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Prediction of oil-water flow patterns, radial distribution of volume fraction, pressure and velocity during separated flows in horizontal pipe*

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Abstract: Flow of two immiscible fluids gives rise to variety of flow patterns, which influence transportation process. In this work, we present detailed analysis on the prediction of flow pattern maps and radial distribution of volume fraction, pressure and velocity of a pair of immiscible liquids through a horizontal pipeline by computational fluid dynamics (CFD) simulation using ANSYS FLUENT 6.3. Moderately viscous oil and water have been taken as the fluid pair for study. Volume of fluid (VOF) method has been employed to predict various flow patterns by assuming unsteady flow, immiscible liquid pair, constant liquid properties, and co-axial flow. From the grid independent study, we have selected 47 037 number of quadrilateral mesh elements for the entire geometry. Simulation successfully predicts almost all the flow patterns (viz., plug, slug, stratified wavy, stratified mixed and annular), except dispersion of oil in water and dispersion of water in oil. The simulated results are validated with experimental results of oil volume fraction and flow pattern map. Radial distribution of volume fraction, pressure and velocity profiles describe the nature of the stratified wavy, stratified mixed and annular flow pattern. These profiles help to developing the phenomenological correlations of interfacial characteristics in two-phase flow.

Key words: computational fluid dynamics (CFD) simulation, volume of fluid (VOF) method, flow pattern transition, prediction of flow transition boundary, viscous oil-water flow

Introduction

The transportation of crude oil through pipelines results in enormous pumping cost owing to its high viscosity, which causes huge pressure drop during flow. Addition of another fluid (with low viscosity than oil) through the same pipe line, reduces pressure drop significantly and in turn pumping cost. In such two-phase flow, the phases (viz., oil and water) arrange themselves in various patterns known as flow patterns or flow regimes. Flow patterns are usually of three categories: separated (viz., stratified smooth, stratified wavy, stratified mixed and core-annular flow), plug/slug and dispersed (oil in water and water in oil). These flow patterns greatly influence pressure drop and hold-up characteristics of pipeline transportation, heat and mass transfer characteristics of upstream operation in refinery (desalter and distillation units), and kinetics between two immiscible phases. Each of the flow patterns has their own importance in different fields. Separated patterns especially, annular flow is preferable in pipeline transportation as the pressure drop for such flow is least as compared to other flow patterns, whereas, dispersed flows are preferable from heat and mass transfer point of view. Knowledge on transition boundaries of different flow patterns is helpful in guiding accurate design of various unit operations and processes.

Several studies have been conducted to predict transition boundaries by experiments[1-6], analytical models[7-9] and computational fluid dynamics (CFD) simulations[10-13] for various systems. Experimentally, identification of flow pattern maps is usually done by visualization, imaging[4] and probe techniques. Probe techniques are of either intrusive[1,3] or non-intrustive[2] type. Analytical models are limited to predict selective

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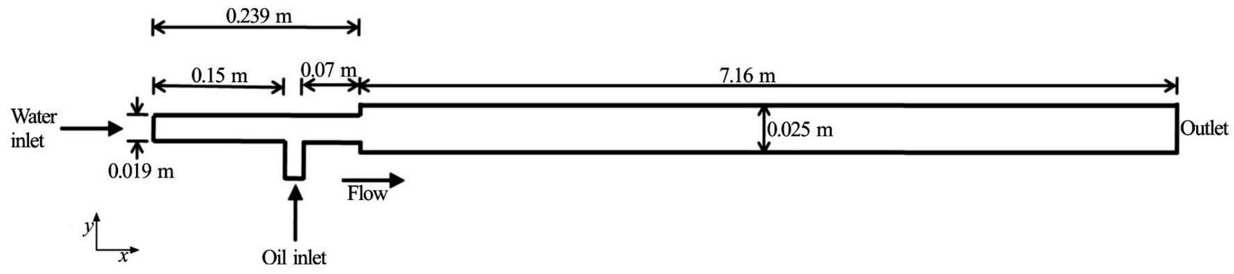

Fig.1 Schematic representation of experimental setup (WT–water tank, OT–oil tank, CP–centrifugal pump, GP–gear pump, C1 to C3–control valves, G1 to G4–gate valves, RM1, RM2–rotameter, PT1 to PT2–pressure taps, B1 to B2–ball valves, MP–manometer panel, EN–entry section, EX–exit section, TS–test section, S–separator)

flow pattern maps, rather than the complete map. For example, Brauner[7] have successfully predicted the transition boundary of stratified to dispersed flow, Brauner and Maron[8] have predicted transition boundary of wavy stratified to stratified mixed flow, and Soleimani and Hanratty[9] have predicted transition boundary for stratified to intermittent (viz., plug and slug) flow. CFD simulations are also being done to intricately understand the hydrodynamics in multiphase flow[14,15]. The success of CFD simulation greatly depends on the models used in the simulation. Prediciton of core-annular flow in a vertically downward circular pipeline[11] based on VOF method, differs from the prediction of Ko et al.[10], who have used different turbulence models for simulation in predicting core-annular flow. Further, Al-Yaari and Abu-Sharkh[16] have predicted the stratified flow pattern for oil-water flow through a horizontal pipeline employing the volume of fluid (VOF) method along with re-noramalization group (RNG) k - ε turbulence model. In addition to these, there are few studies that determine the velocity, void fraction and pressure drop profiles of two-phase flow in pipes[17,18]. Ghorai et al.[17] have performed extensive numerical simulations to predict the flow field characteristics like gas velocity, volume fraction of liquid. They have also developed a correlation between interfacial friction factor and wall friction factor for stratified wavy flow. Sidi-Ali et al.[18] have performed 3-D simulations to investigate interfacial friction factor of horizontal stratified two-phase flow using Fluent. They have noticed good agreement with experimental results. Past literature reveals that development of a generalised flow pattern map for liquid–liquid flow is quite complicated. A single analytical model also cannot predict all the flow pattern maps. VOF method being used largely for the prediction of stratified or core-annular flow. In this work, we present detailed CFD simulations to investigate all probable flow patterns (except dispersion) for moderately viscous oil-water flow through a horizontal pipeline. VOF successfully accounts for the interfacial interaction between the phases. We have also validated our simulation results with the experimental data obtained from experiments on equivalent systems with a wide range of superficial velocities of both oil and water, covering all the flow patterns. Subsequently, efforts have been made to understand the profile of volume fraction, pressure drop and velocity of a separated flow (stratified wavy, stratified mixed and annular flow) using VOF method.

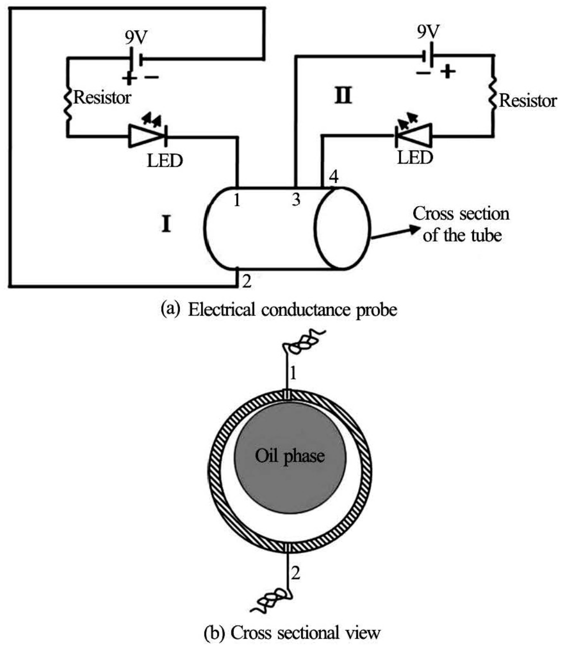

Fig.2 Arrangement of conductance probe and phase configuration