Engineering Journal of Qatar University, Vol. 5, 1992, p. 11 - 21

UNSTEADY STATE TWO PHASE FLOW PRESSURE DROP CALCULATIONS

Shahaboddin Ayatollahi*, Mahmood Moshfeghian* and Robert N. Maddox**
*Department of Chemical Engineering, Shiraz University, Shiraz, Iran.
**School of Chemical Engineering, Oklahoma State University, Stillwater, Oklahoma, U.S.A.

(First Received April 1992; accepted in revised form October 1992)

ABSTRACT

A method is presented to calculate unsteady state two phase flow in a gas-liquid line based on a quasi-steady state approach. A computer program for numerical solution of this method was prepared. Results of calculations using the computer program are presented for several unsteady state two phase flow systems.

NOMENCLATURE

Δt	: time step	hour
Δx	: segment length	mile
L	: flow rate	lb mole/hr
L/F	: liquid fraction	mole basis
P	: pressure	psia
Q	: flow rate	million standard cubic feet per day
T	: temperature	°F
V	: vapor flow rate	lb mole/hr

SUBSCRIPTS

in : inlet
out : outlet
1 : inlet of segment
2 : outlet of segment

INTRODUCTION

Simultaneous flow of vapor and liquid through the same line presents an interesting problem. Because of its importance and complexity, there have been many studies reported on vapor-liquid two phase flow. More than thirty different correlations (3) for predicting the pressure drop and flow characteristics in two phase flow are available in the literature.

Unsteady state two phase flow frequently occurs in real systems. It can be found in different operations circumstances such as start up, failure of pump stations and variation of flow at downstream terminals. Calculations of unsteady state two phase flow pressure drop is an important factor in design and optimization of two phase flow transmission lines.

Multicomponent hydrocarbon mixtures are systems that can involve complex thermodynamic vapor-liquid equilibrium behavior. Whether a system is in a single or two phase region at a given set of conditions is important from the standpoint of properly calculating the physical properties, thermodynamic properties and equilibrium phase compositions. All of these properties are important in estimating the two-phase flow pressure drop. Use of an equation of state is required to reliably predict the phase behavior and properties for any multicomponent hydrocarbon system.

One way to study unsteady state two phase flow is to solve the equations of change for the system using the method of characteristics. This technique has been widely employed to analyze single phase gas or liquid lines. Limitations of the characteristics method include simplifying assumptions such as isothermal operation, constant friction factor and a horizontal line. These assumptions can result in doubtful results from calculations by the characteristics method even for single phase lines (1). The quasi-steady state method, using steady state equations for prediction of conditions during transient flow, can be used for multicomponent two phase systems and does not require any of the simplifying assumptions that must be made to use the method of characteristics. The quasi-steady state method was first presented by Zhou, Erbar and Maddox who successfully used it to analyze the unsteady state behavior of single phase dry gas transmission lines (2).

This paper presents a quasi-steady state algorithm for two phase flow calculations. It also pressents the results obtained for several example problems by a computer program prepared to carry out unsteady state two phase flow calculations. Steady state calculations were performed by use of a computer package developed by Akashah, Erbar and Maddox (3, 4) and specially modified for computations following the quasi-steady state approach. Thermodynamic properties were calculated by a revised version of the Soave-Redlich-Kwong (4, 5) equation of state, and two phase flow pressure drop calculations were made by a modified version of the procedure presented by Lockhard and Martinelli (6). Any other suitable equation of state and/or two phase flow pressure drop calculation methods could have been used. The Jossi, Stiel and Thodos (7) correlation as presented by Reid, Prausnitz and Poling (8) was used for calculation of viscosity, and the surface tension was determined from the modification of the method of Weinaug and Katz (9) presented in the Gas Processors Suppliers Association Engineering Data Book (10).

The calculation of unsteady state two phase flow pressure drop using the quasi-steady approach is a multi-step procedure. The details of the calculation are given by Ayatollahi (11). The steps in the calculation can be summarized as follows:

1. The pipeline, as shown in top sketch in Fig. 1, is divided into a number of segments of equal length, Δx. The lower sketch shows the segment of length Δx and the required input/output conditions.

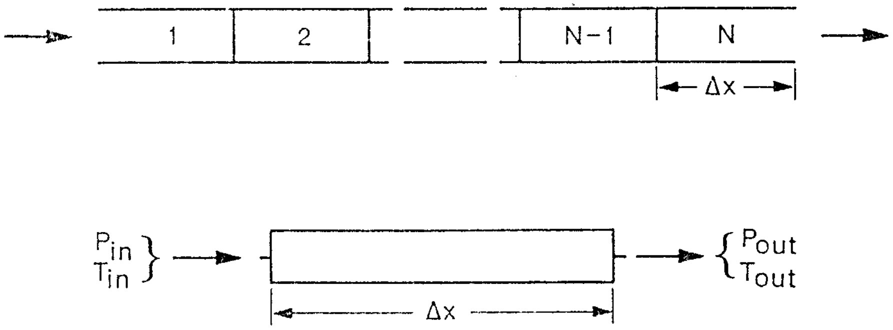

Fig. 1: Segment of Length Δx and Required Input/Output Conditions for Quasi Steady State Two Phase Flow Calculation.

2. A time step, Δt, is chosen. The time step should be much smaller than the anticipated length of time required for the pipeline to reach the new steady state operating condition ($\approx$ 1/100).
3. The pressure, velocity and temperature profiles of the transmission line are calculated under the initial steady state condition based on the Lockhart-Martinelli pressure drop correlation and the Soave-Redlich-Kwong equation of state.
4. The unsteady state condition is initiated by specifying a new constant value for the output pressure.
5. The new output flow rate (Q_2) for the final segment (N) is claculated based on the new pressure drop for the segment.
6. The output temperature is calculated by an energy balance on segment N.
7. The molar flow rate of each phase (L_1, V_1, L_2,V_2) is calculated by performing a flash calculation at the entrance and exit of the segment knowing the pressure and temperature at these two points.

8. The liquid mole fraction in the segment is calculated by mass balance.

$$L_{accumulation} = (L_1 - L_2)\ \Delta t \tag{1}$$

$$V_{accumulation} = (V_1 - V_2) \tag{2}$$

$$L/F = \frac{(L_{holdup} - L_{accumulation})}{[(L_{holdup} - L_{accumulation}) + (V_{holdup} - V_{accumulation})]} \tag{3}$$

9. Using the average temperature and liquid mole fraction in the segment, the average pressure of the segment can be found by a flash calculation. This average pressure (P_{avg}) yields the new input pressure of segment (P_1).

   $$P_1 = 2(P_{avg}) - P_2 \tag{4}$$

   This new input pressure to the segment is equal to the exit pressure of segment N-1.

10. Having the new exit pressure at the end of the next to the last segment, this procedure is continued for other segments until the entrance of the line is reached.

11. A time step, Δt, is added and the above unsteady state calculations procedure is repeated until the specified time limit is reached.

A simplified flow chart of calculations following the above procedure is presented in Fig. 2.

A computer program was written based on the above steps and several unsteady state two phase flow (liquid-vapor) examples were calculated using this program.

RESULTS

To test the capability of the proposed procedure, four unsteady state two phase flow examples were calculated. In each example, steady state under a specified set of parameters was established by calculations using the method of Lockhart and Martinelli. Unsteady state was imposed by suddenly changing the down stream pressure of the transmission line. The resulting pressure and temperature histories of the line were calculated using the proposed procedure.

The pipe line specifications and flow conditions for the four examples are presented in Table 1. Table 2 presents the compositions of the feed for the four examples.

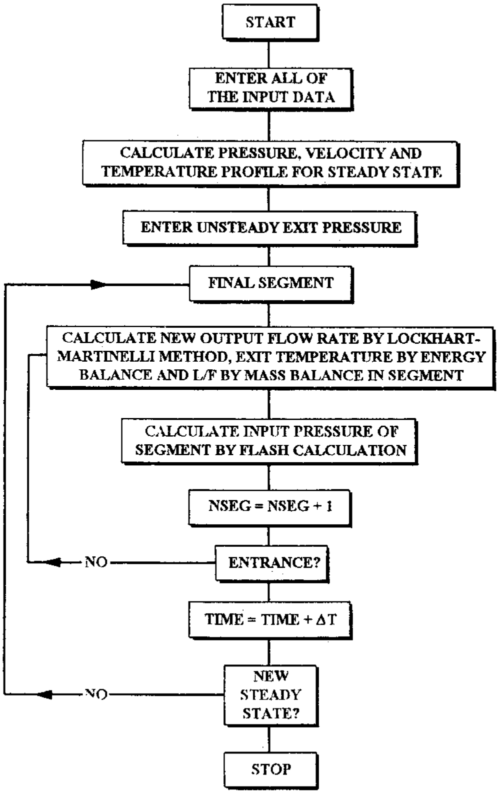

Fig. 2: Computer Flow Chart for Quasi-Steady State Calculation.

Table 1

Pipeline Specifications and Flow Conditions for the Three Gas Compositions Studied

Quantity/Composition	Number I	Number II	Number III
Diameter, inches	15.0	2.99	8.0
Length, miles	30.0	8.0	30.0
Inlet pressure, psia	1600.0	1500.0	1600.0
Outlet pressure, psia	854.0	1091.0	319.0
Flow rate, MMSCFD	100.0	1.6	15.0
Unsteady outlet pressure, psia	950.0	1000.0	600.0
Inlet temperature, °F	140.0	250.0	275.0

Example No. 1

A two phase fluid binary mixture (Mixture 1) consisting of 75 mole percent methane and 25 mole percent n-nonane, at a flow rate of 100 MMSCFD is flowing through a transmission line 15 inches in diameter and 30 miles long. The upstream pressure is 1600 psia and the outlet pressure at steady state is calculated by the Lackhart Martinelli method to be 854 psia.

The outlet pressure was changed suddenly to 950 psia and the computer program was used to calculate line pressure at different time intervals. Fig. 3 shows the calculated pressure profiles at steady state operation (time = 0), 0.1 hours after the upset and after 0.2 hours when the effect of the new discharge pressure has essentially been propagated through the line.

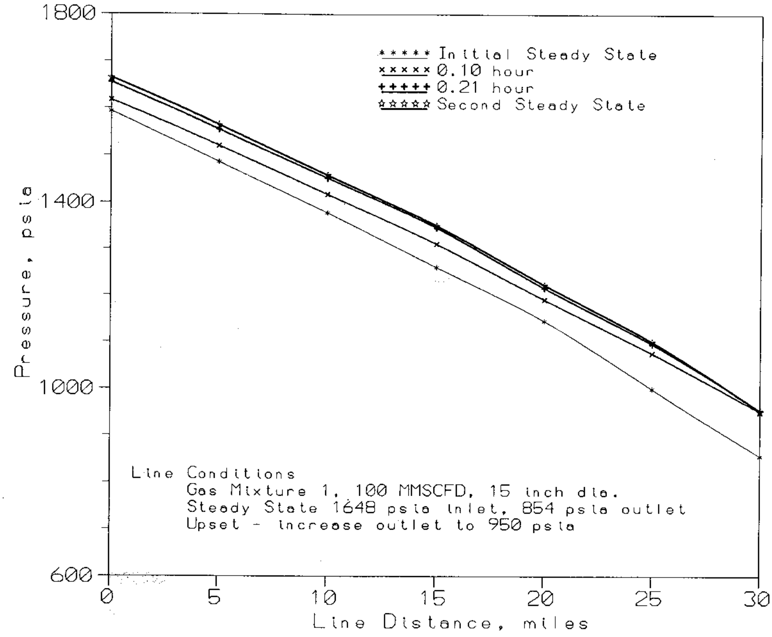

Fig. 3: Calculated Pressure for Example 1.

For comparison purposes, steady state conditions at the new discharge pressure were calculated. As can be seen, the 0.21 hour line is very near to the final steady state conditions for the line. The line pressure profile at the end of the transient period, calculated using the steady state Lockhart-Martinelli procedure based on the new inlet pressure estimated by the unsteady state procedure, shows that the quasi-steady state calculation reproduces the steady state calculation in the limit (time = ∞).

Example No. 2

Mixture 2 in Table 2 is transmitted at a flow rate of 1.58 MMSCFD through a 2.99-inch diameter line with a length of 8 miles. The inlet pressure of 1500 psia and the outlet pressure of 1091 psia are at initial steady state conditions. For unsteady state operation the outlet pressure was decreased to 1000 psia and the calculated pressure history was calculated and is shown in Fig. 4. The outlet pressure change is reflected back toward the entrance at a slow rate because of the relatively low velocity of flow in this example.

Table 2
Compositions for the Three Gases Studied.

Component/Gas	Number I	Number II	Number III
Methane	0.750	0.401	0.301
Ethane	0.000	0.265	0.265
Propane	0.000	0.002	0.002
n-Nonane	0.250	0.000	0.000
n-Heptadecane	0.000	0.332	0.432

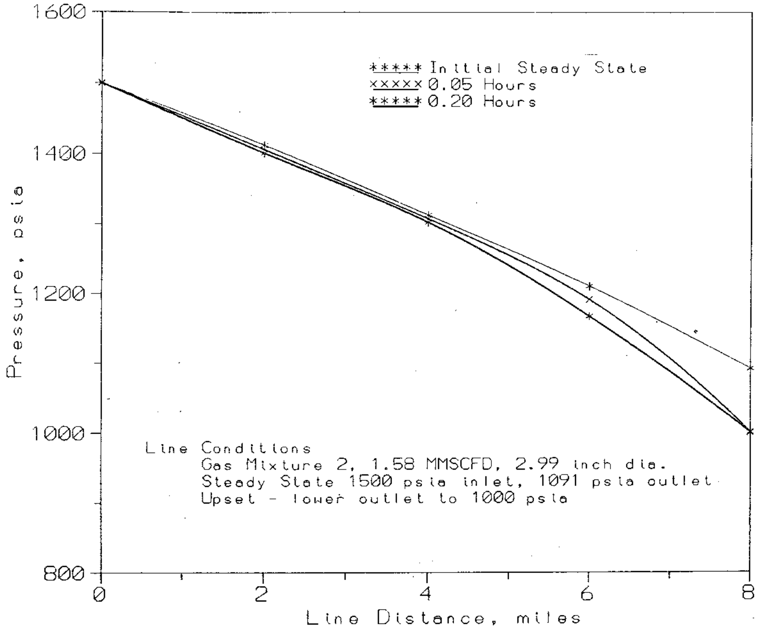

Fig. 4: Calculated Pressure for Example 2.

Example No. 3

Mixture 3 is a multicomponent system transmitted through an 8 inch diameter 30 mile long line at the rate of 15 MMSCFD. Inlet conditions were 1600 psia and 275°F, and the discharge pressure at steady state conditions was 319 psia. The output pressure was suddenly increased to 600 psia to initiate the unsteady state calculation. The pressure history of this line is shown in Fig. 5.

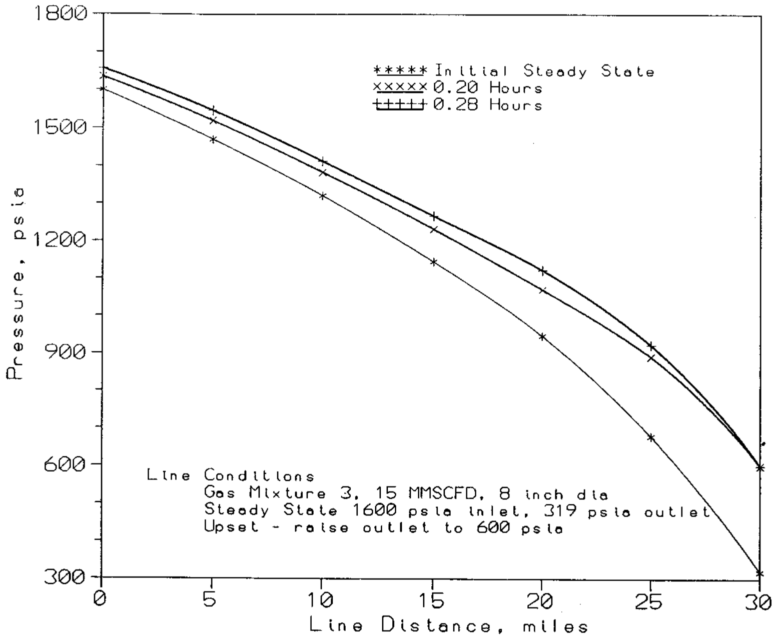

Fig. 5: Calculated Pressure for Example 3.

In two phase flow pressure drop calculations, the relative quantities of vapor and liquid in the mixture at any point in the line are very important. In most two phase flow calculation procedures this parameter is difficult to determine. Using an equation of state, however, the quantities of vapor and liquid can readily be calculated by flashing the mixture at the conditions existing at any point in the line. The profile of the amount of liquid flowing in the system was calculated for Example 1 and is plotted in Fig. 6. Under normal conditions increasing the pressure of the line causes an increase in the amount of liquid relative to the amount of vapor in two phase flow systems.

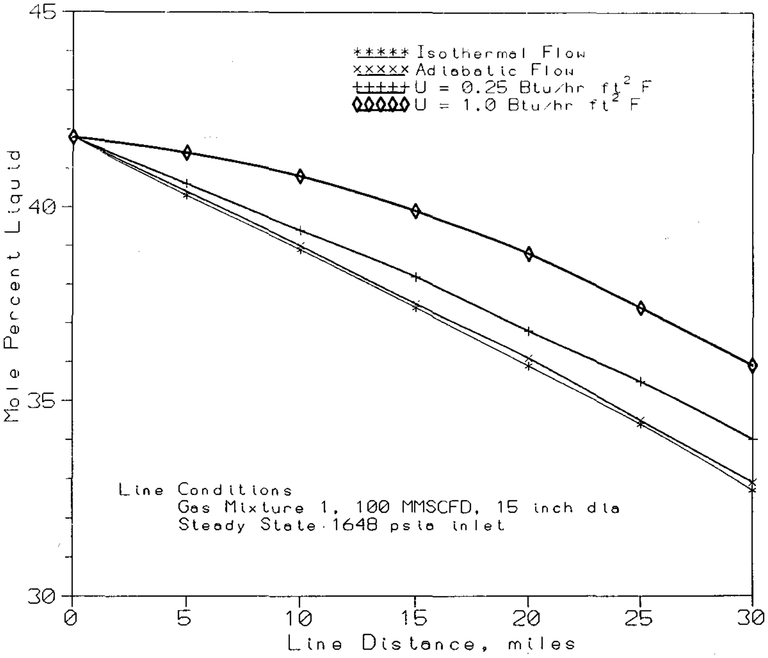

Fig. 6: Calculated Liquid for Example 4.

Example No. 4

Incorporating an equation of state in the calculation of two phase pressure drop offers the program user many advantages. Most two phase pressure drop correlations assume isothermal flow for the fluid mixture (this is also true for single phase pressure drop). Using thermodynamic properties from the equation of state allows for considering Joule-Thomson exapansion and even for heat transfer between the line and the surrounding environment.

To show the affect of heat transfer on the results, Example 1 was run using different sets of parameters to simulate different line flowing conditions. The ratio of liquid to total stream flow was calculated at the inlet and outlet of each line segment for each condition. The first case assumed flow was isothermal at a temperature of 140°F for the entire line. The second case assumed adiabatic flow. Cooling of the two phase mixture occurred because of Joule-Thomson expansion. Under adiabatic flow, the mixture cooled to 133°F. The third case assumed surroundings to the line at a constant 60°F and utilized a constant heat transfer coefficient of 0.25 (Btu/hr•ft²•°F) for the entire length of the line. This made the outlet temperature of the line 105°F. The fourth and last case also used surroundings at 60°F, but used a heat transfer coefficient of 1.0 (Btu/hr•ft^2•°F) for the entire line. This made the discharge temperature from the line 60°F. The liquid to total stream ratios on a molar basis for each case are plotted in Fig. 6.

As the liquid ratio in the line changes, the pressure drop for the two phase mixture must change. This makes duplications of runs with adiabatic flow impossible for a non-adiabatic case. In the cases shown in Fig. 6 the upstream pressure, inlet temperature, flow rate, and composition were the same for all runs. Line pressure drop and discharge temperature varied.

For isothermal flow, the liquid ratio is lowest through the entire length of the line and the discharge pressure is 850 psia. With adiabatic flow the discharge from the line is at 854 psia and the line discharge temperature is 134°F. There is very little difference in the liquid ratios and pressure drops for these two cases.

A heat transfer coefficient of 0.25 causes the two phase mixture to cool to 105°F and the increased liquid increases the discharge pressure to 876 psia. A high heat transfer coefficient of 1.0 lowers the discharge temperature to 60°F and raises the discharge pressure to 917 psia. The influence of increased liquid and lower temperature on pressure drop through decreased linear flow velocity is clearly evident.

The total mass flow rate through the lines can be determined from the compositions and flow rates given in Table 2. Changes in pressure and temperature along the line will change the relative amounts of vapor and liquid in the flowing stream. These changes are reflected in changes in pressure drop per unit of length along the lines.

CONCLUSION

The quasi-steady state method has been employed to analyze unsteady state two phase flow behavior in long lines. With the help of this computer package the pressure profile, temperature profile, and liquid hold up of the line at different time intervals can be claculated. The Soave-Reclich-Kwong equation of state and the Lockhart-Martinelli two phase pressure drop correlation have been used for the calculations reported here.

However, the proposed procedure could employ any one of the many existing two phase flow pressure drop correlations and a different equation of state. The accuracy of the calculations carried out by this method is strictly dependent on the equation of state used for thermodynamic properties and phase behavior prediction and the pressure drop correlation used.

REFERENCES

1. **Mouser, F., Munger, R.** and **Govier, P., 1972,** Compressibility Effect On Transient Gas Flow , Soc. of Pet. Eng., p. 315, Aug.

2. **Zhou, P., Erbar, J.H.** and **Maddox, R.N., 1983,** Analyzing Unsteady State Flow in Gas Pipelines , Oil & Gas J., p. 71, Aug. 15.

3. **Akashah, S.A., 1980,** Pressure Drop in Two-Phase Flow , Ph. D. Dissertation, Oklahoma State University, Stillwater, Oklahoma.

4. **Akashah, S.A., Maddox, R.N.** and **Erbar, J.H., 1982,** Proceedings of the 61st Annual GPA Convention, Dallas, Texas, p. 91-55, March.

5. **Soave, G., 1972,** Equilibrium Constants from the Modified Redlich-Kwong Equation of State, Chem. Eng. Sci., Vol. 27, No. 6, p. 1197.

6. **Lockhart, R.W.,** and **Martinelli, R.C., 1949,** Proposed Correlation for Isothermal Two-Phase, Two-Component Flow in Pipes , Chem. Engg. Prog., 45, p. 39-48.

7. **Jossi, J.A., Stiel, L.I.** and **Thodos, G., 1962,** A.I.Ch. E. Jour., 8, 59.

8. **Reid, R.C., Prausnitz, J.M.** and **Poling, B.E., 1987,** The Properties of Gases and Liquids, 4th Ed., McGraw-Hill Book Company.

9. **Weinaug, C.** and **Katz, D.L., 1943,** Surface Tension of Methane-Propane Mixtures , Ind. Eng. Chem., 35, p. 239.

10. **Gas Processors Suppliers Association, 1979,** Engineering Data Book, 9th Ed., Tulsa, Oklahoma.

11. **Ayatollahi, S., 1988,** Pressure Drop Calculation In Unsteady Two Phase Flow , M.S. Thesis, Shiraz University, Shiraz, Iran.