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Dispersed Bubble Flow Pattern Prediction in Two-Phase Pipe Flow

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Abstract

Multiphase flow is generally encountered in petroleum and chemical industry. The multiphase production of oil and gas through pipelines is characterised by transient phenomenon and accurate definitions and predictions of the flow patterns will guaranty flow assurance.

The existing methods of flow pattern definitions and predictions have been found to be subjective and inaccurate because they are mostly obtained by visual observation. Two-phase computational fluid dynamics (CFD) calculations, using volume of fluid (VOF) model in commercial CFD package FLUENT 6.0, was employed in order to generate velocity profile data for the development of dispersed bubble flow pattern in multiphase flow.

Based on the simulation results from CFD, it was possible to develop an appropriate model for dispersed flow pattern thus eliminated uncertainties associated with flow pattern prediction in multiphase flow in pipeline. The model was found to be consistently accurate when compared with the simulation results. The paper also demonstrated the capability of CFD for multiphase flow pattern prediction. The definition and prediction of dispersed flow pattern will enhance our understanding of multiphase transport in pipeline. It has the potential to predict the flow pattern transition boundaries for multiphase pipe flow.

1.0 Introduction

A large number of flows encountered in oil and gas production are a mixture of phases. The concept of phase in a multiphase flow system is a complex proposition. Therefore the flow of liquid-gas mixture in pipelines results in the manifestation of a number of transient flow pattern depending on the fluid properties, flow rates, pressure drop and pipe orientations. As a result, a number of flow patterns have been identified e.g. stratified wavy, stratified smooth, plug, slug, annular and dispersed bubble flow. Each of these flow patterns exhibits unique flow characteristics. They are very unstable and exhibits constant transition from one flow pattern to another depending on the flow conditions in the pipe. There is always the need to capture and model these changes as the fluids are transported through the pipeline. The pattern changes will have profound effect on the overall flow assurance.

A number of solution procedures are available and can be classified into three categories: numerical models, mechanistic models and empirical correlations [1, 2, 3]. Though all the methods are with some levels of limitations but a combination of two or three approaches may eliminate uncertainties associated with each of the methods significantly. Critical information can be obtained from numerical models such as multi-dimensional distribution of phases, dynamic flow regime transition and turbulent effects. The empirical correlations consider the flow regimes based on physical measurements. In this paper, the focus was on the numerical approach using computational fluid dynamics, CFD of ANSYS FLUENT [4].

The CFD has been employed to determine the velocity profiles for bubble flow pattern because of inherent difficulties associated with experimental measurement. The CFD therefore served as virtual laboratory to generate fluid velocity profiles for a combination of fluid mixtures, oil-gas, water-oil, water-gas and oil-water. As a result, a velocity profile model has been developed for bubble flow pattern by combining analytical equation with point velocity profiles generated numerically.

Two-phase flow patterns in horizontal pipeline

Simultaneous passage of liquid and gas in a transport or export pipeline / tiebacks often results in a variety of flow patterns, see Figures 1. Two-phase flow or three-phase flow is simultaneous flow of any two or three of the discrete phases

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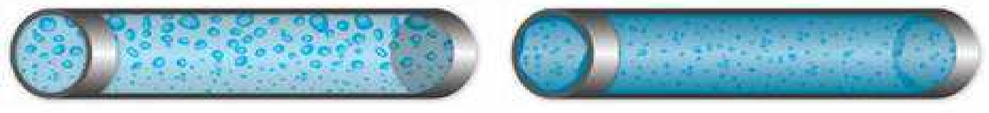
(oil, produced water or associated gas). These phases are commonly encountered in the petroleum production. The formation of particular pattern is dependent on flow rates, fluid properties, pipe size and pressure profiles. The critical issue is how to define flow patterns which are somewhat subjective depending on the researchers own interpretation. This is because flow pattern information in multiphase flow is still largely obtained by visual observation.

The concept of flow patterns in pipes introduces new challenges in the understanding of multiphase fluids principally because of the form in which fluids exist in pipes. For a two-phase liquid-gas system in horizontal pipe, the flow patterns can be grouped into four main classes where each class can be subdivided into sub-classes for detailed descriptions. The following classes of flow patterns have been documented in literatures [5, 6, 7]:

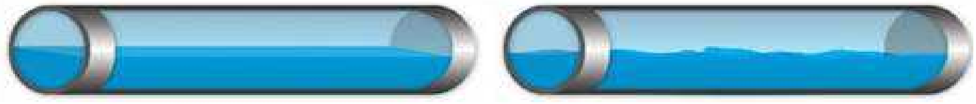
- Stratified flow (Subclasses: stratified smooth, stratified wavy)
- Intermittent flow (Subclasses: elongated bubble, slug, churn)
- Annular flow (Subclass: wispy annular)
- Bubble flow (Subclasses: bubbly, dispersed bubble)

In a horizontal pipes or slightly inclined pipes different flow patterns are recognisable. For oil dominated systems, the possible flow patterns are dispersed bubble and intermittent flow [8]. Experimental results presented by Oddie [9] for water-gas and oil-water-gas flows observed dispersed bubble, churn, elongated bubble; slug and stratified flow dominate in slightly inclined pipes.



i) Dispersed bubble flow *ii) Annular flow with*

iii) Elongated bubble flow *iv)Slug flow*



v) Stratified flow *vi)Stratified wavy flow*

Figure 1: Flow patterns in horizontal pipe [10]

The most common correlation used to calculate the conditions for the transition from one flow pattern to another is the Mandhane plot [11]. However, a number of flow pattern maps exist based on pipe configurations, see Figure 2. Many of these maps result from data covering a rather limited range of fluid properties and pipe diameters. Consequently, large discrepancies are often observed between a predicted flow regime and that actually observed in a subsequent test.

From the flow patterns mentioned above, dispersed bubble flow was of interest here because of its capability to provide large interfacial areas for particle transport (solids) in general and particularly for hydrodynamic transport in multiphase fluid flow. It is important from the designer's point of view to be able to predict accurately what flow pattern will occur for given input flow rates, pipe size, and fluid properties [12]. Only then can the proper flow model be selected. The method adopted here for the prediction of bubble flow pattern was to combine analytical equation with numerical methods such as CFD to generate the appropriate model.

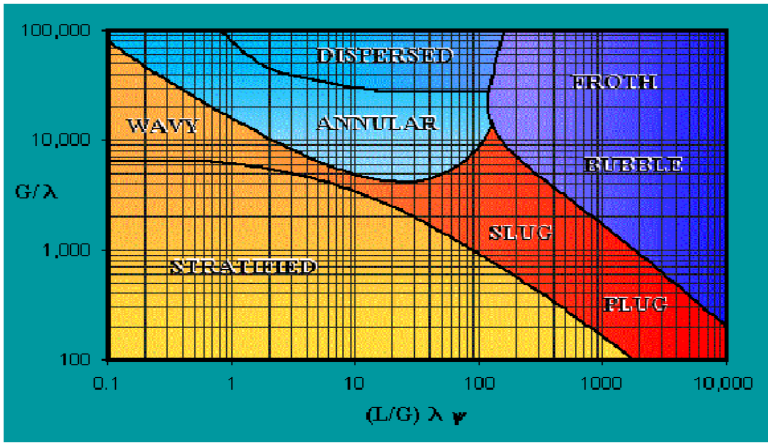


Figure 2: Flow pattern maps for horizontal pipes two-phase, air-water

Flow modelling using CFD

The thrust of this paper was to develop the velocity profiles models for dispersed bubble flow patterns for multiphase fluid flow in pipes. For liquid-gas two-phase or three phase flow in horizontal pipes, there is a number of possible flow patterns discussed in previous sections. A detailed classification of all possible flow patterns relevant to operating conditions such as superficial gas and liquid velocities (water and or oil) was taken into account. Water or oil was considered as the continuous phase, and air considered as the dispersed phase.

Determination of the flow patterns is a central problem in two/three/four phase flow analysis. For the specific case of oil–water systems, oil properties can be quite diverse, and the oil–water viscosity ratio can vary from more than a million to less than one, and its rheological behaviour can be Newtonian or non-Newtonian, so it is quite difficult to determine oil–water flow patterns [13].

A CFD package was used to model the liquid-gas (water, oil & gas) velocity profiles. In the development of velocity profile models, a combination of analytical and numerical methods was adopted. Equation (1) was used as the basis for analytical computation to generate appropriate velocity profile models for dispersed bubble flow pattern. A detail of this equation can be found in [14].

$$V_R = \frac{f}{8} * R_e * V * \left[1 - \left(\frac{r}{R}\right)^2\right] \tag{1}$$

Where,

V_R- Velocity of fluid particle at a particular point in the pipe cross-section,

V – Average velocity of the fluid in the pipeline,

r – Distance from the pipeline centre to any point in the flow field

R - Radius of the pipeline.

R_e- Fluid Reynolds number which defines the fluid flow regime whether laminar or turbulent flow

f = Fluid flow friction factor which is a function of the pipe roughness, fluid flow regime and type of fluid.

Equation (1) is dependent on friction factor and fluid Reynolds number. For single phase flow, the friction factor can generally be estimated by any well known friction factor equations such as Blasius equation. For multiphase flow, the complexity associated with flow patterns makes the basic friction factor equations unsuitable. Among the numerous empirical correlations proposed in the literature for multiphase friction factor, one that was adopted for this study was the correlation based on the work of Garcia et al. [15]. The correlation was a pseudo average friction factors for different flow patterns in multiphase flow. They have developed different models for each of the flow patterns rather than a model fits all as seen from many authors. Full details of model developments can be found in [15] and they proposed the following friction factor model for dispersed bubble flow

$$fm = 0.1067R_e^{-0.2629} + \frac{13.98R_e^{-0.9501} - 0.1067R_e^{-0.2629}}{\left[1+\left(\frac{R_e}{304}\right)^{2.948}\right]^{0.2236}} \tag{2}$$

Where f_m is the mixture friction factor

The flow of multiphase fluids must be treated differently and with caution as it introduces different complexities. There are issues of changing flow patterns as multiphase fluids moves through the pipelines/tiebacks. The knowledge of flow pattern and flow pattern transitions is essential to the development of reliable predictive tools in multiphase fluid transport. As the pattern changes so the pressure variations and transport velocity may vary. In order to track the patterns, velocity profile models have been developed in this case for dispersed bubble flow patterns in multiphase fluid flow in pipe.

Velocity profile for dispersed bubble flow

The first step is the definition of the number of phases and possible flow patterns to enhance selection of the modelling approach. The second step is the choice of the governing equations which describe the multiphase flow. Numerical simulation of any flow problem is based on solving the basic flow equations describing the conservation of mass, momentum and energy in the control volume. And finally, the solution of these governing equations is critical in obtaining appropriate results.

The simulations were carried out as a three dimensional transient flow in a horizontal pipe. In all cases, liquid (water or oil) was considered as the continuous phase, and air was considered as the dispersed phase. The k–ε model was used to treat turbulence phenomena in both phases with adoption of Renormalisation Group (RNG) method. Compared to other turbulence models, RNG k–ε was observed to deliver the best performance in terms of accuracy, computing efficiency, and robustness for modelling in multiphase fluids [2]

The VOF model was used for the numerical calculation of the multiphase flow patterns in horizontal pipe. The existing code in the software was used. For the simulations, an Eulerian–Eulerian approach was chosen, in which the grid is fixed and the fluids are assumed to behave as continuous media. This model solves one single set of conservation equations for both phases and tracks the volume fraction of each of the phases throughout the computational domain. For all simulations, a no-slip condition is imposed at the tube wall. The influence of the gravitational force on the flow has been taken into account as well. At the inlet of the tube, uniform profiles for all the variables have been employed. A pressure outlet boundary is imposed to avoid difficulties with backflow at the outlet of the tube.

The transient behaviour of the multiphase flow requires simulation with a time step of 0.001 seconds to be adopted though it does varies depending on the scaled residual value. Both phases are introduced at the inlet and the transient simulation is initiated. The superficial velocities of the liquid (water or oil) and gas phase, corresponding to a given flow patterns are set as inlet conditions. After a time step as indicated on calculation window, the flow of both phases is observed and flow pattern established.

The physical properties of the fluids are given in Table 1. Water or oil and air entered the horizontal pipe perpendicular to its inlet plane. They have an inlet temperature of 298 K. The fluid pressure at the tube inlet is set to 101,325 Pa.

Table 1: Physical properties of water, oil and air

Sample	**Fluid density, ρ (kg/m3)**	**Fluid viscosity, μ (Pas)**
Tap water	998.8	0.001003
oil	940	0.001001
Air	1.225	0.0000183

Results and discussion

Dispersed bubble flow simulation

The simulations was carried out to obtain results for dispersed bubble flow conditions in the 0.07 and 0.08 meters for pipe diameters and 2 meter long horizontal pipelines using Ansys Fluent for air-liquid (water & oil) system. The liquid and gas superficial velocities are varied in the range from 0.02 to 2.1m/s, and 2 to 15m/s respectively. The simulation results were modelled to obtain representative model for dispersed bubble flow patterns.

Contour plots

The velocity contours for dispersed bubble flow are presented in Figures 3 and 4. Figures 3 & 4 showed high intensity at the centre, an indication of maximum velocity attainable at the pipe centre and low velocity at the pipe wall for dispersed bubble flow. Generally the fluid experience low velocity at the pipe wall and tend to increase toward the centre of the pipe.

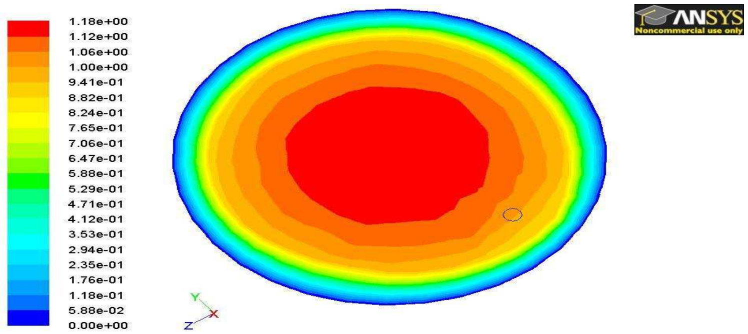


Figure 3: Contours of mixture velocity for water–air flow for dispersed bubble flow in 0.08m pipe.

X-Y plots

Figures 5 & 6 showed the X-Y plots generated for dispersed bubble with 20% and 60% gas fractions respectively. At 60% gas fraction, the gas phase tend to gain higher velocity compared with the liquid phase, a much different scenario with fairly homogenous fluid mixture velocity with 20 % gas fraction. This is an indication that as we begin to see more gas influx into the well stream, the tendency is for the gas to predominate even with constant liquid volume fraction. The gas tends to separate out of the mixture with potential to form stratified flow patterns which may reduce the transport capacity of the flowing fluids.

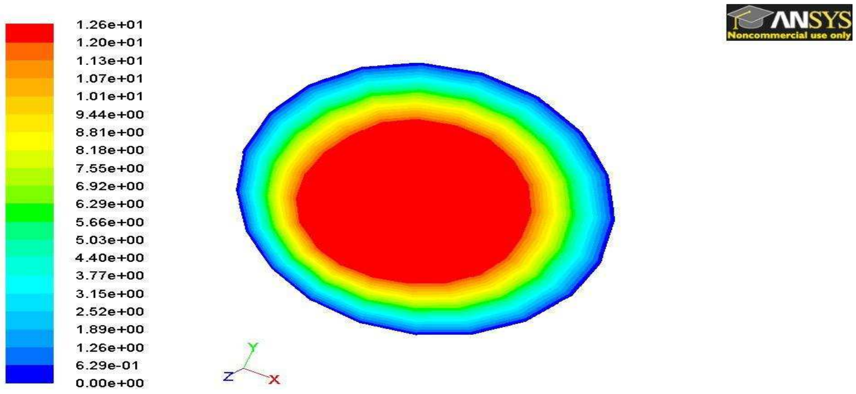


Figure 4: Contours of mixture velocity for water–air flow for dispersed bubble flow in 0.07m pipe.

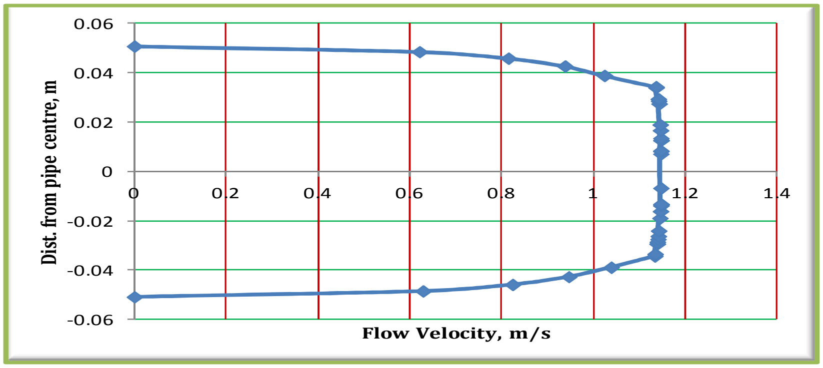


Figure 5: Velocity distribution for dispersed bubble flow, two-phase oil – gas flow with 20 % gas fraction

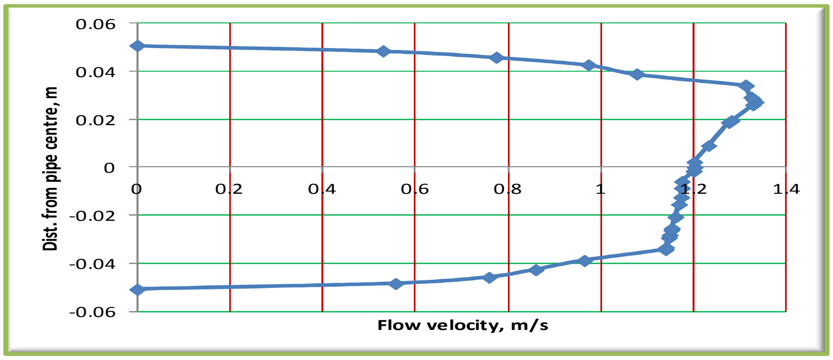


Figure 6: Velocity distribution for dispersed bubble flow, two-phase oil – gas flow with 60 % gas fraction

Velocity profile models

Many approaches have been presented in the literatures especially with the use of CFD to model flow of multiphase in pipelines / tiebacks. What has not been done is the use of CFD to model velocity profiles for different flow patterns. This paper explored and demonstrated the capability of CFD to generate fluid point velocity profile data and when combined with analytical equation able to build velocity profile models for important flow patterns such as dispersed bubble flow.

Due to the complexity of multiphase flow systems, it is not possible to obtain one model that will be suitable to predict multiple flow patterns that exist. The starting point was to identify a base equation stemmed from analytical model for a single phase turbulent flow. Equation (1) was used in this case and as presented below with modification to include underlying constants,

$$V_R = a\frac{f}{8} * R_e^b * V * \left[1-\left(\frac{r}{R}\right)^2\right]^c \tag{1b}$$

The equation is a function of friction factor and the Reynolds number. The friction factor for a gas-liquid mixture can be defined as,

$$f_m = \frac{(\Delta P/L)D}{2\rho_m U_m^2} \tag{3}$$

Where the pressure drop per unit length $(\Delta P/L)$ is related to the wall shear stress, D is the pipe diameter, U_m is the mixture velocity and ρ_m is the mixture density

The mixture Reynolds number can be defined as,

$$R_e = \frac{U_m D}{\upsilon_L} \tag{4}$$

Where, $\upsilon_L = \mu_L / \rho_L$ is the kinematic viscosity of the liquid.

The mixture friction factor of Garcia et al. [15] for dispersed bubble flow patterns have been adopted in this paper (see equations (2)). This was because the empirical models were developed based on large body of data sourced from different reputable researchers. The mixture Reynolds number appropriate for multiphase flow in horizontal pipes is based on the mixture velocity and the liquid kinematic viscosity. Both parameters are greatly important in the development of an appropriate model for velocity profiles.

In order to obtain constants a, b and c in equation (1b), simulations of different flow patterns was conducted with CFD software. A simulation run for varying input superficial velocity for liquid and for gas flow generated a number of point velocity data across the plane of pipe diameter from the pipe wall where the fluid velocity is generally zero to the pipe centre.

Next was fitting the simulated data with the analytical equation defined by (1b) using the multiple constant optimisation method (MCOM) of Microsoft excel solver based on goal seek approach. The schematic of the method is as presented in Figure 7.

The analysis involved combining analytical equation with profiles generated numerically from simulations. This led to the development of velocity profiles for multiphase flow in pipe. The model equation for the dispersed bubble flow pattern is presented in equation (5).

$$V_r = 3.7 * f * R_e^{0.366} * V_m \left[1 - \left(\frac{r}{R} \right)^2 \right]^{0.15} \qquad (5)$$

The simulation results for are as presented in Figures 8 & 9. The figures represent the calculated velocity profiles of mixture two-phase fluids for dispersed bubble flow pattern. The numerically obtained velocity profiles are compared; the agreement between the analytical results and CFD is excellent and are within reasonable error margin (see Table 2).

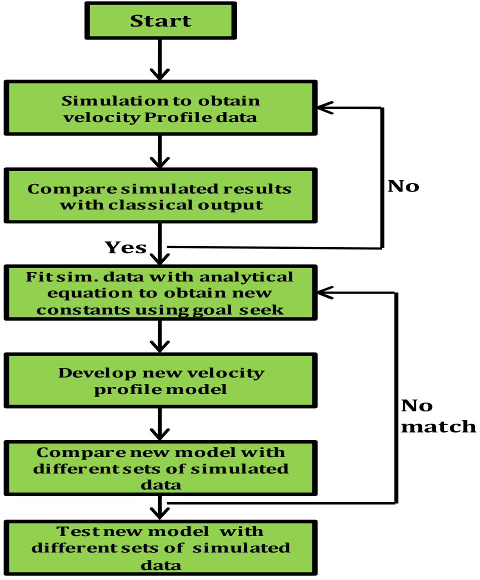


Figure 7: Schematic of the method for velocity profile model development

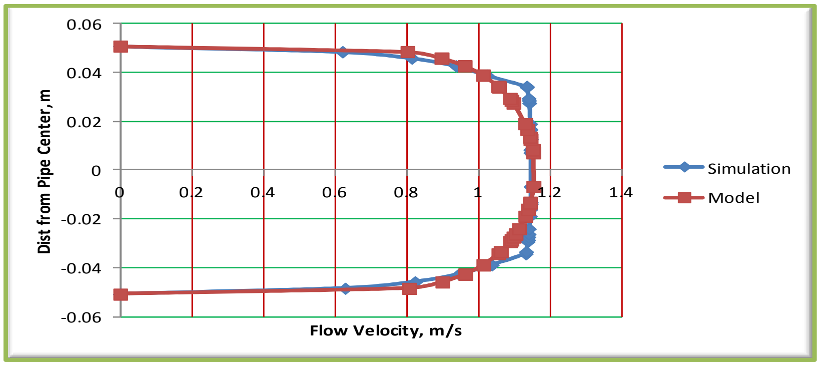


Figure 8: Calculated velocity profile compared with simulation for dispersed bubble flow pattern, Vsl = 0.8m/s, Vsg = 0.2m/s, horizontal pipe

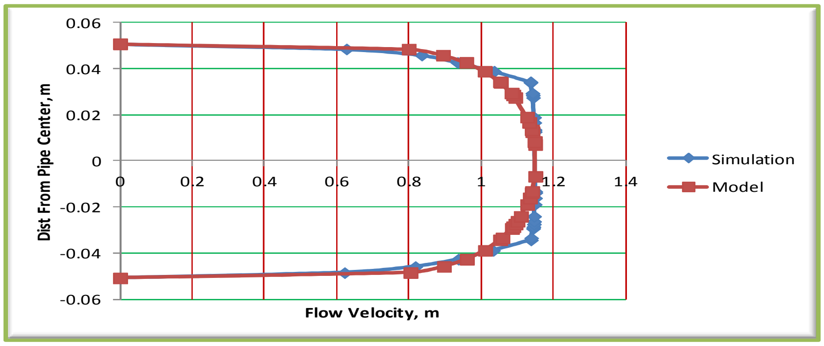


Figure 9: Calculated velocity profile compared with simulation for dispersed bubble flow pattern, Vsl = 0.65m/s, Vsg = 0.35m/s, horizontal pipe

Table 2: Statistical Parameters for the Velocity Profile Models

Average Percent Error (APE)	1.56
R – Square Value (R^2)	0.9289
RSQ & Correlation Coefficient, %	86.92

Conclusion

The main objective of this paper was to explore the potential of CFD tools to model multiphase fluid in horizontal or inclined pipe under different flow conditions. Dispersed bubble flow pattern in multiphase fluids flow in pipes was considered and the results are as presented. There were good agreements between the simulations results and the developed model.

Based on the simulation results, it was possible to develop an appropriate model for dispersed bubble flow patterns by using the numerical results obtained from simulations combined with analytical equation. For the velocity profile model developed, there was a good match between the model predictions and simulation results as can be seen in Figures 10 & 11. It is therefore possible to model multiphase fluids flowing through horizontal or inclined pipe using computational fluid dynamic tools. The definitions and predictions of flow patterns eliminated uncertainties in the flow patterns prediction in multiphase flow. This has potential to solve problems associated with transient phenomenon in multiphase flow thereby providing valuable tools in solving flow assurance issues in multiphase pipe flow.

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