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Viscous Oil-Water Flow Through an Undulated Pipeline in Valley Configuration by Experimental and CFD Simulation

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ABSTRACT

Investigation of flow patterns and their transitions during viscous oil-water flow through undulated pipeline in valley configuration is reported in this paper. Undulated pipeline consists of two inclined sections (downhill and uphill) connected between two horizontal pipes (upstream and downstream). Experiments have been conducted over a wide range of superficial velocities of oil (USO = 0.013 m/s to 1.12 m/s) and water (USW = 0.1 m/s to 1.12 m/s). Seven different flow patterns (viz., plug, slug, wavy stratified, stratified mixed, wispy annular, dispersion of oil in water and dispersion of water in oil) are identified by visual, imaging and conductance probe techniques at all the four sections. Present work reveals that the flow patterns are similar to that of horizontal pipe flow; however, different flow patterns appear at a velocity higher or lower than that of horizontal flow. Using VOF method, it is successfully predicted plug, slug, stratified wavy, stratified mixed and annular flow except dispersion of both oil and water. Volume fraction data of separated flow obtained from CFD is validated with the experimental data with an average absolute error of 19.3%. Good matching is observed when simulated flow pattern data is superimposed on the experimental flow map of present study.

Keywords:—*Undulated pipeline, oil-water flow, Flow pattern, VOF model.*

I. INTRODUCTION

Pipeline transportation is a common and most efficient process to supply crude oil from its sources (viz., oil well) to refineries for further processing. The transportation line is basically a pipe network consists of a n umber of interconnected horizontal and inclined sections, resulting undulation or hilly terrain along the pipe line. The hydrodynamics of multiphase flow through undulated or hilly terrain pipeline is distinct from horizontal or inclined flow. Parametric information of such hydrodynamics is essential for designing of a realistic pipe network. A vast majority of research work is devoted to the flow in horizontal and inclined (including vertical) pipelines. A combination of horizontal and inclined (viz., valley configuration) would behave differently than that of horizontal or inclined alone.

Over the decades, researchers have experimentally identified several flow patterns of oil-water two-phase flow through horizontal [1, 2, 3, 4, 5, 6, 7] vertical [8, 9, 10] and inclined [11, 12, 13, 14, 15, 16] pipes. Horizontal flow is mostly dominated by stratified and dispersed flow [2, 6, 7] whereas annular and dispersed flow are the major flow patterns in vertical pipes [8, 9, 17]. Inclination in the pipe line along the flow introduces instability at the interface [11, 16, 18] between two phases. Therefore, stratified wavy, stratified mixed and dispersed flows are the dominating flow in an inclined pipeline [19]. Due to the buoyancy, annular flow is most stable in vertical pipe and least stable in horizontal pipe [20, 21]. Inclination also strongly influences the slip velocity and it (slip velocity) increases with higher inclination, either downward or upward [13, 22]. Flow patterns are strongly influenced by the pipe diameter, entry geometry and fluid properties. It has been observed that a smaller pipe diameter promotes slug and annular flow [23, 24]. High viscous fluids compared to low viscous one, favor annular flow [14, 20].

Experimental observations are complemented with the help of analytical models [25, 26, 27, 28] and computer simulations [29, 30, 31]. Analytical models are applicable to a s et of s elective flow patterns rather than a complete picture. For example, Brauner and Maron [26] have proposed models based on the stability analysis of flow patterns, to predict the transition boundaries from stratified flow pattern to annular and intermittent. Later on, Brauner et al. [25] have modified their models with the help of two fluid model, to predict the shape of an interface for a stratified wavy flow as a function of system parameters like velocities, fluid properties, etc. In stratified flow, flow dynamics is influenced by entrainment of one phase into another, which has not been incorporated in the above model. Al-wahaibi and Angeli [32] have successfully predicted the entrainment fraction of a horizontal stratified flow in a circular pipeline by balancing "rate of drop entrainment" and "rate of drop deposition" methods, which have been derived from two-fluid model. CFD simulations are also being done to intricately understand the hydrodynamics in multiphase flow. The success of CFD simulation greatly depends on the models used in the simulation. Al-Yaari and Abu-Sharkh [29] have performed 3D simulations to predict the stratified wavy and mixed flow patterns using RNG K- ε multiphase model and validated with experimental results. Ko et al. [19] have found that, shear stres transport model is better than the K-ω turbulence model, to solve the kinetic energy and dissipation equations for turbulent wavy core flow. VOF has also been implemented to investigate interfacial distribution of two-phases through complex geometry like sudden expansion and contraction [31], peak configuration [33], and the simulated results match well with experimental observations.

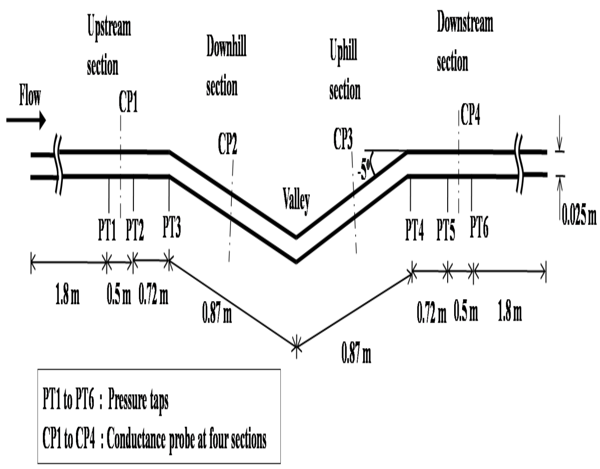
Hydrodynamics of multiphase flow through complicated geometry like undulated pipelines, hilly terrain pipelines are poorly understood. Most studies have focused on gas-liquid (air-water) two-phase flow through these complex pipe networks [34, 35, 36, 37]. Their results showed that slugs can be generated at low elbows, dissipate at top elbows, and shrink or grow in length as they travel along t he pipe. Al-Safran et al. [34] experimentally investigated slug initiation mechanism at valley (lower dip) and they observed five flow categories of s lug flow patterns in valley configuration of a hilly -terrain pipeline. They observed that the slug flow is enhanced due to such geometry. They also investigated the effect of valley on slug length distribution at uphill and downhill sections. Mandal et al. [36] have estimated slug characteristics, dissipation, slug velocity and s lug length in different sections of undulated pipeline from conductivity probe signals applying cross-correlation technique. Beside the gas -liquid flow, a limited number of studies have focused to understand the phenomena of liquid -liquid flow through undulated pipeline [5, 22, 33]. Abduvayt et al. [22] have described the experimental result of flow pattern, pres sure drop, water holdup and s lip of the phases in hilly terrain pipeline (in peak configuration) for oil-water (oil viscosity = 1.88 ± 0.19 mPas) flow. They have reported that the stratified smooth flow was totally absent at +3o uphill and -3o downhill sections of the hilly terrain pipeline and slip increased with increasing the pipe inclination. Mandal [5] have estimated the flow patterns of oil-water flow (oil viscosity = 1.2 mPas) through an undulated pipeline at peak and valley configuration using optical probe. A marginal influence of undulation on transition boundaries of stratified wavy to three -layer flow and three layer to disperse flow at different section have been reported.

Although the hydrodynamics of low viscous oil-water flow through hilly terrain and undulated pipeline has been studied, the flow behavior of moderately viscous oil-water flow is poorly understood. Recently, we have shown detail analysis on flow pattern maps with peak configuration [33]. In this work, we report CFD simulated results on an undulated pipeline with valley configuration (viz., it consists of two interconnected horizontal, one upward and one downward inclined (±5°) section). We describe our experimental findings of various flow patterns of moderately viscous oil-water flow (oil viscosity = 107 mPas), and subsequently, we discus s CFD simulation results based on VOF (Fluent 6.3) model for two-phase flow. Finally, we present a detail comparison of our results with literature.

II. CFD Methodology

2.1. Model Development

Figure 1a shows detailed dimensions of the conduit geometry considered in the present computational work to mimic the actual experimental test loop. The geometry consists of an interconnected downhill and uphill section in between two horizontal pipes with an internal diameter and a length of 0.025 m and 7.36 m respectively. Oil and water were introduced into the pipe through a T-junction at the entry section where water and oil enter into the pipe from the horizontal and vertical directions, respectively. The CFD software package of ANSYS FLUENTTM has been used for simulation. Meshing of the model has been done using GAMBIT. Figure 1b shows the 2D-mesh of the pipe used in simulation. The mesh consists of 50117 quadrilateral mesh elements for entire pipe geometry. Quadrilateral mesh geometry is s elected for accounting surface tens ion effect more accurately [38].



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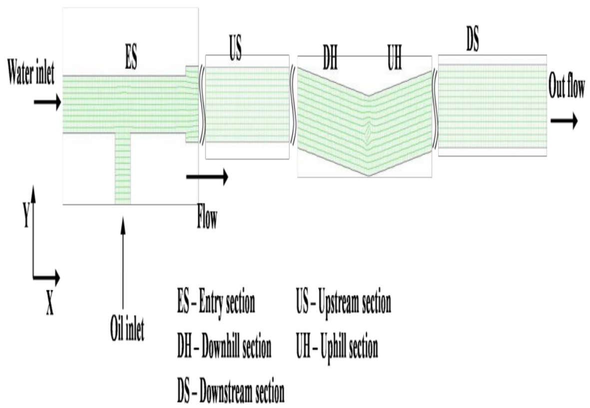


(b)

Figure 1. Undulated pipeline in valley configuration; (a) Detailed dimensions of model; (b) Meshing of the model

Volume of Fluid (VOF) approach for two phase modeling has been s elected in Fluent in which two fluids share a well defined interface. VOF solves as ingle set of momentum equations, which is shared by both the fluids. The details of the governing equations and the treatment of the interface can be obtained from Fluent user's guide 6.3, 2006.

2.1.1. Governing Equations

In VOF approach, the continuity equation can, therefore be written as :

$$\frac{\partial(\rho)}{\partial t} + \nabla \cdot (\rho U) = \sum_q S_q \qquad (1)$$

Where, ρ, U, t, S are density, velocity, time and mass source respectively. In the present case 'S' is zero.

$$\frac{\partial(\rho U)}{\partial t} + \nabla \cdot (\rho U \cdot U) = -\nabla P + \nabla \cdot [\mu(\nabla U + \nabla U^T)] + (\rho g) + F \qquad (2)$$

The equation of momentum conservation can be expressed as follows :

The left hand side corresponds to convection and the first term on the right hand side corresponds to pres sure, while the other terms represent diffusion, gravitational body force and external body force (in the present case, F is considered as surface force) respectively.

Generally, the Volume of Fluid solves the problem by updating the phase volume fraction field, provided the fixed grid, the phase volume fraction, and the velocity field are available in a given time step. If the volume fraction of qth fluid in a cell is denoted as 'αq', the following three possibilities would arise:

α_q =0: the cell does not contain fluid q.

α_q=1: the cell is occupied solely by fluid q.

$0<\alpha_q< 1$: the cell contains the interface

Depending on the local value of αq, the density and viscosity in each cell are calculated by following equations :

$$\rho = \sum_{1}^{p} \rho_q \alpha_q \qquad (3)$$

$$\mu = \sum_{1}^{p} \alpha_q \mu_q \qquad (4)$$

A separate continuity equation for 'α_q' is considered as follows :

$$\frac{\partial \alpha_q}{\partial t} + (U_q \nabla) = S_{\alpha q} \qquad (5)$$

U_q *and* $S_{\alpha q}$ are velocity and source term of volume fraction of q component respectively.

For each of the cells the following relations hip is also valid:

$$\sum_{1}^{p} \alpha_q = 1 \qquad (6)$$

Where "p" is the number of phases. For the present two phase flow, $p = 2$.

2.1.2. Initial and boundary condition

In all cases, the flow has been initialized by filling up the pipe with water at the water inlet with a specified inlet superficial velocity. Oil is then introduced in the pipe. The main steps followed during the simulation are:

- 2-D pressure based segregated solver with implicit formulation is s elected as solver under unsteady state condition.
- Volume of Fluid (VOF) model is s elected with number of phases q = 2. Explicit VOF scheme is selected so that the discretization scheme for VOF changes to Geo-Reconstruct (to get the surface tens ion effect).
- Test fluids are defined using material database of Fluent and the properties are changed according to the present work.
- The operating pres sure is set as atmospheric pressure and gravity is considered in Y-direction as -9.81 m/ s2.
- The inlet velocities of both the fluids are assumed to be uniform and specified as follows :
  - At x = 0, y = 0; $U_x = U_{water}$ and $U_y = 0$ (m/s)
  - At x = 0.15 m and y = -0.0595 m; $U_y = U_{oil}$ and $U_x = 0$ (m/s)
- The wall is assumed to be stationary and no slip condition is imposed. A contact angle of 8.5º [39] is taken to account for the wetting behavior of the wall with the fluids.
- Pressure outlet boundary is selected and the diffusion flux variables at the exit are taken as zero.

2.1.3. Discretization method and convergence

To capture the dynamic nature of two - phase flow, variation of flow patterns with time and space has been considered. A transient simulation has been carried out with a time step of 0.001s. In this simulation, the continuity equations are discretized by PRESTO algorithm [40] while momentum equations are discretized by QUICK scheme [20], which is more accurate on structured meshes aligned with the flow direction. SIMPLE (semi–implicit pres sure linked equation) algorithm is used for pres sure velocity coupling during the numerical analysis of the equations. It employs the relations hip between velocity and pressure corrections to impose the mass conservation in consequence to get the pres sure. The velocities are typically calculated by a segregated solver and it is coupled with the phases (volume fraction) to maintain the volume continuity.

The convergence is decided based on the residual values of calculated variables, namely velocity components, mass and volume fraction. In the present study, the numerical computation is considered converged when the residuals of the different variables are lowered by magnitude of three orders. After reaching to the desired residual value, the flow of the both the phases are tracked to get the flow pattern.

III. Results and Discussion

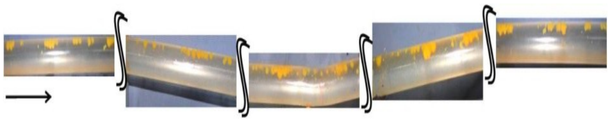
We begin with the discussion on flow patterns from CFD simulation (using VOF). Subsequently, we discuss flow pattern maps at four test sections highlighting effect of undulation on flow patterns. The simulated results are validated by comparing predicted volume fraction value with those obtained from experiment.

3.1. Observed Flow Patterns

Seven different flow patterns are observed during oil-water flow through an undulated pipeline in valley configuration as shown from Figures. 2 to 7. Those are plug flow (P; Figure 2a), s lug flow (S; Figure 3a), stratified wavy flow (SW; Figure 4a), stratified mixed flow (SM; Figure 5a), Wispy annular flow (A; Figure 6a), dispersion of oil in water (DO/W) and dispersion of water in oil (DW/O). Experimental images for dispersed flows are not shown as they are not predicted using CFD. The results do not show a significant influence of this small undulation (undulation is ±5°, see Figure 2a for detail dimension of the set up) on the flow patterns at different sections.

Five different flow patterns are observed during oil-water flow through an undulated pipeline in valley configuration in our simulation using VOF method at the same flow conditions except two dispersions (oil in water and water in oil). We have success fully simulated plug (Figure 2b), slug (Figure 3b), stratified wavy (Figure 4b), stratified mixed (Figure 5b) and wispy annular (Figure 6b) flow patterns. The other flow patterns (viz., dispersion of oil in water and water in oil) observed at higher phase velocities are difficult to predict by using VOF method. This is due to the limitation of VOF method. The interface reconstruction scheme of VOF model fails to capture the oil-water interface properly at higher velocities [17]. Therefore, the dispersed flow patterns observed at higher phase velocities are not simulated in this study. Axial development of the flow patterns at four different sections (upstream, uphill, downhill, and downstream) are briefly described below and compared with experimental results.

Plug flow (P): This flow pattern is observed at lower velocities of both oil (USO = 0.013 m/s) and water velocities (USW = 0.197m/s). The small discrete oil droplets are observed in continuous water phase. Due to the bouncy effect, they are floating up and flowing through the upper s ide of the pipe. These are known as plug flow (P) and appear at all four sections of the undulated pipe. Experimental and simulated images of this flow pattern captured at USW = 0.197 m/s and USO = 0.013 m/s are shown in Figure 2(a) and (b) respectively as a representative results. The figure shows the variation in plug concentration (number of plug) along the length. It is slightly more at valley and les s at up and down stream due to the effect gravity. Water moves faster than the oil at downhill section. Hence, oil plugs are accumulated and its population is increased at this section.



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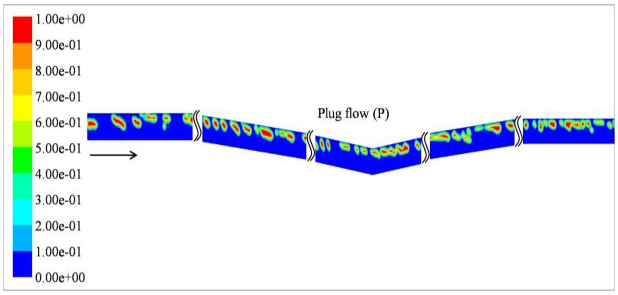
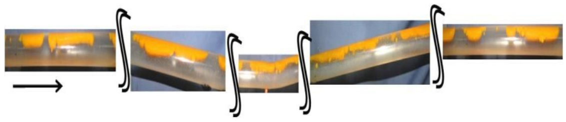


(b)

Figure 2. Plug flow (P) at USW = 0.197 m/s, USO = 0.013 m/s ; (a) Experimental image; (b) Simulated result

- ***Slug flow (S):*** On increasing the oil velocity (USO = 0.02 m/s) keeping water velocity (USW = 0.197 m/s) constant, oil plugs become larger in size and flow pattern termed as slug flow. A representative experimental and simulated result is shown in Figure 3a and Figure 3b respectively. Nose of the slug changes section to section of the undulated pipeline due to the effect of gravity. The diameter and length of an oil s lug grows continuously by gradual increase in oil velocity and s lug flow is trans formed into a stratified flow.
- ***Stratified wavy flow (SW):*** In this flow pattern, oil and water are flowing as two separate layers with a clear wavy oil/water interface. Oil flows on top of the water layer as shown in figure 4a and b. The figure shows a good agreement of simulation (Figure 4b) with experiment (Figure 4a). Nature of the waves formed at the interface is affected by the velocity of both the phases, fluid properties, pipe geometry and orientation (inclination). Wave amplitude increases at downhill section after crossing the upstream section and diminishes at uphill section. This is because of change in angle of inclination from horizontal to valley section. Amplitude of the waves increase at all section with increasing the oil velocity.



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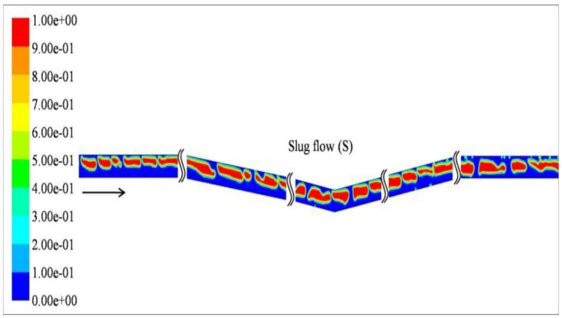
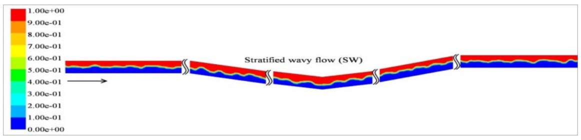


(b)

Figure 3. Slug flow (S) at USW = 0.197 m/s, USO = 0.02 m/s ; (a) Experimental image; (b) Simulated result

(a)

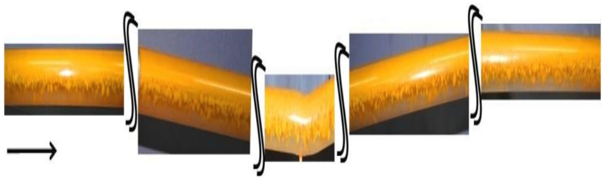


(b)

Figure 4. Stratified wavy flow (SW) at USW = 0.164 m/s, USO = 0.07 m/s ; (a) Experimental image; (b) Simulated result

- ***Stratified mixed flow (SM):*** Further increasing of oil velocity, wave becomes unstable as drag force overcomes the interfacial tens ion and results a number of droplets at the at the oil/water interface. The phenomena leads to form a "three layers" at interface which comprises of a continuous oil layer (on the top), a continuous water layer (at the bottom) and a layer of oil droplets in continuous water medium (in between continuous oil and water layer). This flow pattern is termed as three layer or stratified mixed flow pattern as shown in Figure 5a (an experimental image at USO = 0.132 m/s and USW = 0.3 m/s). We have successfully simulated this flow pattern at the same velocity as reported in Figure 5b. The droplet concentration at the interface is less at upstream section and is more at other three sections. Downhill section enhances the instability at the interface and creates more number of droplets there and effect of downhill persists till upstream section as short length of uphill section in the present work.

- ***Wispy annular flow (A):*** This flow pattern is identified using conductance probe and is noticed at moderate velocities of both the phases. The detailed description of the conductance probe is discussed in Desamala et al. [33]. In this configuration, oil flows at the center of the tube as a continuous core and the water flows as an annulus between oil core and pipe inner wall. Here, a thin water layer wets inside upper wall of the pipe as observed in its actual image (at USW = 0.4 m/s and USO = 0.4 m/s) shown in Figure 6a. Same observation is also noticed by simulation as shown in Figure 6b. Sometimes, wave crest at oil-water interface may touch inner pipe wall at top periodically. In this situation the flow is not perfect annular and it is known as wispy annular flow. Identification of such thin water layer by imaging technique is difficult. So we have us ed the probe technique to identify the annular flow and its transition boundary accurately. This flow pattern is very much important from the energy saving point of view because it gives minimum fractional pres sure drop as pipe wall completely wetted by water only. Interfacial tension and buoyancy opposes this flow while inertia and viscous force stabilize the flow. So it is least stable in case of horizontal flow and observed at moderate velocities.



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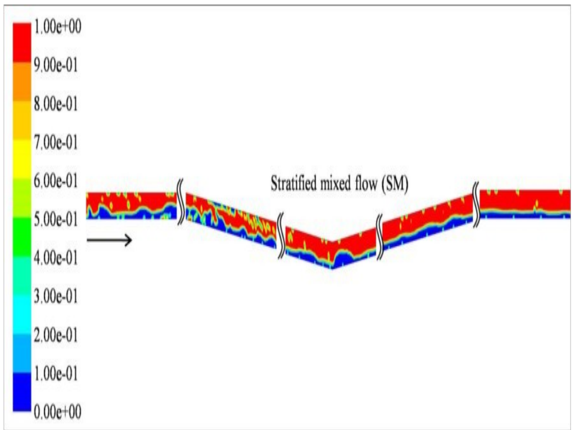
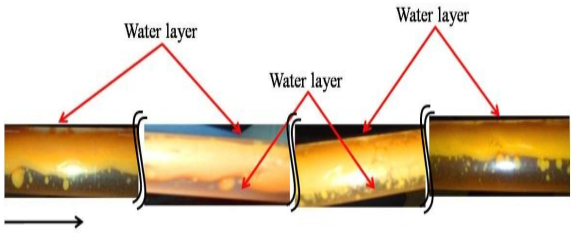


(b)

Figure 5. Stratified mixed flow (SM) at USW = 0.132 m/s, USO = 0.3 m/s ; (a) Experimental image; (b) Simulated result



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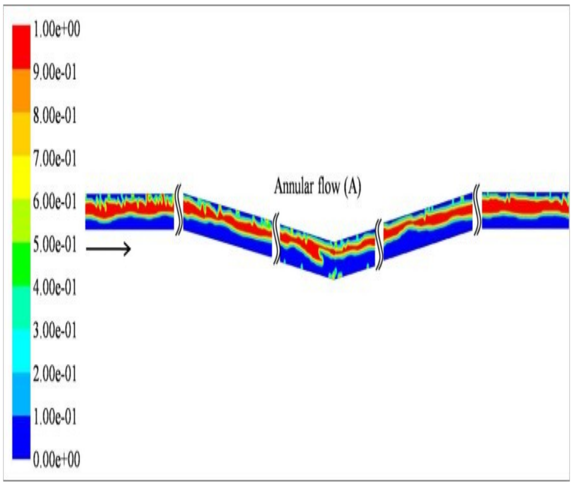
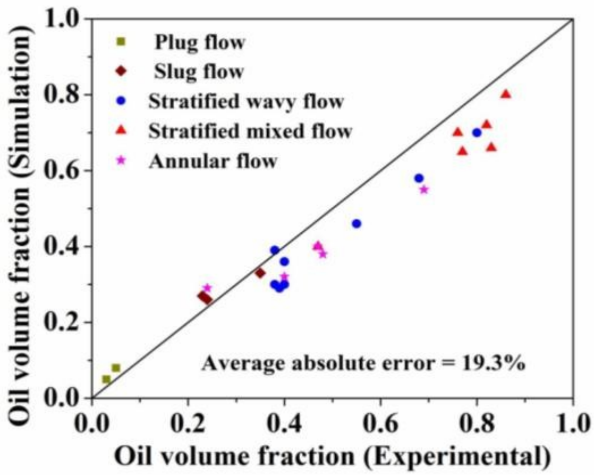


(b)

Figure 6. Annular flow (A) at USW = 0. 4 m/s, USO = 0.4 m/s ; (a) Experimental image; (b) Simulated result

IV. Validation of Simulated Results

In order to validate the simulation, the results are compared with the experimental data of the present work. For this, oil volume fraction of plug, slug, stratified wavy, stratified mixed and wispy annular flow has been simulated and compared with the experimental result as shown in figure 7(a). Area average volume fraction of oil is calculated from simulation and considered as equivalent to the experimental volume fraction. The figure shows a good agreement between simulation and experiments with an average absolute error of 19.3%. We have also validated the model with experimental flow patterns. So, the simulated points (of different flow patterns) have been superimposed on the horizontal flow pattern map (Figure 7b). Scattered data points represent simulated data while solid lines indicate the experimental transition boundaries observed at upstream section of valley configuration. Circled data points represent mismatching of simulated data in the flow pattern map. The result shown in Figure 7b depicts a good matching between the simulated and the experimental flow pattern except few.



(a) Validation of oil volume fraction

Figure 7. Validation of simulation results with experimental results

Flow pattern map (P - Plug flow, S - Slug flow, SW - Stratified wavy flow, SM - Stratified mixed flow, A - Annular flow, Dw/o - Dispersion of water in oil flow, Do/w - Dispersion of oil in water flow)

V. Conclusions

In the present study, we have identified flow patterns of viscous oil-water two-phase flow through undulated pipeline in valley configuration by CFD simulation using VOF method. Five different flow patterns (viz., plug flow, slug flow, stratified wavy flow, stratified mixed flow and wispy annular flow) have been observed at all the four sections. These flow patterns of all four sections are presented in the form of flow pattern maps and compared with each other. Comparison across the sections shows that small undulation (5°) has a marginal effect on the flow behavior of viscous oil-water mixture. VOF method successfully simulates plug, slug, stratified wavy, stratified mixed and annular flow except dispersion of both oil and water. Oil volume fraction validation showed 19.3% error between experimentation and simulation. Good agreement is observed when simulated data of flow patterns superimposed on experimental flow pattern map of the present study. Our observed flow pattern maps are compared with the literature to s how the effect of undulation and effect of viscosity on flow patterns. The understanding on the effect of undulation on the hydrodynamics of two –phase flow would be helpful in industrial design such as, pipe network for oil transportation.

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