16th Australasian Fluid Mechanics Conference
Crown Plaza, Gold Coast, Australia
2-7 December 2007

Transient Flow and Pigging Operation in Gas-Liquid Two Phase Pipelines

S.M. Hosseinalipour[1], A. Salimi[1] and A. Zarif Khalili[1]
[1]CAE Center, CFD Lab, Mechanical Engineering Department
Iran University of Science and Technology (IUST), Narmak, Tehran, Iran
salimi.arash@gmail.com

Abstract

For simulation of transient gas-liquid two phase flow, the continuity, momentum and energy equations for two fluids should be solved, which requires complex calculations. In oil and gas pipelines, it is possible to perform some simplifications on continuity and momentum equations. This will be done by using quasi steady state assumption for gas continuity equation and also local equilibrium momentum balance for both phases in some flow patterns such as stratified, annular, slug and bubbly flows. In this paper, simplified transient simulation with assumption of isothermal flow was utilized together with flow patterns transition criterion and tested against experimental data for verification of the results. For this purpose, a computer code was written and implemented as transient flow simulator. In this code, the one dimensional differential equations were discretized by semi- implicit finite difference method and solved by an iterative manner. Also, a model for pigging operation was developed to analyze the flow parameters in pipeline during and after pigging. The numerical results were compared with the experimental data and it is observed that agreement with experimental data is satisfactory from practical engineering stand point.

Introduction

The most important cases of transient conditions in two phase pipelines are variations of inlet flow rate of fluids, changes in outlet pressure, and the pigging procedure. Pigging with spheres is executed periodically to accumulate and remove the existing liquid in pipeline.

Simulation and analysis of transient operations seem to be necessary in order to implement convenient design and safe operation of pipeline. In this regard, solving the conservation equations of mass, momentum and energy for fluids, gives us the ability to predict hydraulic transient behaviors.

Kohda (1987) used the drift flux model to simulate transient flow and tested against field data water-air mixtures.

Two-phase transient flow in petroleum industry is normally a slow phenomenon, compared with other cases such as nuclear industry. Thus, it is possible to perform some simplifications on mentioned equations in order to overcome the difficulties and complexities of such computer codes and develop the easy-to-use program.

Taitel, Shoham and Brill (1989) proposed the simplified transient solution with quasi steady state assumption for gas together with local equilibrium momentum balance for both phases. Minami and Shoham (1994) modified the model by introducing a new criterion for predicting flow patterns, and then compared it with experimental data.

McDonald and Baker (1964) were the first investigators who considered the pigging in two-phase pipelines. Barua (1982) attempted to improve the McDonald and Baker pigging model and remove some limiting assumptions from the main model. Kohda (1988) proposed the first pigging simulation based on full two-phase transient formulations according to drift flux model.

Minami and Shoham (1991) developed a pigging model and coupled it with the Taitel (1989) simplified transient simulator. A mixed Eulerean-Lagrangean approach with fixed and moving coordinate system was used to model the pig movement.

Simplified Transient Model

For gas phase, quasi steady state assumption is applied. Thus, the continuity equation is summarized to

$$\dot{m}_g = \rho_g Q_g = \rho_g V_g A_g \qquad (1)$$

And the liquid continuity equation is

$$\frac{\partial(\rho_\ell A_\ell)}{\partial t} + \frac{\partial(\rho_\ell A_\ell V_\ell)}{\partial x} = 0 \qquad (2)$$

In above equations, m_g is the gas mass flow rate, Q_g is the volumetric gas flow rate, V_g and V_l are the gas and liquid velocities, ρ_g and ρ_l are the gas and liquid densities, and A_g and A_l are the cross sections which are occupied by gas and liquid. Also, x and t are the axial and time coordinates.

Stratified Flow. In this regime, the momentum equations for two fluids with the assumption of local equilibrium balance are expressed by Eq. (3) and (4).

- Liquid momentum equation for Stratified flow

$$\frac{1}{\rho_\ell}\frac{dp}{dx} + \frac{C_{w\ell}}{y_\ell}V_\ell|V_\ell| - C_i\frac{\rho_g}{\rho_\ell y_\ell}(V_g - V_\ell)|V_g - V_\ell| + gSin\theta = 0 \qquad (3)$$

- Gas momentum equation for Stratified flow

$$\frac{1}{\rho_g}\frac{dp}{dx} + \frac{C_{wg}}{1-y_\ell}V_g^{\,2} + \frac{C_i}{1-y_\ell}(V_g - V_\ell)|V_g - V_\ell| + gSin\theta = 0 \qquad (4)$$

In equations (3) and (4), p is the pressure, y_l is the liquid holdup, C_{wg}, C_{wl} and C_i are the gas, liquid and interfacial shear coefficients, g is the gravity acceleration, and θ is the pipe inclination angle.

Annular Flow. This regime is similar to the stratified flow. Equations (3) and (4) are equally valid for annular flow except that gas does not wet the pipe wall (C_{wg} =0).

Bubbly or Mist flow. For these two regimes, it is assumed that there is no slippage between gas and liquid phase. Therefore, the homogenous model can be used.

- Mixture momentum equation

$$\frac{dp}{dx} = -\frac{2f_m\rho_m V_m^{\,2}}{D} - \rho_m gSin\theta \qquad (5)$$

where f_m, ρ_m and V_m are friction factor, density and velocity related to mixture flow respectively, and D is the pipe diameter.

Slug flow. The slug flow is divided into two regions: dispersed bubble and stratified. Fig. 1 shows the slug flow structure for horizontal and near horizontal pipe.

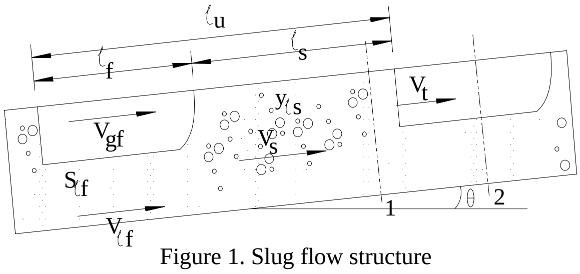

Figure 1. Slug flow structure

The liquid slug of length l_s is moving with translational velocity V_t. The slug contains gas bubbles and the liquid hold up in the slug is y_{ls}. For slug flow, the average liquid flow rate is given by

$$Q_\ell = A y_{\ell s} V_s \frac{\ell_s}{\ell} - A y_{\ell f} V_{\ell f} \frac{\ell_f}{\ell} \tag{6}$$

Also, the average liquid flow rate can be found from another relation:

$$Q_\ell = V_s A - Q_g \tag{7}$$

V_s and V_{lf} are the slug velocity and film region liquid velocity, l_s and l_f are the length of the slug and film regions, l is the total length of one slug unit, and y_{ls} and y_{lf} are the liquid holdup related to the slug and film regions. Note that V_{lf} is considered positive in the upstream direction.

Another equation can be derived using a liquid continuity balance relative to a moving coordinate system that travels with the slug translational velocity.

$$y_{\ell f}\left(V_t + V_{\ell f}\right) = y_{\ell s}\left(V_t - V_s\right) \tag{8}$$

The average liquid holdup for a slug unit is defined as

$$y_\ell = y_{\ell s}\frac{\ell_s}{\ell} + y_{\ell f}\frac{\ell_f}{\ell} \tag{9}$$

The translational velocity is expressed in terms of the slug velocity

$$V_t = C V_s + V_d \tag{10}$$

In equation (10), V_d is the drift velocity and C coefficient is determined experimentally. In this research C is 1.2.

Using equations (6)-(10), the final equation for predicting the slug velocity is defined as

$$V_s = \frac{Q_g/A - V_d\left(y_{\ell s} - y_\ell\right)}{1 - y_\ell C + (C-1) y_{\ell s}} \tag{11}$$

To calculate the slug velocity, liquid holdup in the slug should be determined; in this study the Gregory correlation is used.

$$y_{\ell s} = \frac{1}{1 + \left(\dfrac{V_s}{8.66}\right)^{1.39}} \tag{12}$$

By using a trial and error procedure, slug velocity and holdup will be calculated from equations (11) and (12). To calculate the pressure gradient in the stratified (or film) region, the equations (3) and (4) together with following mass balance will be used.

$$V_{gf} A_{gf} - V_{\ell f} A_{\ell f} = V_s A \tag{13}$$

In the above equation subscript f represents the parameters in film region.

Thus, the average pressure gradient in the slug flow can be determined.

$$\left(\frac{dp}{dx}\right)_{ave.} = -\left(\frac{2f_s}{D}\rho_s V_s^2 + \rho_s g Sin\theta\right)\frac{\ell_s}{\ell} - \frac{C_{wg,f}}{1-y_{\ell f}}\rho_g V_g^2 + \frac{C_i}{1-y_{\ell f}}\rho_g\left(V_{gf} + V_{\ell f}\right)\left|V_{gf} + V_{\ell f}\right| + \rho_g g Sin\theta\frac{\ell_f}{\ell} \tag{14}$$

In the above equation, f_s and ρ_s are friction factor and density of slug region respectively. Shear coefficient is expressed as follows

$$C = \frac{f\ S}{2A} \tag{15}$$

where S is the pipe perimeter, A is pipe cross sectional area and f is the friction factor which is given by Hall equation in case of turbulence flow for each phase. In laminar flow in which Reynolds number is less than 2000, the friction factor is 64/Re.

$$f = 0.001375\left[1 + \left(2\times10^4\frac{\varepsilon}{D_h} + \frac{10^6}{\text{Re}}\right)^{1/3}\right] \tag{16}$$

In equation (16), ε is the pipe roughness, D_h is hydraulic diameter and Re represents the Reynolds number.

In stratified flow, the interfacial friction factor is equal to 0.014, according to research of Cohen and Hanratty (1968).

In annular flow, the interfacial friction factor is given by Wallis (1969) relation:

$$f_i = 0.005\left(1 + 300\frac{\delta}{D}\right) \tag{17}$$

Where δ is the annulus thickness.

It is necessary to implement a criterion to determine flow pattern in each pipe section, which the calculation procedure depends on it. If the flow pattern changes, the method for solving the continuity and momentum equations will also change. Flow pattern prediction has been described by Taitel and Dukler (1976), Taitel (1980), Barnea (1986), Minami (1991). In this research the method of slug instability was used which was presented by Minami (1991).

Pigging Model

The model used in this study is based on research of Minami (1991), whose physical model is presented in Fig. 2. According to this model the pipeline is divided into three zones. The first one is upstream transient two phase flow; the second is slug section just ahead of the pig, and the third is downstream transient two phase flow.

For modeling of pig movement through pipeline, mass and momentum conservation in a moving coordinate is applied to the slug zone. For a moving and expanding control volume, the mentioned equations are expressed as below

$$\frac{d}{dt}\int_{v(t)} \rho dV + \int_{A(t)} \rho(\vec{v} - \vec{v}_{c.s}) d\vec{A} = 0 \tag{18}$$

$$\frac{d}{dt}\int_{V(t)} \rho\vec{V} dV + \int_{A(t)} \rho\vec{V}\left(\vec{V} - \vec{V}_{C.S}\right) d\vec{A} = \left(P_p - P_f\right)A - g\int_{x_p}^{x_f} \rho_s A Sin\theta dx - \tau_s \pi d L_s \tag{19}$$

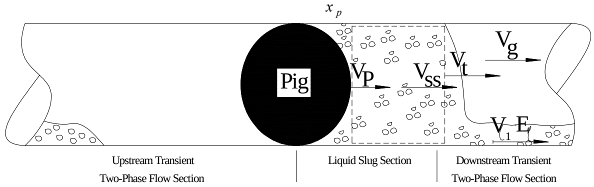

Figure 2. Pigging model

By applying equation (18) for the liquid phase inside the control volume, which is shown in Fig. 2, the following equation will be obtained

$$\frac{d}{dt}(\rho_\ell E_{\ell s} A L_s) + \rho_\ell (V_\ell - V_t) E_\ell A + \rho_\ell (0 - V_p)(1 - E)(-A) = 0 \tag{20}$$

In equation (20), E_{ls} is the liquid holdup in slug, E is the pigging efficiency or gas void fraction left after the passage of the pig, and V_p is the pig velocity.

The time rate of change of length of the liquid slug can be expressed in terms of differences between translational velocity and slug velocity. Therefore, the translational velocity is obtained as

$$V_t = \frac{E_{\ell s} V_p - E_\ell V_\ell - V_p (1 - E)}{E_{\ell s} - E_\ell} \tag{21}$$

where V_l and E_l are liquid velocity and holdup just downstream of slug front.

Also the liquid holdup in slug can be found by Gregory formula and slug velocity (V_{ss}) is obtained by applying the mass balance between a cross section just upstream and downstream of the pig

$$V_{ss} = V_p \left(1 - \frac{1 - E}{E_{\ell s}}\right) \tag{22}$$

Similarly, equation (22) will be simplified to

$$\rho_\ell V_{ss}\left(V_t - V_p\right) E_{\ell s} A + \rho_\ell V_\ell \left(V_\ell - V_t\right) E_\ell A = \left(P_p - P_f\right) A - \rho_s g A \left(Z_f - Z_p\right) - \tau_s \pi d L_S \tag{23}$$

In above equation, P_p and P_f are the pressure in the pig and slug front positions, Z_p and Z_f are the pipe elevations in the pig and slug front positions, τ_s is the average wall shear stress in slug region and L_s is the length of slug in front of the pig.

Solving equation (23) yields the total pressure drop in the liquid slug section.

Numerical Solution

In order to solve the simplified transient model, semi implicit finite difference approach is used to discrete continuity and momentum equations. Also, a rectangular grid system is employed, using backward differences approximations for gas and liquid continuity equations, and forward differences for the pressure equations. To simulate the transient behavior during and after pigging, we need to couple pigging model with transient model described earlier. The pig is assumed to be a moving boundary through which no gas is allowed to pass although some liquid is allowed to slip past it. The front of slug is also a moving boundary.

At each time step the new position of pig is calculated by using pig velocity, which equals to the gas velocity behind it, and the new position of slug front is also calculated by translational velocity obtained from equation (21). After the positions of pig and slug front are found, the simplified transient model is performed in the downstream transient zone to determine the pressure just ahead of the slug front. The boundary conditions are specified pressure in the pipe outlet and inlet flow rate, which can be found by using a mass balance between a cross section in the liquid slug section and a cross section in the downstream two phase flow for gas and liquid. For gas the relation will be found as

$$\left(1 - E_{\ell S}\right)\left(V_t - V_S\right) = \left(1 - E_\ell\right)\left(V_t - V_g\right) \tag{24}$$

Hence, the gas flow rate will be obtained by calculating gas velocity from equation (24). The same manner is used for liquid flow rate.

After solving the downstream flow zone, the pressure drop across the liquid slug section is found by equation (23). In that case, the pressure upstream from the pig is determined by adding the pressure drop across the pig. The empirical correlation was used to find the pressure drop across the pig which was given by Kohda, Suzukawa and Furukawa (1988).

For the upstream flow zone, another one-time step simplified transient model is implemented with pressure at the pig as the outlet boundary condition and given inlet flow rate for gas and liquid.

Results and Discussion

In order to examine the validity of the model, one case of pigging operation was computed and compared with the experimental data, which were collected in a test station by Minami (1991).

At first, steady state condition for a 420 meter length pipeline with diameter of 80 millimeter was computed. The inlet liquid flow rate was 0.0004 m^3/s and inlet gas flow rate was 0.085 m^3/s with outlet pressure of 183 kPa. The pig was introduced in the launcher at t = 66 s. Stratified flow was the observed flow pattern in the pipeline before pigging.

Figure 3 shows the pressure variations in two measurement stations, which were located at 64 and 203 meter from the pipe inlet. After putting the pig into the launcher, the pressure tends to decrease because the flow rate in the downstream of the pig decreases. When the slug front arrives at the first station, the pressure sharply increases until the pig passes through the station; also the growth of liquid slug length cause more gradual increase of the pressure. Discharging the slug into the separator causes the sharply decreasing of the pressure in all stations.

As it can be seen, there is a difference between predicated and measured pressures in the case of steady state flow before and after pigging. It shows that the steady state model used is not very accurate due to simplifying assumptions mentioned earlier.

The predicted pig arrival time to the receiver is less than actual time showing that the predicted pig velocity is higher than experimental measurement. This is because no gas is allowed to pass from upstream to downstream of the pig; however, we know that gas can bypass the pig. This difference between predicted and actual velocity also causes more pressure drop during pig motion than observed one.

In Fig. 4, the liquid holdup variation is shown at the first station and forth station which is located at 398 meters from the inlet.

The predicted trend of liquid holdup variations seems to be reasonable compared with observations, but there is an error in prediction of holdup in slug region because of inaccuracy in Gregory correlation.

Also, a little error is observed in the prediction of liquid holdup in upstream of the pig and downstream of the slug region which is related to calculation of holdup from steady state model.

Figure 5 represents the liquid holdup distribution in the pipe during and after pigging. It is observed that during pigging, there is a gas zone behind the pig and two phase flow will be formed near the pipe inlet. It can be seen that after pigging, liquid build up phenomenon will be occurred.

Conclusion

The simplified model together with slug instability flow pattern criteria was introduced to solve the transient two phase flow. Also, a model for simulation of pigging operation was used. Two models were coupled together and solved in a mixed moving and fixed coordinate by finite difference method. The results were compared with experimental data, which was achieved in a test station by Minami (1991). The model seems to be accurate in prediction of pig and slug parameters except for the pig velocity and liquid holdup in slug, which have small errors owing to the assumption of no gas flow from upstream to downstream of the pig. For practical engineering calculation and design, the above-mentioned errors are always on the safe side and the model can be considered excellent from this stand point.

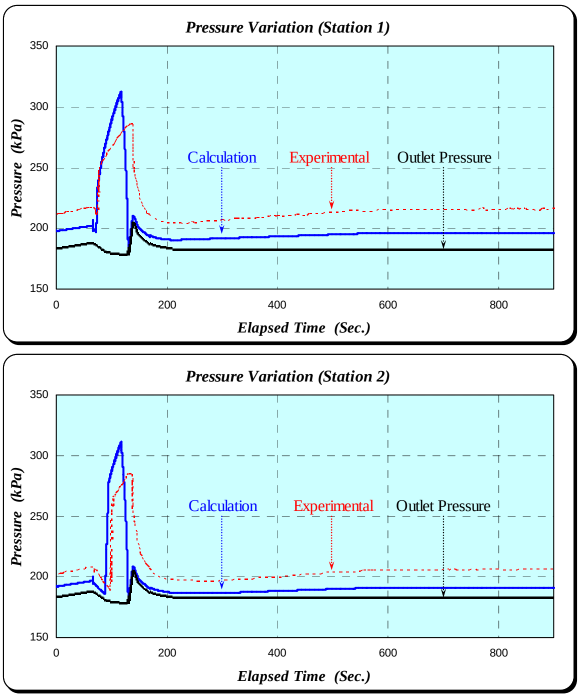

Figure 3. Pressure variations in first and second stations

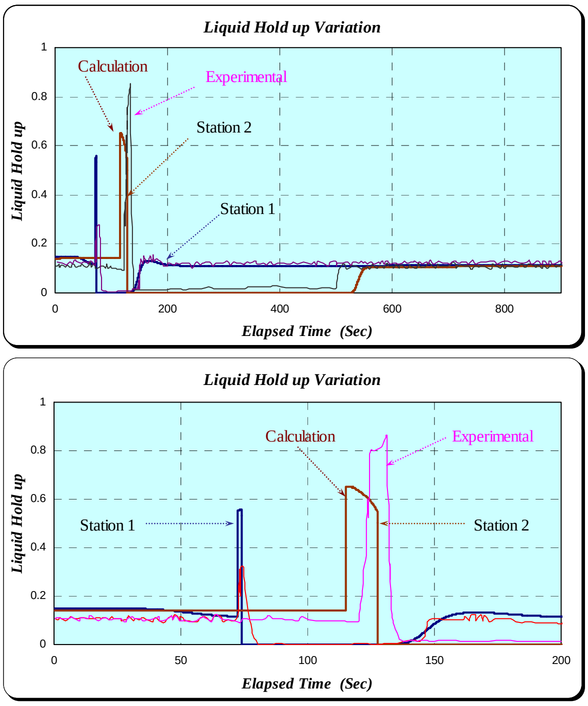

Figure 4. Liquid holdup variations in stations

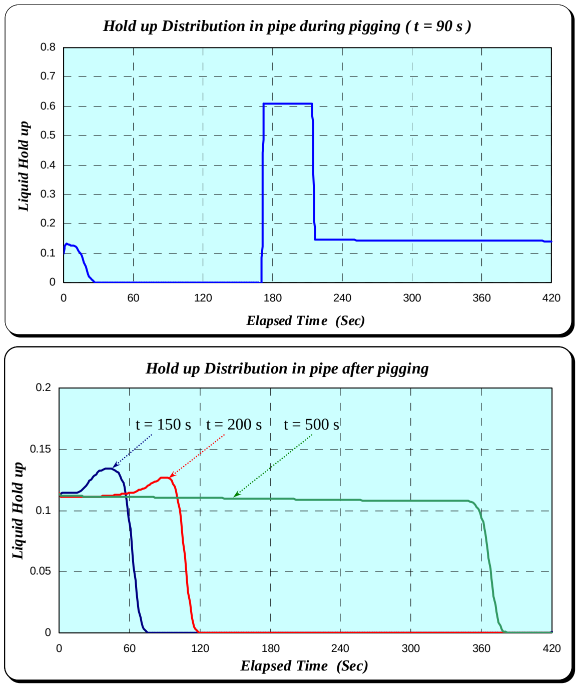

Figure 5. Liquid holdup distribution during and after pigging

Acknowledgments

We thank the Iranian National Gas Company for supporting pig project and all personnel who contributed to this study.

References

[1] K. Minami, 1991, “Transient flow and pigging dynamics in two-phase pipelines”, PhD dissertation, Tulsa university, Ok (1991)

[2] K. Minami, O. Shoham, 1995, “Pigging dynamics in two-phase flow pipelines: experiment and modeling”, SPE production & Facilities, November 1995, 10(4), 225-231.

[3] Hoi C. Yeung, P.C.R Lima, 2002, “Modeling of pig assisted production methods’, Journal of Energy Resources Technology, March 2002, Vol-124, 8-13.

[4] K. Kohda, Y. Suzukawa, H. Furukawa, 1988, “Pigging analysis for gas-liquid two-phase flow in pipelines”, ASME annual Energy Resources Technology Conference and Exhibition, New Orleans, 33-38

[5] K. Minami, O. Shoham, 1994, “Transient two-phase flow behavior in pipelines: experiment and modeling”. International Journal of multiphase Flow Vol.20, No.4, PP 734-752.

[6] Y. Taitel, O. Shoham, J.P. Brill, 1989, “Simplified transient solution and simulation of two-phase flow in pipelines”, Chemical Engineering Science, Vol. 44, No. 6, 1353-1359.

[7] A.E. Dukler, M. G. Hubbard, 1975, “A model for gas-liquid slug flow in horizontal and near horizontal tubes”, Ind. Eng. Chem., Fundam., Vol. 14, No. 4, 337-347.

[8] Y. Taitel, A.E. Dukler, 1976, “A model for predicting flow regime transitions in horizontal and near horizontal gas-liquid flow”, Journal of AIChe, Vol. 22, No. 1, 47-55