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Transient Slug Flow Modelling of Subsea Riser Flowline System

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Authors' contributions

This work was carried out in collaboration between both authors. Author AAM designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Author TAB managed the analyses of the study and managed the literature searches. Both authors read and approved the final manuscript.

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ABSTRACT

A gas-water system slug velocity was modelled with slug flow like a train of slug units streaming through a steel flowline riser of roughness 0.025 was modelled, the flowline was 2700 m, and the riser was 100 m with a diameter of 0.254 m, with each slug unit having a liquid slug of 100 m and its gas bubble of 200 m. Presumptuously the liquid phase was not compressible; that is, no gas was entrapped in the liquid; there is also no liquid was trapped within the gas. Unsteady state flow was modelled as a mass-spring system with damping. Liquid phase represented the mass, whereas the gas represented the spring and damping as the force of friction that acts on the fluids in motion by the wall. A quasi-steady-state model having a slug velocity of 4 ms^{-1} was used to simplify the numerical correlations and algorithm and to relate with outcomes of the unsteady state model. Outputs from both models show that pressure and rate vary sinusoidally at fixed points in the system. Both models are unconcealed that the velocity of every slug unit was most at the end of flowline to the separator. The result from the transient state model is complex for weighing up with other results from the literature. This procedure was as a product of over-simplification owing to some assumptions made. Also, simultaneous solutions to the differential equations were solved with

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hand. It is determined that quasi-steady-state outputs are more reliable than the unsteady state model for flowlines that are not situated on heaving surfaces because the model is less complicated and follows the predictable trend.

Keywords: Slug velocity; quasi-steady-state model; unsteady-state model; gas-water system.

NOMENCLATURES

T : *Absolute temperature (Kelvin)*
g : *Acceleration due to gravity* (ms^{-2})
H_L : *Average hold-up of slug unit*
Z : *Compressibility factor.*
ρ_l : *Density of liquid* (kg/m^3)
ρ_g : *Density of gas* (kg/m^3), *f – Friction factor (-)*
H_{LS} : *Hold-up of liquid in the liquid slug*
H_{LG} : *Hold-up of liquid in the gas bubble*
R : *Ideal or molar gas constant (J/mol.K)*
L_L : *Length of liquid slug (m)*
L_G : *Length of the gas bubble (m)*
$\dot{m}$: *Mass flow rate* (kgs^{-1})
Xg : *Mass fraction of gas (kg)*
M_L : *Mass of liquid slug (kg)*
M_G : *Mass of the gas bubble (kg)*
ρ_m : *Molar density of ideal gas* ($mole/m^3$)
M_{air} : *The molar mass of air (kg/kmol)*
υ_m : *The molar volume of gas in* ($m^3/mole$)
$\prod$: *Pi*
A : *Pipe cross-sectional area* (m^2)
d : *Pipe diameter (m)*
P_L : *Pressure in a single liquid slug (psia)*
P_G : *Pressure in a single gas bubble (psia)*
γ : *Ratio of enthalpy to the internal energy of the system or heat capacity ratio*
Re : *Reynolds number (-)*
τ : *Shear stress* (N/m^2)
a : *Speed of sound* (ms^{-1})
U_{sl} : *Superficial velocity of liquid* (ms^{-1})
U_{sg} : *Superficial velocity of gas* (ms^{-1})
U_m : *Sum of superficial velocities of liquid and gas* (ms^{-1})
t : *Time (seconds)*
V_{gscp} : *Velocity of gas at pipe exit into phase separator*
V_G : *Velocity of the gas bubble* (ms^{-1})
V_L : *Velocity of liquid slug* (ms^{-1})
υ_{og} : *Volume of the gas bubble* (ms^{-1})
υ_{ol} : *Volume of liquid slug* (m^3)

1. INTRODUCTION

Slug flow is a category of intermittent multiphase flow pattern, where fluid transport with the effect of gravity at the upstream part of the line where the liquid phase experiences settling and with gas-phase occupying the other half of the flowline [1]. Issa and Kempf [2] could demonstrate that model prediction for change from stratified to slug flow was within acceptable boundaries when weighed up with experimental outcomes and the widely accepted Taitel and Dukler [3] flow limits. Series of numerical evaluations were conducted on individual pipe configurations including – horizontal, slightly vertical and v-section pipes.

This was conducted to confirm that when slugs became stable, specific characteristics such as slug frequency and length were in harmony with experimental outcomes. They suggested that the closure relationship utilised to define liquid-wall shear force largely affected the reliability of the calculations [4]. Matsubara and Naito [5] experimented on the impact of liquid viscosity on flow type of gas-liquid in a horizontal flowline utilising either water or an aqueous solution as the liquid phase. The experimental outcomes were evaluated against the mature Taitel and Dukler [3] flow map. Hiroaki and Naito discovered that when water (1cP) was utilised as the aqueous phase, the gas velocity where flow change takes place is significantly high. This is consistent with the outcome from Taitel and Dukler [3] flow map. The variations in outcomes from both experimental work and Taitel-Dukler model is because of the mathematical assumptions of the model. For example, to determine a flow change criteria, the liquid height to diameter (h_l/d) ratio was calculated with a one-dimensional momentum balance. It was considered that balanced stratified flow occurs and flow transition depended on this ratio.

The many flow types experienced while conveying hydrocarbon fluids affect the modelling of slug flow [6]. Incorrect assumptions on these flow types at any time during flow leads to substandard modelling of slug flow, which brings about the inefficient design of transport equipment with poor reliability. The aftermath of this is to reduce forecasted design life and a likely reduction in production efficiency. Also, most of older slug models developed considered mainly horizontal flowline systems with little or no consideration of risers [7].

The work aims at carrying out a transient slug flow modelling of subsea FLOWLINE-RISER system using MATLAB. While attaining this aim, the following objectives shall be met:

i. Evaluation and determination of options for building an unsteady state multi-phase slug flow-model.
ii. Critical choice of the ideal choice.
iii. Establish the drawbacks of the new model and carry out sensitivity analysis and comparison of trends using the quasi-steady-state model.

The subsea petroleum industry is unceasingly requiring improvements on its systems; therefore, improvement of slug flow models is key to reliable designs, improved system reliability, extended lifetime estimate of equipment increased production output and afterwards an excellent reputation for the operators [8].

The scopes of the work are

i. Evaluation and identification of alternatives for building an unsteady state multi-phase slug flow model.
ii. Critical selection of the preferred option.
iii. Developing transient and quasi-steady-state slug models
iv. Testing of the models with MATLAB (for transient model) and excel (for the quasi-steady state model)
v. Comparison of the plot trends of the models with trends reported in the literature.
vi. Identification of the limitations of the new model and carrying out of sensitivity analysis.

The limitations of the work include:

i. The modelling was hand derived, and assumptions were made due to the unavailability of data
ii. Energy balance within the flowline configuration was not conducted
iii. The thermal loss in the system was not conducted, i.e. an isothermal temperature was made
iv. There was no transfer of mass between the two phases

2. MATERIALS AND METHODS

2.1 Description of the Model

A slug unit approach was utilised in this study. That is, a unit comprises a liquid slug and its corresponding gas bubble [9]. The liquid slug was presumed incompressible, which implies no gas was entrapped in it and no liquid in the gas bubble [10]. Transport through the flowline-riser configuration (see Fig. 1) was presumed isothermal, and the ideal gas expression was utilised to cater for the variations in gas characteristics [11]. Flowing through the system are air and water.

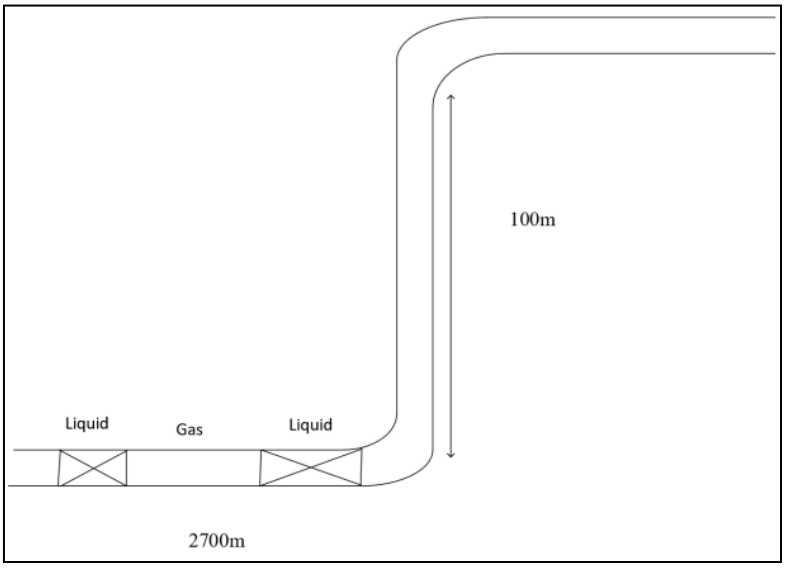

Fig. 1. Slug velocity model of a flowline-riser system

Unsteady state transport was simulated like a mass-spring system with damping. The liquid phase is presumed to be the mass, while the gas is the spring and damping is the frictional force from the wall on the moving fluids [12]. Generally, the configuration comprises a set of mass and momentum conservation expressions for individual phases. A one-dimensional two-fluid equation was utilised, and it was presumed that there was no mass exchange between the phases [13]. The transition in numerical factors including the velocity, pressure and mass flow-rate with time at a steady position will be predicted from solving the ordinary differential expressions given below.

2.2 Unsteady State Equations for Slug Units within the System

For the liquid slug, the momentum balance equation is [13]:

$$\frac{dV_l}{dt} = \frac{1}{M_l}\left[\left(\frac{dP_l}{dt} \times A\right) - \tau_l \pi D L_l - L_l \rho_l A g\right] \quad (1)$$

where, $M_l(kg), L_l(m), D(m), A(m^2), g(m/s^2), \rho_l(kg/m^3)\ P_l(psia)\ , V_l(m/s)$ are mass of liquid slug, length of liquid slug, the diameter of the pipe, cross-sectional pipe area, acceleration due to gravity, the density of the liquid, pressure in a single liquid slug, and velocity of the liquid, respectively.

Closure relationships for this expression are:

$$M_l = A L_l \rho_l \quad (2)$$

$$\frac{dP_l}{dt} = \frac{-P_l}{V_{ol}}\left(\frac{dV_{ol}}{dt}\right) \quad (3)$$

$$\frac{dv_{ol}}{dt} = V_l A \quad (4)$$

where $v_{ol}(m^3)$ the volume of the liquid slug

The accompanying momentum balance for the gas bubble is given as:

$$\frac{dV_g}{dt} = \frac{1}{M_g}\left[\left(\frac{dP_g}{dt} \times A\right) - \tau_g \pi D L_g - L_g \rho_g A g\right] \quad (5)$$

where, $M_g(kg), L_g(m), D(m), A(m^2), g(m/s^2), \rho_g(kg/m^3)\ P_g(kPa)\ , V_g(m/s)$ are mass of gas bubble, length of the gas bubble, the diameter of the pipe, Area of pipe, acceleration due to gravity, the density of the gas, pressure of the gas in the pipe, and velocity of the gas, respectively.

Closure relationships applied to the momentum balance equation are:

$$M_g = A L_g \rho_g \quad (6)$$

$$\frac{dP_g}{dt} = \frac{-P_g}{V_{og}}\left(\frac{dV_{og}}{dt}\right) \quad (7)$$

$$\frac{dv_{og}}{dt} = V_g A \quad (8)$$

Where, $v_{og}(m^3), V_g(m/s), P_g(psia) and\ A$ are volume of the gas bubble, velocity of the gas bubble, pressure in a single gas bubble, and area, respectively.

Assuming turbulent flow with Reynolds number (Re > 2300), the shear stress of flowing liquid or gas on flowline wall is given as [14]:

For inclination tilts within 0° and 45°;

$$\tau_{wl} = \frac{f_l \rho_l V_l^2}{2} \quad (9)$$

where, $\tau_{wl}\ (N/m^2)$, $f_g(-)$ are shear stress of liquid at the wall, and friction factor

$$\tau_{wg} = \frac{f_g \rho_g V_g^2}{2} \quad (10)$$

where, $\tau_{wg}\ (N/m^2)$, $f_g(-)$ are shear stress of gas at the wall, and friction factor

$$f_l = 0.0262(\alpha Re_l)^{-0.139} \quad (11)$$

Where $Re_l(-)$ is Reynold's number

$$f_g = 0.046\left(Re_g\right)^{-0.2} \quad (12)$$

For tilts above 45°, the shear stress was calculated using:

$$\tau_{wl} = \frac{1}{2}\frac{f_{wl}}{d}\rho_l V_l^2 \pi d \quad (13)$$

$$\tau_{wg} = \frac{1}{2}\frac{f_{wg}}{d}\rho_l V_g^2 \pi d \qquad (14)$$

$$f_{wl} = 0.079(Re_l)^{-0.25} \qquad (15)$$

2.3 Unsteady State Correlations for Slug Units Exiting the System

Momentum balance equation for gas bubble exiting the system is [13]:

$$\frac{dV_g}{dt} = \frac{1}{M_g}[\left(\frac{dP_g}{dt} \times A\right) - \tau_g \pi D L_g - L_g \rho_g A g - \dot{m}(V_{gsep} - V_{gj})] \qquad (16)$$

where, $V_{gsep}(m/s)$ is the velocity of the gas at pipe exit in the two-phase separator

Closure relationships for the above correlation are given as:

$$M_g = AL_g\rho_g \qquad (17)$$

$$\frac{dP_g}{dt} = \frac{1}{V_0}[ZRTx_g\frac{dM_g}{dt} - P_g\frac{dV_{og}}{dt}] \qquad (18)$$

where, $Z(-), T(K), x_g(-)\ and\ R(\frac{J}{mol.K})$ are compressibility factor, absolute temperature, gas fraction, and molar gas constant, respectively.

$$\dot{m}_g = \rho_g A V_g \qquad (19)$$

$$\frac{dV_{og}}{dt} = V_g A t \qquad (20)$$

The solution of the simultaneous equation to the two ordinary differential expressions, which are equations (16) and (18).

For the liquid slugs leaving the flowline-riser configuration, the two correlations are given:

$$\frac{dV_l}{dt} = \frac{1}{M_l}[\left(\frac{dP_l}{dt} \times A\right) - \tau_l \pi D L_l - L_l \rho_l A g - \dot{m}(V_{lsep} - V_{lj})] \qquad (21)$$

$$\frac{dP_l}{dt} = \frac{-P_l}{V_{ol}}\left[\frac{dV_{ol}}{dt}\right] \qquad (22)$$

Outcomes from the transient state model were matched with a very simplified quasi-steady-state model [3].

2.3.1 Boundary conditions

The average hold-up, H_L, of a slug unit, considered for both liquid slug and gas bubble at the entry of the line has been provided in terms of superficial rates [15]:

$$H_L = \frac{U_{sl}}{U_{sl}+U_{sg}} \qquad (23)$$

The ratio of the gas bubble to liquid slug length:

$$\frac{L_g}{L_l} = \frac{H_{LS} - H_L}{H_L - H_{LG}} \qquad (24)$$

where, $U_{si}, U_{sg}(m/s)$ are the superficial velocity of liquid and gas, respectively, H_{LS}, H_{LG} are hold-up of liquid in liquid slug and gas bubble, respectively.

It is assumed that no gas bubbles are entrapped in liquid slug to simplify the calculation process. Hence, H_{LG} it is zero and Equation (21) becomes:

$$\frac{L_g}{L_l} = \frac{H_{LS}}{H_L} - 1 \qquad (25)$$

where, L_L(m) and H_L are the length of liquid slug and average hold-up of slug unit, respectively.

From Gregory et al. [9], liquid slug holdup, HLS can be calculated with the equation:

$$H_{LS} = \frac{1}{1+(0.0352U_m)^{1.39}} \qquad (26)$$

Where $U_m(m/s)$ is the sum of superficial velocities of liquid and gas

Length of liquid slug, L_L has been estimated with Beggs et al. [16] correlation;

$$\ln(L_L) = -2.663 + 5.441(\ln(D))^2 + 0.059\ln(V_m) \qquad (27)$$

The set boundary condition was the phase separator pressure at flowline-riser exit situated downstream [17]. It was assumed that this pressure remained the same, despite velocity fluctuations at the vessel entry point [18].

2.4 Solution Methods

Mathematical integration, with a fourth-order Runge-Kutta technique, was used [19]. Flow rate transition with respect to time for each phase was gotten by solving the velocity differential equation simultaneously with pressure differential equation [20].

3. RESULTS AND DISCUSSION

3.1 Result Presentation

3.1.1 Unsteady state modelling outcomes

Figs. 2 to 5 are graphs of the results gotten from the unsteady state model of the flowline-riser-flowline system as in the methodology with the assumptions made.

3.1.2 Quasi-steady-state results

The Figs. 7 to 10 are graphs of the results gotten from the quasi-state model of the flowline-riser-flowline system after sensitivity analysis was carried out.

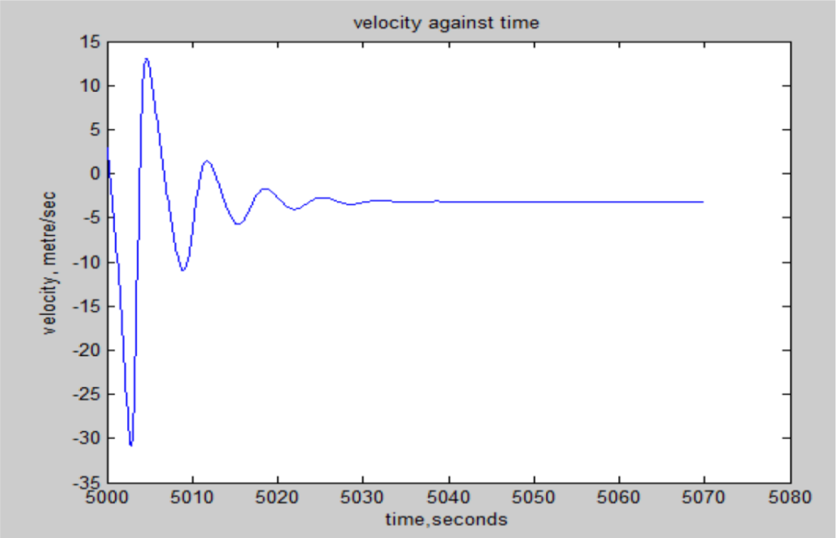

Fig. 2. Velocity versus time for liquid slug inside the flowline-riser system

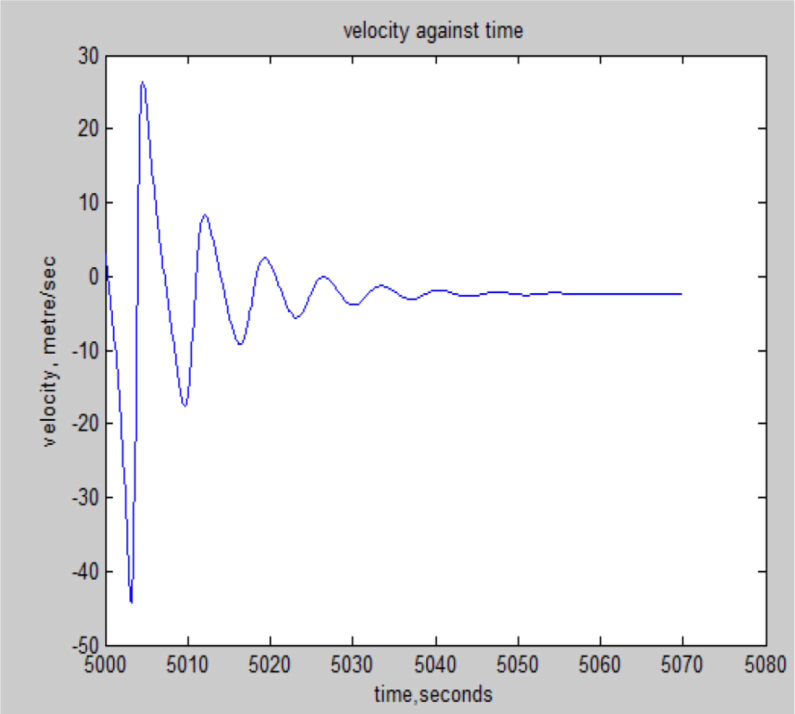

Fig. 3. Velocity versus time for gas bubble inside the flowline-riser system

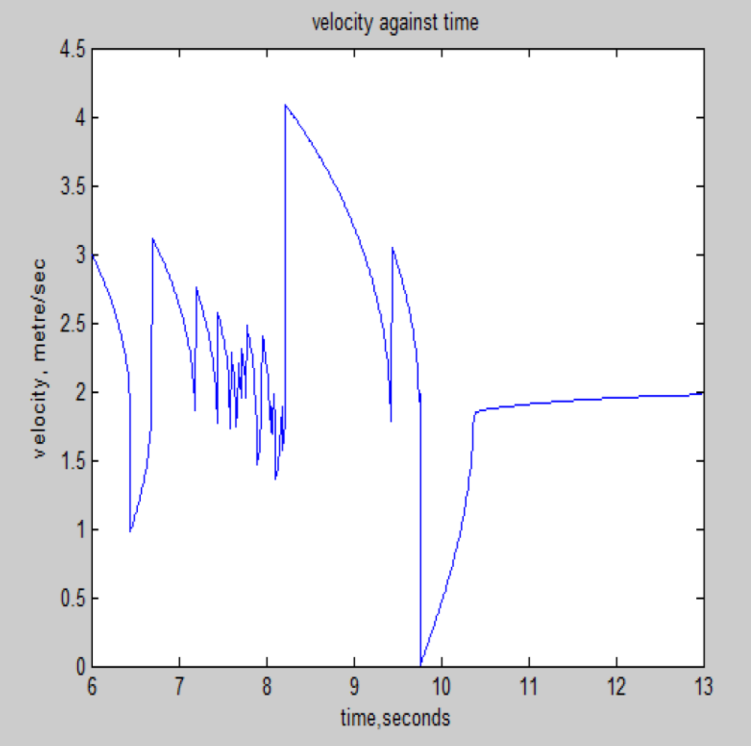

Fig. 4. Liquid slug unsteady state velocity leaving the system

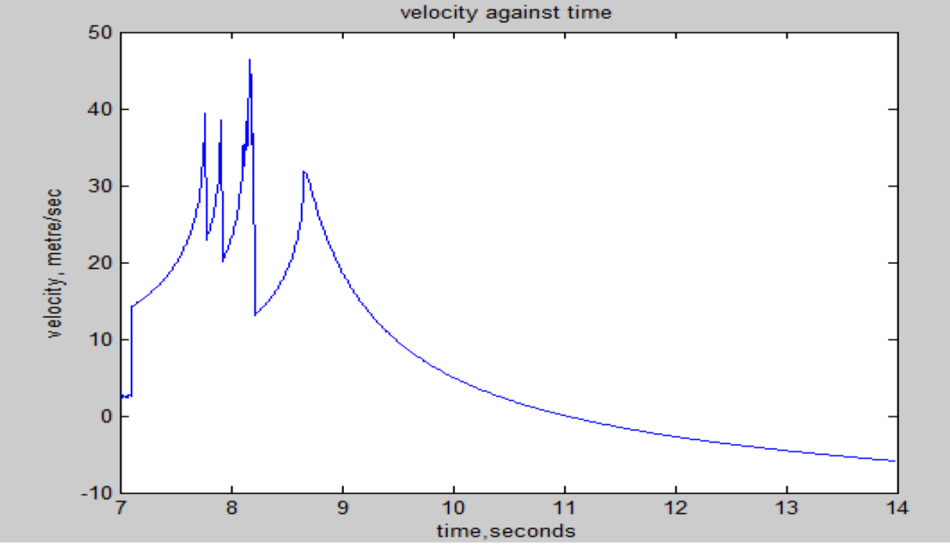

Fig. 5. Gas bubble unsteady state velocity leaving the system

3.2 Discussion

The line configuration used comprises of a 2.7 km steel horizontal subsea flowline which precedes a 100 m vertical flowline and a 100 m horizontal pipe connected to phase separator at the topside [21]. Flowline size was 0.254 m and had a roughness of 0.025 and pressure at the phase separator was fixed at 15 bar [22]. Figs. 2 to 6 illustrates velocity changes concerning the time at various points inside the flowline and flowline exit to separator vessel for a slug unit. Fluids within lines are air and water [23].

Fig. 2 illustrates the velocity transition of the liquid slug at the riser base. The plot is sinusoidal, and the amplitude of oscillation reduced with time. Pressure decreased due to friction and velocity increased as liquid slug flows via the vertical flowline is the reason for the decrease in amplitude of oscillation [24].

In Fig. 3, the velocity change for the gas bubble is seen. As shown on the plot, the velocity of the gas bubble dropped to about -45 m/s within the initial five seconds. However, overall, it experienced a similar trend to the liquid slug. Though the peak velocity of the liquid is not as high as the gas bubble velocity peak. However, oscillations in the velocity of the gas dropped a lot quicker than in liquid.

The fast decline in the velocity of the gas bubble behind the liquid is seen to happen when it forces the liquid part out of the vertical flowline [25]. The sharp rise in the velocity of the gas at this time happens when gas pressure at the base is sufficient enough to push the liquid part out of the riser.

In Fig. 4, the time change of liquid slug velocity as it flows out of the flowline-riser system into the separator is seen from the plot. It is revealed that as the liquid slug leaves the system, the velocity drops and this happens because the length of

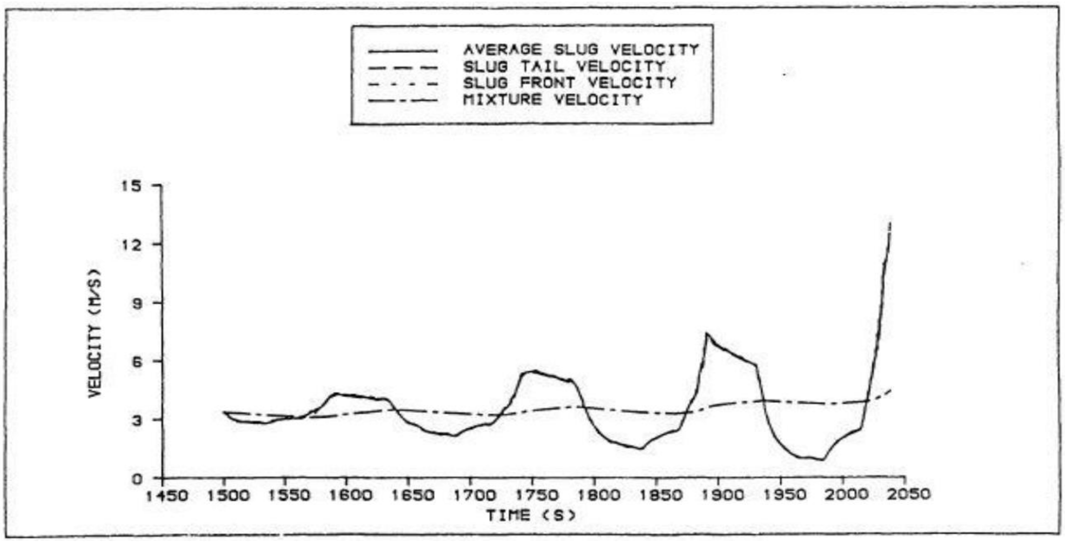

Fig. 6. Result of transient analysis by Wong and Gilchrist (1993)

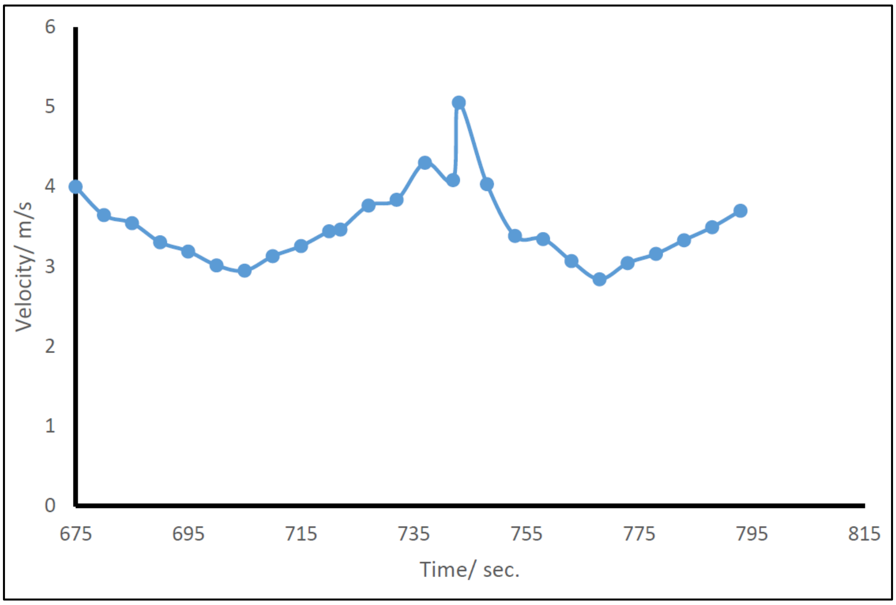

Fig. 7. Quasi steady-state velocity transition from the base of the riser to the exit of the system

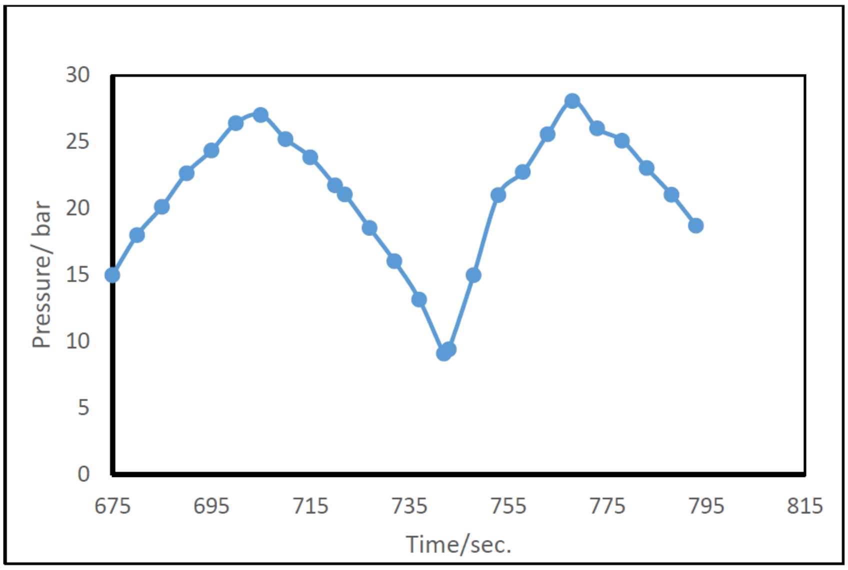

Fig. 8. Quasi steady-state pressure change at the base of the riser

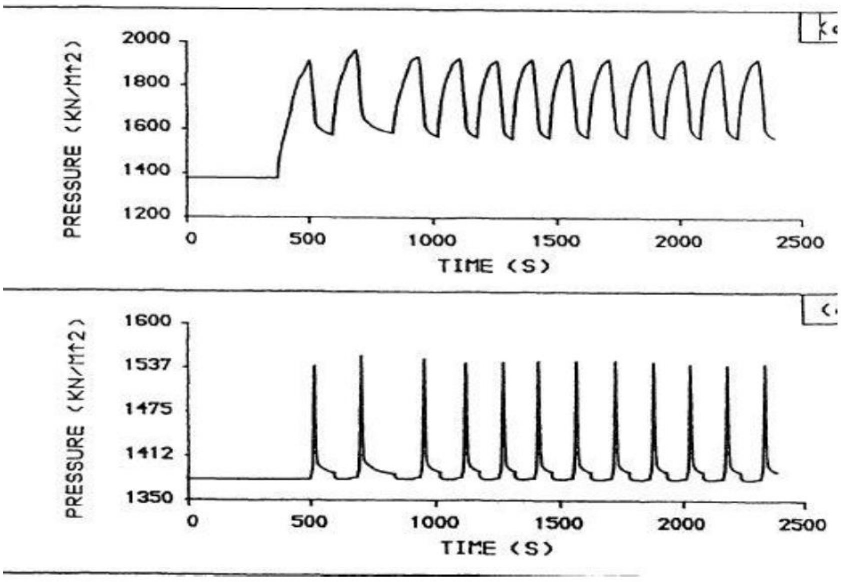

Fig. 9. Plot showing the change in pressure at the base and top of the riser by Wong and Gilchrist (1993)

the slug in the riser is also reducing because of the increase in velocity of the gas bubble beneath it [18]. When the slug height increases again, the velocity of the liquid also increases and more liquid exits the system [26]. This trend continues till after approximately the first 4 seconds of the exit flow. After the first two seconds of flow, the peak velocity was recorded, which was about 4 m/s.

Fig. 5 illustrates the time change of gas velocity as it flows into the phase separator. Also, it is observed that when a gas bubble exits the flowline, a sudden increase in velocity due to the velocity increase of the liquid slug behind it is observed [27]. Fluctuations in velocity during this short period can cause serious vibration of any process plant located on the platform.

Comparison of these outcomes with literature shows that the plots from the model are complex due to the simplification of the model as a result of the assumptions made. Also, the simultaneous solution to the differential equations was done by hand before inputting to MATLAB. Sequel to these reasons, the model result may not have a very high level of accuracy [28]. However, the results were consistent with a similar work done by Wong and Gilchrist [29] shown in Fig. 6 and Fig. 9 from Wong and Gilchrist [13] work, their transient analysis also yielded fluctuating velocity variation, and they attributed these fluctuations to the constant piston velocity used in their analysis.

A quasi-steady state correlation was utilised to further simplify the mathematical equations in this study and to match the solution with the unsteady-state model as a form of sensitivity analysis [30]. The steady-state condition was assumed for distinct time steps at specific points inside the flowline. Pressure and velocity changes with time at riser base, top and exit to process plant at the platform was considered too [31].

Fig. 7 illustrates the velocity variation at the riser bottom. For the initial 30 seconds from 675 secs to 705 secs, there was a reduction in velocity (2.9 ms-1) as liquid slug approaches the riser and fills it up [32]. This process is caused by the pressure drop of liquid due to friction for every time step, and the accompanying rise of hydrostatic pressure at the bottom of the riser [33]. When it happens, reverse pressure at slug bottom rises and compresses the gas bubble behind it. Immediately the riser is full of liquid; the gas pressure is just enough to force liquid slug from the vertical flowline [28]. That is why there is an accompanying velocity increase after 30 seconds. The trend continues; hence, the plot becomes sinusoidal.

Fig. 8 shows the pressure variation at the bottom of the riser base. Pressure trend is the direct opposite to that of the velocity. Pressure rises till it approaches its peak level (27.02bar) after 30 seconds from 675 secs to 705 secs as the liquid fills up the riser [34]. At this period, pressure starts to decline. That is so because liquid starts to fill up, hydrostatic pressure at the bottom is at its peak. Hence, the pressure at the slug bottom is highest [35]. The aftermath of this causes pressure in the gas bubble just behind slug is sufficient to ‘push’ the liquid through, and out of the riser. As liquid travels upward, hydrostatic pressure at riser bottom decreases since the gas stream fills the riser. The trend continues as liquid and gas cross each other via the riser and out to the separator [36].

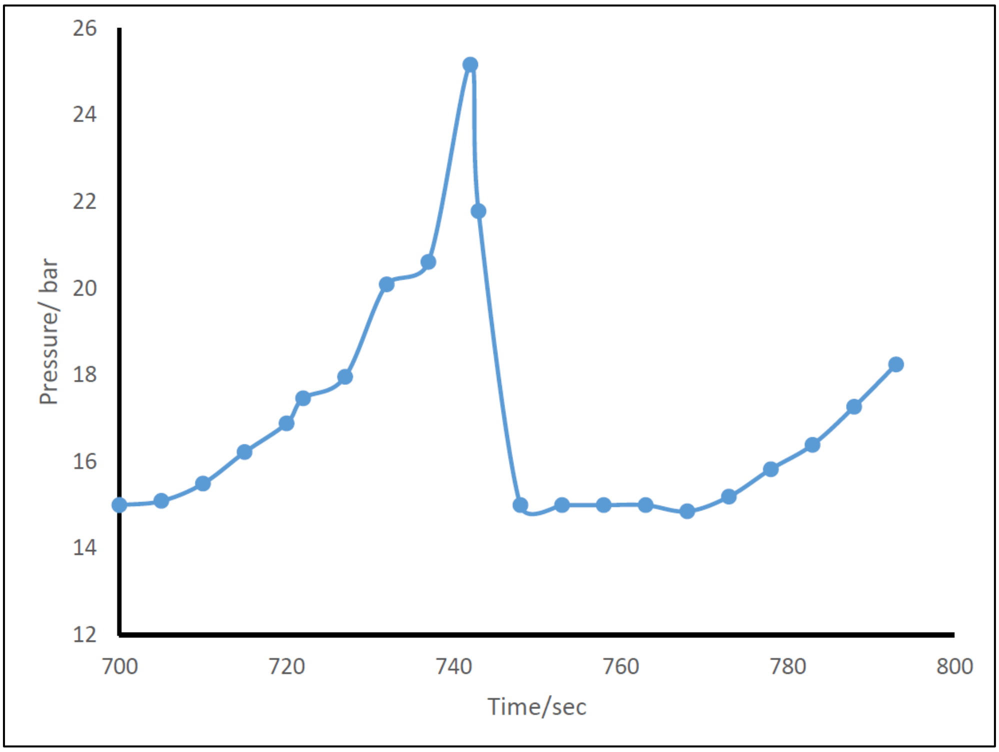

Fig. 10. Quasi steady-state pressure change downstream of the riser

Figs. 7 and 10 show velocity and pressure variations in the downstream of the riser. As the quasi-steady-state pressure changes. The same trend of the plots was observed. The only variation is that at the top half of the vertical flowline, velocity rises at the start as the liquid slug is forced out of the vertical flowline [37]. The pressure at the top of the vertical flowline fluctuates around an average value of 15 bar, and its increases as the slug move upwards of the riser to fill the riser and flowline after it [38]. The difference is at 743 seconds when pressure is at its peak at 25.16 bar. At this point, the vertical and horizontal flowlines are both filled with a high-velocity stream of gas. At the time is 743 secs. The velocity of the gas is at the maximum at 5.05 ms^{-1}.

At flowline exit to the separator which is Fig. 7, the first liquid slug unit reaches after about 705 secs at about 2.9 ms^{-1} and increases to a peak of about 4.3 ms^{-1} when it exits into the separator around 732 secs. Gas following it arrives at the peak of 5.05 ms^{-1}at around 747 secs this happens when the flowline is filled with the gas bubble before exiting from the system. As flow trend continues, liquid enters the flowline again, and velocity starts decreasing until the gas bubble enters the flowline again [39].

4. SUMMARY

A subsea flowline riser system with a diameter of 0.124 m with an air-water system was modelled, Evaluation and determination of options for building an unsteady state multi-phase slug flow model, developing a transient state model by establishing the drawbacks of the new model and carrying out sensitivity analysis and comparison of trends using the quasi-steady-state model. The length of the flowline was 2700 km, the riser was 100m with slug velocity of 4m/s and with a roughness of 0.024 m, an unsteady state system was assumed all through the flow at first, and the model was compared to literature then sensitivity analysis was carried out using the quasi-steady-state flow, the quasi-steady state gave better results when compared to literature [40].

5. CONCLUSION

Outcomes from both unsteady state and quasi-steady-state correlations showed that velocity changes sinusoidally at certain points inside the flowline-riser system. Both models reported that the velocity of each slug unit peaks at pipe exit to the phase separator. Outcomes of the transient model, though follow the expected trends and sequence from qualitative analysis and literature data may not be highly reliable. This is due to the assumptions made, and closure relationships applied. Also, the simultaneous solution to the differential expressions using substitution method was done by hand. This means that the outcomes could be prone to errors of ±20-30%. Quasi-steady-state outcomes are more accurate compared to others because the correlation is simpler and also follows the expected trend. Flow terms, including shear stress and viscosity, have varied directly with flow regime changes. Shear stress varies proportionally with fluid viscosity. As in, the higher fluid viscosities, size of shear stress needed to cause slugging decreases. Because of this, slugs may appear at a lower liquid velocity when the viscosity increases. The correctness of a correlation result depends on the quality of the hydrodynamic slip concept applied. It dramatically affects the unsteady state nature of system feedback. Also, the parameters in the velocity differential or momentum balance expression for different correlations dominate the quick system reaction. This scenario is more obvious in models such as the two-fluid model.

The energy balance within the flowline configuration should be conducted for future works in order to predict the temperature profile of the system. This process is important because if the temperature drops too low, it could cause the appearance of hydrates within the flowline system. With this, higher accuracy and reliability in flowline insulation design would be obtained. The liquid slug was presumed to have no gas entrapped in it and no liquid entrained in the gas bubble. This assumption is not realistic because, in slug flow, gas bubbles are entrapped in liquid slugs, particularly at the mixing point where high-velocity liquid slug alternates with a gas bubble. Turbulence at this time makes gas bubbles to be entrapped in the liquid. Accurate modelling of slug flow can be obtained with 3-D models using robust software such as ANSYS Fluent, COMSOL Multiphysics.

This present study will serve as reference material and a prototype for the future design of subsea flowline systems having pipelines and risers connecting to the platforms. This work has evaluated the impact of different assumptions typical of slug flow models and other flow assurance operations due including the roughness of the pipe. It has been perceived from this work that the assumption of the unsteady state of the system is not very accurate. It is more preferred to work with pseudo/quasi-steady state of the system. Before now, most of the past works on slug flow modelling only considered horizontal flowlines; however, subsea operations usually make use of tiebacks such as risers to get the recovered fluids to the platform. This work has developed a model for both transient and pseudo-state operations considering both horizontal flowlines and riser, noting that the pseudo-state assumption of the system gives a better and more accurate design of the system.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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