NUMERICAL STUDY OF OIL-WATER TWO PHASE FLOW IN HORIZONTAL & INCLINED TUBES

A DISSERTATION

Submitted in the fulfillment of the requirement for

the award of the degree

Of

MASTER OF TECHNOLOGY

In

CHEMICAL ENGINEERING

(With Specialization in Computer Aided process plant design)

By

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JUNE-2014

DECLARATION

I hereby assure that the work presented in this project report entitled **"Numerical Study of Oil Water Two Phase Flow in Horizontal/Inclined Tubes**" is submitted towards completion of research project work in M.Tech (CAPPD) at the Indian Institute of Technology Roorkee, is an authentic record of my original work carried out under the guidance of **Dr. Vimal Kumar**, Assistant Professor. I have not submitted the matter embodied in this project report for the award of any other degree.

Place: Roorkee **Vikas Kumar**

Date:

CERTIFICATE

This is to certify that Mr. VIKAS KUMAR has completed the research project report entitled "**Numerical Study of Oil Water Two Phase Flow in Horizontal/Inclined Tubes**" under my supervision. This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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ACKNOWLEDGEMENT

I would like to express my sincere gratitude to my supervisor, **Dr. Vimal Kumar**, Assistant Professor, Department of Chemical Engineering, Indian Institute of Technology, Roorkee, Whose Strengthen presence was a source of great inspiration for the successful completion of this project report. His constant guidance, useful criticism and constant help in the hours of need have been immensely useful.

I thank all well-wishers who in any manner directly or indirectly have put hands in any part of this work.

Vikas Kumar

Abstract

Oil-water two-phase flows in 0.056 m horizontal and inclined straight tubes have been simulated using control volume finite difference method (CVFDM). Volume of Fluid (VOF) model for multiphase flow and RNG k-ε turbulence model is adopted for simulated oil-water stratified flow. The volume of fraction (VOF) approach has been used to track the interface between oil and water phases. The angle of inclination has been varied from $\pm 5^0$, 0^0, $\pm 10^0$ from the horizontal. The simulations were carried out at different Reynolds numbers, i.e. 28324 and 58800, which resulted into turbulent regime. Due to very high Reynolds number considered in the present work, the Reynolds renormalize group (RNG) k–ε turbulent model has been used. The effect of inclination on velocity profiles, pressure drop, slip ratio and local phase fraction, and turbulent characteristics (i.e. turbulent kinetic energy and energy dissipation) are predicted. The estimated model is validated against numerical and experimental data reported in the literature for single phase flow in pipes. The main finding is the large difference between the results for the inclinations of tubes. It is postulated that the presence of gravity and magnitude of velocity responsible for the variation in velocity of individual phases, generation of turbulence, and volume phase fraction.

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Notations

Parameter	**Dimension**	**Definition**
g	ms^{-2}	acceleration due to gravity
k	m^2s^{-2}	turbulent kinetic energy
t	s	time
ε	m^2s^{-3}	turbulent dissipation rate
ρ	kg/m^3	density
µ	Pa.s	viscosity
ν	ms^{-1}	Velocity
V_q	ms^{-1}	q direction velocity
α_q		q-th phase fraction
α_o		volume fraction of oil
α_w		volume fraction of water
σ		surface tension
Re	[–]	Reynolds number
Pr	[–]	Prandtl number
U_x	ms-^{1}	Superficial velocity of phase x
S		Slip ratio
A+10		Angle +10^0
A+5		Angle +5^0
A-5		Angle -5^0
A-1		Angle +5^0

Abbreviations

CFD	Computational Fluid Dynamics
ID	inner diameter
OD	Outer diameter
VOF	volume of Fluid
RNG	Renormalized group

CHAPTER 1

INTRODUCTION

Analysis of immiscible liquid-liquid multiphase phase flow in tubes has been a subject of intense research for several decades due to its fundamental significance as well as many related industrial application, especially in the petroleum and process industries. Though liquid-liquid flow systems plays very significant roles in the petroleum and other industries, however very less attention has given as compared to the gas–liquid flow systems. Now-a-days, due to continues development in the technological development, liquid–liquid flow systems have attracted more and more interest in offshore oil industry. Typically immiscible liquid-liquid multiphase, i.e. oil–water, flow occurs in co-current manner of in petroleum products transportation, since oil and water are mostly produced at the same time. The transportation of crude oil is very important in the offshore facilities, where the oil is transported using pipelines to the processing facility. The water present in the crude oil significantly affects the transportation of petroleum oil from the well to an onshore platform (Al-Yaari et. al 2005). The oil transportation tubes lie on the seabed in either horizontal or inclined ways. During the transportation process the variation in water or oil volume fraction in the tubes can have a significant influence on pumping power required to pump the fluid, due to the change in the pressure drop across the pipeline.

During the oil production from the well, single – phase oil is produced during first period of its lifetime An oil reservoir is consisting of three zones due to the difference in density: a gas zone on top, an oil zone in the central and a water zone at the bottom.. As time proceed water come into the well from the reservoir, and well also produce water in addition to crude oil (Elseth et al., 2000). Further as the time proceed the water production from the well increases. The oil production from the oil production wells may be economical or not economical to operate even if the water cut is ≈90%. The presence of water in the pipe has significant effect on the transportation of mixture of oil and water from the reservoir to the onshore or processing platform, since the behaviour of liquid liquid two phase flow in a tubes behave different from single-phase flow (Kumara et al., 2010). For variable mixture velocities and the water volume fraction, the fluid might have different flow regimes in the pipe, which might influence the input power requirement during the pumping of the mixture.

The different parameters affects the flow regimes/patterns and water-oil distribution across the tubes cross-section are oil viscosity, input water cut and the pipe inclination input mixture velocity,. An extensive work is available for pressure drop and flow patterns in the horizontal pipes (Guo et al., 2003, Elseth et al., 2000, and Kumara et al., 2010). However, very less attention has been made on water oil flows in inclined tubes.. The oil flow through inclined pipes is very common for oil production from horizontal and deviated wells. Figure 1.1 shows a typical subsea oil production facility, which shows that the terrain for transportation of oil-water mixtures is not horizontal and encounter a flow through inclined tubes. Further on the offshore the mixture of water oil sometimes is transported through hilly areas as. Due to inclination of tubes may lead to more mixing of the water mixture and therefore affect the flow-patterns/regimes, holdup and pressure drop (Vedapuri et al., 1999).

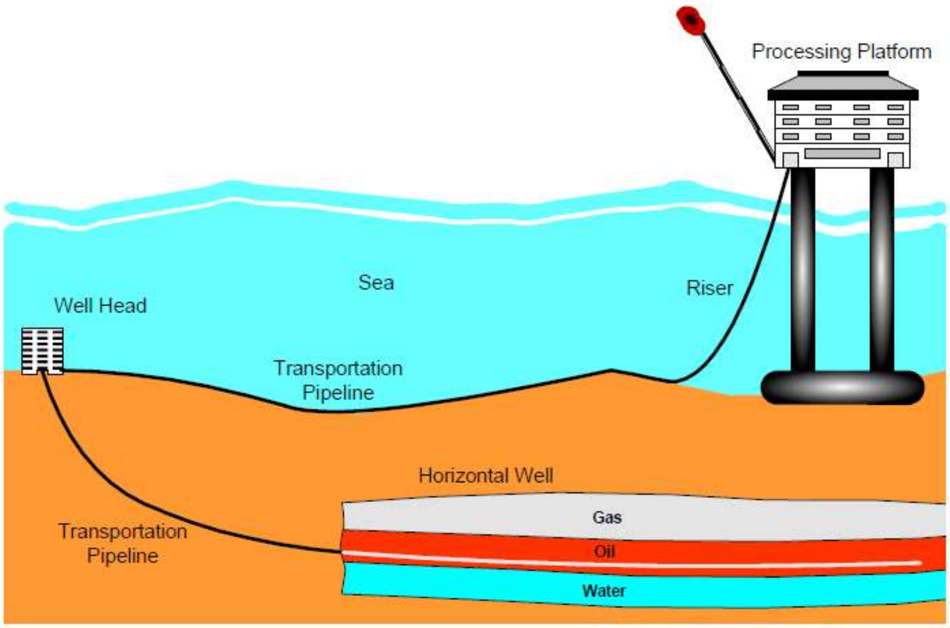


Figure 1.1 Schematic of the subsea processing arrangements. (Kumara et al., 2010)

1.1 Multiphase

Typically, in petroleum-industry a mixture of water and crude oil is transported from the drilling site to the offshore platforms and transportation of crude oil from one location to another location, which forms a multiphase flow system. A system which deals with the mixture of different immiscible phases is termed as the multiphase system. In multiphase flow systems a phase is a class of matter with a separate boundary and a unique dynamic response to the surrounding flow. Mostly, the phases are classified by solid, liquid and gases. Multiphase flow in process industries is simultaneous flow of materials with different states (solid, liquid, gas) and with different physical or chemical properties but in the same phase, i.e.

1. Gas-liquid
2. Liquid-solid flows
3. Liquid – liquid (e.g. oil–water)
4. Gas-solid flows
5. Three-phase flows

During gas-liquid or liquid-liquid flow in horizontal, vertical and inclined pipes, the fluid flow behaviour is different from the single phase flow systems. The simultaneous flow of different phases resulted into different flow patterns/regimes. These flow patterns may result from different flow rates of different phases. Some of the flow regimes are shown in Figure 1.2 and are also listed below:

1. Stratified/free-surface flow: immiscible fluid flow with a clear interface between the two fluids.
2. Wavy stratified flow: immiscible fluid flow with waves at the interface between the two fluids.
3. Bubbly flow: flow of fluid/gaseous bubbles in a continuous medium.
4. Slug flow: large bubbles flow in a continuous medium.
5. Droplet flow: flow of disperse fluid droplets in a continuous medium.

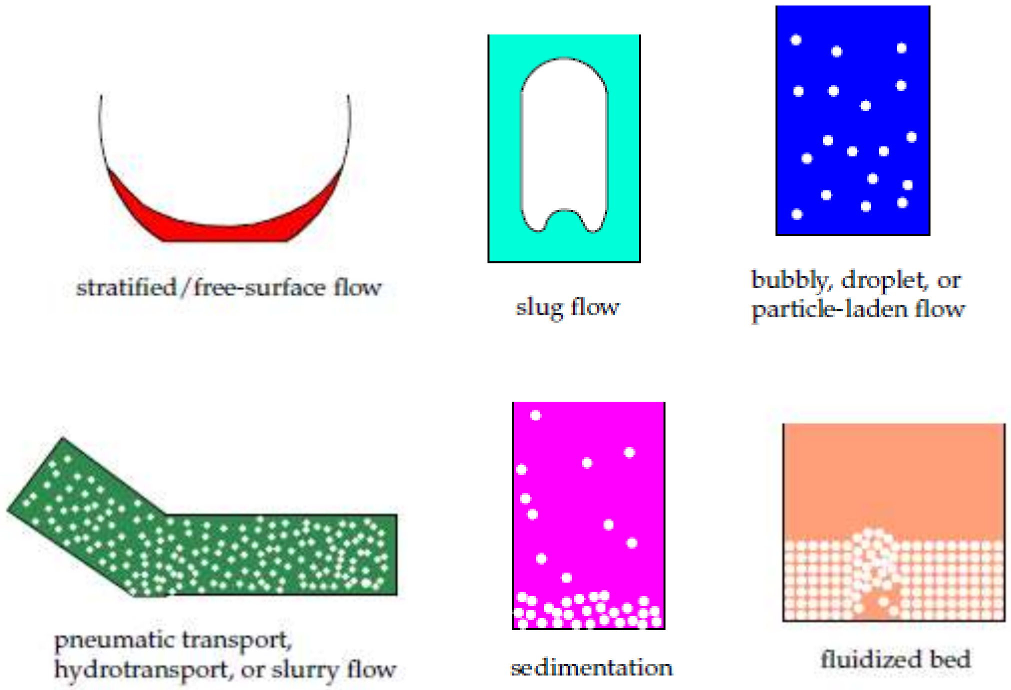


Figure 1.2 Types of multiphase flow (Source: Fluent Documentation 6.3, http://aerojet.engr.ucdavis.edu/fluenthelp/html/ug/node873.htm)

1.2 Objectives:-

The overall objective of the present work is to study the flow and volume fraction patterns, turbulent kinetic energy, turbulent energy dissipation, pressure drop and slip ratio for oil–water two phase stratified flow in pipes. The specified objectives of the present work are as follows:

1. State of art literature review of liquid-liquid (oil–water) two phase flow in pipes.
2. Model selection for turbulent and multiphase flow, and meshing of the geometry.
3. Grid sensitivity analysis and results validation.
4. Analysis of velocity profiles, flow patterns, liquid hold-up in horizontal and inclined straight pipes.
5. Analysis of Pressure drop, slip ratio and turbulence characteristics in two phase oil-water horizontal and incline pipe.

CHAPTER 2

LITERATURE REVIEW

An extensive literature has been studied for liquid–liquid two phase flow in pipes. It has been observed that most of these studied were focused on the observation of flow patterns, i.e. shape and spatial distribution of the liquid–liquid two–phase flow within the cross–section of the pipe; and pressure drop. It was further observed that a detailed understanding of liquid–liquid two–phase flow, in particular with oil–water two–phase flow, has been established through these years in horizontal and vertical flow systems. However, it has been observed that very less attention has been made on liquid–liquid two–phase flow in inclined pipes, though the angle of inclination affects the two phase flow patterns, which may also affect the pressure drop. Due to gravity buoyancy forces may lead to large slippage between the water-oil layers leading to an increased water volume fraction in the tubes.

Therefore the angle of inclination is an important parameter for crude oil transportation, which is a blend of crude oil and water, in petroleum industry. So it was essential to study the fundamentals of liquid-liquid two phase flow with primary concern on flow regime and volume fraction evaluation at various tubes inclinations (Vedapuri et al., 1999). In this chapter the literature is limited to some of the important work done on liquid–liquid two–phase flow, i.e. water oil two phase flows in straight horizontal and inclined tubes.

2.1 Oil – water two phase flow in horizontal pipes

There is an extensive literature available on the water-oil two–phase flow in straight horizontal pipes. In this review, the work carried out in last two decades has been reported for water and oil two–phase flow in straight horizontal tubes. Angeli *et al.* (1998) experimentally studied the pressure gradients for co-current flow of low viscosity water-oil in horizontal pipes ($D = 0.0254$ m), made of stainless steel and acrylic resin, for different velocities and water volume fractions. The large difference between the results due to tube materials was reported, which cannot be expressed not only in terms of the difference in tube roughness but the different wettability characteristics properties of the tubes formation materials is also responsible for this incongruity. It was also found that at high Reynolds number, where dispersed flow patterns occurs, there was a peak in pressure gradient during phase inversion and an apparent drag reduction effect when oil is the continuous phase.

Gao *et al.* (2003) numerically studied the pressure drop, liquid holdup, the axial velocity and slippage , for the water-oil two phase flow in the straight horizontal pipe and also verified with experimental data in literature. Stratified water oil two phase flow in a straight horizontal pipes is simulated numerically with VOF model. The simulation is done in a time dependent way and the final solution which relates to steady-state flow is studied. Numerical results the flow field characteristics, correlations for pressure-drop and liquid holdup are presented. Based on the simulated results, the correlation for pressure loss per unit length is regenerate as:-

$$\left(\frac{dp}{dz}\right)_{TP} = \phi^{-1.87} X^{-2.02} \left(\frac{dp}{dz}\right)_{m} \tag{2.1}$$

where $\left(\frac{dp}{dz}\right)_{TP}$ is the two–phase oil–water stratified flow pressure loss and $\left(\frac{dp}{dz}\right)_{m}$ is frictional pressure drop.

Elseth *et al.* (2001) experimentally study the behavior of flow of water-oil in horizontal straight pipe (D =0.0508m). Pressure drops, slip ratio, velocity profiles, turbulence distributions and liquid holdup are measured for a various number of flow-conditions. A typical flow parameters measuring instrument laser Doppler anemometer (LDA) is used and applied at a transparent part of test pipe. Stratified and dispersed types of flow are observed. Experimental works involved two flow facilities, model oil facility and match refractive index facility which act as model for horizontal pipes and good for oil production.

Walvekar *et al.* (2009) has been studied volume phase fraction profiles and average in-situ phase fraction on the 3D flow of liquid-liquid immiscible fluids in a horizontal pipe using computational fluid dynamics models. The unsteady state numerical simulations of liquid-liquid two-phase dispersed type flow in a pipe of inner diameter=0.0024 m have been done using commercial Computation fluid dynamics software FLUENT with multiphase model. Oil–water system is selected as the two-phase system in this work. The k−ε viscosity model was implemented to explain the turbulence characteristics in continuous phase.

Cai *et al.* (2012) Experimental studied about cause of corrosion due to wettability properties of oil and water on a pipe wall during transportation of water and oil two phase flow in straight horizontal tubes. Experiments were conducted in a large diameter inner diameter = 0.1m) horizontal loop using four measurement methods: conductivity pins, fluid sampling and monitoring of corrosion-rate and flow-pattern visualization, Five different oil/water flow patterns were observed and a flow regime map was formed. The results from the conductivity pins measurement techniques showed three types of wetting behaviors: stable water wetting, intermittent-wetting and stable oil wetting. The results of the fluid sampling which was using for conducted experiments were consistent with the wetting results from the one of the measuring technique i.e conductivity pins.

Al-Wahaibi *et al.* (2012) pressure drop per unit length correlation for straight horizontal water-oil separated flow (stratified and dual continuous flows) was reported based on the on experimental work of Angeli and Hewitt (1998). Zigrang and Sylvester friction factor correlation was changed and modified for water-oil multiphase flow. The pressure gradient equation was validated with the experimental pressure gradient results.This is the first pressure drop/gradient work that published for water oil flow which includes good range of working conditions, fluid properties, pipe diameters and materials The correctness of the equaiton was also checked with the two-fluid model. The % errors and standard-deviation for the predicted and measured results were shown. The proposed equation predicts the pressure drop per unit length with larger accuracy than the two-fluid model.

2.2 Oil – water two phase flow in inclined pipes

Oddie *et al.* (2003) experimentally study types of flow, holdup using unsteady-state and steady state experiments of gas water, oil water and oil–water–gas multiphase flows on a a transparent and inclined tubes with kerosene, water and N_2(nitrogen) (11 m long, D =15 cm). Large number of experiments conducted using inclined pipes The scope of pipe inclinations were from 0^0 (vertical) to 92^0 and the flow rates of each phase were varied over wide ranges.. more results for phase fraction as a relation with flow rates, flow pattern and pipe inclination is presented, and the various methods for measuring holdup are compared.

Rodriguez and Oliemans (2006) Conducted experiments on mineral-0il and brine two phase flow in a (15 m length , .0.828 mm dia) inclined steel tubes. A stratified wavy flow pattern was obtained in downward direction flow and upward direction flow. large results of phase fraction and two-phase pressure drop as a relation with superficial velocities, flow pattern and inclinations are presented. Two phase pressure drop and local phase fraction were taken over the large range of flow rates and for tube inclinations $\pm 5^o$, $\pm 2^o$, $\pm 1.5^o$, 0^o, $\pm 1^o$..

Rodriguez *et al.* (2012) Pressure gradient and holdup data are studied for oil–water flow in a horizontal and inclined pipe (D = .026 m) with different inclinations of $\pm 10^0$, -20^0, from horizontal. A wavy\stratified flow is observed in the laminar turbulent region . The relatively low Reynolds number leads the friction and the low Eotvos number indicates the existence of a wavy and curved interface pattern. A good correlation for the friction factor is presented which is based on the equivalent-sand-roughness parameter concepts. An explicit\equation for the interface structure which. is a function of the Eotvos number, phase fraction and contact angle based on the constant-curvature-arc model is given, It was also find that lighter phase has lower friction factor than single phase friction factor.

CHAPTER 3

MODELLING AND SIMULATION

There are different types of turbulent and multiphase flow models are available in the literature. In the present work volume of fraction approach has been used to track the interface between oil and water phases. The brief description of multiphase and turbulent flow models are reported in sections 3.1 and 3.2, respectively. Further the geometrical and physical parameters used in the present word are discussed in section 3.3. In section 3.4 the grid topology and boundary conditions considered in the present work are discussed.

3.1 Modeling approach for multiphase flow

There are two approach of numerical calculation of multiphase flow:-

1. Euler-Euler approach
2. Euler-Lagrange approach

3.1.1 Euler-Euler approach

. There are three different Euler-Euler multiphase models are available:

1. The volume of fluid model.
2. The mixture model.
3. The Eulerian model.

In the Euler-Euler approach, the different phases are treated mathematically as interpenetrating continua. Due to volume of phase of a one fluid cannot be occupied by the other phases, the concept of phase's volume fraction is presented. These volume fractions of one of the phase are assumed to have continuous relation of space and time and other phase is second phase so that their sum = 1. Mass, Momentum, energy conservation equations for each phase are expressed and derived for obtain a set of equations, which have same nature for all phases. These equations are closed by providing constitutive relations that are obtained from empirical information, or, in the case of granular flows, by application of kinetic theory

3.1.1.1 Volume of Fluid (VOF):-

The VOF model is a surface-tracking tool applied to a not moving i.e fixed Eulerian mesh. It is formed for multiphase immiscible fluids when the surface of interface between the fluids is our interest. In this model, a single set of momentum equations is used by the liquid/gas multiphase fluids, and the holdup of each of the fluids in each computational grid is tracked throughout the interseted domain. This model technique is used for simulating the oil-liquid two phase flow on FLUENT 6.2.23

In this study, the Volume of fluid model is used to study the dynamics of stratified fflow of water and oil in horizontal/incline straight pipes. In the volume of fluid model, a marker function (phase fraction) is used to check the interface of fluid phases. If α_q is the volume phase fraction of the qth phase in a computational grid, then the expression $\alpha_q=1$ entail that the computational grid completely filled with phase q, $\alpha_q = 0$ entail that the computational cell has no phase q, and a value of α_q in the range of zero and one implies that the unit control volume contains the interface between phases p and q.:-

$$\frac{\partial}{\partial t}(\rho) + \nabla.(\rho\bar{v}) = 0 \tag{3.1}$$

$$\frac{\partial}{\partial t}(\rho\vec{v}) + \nabla.(\rho\vec{v}\vec{v}) = -\nabla p + \nabla.[\mu(\nabla\vec{v} + (\nabla\vec{v})^T] + \rho\vec{g} + \vec{F} \tag{3.2}$$

ρ is the volume-fraction-weighted density, which is defined as

$$\rho = \alpha_q\rho_q + (1 - \alpha_q)\rho_p \tag{3.3}$$

The phase fraction correlation will not be solved for primary phase; the primary phase fraction will be calculated based on the following constraint:-

$$\sum_{q=1}^{n} \alpha_q = 1 \tag{3.4}$$

The surface tension (F) used in eq. 3.2 was calculated using the eq. 3.5 as given below

$$\vec{F} = \sigma \left[\frac{\rho \kappa \acute{n}}{\left(\frac{1}{2}\right)\left(\rho_p + \rho_q\right)} \right] \qquad (3.5)$$

where κ the local surface curvature and is given by

$$\kappa = \nabla . \acute{n} \qquad (3.6)$$

σ is the coefficient of surface tension, nˆ the surface normal vector expressed in term of oil holdup valve θ_0 , as $n = \nabla\theta_0$.

3.2 Turbulence

A turbulence model is a computational procedure to the close system of mean flow equations. General turbulence models are

Classical models. -Based on Re Averaged-Navier-Stokes (RANS) equations (time averaged):

1. 1 equation model: Spalart Almaras.
2. 2 equations models: k-ε styles models (standard, RNG, realizable), k-ω model and ASM Non-liner models.
3. 7 equation model- Re stress model
4. mixing length model- Zero equation model:

- The number of equation represents the number of extra PDEs used for calculations.

3.2.1 Two - equation model:-

By using a two-layer turbulence model the turbulent viscosity is calculated. The full computational domain is divided into a viscosity-affected region and a fully turbulent region determined by a wall-distance based turbulent Reynolds number Re. (Gao et al. 2003)

$$Re_n = \frac{\rho\sqrt{k}\eta}{\mu} \qquad (3.7)$$

where η is the perpendicular distance from the wall to the cell centers. RNG k–ε model is employed in the fully turbulent portion (Re > 200), although in the viscosity affected region (Re< 200), a low Re k–ε model is used. The RNG k–ε model used in the present work is derived using a good mathematical technique, which has an additional term in its ε equation which largely enhance the accuracy.A fine mesh was considered near the solid surface with a mesh size of 0.0001, and a standard wall function was used to capture turbulence behavior near the solid surface. The k- ε model has been the standard turbulent model for the engineering purposes due to its stability and fairly good performance in simulation of many industrial flows. Complete set of continuity and RANS equations with standard k-ε closure model (from Fluent 6.3) has been described as follows:

$$\frac{\partial U_i}{\partial t} + U_j\frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x_j} - \frac{2}{3}\frac{\partial k}{\partial x_i} + (\nu + \nu_i)\frac{\partial}{\partial x_j}\left(\frac{\partial U_i}{x_j} + \frac{\partial U_j}{x_i}\right) \qquad (3.8)$$

$$\frac{\partial k}{\partial t} + U_j\frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\nu + \frac{\nu_t}{\sigma_k}\frac{\partial k}{\partial x_j}\right) + (\nu_t)\left[\left(\frac{\partial U_i}{x_j} + \frac{\partial U_j}{x_i}\right)\frac{\partial U_i}{x_j}\right] - \varepsilon \qquad (3.9)$$

$$\frac{\partial \varepsilon}{\partial t} + U_j\frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\nu + \frac{\nu_t}{\sigma_k}\frac{\partial k}{\partial x_j}\right) + \left(C_{\varepsilon 1}\nu_t\frac{\varepsilon}{k}\right)\left[\left(\frac{\partial U_i}{x_j} + \frac{\partial U_j}{x_i}\right)\frac{\partial U_i}{x_j}\right] - C_{\varepsilon 2}\frac{\varepsilon^2}{k} \qquad (3.10)$$

$$\nu_t = C_\mu\frac{k^2}{\varepsilon} \qquad (3.11)$$

The values of the constants appearing in equation 3.8 – 3.11 are as follows:

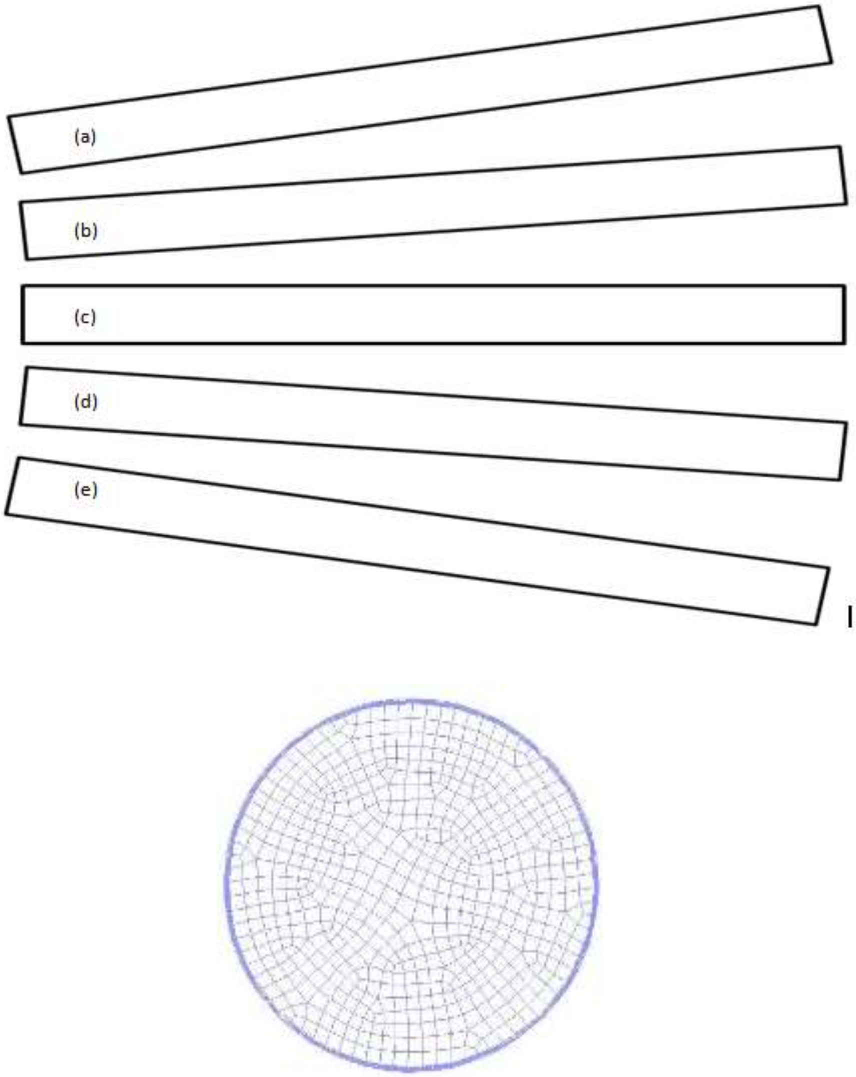
$C_\mu = 0.09, \sigma_k = 1, \sigma_{z1} = 1.3, C_{z1} = 1.44, C_{z2} = 1.92$

3.3 Physical Parameters and Geometrical Details

The three dimensional flow of immiscible oil -water multiphase system in a horizontal and incline straight pipe was numerically studied considering Exxsol-D60 as dispersed phase and water as continuous phase. The geometrical and physical properties of fluids considered in the present work and the Reynolds for the considered oil and water are shown in Table 3.1 and 3.2, respectively. Stratified oil–water two-phase turbulent flow in a horizontal/incline pipe is numerically simulated using a volume of fluid model, ANSYS, Fluent 6.3.26.. The angle of inclination was considered as $\pm 10^0$, 0^0, $\pm 5^0$ from the horizontal. The total length of pipe considered was 5 m, which is more than that required to develop the fully developed (≈5D) flow in pipes. The geometrical and physical parameters considered were taken from the Elseth et al. (2003). The geometry and grid formation are carried out in Gambit 2.4.6, and are shown in Figure 3.2. The total 501,500 mesh volume of hexahedral type meshing scheme were considered. A refined grid was considered near the solid surface with 0.0001 grid size, increasing at an interval of 1.1 till 5 mesh point. The simulations were carried out on a 2.40 GHz Xenon Processor CPU, and which took ≈9 seconds for a single iteration.

Table 3.1 Fluid Properties and Geometrical details (Source: Elseth, 2006)

Parameters	Oil: Exxsol D-60	Water
Density (kg/m^3)	790	1000
Viscosity @ 20 ^{0}C (kg/m.s)	0.00164	0.00102
Interfacial tension @ 25 ^{0}C (N/m)	0.043	
Inner pipe diameter (m)	0.056	
Pipe roughness (m)	0.00001	
Pipe inclination	$\pm 10^0$, 0^0, $\pm 5^0$	
Length of pipe(m)	5	



(f)

Figure 3.1 (a) +10^{o} incline straight pipe geometry, (b) +5^{o} incline straight pipe geometry (c) horizontal straight pipe geometry, (d) -5^{o} incline straight pipe, (e) -10^{o} incline straight pipe geometry and (f) grid Topology at a cross section in the pipe.

Table 3.2 Reynold's Number for oil and water phases.

Reynolds's Number		
Velocity m/s	Oil	Water
0.25	6743	14000
1.05	28324	58800

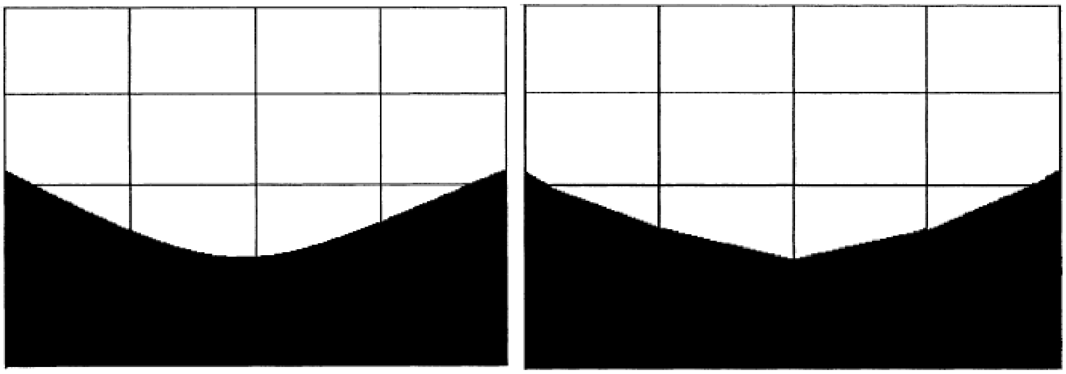
3.4 Boundary conditions:

There are three types of boundary conditions are used for this work: the inlet boundary, the wall boundary and the outlet boundary. Flat and constant mixture velocity profile for water and oil were introduced at the inlet. The outlet boundary condition for the model was set up as a pressure outlet boundary, i.e. all the flux becomes zero at the outflow boundary. No slip boundary condition was implemented to model liquid velocity at the wall.

$V_z = V_y = V_x = k = \mu_t = d\varepsilon/dx_i = 0.0$

where xi is the vector perpendicular to the pipe wall.

In order to track the interface between the two immiscible phases the fluxes (such as convection and diffusion) through the control-volume were predicted using geometric reconstruction scheme with a piecewise-linear approach. The geometric reconstruction scheme assumes that the interface between two fluids is a linear slope within each cell. Figure 3.2 illustrates the reconstruction of the interface using of the geometric reconstruction scheme. The details for the geometric reconstruction scheme can be seen from the Fluent documentation (ANSYS).



(a) (b)

Figure 3.2 (a) Actual shape of the interface, and (b) the shape of the interface calculated using geometric reconstruction technique.

The physical boundary conditions considered in the pipe for multiphase flow of oil and water are as follows: initially at time (t) = 0, flow in a pipe is saturated with water, i.e. oil fraction is 0. As the time proceeds, i.e. t > 0, oil was started entering through the inlet boundary with velocity, v m/s, in a positive x–direction at a specified water cut.

CHAPTER 4

NUMERICAL MODELLING OF OIL-WATER TWO-PHASE FLOW IN STRAIGHT INCLINED AND HORIZONTAL TUBES

The computational fluid dynamic models are used to study the stratified water oil two phase flow in straight horizontal and inclined tubes. The velocity and volume fraction profiles, pressure drop, slip ratio, turbulent kinetic energy and energy dissipation were estimated at different Reynolds number and water cut. The velocity profiles in horizontal tubes were validated with experimental data available in the literature and are discussed in section 4.1.

4.1 Validation of numerical model with experimental data in horizontal pipe

The results of oil-water two phase stratified flow in horizontal straight pipe is validated with the experimental results of Elseth *et al.* (2000) and numerical results of Gao *et al.* (2003) and are shown in Figures 4.1 (a–c). In case of horizontal pipe the simulations were carried out at different water cuts (25%, 50%, and 75%) and for velocity of 1.05 m/s (Elseth *et al.*, 2000; Gao *et al.*, 2003). The present predictions of velocity profiles at different water cut were found in good agreement with the experimental data of Elseth *et al.* (2003) and numerical predictions of Gao *et al.* (2003). Further it can be seen that the present predictions are in good relation with the experiemtnal results as compared to the results reported by Gao *et al.* (2003). Figures 4.1a show that in case of 50% water cut the velocity profiles are not symmetrical; however it shows higher velocities at the upper half section of the pipe. For 25% water cut the maximum velocity was in the oil–phase region (i.e. upper half of the pipe).

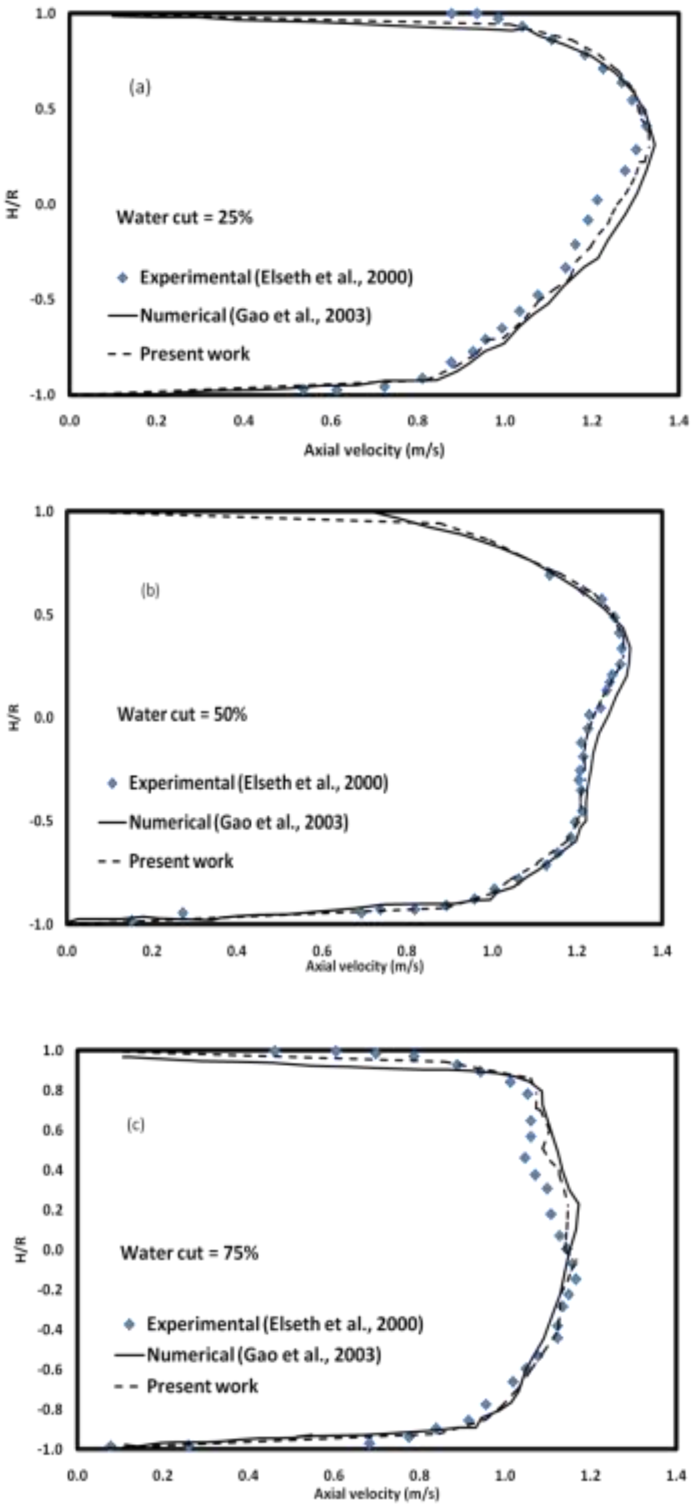


Figure 4.1 Comparison of velocity profiles of predicted in the present work with the experimental data of Elseth *et al.* (2001), and numerical results of Gao *et al.* (2003) for oil-water two phase flow in horizontal pipe at different water cuts (a) 25%, (b) 50% and (c) 75%.

4.2 Phase fraction profiles in horizontal and inclined pipes at different water cuts and velocities

The phase fraction contours and profiles are shown in Figures 4.2–4.3 and 4.4–4.5, respectively, at different velocities and water cut. The contours for phase fraction analysis were captured near the outflow boundary. The red color in the contours indicates the oil–phase and the blue color indicates the water–phase. Figure 4.2, shows that, at higher velocity, as the angle of inclination increase from horizontal the turbulence in the pipe cross–section increases. Further Figure 4.2 also shows that for horizontal pipe the flow is stable, however in case of pipe with $+10^0$ inclinations the flow is highly unstable, and looks like chaotic flow. However, in case of fluid flow with low Reynolds number (or velocity) there is not turbulence in the pipe cross–section and the flow is stable in all the cases.

Further it was observed that the liquid hold-up increases as the angle of inclination increase and decrease as the angle of inclination decreases in case of low Reynolds number for all the water cut studied in the present work (25%, 50% and 75%). However, no effect of angle of inclination was observed on liquid – holdup at higher Reynolds numbers. The similar observations can be seen, from Figures 4.3 and 4.4, i.e. phase fraction profiles. It can be seen that at higher Reynolds number (i.e. v = 1.05 m/s) fluid flow is highly turbulent and it is not stabilized for the domain considered in the present work, i.e. the pipe length of 5 m.

From Figure 4.4b and 4.4c (Re = 28000) it can be seen that the liquid hold–up is same for $+5^0$ and $+10^0$ inclined pipes. Figure 4.5 shows that at lower water cut values there are high fluctuations in the phase fraction profiles for $+10^0$ inclined pipes. The liquid hold–up is affected by the angle of inclination at higher water cut, however at low water cut there is minor change in the liquid hold–up.

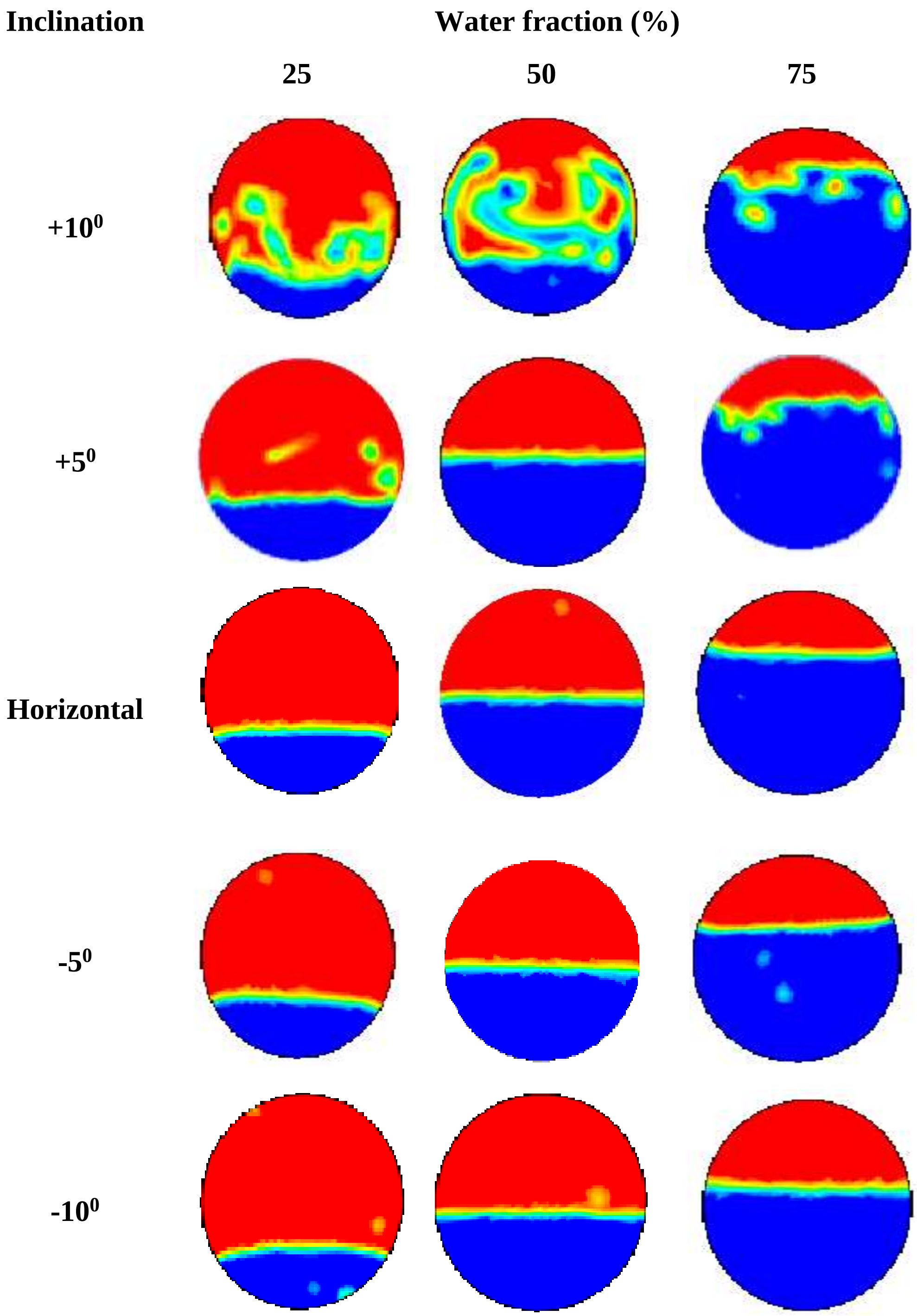


Figure 4.2 Contours of phase fraction for different inclination at cross section plane & V = 1.05 m/s near the outlet of pipe (red colur denote oil phase while blue colour denote water phase).

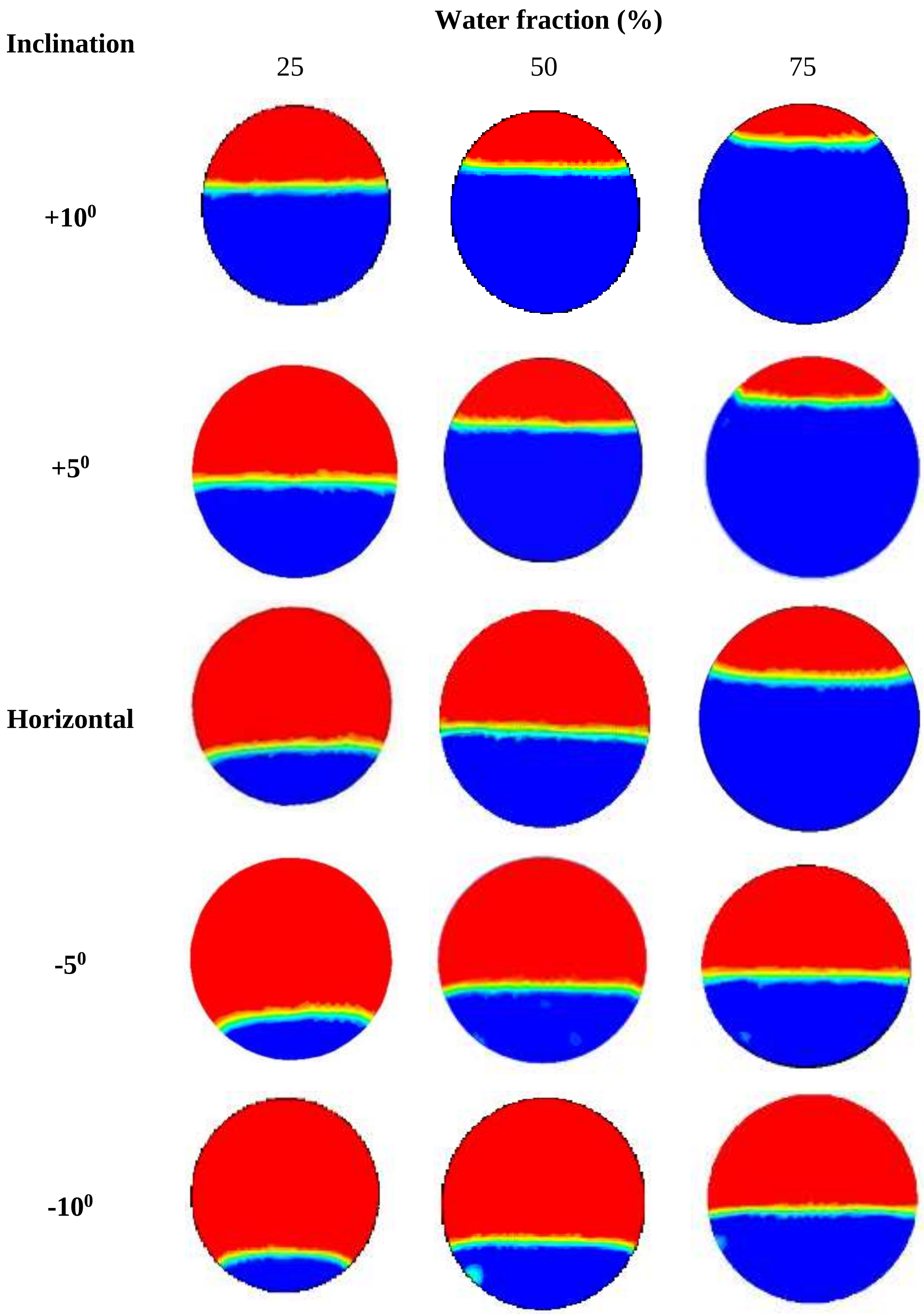


Figure 4.3 Contours of phase fractions for different inclinations at cross section plane & V = 0.25 m/s near the outlet of pipe (red colur denote oil phase while blue colour denote water phase).

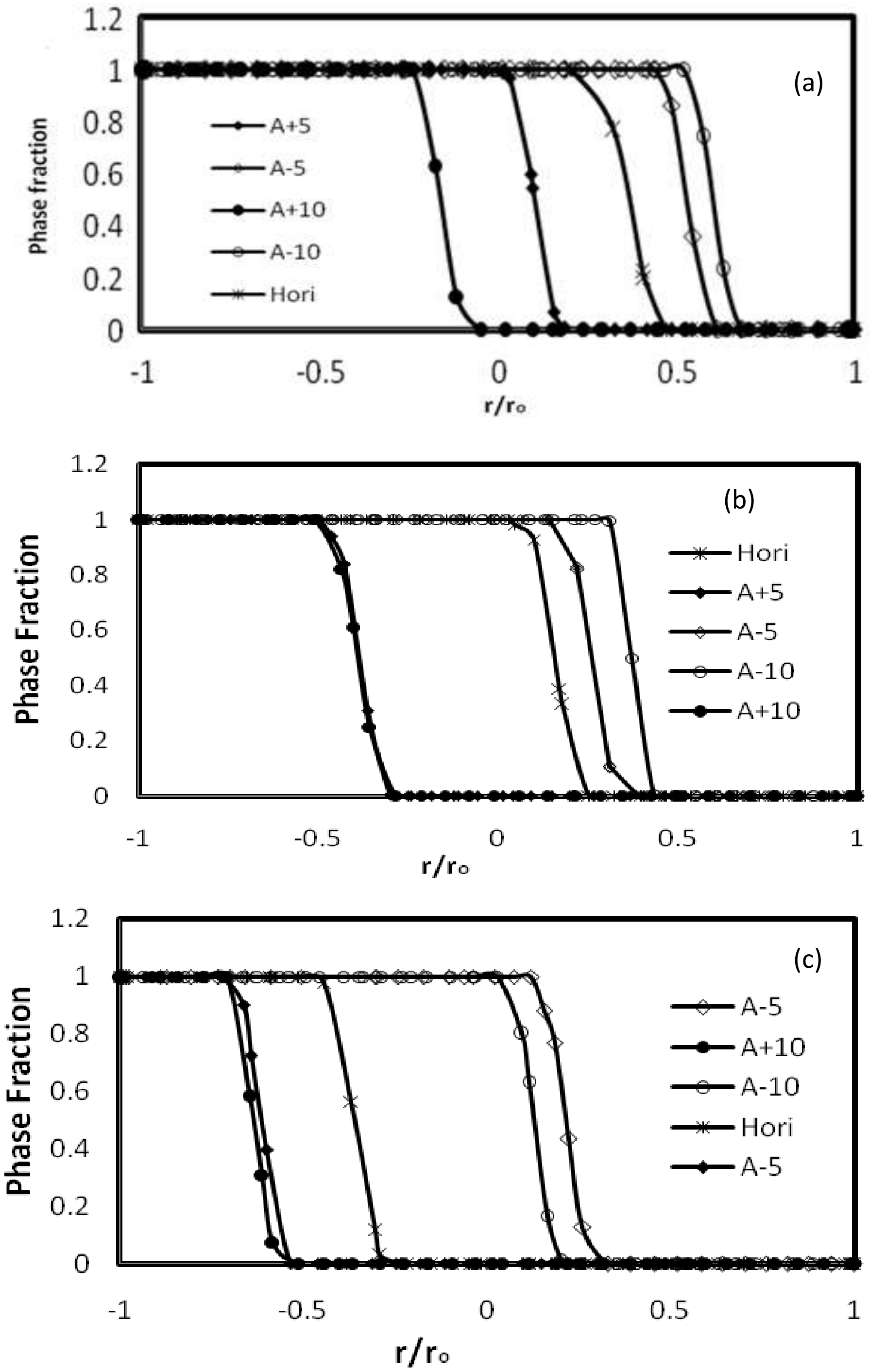


Figure 4.4 Oil fraction profiles in horizontal and inclined straight tubes at different angle of inclinations for 0.25 m/s velocity at vertical centerline at different water cut (a) 25%, (b) 50%, (c) 75%

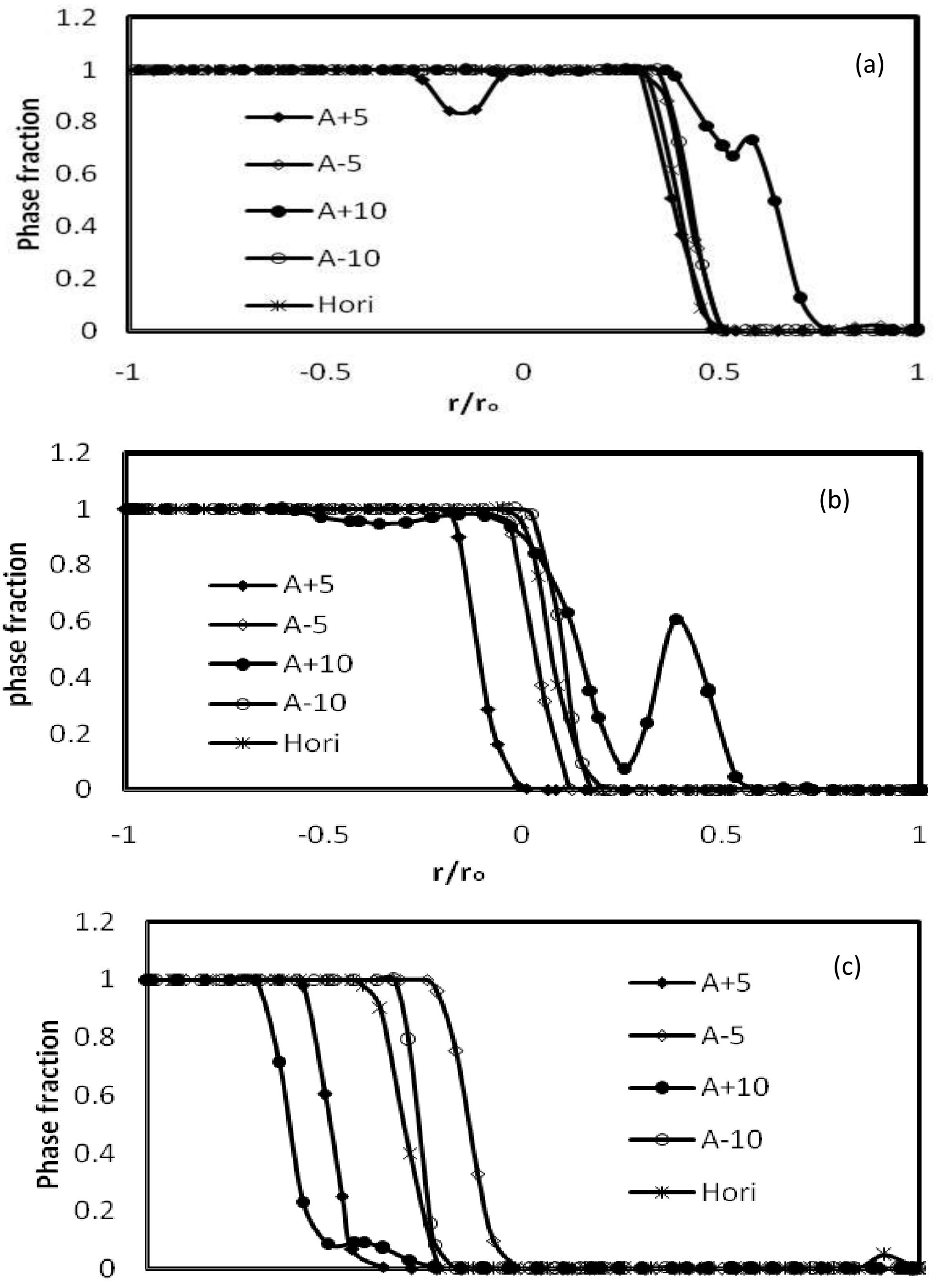


Figure 4.5 Oil fraction profiles in horizontal and inclined straight tubes at different angle of inclinations for 1.05 m/s velocity at vertical centerline at different water cut (a) 25%, (b) 50%, (c) 75%

4.3 Velocity profiles in horizontal and inclined pipes at different water cut and velocities

The velocity contours near the outflow boundary conditions are shown in Figure 4.6 at higher Reynolds number (68800). It can be seen from the Figure 4.6 that as the angle of inclination decreases from $+10^0$ to $–10^0$ the maximum velocity is shifting from upper half cross–section of the pipe to the lower half cross–section of the pipe for all water cut considered in the present work. In case of higher inclination angle the maximum velocity is in the oil phase, while in case of negative inclination from horizontal the maximum velocity is in the water phase, which clearly shows the effect of gravity. It may also be due to the fluid acceleration in case of negative inclination from horizontal and crawling effects in positive angle of inclination from horizontal. For horizontal tube there maximum velocity is near the centre of the tube.

Figures 4.7 – 4.12 show the velocity profiles in the radial direction for different water cut (25%, 50%, and 75%), angle of indications ($\pm5^0$, 0^0, and $\pm 10^0$) and Reynolds number (28800 and 68800) at vertical and horizontal centerlines. Simillar observation were made from the velocity profiles as in case of velocity contours for differnet parameters considerd in the present wotk. From Figure 4.7 it can be seen that in case of $+5^0$ and $+10^0$ inclined straight tube the maxmium velocity are on the upper section of the pipe at a plane, which may be due to the crawling of high density fluid in the bottom section of the pipe.

In case of $–5^0$ and $–10^0$ inclined straight tube the maxmium velocity are on the lower section of the pipe at a plane, which may be due to the accleration in high density fluid in the bottom section of the pipe. However in case of horiozontal pipe no such phenomenon was observed symmetrical in the axial direction. At higher inclination the velocity gradient were higher. In case horizontal centerlines, it can be seen that the velocity profiles were nearly symmetrical (Figures 4.7b–4.12b). However it was observed that the velocity profiles were more flatter at higher inclinations (i.e. at $+10^0$) at horizontal centerlines.

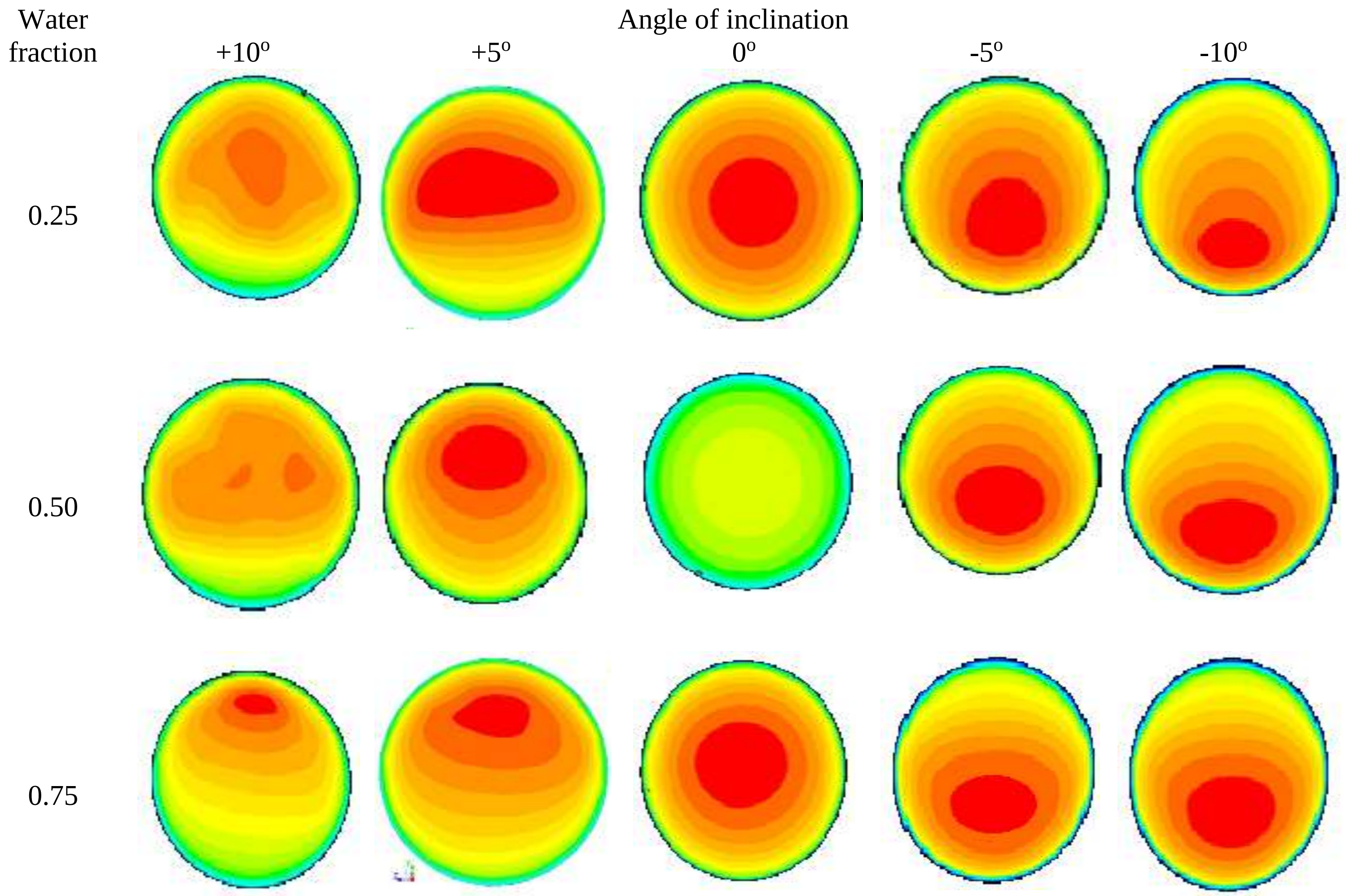


Figure 4.6 Contours of velocity for different inclinations and different water volume fraction at cross section plane near the outlet of pipes.

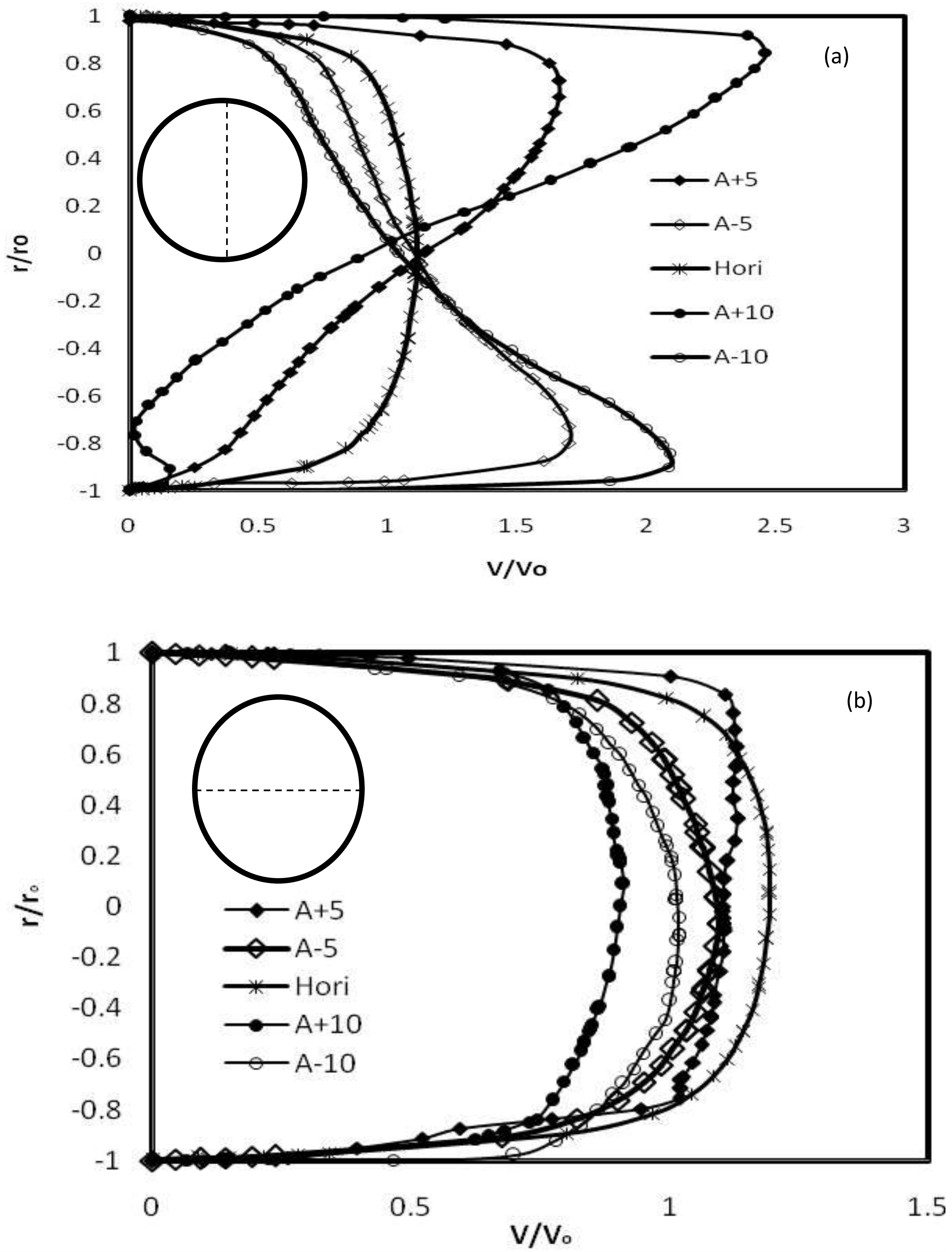


Figure 4.7 Velocity profiles in horizontal and inclined straight tubes at different angle of inclinations for 25% water cut and 0.25 m/s velocity at (a) vertical centerline and (b) horizontal centerline.

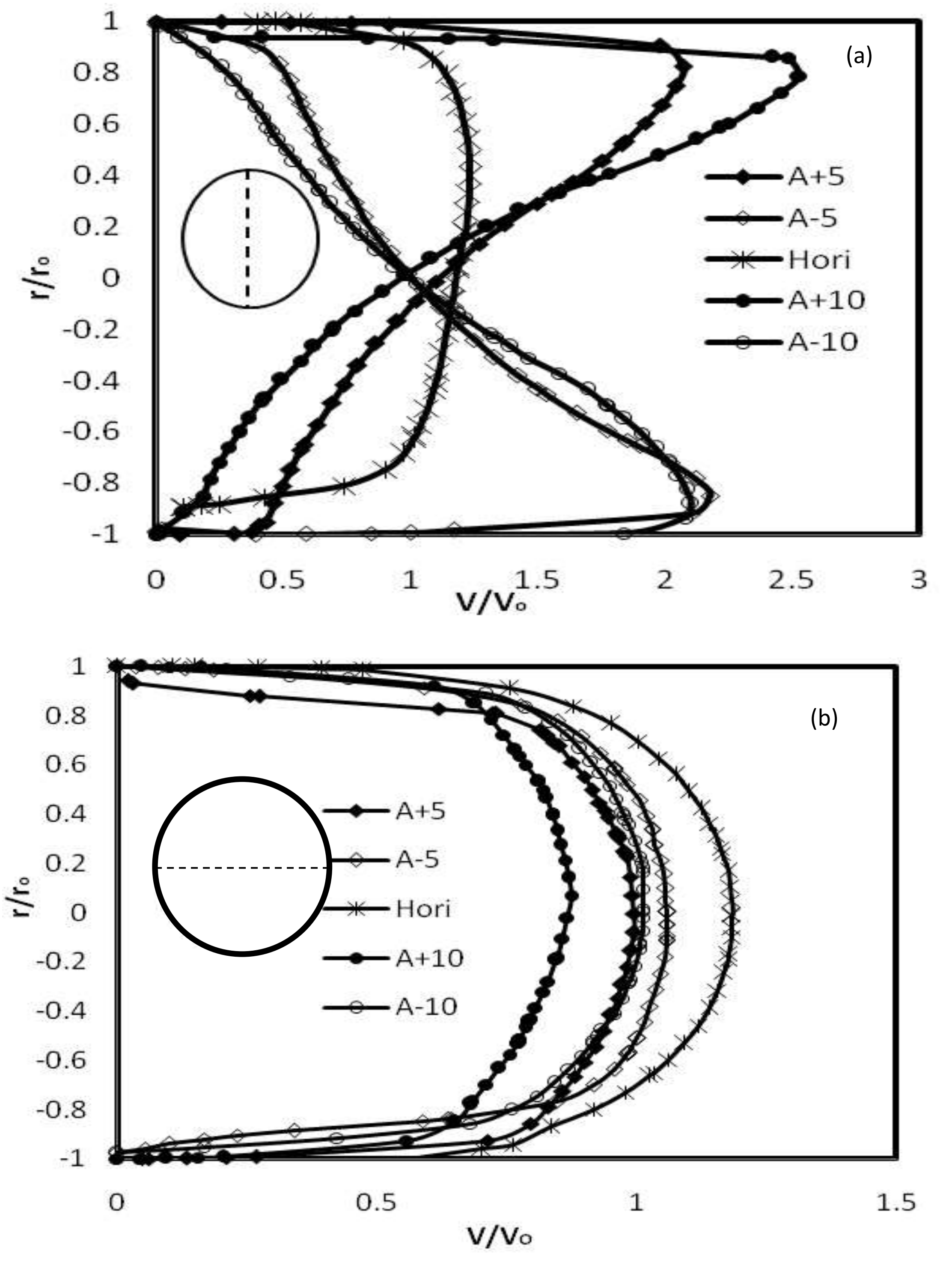


Figure 4.8 Velocity profiles in horizontal and inclined straight tubes at different angle of inclinations for 50% water cut and 0.25 m/s velocity at (a) vertical centerline and (b) horizontal-centerline.

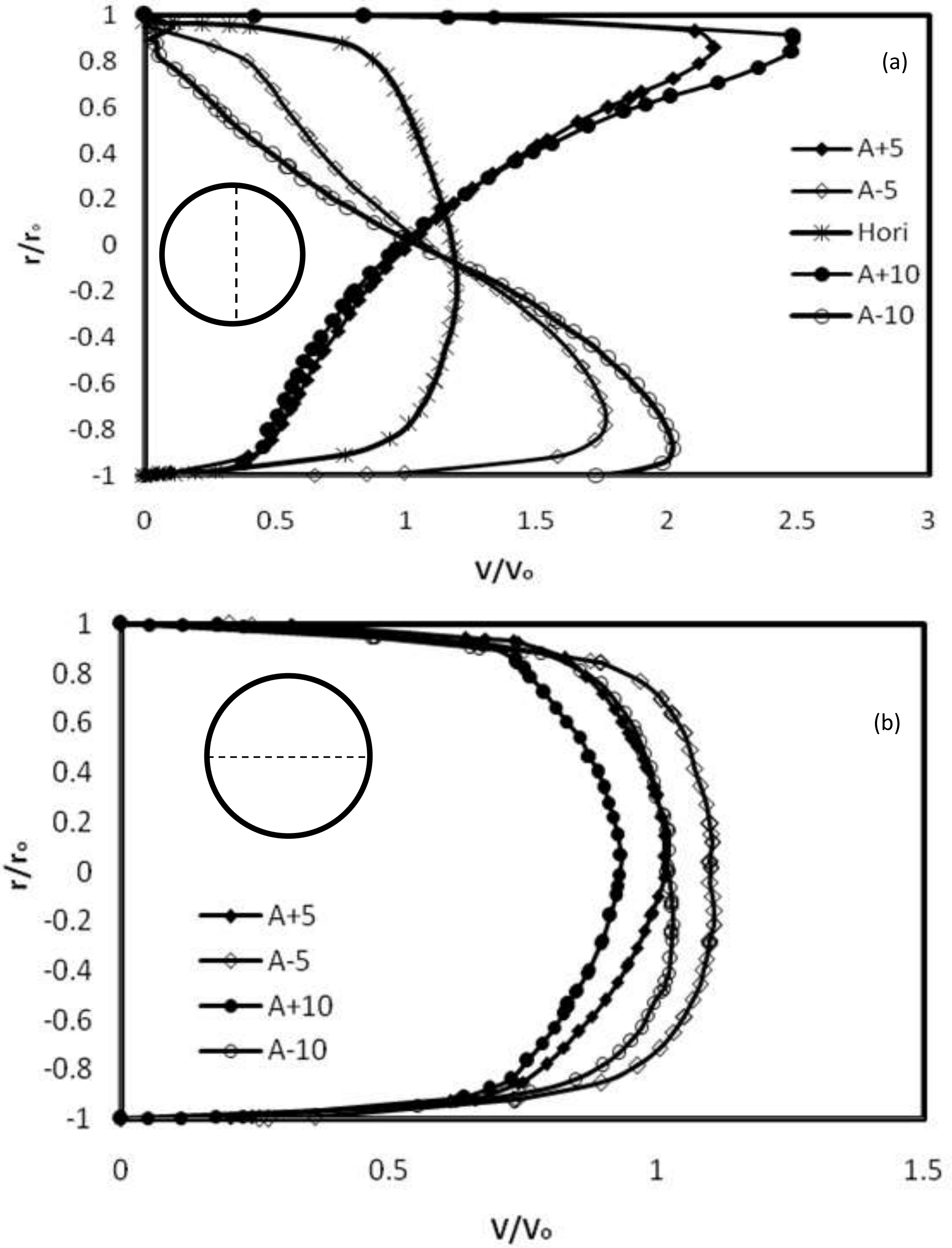


Figure 4.9 Velocity profiles in horizontal and inclined straight tubes at different angle of inclinations for 75% water cut and 0.25 m/s velocity at (a) vertical centerline and (b) horizontal centerline.

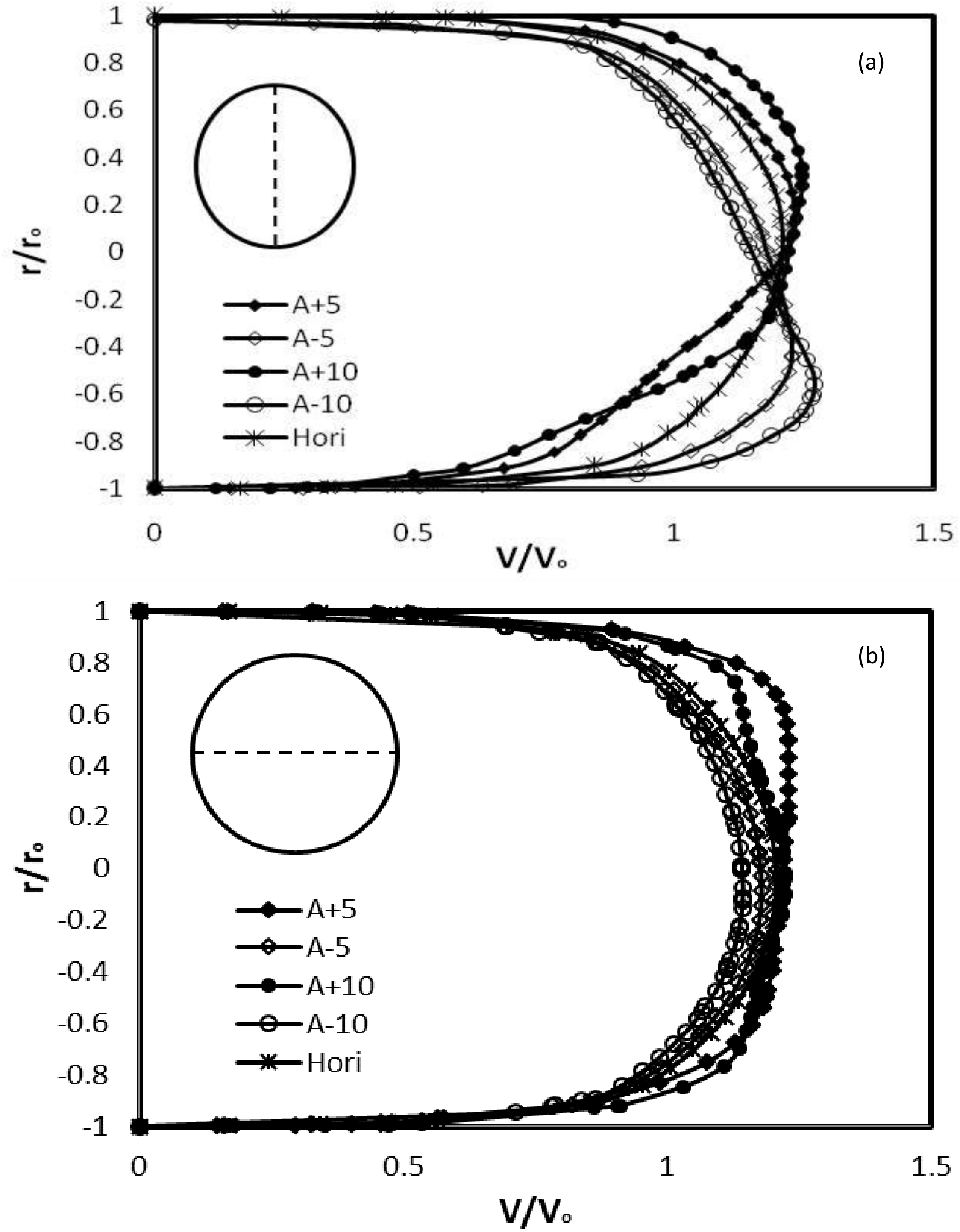
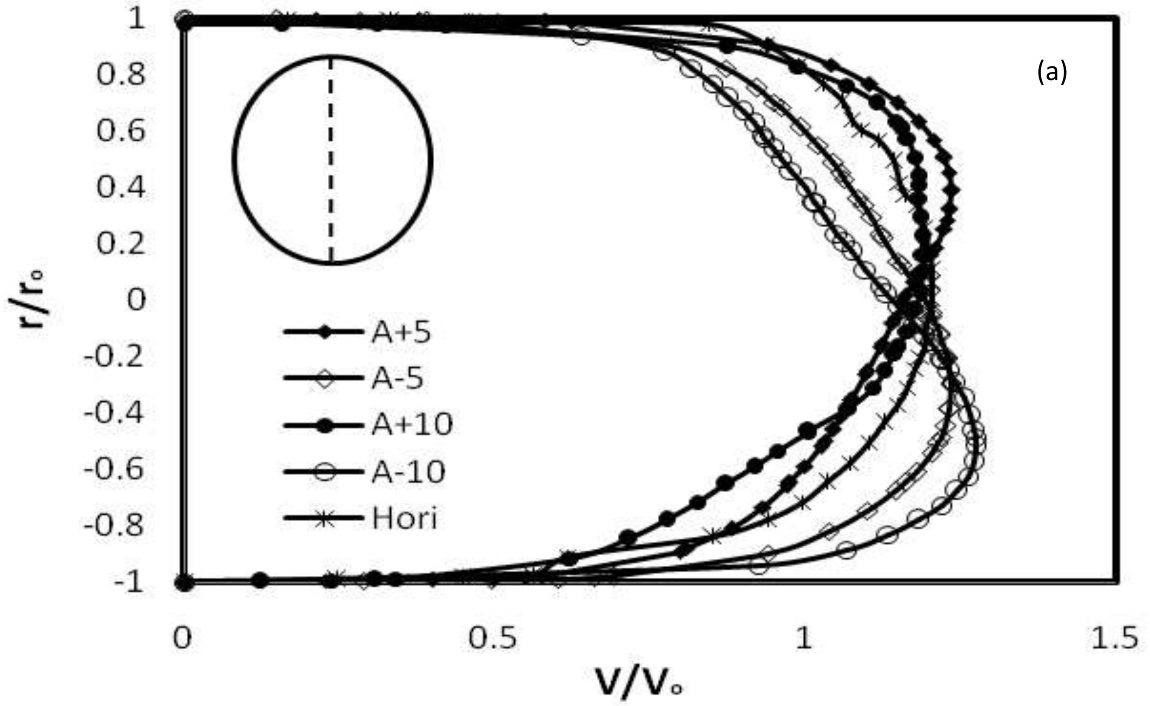


Figure 4.10 Velocity profiles in horizontal and inclined straight tubes at different angle of inclinations for 25% water cut and 1.05 m/s velocity at (a) vertical centerline and (b) horizontal centerline.



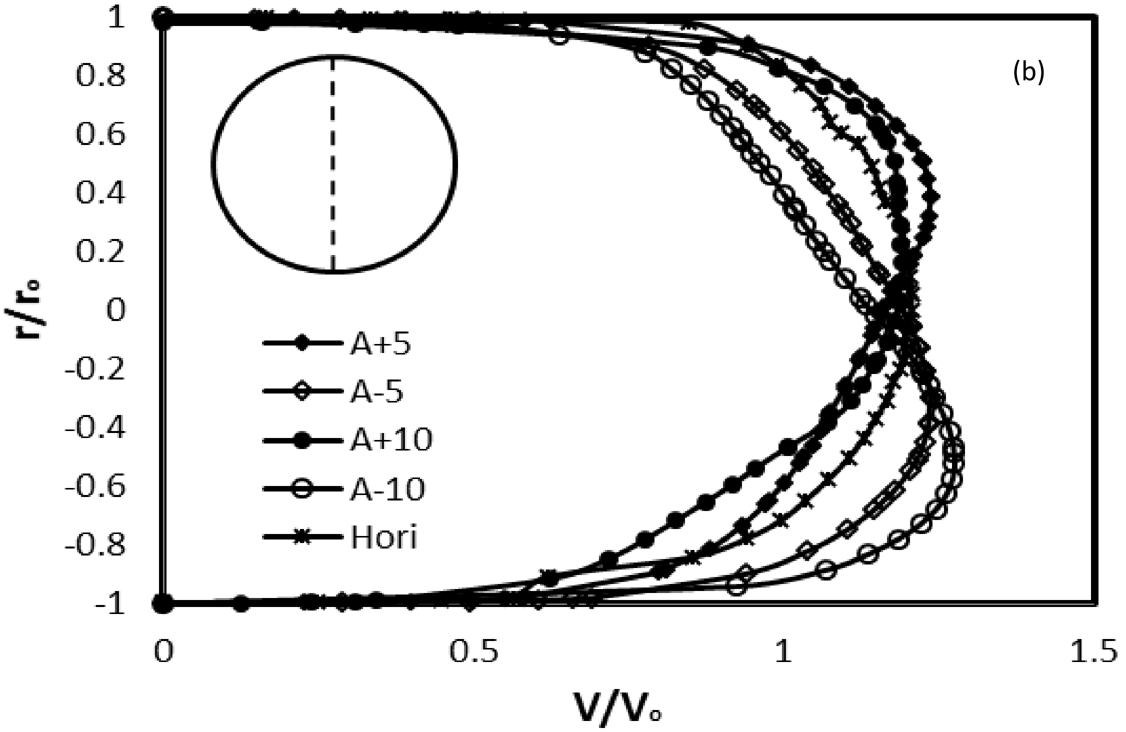


Figure 4.11 Velocity profiles in horizontal and inclined straight tubes at different angle of inclinations for 50% water cut and 1.05 m/s velocity at (a) vertical centerline and (b) horizontal centerline

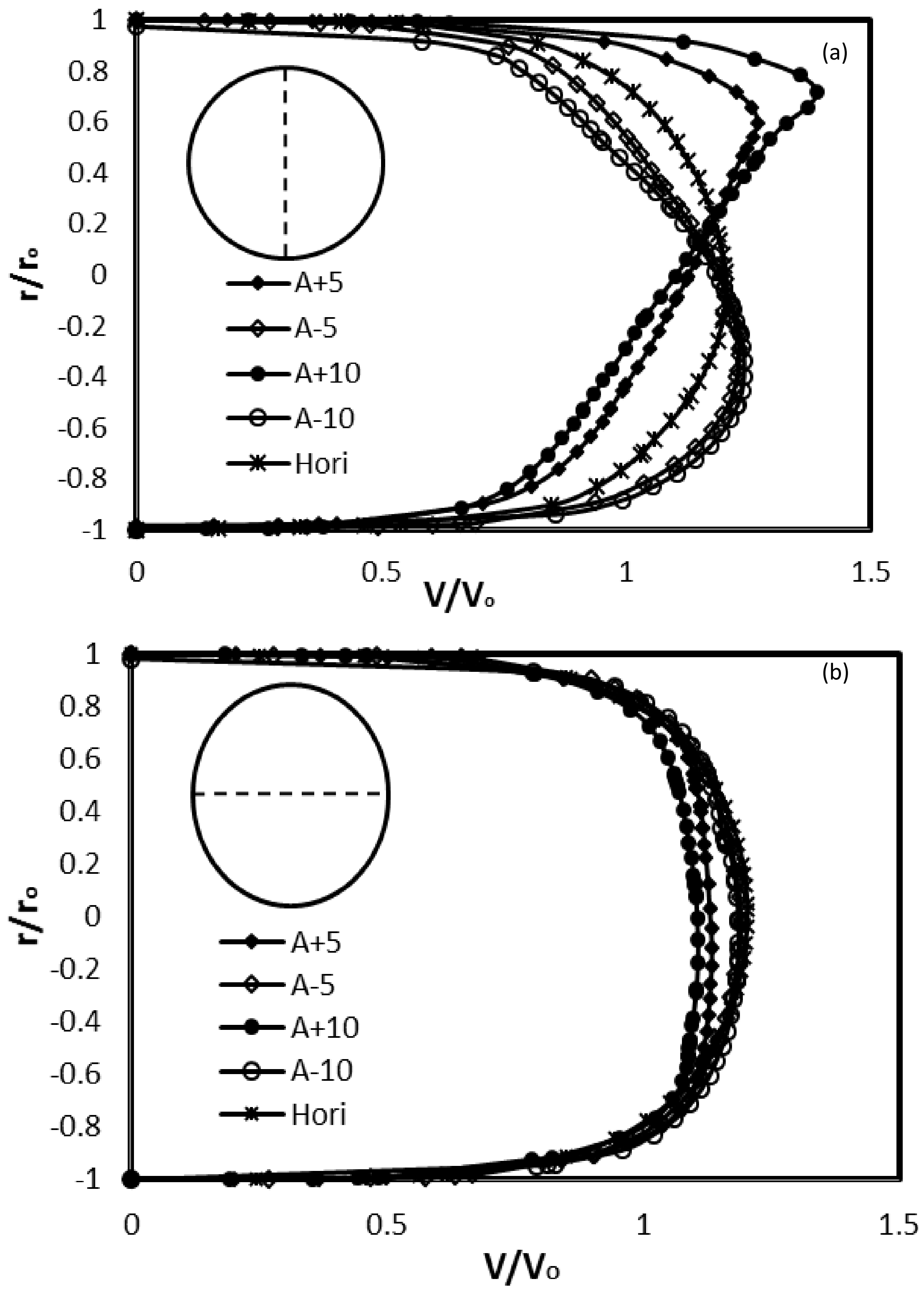


Figure 4.12 Velocity profiles in horizontal and inclined straight tubes at different angle of inclinations for 75% water cut and 1.05 m/s velocity at (a) vertical centerline and (b) horizontal centerline

4.4 Slip ratio and pressure drop in horizontal and inclined pipes at different water cut and velocities

Slip ratio in stratified liquid-liquid (two phase flow), is defined as the ratio of the velocity of less density phase to high denity phase. In the present work the slip ratio is the ratio of velocity of oil to velocity of water. The slip ratio is plotted against the water fraction for different angle of inclinations (i.e. ±10^0, 0^0, and ±5^0).

$$S = \frac{u_o}{u_w} = \frac{A_w U_o}{A_o U_w} = \frac{U_o(1-\varepsilon_o)}{U_w \varepsilon_o} \tag{4.1}$$

where U_o and U_w are oil phase and water phase superfical velocity, respectively. If S is greater than 1 then oil is flowing faster, conversly if S is less than 1 then water is flowing faster than oil.

Figure 4.13a it can be seen that the numerically predictions are in good agreement with the experimental data of Elseth *et al.* (2001) for stratified oil–water two phase in horizontal pipe, for water fraction ranging from 0.25 to 0.90. For lower water fraction values the deviation was higher (≈18%), howevrer for higher water fraction values the deviation was ≈5%. Figure 4.13b shows the numerical predictions of slip ratio for inclined tubes. IT can be seen that the slip ratio is more than 1 for pipe having inclination +5^o and +10^o for water fraction less then 0.8, which means oil is flowing faster than water, conversly slip ratio is less than 1 for pipes having inclinations -5^o and -10^o for water fraction in the range of 0.25 to 0.90.

Pressure drop of stratified flow of oil-water two phase is shown in Fig 4.14. In Figure 4.14b the predicted results for pressure drop were comapred with the experimental data of Elseth *et al.* (2001). At low water volume fraction the deviation in numerical prediction and experimental results is ≈18%, however at high water volume fraction (0.85) the deviation is less than 2%. Figure 4.14a show numerical predictions of pressure drop with water volume fraction at various angle of inclincations (±10^0, ±5^0). The pressure drop was same for ±5^0 angle of inclinations, however in case of –10^0 the pressure drop is twice as comapred to the +10^0 inclined pipe.

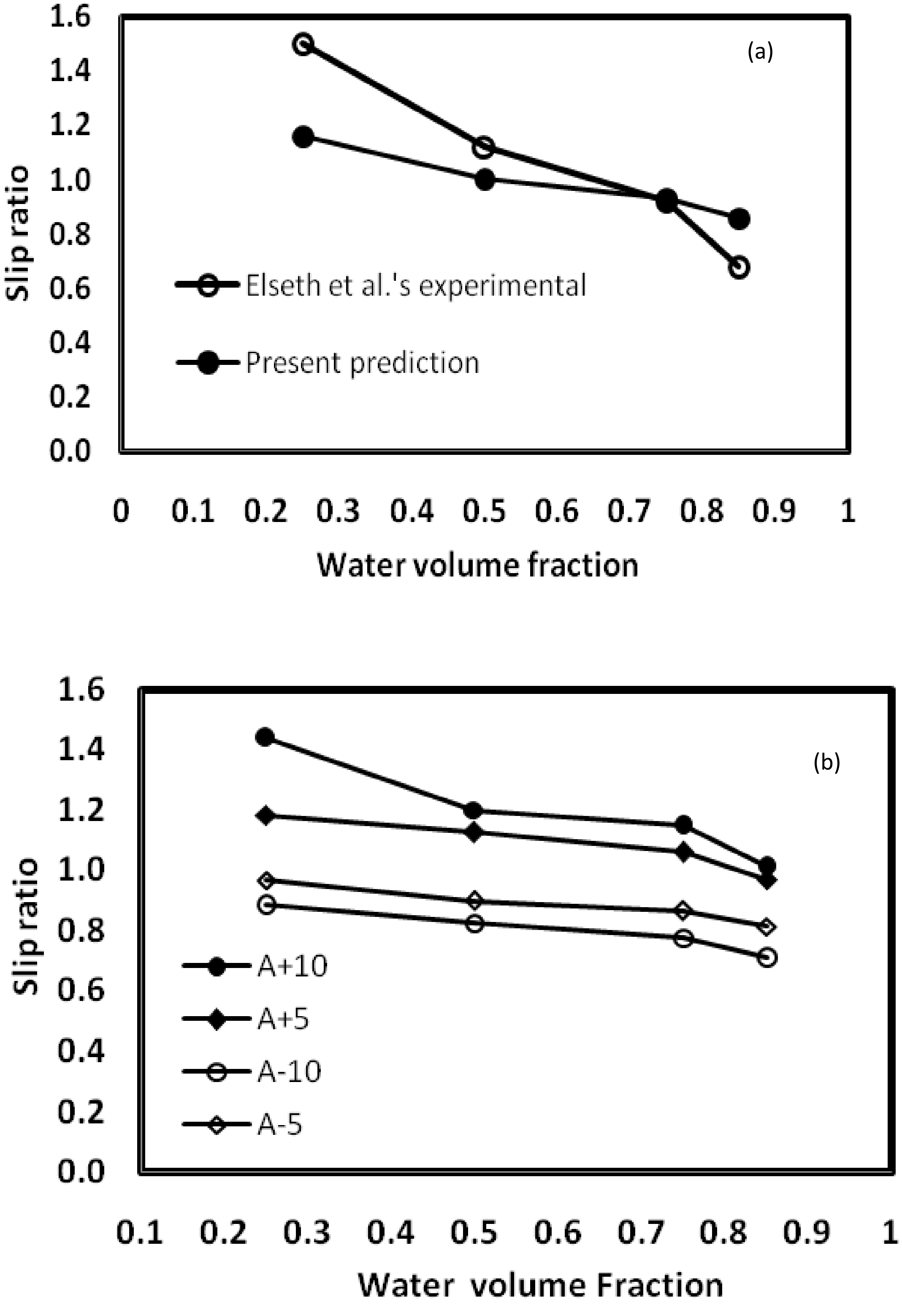


Figure 4.13 (a) Comparision between predicted and experimental values of silp ratio for horizontal pipe, and (b) slip ratio for different inclination verse water volume fraction.

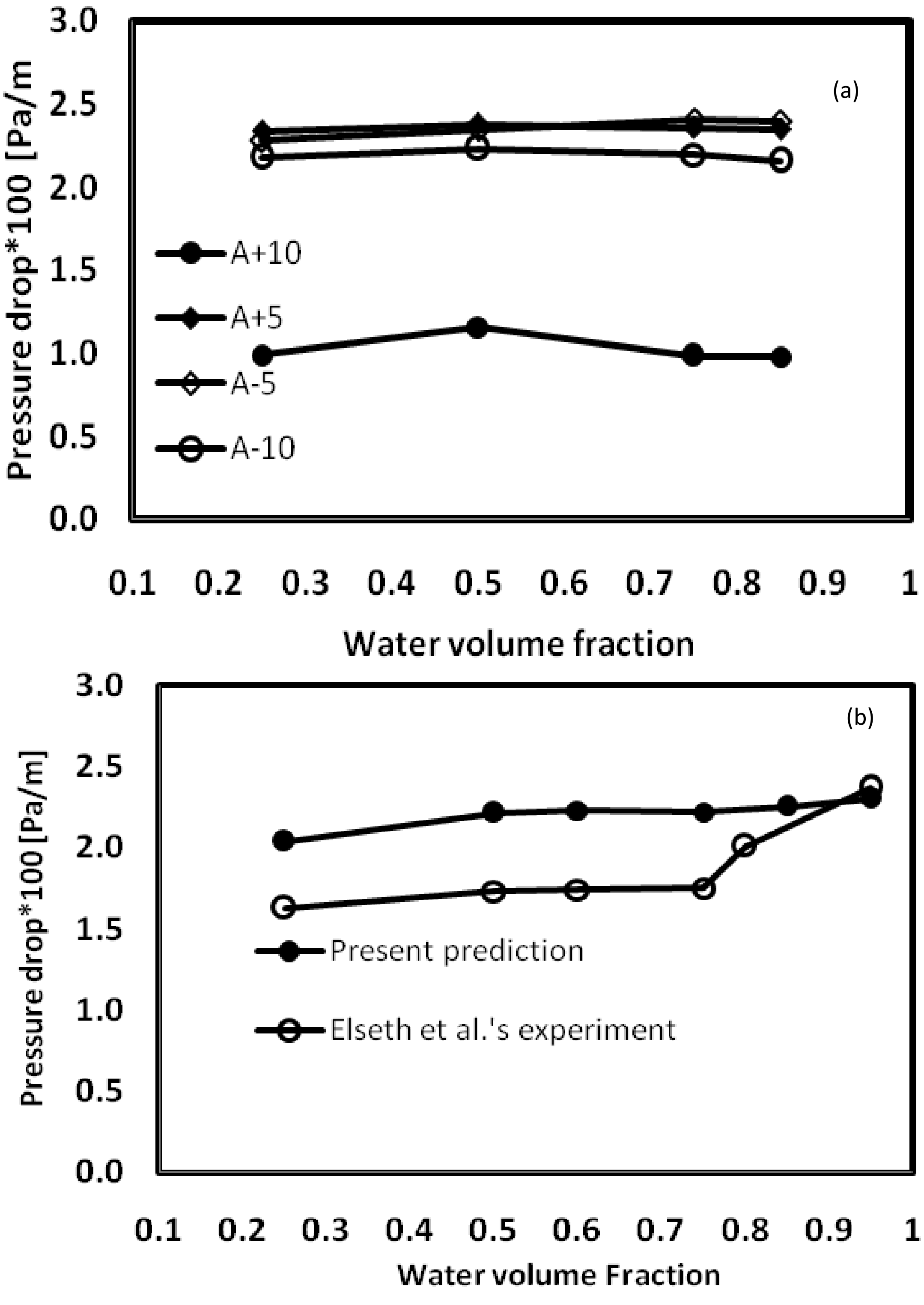


Figure 4.14 Pressure drop for (a) different inclination verse water volume fraction, and (b) comparision between predicted and experimental values of pressure drop for horizontal pipe.

4.5 Turbulent kinetic energy and turbulent dissipation rate

It is observed that at low velocity 0.25 m/s flow become stratified after 5D or 6D (D = diameter) of pipe (±5^0, ±10^0, 0^0) but for high velocity 1.05 m/s flow doesn't stratified till the end of pipe, this indicate that for stratified flow velocity should be low for all water cuts.

At high velocity = 1.05 m/s, in horizontal and inclined straight tubes there was less velocity gradient on vertical centreline than at velocity = 0.25m/s, but acceleration and crawling phenomenon were similar as at velocity 0.25 m/s. Turbulence is observed for all water volume fraction at velocity 1.05 m/s for $+10^0$ inclined pipe (Figure 4.15). As inclnation change from negative to positive the turbulent kinetic energy increases and the the maximum turbulent kinetic energy value is shifting from bottom hafl cross-estion to top half cross–section (Figure 4.15). The turbulent energy dissipation near the solid surface is shown in Figure 4.16 on a cross–section near outflow boundary condition. Figure 4.17a and 4.17b show the turbulent kinetic energy and energy dissipation profiles for horizontal as well as inclined pipes.

4.6 Phase fraction contours at central plane in horizontal and inclined pipes at different water cut and velocity

To understand the flow behaviour near the entrance region the phase fraction contours at the central plane in horizontal as well as inclined pipes are shown in Figure 4.18 at Re = 28800 for different water cut and angle of inclinations. It was observed that at low Reynolds numbers flow become stratified after 5D of pipe. Similar results were analysed for higher Reynolds number, and a high turbulence was observed at the central plane, which shows that fluid flow is not smooth till the end of the pipe.

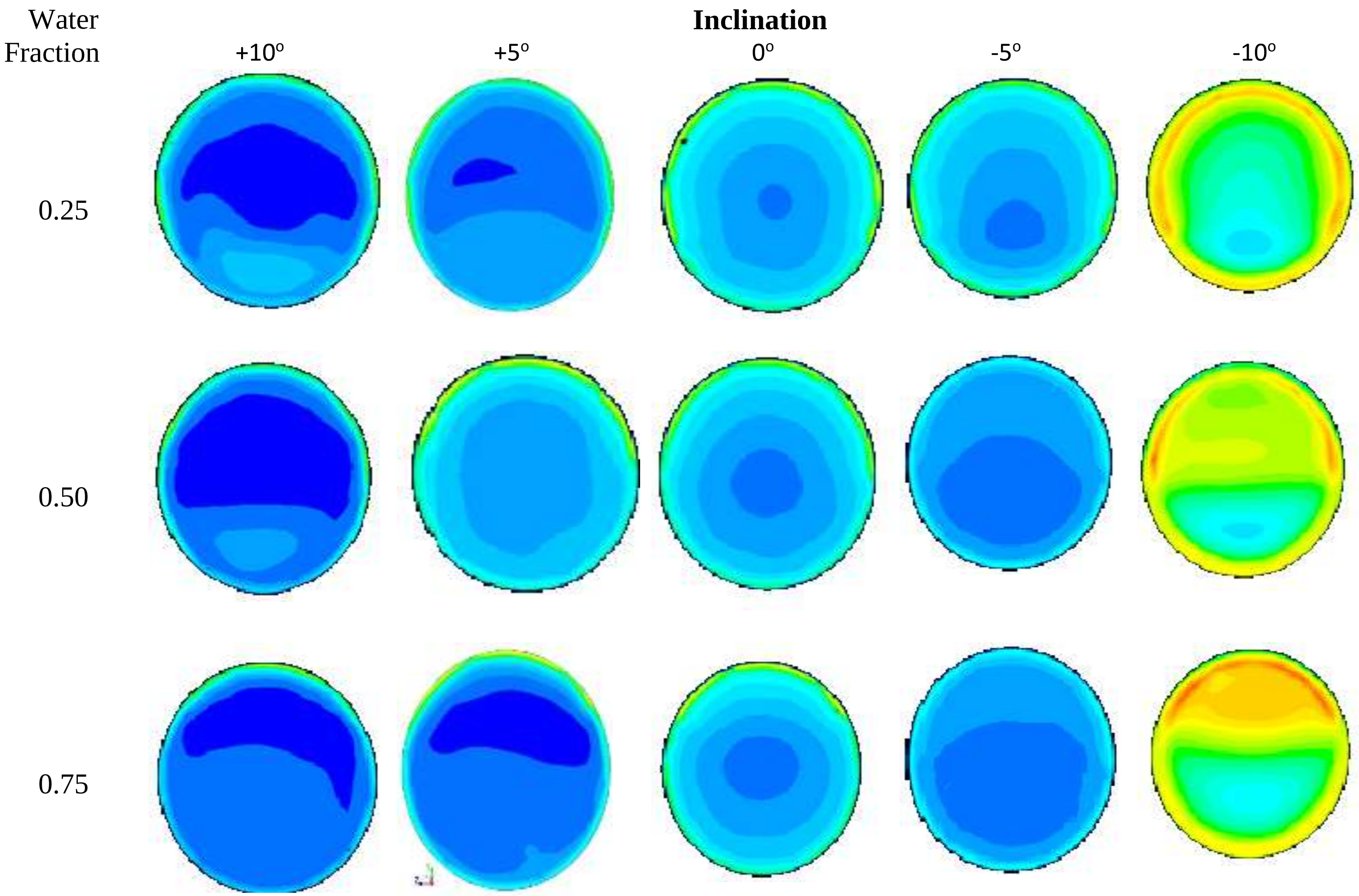


Figure 4.15 Contours of turbulent kinetic energy for different inclinations and different water volume fraction at cross section plane near the outlet of pipe.

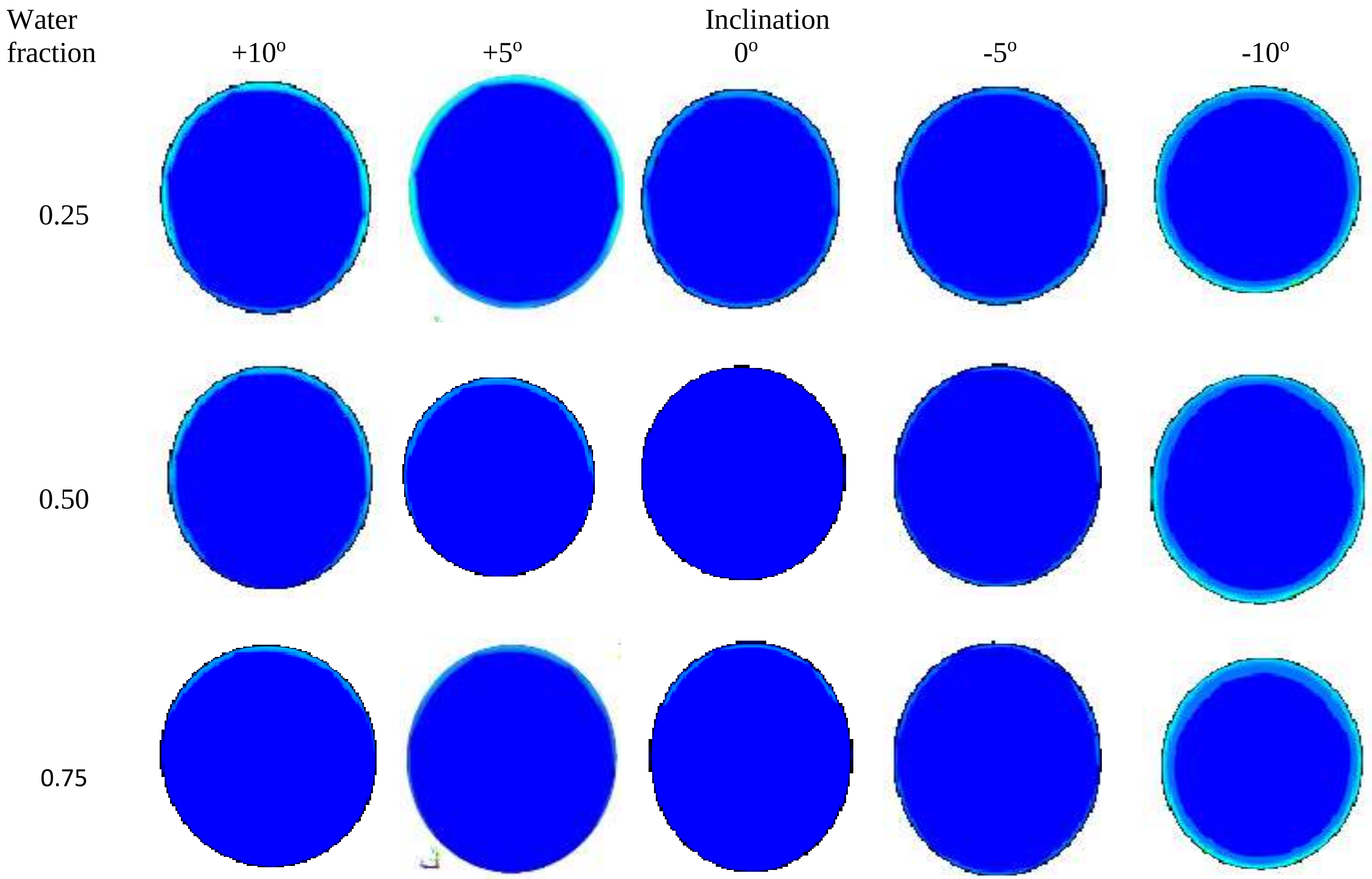


Figure 4.16 Contours of turbulent dissipation rate for different inclinations and different water volume fraction at cross section plane near the outlet of pipe.

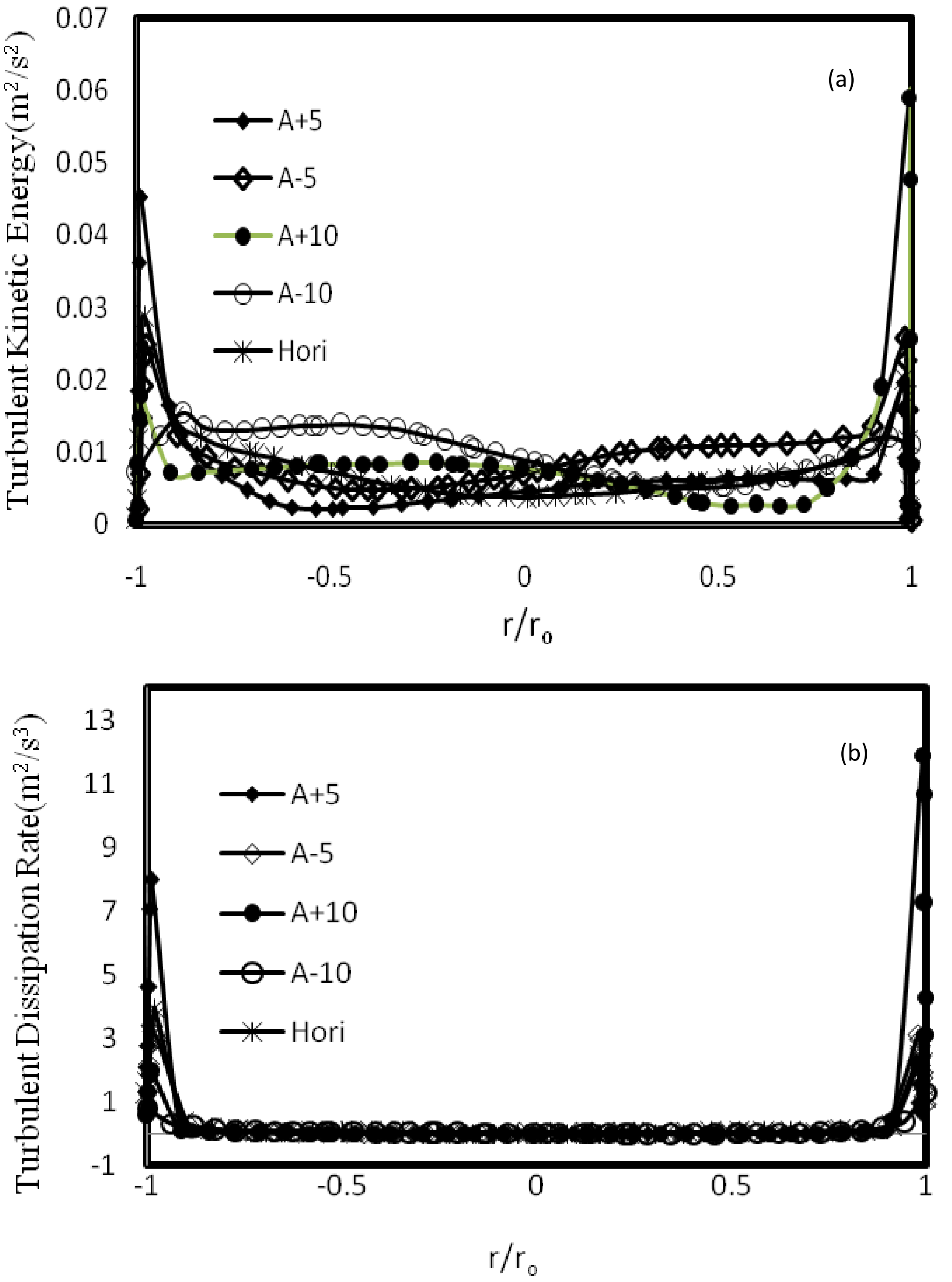
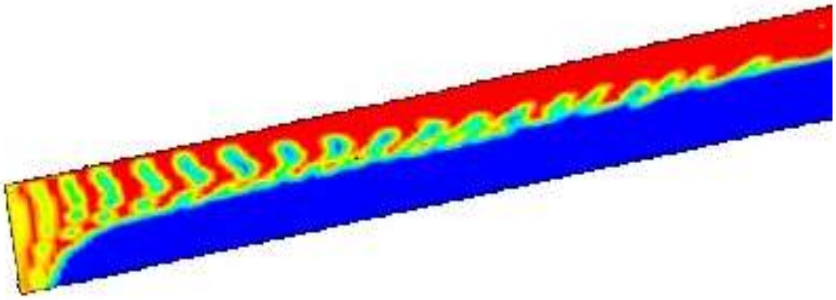
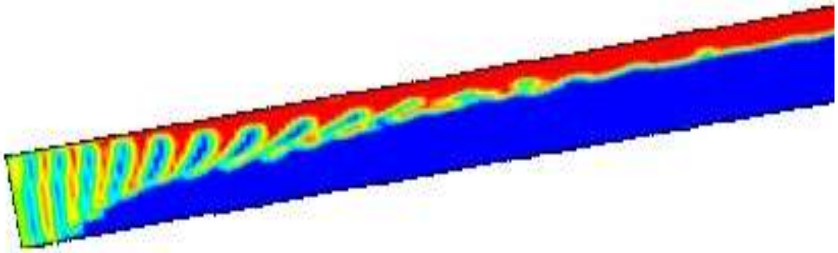
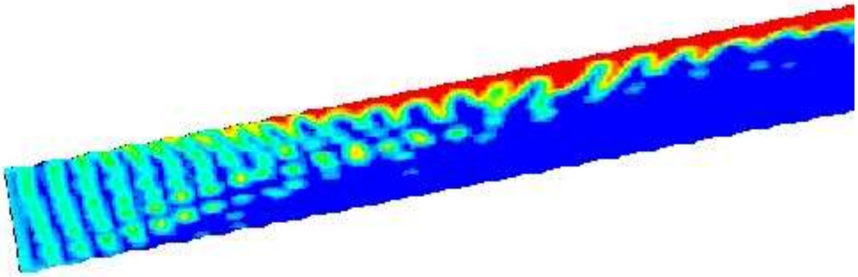
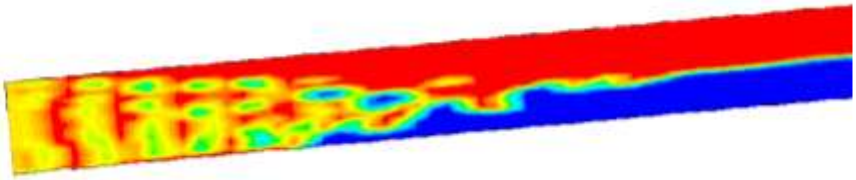
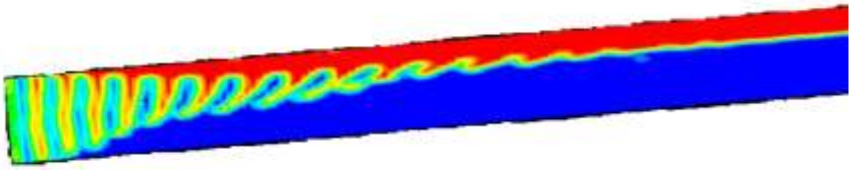
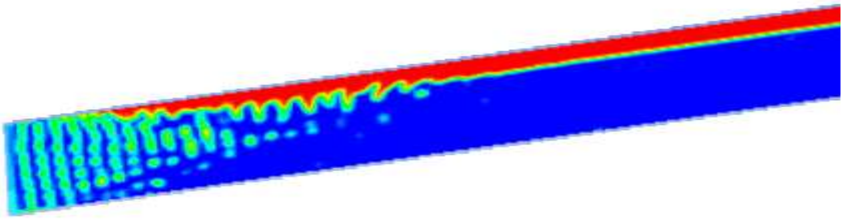


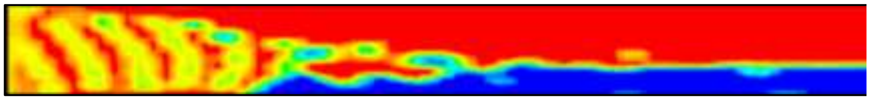
Figure 4.17 (a) Turbulent kinetic energy and (b) turbulent dissipation rate for different inclinations.

Water Fraction	Inclination	
0.25	$+10^0$	
0.50	$+10^0$	
0.75	$+10^0$	
0.25	$+5^0$	
0.50	$+5^0$	

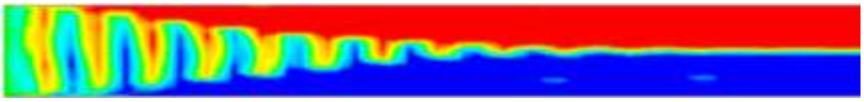
0.75 $+5^0$



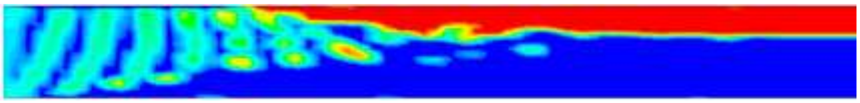
0.25 Horizontal



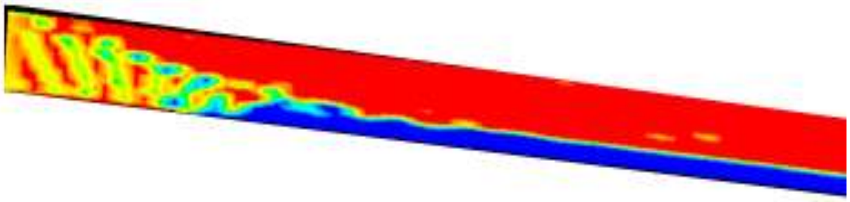
0.50 Horizontal



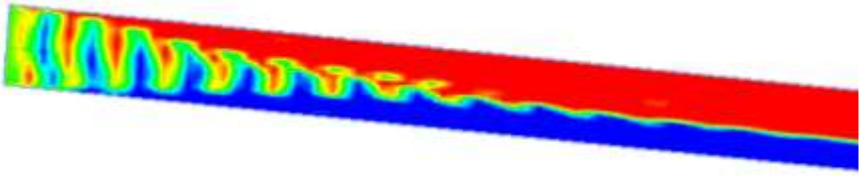
0.75 Horizontal



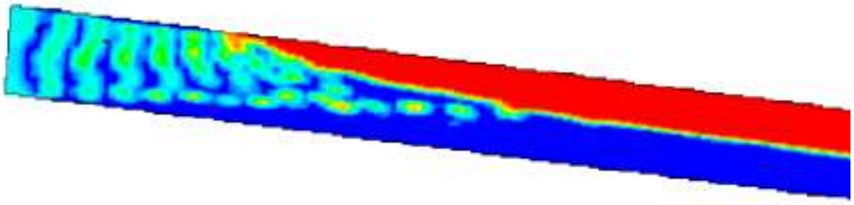
0.25 -5^0



0.50 -5^0



0.75 -5^0



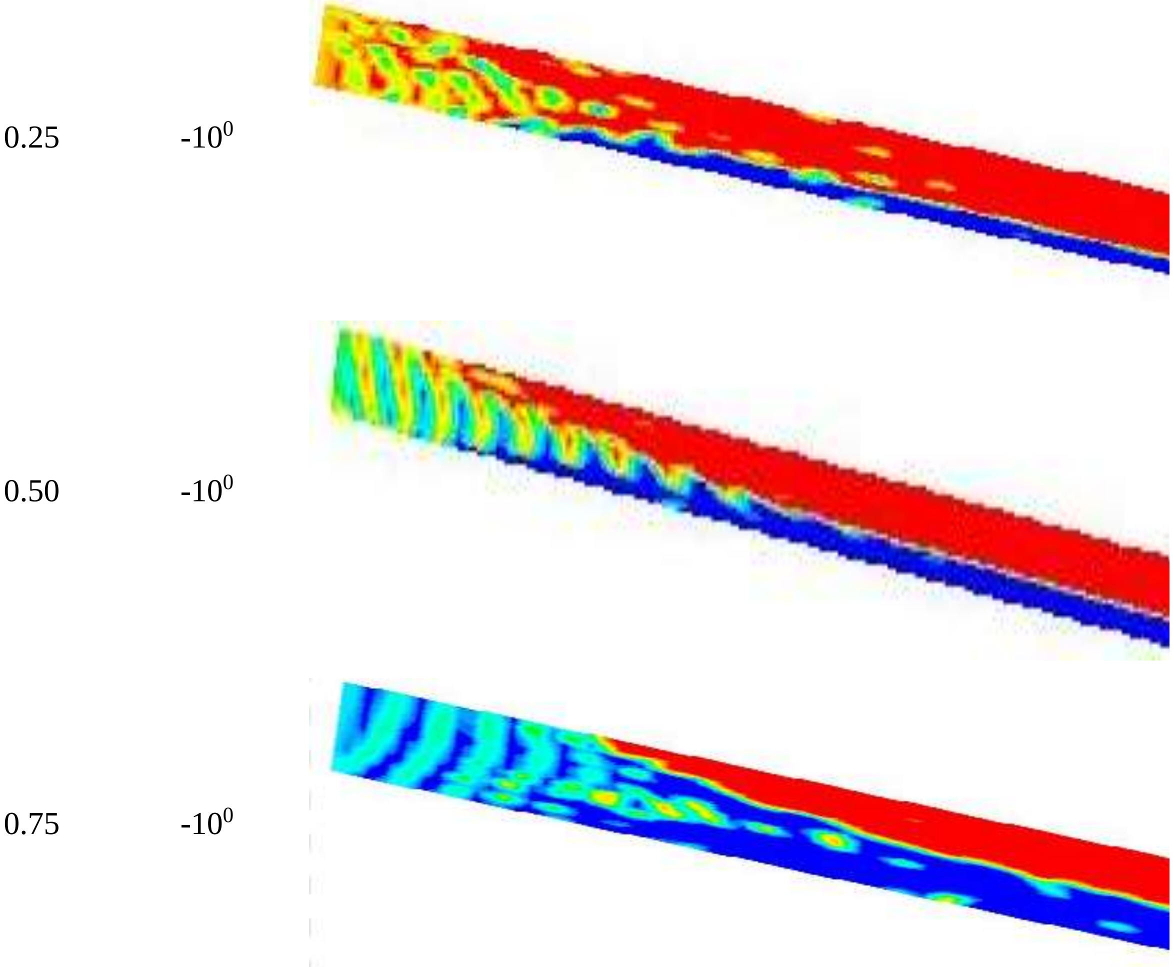


Figure 4.18 Phase fraction contours at central plane at v = 0.25m/s

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In the present work water oil two phase stratified flow in the horizontal and inclined tubes was numerically simulated using commercially available computational fluid dynamic software ANSYS FLUENT. Interface of oil-water was numerically calculated using volume of fraction (VOF) approach and turbulence characteristics were determined using two equation k-ε turbulence model (RNG). Selected models were successfully predicted the flow pattern, local phase fraction, slip ratio, pressure drop, turbulent kinetic energy and turbulent energy dissipation rate. Simulated results for horizontal pipes are also validated experimentally Elseth *et al.* (2001) and numerically Gao *et al.* (2003).

It was found that variation in flow pattern, local phase fraction, slip ratio, pressure drop, turbulent kinetic energy and turbulent energy dissipation rate are due to crawling and acceleration in upward inclined tubes and downward inclined tubes respectively. It was observed that at low Reynolds number flow become stratified after 3D or 4D at all inclinations ($\pm 5^0$, 0, $\pm 10^0$) and for different phase fraction (25%, 50%, 75%) but at high Reynolds number flow does not stratified up to the end of pipe (length of pipe = 5m) for all inclinations ($\pm 5^0$, $\pm 10^0$) and for different phase fractions (25%, 50%, 75%).

5.2 Recommendations

In the present work the numerical study was carried to study the flow patterns, turbulent characteristics pressure drop, local phase fraction, and slip ratio considering 90^0 contact angle. Further it is proposed to study the above mentioned parameters by varying different contact angles, surface tensions and viscosity (i.e., different fluids).

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