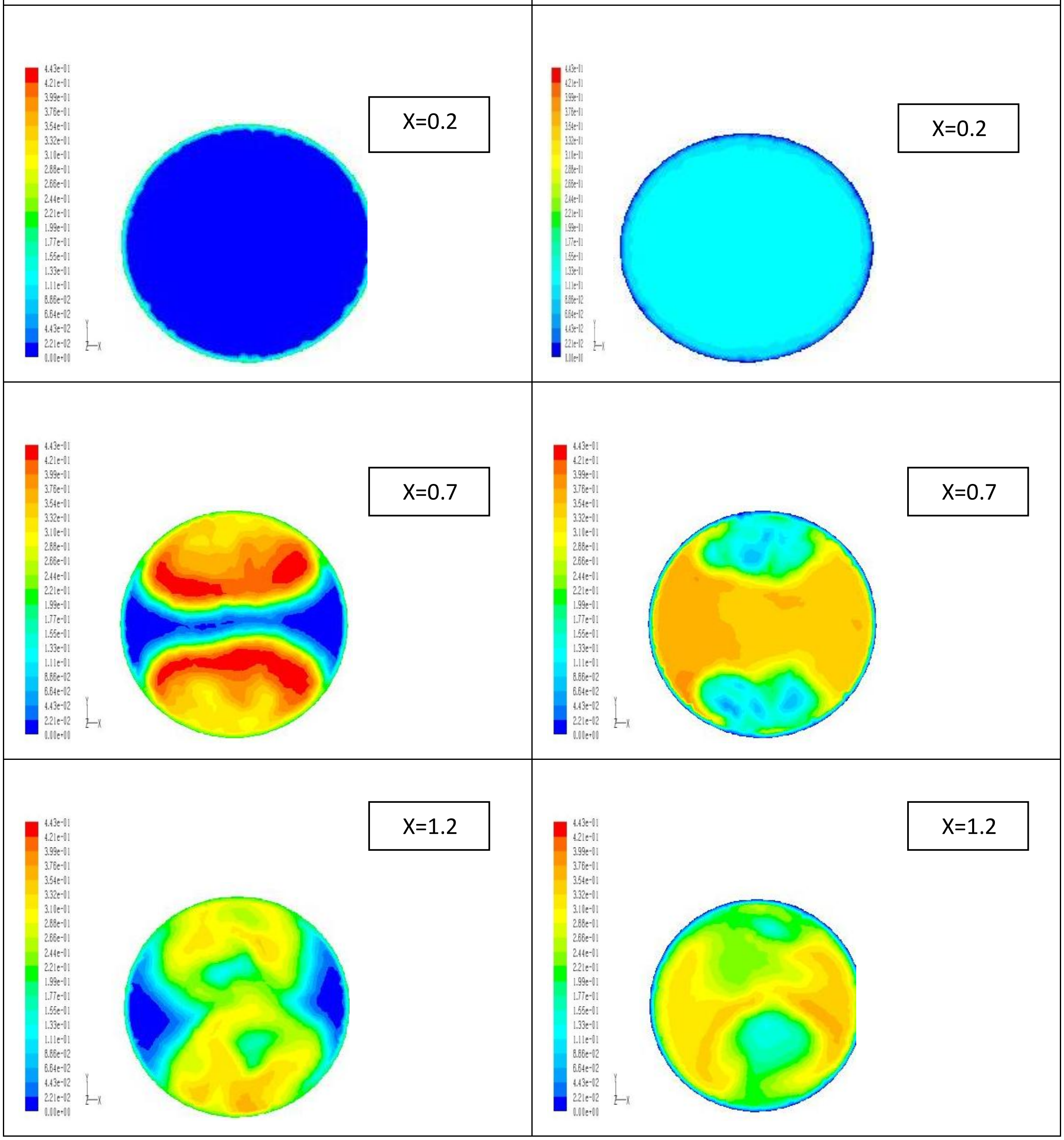
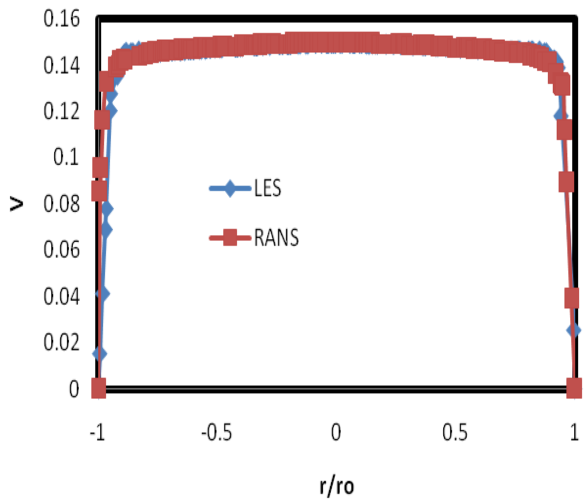


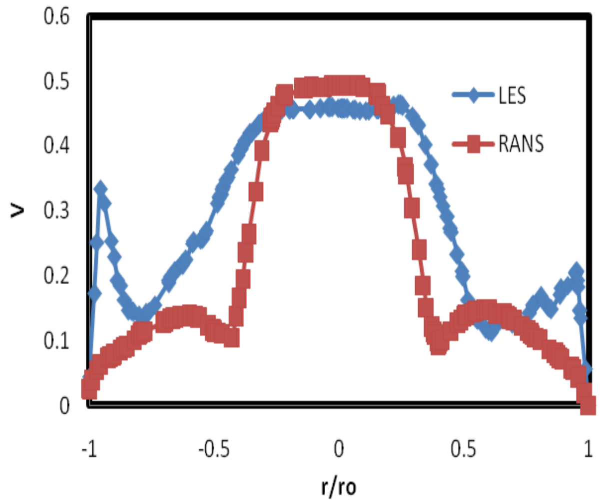
Figure 7.12 shows the cross-sectional views of distribution of temperature on the left and velocity on the right at different locations along the length of the pipe using LES model

7.6 Velocity profiles for T-junction oppiste to each other.

AT X=0.2 m



AT X=0.7 m



AT X=1.2 m

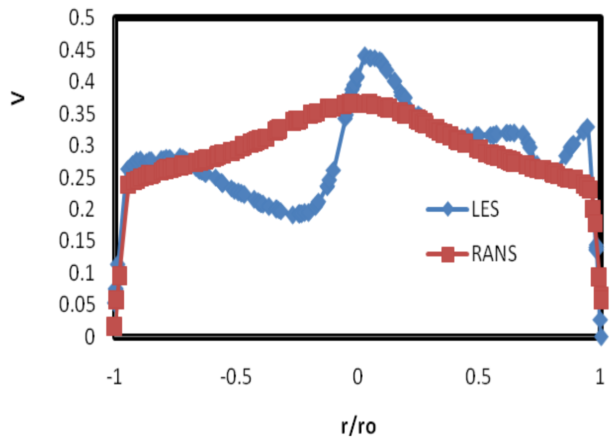


Figure 7.13comparison of velocity distribution along vertical direction at different locations using LES and RANS model.

It can be seen that before the junction, the velocity profiles are approximately same for both the models, but near and after the junction, i.e at x=0.7 m and x=1.2 m, velocity profiles are slightly different. This is due to the fact that LES models consider all the small scale eddies and also velocity reduces, this due to the high momentum ratio.

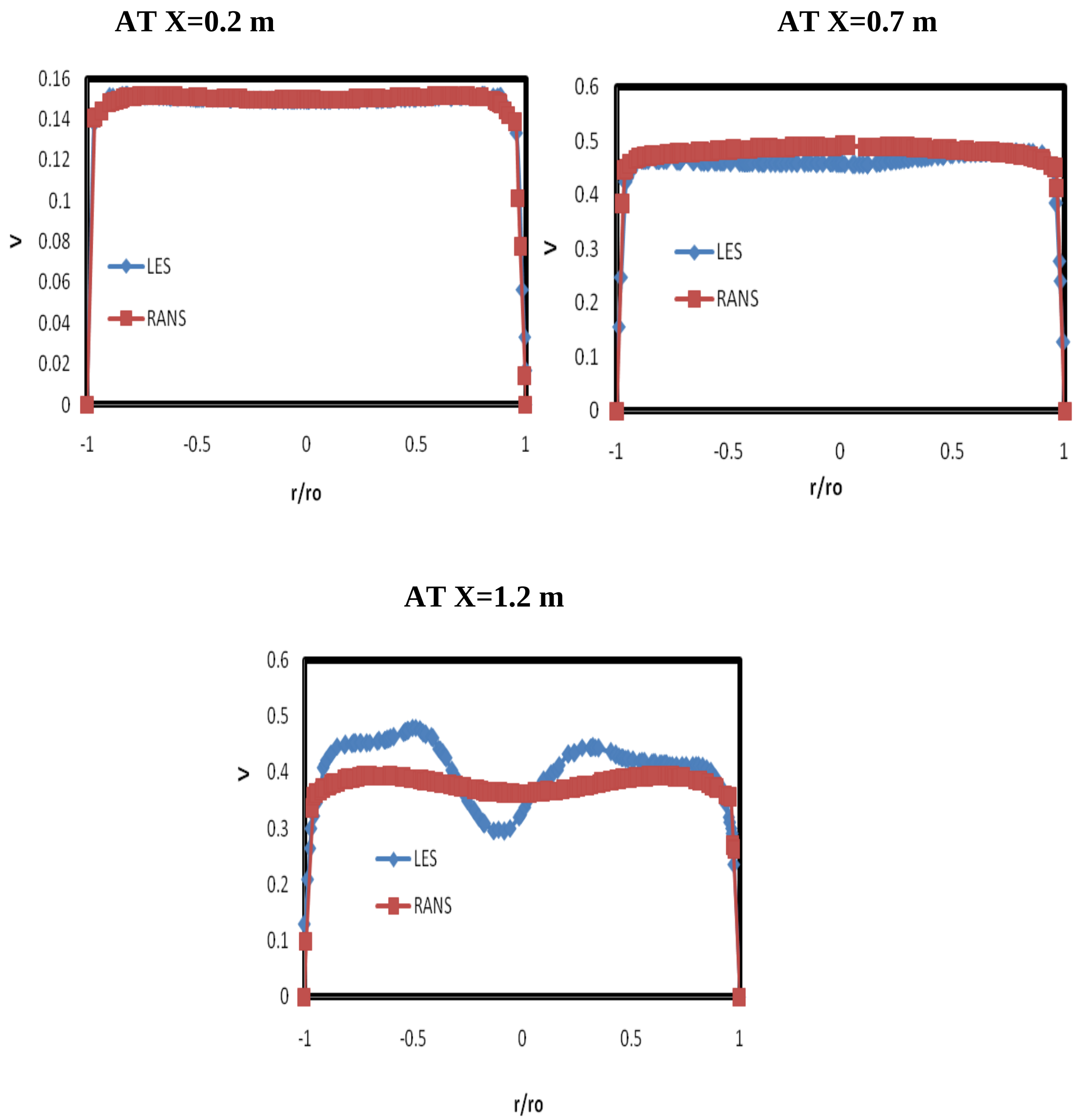


Figure 7.14 Comparison of velocity distribution along horizontal direction at different locations using LES and RANS model.

It can be clearly seen from the graphs that at x=0.2 m and at x=0.7 m, the velocity profiles are almost same. But at x=1.2 m velocity profiles are different, this is due to the fact that LES model consider all the small scale eddies while RANS model only gives the average velocity distribution.

Comparison of outlet temperatures in case a) and case b) using RANS and LES models

CASE a)

	RANS	LES
Hot Inlet1	36 K	36 K
Hot Inlet2	36 K	36 K
Cold Inlet	19 K	19 K
Outlet	21.71 K	20.66 K

CASE b)

	RANS	LES
Hot inlet1	36 K	36 K
Hot inlet2	36 K	36 K
Cold inlet	19 K	19 K
Outlet	24.91 K	24.09 K

CHAPTER 8

Conclusion

A CFD study was performed using streams of water at dissimilar temperatures in a different geometries of multi tee junction and,then compared using RANS(unsteady) and LES models. LES computations which uses eddy viscosity SGS model for calculations outcomed in adequately precise calculation of alterations in velocity and temperature. These alterations in temperature and velocity are essential to illustrate thermal fatigue. while the results of RANS computations, ,do not give adequate results.

Graphs presents the profiles of vertical and horizontal time averaged profiles of velocity at dissimilar locations. After junction, velocity profiles given by the two models are different. This is due to the fact that LES models consider all the small scale eddies while Rans model gives only average velocity distribution. It is observed magnitude of velocity reduces at the top of the pipe, due to the high momentum ratio in the pipe which is connected to horizontal pipe at the top. Due to this flow through the main pipe is blocked.

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