Sigma J Eng & Nat Sci 38 (1), 2020, 1-19

Sigma Journal of Engineering and Natural Sciences
Sigma Mühendislik ve Fen Bilimleri Dergisi

Research Article

CFD PREDICTION OF OIL-WATER TWO-PHASE STRATIFIED FLOW IN A HORIZONTAL CHANNEL: COUPLED LEVEL SET - VOF APPROACH

Satish Kumar DEWANGAN*[1], Santosh Kumar SENAPATI[2], Vivek DESHMUKH[3]

[1]*Mechanical Engineering Department, National Institute of Technology, Raipur (CG) 492010, INDIA;* ORCID: 0000-0001-6698-3247
[2]*Department of Mechanical Engineering, Indian Institute of Technology Kharagpur (West Bengal), 721302 INDIA;* ORCID: 0000-0002-5598-919X
[3]*Mechanical Engineering Department); National Institute of Technology Raipur (CG) 492010, INDIA;* ORCID: 0000-0002-3796-751X

Received: 01.12.2019 Revised: 23.05.2019 Accepted: 17.09.2019

ABSTRACT

The present work focuses on the investigation of the effects of (a) superficial oil velocity, and (b) inlet temperature to wall temperature ratio considering the two dimensional oil-water stratified flow in a horizontal pipe using ANSYS Fluent. Coupled level set and volume of fluid (CLSVOF) have been used to capture the evolving interface assuming unsteady, coaxial flow with constant fluid properties. For both cases, the radial variation of oil volume fraction, mixture velocity, total pressure, and pressure gradient has been studied. The stratified flow pattern has been obtained for both cases. The pressure gradient has not been found to be very much sensitive to the inlet to wall temperature ratio. The analysis can helpful in predicting & preventing the blockage of the oil pipeline due to wax formation, by managing to control the fall of oil temperature below wax appearance state. Hence these findings could be useful in designing the transportation pipeline in the petroleum industries, chemical industries etc. and also in pipeline flow control administration.
Keywords: Oil-water stratified flow, horizontal channel, CLSVOF.

1. INTRODUCTION

Two-phase flows are very common in nature and industries such as oil industries, power plants, nuclear industries, chemical industries, etc. Although the simultaneous flow of as many as four phases namely, water, crude oil, gas and sand are not uncommon during oil exploration. The flow of two-phase mixtures is the most common occurrence in the industry. It covers a diverse range of flow phenomena involving various combinations of phases like solid, liquid and gas. The present work focuses on one of the commonly found flow pattern known as stratified flow pattern. Stratified flows are important in many practical applications such as in the transportation pipeline of the petroleum industry, heat exchangers, thermal storage tanks, geothermal industry, nuclear industry, chemical industry, process industry etc. Stratified flow is characterized by the presence of a clear interface between the phases. The interface may be smooth, wavy and may

* Corresponding Author: e-mail: skdewangan.amech@nitrr.ac.in, tel: (+91) 94060-75050

also have slight dispersion of one phase into other. Also, the interface evolves with space and time. Hydrodynamics of such a flow is complicated firstly because of the presence of two phases and secondly because of the presence of an evolving interface. However, hydrodynamics of such a flow is essential for the design of the transportation pipe line, pipe networks, mixtures, emulsifiers etc.

Several researchers have analyzed stratified flow pattern using the experimental, analytical and computational method. Elseth (2001) studied the behavior of the simultaneous flow of oil and water in horizontal pipes. The effect of mixture velocity and inlet water cutoff on flow pattern transition was studied. The pressure gradient, water hold up, axial velocity and turbulent quantities were measured and compared for a different combination of inlet mixture velocity and water holdup for both stratified and disperse flow. Pandey *et al.* (2006) investigated the liquid-liquid two phase flow in a horizontal pipe and reported that that higher water velocities have hardly any influence on stratified flow. Similarly, superficial phase velocities were found to enhance the water take off in both stratified smooth and wavy regimes. Mandal *et al.* (2007) predicted the effect of pipe diameter on flow pattern experimentally. They obtained wavy stratified flow in small diameter pipe and smooth stratified flow observed in large diameter pipes. Rodriguez and Baldani (2012) studied the effect of superficial velocities of oil, water and inclination angles on the pressure gradient and hold up in the oil-water stratified flow. Barral and Anjeli (2014) investigated the wavy interface of oil-water stratified flow using wire conductance probe. Goldstein *et al.* (2015) presented analytical expressions for velocity profile, pressure gradient and shear stress in laminar stratified flow for both concave and convex interfaces in horizontal and inclined flow systems. For simplicity, they assumed interface curvature to be constant and smooth throughout. Dutta *et al.* (2011) presented a non-dimensional analytical solution for fully developed two-phase stratified flow in a 2D channel and in a 3D square duct. Gada and Sharma (2011) presented an analytical solution for fully developed two-phase Stratified flow in an inclined channel. Das *et al.* (2015) presented a non-dimensional analytical solution for fully developed two-phase stratified flow in a pipe. However, the experimental and analytical methods have their own limitations and hence the use of multiphase computational fluid dynamics has become more popular in the last two decades. Das *et al.* (2015) used Level set method (LSM) to investigate the effect of viscosity ratio on the laminar two-phase stratified flow pattern in a circular cross-section pipe. Li *et al.* (2015) investigated the heat transfer in three fluid stratified flow in a two-dimensional channel with prescribed wall temperature numerically using Level set method. The effect of Froude number, inlet velocity ratio, thermal conductivity and viscosity ratio on the velocity field, temperature field at fully developed condition was studied. It was observed that except at the entrance region the parameters were hardly influenced by surface tension and gravity. Rezaie *et al.* (2013) investigated the effect of several important parameters on the velocity field, temperature field and entropy generation for both air-water and oil-water stratified flow. Li *et al.* (2014**)** investigated the three fluid stratified flows using the LSM. Desamala *et al.* (2014) studied the slug, stratified and flow patterns for oil-water two-phase flow in the horizontal channel using Volume of fluid method. They compared the volume fraction profile, velocity profile and pressure profile for different flow pattern. Avila and Rodriguez (2014) obtained the pressure gradient for oil-water stratified flow using CFD. Gada *et al.* (2011) studied the two-phase stratified flow with and without phase change in a plane channel subjected to different thermal boundary conditions. Gada and Sharma (2011) introduced a novel dual grid LSM (DGLSM) for two-phase stratified flow simulation. This method was successfully applied in the analysis of two-phase stratified flow in a horizontal and inclined channel.

From a careful survey of available literatures, it is concluded that mostly liquid-gas stratified flow has been studied as compared to the liquid-liquid stratified flow. Also, the VOF method has been used mainly to capture evolving interfaces. More focus has been given on the improvisation of level set and the CLSVOF methods and testing them for standard cases only. Application of this method for the simulation of oil-water stratified flow in ANSYS Fluent is found to be rare.

Several important aspects of stratified flow such as the effect of non-Newtonian behavior of fluid, temperature analysis using CLSVOF has not been done yet, within the literature observed by authors. Application of the different and advanced methods are helpful in prediction of multiphase flow cases. Stratifeid flow is one of the many classes of multiphase flow situations. Hatami and Ganji (2013), Hatami *et al.* (2014), Dogonchi *et al.* (2015), Hatami *et al.* (2016), Tang *et al.* (2017) asserts this idea in their multiphase flow analysis.

Considering all these, in the present work attempt has been made to investigate the stratified flow phenomena using CLSVOF to capture the interface. The various cases that have been simulated in this work are listed in the table below.

Table 1. Details of cases simulated

Cases	Description		
1	Prediction of the effect of oil velocity		
	S. N.	Oil velocity(m/s)	Water velocity (m/s)
	1	0.2	0.23
	2	0.23	0.23
	3	0.3	0.23
2	Prediction of the effect of inlet and wall temperature on stratified flow		
	S. N.	Ratio of inlet fluid temperature to the wall temperature	
	1	14	
	2	9.22	
	3	7.07	

2. MATHEMATICAL MODELING

This method utilizes some advantages of both the VOF (Piecewise linear interpolation scheme VOF) and LSM. Thus it makes it superior to either of the method alone. The mass enclosed by the zero level set is not conserved in the LSM. Similarly, spurious current is observed in VOF. So in CLSVOF, the interface is represented by volume fraction function so that mass is conserved while still maintaining a sharp representation of the interface.

2.1. Volume of fluid method [Ansys-Fluent manuals (2012)]

This method uses a volume fraction function (r) to indicate what fraction of the total cell volume is occupied by a particular fluid. In each control volume, the volume fractions of all phases sum to unity. Hence r is 0 or 1 indicates pure fluid cell whereas $0 < r < 1$ in two-phase cells.

The continuity and momentum equation for the different phases is given as ;

$$\frac{\partial\rho}{\partial t} + \nabla.(\rho V) = 0 \tag{1}$$

$$\frac{\partial(\rho V)}{\partial t} + \nabla.(\rho VV) = \nabla\tau - \nabla p + B \tag{2}$$

The density and the viscosity are evaluated as mentioned below:

$$\rho = \sum_{k=1}^{n} r^{(k)}\rho^{(k)} \tag{3}$$

$$\mu = \sum_{k=1}^{n} r^{(k)}\mu^{(k)} \tag{4}$$

Where B is the body force, n is the number of fluid and r^k is the volume fraction of k[th] fluid. The volume fraction advection equation is given below.

$$\frac{\partial(\rho r^k)}{\partial t} + V.\nabla r^k = 0, for\ k = 1,2,3 \dots\dots,(n-1) \tag{5}$$

$$\sum_{k=1}^{n} r^{(k)} = 1, for\ k = 1,2,3 \dots\dots,(n-1) \tag{6}$$

2.2. Level set method (LSM)

In this method, a Level set function (ϕ) is defined all over the computational domain. This function has two attributes namely magnitude and sign. The magnitude of level set function at any location of the computational domain is defined as the normal distance of the point from the interface. It is positive on one side of the interface and negative on the other side. So at a particular instant of time ϕ varies from one point to another and as the interface evolves with time the value of ϕ changes throughout the computational domain. Thus the level set function is a continuous function of space coordinates and time i.e. $\phi = \phi(x,t)$. Since the distance is measured from the interface so the level set function is automatically set to zero for all the points located on the interface. In other words, an interface is defined as that surface at every point of which $\phi(x,t) = 0$. Mathematically, $\Gamma_t = \{x |\ \phi(x,t) = 0\}$.

The level set method uses three functions namely: the Level set function, the Heaviside function or unit step function and the Dirac delta function. The Level set function describes the interface as described above in this article, the Heaviside function itself is a function of level set function and is used for calculating the mean fluid properties required at the interface and the Dirac delta function is used for taking into account the effect of surface tension or interfacial mass transfer etc. into the modeling. Gada and Sharma (2009) has derived the governing equations and described the physical significance of the terms used in Level set method.
The Heaviside function is defined as

$$H(\phi) = \begin{cases} 0 & if\ \phi < \epsilon \\ \frac{\phi+\epsilon}{2\epsilon} + \frac{1}{2\pi} sin(\frac{\phi\pi}{\epsilon}) & if\ |\phi| \le \epsilon \\ 1 & if\ \phi > \epsilon \end{cases} \tag{7}$$

The Dirac delta function is defined as

$$\delta(\phi) = \begin{cases} \frac{1}{2\epsilon} + \frac{1}{2\epsilon} cos(\frac{\phi\pi}{\epsilon}) & if\ \phi = 0 \\ 0 & otherwise \end{cases} \tag{8}$$

The law of conservation of mass, level set advection equation, momentum equation, energy equation and re-initialization equation are described in equations (9), (10), (11), (12) and (13) respectively.

$$\nabla.\vec{u} = (\frac{1}{\rho_2} - \frac{1}{\rho_1})\ \dot{m}\frac{\Delta Si}{\Delta V} = \left(\frac{1}{\rho_2} - \frac{1}{\rho_1}\right)\dot{m}\ \delta(\phi) \tag{9}$$

$$\frac{\partial\phi}{\partial t} + \vec{u}_t.\nabla\phi = 0 \tag{10}$$

$$\frac{\partial(\rho_m\overrightarrow{u})}{\partial t} + \nabla.(\rho_m\vec{u}\ \vec{u}) = -\nabla P + \nabla.\mu_m(\nabla.\vec{u} + \nabla.\vec{u}^T) + \sigma k\hat{n}\,\delta(\phi) + \vec{B} \tag{11}$$

$$\frac{\partial T}{\partial t} + \nabla.(\vec{u}\,T) = \alpha N\nabla^2 T \tag{12}$$

$$\frac{\partial\phi}{\partial t_s} + S_\epsilon(\phi_0)(|\nabla\phi| - 1) = 0 \tag{13}$$

Where t_s is the pseudo time, $S_\epsilon(\phi_0) = \frac{\phi_0}{\sqrt{{\phi_0}^2+\epsilon^2}}$ is the smoothed sign function.

3. NUMERICAL FORMULATION

In the present case for the analysis of oil-water two phases stratified flow a two-dimensional rectangular domain has been chosen. The geometry and detailed dimensions of the domain is shown in the figure below. The test section axis is taken as reference for the plotting of various graphs and its radius (R) varies from y = - 0.125 m to y = 0.125 m. Water and oil enter into the test section from different inlets through a T- junction. Water enters from horizontal direction and oil from a vertical direction. The entire domain has been divided into four sections namely: water inlet, oil inlet, outlet, and test section. Figure 1 shows the schematic representation of the domain with detailed dimensions. The entire domain has been divided into quadrilateral cells to capture surface tension effect more accurately. Figure 2 depicts the meshing of the considered domain.

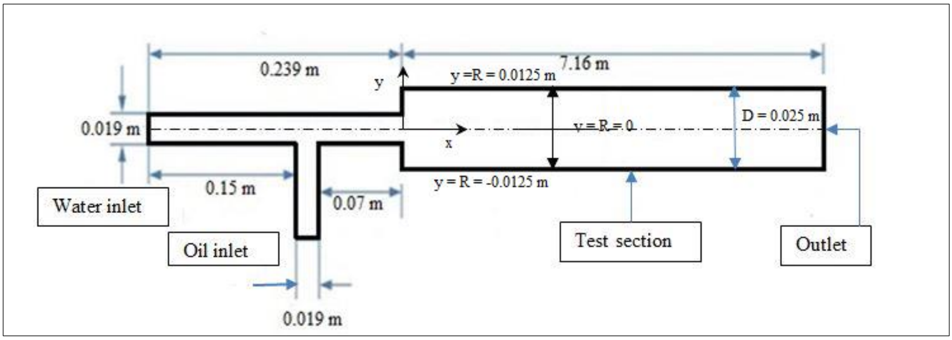

Figure 1. Schematic representation of the domain with detailed dimensions

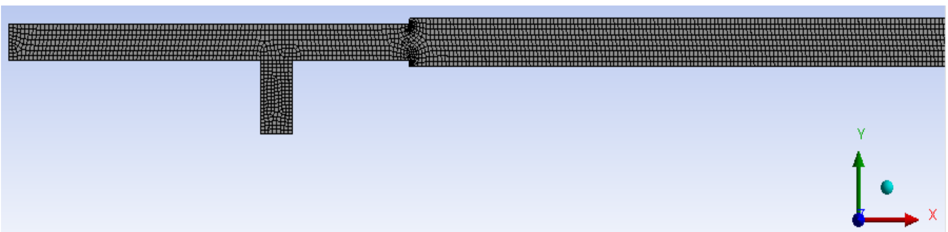

Figure 2. Meshing of channel

3.1. Procedure

For all cases first of all the channel has been filled with water from the water inlet and then oil has been introduced into it. The steps followed during the simulation are described below.

a. 2D pressure-based solver with absolute velocity formulation is chosen as the solver under transient condition. Gravity is considered in the Y-direction as - 9.81 m/s^2 and Atmospheric pressure is set as the operating pressure.

b. CLSVOF is selected with two Eulerian phases. Oil is set as the primary phase and water as the secondary phase. Surface tension is taken into the account using surface tension force modeling.

c. The fluids oil and water are chosen from the fluent database and the properties are set to the desired value depending upon the case as mentioned in the table below. For predicting the effect of non-Newtonian behavior power law model is selected for oil.

Table 2. Details of properties of fluid used in the simulation

Fluid	**Density, ρ (kg/m³)**	**Viscosity, μ (Kg/ms)**	**Thermal conductivity, k (W/mK)**	**Specific heat, C_p (J/KgK)**	**Surface tension, σ (N/m)**	**Contact angle, α (degree)**
Oil	888.398	0.107321	0.0944	1897.214	0.024	8.5
Water	998.200	0.001003	0.6019	4156		

d. The following boundary conditions are used for the simulation of the three cases. Temperature boundary conditions are used for the third case only.

Table 3. Details of boundary conditions

Oil inlet	Specified superficial velocity of oil, phase-2 volume fraction = 0, oil temperature at inlet.
Water	Specified superficial velocity of oil, phase-2 volume fraction = 1,water temperature at the inlet.
Wall	Stationary wall with no-slip boundary condition, contact angle, wall temperature.
outlet	Pressure outlet with zero gauge pressure.

e. PISO scheme is used for pressure-velocity coupling. PRESTO is used for pressure discretization. The volume fraction is discretized using geo-reconstruct. Power law scheme is used for momentum and level set function. First-order implicit is used for the transient formulation. Under-relaxation parameters are retained at default values. Residue value is set at 10^{-4}.

f. Variable time-stepping method with iterative time stepping is used. Courant number is always kept below 1. The results are taken when steady state is achieved.

3.2. Mesh refinement study

Figure 3 shows the variation of oil volume fraction with radial distance for all the five meshes. From the graphs, it is observed that there is significant variation of oil volume fraction when the mesh is refined from 27953 cells to 35830 cells. However, the variation oil volume fraction for meshes with 48152 cells, 56502 cells and 69570 cells are almost identical. More particularly the results of fourth (56502 cells) and fifth mesh (69570 cells) are almost overlapping. Thus the fourth mesh with 56502 numbers of cells has been selected as the optimum mesh for simulation.

Table 4. Details of different mesh

Mesh no.	**Number of divisions in the horizontal portion of test section**	**Number of divisions in the vertical portion(outlet) of test section**	**Number of cells**	**Number of nodes**
Mesh1	2996	11	27953	31082
Mesh2	3445	20	35830	39438
Mesh3	4194	30	48154	52555
Mesh4	4494	40	56502	61232
Mesh5	5093	50	69570	74945

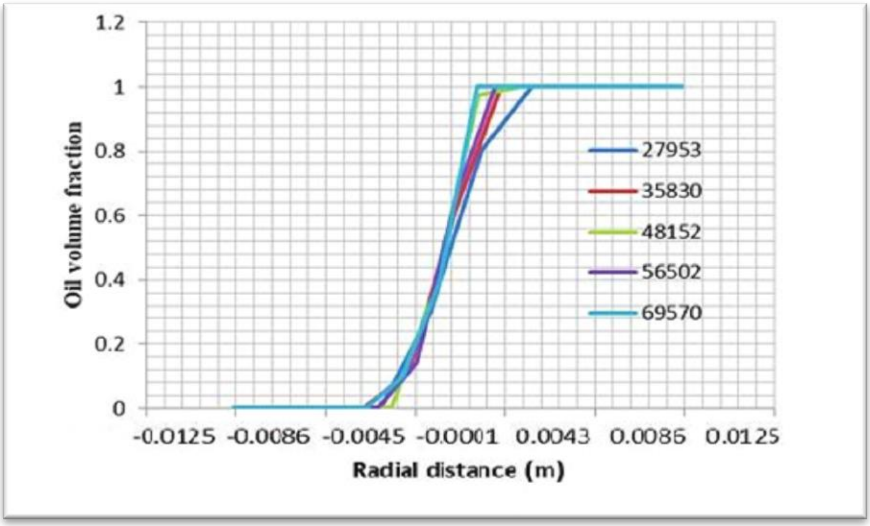

Figure 3. Radial variation oil volume fraction for different mesh size

3.3. Validation

The procedure followed in fluent for the analysis of oil-water stratified flow has been validated with the experimental results of Elseth (2001).

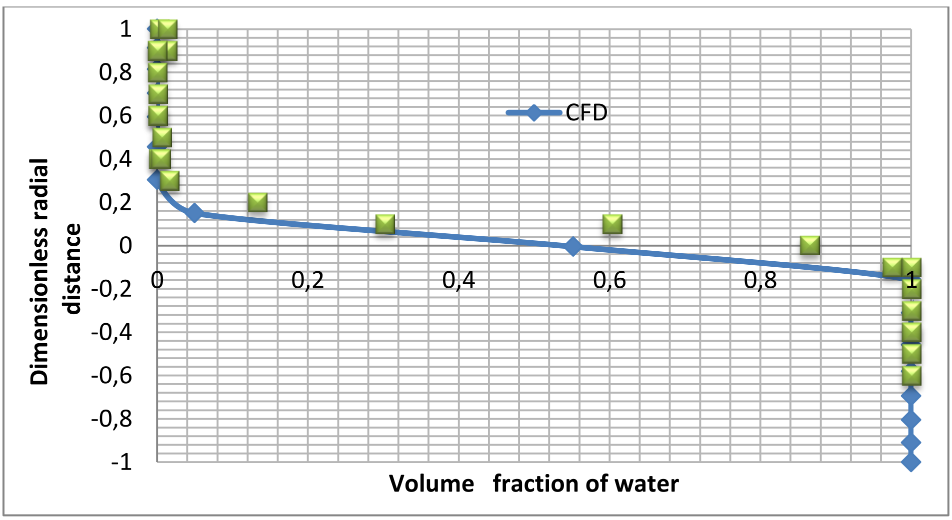

Figure 4. Comparison of water volume fraction profile with Elseth (2001)

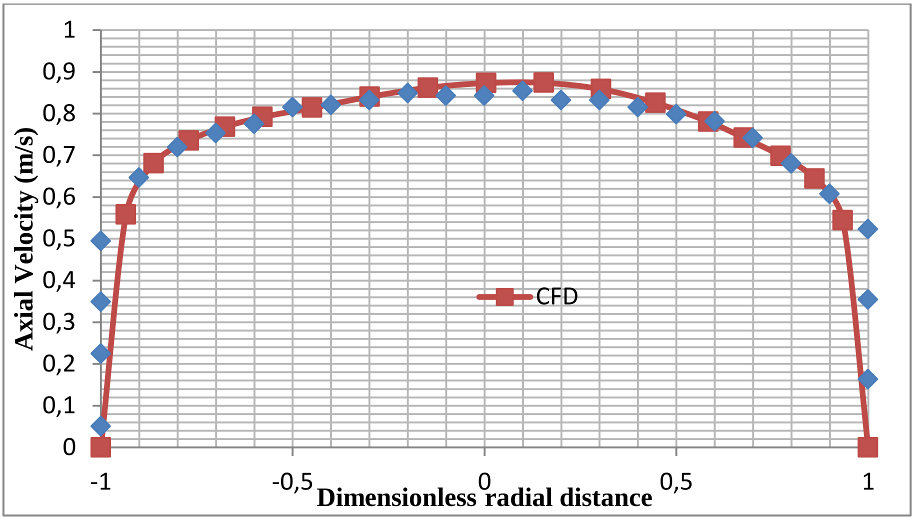

Figure 5. Comparison of axial velocity profile with Elseth (2001)

Out of several experimental cases of Elseth (2011) one case has been chosen for the validation purpose in which the mixture velocity at the inlet is 0.67 m/s and the inlet water cut (volume fraction) is 0.5. The diameter of the pipe is 0.05575 m and the length of the test section is chosen as 5 m so that a fully developed condition is attained within the pipe length. For validation purpose, the same geometry and dimensions of the domain as well as the fluid properties have been used as used by Elseth (2001). However, instead of a pipe, a two-dimensional channel has been chosen to reduce the computational time and cost. k-ω turbulence model has been used. The relaxation parameters used during the simulation is given in table 5. The result is obtained at a section which is at a distance of 1.16 m before the outlet and dimensionalized for the comparison. The volume fraction profile of water and the velocity profile have been compared with the experimental results and an excellent agreement is obtained between the experimental work and the CFD even for the two-dimensional domain as shown in figure 4 and figure 5 respectively. Thus the computational procedure is found to be a good one and hence the same procedure has been used throughout the simulation.

Table 5. Details of under-relaxation parameters

Variable for the under relaxation parameter	Value of the under relaxation parameter
Pressure	0.3
Density	1
Body forces	1
Momentum	0.4
Level set function	0.3

4. RESULTS AND DISCUSSION

4.1. Effect of variation of superficial oil velocity

In order to predict the effect of oil, superficial velocity three subcases have been considered. Simulations have been performed at three different superficial oil velocities keeping superficial water velocity constant to predict its impact on the Radial variation of oil volume fraction, mixture velocity and total pressure in the fully developed region. Pressure drop which is one of the most important parameters in all kind of flow pattern study has also been obtained for each case. The water velocity in all cases has been kept constant at 0.23 m/s whereas the effect of oil velocity of 0.2m/s, 0.24m/s and 0.3 m/s has been investigated. In all cases, the CLSVOF successfully predicts Stratified flow pattern with the phases separated by a diffused and wavy interface of finite thickness. The waviness of the interface is found to increase with the increase in oil velocity. The oil phase contours for the three sub-cases are shown in figure 6. The result for all the graphs & contours in this study has been obtained at a distance of 1.16 m upstream the outlet as at this distance flow is fully developed.

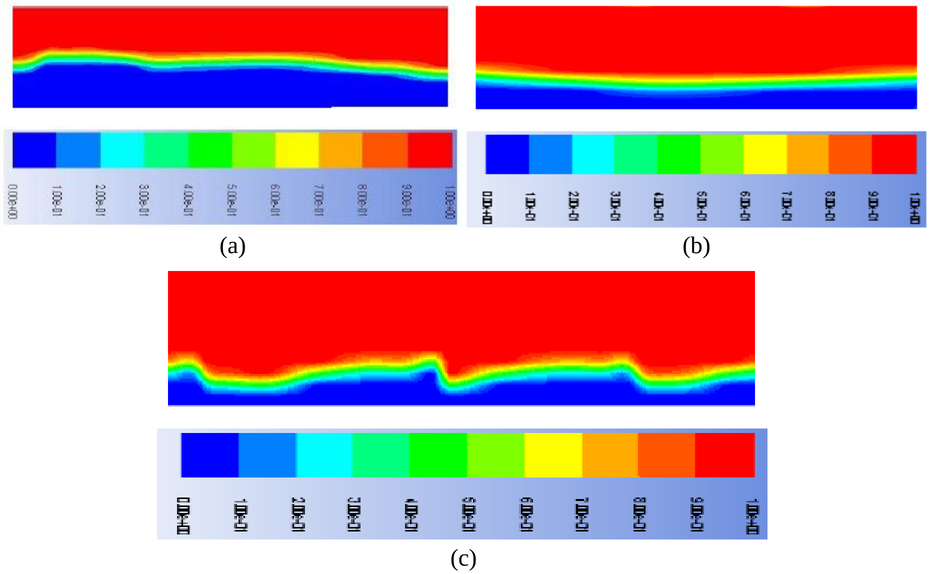

Figure 6. Contours of oil (phase1) volume fraction for (a) $V_o = 0.2$ m/s, (b) $V_o = 0.23$ m/s, and (c) $V_o = 0.3$ m/s

The radial variation of oil volume fraction at different oil velocities in the fully developed region is shown in the figure 7. The graph shows a significant change in the radial variation of oil volume fraction with a change in oil superficial velocity. As can be seen from the graph in all the three cases water phase occupies the entire bottom portion (oil volume fraction = 0) of the channel and the oil phase occupies the entire top portion (oil volume fraction = 1) due to the difference in their densities. The density difference causes the buoyancy force to set up that lifts the lighter oil phase upward.

As can be noticed from the figure 7, in between there exist a region where the oil volume fraction lies between 0 and 1.This shows the dispersion of both the phases in this region. This diffusion gives some thickness to the interface otherwise it would have been completely sharp. As the superficial oil velocity is increased from 0.2 m/s to 0.3 m/s the oil phase at a particular Radial section is observed to occupy more portion than the water phase. In other words, an increase in superficial oil velocity tends to cause an increase in oil phase thickness provided other parameters remain constant.

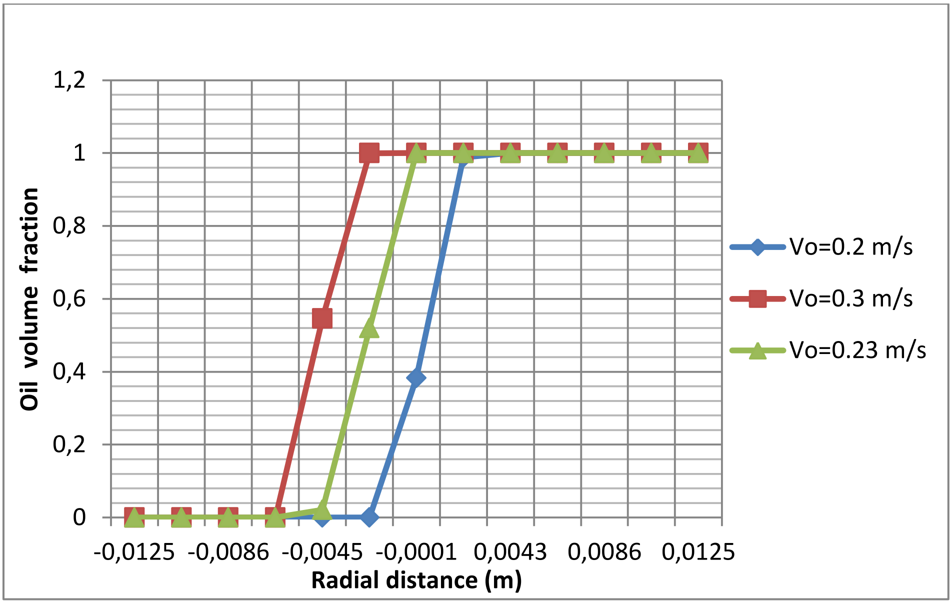

Figure 7. Radial distribution of oil volume fraction at different superficial oil velocity

The effect of superficial oil velocities on the radial distribution mixture velocity is shown in figure 8. From the graph, it is observed that the inlet oil velocity significantly affects the radial distribution of the mixture velocity in the stratified flow pattern. However, the radial distribution of mixture velocity is observed to have almost the same trend for all three subcases. For considered superficial oil velocity the mixture velocity starts from zero value at the bottom of the channel then increases, attains a maximum value; then decreases and finally reaches to zero value at the top portion of channel; thus rightly predicting the physics of the problem.

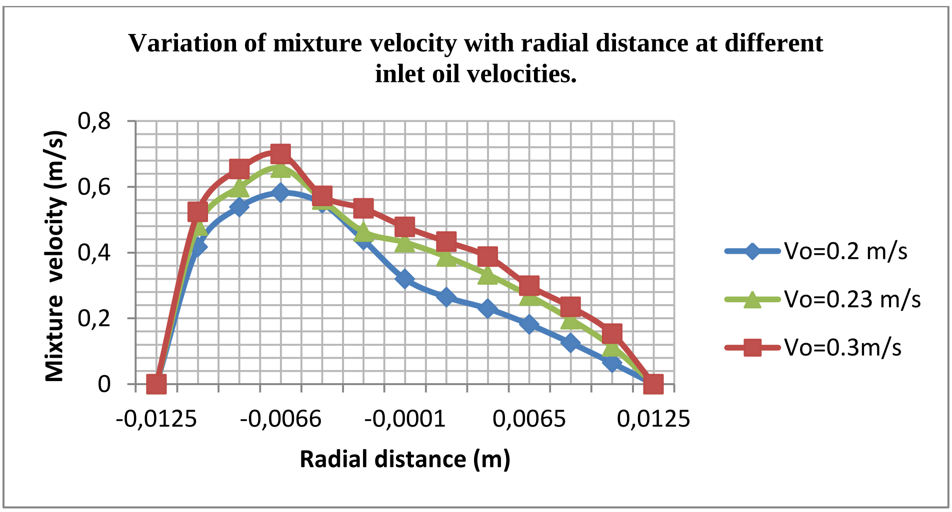

Figure 8. Radial distribution of mixture velocity at different superficial oil velocity

Figure 8 describes that the mixture velocity is higher in the water phase and slightly lower in the oil phase. The variation is very sharp in the bottom portion of the channel then becomes gradual towards the top portion of the channel. Also with the increase in oil superficial velocity the mixture velocity at a location increases. The maximum mixture velocity is reported to be 0.58 m/s, 0.66 m/s and 0.69 m/s corresponding to the inlet oil velocities of 0.2 m/s, 0.24 m/s and 0.3 m/s respectively. For all the three subcases maximum velocity is reported at a point lying in the interface region. Also, the radial location of the point at which maximum velocity occurs is found to be independent of inlet oil velocity.

The variation of pressure in the radial direction at different superficial oil velocities is shown in figure 9. As the mixture velocity is significantly affected by variation in superficial oil velocity hence the total pressure of the mixture also gets affected by superficial oil velocity. Like mixture velocity, the variation of total mixture pressure also shows the same trend for each subcase. As it can be observed from the graph (figure 9) at given superficial oil velocity total pressure of the mixture first increase then attains a maximum value and then decreases. As the superficial velocity of oil increases, the total pressure of the mixture also increases.

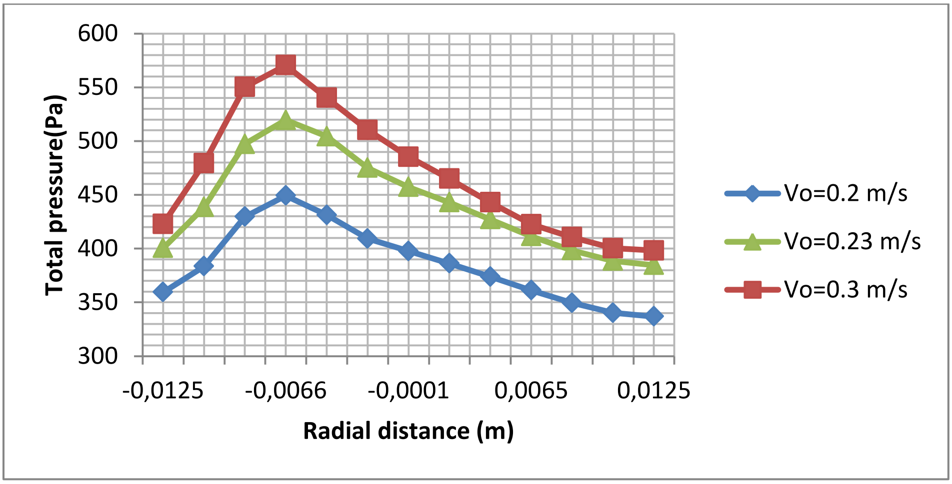

Figure 9. Radial distribution of total pressure at different superficial oil velocity

The maximum value of the total pressure is observed at the interface. This can be attributed to the fact that at the interface dispersion of oil phase and water phase takes place which causes slip between the phases as a result mixture velocity attains maximum value at the interface as depicted in figure 7; higher velocity causes higher pressure at the interface. Hence as the superficial oil velocity increases the dispersion of oil and water becomes more severe which causes more slip between the phases resulting higher pressure. This is depicted in figure 9. The maximum value of total pressure is reported to be 449.2 Pa, 519.56 Pa and 570.43 Pa corresponding to superficial oil velocity of 0.2 m/s, 0.24 m/s and 0.3 m/s respectively. Thus the total pressure of the mixture is found to be a strong function of the superficial velocity of oil.

Pressure drop is perhaps the most important parameter of interest as it directly governs the pumping power. The pressure gradient along the channel for the superficial oil velocity 0.20 m/s, 0.23 m/s and 0.30 m/s are 287.16 Pa/m, 292.30 Pa/m and 300 Pa/m respectively. As the superficial oil velocity increases the pressure gradient along the length of the channel also increases. This is because as the superficial oil velocity increases the mixture velocity also increases which causes more pressure drop. Thus it is observed that oil superficial velocity has a significant impact on the volume fraction profile, mixture velocity profile, total pressure of mixture and pressure drop as well for oil-water flow in a horizontal channel when both the fluids are treated as Newtonian. On increasing the superficial velocity from 0.20 m/s to 0.30 there is an increase of 4% in pressure gradient.

4.2. Effect of the inlet to wall temperature ratio on stratified flow

In this section the effect of the inlet to wall temperature ratio (θ) on volume fraction, velocity, pressure and pressure ratio has been investigated. This analysis is very important as the fluid properties vary significantly with the variation in the temperature of the mixture in the pipe/channel. The temperature of seawater is very low as compared to the inlet temperature of fluids. Hence as the oil-water flows through the channel a significant amount of heat transfer takes place from the mixture to the surrounding seawater. So the temperature of the stratified mixture decreases continuously. If the temperature falls below the wax appearing temperature of oil then wax begins to form and hence can block the flow passage restricting the flow. This may result in a higher pressure drop. The oil volume fraction contours are shown in figure 10. Figure 11 shows the radial variation of oil volume fraction at the different inlet to wall temperature ratio (θ) provided other parameters are constant.

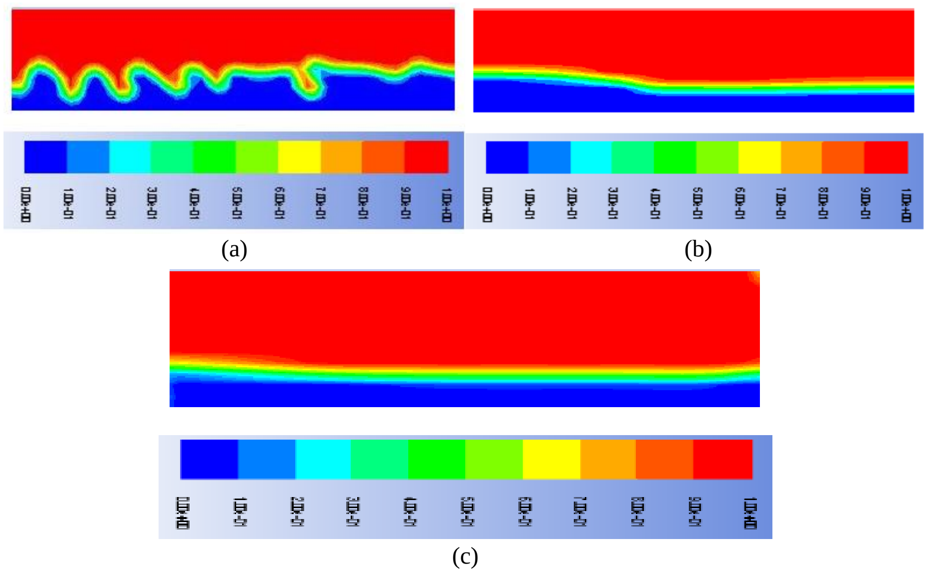

Figure 10. Contours of oil (phase 1) volume fraction for (a) θ =14, (b) θ=9.22 and (c) θ=7.07

Superficial oil velocity and water velocity used in this case are 0.23 m/s and 0.2 m/s respectively. As seen from the graph (figure 11) stratified flow pattern with water at bottom and oil at the top is obtained for all three values of θ. As observed from the graph with a decrease in θ oil phase occupies more portions in the channel. In other words the oil phase thickness increases. The difference in oil phase thickness is not much for θ = 7.07 and 9.22. However, a noticeable difference is seen for θ = 14.

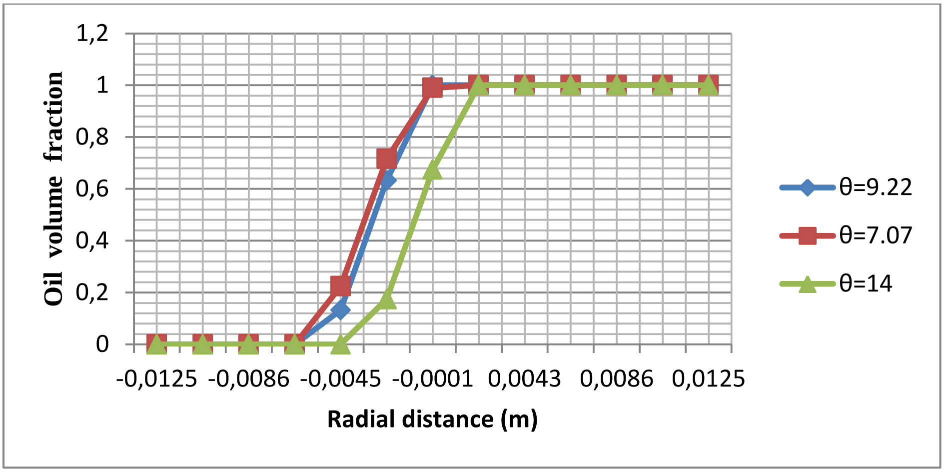

Figure 11. Radial variation of oil volume fraction at the different inlet to wall temperature ratio (θ)

Figure 12 shows the radial variation of mixture velocity at the different inlet to wall temperature ratio. It is observed that the mixture velocity is mainly affected by the inlet to wall temperature ratio in the oil phase region. In the water phase region, all three curves coincide. For a given inlet to wall temperature ratio the mixture velocity increases sharply then attains maximum value somewhere in the interface zone and then gradually decreases to zero. However with inlet to wall temperature ratio the mixture velocity does not show much variation. The difference in mixture velocity comes in to picture in the interface region. As can be seen from the figure 12 that the maximum velocity is obtained for $\theta = 14$ whereas the curves are almost identical for $\theta = 7.07$ and 9.22.

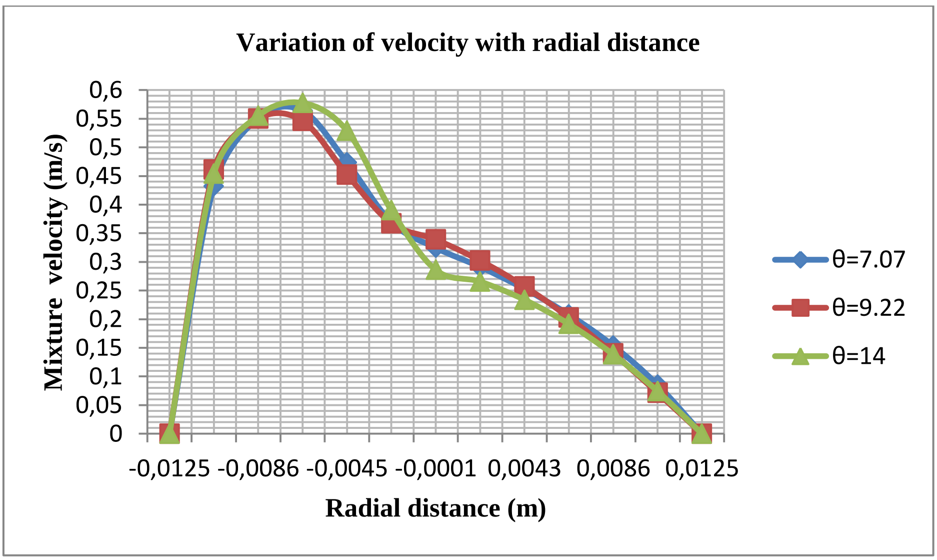

Figure 12. Radial variation of mixture velocity for the different inlet to wall temperature ratio (θ)

Figure 13 shows the radial variation of the total pressure of the mixture at the different inlet to wall temperature ratio. As seen from the figure 13 that the total pressure of the mixture is significantly affected by the change in θ. All pressure variations are gradual and the trend is the same for all sub-cases. At a particular value of θ the total pressure of the mixture first increases attains a maximum and then decreases. With an increase in the inlet to wall temperature ratio, the total pressure of the mixture at a location decreases. This can be attributed to the fact that as the inlet to wall temperature ratio increases the temperature of the mixture inside the channel decreases as shown in figure 15. Thus intermolecular forces become stronger which in turn makes the viscous forces stronger. Thus the slip between the phases decreases. Thus total pressure of mixture also decreases at a higher value of inlet to wall temperature ratio. The maximum occurs in the interface. The reason is that the interface is diffused where both oil and water phases are present simultaneously. As a result, the slip between the phases is maximum at the interface as compared to other region which causes higher pressure in the interface region. The maximum value of pressure is found to be 498.68 Pa, 450.874 Pa and 418.528 Pa for the inlet to wall temperature ratio of 7.07,9.22 and 14 respectively.

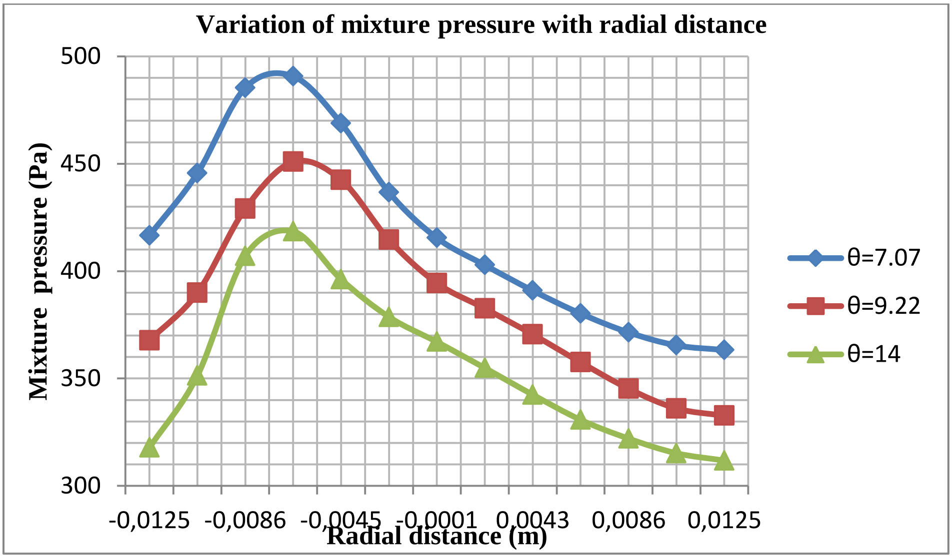

Figure 13. Radial variation of total pressure at different inlet to wall temperature ratio (θ)

The pressure gradient along the channel for inlet to wall temperature ratio (θ) of 14, 9.22 and 7.07 are 274.58 Pa/m, 277.09 Pa/m and 282.45 Pa/m respectively. The pressure gradient along the length of the channel decreases with an increase in the inlet to wall temperature ratio although the variation is not much. On increasing the inlet to wall temperature ratio from (θ) 7.07 to 14 there is decrease in pressure gradient of 2.78%.

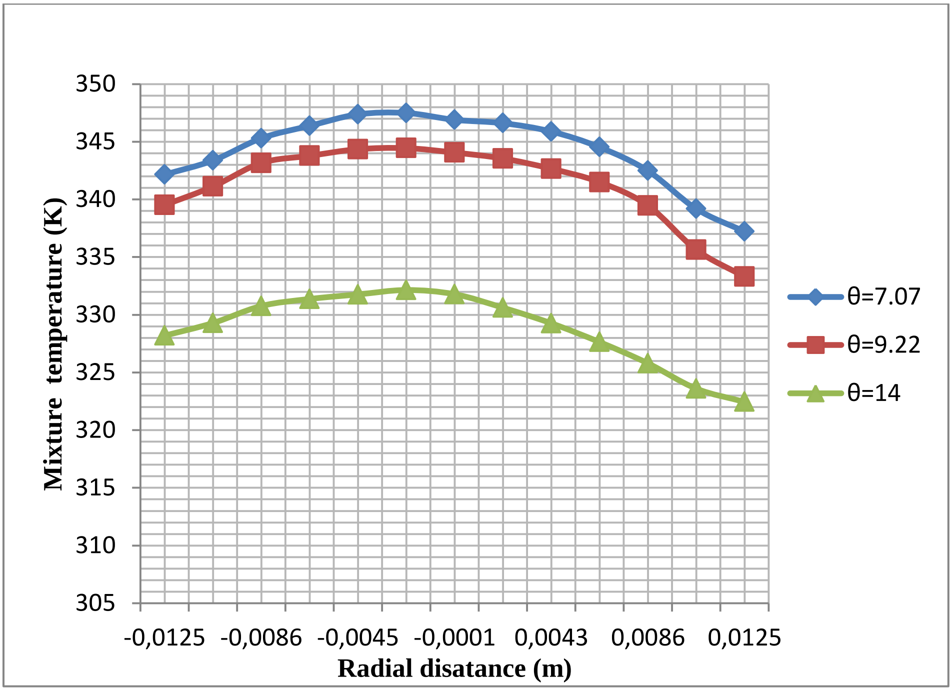

Figure 14. Radial variation of total temperature of mixture at the different inlet to wall temperature ratio (θ)

Figure 14 shows the Radial variation of temperature of the mixture at the different inlet to wall temperature ratio. It is observed that for the trend for Radial temperature variation is the same at all values of θ. With the increase in θ, the temperature of the mixture is found to decrease. Also, the temperature is found to higher for the water phase as compared to the oil phase.

The maximum values of temperature are obtained in the interface region for all the three subcases. This is because of the fact that in the interface region the slip between the phases is maximum because of which the friction in the flow increases which causes viscous dissipation. Hence the internal energy of the fluid increases.

5. CONCLUSIONS

The attempts have been made to investigate one of the commonly found flow patterns in petroleum industries known as the stratified flow pattern. The simulations have been done for oil-water two-phase flow in a rectangular 2D channel in unsteady mode. The interface between oil and water has been successfully captured using Coupled level set volume of fluid (CLSVOF) technique which has been proved to be better than simply the Volume of fluid technique and Level set techniques, taken individually. All results have been obtained only after attainment of the steady state. The simulation has been validated with the experimental data of Elseth (2001) for stratified flow pattern and satisfactory agreement is obtained. Two cases have been investigated to understand some of the characteristics of stratified flow pattern. In each case, the radial variation of volume fraction, mixture velocity, total pressure and pressure drop have been studied. In the first case, the effect of superficial oil velocity has been investigated keeping all other parameters constant. The stratified flow pattern is obtained for all three values of superficial oil velocities and considerable variation are observed in parameters and thus found to be one of the key factors affecting stratified flow pattern. In the second case, the effect of the inlet to wall temperature ratio has been investigated to predict the variation of temperature in the flow and its effect on the other parameters. The analysis can helpful in predicting whether the temperature of oil falls below wax appearing temperature for a given set of conditions or not and thus preventing the blocking of the pipe due to the formation of wax. The results obtained could be useful in the design of transportation pipeline in the oil industries.

Acknowledgment

Authors heartily acknowledge National Institute of Technology, Raipur for providing permission to access Laboratory, library and other resources for writing this article.

Nomenclature

Symbols	**Greek letters**
k = Thermal conductivity of fluid (W/m-k)	ρ = Density of fluid
C_p = Specific heat of fluid (J/kg-K)	μ = Viscosity of fluid
K = Flow consistency index	σ = Surface tension coefficient
n = flow behavior index	α = contact angle
P = Pressure (Pa)	τ = shear stress
T = Temperature (k)	ϕ = Level set function
$\dot{m}$ = mass flux (Kg-s^{-1}/m^2)	δ = Dirac delta function
r = Volume fraction	Γ = interface
V = Mixture velocity (m/s)	θ = inlet to wall temperature ratio
V_o = Superficial velocity of oil (m/s)	€ = Half of the thickness of interface
V_w = Superficial velocity of water (m/s)	**Subscript**
B = Body force per unit volume	m = mean
x = space coordinate	1= phase 1
t = time (s)	2 = phase 2
h_{12} = latent heat of phase change (J/kg)	
$\hat{n}(\phi)$ = unit vector normal to interface.	
$S_{€}$ = smoothed sign function	
ΔX ΔY = size of control volume in x and y directions	
H = Heaviside function/Unit step function	
∂P/∂x = pressure gradient (Pa/m)	

REFERENCES

[1] Ansys Fluent manuals (2012) - Theory and theory guide.

[2] Ayati A.A., Kolaas J., Jensen A. and Johnson G.W. (2014). A PIV investigation of stratified gas–liquid flow in a horizontal pipe. *International Journal of Multiphase Flow, vol. 61, pp.129–143.*

[3] Ayati A.A., Kolaas J., Jensen A. and Johnson G.W. (2015). Combined simultaneous two-phase PIV and interface elevation. *International Journal of Multiphase Flow, vol.74, pp. 45–58.*

[4] Brackbill J.U., Kothe D.B. and Zemach C. (1992). A continuum method for modeling surface tension. *Journal of Computational Physics, vol.100, pp.335-354.*

[5] Brauner N., Rovinsky J., Moalem D. and Maron D. (1996). Analytical Solution for Laminar-Laminar Two-Phase Flow in Circular Conduits. *Chem. Eng. Comm., vol. 141/142, pp. 103–143.*

[6] Chang Y.C., Hou T.Y., Merriman B.and Osher S. (1996). A Level set Formulation of Eulerian Interface capturing methods for incompressible fluid flows, *Journal of computational physics vol.124, pp.449-464.*

[7] Das S., Gada V.H. and Sharma A. (2015). Analytical and Level set method-Based numerical study for two phase stratified flow in a pipe. *Numerical Heat Transfer, Part A, vol. 67, pp.1253–1281.*

[8] Datta D., Gada V.H. and Sharma A. (2011). Analytical and Level-Set Method-Based Numerical Study for Two-Phase Stratified Flow in a Plane Channel and a Square Duct. *Numerical Heat Transfer, Part A: Applications: An International Journal of Computation and Methodology, vol.60:4, pp. 347-380.*

[9] Desamala B., Dasamahapatra A. and Mandal T. (2014). Oil-Water Two-Phase Flow Characteristics in Horizontal Pipeline – A Comprehensive CFD Study. *International Journal of Chemical, Molecular, Nuclear, Materials and Metallurgical Engineering, vol.8, issue 4.*

[10] Dogonchi A. S., Hatami. M. and Domairry G. (2015). Motion analysis of a spherical solid particle in plane Couette Newtonian fluid flow. *Powder Technology, vol. 274, p.p.186–192.*

[11] Duan J., Gong J., Yao H., Deng T. and Zhou J. (2014). Numerical modeling for stratified gas–liquid flow and heat transfer in pipeline. *Applied Energy, vol. 115, pp.83–94.*

[12] Elseth G. (2001). An Experimental Study of Oil / Water Flow in Horizontal Pipes. *The Norwegian University of Science and Technology (NTNU) for the degree of Dr. Ing.*

[13] Faccini J., Filho J., Sampaio P. and Su J. (2015). Experimental and Numerical Investigation of Stratified Gas–Liquid Flow in Downward- inclined Pipes. *Heat Transfer Engineering, Vol.36:11, pp. 943-951.*

[14] Gada V.H. and Sharma A. (2011) .On a Novel Dual grid Level Set method for two phase flow simulation. *Numerical heat Transfer part-B Fundamentals,* v*ol. 59(1), pp. 26-57.*

[15] Gada V.H. and Sharma A. (2012). Analytical and level-set method based numerical study on oil–water smooth/wavy stratified-flow in an inclined plane-channel, *International journal of Multiphase flow, vol. 38, issue 1, pp.99-117*.

[16] Gada V.H. and Sharma. A (2009). on derivation and physical interpretation of Level set-Based equation for two phase flow simulation. *Numerical heat Transfer part-B Fundamentals, vol. 56(4), pp.307-322*

[17] Goldstein A., Ullmann A. and Brauner N. (2015). Characteristics of stratified laminar flows in inclined pipes. *International Journal of Multiphase Flow, vol.75, pp.267–287.*

[18] Hatami. M. and Ganji D.D. (2014b). Motion of a spherical particle on a rotating parabola using Lagrangian and high accuracy Multi-step Differential Transformation Method. *Powder Technology, vol. 258, pp.94–98.*

[19] Hatami. M. and Ganji D.D.(2014a). Motion of a spherical particle in a fluid forced vortex by DQM and DTM. *Particuology, vol. 16 pp. 206-212.*

[20] Hatami. M., Sheikholeslami M., and Domairry G. (2014). High accuracy analysis for motion of a spherical particle in plane Couette fluid flow by Multi-step Differential Transformation Method. *Powder Technology, Vol. 260, p.p.59–67.*

[21] Hatami. M., Song D. and Jing D. (2016). Optimization of a circular-wavy cavity filled by nanofluid under the natural convection heat transfer condition. *International Journal of Heat and Mass Transfer, vol. 98, p.p.758–767.*

[22] Joyce G. and Soliman H.M. (2016). Pressure drop for two-phase mixtures combining in a tee junction with wavy flow in the combined side. *Experimental Thermal and Fluid Science, vol.70, pp.307–315.*

[23] Lee S., Euh D., Kim S., and Song C (2015).quantitative observation of co-current stratified two-phase flow in a horizontal rectangular channel. *Nuclear engineering technology, vol.47, pp. 267-283.*

[24] Li H.Y., Yap Y.F., Lou J. and Shang Z. (2014) .Numerical modeling of three-fluid flow using the level-set method. *Chemical Engineering Science, vol. 126, pp. 224-236.*

[25] Li H.Y., Yap Y.F., Lou J. and Shang Z. (2014). Numerical investigation of heat transfer in three-fluid stratified flows. *International journal of Heat and Mass transfer vol.89, pp. 576-587.*

[26] Mark S., Peter S .and Stanley O. (1994). A Level Set approach for computing solution to incompressible two phase flow, *Journal of computational physics, vol.114, pp.146-159.*

[27] Mehravaran M. and Hannani S. (2008). Simulation of incompressible two-phase flows with large density differences employing lattice Boltzmann and level set methods. *Comput. Methods Appl. Mech. Engrg, vol. 198, pp. 223–233*.

[28] Min C. (2010).On reinitializing Level Set function. *Journal of computational physics, vol. 229 pp. 2764–2772.*

[29] Pandey S., Gupta A., Chakrabarti D., Das G. and Ray S. (2006). Liquid–liquid two phase flow through a horizontal t-junction. *Chemical Engineering Research and Design, vol. 84(A10), pp. 895–904.*

[30] Picchi D., Correra S. and Poesio P. (2014). Flow pattern transition, pressure gradient, hold-up predictions in gas/non-Newtonian power-law fluid stratified flow. *International Journal of Multiphase Flow, Vol. 63, PP.105–115.*

[31] Pitton et al. (2014). An experimental study of stratified–dispersed flow in horizontal pipes. *International Journal of Multiphase Flow, vol. 67, pp.92–103.*

[32] Rezaie N.Z., Avval M.S. and Mirzaei M. (2014). Analytical and numerical investigation of heat transfer and entropy generation of stratified two-phase flow in mini-channel, *International Journal of Thermal Sciences, vol. 90, pp.24-37.*

[33] Rodriguez O.M.H. and Baldani L.S. (2012). Prediction of pressure gradient and holdup in wavy stratified liquid–liquid inclined pipe flow. *Journal of Petroleum Science and Engineering ,vol. 96-97,pp. 140–151*

[34] Rodriguez.O and Castro.M (2014). Interfacial-tension-force model for the wavy-stratified liquid–liquid flow pattern transition. *International Journal of Multiphase Flow, vol. 58, pp. 114–126.*

[35] Sabelnikov V., Ovsyannikov A. and Gorokhovski M. (2014). Modified level set equation and its numerical assessment. *Journal of computational physics, vol.278, pp.1-30*.

[36] Salih A. and Ghosh M. (2009). Some numerical studies of interface advection properties of Level set method, *Sadhana, vol. 34(2), pp. 271–298.*

[37] Seikhi A. and Ecder A. (2013) Level Set Analysis of Two-Fluid Interfacial Flows. *International conference on computational science, ICCS, Procedia Computer Science, vol.18, pp. 2420 – 2423*.

[38] Sethian J.A (1999). Level Set Methods and Fast Marching Methods, 2nd ed. *Cambridge University Press, New York.*

[39] Simoes E., Carneiro J. and Nieckele A. (2014). Numerical prediction of non-boiling heat transfer in horizontal stratified and slug flow by the Two-Fluid Model. *International Journal of Heat and Fluid Flow, vol.47, pp. 135–145.*

[40] Son G. (2003). Efficient implementation of a coupled level set and volume-of-fluid method for three-dimensional incompressible Two-phase flows, *numerical heat transfer, part B: fundamentals, vol. 43(6), pp. 549-565.*

[41] Son G. and Hur N. (2010). a coupled level set and volume-of-fluid method for the buoyancy-driven motion of fluid particles. *Numerical Heat Transfer, Part B: Fundamentals, vol. 42(6), pp.523-542.*

[42] Sun D. and Tao W. (2009). A coupled volume-of-fluid and level set (VOSET) method for computing incompressible two-phase flows. *International Journal of Heat and Mass Transfer, vol.53, pp.645– 655.*

[43] Tang W., Hatami. M., Zhou J. and Jing D. (2017). Natural convection heat transfer in a nanofluid-filled cavity with double sinusoidal wavy walls of various phase deviations. *International Journal of Heat and Mass Transfer, vol. 115, p.p.430–440.*

[44] Tanguy S., Me'nard T. and Berlemont A. (2006). A Level Set Method for vaporizing two-phase flows. *Journal of Computational Physics, vol. 221 pp.837–853.*

[45] Yap Y.F., Chai J.C., Toh K.C. and Wong T.N. (2006). Modeling the flows of two Immiscible Fluids in a three-Dimensional square Channel Using the Level-Set Method. *Numerical Heat Transfer, Part A: Applications: An International Journal of Computation and Methodology, vol. 49:9, pp.893-904.*