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TRANSIENT TWO-PHASE FLOW BEHAVIOR IN PIPELINES—EXPERIMENT AND MODELING

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Abstract—An extensive experimental program has been carried out to acquire two-phase transient flow data on 420 m long, 77.9 mm dia horizontal pipeline, using kerosene–air mixtures. A computer-based data acquisition system has been utilized to obtain rapidly changing and detailed information on the flow behavior during the transient tests. Pressure, *in situ* liquid holdup, translational velocity and flow pattern changes were monitored at four measurement stations installed along the pipeline.

An existing simplified model for predicting two-phase transient flow behavior that uses physically-based flow pattern-dependent mechanistic models has been modified and improved. The resulting set of differential equations is solved numerically utilizing a semi-implicit numerical scheme.

Comparisons of the predictions of the numerical model against the experimental data show that the proposed simplified transient model is well suited for simulating several types of transient behavior encountered in two-phase pipelines.

Key Words: two-phase, transient, pipeline, data

INTRODUCTION

Early studies on two-phase transient flow were pioneered by the nuclear industry, where prediction of the fast transient behavior during a loss of coolant accident (LOCA) has become mandatory for licensing a reactor. Numerical codes such as, RELAP, RETRAN, TRAC, COBRA and CATHARE, based on the simultaneous solutions of the continuity, momentum and energy equations for the gas and liquid phases, were developed. These codes were widely used in spite of many unresolved problems such as well posedness and stability of the mathematical formulation for the two-fluid and the drift flux models. Although the equations for describing the transient phenomena are complex, the thermodynamic properties of the two phases involved in the nuclear industry (steam–water) are relatively simpler.

Two-phase transient flow phenomena in the petroleum industry, on the other hand, are normally slow when compared to LOCA in the nuclear industry. Examples of slow transients are changes of inlet flow rates, changes in outlet pressure and opening or closing of valves. Pipeline rupture and pigging are examples of faster transients that can occur in a hydrocarbon transport line. In each of these cases, detailed pertinent information of the flow behavior is necessary for the designer and the operator of the system to construct and operate the pipeline economically and safely. A model for predicting the overall flow behavior in terms of pressure, liquid holdup and flow rate distributions for these different transient conditions is, thus, desirable. Nevertheless, the difficulties in solving the full set of conservation equations and the complex thermodynamic phase behavior of the hydrocarbon mixtures have hindered the development of easy-to-use simulation programs.

One of the earliest models for transient two-phase flow in pipelines was developed by Scoggins (1977). The formulation was based on homogeneous slip flow conditions, utilizing an empirical correlation for the determination of the liquid holdup.

Kohda *et al.* (1987) developed the transient two-phase flow simulator TFPDYN-2 based on the drift flux model. The model was validated against field data of Cunliffe (1978), and new experimental transient data collected in a horizontal, 1436.5 m long, 105.3 mm dia test pipeline, using low pressure air and water mixtures.

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The best known and one of the few commercially available two-phase transient computational pipeline codes is OLGA (Bendiksen *et al.* 1986, 1991). This code has been continuously updated since 1983 and is now comprised of tens of thousands of code lines. It is based on an "extended two-fluid model", which assumes the existence of three separate phases, namely, gas, liquid film and liquid droplets. OLGA has been validated against a few dynamic experimental data with good match, but the bulk of the data was from the SINTEF laboratory where the code was developed.

In order to overcome the difficulties of implementing and later using a computer code based on the full set of equations resulting from a rigorous theoretical transient analysis, Taitel *et al.* (1989) presented a new simplified approach for modeling two-phase transient flow in pipes. The two key assumptions of the simplified model are a quasi-steady state condition for the gas phase, and local momentum equilibrium considerations. It was assumed that for the relatively slow transient phenomena occurring in hydrocarbon transport pipelines, these simplifications were justified. The assumption of local momentum equilibrium allowed the use of well accepted mechanistic models for the different flow patterns.

With the assumptions of quasi-steady-state for the gas phase, incompressible liquid, no mass transfer at the interface, and isothermal flow, the following gas and liquid mass balance equations were presented:

$$\dot{m}_G = Q_G \rho_G = \text{constant} \qquad [1]$$

and

$$\frac{\partial A_L}{\partial t} + \frac{\partial Q_L}{\partial x} = 0, \qquad [2]$$

where $\dot{m}$ and Q are the mass flow rate and the volumetric flow rate, respectively, ρ is the density, A is the cross-sectional area, t is time and x is the coordinate in the flow direction. The subscripts L and G denote liquid and gas, respectively. Equation [1] implies that the gas mass flow rate at any cross section of the pipe is constant. Equation [2] is the only partial differential equation in the model to be solved for the liquid phase cross-sectional area, A_L, as a function of time and space.

For the linear momentum equations, Taitel *et al.* suggested the use of standard flow pattern dependent steady-state models. For stratified flow, the gas phase and the combined linear momentum equations are used, given respectively by

$$-A_G \frac{dP}{dx} - \rho_G g A_G \sin\theta - \tau_i S_i - \tau_G S_G = 0, \qquad [3]$$

and,

$$-\frac{\tau_L S_L}{A_L} + \frac{\tau_G S_G}{A_G} + \tau_i S_i\left(\frac{1}{A_L} + \frac{1}{A_G}\right) - (\rho_L - \rho_G) g \sin\theta = 0. \qquad [4]$$

where P is the pressure, g is the acceleration of gravity, θ is the inclination angle from the horizontal, τ is the shear stress and S is the perimeter over which τ acts. The subscript i denotes the gas–liquid interface. Equation [4] is an implicit equation for the liquid phase velocity v_L, once the gas flow rate and the liquid holdup are given. The calculated liquid velocity yields the local liquid flow rate that can be used for solving the liquid continuity [2], and the pressure gradient from [3].

For slug flow, a more complex analysis was used based on a physical model similar to Dukler & Hubbard (1975). The slug velocity, v_S, can be obtained from overall mass and volume balances on a slug unit, as follows:

$$v_s = \frac{v_{sG} - v_d(E_{Ls} - E_L)}{1 - E_L C_o + (C_o - 1)E_{Ls}}. \qquad [5]$$

where C_o is a velocity coefficient taken as 1.2 (Nicholson *et al.* 1978), E_{Ls} is the liquid holdup in the slug body given by the Gregory *et al.* (1978) correlation, v_d is the drift velocity given by Bendiksen (1984), E_L is the average liquid holdup in a slug unit and v_{sG} is the superficial gas velocity. Using [5], for a given gas flow rate and knowing the liquid holdup, the average liquid flow rate can be easily determined by $Q_L = (v_s - v_{sG})A$. Finally, the overall pressure drop, $(dp/dx)|_T$, can be found from

$$\left.\frac{dP}{dx}\right|_T = -\left(\frac{2}{D} f_s \rho_s v_s^2 + \rho_s g \sin\theta\right)\frac{l_s}{l_u} - \left(\frac{\tau_{Gf} S_{Gf}}{A_{Gf}} + \frac{\tau_{if} S_{if}}{A_{Gf}} + \rho_G g \sin\theta\right)\frac{l_f}{l_u} \quad [6]$$

where the first term in the right hand side is the pressure drop in the slug body, and the second term is the pressure drop in the gas and film region. The variables l_s, l_f and l_u are the slug, film and total slug unit lengths, respectively.

Similarly, models for annular and bubble flow can be developed. These models are not presented here for brevity.

For switching among the possible flow pattern dependent set of equations, the use of the Taitel & Dukler (1976) steady-state flow pattern transition criteria for horizontal and near horizontal pipes was proposed. In this case, local gas and liquid flow rates are used to determine the existing flow pattern.

In the present study, the Taitel *et al.* simplified transient model is improved by developing a new flow pattern prediction method for transient conditions. Also, an extensive experimental program has been carried out to acquire pertinent data for the validation of the model.

FLOW PATTERN TRANSITION

Taitel *et al.* (1989) suggested the use of the Taitel & Dukler (1976) steady-state transition criteria based on the local gas and liquid flow rates. However, the Taitel and Dukler criteria are not utilized in this study because they did not yield satisfactory results. Since for each flow pattern a distinct liquid velocity can be calculated, there are four different liquid velocities, one for each flow pattern, to be used for checking the transition boundaries. Therefore, more than one possible flow pattern for a given liquid holdup is likely to be encountered.

Another possible alternative for detecting the existing flow pattern in transient flow is to use the average liquid height corresponding to the local liquid holdup, and check for the Kelvin–Holmhotz instability and other transition criteria. This method was initially tried in this work but it sometimes resulted in oscillating liquid holdup and pressure distribution predictions along the line. The discontinuous nature of the flow pattern-dependent models contributed to this undesirable result.

The method employed in the OLGA model for determining the local flow pattern, based on the minimum slip concept, could not be used in this study. It would result in the preferential use of the dispersed bubble flow model that assumed no slippage between the two phases. This problem was probably not encountered in the OLGA simulator because only two sets of equations are used, and neither of them assumes a no-slip condition.

Some transient two-phase flow investigators in the nuclear industry have used a much simpler criteria to determine the flow pattern under transient flow conditions. The transition boundaries in these maps were usually correlated with the gas void fraction and the total mass flux. To prevent discontinuities in the liquid and gas velocity solutions, a transition zone between two different flow patterns is provided. However, this approach is also not used in this study because it is over-simplified and does not account for the physical mechanisms that govern the flow pattern transition phenomena.

As can be seen, the existing procedures for predicting the flow pattern transition boundaries in transient flow condition are not adequate. A new method for predicting flow pattern in transient flow is, therefore, developed and presented next. It is based on the stability of the slug flow structure. The method first assumes that the slug flow pattern will exist. Then, all the slug flow characteristics are determined using appropriate slug flow equations. The analysis of these characteristics yields the existing flow pattern.

The first two slug flow parameters to be calculated are the liquid holdup in the slug body, E_{Ls}, from the Gregory *et al.* (1978) correlation, and the velocity within the slug, v_s, from [5]. These two equations must be solved simultaneously. If E_{Ls} is found to be lower than the local average liquid holdup, E_L, then this implies that the liquid holdup in the film region must be larger than the liquid holdup in the slug body, which is physically not possible. When this situation occurs, it is assumed that the flow pattern is dispersed bubble because the average liquid holdup is higher than the liquid holdup in a normal slug body. Scott & Kouba (1990) suggested a minimum possible liquid holdup within a slug body of 0.26, assuming a rhombohedral packing of equal size spherical gas bubbles, as opposed to the 0.48 suggested by Barnea & Brauner (1985), assuming cubical packing. If the calculated E_{Ls} is below 0.26, then it is assumed that neither bubble flow nor slug flow structures can exist, and the flow pattern will be either stratified or annular. In summary, the analysis of E_{Ls} gives two flow pattern transition criteria:

if $0.26 < E_{Ls} < E_L$, then the flow pattern is dispersed bubble,

and

if $E_{Ls} < 0.26$, then flow is either stratified or annular.

Once E_{Ls} is found to be within acceptable bounds, that is $E_{Ls} \geqslant 0.26$ and $E_{Ls} \geqslant E_L$, then the remaining slug characteristics can be calculated from a slug flow model. The parameter l_s/l_u yields two other flow pattern transition boundaries, based on the following criteria:

if $l_s/l_u > 1$, then the flow pattern is dispersed bubble,

and

if $l_s/l_u < 0$, then flow is either stratified or annular.

Similar slug flow to dispersed bubble flow transition criterion was suggested by Scott & Kouba (1990).

For the stratified to annular flow boundary, the Kelvin–Helmholtz instability criterion is used (Taitel & Dukler 1976):

$$v_G > \left(1 - \frac{h_L}{D}\right)\sqrt{\frac{(\rho_L - \rho_G)g \cos\theta A_G}{\rho_G \dfrac{dA_L}{dh_L}}}. \qquad [7]$$

where h_L is the equilibrium liquid level and D is the pipe diameter.

The implementation of this method results in only one possible flow pattern for a given liquid holdup, and the transitions normally occur with minor liquid velocity discontinuities at the flow pattern transition boundaries. This method of determining flow pattern in transient two-phase flow can also be used for the steady-state condition. For illustrative purposes, a flow pattern map for a steady-state water–air flow in a 78.0 mm dia horizontal pipe at atmospheric conditions has been generated using the above method. Figure 1 presents the flow pattern boundaries predicted by the proposed method plotted over the flow pattern map obtained from the Taitel & Dukler model. It shows that the flow pattern transition model based on the stability of the slug flow structure compares reasonably well with the Taitel & Dukler flow pattern boundaries. The slug to stratified flow boundary predicted by the present model, however, occurs at much lower liquid flow rates.

NUMERICAL SOLUTION

The simplified transient model represented by [1]–[6], incorporating the new flow pattern prediction model, has been solved using a semi-implicit finite difference scheme. This method has been selected because its implementation in a computer program is straightforward.

A fully implicit scheme, although preferred from the stand point of maximum allowable time-step size, is much more complex to program. Also, an iterative technique is always necessary to obtain a fully implicit solution of a transient two-phase flow problem, because of the non-linearity of the differential equation set. Computer time spent on one iteration of an iterative technique is about the same as the time spent in one single time-step calculation of an explicit scheme. Therefore, part of the advantage of the fully implicit method that allows larger time-step sizes to reduce the overall computing time is offset.

A more detailed description of the numerical solution method used in this study is given in Minami (1991). A rectangular grid system is employed, using backward difference approximations for the gas and liquid continuity equations, and forward difference for the pressure equation. These approximations were selected as a result of the pressure and flow rate boundary conditions.

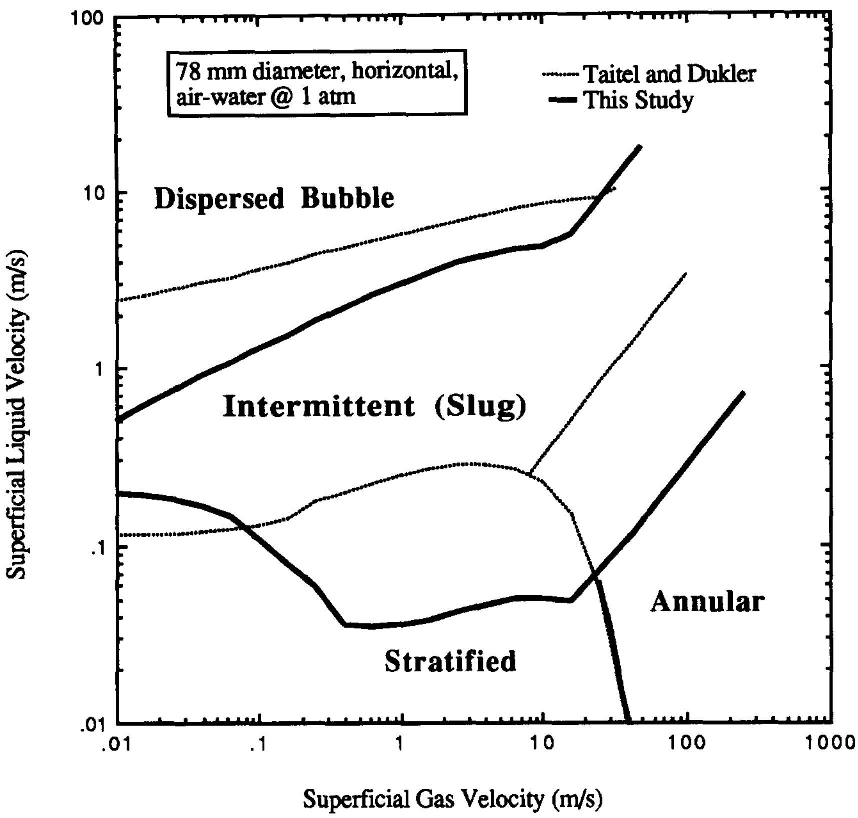

Figure 1. Proposed vs Taitel & Dukler flow pattern transition boundaries.

EXPERIMENTAL PROGRAM

An extensive experimental program has been conducted to acquire pertinent transient data. The test section comprised of a 77.9 mm dia, 420 m long horizontal steel pipe. Four 3 m long transparent measurement stations, made of clear PVC pipe, were installed along the flow loop, located at 63.7, 202.7, 230.8 and 398 m from the mixing tee, respectively. Figure 2 shows a schematic diagram of the experimental facility with approximate locations of the instruments. Descriptions of the various components of the system, the calibration procedure for the instruments, and testing procedures can be found in Minami (1991). Compressed air and kerosene were used as the two-phase mixture.

The bulk of the instrumentation for the experimental study was located in the four measurement stations distributed along the line. Each measurement station consisted of an absolute and a differential pressure transducer, and two capacitance sensors for measuring liquid holdup. Pressure at the mixing tee and at the separator was also measured by two transducers. The inlet flow rates from the turbine meters, the flowing temperature and the weight information from the weighing tank, installed at the pipeline exit, completed the set of signals to be logged.

All the analog signals from the different instruments were wired into a computer-based data acquisition system. This system allowed sampling of 23 channels at a rate of up to 40 samples/s/channel, or, each channel sampled every 1/50 of a second. The outlet liquid flow rate was measured by deviating the flow into a pressurized tank equipped with a weight sensor.

Various types of transient conditions were generated by applying different time-dependent boundary conditions at the inlet. At the outlet, a constant pressure boundary condition was applied. Prior to introducing a change in the inlet boundary condition, steady-state flow was usually obtained by flowing approximately one half hour with constant rates, with the outflow directed to the separator. Once a steady-state condition existed, the data logging was initiated and the outflow was directed to the weighing tank. A few minutes later the change in the boundary was

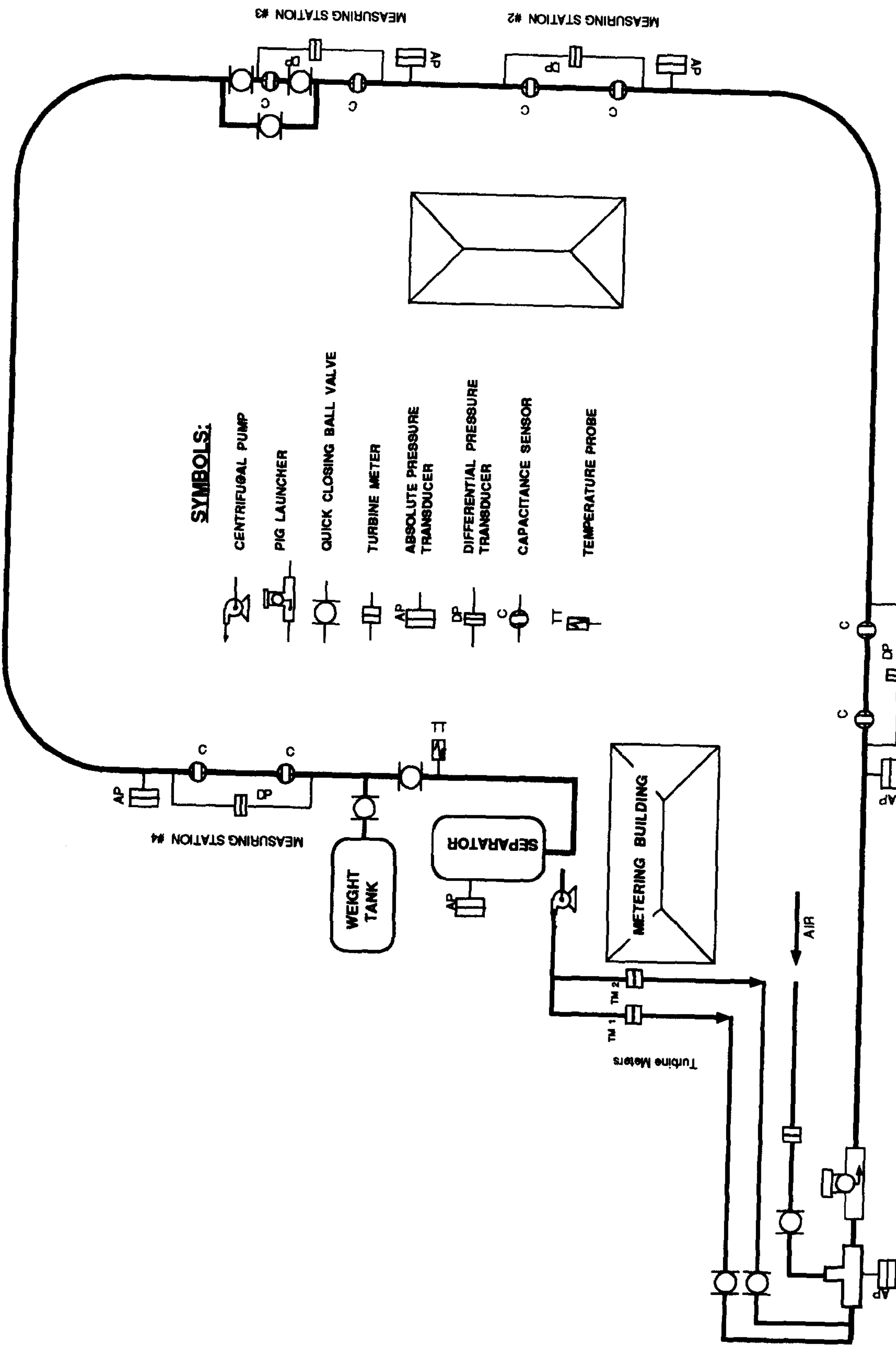

Figure 2. Schematic diagram of the two-phase test facility.

applied by changing the inlet flow rate through manually operating the liquid and air needle valves. The data logging period usually lasted from 20 to 60 min, until a new steady-state condition was observed.

RESULTS AND DISCUSSION

The use of a fast computer data acquisition system produced experimental transient data sets of unique characteristics. From about 530,000 to 1,250,000 data points are generated for each experimental run, corresponding to approx. 20–60 min of logging time at a sampling rate from 10 to 50 samples/s/channel. Very detailed information on the flow structure can be determined from these data sets. This includes, for example, flow pattern, slug frequency, slug holdup, film height and translational velocities.

For the analysis of overall transient flow behavior, without the microscopic information on the flow, time averaged values are used rather than instantaneous values. In this case, the continuously sampled data are averaged over a certain time span to smooth out the fluctuations pertaining to the localized flow structure. During this process, part of the detailed information on the flow structure, mainly under slug flow conditions, is lost.

Case 1—change in gas flow rate

Change in gas flow rates is one of the most discussed transient two-phase flow behaviors in pipelines. Fast increase in gas flow rate after the establishment of a steady-state flow is known to induce a temporary slugging and also a significant pressure drop increase in the pipeline. The slugging can cause flooding of the downstream gas–liquid separator, and the pressure increase can lead to a shut down of the upstream compression facility due to the high pressure.

The initial condition is a steady-state two-phase flow in the entire pipeline, with the gas and liquid flow rates set around 0.065 and 0.00085 m^3/s, respectively, and the separator pressure kept around 205 MPa. The change in the boundary condition is introduced at $t = 87$ s, when the inlet gas flow rate is suddenly increased to 0.105 m^3/s. The inlet flow rate and the separator pressure are kept unchanged.

The transient flow behavior occurring during the test run is shown in figure 3. Three graphs are presented in this figure. The x-axis in these graphs represents the elapsed time since the start of the test run. The top graph summarizes the applied inlet flow rate boundary conditions, and also presents the measured outlet liquid flow rate. The outlet liquid flow rate data are not available for the entire duration of the run because after some time, the total weight in the weighing tank exceeded the capacity of the load cell, saturating completely the electric signal. The middle graph shows the pressure behavior at stations 1 and 2, and at the pipeline exit. The bottom curve in the middle graph is the separator pressure at the pipeline exit, which is also the applied outlet pressure boundary condition. Finally, the bottom graph presents the liquid holdup as observed in stations 2 and 4.

The pressure drop in the pipeline increases substantially immediately following the increase of the gas flow rate. The outlet liquid flow rate shows a clear indication of intense slugging. The total pressure drop as well as the liquid flow rate at the pipeline exit increased more than two-fold. In the time period following the disturbance, pressure, liquid holdup and outlet liquid flow rate gradually readjusted to the new steady-state conditions. It is interesting to note that the time required to achieve a new steady-state condition (about 500 s) is fairly long, even for this relatively short test pipeline.

The measured boundary conditions are used as input for the computer simulator developed in this study. The measured initial conditions are also entered directly into the computer program rather than finding the initial conditions from a steady-state model. This is justified because the main purpose of this study is to investigate the transient nature of the phenomena and not the performance of the steady-state models. For properly evaluating a transient model, it is important to start from the correct (measured) initial conditions.

Figure 4 is very similar to figure 3, and summarizes the whole experimental data and the results of the simulation. The calculated pressure and liquid holdup distributions match the experimental

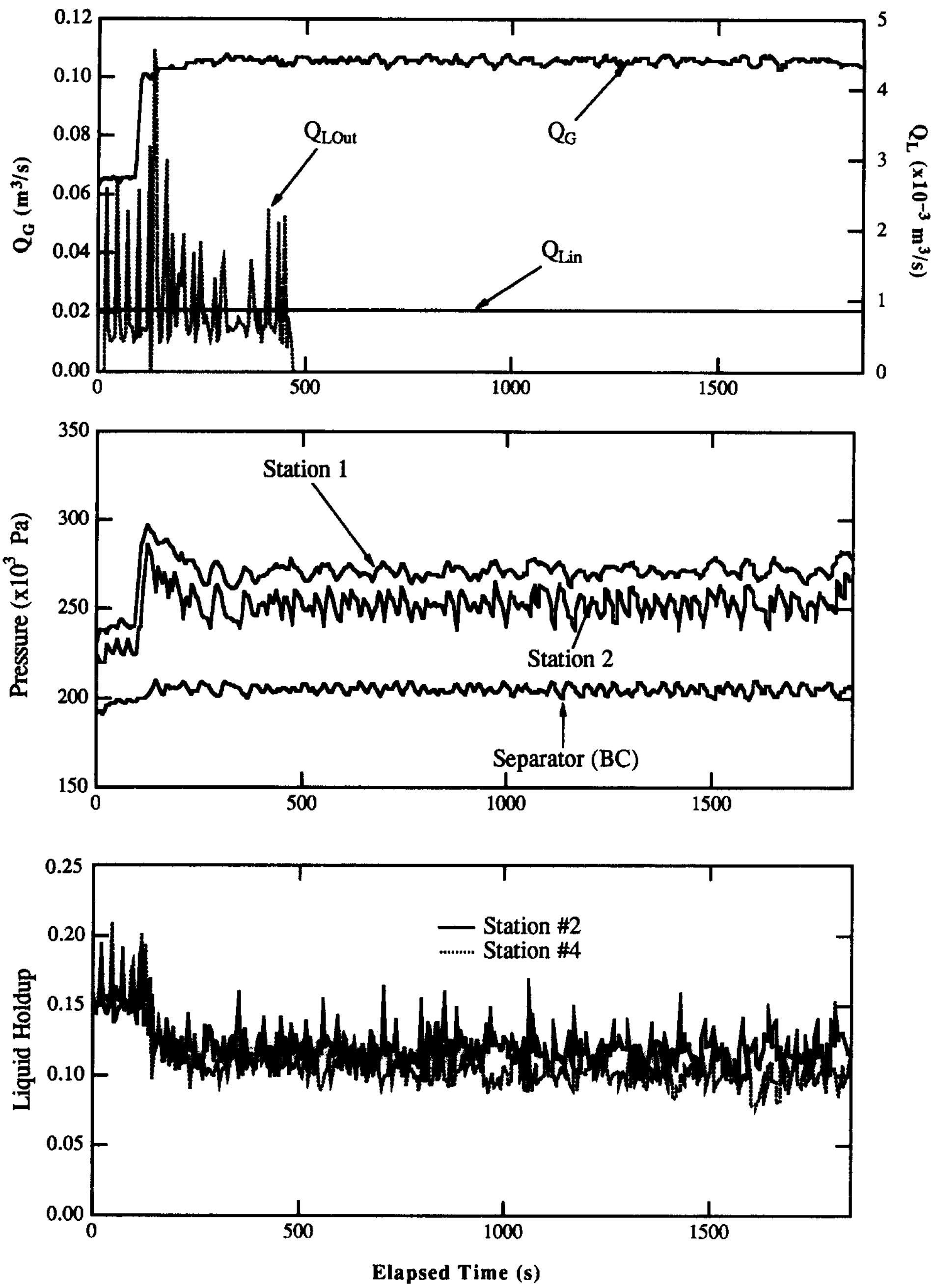

Figure 3. Observed transient flow behavior for run 3.

data quite well. It can be observed that initially the calculated pressure increases faster and reaches values slightly higher than the observed pressure. This is probably due to the quasi-steady state assumption for the gas phase in the simplified transient model. The model assumes that the gas flow rate increase is instantaneously propagated throughout the pipeline. However, after the initial peak in pressure, the agreement between the measured and predicted pressure is remarkable. The predictions of the liquid holdup as compared to the experimental data shown at the bottom graph of figure 4 are also excellent.

Evaluation of the predicted liquid flow rate at the pipeline outlet is difficult because the measured data oscillate significantly as a result of the slugging occurring at the pipeline exit. For example, at one specific instance, a maximum above 0.004 m^3/s is observed. The slug flow model does not

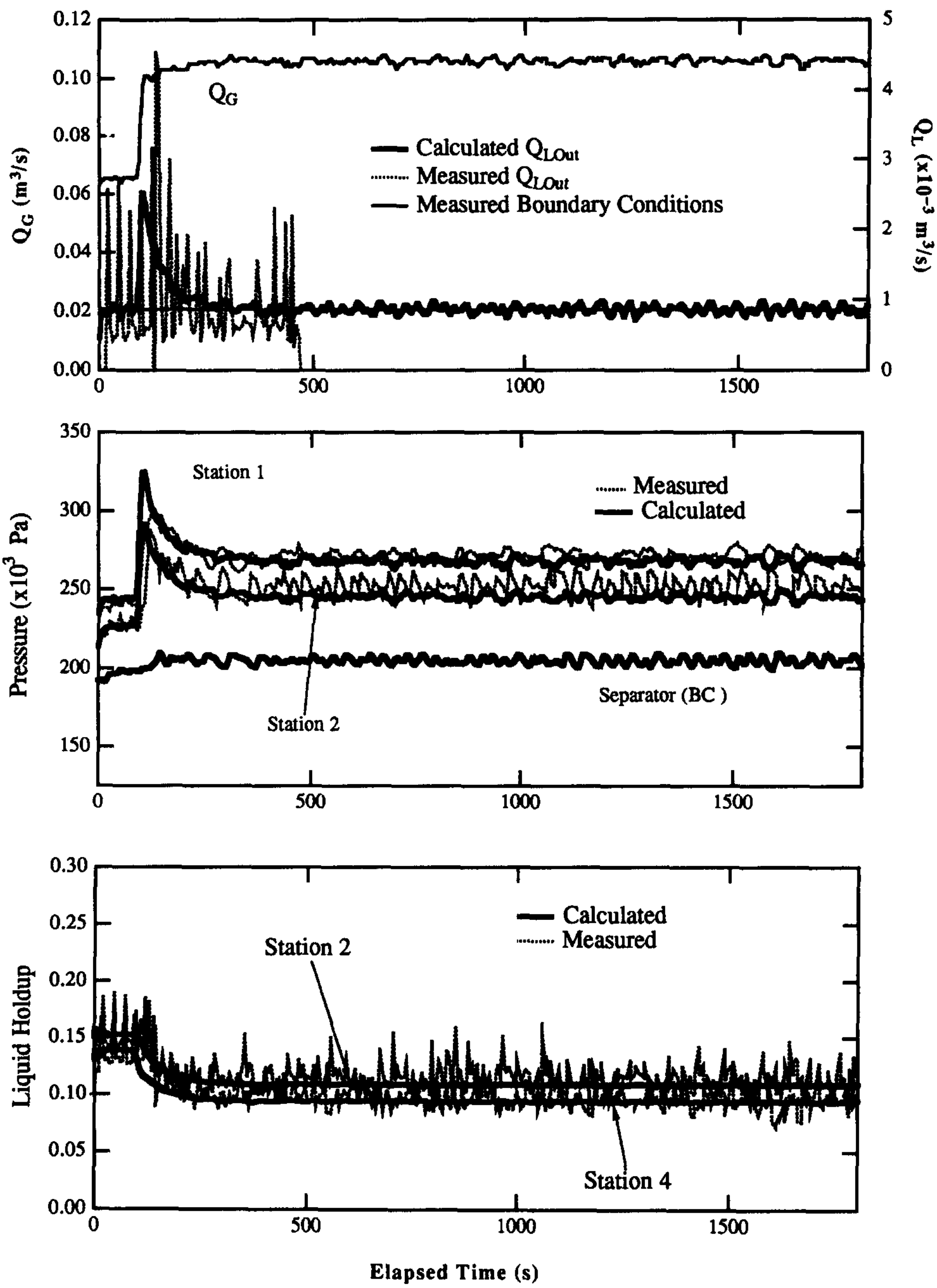

Figure 4. Comparison between predicted and measured transient flow behavior for run 3.

consider the flow rate of individual slugs. Instead, the liquid flow rate is determined based on the average value for the flow structure. The predicted values for the liquid flow rate, on the average, seem to be consistent with the measured data.

Both theory and experiment show that a rapid increase in gas flow rate in a pre-established steady-state flow condition does, indeed, cause a temporary pressure drop increase and a temporary intense slugging period that induces high outlet liquid flow rate. The assumption of quasi-steady state for the gas phase in the model seems to be acceptable for this type of transient flow condition. However, due to this assumption, the model tends to yield conservative predictions for the inlet pressure (higher pressure drop), and also a conservative prediction for the outlet liquid flow rate (higher flow rate).

Case 2—change in liquid flow rate

The initial condition for this run is a steady-state slug flow with an average inlet gas flow rate of 0.067 m^3/s, an average inlet liquid flow rate of 0.00119 m^3/s and a separation pressure of 185 MPa. The liquid flow rate is suddenly increased to 0.0024 m^3/s at $t = 313$ s. The final steady-state condition is also in slug flow. The observed and predicted hydrodynamic behavior are given in figure 5.

The liquid flow rate data at the pipeline outlet are only available for the time span $t = 211$ s to $t = 495$ s. This is due to the fact that the two-phase mixture was only deviated from the separator into the weighing tank at $t = 211$ s. At $t = 495$ s the total liquid weight in the weighing tank exceeded the maximum capacity of the load cell. After the increase in liquid flow rate, the pressure builds up gradually and the averaged liquid holdup increases slowly to the new steady-state value.

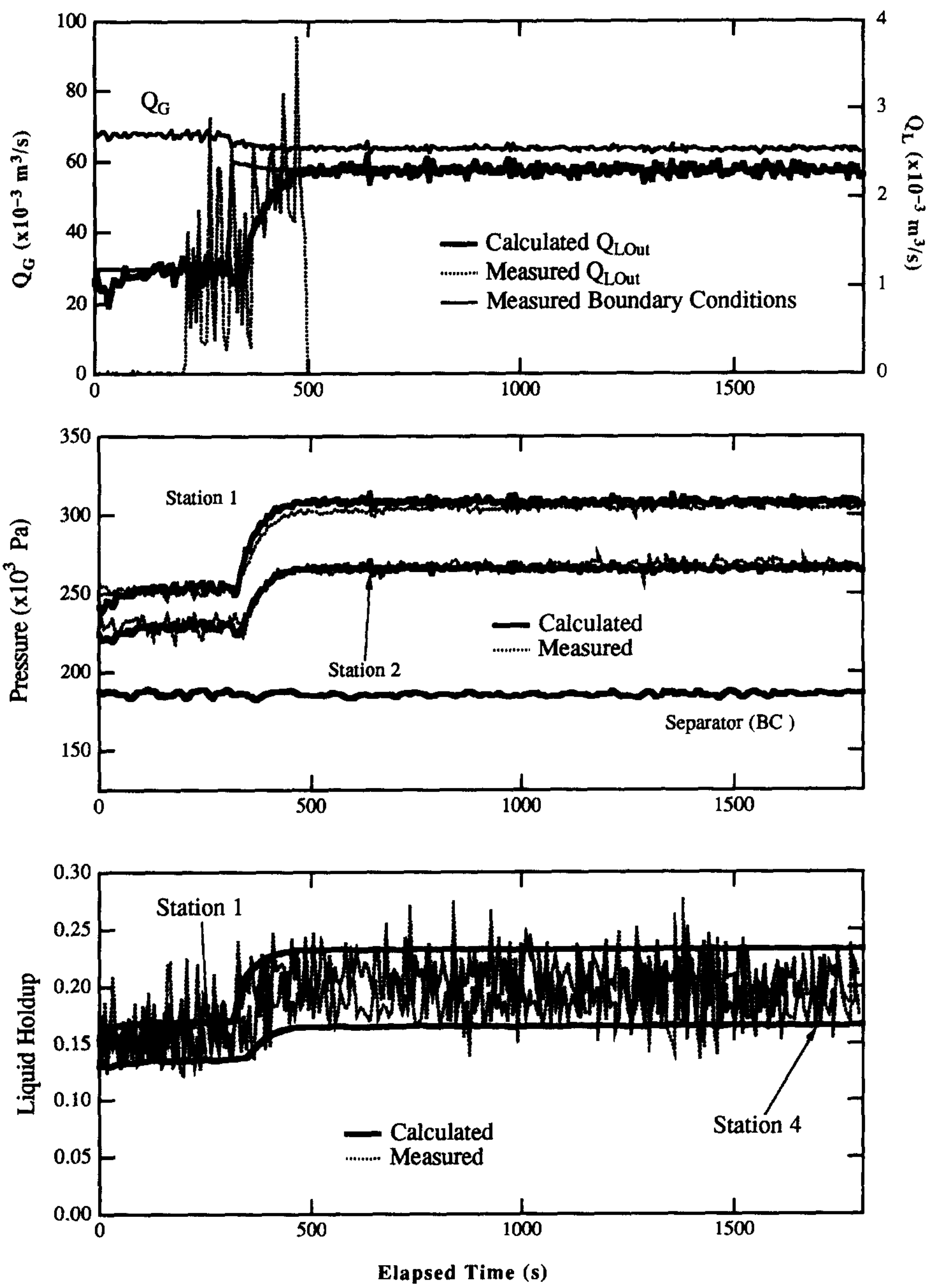

Figure 5. Comparison between predicted and measured transient flow behavior for run 19.

A response delay is observed in the outlet liquid flow rate. It stays at the initial condition level for a relatively long period of time and then increases gradually to the new steady-state level. This behavior is observed in both the experimental data and the prediction of the model. The simulated results match very well the pressure, liquid holdup and liquid flow rate measured data.

The analysis of the experimental data and simulated results indicates that a sudden change in liquid flow rate does not create any severe operational problems. All the changes occur slowly and predictably. The assumption of a quasi-steady state condition for the gas phase and the equilibrium momentum consideration seem to be totally acceptable for transient conditions induced by changes in liquid flow rate.

Case 3—liquid buildup

Liquid buildup transient flow conditions are encountered when a liquid phase is introduced into a pipeline initially flowing single-phase gas. For example, during a pigging operation of a wet-gas pipeline, the pig removes most of the liquid phase, leaving the line almost liquid free. The continuous feeding of a two-phase mixture causes a gradual liquid buildup, creating a liquid front that moves from the pipeline inlet to the pipeline exit. The initial condition for this case is given by a steady-state single-phase gas flow with an inlet gas flow rate, Q_G, of 0.064 m^3/s and separation pressure, P_{out}, of 185 MPa. The liquid flow is initiated at $t = 275$ s at 0.0018 m^3/s. The applied flow rate boundary conditions, and the observed and simulated results are reported in figure 6.

The liquid buildup process takes a relatively long time. The liquid front only reaches the pipeline exit more than 200 s after the initiation of liquid flow at the inlet. During the transient period, the pressure drop gradually increases as the liquid phase builds up and the liquid front advances. The advance of the liquid front can be clearly seen in the liquid holdup plot in figure 6. The front first arrives at measurement station 1 and sequentially passes through the other stations. It is interesting to note that just behind the liquid front, a slug flow pattern is present as shown by the oscillating liquid holdup measurement. The final steady-state condition is achieved shortly after the liquid front arrives at the pipeline exit.

Figure 6 shows that the simplified transient model once again performed very well in comparison with the experimental data. Near perfect matches exist for the pressure drop and for the liquid holdup. The time period for the liquid front to arrive at the pipeline exit is also simulated very accurately. This observation indicates that the simplified transient model is a well suited model to be used in pigging analysis.

Case 4—liquid blow down

Liquid blow down occurs when single-phase gas is fed into a pipeline with some liquid present initially. The parameters of interest are how fast the liquid is removed from the line, and the distribution of the pressure and liquid holdup during this process. For this case the initial condition is a steady-state two-phase flow condition, and the transient feature is introduced by suddenly interrupting the liquid flow input at the pipeline inlet. The initial steady-state condition is defined by $Q_G = 0.079$ m^3/s, $Q_L = 0.00147$ m^3/s and $P_{out} = 188$ MPa. Slug flow is observed for this initial condition. The liquid blow down process was initiated at $t = 92.1$ s, at which time the liquid flow rate was discontinued, while the gas flow rate was kept constant.

Figure 7 presents a summary of the observed and simulated transient behavior for this run. Following the interruption of the liquid flow, a steep decrease in the pressure is observed in all measurement stations. The observed outlet liquid flow rate indicates that slug flow continues to exist for a reasonable period of time after the interruption of the flow. After some time this flow pattern switches to stratified flow and remains stratified throughout the test. The bottom graph of figure 7 shows that the measured liquid holdup at station 1 decreases very fast immediately following the shut down of the liquid flow, and decreases much slower afterwards. The same behavior is observed at station 4. The time period necessary to blow down the liquid phase is excessively large even for this relatively short test pipeline. Some liquid is still present at station 4, 25 min after interruption of the liquid flow at the pipeline inlet occurred.

The simulated pressure matches the experimental data quite well. However, the liquid holdup predictions are not as good. The simplified transient model predicts a very unusual liquid holdup variation with respect to time. At some time in the simulation, the calculated liquid holdup presents

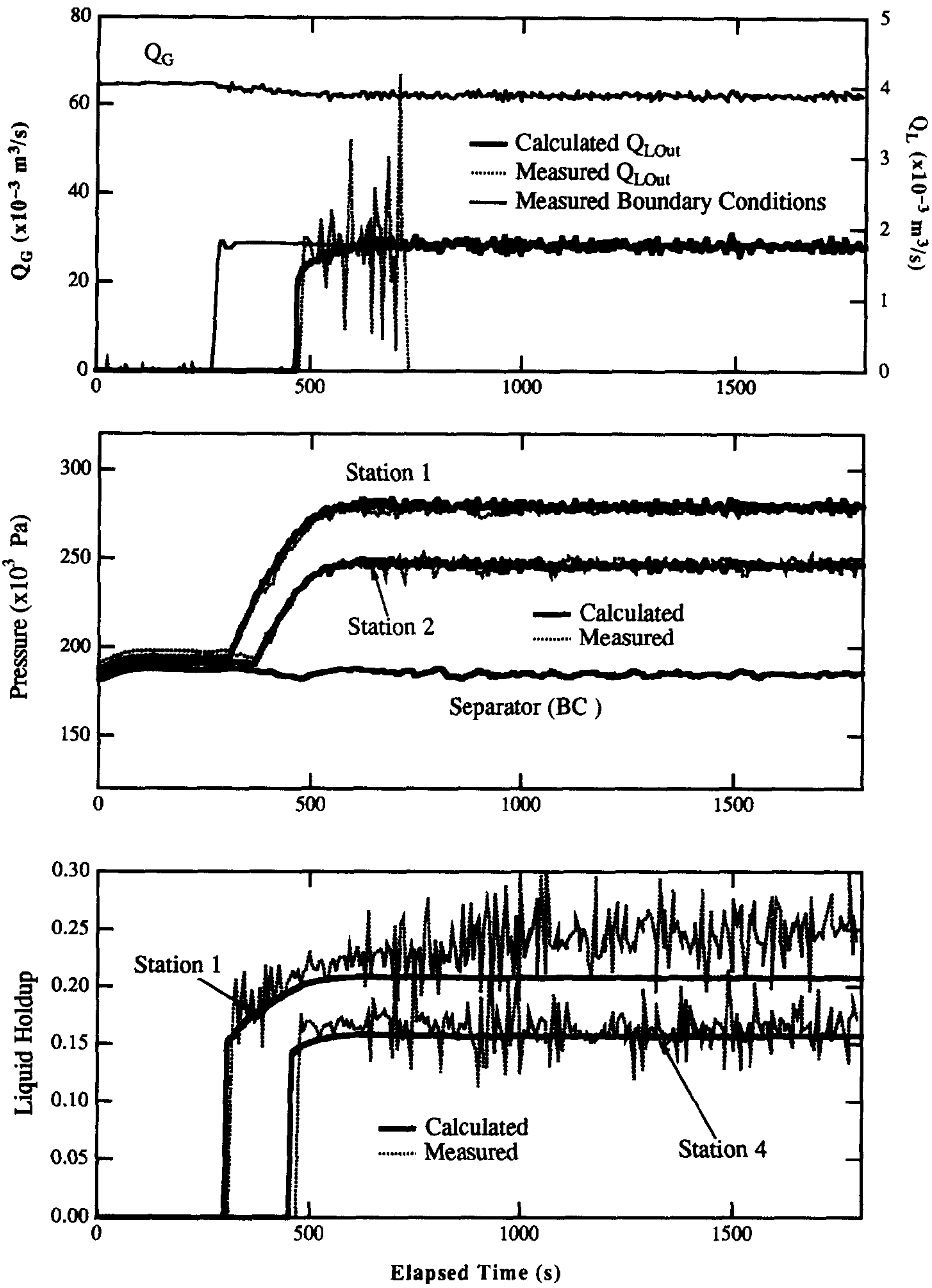

Figure 6. Comparison between predicted and measured transient flow behavior for run 18.

an abrupt change at both stations. A careful examination of the simulation output listing indicates that the step changes predicted in the liquid holdup curves always occur very near the slug to stratified flow pattern transition boundary. At this flow pattern boundary, the slug flow and the stratified flow models yield very different calculated liquid flow rates. This is clearly seen in the predicted liquid flow rate at the pipeline outlet. Once the flow pattern at the pipeline exit switches to stratified flow, the liquid flow rate is suddenly decreased. The discontinuous nature of these models causes this unusual behavior of the simulated results.

The liquid holdup graph of figure 7 also shows that the model fails to accurately predict the time necessary to remove the liquid phase from the pipeline. A residual liquid holdup of about 0.03 is left in the pipe even after a long time. Apparently, the liquid would never be removed completely. This indicates that, in the simulation, the liquid phase is barely moving after the liquid holdup

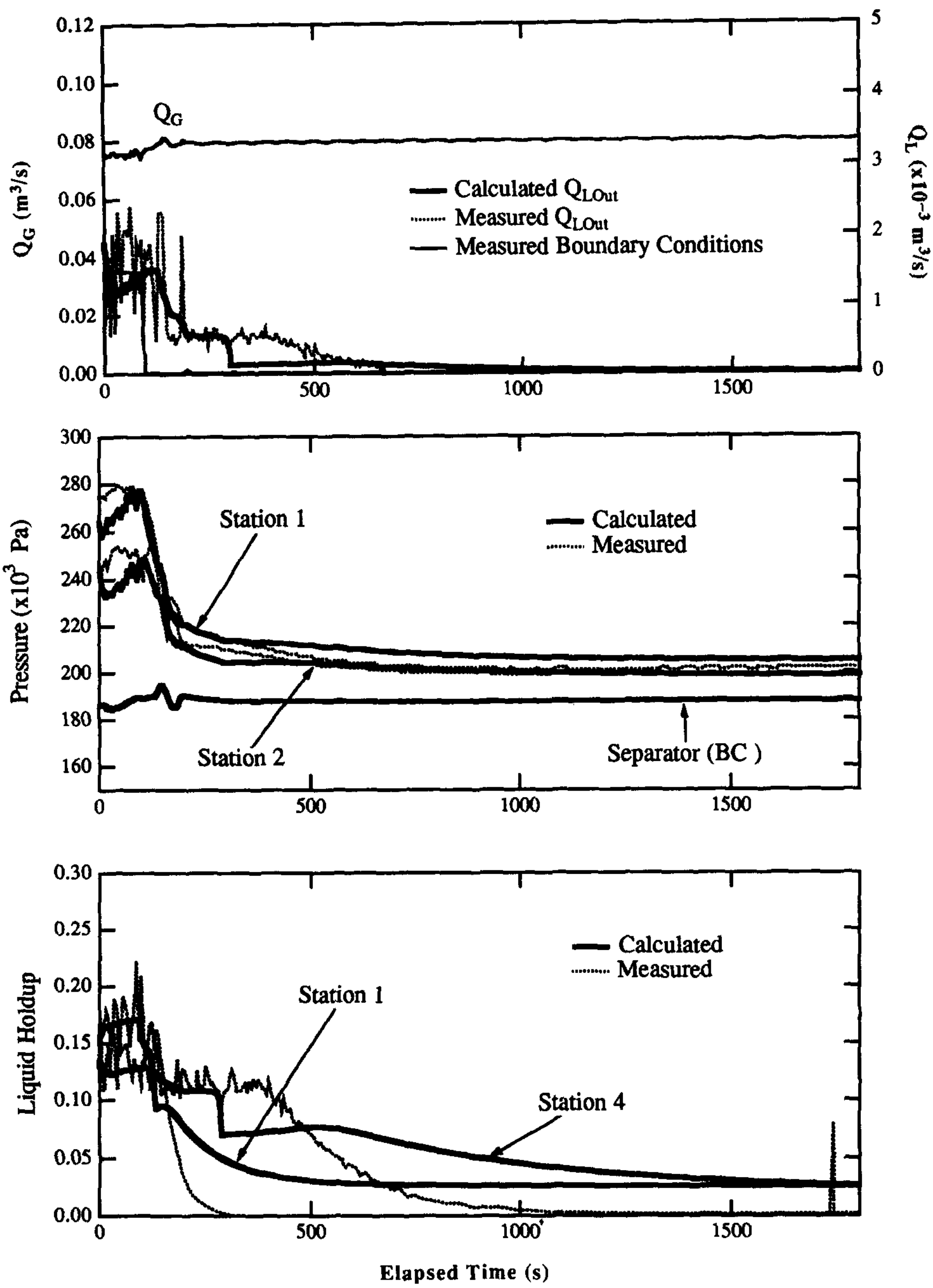

Figure 7. Comparison between predicted and measured transient flow behavior for run 8.

reaches this low value. It can be concluded that the stratified flow model used in the simulator predicts low liquid velocities under low liquid holdup conditions. Improvement of the stratified flow model for these flow conditions is thus needed.

SUMMARY AND CONCLUSIONS

An extensive experimental program has been carried out to acquire two-phase transient flow data on a 420 m long, 77.9 mm dia horizontal pipeline, using kerosene–air mixtures. The data include time variation of pressure, *in situ* liquid holdup, translational velocity and flow pattern along the pipeline.

The simplified transient model developed by Taitel *et al.* (1988) has been improved by developing a new flow pattern transition criteria suitable for transient two-phase flow, based on the stability of slug flow structure. The numerical solution scheme has also been improved by using a semi-implicit scheme instead of an explicit scheme.

The simulated results using the modified simplified transient model matched the experimental data very well for most of the transient conditions of the test runs. The assumption of a quasi-steady-state condition for the gas phase results in slightly higher pipeline pressure drop whenever an increase in gas flow rate is applied at the pipeline inlet. For the case of a change in liquid flow rate at the pipeline inlet, this assumption was not found to cause any deficiency. Unsatisfactory predictions of the modified simplified transient model occurred only for the liquid blow down tests where the flowing conditions were very close to the slug to stratified flow pattern transition boundary.

The observed and theoretically predicted transient flow behavior indicate that, for the transient induced by a fast inlet gas flow rate increase, a high pressure drop and a temporary intense slugging should be expected. A change in liquid flow rate was found to induce a slow and predictable transient behavior which does not cause any major pipeline operational problem.

The simplified transient approach, assuming a quasi-steady-state condition for the gas phase and equilibrium momentum considerations, is not suited for analyzing transient phenomena where the gas accumulation term becomes important. Pipeline rupture is one example of where the simplified transient approach will certainly be unsuitable.

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