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NUMERICAL VALIDATION OF GAS-LIQUID SLUG FLOW INSIDE HORIZONTAL PIPE

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ABSTRACT

The transition of one flow regime into another is a very complex phenomenon in pipeline networks, which could be potentially hazardous for the structural integrity of the pipeline. The horizontal air-water two-phase slug flow regimes in the experimental pipe were modeled using Fluent 16.1. The diameter of the pipe and pipe length were 74 mm and 8 m respectively. The transient calculations were accomplished using Volume of Fluid (VOF) model. A comparison between numerical simulations with the hi-speed photographs of slug formation and translational velocities showed a good agreement. The present work was part of a quality control and assurance process to ensure correctness of the methodology and numerical model before deployment.

Keywords: numerical simulation; two-phase flow; VOF technique; CFD; modeling; slug flow.

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1. INTRODUCTION

Slug flow is known to cause mechanical fatigue to the pipelines. Consequently, accurate numerical prediction of slug body length and slug holdup were necessary for downstream infrastructure and separation process design before actual work being carryout.

Numerous developed correlations from previous researches for predicting slug flow characteristics such as slug initiation, slug body holdup, slug length and translation slug velocity were produced empiricallyfrom limited data sets. Hence, most part of these models were not considered practical for operational use in oil and gas industry. Nevertheless, these correlationsprovided valuable background information such as the fluid properties, flow regime observations, geometry and various underlying assumptions [1]. Apart from that, several numerical investigation on slug or intermittent flow regimes in the horizontal pipelines reported [2-6] that the flow behavior and patterns could be predicted using commercial CFD models. Due to faster computing facilities nowadays, the calculation of package has become more powerful and efficient tool than pure experimental investigation for understanding complex behavior of transient multiphase flow inpipelines [7].

In [8]used FLUENT 6.0 to model air-water two-phase flow in a horizontal pipe.The VOF models was found suitable for simulating interface between two or more fluids in this work. Their approach was used to study the volume fraction of liquid, gas velocity and interfacial roughness. The comparison of their numerical model between the predicted interfacial roughness and the data in the literature were validated.The VOF technique was performed by[9] to studyexperimentaland numerical investigations onoil and gas two-phase flow characteristics in the large scale horizontal pipe with an inner diameter of 125 mm. They concluded that, for a flow transition from stratified flow to slug flow, a critical liquid superficial velocity of 0.113 m/s is required. Also, the gas superficial velocity decreased with the increasing of the liquid superficial velocity. In addition, the appearance of a slug flow was found to be independent of the gas superficial velocity. Later, in[10] claimed that VOF formulation were able to predict the gas-liquid flow regimes in horizontal pipes by comparing their results with Baker chart. Later, in this paper, we will show that some in [10] results were not able to predict the flow pattern correctly according to Baker's original flow regime definition. Similar method of interface tracking was implemented in CFX-5.7 by Frank to model air-water two-phase slug flow regime in horizontal pipes [11]. The slug formation, slug propagation and slug holdup of gas-liquid two phase flow in a horizontal circular pipe was investigated. More recently, in[12] used VOF to conclude that the gas superficial velocity was significantly affected by the liquid plug holdup. They also found that gas slug length was higher than liquid slug length for all conditions. In [13] pointed out that some issues related to VOF were specifically identified with a poor model parameterization because of the discretization scheme. In [14] demonstrated the transient slug flow of two fluid model to capture the slug flow initiation process in horizontal and near horizontal pipes and categorized them into empirical slug specification, slug tracking and slug capturing models. Most recently, in [15] used FLUENT and in[16] to investigate two-phase flow and concluded that one-dimensional results in OLGA cannot be compared realistically with FLUENT.

The objective of this paper is to report a series of validation that were carried outas part of quality control and assurance process by comparing the present numerical model with experimental work by[17], where original raw data were available to us.

2. METHODOLOGY

2.1. Experimental Procedure

The present study used the experimental result of Mohammed for the validation of the present model [17]. A pipe model exactly the same as the experimental test section with D = 0.074 m (3 inches) internal diameter (ID) and 8 m long was built. Air and water were used for two-phase flow. The gas and liquid physical properties from the experiment is shown in Table 1 and air and water superficial velocities were in the ranges U_{SG} = 1-3.5 m/s and U_{SL} = 0.7-1 m/s respectively. The entire experimental tests were performed under the atmospheric pressure (101.3 kPa) in the room temperature of 24 ^{o}C (air-conditioned).

Table 1. Physical properties of air and water in the experiment[17]

	ρ (kg/m^3)	μ (Pa s)	σ (N/m)
Water	998.6	0.08899	0.074
Air	1.185	0.001831	-

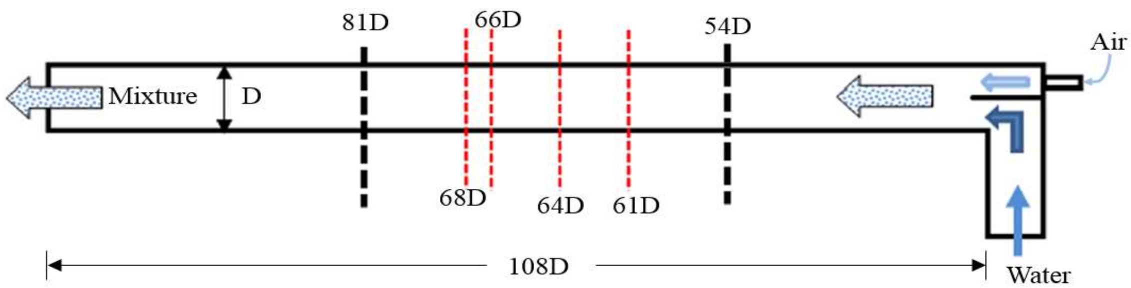

Fig.1. The experimental test section and measurement points [17]

The measurement points were specified along the test pipe for the appropriate calculations of slug flow regime. As shown in Fig. 1, the distance of each point from the reference section 54D was taken to be 7D, 10D, 12D and 14D to make sure that the distance between the two sections were not affecting the obtained results and also to calculate the slug velocity along this test section.

2.2. Multiphase Flow Modeling

FLUENT 16.1 is based on the Finite Volume Method (FVM) to discretize the governing equations [18-19]. The present work used the Eulerian multiphase approach with VOF where liquid and gas were treated as two distinct phases. The VOF model is a method used to track and capture the gas-liquid immiscible interface by finding the solution of a single set of momentum equations and tracking the volume fraction of gas and liquid phase throughout the domain [18]. The k-ε model was employed to treat turbulence phenomena in the fluids.

If α_k is the volume fraction of the k-th phase in a computational cell, when α_k equals 0 means that the cell is empty of the k-th fluid. Otherwise, ifα_k equal to 1, the cell is full of the k-th fluid.The cell consists of the mixture of the k-th fluid and one or more types of fluids when α_k is between 0 to 1. Based on these appropriate properties of α_k, variables are assigned to each computational cell.

A single set of mass conservation formula of Equation (1) and momentum formula of Equation (2) are shared by the fluids. The phase tracking is accomplished by solving an additional continuity formula ofEquation (3) for gas phase, α_G. The volume fraction of the secondary phase, α_L, can be computed as 1 -α_G[18, 20].

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

$$\frac{\partial}{\partial t}(\rho U)+\nabla\cdot(\rho UU)=-\nabla p+\nabla\cdot\left[\mu\left(\nabla U+\nabla U^{T}\right)\right]+\rho g+F \tag{2}$$

$$\frac{\partial \alpha_G}{\partial t}+U\cdot\nabla\alpha_G=0 \tag{3}$$

wheret is time, ρ is fluid density, U is the fluid velocity, p is pressure, μ is fluid viscosity, g is the acceleration of gravity and F is body forces.

The body force(F) in Equation (2) accounts for the surface tension(σ) and the contact angle. This body force is computed in FLUENT as the continuum surface force model (CSF), F_{CSF} [21].The model used the value of contact angle to adjust the interface normal in each cells near the wall rather than imposing the effect of contact angle as the boundary condition of the wall.

In Volume of Fluid(VOF)multiphase flow model, the sum of gas and liquid volume fractions in each control volume is equal to one. When the mixture is fully saturated

$$\sum_{k=1}^{n}\alpha_k=1 \tag{4}$$

where α is the volume fraction of k-th phase, n phases in total. The Equation (4) specifies that the computation of the volume fraction from the phase continuity equation could be omitted for one phase.In most cases, the volume fraction of the continuous phase is resolved with Equation (4) from the fractions of the other phases. The mixture properties of density(ρ) and viscosity(μ) are defined as follows [8]

$$\rho=\sum_{k=1}^{n}\alpha_k\rho_k\,,\quad \mu=\sum_{k=1}^{n}\alpha_k\mu_k \tag{5}$$

2.3. Mesh Geometry

The horizontal pipe was meshed with an inner diameter of 0.074 m and a length of 8 m. The hexahedral meshes were generated using the mesh generation tool ICEM/CFD-Hexa. Fig. 2 illustrates the volume tessellation in the computational domain of the pipe.

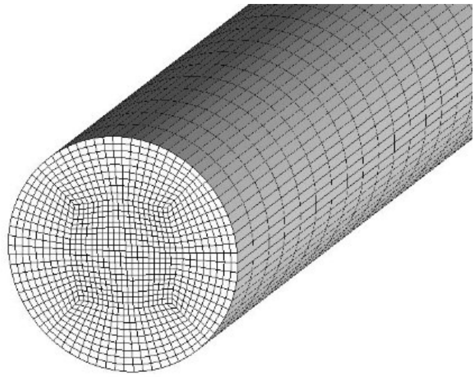

Fig.2. Mesh of the domain-hexahedral mesh, 522.5 thousands hexahedral cells

Suitability of the mesh is carried out to study the mesh dependent convergence behavior. Several runs of simulation had been performed by varying the cells density. The average pressure gradient in the horizontal pipe of a slug flow is used as the criteria to check on the convergence behavior. The finding showed that the simulation results with mesh size around 500,000 ~ 600,000 cells as being the most suitable candidate.

2.4. Initial and Boundary Conditions

The initial condition is set in such a way that the gas-liquid volume fraction is shared 50-50 volume-wise with only liquid occupying the bottom of the pipeline and gas phase filling the top of the liquid surface. This is implicitly implying that the starting condition is the stratified gas and liquid phase with zero velocity [2, 4-5, 8-9, 11]. The no-slip boundary condition was applied at the pipe walls and pressure outlet is set at atmospheric condition. A surface tension was set to 0.074 N/m between air and water. The influence of the gravitational force on the flow has been taken into account. All of the inlet values of the velocities were taken from the experiments by[17]. The boundary conditions of the CFD simulations in terms of representing the experimental configuration of the two-phase flow in the horizontal pipe were chosen based on the experimental setup.

2.5. Solution Method

Due to the hydrodynamic behavior of the gas-liquid two-phase flow, the transient calculations of the simulation were implemented with a time step of 0.001 sec for all cases. All the calculation runs,the Courant number (Co) was fixed at 0.25 for the volume fraction equations. A combination of the PISO (pressure implicit with splitting of operators) algorithm for pressure-velocity coupling and the second order upwind calculation scheme for the determination of volume fraction and momentum were used to perform the calculations [19].The residual value of the calculated variables for the mass, velocity components and volume fraction of two-phase are contributed to the convergence criterion. The scaled residuals of the different parameters wereselected to be 10^{-4}, the numerical calculations was considered converged in this works.

3. RESULTS AND DISCUSSION

3.1. Comparison between CFD and Experiment

The steps of slug development in a horizontal pipe between the present model and experimental photographs are shown in Fig. 3. The slug development started from the slug initiation which was initially equal to 50% water volume fraction in the test section as shown in Fig. 3(a).As can be seen by the drawn ellipse in Fig. 3(b) and 3(c), the slug was initiated after the occurrence of the hydraulic jump which the liquid holdup was increased to about H_{Ls} = 0.75.Then, this slug of liquid holdup was propagated downstream as liquid body slug started to form. When the liquid superficial velocity increased to 0.93 m/s, the momentum of the liquid was increased which could be a reason that delayed the hydraulic jump occurrence. Consequently, the slug flow regime developed further in the pipeline. The slug initiation is consistent with the results reported by [22].

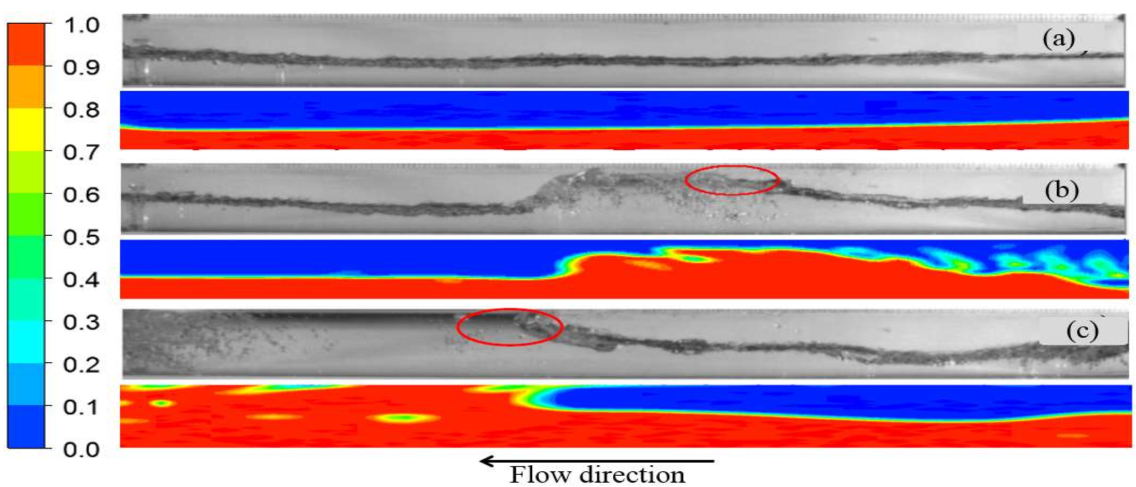

Fig.3. Liquid volume fraction comparison of the slug development steps between CFD simulation and experiment for U_{SG} = 2.1 m/s, U_{SL} = 0.93 m/s (a) Stratified flow, (b) Hydraulic jump and (c) slug flow

The comparison of slug flow morphology along the horizontal pipe with the time sequences between the present model and the experiment were illustrated in Fig. 4. The slug is moving along the pipe at U_{SG} = 2.44 m/s and U_{SL} = 0.86 m/s. There are good agreement between experimental photographs and present contours of liquid phase, indicating that the VOF model has been used correctly to capture the gas and liquid interface.

The slug flow appeared in Fig. 4 could be interpreted as elongated slug. Based on the experimental procedure, the photograph of slug 1 in Fig. 4 has the length of 1.24 m and utilized the camera resolution of 960×480 pixels that physically covered 1 m from the pipe length. In Fig. 4, each 1 cm of scale represented 0.034 m of reality.Therefore, the first photograph of Fig. 4 showed a segment of about 0.95 m length from total length of slug 1.

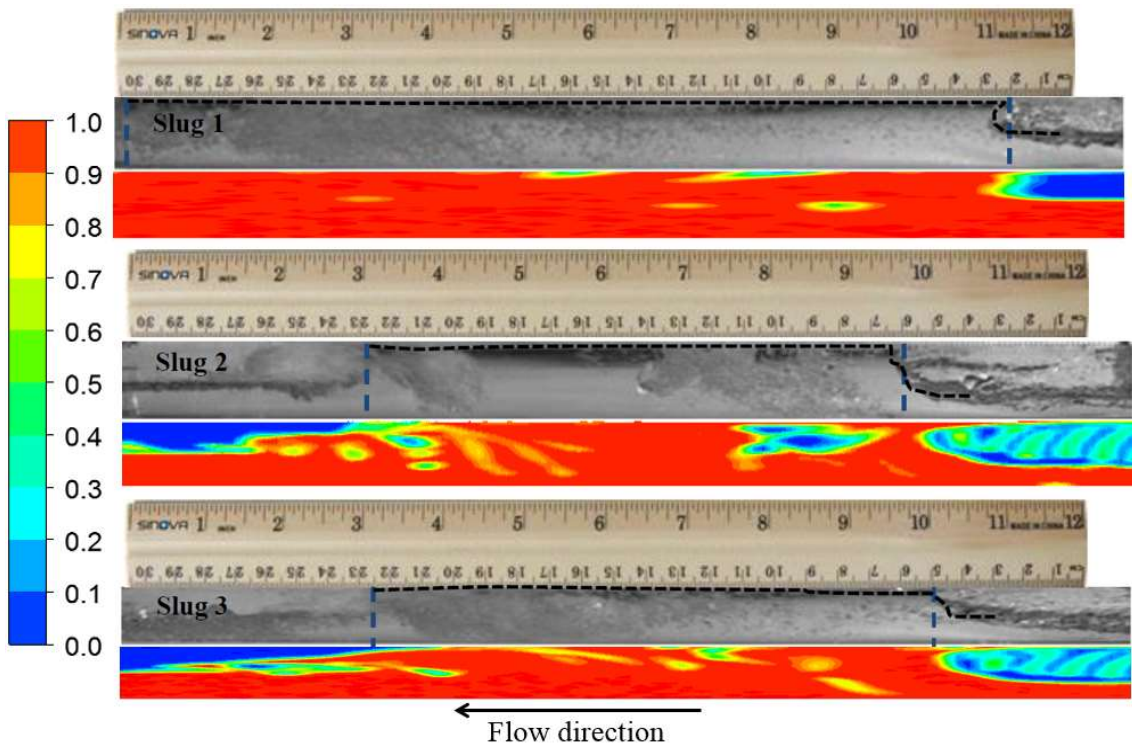

Fig.4. Water volume fraction of slug flow morphology, photographs and CFD for U_{SG} = 2.44 m/s, U_{SL} = 0.86 m/s

3.2. Slug Translational Velocity

Slug flow regime is unsteady, therefore its translational slug velocity varied along the pipe and is difficult to be measured accurately. Based on the experimental works, in order to determine the average velocities magnitude for each case of different superficial air and water velocities, translational velocities at four positions: 61D, 64D, 66D and 68D (refer to Fig. 1) were taken and averaged. These averaged translational slug velocities were reported for three superficial liquid velocities at U_{SL}= 0.7, 0.86 and 1 m/s corresponding to four superficial gas velocities U_{SG}= 1, 2.1, 2.44, 2.79 and 3.14 m/s.

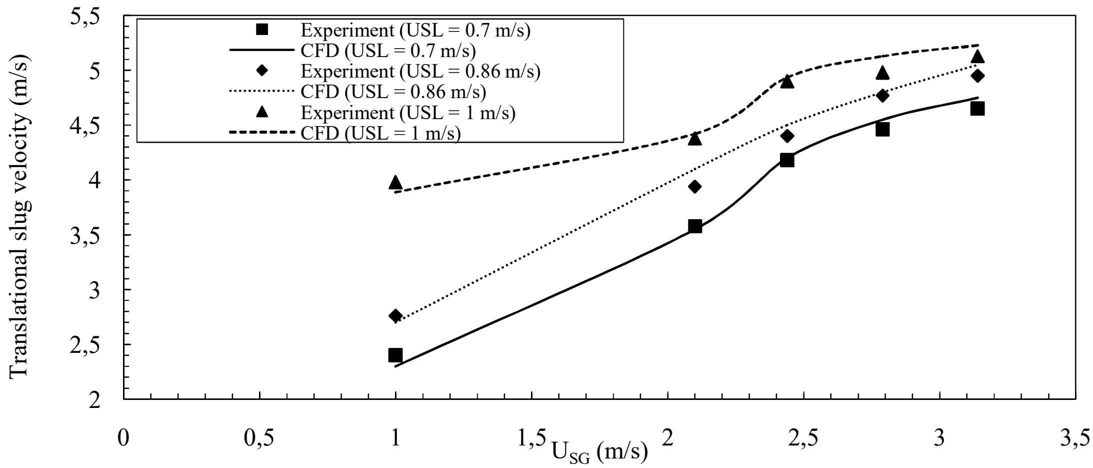

Fig.5. The comparison of translational slug velocity between present model and experimental data for different gas and liquid superficial velocities [17]

As illustrated in Fig. 5, a good agreement was achieved for the comparison of translational slug velocity between present model and experimental data for the various gas and liquid superficial velocities. The translational slug velocity for a constant superficial liquid velocity increased with increasing gas superficial velocity. Also, as liquid superficial velocity increases, the translational slug velocity is increased.

4. CONCLUSION

The interfacial behaviors of air-water two-phase slug flow in horizontal pipe were investigated numerically and validated against experimental data. The CFD [23] predictions of slug development and its translational velocity in horizontal pipe of 74 mm and 8 m long were achieved successfully. The VOF technique in multiphase flow model was performed to describe the whole phenomena of slug behavior in horizontal pipe. It is envisage that further validation will be conducted for slug length and slug holdup in the near future.

5. ACKNOWLEDGEMENTS

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