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CFD Simulation of Two -Phase Severe Slugging Circulating Through a Pipeline-Riser System

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Abstract: Of all flow patterns encountered in multiphase flow field operations, slug flow is the dominant one. Classical flow maps show that the intermittent regime exists for a wide range of gas and liquid flow rates. The objective of this study is to investigate two-phase slug flow in a pipeline-riser system. Thus, Volume of Fluid (VOF) method implemented in ANSYS FLUENT 16.1 is used to capture the transient distribution of gas/liquid interface through the pipe. The simulation of model parameters are the same as recent experimental study conducted by Wangetc. The inner diameter of riser and flow line is 51.4 mm. The riser is 3.5 meters high and the flow line is 12 meters long inclined downward of 4°. In the simulations, air and water were used as flowing fluids. Results of void fraction, pressure and liquid holdup are presented. The results obtained numerically with the developed model are in very good agreement with the experimental.

INTRODUCTION

Due to the geometry and some physical phenomenon in pipeline-riser system, severe slugging might occur. This slugging is also called terrain slugging or riser slugging. This phenomenon was first reported by Yocum[1] and it is defined as a cyclical phenomenon that might happen at low flow rate conditions when a downwards inclined pipeline is followed by a vertical riser and characterized by the accumulation of liquid at certain areas of the pipe and generation of long liquid slugs that are followed by a fast gas blow down, large pressure fluctuations at the base of the riser and is accompanied by fluctuations in fluid delivery from the top of the riser are also observed[2, 3]. This kind of regime is undesirable because in oil and gas production equipment are affected by the large pressure and flow rate fluctuations. During the liquid and gas surges, the peak flow rates might cause over pressurization of the separator which consequently might lead to the complete shutdown of a production facility. Moreover, an increased back pressure at the wellhead may lead to the end of the production and abandonment of the well. These repeating impacts provoke a faster mechanical fatigue and can eventually lead to a rupture. Therefore, the accurate prediction of severe slugging characteristics is essential for the proper design and operation of two-phase flow in these systems. Schmidt *et al*.[2] was the first to give a detailed description of sever slugging cycle, four main stages can be cited (Fig. 1).

Slug generation: In the first step, a pressure build-up is seen at the riser base as liquid is accumulating downstream the bend.

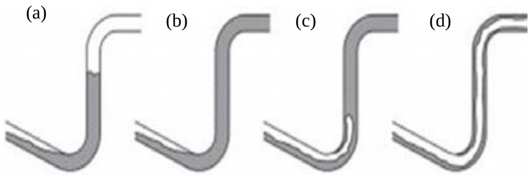

Fig. 1(a-d): Typical cycle of severe slugging, (a) Slug generation, (b) Slug production, (c) Bubble production and (d) Gas blowdown

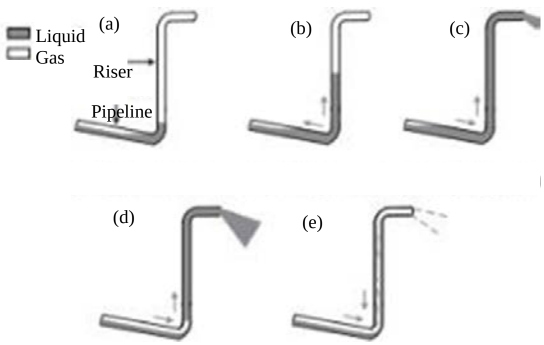

Fig. 2(a-e): Severe slugging type I, (a) Blockage of the riser base, (b) Slug growth, (c) Liquid production, (d) Fast liquid production and (e) Gas blowdown gas

Slug production: When the liquid reaches the outlet, the slug is produced until the gas reaches the riser base.

Bubbles penetration: In this step, gas is again supplied to the riser, decreasing the hydrostatic pressure and hence increasing the gas flow.

Gas blowdown: In the final step, gas reaches the riser outlet, the pressure level is minimal and the liquid is no longer gas lifted, this initiates a new cycle.

Severe slugging can be quite diverse; they can be devised according to certain characteristics like slug length or upstream pipe geometries (undulating, horizontal or inclined). According to Balino *et al*.[4], four type of severe slugging can be summarized:

Severe slugging I: The maximum pressure at the bottom of the riser is equal to the hydrostatic head of the riser filled with liquid and the liquid slug length is equal or bigger than the riser length. We can describe a cycle of SS1 in five stages: Blockage of the riser base; slug growth; liquid production; fast liquid production; gas blowdown. These five stages are illustrated in Fig. 2.

Severe slugging II: The liquid slug length is smaller than the riser length and there is a full blockage at the bottom

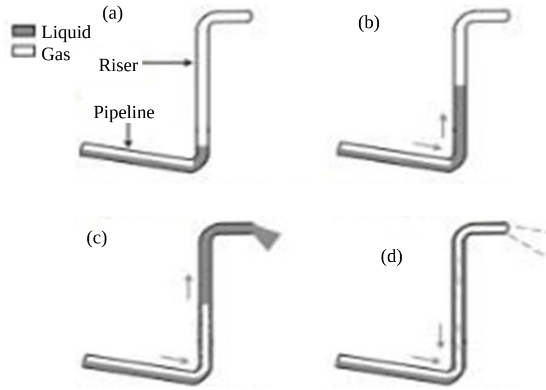

Fig. 3(a-d): Severe slugging type II, (a) Blockage of the riser base, (b) Slug growth, (c) Fast liquid production and (d) Gas blowdown

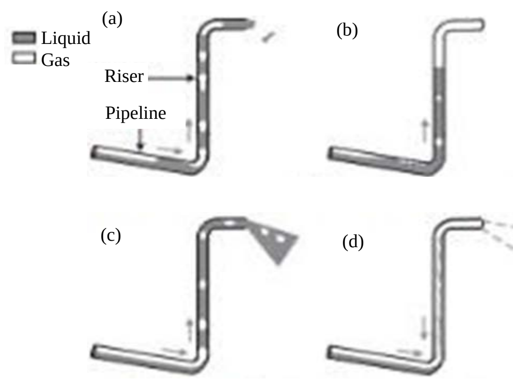

Fig. 4(a-d): Severe slugging type III, (a) Transient liquid production, (b) Aerated Slug growth, (c) Fast acrated liquid production and (d) Gas blowdown

of the riser until the blowout. The transitional severe slugging of type 2 is qualitatively similar to SS1, but the slug length is shorter than the height of the riser and it often has intermittent unstable oscillations. In Fig. 3 four stages of SS2 are illustrated.

Severe slugging III: The bottom of the riser is never fully blocked so gas can still pass. Pressure and slug length are smaller compared to sever slugging type I. We describe a cycle of SS3 in four stages: transient slugs; aerated slug growth; fast aerated liquid production; gas lowdown. In Fig. 4 these four stages are illustrated.

Unstable oscillations: In this regime both gas and liquid flow into the riser and there isn't a vigorous blowdown. This type is not even considered severe slugging by some as it usually as very small pressure oscillations compared to the other types (Table 1).

Table 1: Parameters of the riser system and sever slugging flow

Parameters	Value and unit
Pipe inner diameter	51.4 mm
Inclined pipeline	12 m
Riser height	3.5 m
Inclination angle	4°
Liquid density	1000 kg m^{-3}
Liquid viscosity	0.001 Pa.s
Surface tension	7.28*10-2 N.m^{-1}

Taitel and Dukler[5] presented a model to describe the physical phenomenon but results were not accurate compared with experimental data due to the unsatisfied condition of gas continuity in the riser. Fabre and Line[6] developed a model based on the continuous gas penetration through the riser and did not consider the slug formation blocking the gas passage. The model was not able to simulate certain specifics conditions obtained in their own experimental facilities. Sarica and Shoham[7] presented a simplified transient model to describe the phenomena physically.

In our research, we are going to replicate the experimental work of Wang *et al*.[8] numerically with the same geometry, fluids properties and boundary conditions. Due to the difficulty of capturing such a complicated phenomenon, the numerical study is going to enrich the comprehension of the problem with giving additional information that experimental studies are not capable to do, due to the limitation of experimental detection tools.

Computational fluid dynamics CFD simulations are conducted using the Volume of Fluid (VOF) Model to investigate the hydrodynamics of severe slugging in pipeline- riser system, results of pressure, liquid holdup are presented. In the simulations, air and water were used as flowing fluids.

Numerical procedure: The development of a 2D Model is built with the dimension equivalent to circular pipe riser system of Wang *et al*.[8]. Wang *et al*.[8] studied experimentally severe slugging occurrence in a downward pipeline connected to a vertical riser, a typical setup for an offshore production facility. The experimental setup consists in a 12 m pipeline with an inclination of 4° followed by a vertical riser of 3.5 m.

As in any CFD problem, the equations describing the fluid flow through a specific domain need to be numerically closed stipulating the boundary conditions. Impute flow variables are defined in terms of the superficial velocities, at standard conditions (pressure P = 1.013 bar, temperature T = 293 k). The imput parameters are chosen from Wang *et al*.[8] experimental data.

MATERIALS AND METHODS

Mathematical model: For the mathematical model, Eulerian based volume of fluid VOF technique for two phase modeling were employed to investigate the two phase pattern in a pipeline riser system. In this model, liquid is considered to be the continuous and primary phase and gas considered to be the dispersed and secondary phase. The fluid in both phases is Newtonian, viscous and incompressible. The uniform pressure field is assumed to be shared by both phases, the flow is considered isothermal, so, the energy equations are not needed.

The VOF method has the advantages of high precision and traces the volume of fluid in the grid, not the motion of fluid particles. In the VOF model, a single set of momentum equations is shared by the fluids, and the fluid volume fraction in each computational cell is tracked throughout the domain. This model has been found to be suitable for simulating interface among two or more fluids Ghorai and Nigam[9].

The VOF method utilizes the volume fraction which means the fraction of the filled fluid volume in the grid to achieve the goal. The indicator function is defined as 0 for a cell with pure gas, 1 for a cell with pure liquid, and for a cell with a mixture of gas and liquid. An interface exists in those cells that give a volume of fluid value of neither 0 nor 1. Since, the indicator function is not explicitly associated with a particular front grid an algorithm is needed to reconstruct the interface[10]:

$$\alpha = \begin{cases} 0 \text{ in pur gas} \\ 0 < \alpha < 1 \quad \text{gas-liquid interface} \\ 1 \text{in pur liquid} \end{cases} \tag{1}$$

Governing equation: Numerical simulation of any flow problem is based on solving the basic flow equations describing continuity, momentum and turbulence. The principal equations are solved for each phase and can be written as follow Eq. 2-3:

$$\frac{\partial(\alpha\rho)}{\partial t} + \nabla.(\alpha\rho\vec{v}) = 0 \tag{2}$$

Continuity equation:

$$\frac{(\alpha\rho\vec{v})}{\partial t}\nabla.(\alpha\rho\vec{v}\vec{v}) = -\alpha\nabla p + \alpha\nabla.\left[\mu\left(\nabla\vec{v}+\nabla\vec{v}^{T}\right)\right] + \alpha\rho\vec{g} + \alpha\vec{F} \tag{3}$$

The void fraction α is the void fraction of water or liquid phase.

Turbulent model: The Reynolds Stress Model (RSM) is a higher level, elaborate turbulence model. It is usually called a Second Order Closure. This modeling approach originates from the work by Launder *et al*.[11] in RSM, the eddy viscosity approach has been discarded and the

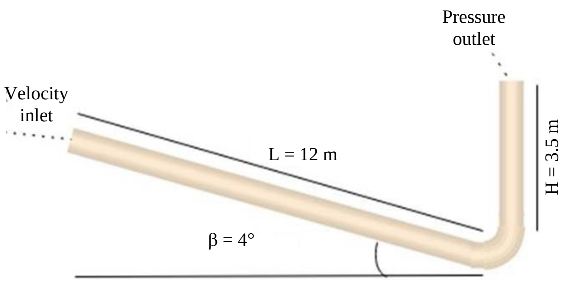

Fig. 5: Computational domain and boundary conditions

Reynolds stress is directly computed. The model can be used to predict the turbulent anisotropic level in the flow. Given that the two-phase flows are very unstable and highly anisotropic:

$$\frac{\left(\rho\bar{\alpha}\tilde{R}_{ij}\right)}{\partial t}+\frac{\partial}{\partial x_k}\left(\rho\tilde{\alpha}\overset{\square}{U}_k\tilde{R}_{ij}\right) = -\rho\bar{\alpha}\left[\tilde{R}_{ij}\left(\nabla\overset{\square}{U}_k\right)^T+\left(\nabla\overset{\square}{U}_k\right)\tilde{R}_{ij}\right]+ \frac{\partial}{\partial x_k}\left[\bar{\alpha}\mu\frac{\partial\tilde{R}_{ij}}{\partial x_k}\right]-\frac{\partial}{\partial x_k}\left[\rho\bar{\alpha}\overline{u_1^{'}u_J^{'}u_k^{'}}\right]+\bar{\alpha}p\left(\frac{\partial u_\iota^{'}}{\partial x_J}+\frac{\partial u_J^{'}}{\partial x_\iota}\right)-\bar{\alpha}\rho\tilde{\varepsilon}_{ij}+\frac{2}{3}\delta_{ik}\Pi_k \quad (4)$$

Numerical procedure: The experimental geometry has been modeled using an axi-symmetric 2D geometry. The simulation was performed using the commercial CFD code ANSYS FLUENT 16.1 at double precision solver mode, with an implicit scheme for all variables and a fixed time step t = 0.001 s for computation. To solve the momentum transport equation the Quick (quadratic upwind interpolation) scheme was used for pressure the PRESTO (PREssure STaggering Option) scheme increases stability in the solution. The phase-coupled PISO algorithm is used for the pressure-velocity coupling. RSM model has been used for turbulent two phase-flows. These schemes ensured, in general, satisfactory accuracy, stability and convergence. In addition, the steady-state solution strategy was employed. The convergence criterion is decided based on the residual value of the calculated variables, namely mass, velocity components and pressure. In the present study, the numerical computation is considered converged when the residuals of the different variables are lowered by five orders of magnitude (Fig. 5).

Inlet boundary: The velocity of the fluids is specified at the inlet.

Outlet boundary condition: At the outlet, pressure outlet boundary is used.

RESULTS AND DISCUSSION

Slug identification: Based on the time revolution of slug development, Fig. 6 illustrate a clear cut of simulation result of slug flow pattern with Vsg = 0.206 and Vsl = 0.423 m/sec. When a high gas superficial velocity pass across the pipe, the liquid phase start to aerate and small gas bubble deform within the liquid slug. The simulation successfully shows an acceptable result of slug flow.

Figure 7 represent a few representative simulations of flow distribution, the blue and red colors indicate the gas and water respectively, the contour of slug flow regime obtained from the simulation of inclined horizontal channel was compared with experimental result from[12,13]. Figure 8 depicts a reasonable matching between the simulation and experimental flow pattern.

Slug evolution: For a given gas velocity and very small liquid velocity slugs will not be observed in the inclined pipeline. At large enough liquid and gas flow rates, the symmetric waves assume large amplitude. One of these waves can suddenly jump up to form a liquid bridge across the pipe. This bridge can collapse or grow in length to form a slug. When the slug moves out, one or more slugs form in the pipeline much closer in the inlet; in addition, more than one slug exists in the pipe at a given time. Figure 9 depicts the evolution of the flow on the elbow, in this region; the slug's liquid blocks the whole surface of the elbow and moves as a coherent mass downstream.

Figure10 shows the phase distribution in the riser (vertical part of the geometry). When the flow is in the vertical part of the geometry, gravity forces are against the flow in the opposite direction which gives a better mix of both phases gas and liquid. This mix of phases is inhomogeneous but we can see that there is gas and liquid everywhere in the pipe without restriction comparing with to the horizontal case (Fig. 9) where the liquid is in the down part of the pipe and the gas in the higher part due to the effect of the gravity and the fact that the density of the liquid is bigger than the density of the gas. We can also see that the gas phase is using walls to make it faster to the top with reducing the interaction interface between the gas and the liquid. The results obtained numerically are in very good agreement with the experimental ones by Wang *et al*.[8].

Slug pressure: The pressure trend throughout the pipe-riser system at different position evolved as a function of time is depicted in figure. We observe the same evolution for the pressure in different positions of the system, pressure fluctuations are remarkably identical to how severe slugging propagates in a single riser system. Pressure increase corresponds to the slug generation step. Then, the pressure is maintained due to the slug production and finally the pressure decreases due the gas penetration and gas blow down steps. As

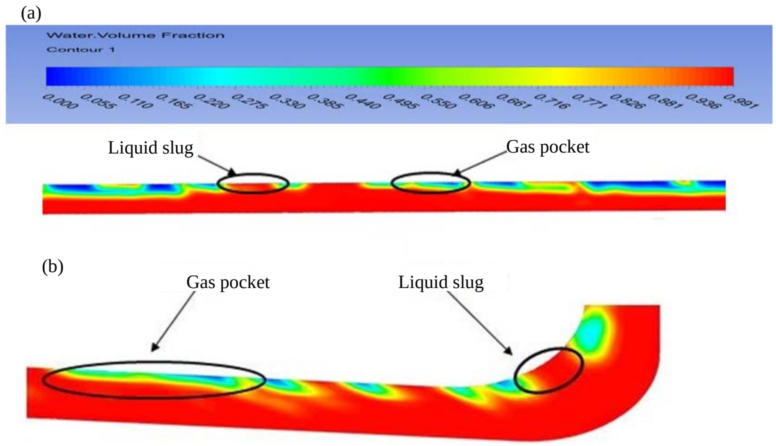

Fig. 6(a, b): Water volume fraction contours for slug flow regime (a) Inclined pipe and (b) At the elbow

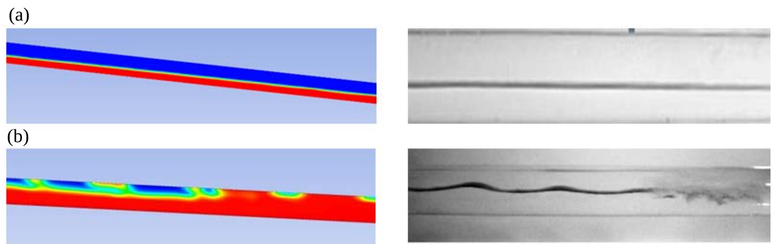

Fig. 7(a, b): Comparison of simulations results with current model between experimental results from Belgacem[13], (a) Stratified flow at the inclined pipeline and (b) slug flow at the inclined pipeline

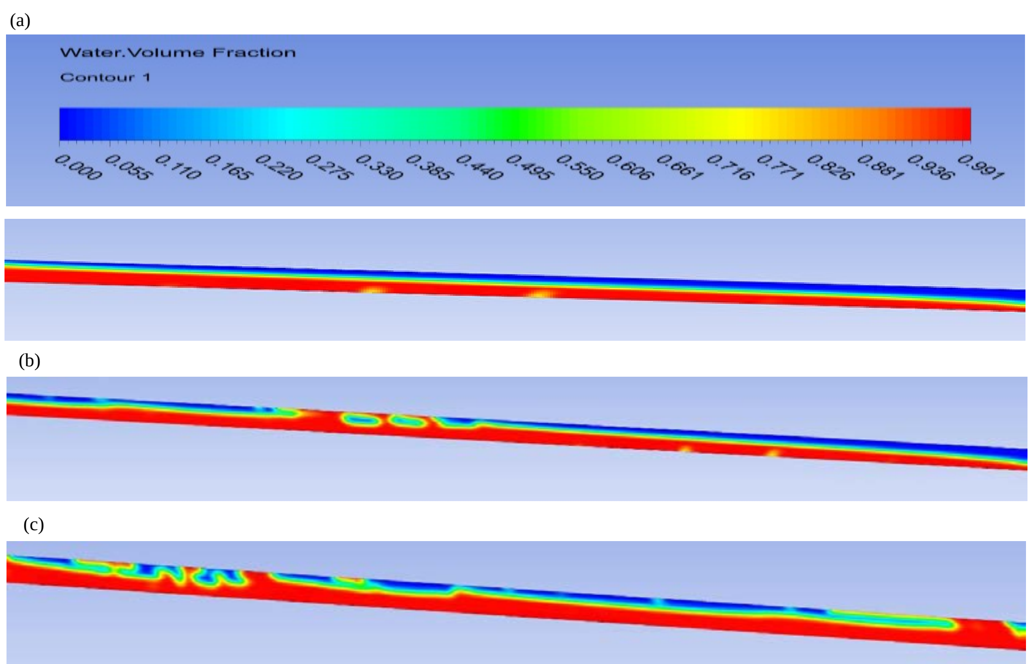

Fig. 8(a-h): Continue

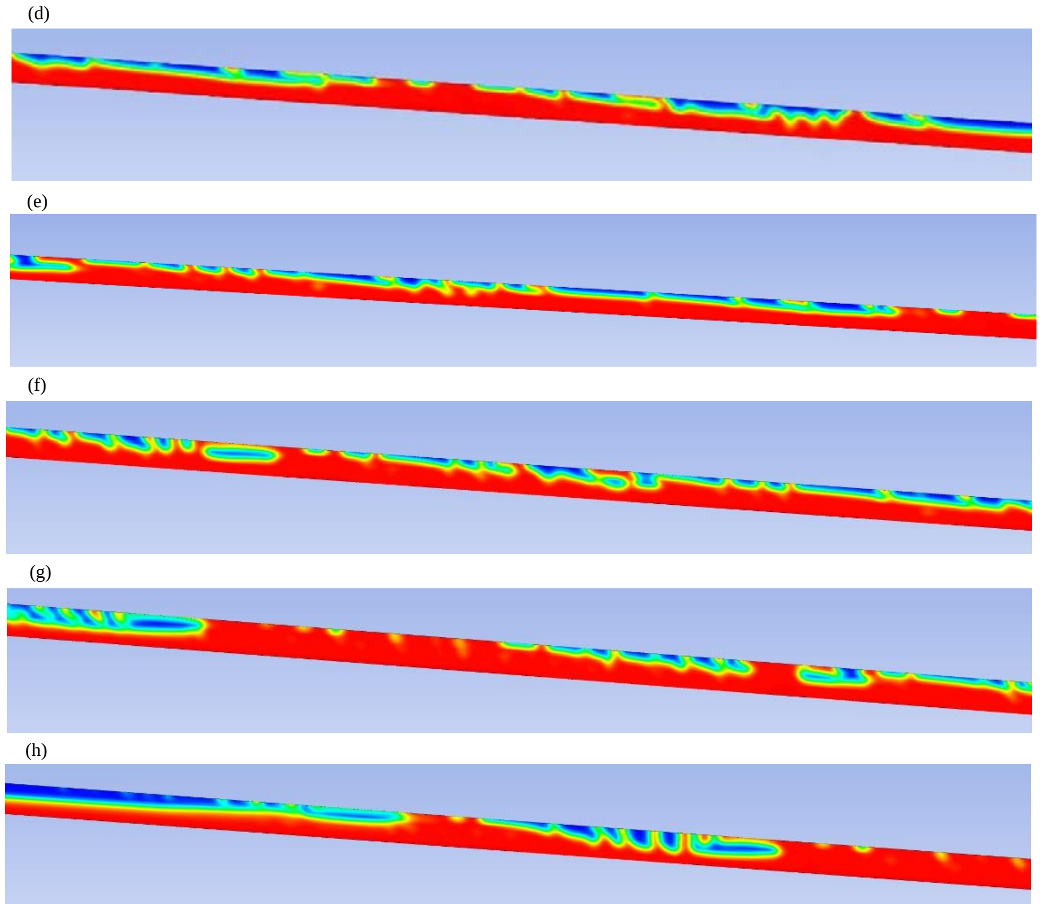

Fig. 8(a-h): Flow evolution on the inclined pipeline, (a) t = 4 s, (b) t = 9 s, (c) t = 10 s, (d) t = 11 s, (e) t = 12 s, (f) t = 13 s, (g) t = 14 s and (h) t = 15 s

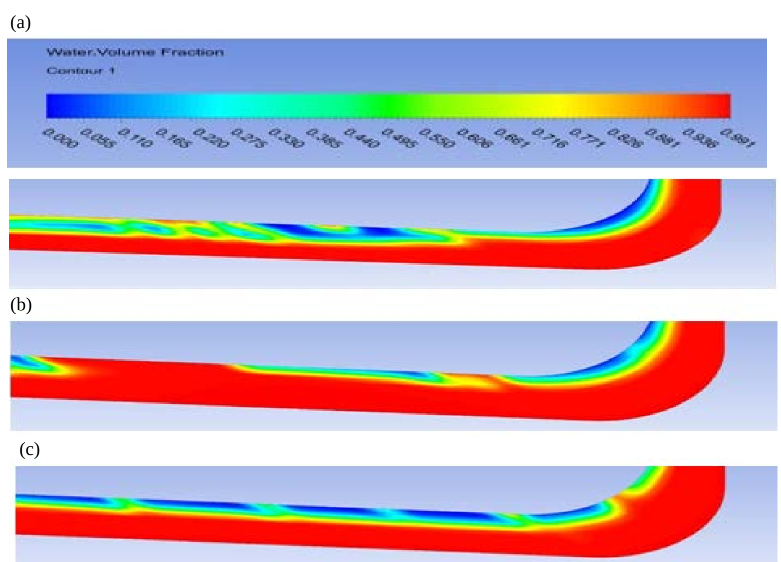

Fig. 9(a-e): Continue

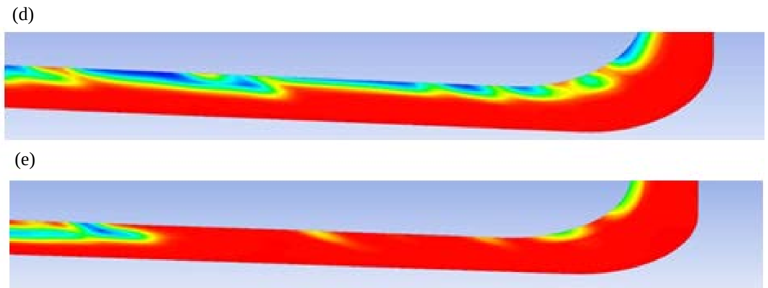

Fig. 9(a-e): Flow evolution on the elbow, (a) t = 11.6 s, (b) t = 13.4 s, (c) t = 14.6 s, (d) t = 15.6 s and (e) t = 16.6 s

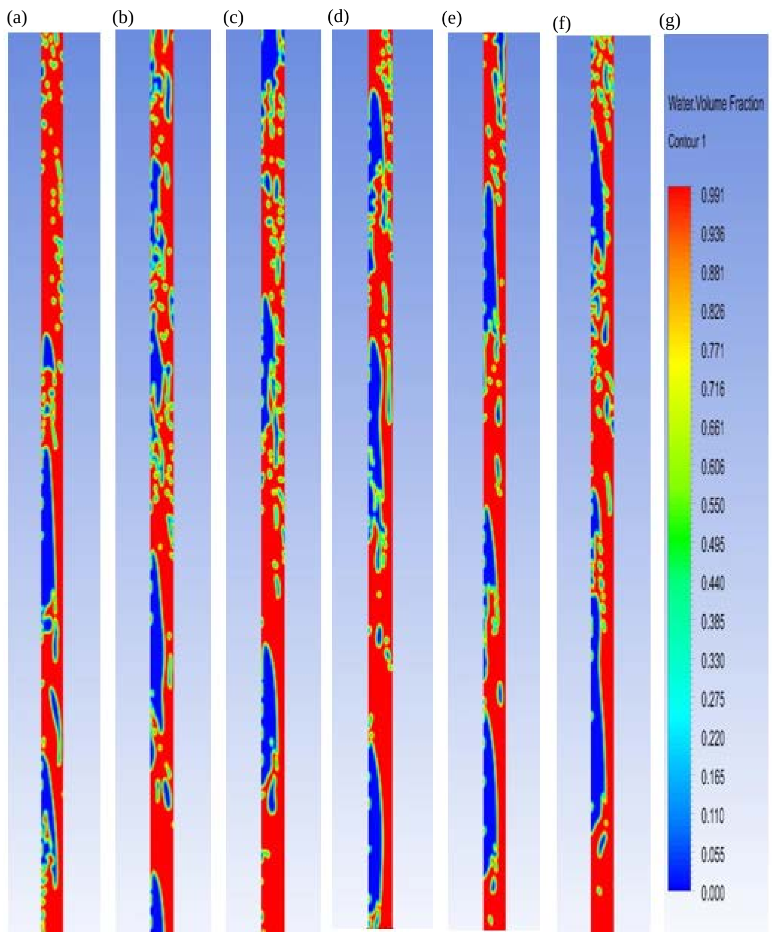

Fig. 10(a-f): Flow evolution on the pipeline riser, (a) t = 13s, (b) t = 13.2s, (c) t = 13.4s, (d) t = 13.6s, (e) t = 13.8s and (f) t = 14s

expected, it is possible to see in Fig. 11 that the pressure reaches its maximum when the slug reaches the top of the riser. The analysis of the pressure shows that the fall of pressure of the film zone between two slugs can be neglected compared with that produced in the zone of mixture[13]. Even when a fluctuating pressure was to be expected knowing for sure that at this conditions there was indeed a slug flow pattern in the system[12], these results do not allow to clearly identify the slug cycle (generation, production, penetration, blowdown)[14,15] but rather show the general amplitude of the pressure fluctuation[15, 16].

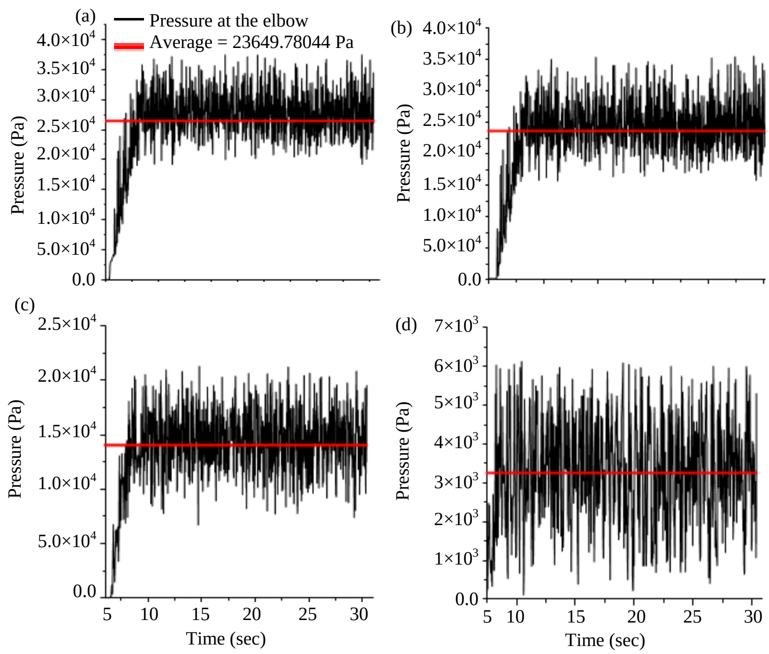

Fig. 11(a-d): Simulation results for J_l = 0.369 m/s, J_g = 0.382 m/sec

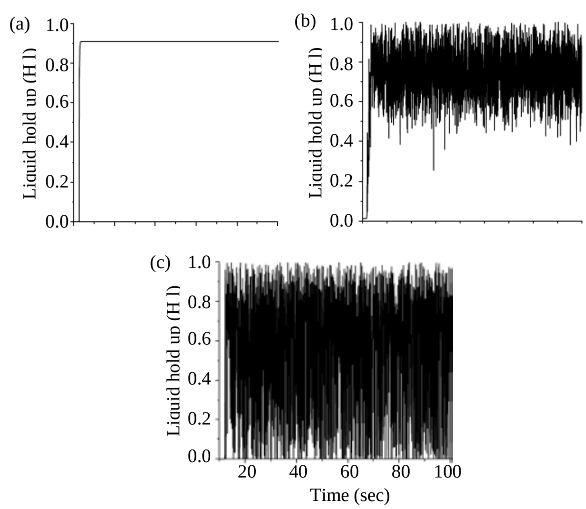

Fig. 12(a-c): Liquid hold-up (a) 9 m upstream the elbow, (b) In the elbow and (c) +1.5 m downstream the elbow

Liquid holdup: Liquid holdup (volume of liquid in a pipe) profiles through the system for different positions (-9 m upstream the elbow, at the elbow, +1.5 downstream the elbow) J_l = 0.369 m/s, J_g = 0.369 m/sec for are depicted in Fig. 12. The liquid hold-up is the fraction of the liquid volume with respect to the internal diameter of the pipe.

Full blockage by water is observed by holdup prediction in both the elbow and the riser (downstream the elbow) in figure b and c respectively. This means that both positions are full of water over the slug generation. In the other hand the value of the liquid holdup is constant and reaches around 0.85 which confirms the presence of stratified flow in the inclined pipe.

CONCLUSION

In this study, numerical investigation of slug formation and characteristics of gas-liquid two-phase flow in a riser system has been carried out. A two-dimensional (2D) Model for the system was developed using ANSYS

CFD software package, and volume of fluid method was adopted to detect the void fraction gas/liquid. The chief impacts are to predict the slug formation, evolution and some parameters such as pressure and liquid hold-up. The following general conclusions could be derived from the analysis of the results and review of the literature.

The results obtained numerically with the developed model are in very good agreement with the experimental ones. The analysis shows that the model can be used to generate useful information of the hydrodynamics of the flow:

Nomenclature:

α = Void fraction. Volume of the phase over total volume of the mixture
ρ = Density
$\vec{g}$ = Gravitational constant
$\vec{v}$ = Velocity
μ = Dynamic viscosity
p = Pressure
$\vec{F}$ = External forces
J_l = Liquid flux
Jg = Gas flux
T = Temperature

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