UNIFIED MECHANISTIC MODEL
OF MULTIPHASE FLOW IN PIPES AND WELLS

by

Jili Cao

A thesis submitted to the Faculty and Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirement for the degree of Master of Science (Petroleum Engineering).

Golden, Colorado

Date Nov. 10. 2005

Signed:

Jili Cao

Approved: John R Fanchi

Dr. John R. Fanchi

Thesis Advisor

Golden, Colorado

Date November 11, 2005

Craig W. Van Kirk

Dr. Craig W. Van Kirk

Professor and Head

Department of Petroleum Engineering

ABSTRACT

The primary purpose of this thesis is to improve models of multiphase flow in pipes and wells. An improved model will help operators design and manage wells. There are four objectives for this thesis.

The first objective is to develop a computer program that can be applied to various flow regimes, pipe inclination angles from 0° to 90°, different pipe diameters, and different pipe roughness. The computer program, called PAWS (pipe and well simulator), was developed using FORTRAN 90 and is a unified mechanistic model. The length interval for the pressure drop calculation is automatically determined.

The second objective is to use fuzzy mathematics to describe the uncertainty associated with the velocity distribution coefficient (C_0) for bubble flow. This feature lets users incorporate their knowledge of the variability of the distribution coefficient into a fuzzy analysis of pressure drop.

The third objective is to investigate the effect of the acceleration component in the pressure gradient equation.

The fourth objective is to formulate a new algorithm for identifying the upper boundary of liquid level in pipe. This helps determine the existence of stratified flow.

This thesis presents the formulation of the fluid flow model and describes the implementation of the formulation as a FORTRAN 90 program. Examples are used to validate the simulator and evaluate the effect of fuzzification, inclusion of the acceleration component, wellbore inclination, and pipe diameter. An objective function is defined and used to quantify the comparison of model results.

These examples support the following conclusions. First, the simulator presented in this thesis modeled fluid data more accurately than other models based on a comparison of objective function results. Second, the acceleration component can be neglected for stable flow, but should be included if the flow pattern is unstable or the flow rate is very high. Third, the fuzzification of the distribution coefficient has a significant impact on the pressure drop. Fourth, the well inclination angle significantly influences both pressure drop and flow patterns. Finally, pipe diameter plays a significant role in calculating pressure drop associated with multiphase flow in pipes and wells.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

I would like to thank my thesis advisor, Dr. John R. Fanchi, for the support and assistance he provided.

I would also like to thank my committee members, Dr. Richard L. Christiansen and Dr. Mark G. Miller, for their help. Thanks also need to be extended to the other professors in the Petroleum Engineering Department for teaching and helps in my study.

Special thanks go to my family and friends for their moral and financial support for my study.

Chapter 1

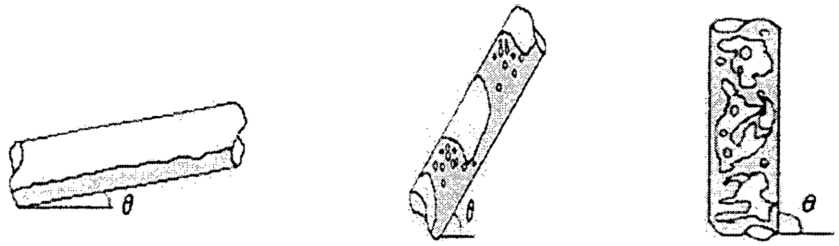
INTRODUCTION

Petroleum production and testing, chemical processing, refineries, and geothermal plants involve multiphase fluid flow of gas and liquid in wells and pipes. As Fanchi and Christiansen [2004] observed, more accurate models of multiphase flow are essential for more effective production and transport of fluids. Within the context of the petroleum industry, the three types of multiphase flow models most commonly used are empirical correlations, homogenous models, and mechanistic models. Earlier predictive techniques for two-phase flow were based on homogenous models and correlation methods. Among the three types of models, the homogenous flow model is the simplest of all. This model assumes that the fluids in the system are perfectly mixed together, flowing with no slip between the phases.

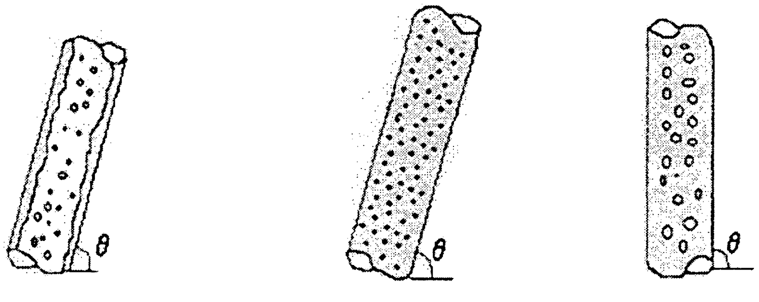
Empirical correlations are based on curve fitting of experimental data. Their applicability is generally limited to the range of variables explored in the experiments. These correlations can be either specific to a flow pattern or can be flow pattern independent. This approach cannot be applied to all types of flow geometry and patterns. Gomez, et al. [2000] concluded that empirical correlations were "very successful for solving two-phase flow problems for more than forty years with an updated performance of 30% errors. And it is believed that no further or better accuracy can be achieved through this approach."

Although the drift-flux model developed from the homogenous model and empirical correlations has the advantage of being continuous and differentiable, the drift-flux model is still restricted to specific cases explored in experiments. For example, the drift-flux model provided by Shi, et al. [2005] applies only to vertical bubble and slug flow.

Mechanistic models are, in general, the most accurate because they are built on detailed physics of each of the different flow patterns. The mechanistic model emerged in the early 1980's. This approach attempts to develop a model based on the physics of each flow pattern, which includes stratified flow, bubble flow, dispersed bubble flow, slug flow, churn flow, and annular flow. These flow patterns are shown schematically in Figure 1-1. There are two steps in this approach: first to determine the flow pattern for a given system, then to estimate the holdup and pressure drop by the corresponding model developed for the flow pattern. These models are expected to be more reliable and general as they incorporate the mechanisms and the important parameters of the flow. The mechanistic models developed over the past two decades have been formulated for vertical or sharply inclined wellbores, horizontal or nearly horizontal pipelines, and unified wellbores and pipelines.



Stratified Slug Churn



Annulur Dispersed Bubble Bubble

Figure 1-1. Flow Patterns for Horizontal to Vertical Flow (from Gomez, et al. [2000])

We present a brief review of the literature for three mechanistic models in Section 1.1 and justify the selection of the unified mechanistic model as the basis for the present study in Section 1.2. The modifications that are made to the mechanistic models in this work are outlined in Section 1.3. Section 1.4 summarizes the objectives of the thesis.

1.1 Literature Review

Three types of mechanistic models are reviewed in this section. They cover vertical or sharply inclined pipes, horizontal or nearly horizontal pipes, and unified models. The unified models apply to pipes that range from vertical to horizontal. The term "pipes" is used to mean flow conduits that comprise either pipelines or wells.

1.1.1 Vertical or Sharply Inclined Pipe Models

Vertical or sharply inclined pipe models apply primarily to flow in vertical or nearly vertical pipes. Taitel et al. [1980] proposed a flow pattern prediction model for vertical flow, and this model was extended to sharply inclined flow by Barnea et al. [1985], Ozon et al. [1987], Hasan and Kabir [1988], Ansari et al. [1994], and Chokshi et al. [1996] presented comprehensive mechanistic models for vertical flow. A number of specific models have been developed respectively for bubble flow, slug flow and annular flow.

1.1.2 Horizontal or Nearly Horizontal Pipe Models

Horizontal or nearly horizontal pipe models apply primarily to flow in horizontal or nearly horizontal pipes. In 1976, Taitel and Duckler [1976] presented a model for predicting flow patterns in pipelines. Xiao et al. [1990] and Petalas and Aziz [2000] proposed a comprehensive mechanistic model, which included flow pattern transition models and the models for the different flow patterns. Many investigators have also developed specific models for stratified, slug, annular, and dispersed bubble flows.

1.1.3 Unified Models

Unified models developed in recent years apply to the entire range of inclination angles from horizontal to vertical flow. Because they incorporate inclination angle, these models are more practical than others. In 1987, Barnea [1987] proposed a unified flow pattern prediction model. Petalas and Aziz [1996] presented a unified mechanistic model that was tested against a large set of laboratory and field data. Gomez, et al. [2000] presented a unified flow model for steady state, two-phase flow in pipes that covers inclination angles that range from horizontal to vertical.

1.2 Model Selection for the Present Study

The present study focuses on the development of a model of multiphase fluid flow in pipes that is based on unified mechanistic models because they cover the range of inclination angles from horizontal to vertical. In addition, the accuracy of unified mechanistic models has been commendable. Unified mechanistic models have predicted pressure loss "with -1.3% average error, 5.5% absolute average error, and 6.2 standard deviation" Gomez, et al. [2000]. Modifications to the unified mechanistic models that are made in this study are outlined below.

1.3 Modifications to Documented Unified Mechanistic Models

Although many kinds of mechanistic models have been developed for multiphase flow in pipes, no models can exactly describe observed multiphase flow. Even the recent unified mechanistic model proposed by Gomez, et al. [2000] has a 5.5% absolute average error. Both the uncertainty of multiphase flow and the neglect of the acceleration component in model formulation may be responsible for the error. These effects are examined in this study by making the following modifications to documented unified mechanistic models.

1.3.1 Uncertain Distribution Coefficient

All models require a number of flow parameters. One of the most important parameters is the profile parameter (or distribution coefficient), C_0, which describes the effect of the velocity and concentration profiles. This parameter plays a significant role in determining flow patterns, holdup, and pressure drop. Despite its importance, the distribution coefficient is not well known. Zuber and Findlay [1965] reported values for C_0 ranging from 1.0 to 1.5; Gomez, et al. [2000] proposed the value for C_0 of 1.16, while Shi, et al. [2005] use the value of 1.2 for bubble and slug flow and 1.0 in the annular mist regime in their drift-flux model. In addition, the distribution coefficient depends on pipe diameter. Zahradnik and Kastanek [1979] reported a C_0 value of 1.95 for a large diameter (>127 mm) bubble column. The uncertainty associated with the distribution coefficient is not included in existing pipe flow models.

The value for C_0 might change with pipe size, pipe direction, fluid properties, and environmental factors such as temperature and pressure. However, we do not know if the change in value for C_0 is abrupt or gradual with the above conditions. In this paper, fuzzy mathematics is used to quantify the uncertainty associated with C_0 and its influence on pressure loss.

1.3.2 Neglected Acceleration Component

In the unified mechanistic model, two-phase pipe flow models typically neglect the acceleration component, especially for slug, annular, and stratified flow. For example, Ansari, et al. [1994] and Gomez, et al. [2000] ignored the acceleration component in their models. The computer program developed in this thesis includes a model of the acceleration component and is used to assess the effect of neglecting the acceleration component on the accuracy of pipe flow results.

1.3.3 New Boundary for the Transition of Stratified to Non-Stratified Flow

In 1976, Taitel and Dukler [1976] proposed a complex criterion for the transition from stratified to non-stratified flow. To tell if the flow is stratified, we have to determine the liquid high level in the pipe. A boundary is needed to distinguish the transition from stratified flow to non-stratified flow. In Chapter 3, an upper boundary of the liquid high level for the existence of stratified flow is proposed.

1.4 Objectives of This Thesis

There are four objectives in this thesis. The first objective is to develop a unified mechanistic pipe flow model that is applicable to several flow regimes. The new code is designed to predict the flow patterns and pressure drop for various flow regimes, pipe inclination angles from 0° to 90°, different pipe diameters, and different pipe roughness. The code should overcome some limits of the original models that are used to predict pressure drop. Furthermore, the code should improve the accuracy of the calculated pressure change in the pipe. The code is called PAWS ("Pipe And Well Simulator") for ease of reference.

The second objective is to use fuzzy mathematics to describe the uncertainty of the distribution coefficient for bubble flow. The effect of the uncertainty is assessed in a realistic example.

The third goal is to investigate the effect of the acceleration component in pressure gradient equation.

The fourth goal is to formulate a new algorithm for identifying the upper boundary of liquid level in pipe and determining the existence of stratified flow.

Chapter 2

FUZZY MECHANISTIC MODEL FOR BUBBLE FLOW

A fuzzy model for the velocity distribution coefficient C_0 is introduced here. We begin by providing a brief introduction to the fuzzy mathematics used in this study. The distribution coefficient is fuzzified by triangular fuzzy set. Rules for predicting pressure loss using the fuzzy model are then presented.

2.1 Elementary Background

In this section, the fuzzy mathematics used to fuzzify the mechanistic model is introduced. A reference for fuzzy mathematics is provided by James et al. [2002]. Bubble and dispersed bubble mechanistic models are then described.

For ease of reference, "$\in$" means that one member belongs to a set. The term $\max\{x|x \in A\}$ denotes the maximum value of all members of set A, while $\min\{x|x \in A\}$ denotes the minimum value.

Fuzzy Set Definition

If Ω is some set, then a fuzzy set $\overline{A}$ of Ω is defined by its membership function, written as $\overline{A}(x)$, which produces values in the interval [0, 1] for all values of x in the set Ω.

Triangular Fuzzy Set

A triangular fuzzy number $\overline{A}$ is defined by three numbers a<b<c where the base of the triangular distribution is the interval [a, c] and its vertex is at x=b. The fuzzy set $\overline{A}$ is written as the triangular fuzzy number $\overline{A} = (a/b/c)$.

Alpha-Cuts

Alpha-cuts are slices through a fuzzy set producing regular (non-fuzzy) sets. If $\overline{A}$ is a fuzzy set of some set Ω, then the alpha-cut of $\overline{A}$, written as $\overline{A}[\alpha]$, is defined as

$$\overline{A}[\alpha] = \{x \in \Omega | \overline{A}(x) \geq \alpha\} \tag{2.1}$$

for all values of α in the range $0 \leq \alpha \leq 1$.

Alpha-Cuts of a Triangular Fuzzy Number

Based on the definition of a triangular fuzzy number and alpha-cut, if $\overline{A} = (a/b/c)$, then the alpha-cut is represented by

$$\overline{A}[\alpha] = [a + \alpha(b - a), c - \alpha(c - b)] \tag{2.2}$$

Relationship between a Fuzzy Set and Alpha-Cuts

The fuzzy set $\overline{A}(x)$ is related to the alpha-cut by

$$\overline{A}(x) = \max_{0 \leq \alpha \leq 1} \{\alpha | x \in \overline{A}(\alpha)\} \tag{2.3}$$

Fuzzy Function

A fuzzy function is a mapping from fuzzy numbers $\overline{X}$ into fuzzy numbers $\overline{Z}$, thus

$$G(\overline{X}) = \overline{Z} \tag{2.4}$$

where G is the mapping.

Extension Principle of the Fuzzy Function $G(\overline{X}) = \overline{Z}$

Any mapping $G : [a,b] \rightarrow R$ may be extended to $G(\overline{X}) = \overline{Z}$ by the relationship

$$\overline{Z}(z) = \max\{\overline{X}(x) | G(x) = z, a \leq x \leq b\}, \tag{2.5}$$

Equation (2.5) defines the membership function of Z for any triangular fuzzy number $\overline{X}$ on the base of [a, b].

Alpha-cuts of the Fuzzy Function $G(\overline{X}) = \overline{Z}$

If G(x) is a continuous function, then the interval for the function Z in terms of alpha-cuts is $Z[\alpha]=[z_1(\alpha), z_2(\alpha)]$ where

$$z_1(\alpha) = \min\{G(x) | x \in X(\alpha)\} \tag{2.6}$$

and

$$z_2(\alpha) = \max\{G(x) | x \in X(\alpha)\} \tag{2.7}$$

for $0 \le \alpha \le 1$.

2.2 Fuzzy Model for Bubble Flow

The distribution coefficient for bubble flow is an uncertain value that is modeled here as a fuzzy number. The fuzzy model for the distribution coefficient is developed as a relationship between the distribution coefficient and the pressure loss. Then, based on the literature and experimental data, a fuzzy set of the distribution coefficient is proposed to describe its uncertain characteristics. Finally, a fuzzy model for bubble flow for predicting the pressure loss is provided through the fuzzy function and extension principle.

2.2.1 Regular Relationship of Pressure Loss with Distribution Coefficient

The regular (non-fuzzy) model relating distribution coefficient and pressure loss is introduced before presenting the fuzzy model for bubble flow. We begin by considering the pressure gradient model given by Harmathy [1960], namely

$$\frac{dp}{dL} = g\rho_M \sin\theta + \frac{f_m {v_M}^2 \rho_M}{2d} + \rho_M v_M \frac{dv_M}{dL} \tag{2.9}$$

where the first term is the potential energy term for gravity, the second term is the friction term for the friction factor f_m, and the third term is the kinetic energy term. Mixture properties are given by

$$\rho_M = H_L \rho_L + (1 - H_L)\rho_G \tag{2.10}$$

and

$$H_L = 1 - \frac{v_{SG}}{C_o v_M + v_\infty \sin\theta \sqrt{H_L}} \tag{2.11}$$

We can see the relationship between pressure loss and the velocity distribution coefficient C_0 using the above equations. From Eq. (2.11), the liquid holdup positively correlates with the distribution coefficient. Equation (2.10) shows that mixture density linearly increases with C_0, and Eq. (2.9) shows that the pressure loss also increases with the increase of mixture density. Combining these three ideas tells us that the pressure loss has a positive correlation with the distribution coefficient. This relationship can be presented by

$$P_{loss} = P_{loss}(C_0) \tag{2.12}$$

2.2.2 Fuzzifying the Distribution Coefficient, C_0

In this paper, the fuzzy number of C_0 is defined as a triangular (shaped) fuzzy number, namely, $\overline{C_0}$=(a/b/c). We can define a, b, and c with different conditions of inclination, fluid properties, pipe diameters, and environment. Based on the literature review, for a small diameter pipe, C_0 is fuzzified as $\overline{C_0}$=(1.1/1.2/2), namely, a=1.1, b=1.2, and c=2. The fuzzy set is shown in Figure 2-1. According to Eq. (2.2), alpha-cuts of $\overline{C_0}$ are

$$\overline{C_0}(\alpha) = [1.1 + 0.1\alpha, 2 - 0.8\alpha] \tag{2.13}$$

for $0 \le \alpha \le 1$.

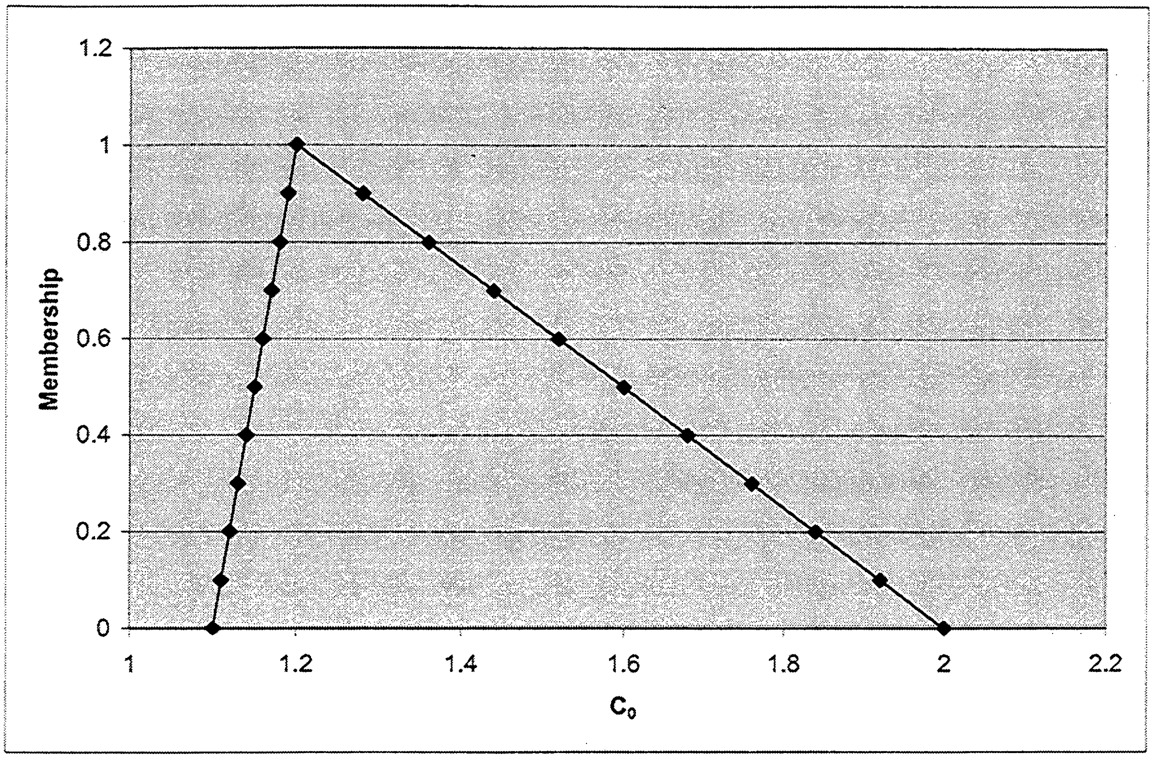


Figure 2-1. Triangular Membership Function for Fuzzified C_0

2.2.3 Fuzzy Model

Once a triangular membership function is specified for the distribution coefficient C_0, we can get a fuzzy pressure loss with Eq. (2.11). We need to construct the membership function for the fuzzy set of pressure loss. To provide a general model, the fuzzy set (a/b/c) is used for the distribution coefficient C_0. The membership function of pressure loss is

$$\overline{P_{loss}}(P_{loss}) = \left\{\overline{C_0}(c_0) \middle| P_{loss}(c_0) = P_{loss}, a \le c_0 \le c\right\}, \tag{2.14}$$

2.2.3.1 Alpha-cuts of $\overline{P_{loss}}$

It is difficult to solve engineering problems using Eq. (2.14) as it is a theoretical equation. To apply it to engineering and science, alpha-cuts of pressure loss should be given. Suppose alpha-cuts of $\overline{C_0}$ are $[c_{01}, c_{02}]$, then the alpha-cuts of $\overline{P_{loss}}$ are

$$\overline{P}_{loss}[\alpha] = [P_{loss}(c_{01}), P_{loss}(c_{02})] \tag{2.15}$$

for $0 \le \alpha \le 1$. Equation (2.15) is constructed as follows.

Suppose alpha-cuts of $\overline{P_{loss}}$ are $[P_{loss1}(\alpha), P_{loss2}(\alpha)]$. According to Eqs. (2.6) and (2.7),

$$P_{loss1}(\alpha) = \min\left\{P_{loss}(c_0) \middle| c_0 \in [c_{01}, c_{02}]\right\} \tag{2.16}$$

Because pressure loss monotonically increases with an increase in C_0, the following equation is obtained

$$\min\left\{P_{loss}(c_0) \middle| c_0 \in [c_{01}, c_{02}]\right\} = P_{loss}(c_{01}) \tag{2.17}$$

Equation (2.17) implies

$P_{loss1}(\alpha) = P_{loss}(c_{01})$

and

$P_{loss2}(\alpha) = P_{loss}(c_{02})$

which leads to Eq. (2.15).

The alpha-cuts of $\overline{C_0}$ are represented by a triangular membership function with the form $\overline{C_0} = [a + \alpha(b-a), c - \alpha(c-b)]$. The alpha-cuts of $\overline{P_{loss}}$ can be approximated by

$$\overline{P}_{loss}(\alpha) = [P_{loss}(a + \alpha(b-a)), P_{loss}(c - \alpha(c-b))] \tag{2.18}$$

for $0 \le \alpha \le 1$. In this thesis, C₀=(1.1/1.2/2) and the alpha-cuts of $\overline{P_{loss}}$ can be written as

$$\overline{P}_{loss}(\alpha) = [P_{loss}(1.1 + 0.1\alpha), P_{loss}(2 - 0.8\alpha)], \tag{2.19}$$

for $0 \le \alpha \le 1$.

2.2.3.2 Membership Function of $\overline{P_{loss}}$

The solution of a fuzzy problem can be obtained by manipulating fuzzy sets using regular mathematics so that they can be solved with regular mathematical tools. A fuzzy set can be expressed by regular mathematics through alpha-cuts since alpha-cuts are regular (non-fuzzy) sets.

Based on Eq. (2.8), $\overline{P_{loss}}$ can be given by

$$\overline{P}_{loss}(p_{loss}) = \max_{\alpha}\{\alpha | p_{loss} \in [P_{loss}(a + \alpha(b-a)), P_{loss}(c - \alpha(c-b))]\} \tag{2.20}$$

Equation (2.20) lets us use established mathematical tools to solve fuzzy problems. The membership function for pressure loss is obtained by using a series of alpha values in the range from 0 to 1 to derive a corresponding series of membership values of pressure loss. With the help of a computer, a fuzzy membership function is obtained using fitting method. An example of membership functions is shown in Chapter 6.

Chapter 3

THE UPPER BOUNDARY OF LIQUID LEVEL FOR STRATIFIED FLOW

Using the mechanistic model, it is difficult to determine the transition from stratified flow to non-stratified flow, especially for inclined pipe. One common method (Taitel and Dukler [1976]) is to use the liquid high level in pipe to distinguish between stratified and non-stratified flow. However, the solution of the high liquid level involves an equation with multiple solutions, and the Newton-Raphson method cannot be used because the equation does not have derivative with respect to liquid level. To find the high liquid level, it is helpful to define a boundary for the transition from stratified flow to non-stratified flow. In this chapter we propose an upper boundary of high liquid level in pipe for the stratified flow.

3.1 An Upper Boundary of Liquid High Level in Pipes

This boundary is derived from the transition criteria, proposed by Taitel and Dukler [1976] for stratified to non-stratified flow. The upper boundary of liquid level in a pipe is

$$H_B = d\left\{1-\left(\frac{q}{2}\right)^{\frac{1}{3}}\left[\sqrt[3]{1+\sqrt{1+\frac{4q}{27}}}+\sqrt[3]{1-\sqrt{1+\frac{4q}{27}}}\right]\right\} \tag{3.1}$$

where

$$q=\frac{4v_{SG}\rho_G}{\pi dg\cos\theta(\rho_L-\rho_G)} \tag{3.2}$$

Equation (3.1) is derived as follows.

Step 1. The equation for the transition between stratified and non-stratified flow is found as follows.

Flow is stratified when the following condition holds [Taitel and Dukler, 1976]:

$$v_G \leq \left(1-\frac{h}{d}\right)\left[\frac{g\cos\theta(\rho_L-\rho_G)A_G}{\rho_G(dA_L/dh)}\right]^{0.5} \tag{3.3}$$

where

$$v_G = \frac{v_{SG}A}{A_G} \tag{3.4}$$

and

$$dA_L/dh = d\sqrt{\frac{h}{d}\left(1-\frac{h}{d}\right)} \tag{3.5}$$

Step 2. Simplify Eq. (3.3) by letting

$$a = \frac{g\cos\theta(\rho_L-\rho_G)}{d\rho_G} \tag{3.6}$$

$$x = 1-\frac{h}{d} \text{ and } 0 < x < 1$$

Combining Eqs. (3.1) through (3.5) gives

$$\frac{v_{SG}A^3}{A_G{}^3aA} \leq \frac{x^2}{\sqrt{x(1-x)}} \tag{3.7}$$

Since $A \geq A_G$, Eq. (3.7) can be changed into

$$\frac{v_{SG}}{aA} \leq \frac{x^2}{\sqrt{x(1-x)}} \tag{3.8}$$

Step 3. The mathematical support for the upper boundary follows. The derivative of the right hand side of Eq. (3.8) with respect to x is

$$\frac{d\left(\frac{x^2}{\sqrt{x(1-x)}}\right)}{dx} = \frac{x(3-2x)}{2(1-x)\sqrt{x(1-x)}} \geq 0 \tag{3.9}$$

for $0 < x < 1$. Suppose $q = \left(\frac{v_{SG}}{aA} \right)^2$, and change Eq. (3.9) into the following equation to find the upper boundary.

$$x^3 + qx - q = 0 \tag{3.10}$$

Based on Cardan theorem, there is only one real root for Eq. (3.10), and it is

$$x_0 = \left(\frac{q}{2} \right)^{\frac{1}{3}} \left[\sqrt[3]{1 + \sqrt{1 + \frac{4q}{27}}} + \sqrt[3]{1 - \sqrt{1 + \frac{4q}{27}}} \right] \tag{3.11}$$

Step 4. Constructing the upper boundary

Equation (3.9) implies that the right hand side of Eq. (3.7) is a monotonically increasing function of x. So for any $x > x_0$, Eq. (3.8) holds. If the flow is stratified, then the following inequality must hold:

$$1 - \frac{h}{d} \geq \left(\frac{q}{2} \right)^{\frac{1}{3}} \left[\sqrt[3]{1 + \sqrt{1 + \frac{4q}{27}}} + \sqrt[3]{1 - \sqrt{1 + \frac{4q}{27}}} \right] \tag{3.12}$$

The upper boundary of the liquid level in the pipe is given by Eq. (3.1).

Chapter 4

FORMULATION OF COMPUTER PROGRAM (PAWS)

In this chapter, the unified mechanistic models that contribute to the formulation of the simulator PAWS used in this study are described. Some of them are modified to improve the accuracy of pressure loss calculations and to simplify the calculation procedure. The fuzzy set for pressure loss of bubble flow is developed in Section 4.2.1. The four parts of this chapter discuss flow pattern criteria, prediction of the gradient for pressure loss, gas properties, and friction factor.

4.1 Unified Flow Pattern Criteria

The flow pattern prediction model is mainly from the Barnea [1985] model, which is applicable to inclination angles ranging from upward vertical flow to downward vertical flow. Below is a summary of the transition criteria for stratified to non-stratified flow, slug to dispersed bubble flow, annular to slug flow, and bubble to slug flow.

4.1.1 Bubble to Non-Bubble Transition

Three conditions are used to determine bubble flow: a very low flow rate, a relatively large pipe diameter, and a high inclination angle from the horizontal plane. The conditions are listed below.

$$v_{SG} < \left(0.43 v_{SG} + 0.357 v_{0\infty}\right)\sin\theta \tag{4.1}$$

$$d > 19.1\sqrt{\sigma / g\left(\rho_L - \rho_g\right)} \tag{4.2}$$

and

$$\theta > \theta^* \tag{4.3}$$

where

$$v_{0\infty} = 1.53\left[\frac{g\sigma(\rho_L - \rho_G)}{\rho_L^2}\right]^{0.25} \tag{4.4}$$

$$\theta^* = \cos^{-1}\left(\frac{-1+\sqrt{1+4a^2}}{2}\right) \tag{4.4}$$

$$a = \frac{3}{4}\cos 45^\circ \frac{v_\infty}{g}\left(\frac{0.8r^2}{d}\right) \text{ and } 1.1 < \gamma < 1.5 \tag{4.5}$$

Equations (4.1), (4.2), (4.3), and (4.4) are presented by Hasan and Kabir[2002], Taitel et al. [1980], Bornea et al. [1985], and Harmthy [1960], respectively. Bubble flow is present when the above three conditions are satisfied.

4.1.2 Slug to Dispersed Bubble Transition

This transition occurs at high liquid flow rate when the turbulent forces break the Taylor bubbles into small bubbles, forming dispersed bubble flow. Equivalently, to predict whether a slug flow transitions to a dispersed bubble flow is equivalent to determining if the turbulent force breaks the Taylor bubbles into small bubbles. To figure out whether the turbulent force has an influence on Taylor bubbles, one boundary and three critical diameters (Gomez, et al. [2000]) are proposed in this section.

Transition Boundary

This boundary is given by

$$\frac{v_{SG}}{v_{SL} + v_{SG}} = 0.52 \tag{4.8}$$

When the gas friction factor is more than 0.52, it is independent of the turbulent forces for bubbles to agglomerate to Taylor bubbles. This means that when the gas fraction factor is more than 0.52, the slug flow cannot transition to the dispersed bubble flow no matter how large the turbulent force is.-*

Three Critical Diameters

At high flow rates, when the turbulent force overcomes the interfacial tension force, the Taylor bubbles are dispersed into small bubbles. The first critical diameter is the maximum diameter of the dispersed bubbles, denoted by d_{max}, which can be determined from

$$d_{\max} = \left\{ 4.15 \left(\frac{v_{SG}}{v_M} \right)^{0.5} + 0.725 \right\} \left(\frac{\sigma}{\rho_L} \right)^{0.6} \left(\frac{2 f_M v_M{}^3}{d} \right)^{-0.4} \tag{4.9}$$

The second critical diameter is the critical deformed diameter, denoted by d_{CD} determined by

$$d_{CD} = 2\left[\frac{0.4\sigma}{(\rho_L - \rho_G) g} \right]^{0.5} \tag{4.10}$$

Once the bubble diameter reaches d_{CD}, the bubble cannot agglomerate or coalescence any more. In this case, the size of the Taylor bubble in the slug flow is less than d_{CD}. If the maximum dispersed bubble diameter is more than this critical deformed diameter, the turbulent force has no influence on the size of the Taylor bubbles, namely, no transition between slug flow and dispersed bubble flow can occur. On the other hand, the transition occurs when the turbulent force disperses Taylor bubbles into small bubbles.

The third critical diameter is the critical buoyancy diameter, denoted by d_{CB}. It is determined by

$$d_{CB} = \frac{3}{8} \frac{\rho_L}{(\rho_L - \rho_G)} \frac{f v_M^2}{g \cos\theta} \tag{4.11}$$

This critical diameter is applicable to horizontal and nearly horizontal wells, where “as a result of buoyancy, bubbles might migrate to the upper part of the pipe causing ‘creaming’ transition to slug flow” (Gomez, et al. [2000]). If the critical buoyancy diameter is less than the maximum dispersed bubble flow, the turbulent force cannot avoid such “creaming” transition to slug flow. In this way, the dispersed bubble flow cannot happen.

In summary, the transition from slug flow to dispersed bubble flow occurs when the following conditions hold:

$$d_{\max} < d_{CD} \quad \text{or} \quad d_{\max} < d_{CB} \tag{4.12}$$

and

$$\frac{v_{SG}}{v_{SL} + v_{SG}} < 0.52 \tag{4.13}$$

4.1.3 Stratified to Non-Stratified Transition

Two criteria are used to determine whether flow is stratified flow or non-stratified flow. The first criterion uses the gas velocity derived by Taitel and Dukler [1976], the other criterion uses the upper boundary of inclination angle presented in Chapter 3.

A relationship for the gas velocity at which the transition from stratified flow to non-stratified flow takes place is given by the equation

$$v_G > \left(1 - \frac{h}{d}\right)\left[\frac{g\cos\theta(\rho_L - \rho_G)A_G}{\rho_G(dA_L / dh)}\right] \tag{4.15}$$

where the parameters in Eq. (4.15) are shown in Figure 4-1, dA_L/dh is the derivative of liquid cross sectional area A_L with respect to the high liquid level, and we have the relations

$$dA_L / dh = d\sqrt{1 - \xi^2} \tag{4.16}$$

$$A_G = \frac{d^2}{4}\left(\cos^{-1}(\xi) - \xi\sqrt{1-\xi^2}\right) \tag{4.17}$$

$$\xi = \frac{2h}{d} - 1 \tag{4.18}$$

4.1.4 Annular to Slug Transition

The transition from annular flow to slug flow results from the blockage of the gas core by the liquid phase. Based on the characteristics of the film structure in the annular flow, two mechanisms can be responsible for the transition. One is that the downward flow near the wall results in the instability of the liquid film; the other is that sufficient liquid supply from the film makes the waves grow on the interface, resulting in slug flow. The two criteria from the two mechanisms are called the instability criterion and the wave bridging criterion. The instability criterion is obtained from the solution of the two dimensionless equations

$$Y = \frac{1+75H_L}{(1-H_L)^{2.5}H_L} - \frac{1}{H_L^{\,3}}X^2 \tag{4.19}$$

and

$$Y \geq \frac{2-\frac{3}{2}H_L}{H_L^{\,3}\left(1-\frac{3}{2}H_L\right)}X^2 \tag{4.20}$$

where X is the Lockhart and Martinelli parameter and Y is a dimensionless gravity group defined respectively by

$$X^2 = \frac{\left[\left(\frac{dp}{dL}\right)_{SL}\right]_F}{\left[\left(\frac{dp}{dL}\right)_{SG}\right]_F} \tag{4.21}$$

and

$$Y = \frac{(\rho_L - \rho_G) g \sin\theta}{\left[\left(\frac{dp}{dL}\right)_{SG}\right]_F} \tag{4.22}$$

The subscript F denotes the frictional component.

The wave bridging criterion is given by the equation

$$H_L \geq 0.24 \tag{4.23}$$

In summary, the transition from annular flow to slug flow occurs when either of the two criteria is satisfied.

4.2 Prediction of Pressure Drop Gradients

After the flow pattern is determined, the holdup and pressure loss for the flow pattern can be calculated. Four types of flow pattern models are presented in this section. They are the stratified flow pattern, bubble and dispersed bubble flow pattern, annular flow pattern, and slug flow pattern models. In addition, how to set up the bubble flow fuzzy model is discussed.

4.2.1 Bubble Flow and Dispersed Bubble Flow

The bubble flow and dispersed bubble flow calculation is described here. It includes a discussion of the fuzzy set calculation.

4.2.1.1 Formula for Prediction of Pressure Loss Gradient for Any Given C_0

Terminal rise velocity, liquid holdup, mixture density and friction factor of a fluid mixture are calculated using the following relations:

Bubble Terminal-Rise Velocity (Harmathy [1960])

$$v_{0\infty} = 1.53\left[\frac{g\sigma(\rho_L - \rho_G)}{\rho_L^2}\right]^{0.25} \tag{4.24}$$

Liquid holdup

$$H_L = 1 - \frac{v_{SG}}{C_o v_m + v_{0\infty}\sin\theta\sqrt{H_L}} \tag{4.25}$$

Mixture density

$$\rho_M = H_L\rho_L + (1 - H_L)\rho_G \tag{4.26}$$

The friction factor formula is given in Section 4.4

The pressure gradient is calculated using the above results and

$$\frac{dp}{dL} = g\rho_M \sin\theta + \frac{f_m v_m^2 \rho_M}{2d} + \rho_M v_m \frac{dv_m}{dL} \tag{4.27}$$

where f_m is a Moody friction factor.

4.2.1.2 Calculation Procedure for the Fuzzy Set of Pressure Loss

Based on the discussion presented in Chapter 2, the fuzzy set of pressure loss for bubble flow is constructed using the following procedure.

Step1. Determine alpha-cuts of $\overline{C}_0$. Based on Eq. (2.2), alpha-cuts of $\overline{C}_0$ are

$$C_0[\alpha] = [a + \alpha(b - a), c - \alpha(c - b)] \text{ and for } \alpha \in [0,1]$$

Step2. Predict pressure loss with $C_{0_1} = a + \alpha(b - a)$ and $C_{0_2} = c - \alpha(c - b)$, respectively.

In this step, use Eq. (4.24) to calculate the single bubble terminal-rise velocity, use Eq. (4.25) to calculate liquid holdup, use Eq. (4.26) to calculate the mixture density, calculate friction factor, use Eq. (4.27) to predict the pressure gradient, and finally, calculate P_{loss1} and P_{loss2}.

Step 3. Based on Eq. (2.15), the alpha-cut of pressure loss is given as

$$\overline{P}_{loss}[\alpha] = [P_{loss}(a+\alpha(b-a)), P_{loss}(c-\alpha(c-b))] = [P_{loss1}, P_{loss2}]$$

Step 4. Let $\alpha = 0.1, 0.2, 0.3, \ldots, 0.9$, and 1. Repeat the calculation from step 1 to step 3. The membership function for pressure loss is built using a series of alpha-cuts of pressure loss.

Step 5. With the series of alpha-cuts, a fuzzy set of pressure loss is constructed using Eq. (2.3).

4.2.2 Stratified Flow

In this section, the formulas for predicting pressure gradient are given. They include the pressure gradient, friction factor, shear stress, and liquid holdup (high liquid level). The calculation for stratified flow is presented.

4.2.2.1 Formulas

Pressure Gradient (Momentum Balance) Equations

Liquid:
$$A_L \frac{dp}{dL} - \tau_{WL} S_L + \tau_I S_I - \rho_L A_L g \sin\theta = 0 \tag{4.28}$$

Gas:
$$A_G \frac{dp}{dL} - \tau_{WG} S_G - \tau_I S_I - \rho_G A_G g \sin\theta = 0 \tag{4.29}$$

The parameters in the above two equations are shown in Figure 4-1.

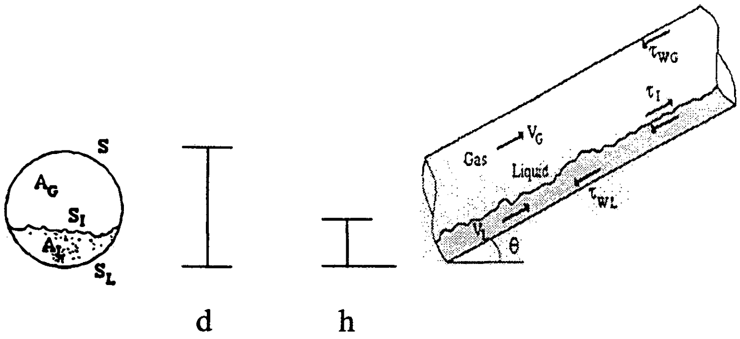


Figure 4-1. Physical Model for Stratified Flow (from Gomez, et al. [2000])

Liquid Level Equation

The following equation is obtained by combing of Eqs. (4.28) and (4.29):

$$\tau_{WL}\frac{S_L}{A_L}-\tau_{WG}\frac{S_G}{A_G}-\tau_I S_I\left(\frac{1}{A_L}+\frac{1}{A_G}\right)+\left(\rho_L-\rho_G\right)g\sin\theta=0 \tag{4.30}$$

This is an implicit equation for the liquid level in the pipe. The liquid level can be solved by a trial and error procedure once the different geometrical, velocity and stress variables are determined. With high gas and liquid flow rates, multiple solutions may occur. “It can be shown that, in this case, the smallest of the three solutions is the physical and stable solution.” (Gomez et al [2000]).

Formulas for liquid holdup, wall shear stress, hydraulic diameter, Reynolds number, friction factor, and interfacial shear stress follow.

Liquid Holdup

Once the liquid level, h, is determined, the liquid holdup, H_L, is calculated directly from geometrical relationships, thus

$$H_L = \frac{\pi - \cos^{-1}\left(2\frac{h}{d}-1\right)+\left(2\frac{h}{d}-1\right)\left(\sqrt{1-\left(2\frac{h}{d}-1\right)^2}\right)}{\pi} \tag{4.31}$$

Wall Shear Stress

The wall shear stress corresponding to each phase are determined by single-phase analysis using the hydraulic diameter concept. The wall shear stress for liquid is

$$\tau_{WL} = f_L \frac{\rho_L v_L^2}{2} \tag{4.32}$$

and for gas is

$$\tau_{WG} = f_G \frac{\rho_G v_G^2}{2} \tag{4.33}$$

The hydraulic diameters of the liquid and gas phases are

$$d_L = \frac{4A_L}{S_L} \tag{4.34}$$

and

$$d_G = \frac{4A_G}{S_G + S_I} \tag{4.35}$$

Reynolds numbers for each phase are

$$\mathrm{Re}_L = \frac{d_L v_L \rho_L}{\mu_L} \tag{4.36}$$

and

$$\mathrm{Re}_G = \frac{d_G v_G \rho_G}{\mu_G} \tag{4.37}$$

The gas friction factor is

$$f_G = \frac{16}{\mathrm{Re}_G} \qquad \text{for} \quad \mathrm{Re}_G \le 2300 \tag{4.39}$$

and

$$f_G = 0.001375\left\{1+\left[2\times10^4\frac{\varepsilon}{d}+\frac{10^6}{\mathrm{Re}_G}\right]^{\frac{1}{3}}\right\} \text{ for } \mathrm{Re}_G > 2300 \tag{4.40}$$

The liquid friction factor is

$$f_L = \frac{1.6291}{\mathrm{Re}_L^{0.5161}}\left(\frac{v_{SG}}{v_{SL}}\right)^{0.0926} \tag{4.41}$$

The interfacial shear stress is

$$\tau_I = f_I\frac{\rho_G(v_G - V_L)^2}{2} \tag{4.42}$$

The interfacial friction factor recommended by Xiao, et al. [1990] follows:

For $d \leq 0.5$ inch, if $v_{SG} \leq v_{SGT}$, then

$$f_I = f_G \tag{4.43}$$

If $v_{SG} > v_{SGT}$, then

$$f_I = f_G\left[1+15v_{SGT}(v_{SG} - v_{SGT})\sqrt{\frac{h}{d}}\right] \tag{4.44}$$

where v_{SGT} is the critical superficial velocity for the transition from smooth flow to the waxy regime. The critical superficial velocity is

$$v_{SGT} = 5\sqrt{p_S / p} \tag{4.45}$$

where p_S is standard atmospheric pressure (14.7 psi) and P is the pressure in the wellbore.

For d > 0.5 inch, if $\phi \leq 0.005$, then the absolute pipeline roughness is

$$\varepsilon = \frac{34\sigma}{\rho_G v_L^2} \tag{4.46}$$

If $\phi > 0.005$, then the roughness is

$$\varepsilon = \frac{170\sigma}{\rho_G v_L^2}\left(\frac{\rho_G v_L^2 \varepsilon}{\sigma}\frac{\mu_L^2}{\sigma \rho_L \varepsilon}\right)^{0.3} \tag{4.47}$$

where

$$\Phi = \left(\frac{\rho_G v_L^2 \varepsilon}{\sigma}\frac{\mu_L^2}{\sigma \rho_L \varepsilon}\right) \tag{4.48}$$

4.2.2.2 Calculation Procedure for Pressure Gradient

To calculate the pressure gradient, we proceed as follows:

Step1. Determine liquid level using Eq. (4.30)

Step 2. Determine liquid holdup using Eq. (4.31)

Step 3. Determine other parameters such as shear stress and liquid cross sectional area using Eqs. (4.32) to (4.48)

Step 4. Solve the pressure gradient using Eq. (4.28) or Eq. (4.29)

Step 5. Incorporate the acceleration component as specified by the user into the pressure loss calculation. The detail of this step is shown in Figure 5-2.

4.2.3 Unified Slug Model

The Gomez, et al. [2000] model is discussed in this section. Modifications to this model are then described.

4.2.3.1 Pressure Loss Gradient Equation

The slug unit is divided into two parts: slug and Taylor bubble. The physical model is shown in Figure 4-2. This section presents pressure loss gradient equations, correlation equations, liquid holdup in Taylor bubble, and mass balance equations.

$$\frac{dp}{dL} = \rho_U g \sin\theta + \frac{\tau_S \pi d}{A}\frac{L_S}{L_U} + \frac{\tau_{WF} S_F + \tau_{WG} S_G}{A}\frac{L_F}{L_U} \tag{4.49}$$

where

$$\rho_U = H_{SLU}\rho_L + (1 - H_{SLU})\rho_G \tag{4.50}$$

and

$$L_U = L_S \frac{v_{LLS} H_{LLS} - V_{LTB} H_{LTB}}{v_{SL} - v_{LTB} H_{LTB}} \tag{4.51}$$

The parameters in Eqs. (4.49) and (4.50) are shown in Figure 4-2.

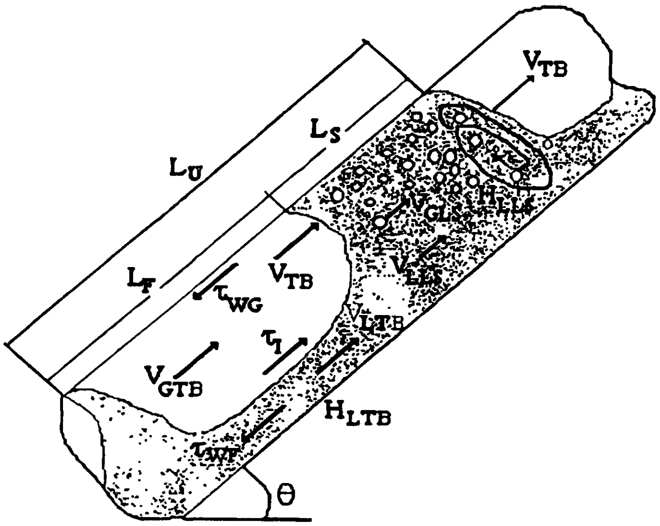


Figure 4-2. Physical Model for Slug Flow (from Gomez, et al. [2000])

4.2.3.2 Correlation Equations

Correlation equations are used to determine the length of the slug (L_S), liquid holdup in the slug (H_{LLS}), and gas velocity in the slug.

Length of Slug

Calculation of the length of slug is divided into three steps: the length of slug in a vertical segment, the length of slug in a horizontal segment, and the length for a segment with any inclination angle.

The length of slug in a vertical segment is

$$L_{SV} = 30d \tag{4.51}$$

The length of slug in a horizontal segment is

$$L_{SH} = 20d \qquad \text{when d < 2 inches} \tag{4.52}$$

$$L_{SH} = \exp\left[-25.4 + 28.5(\ln(d))^{0.1}\right] \qquad \text{when d} \geq 2 \text{ inches} \tag{4.53}$$

Equation (4.53) is presented by Scott et al. [1989], and the unit in this equation for L_{SH} is in feet and d is in inch.

The length of slug in a segment with any inclination angle θ is

$$L_S = L_{SV} \sin^2 \theta + L_{SH} \cos^2 \theta \tag{4.54}$$

Liquid Holdup in Slug, H_{LLS} (presented by Gomez, et al. [2000])

$$H_{LLS} = 1.0 \exp\left[-\left(0.45\theta + 10^{-6} * 2.48 \text{Re}_{LS}\right)\right] \tag{4.55}$$

where $\text{Re}_{LS} = \dfrac{\rho_L v_M d}{\mu_L}$

Gas Velocity in Slug, v_{GLS}

$$v_{GLS} = 1.2 v_M + v_{0\infty} \sin\theta \sqrt{H_{LLS}}$$

(4.56)

where $v_{0\infty}$ is given by Eq. (4.24).

4.2.3.3 Liquid Holdup in Taylor Bubble Parts

The flow behavior in Taylor bubble flow is similar to the flow behavior in stratified flow. Liquid holdup in Taylor bubble flow, H_{LTB}, is obtained by using a trial and error procedure to solve

$$\tau_{WF}\frac{S_F}{A_L}-\tau_{WG}\frac{S_G}{A_G}-\tau_I S_I\left(\frac{1}{A_F}-\frac{1}{A_G}\right)+(\rho_L-\rho_G)g\sin\theta=0 \tag{4.57}$$

The solution of Eq. (4.57) yields the uniform (equilibrium) film thickness in Taylor bubble flow.

4.2.3.4 Mass Balance Equations

An overall liquid mass balance for a slug unit is

$$v_{SL}=v_{LLS}H_{LLS}\frac{L_S}{L_U}+v_{LTB}H_{LTB}\frac{L_F}{L_U} \tag{4.58}$$

The mass balance equations are presented by Bendiksen [1984]. They are

$$(v_{ITB}-v_{LLS})H_{LLS}=(v_{ITB}+v_{LTB})H_{LLB} \tag{4.59}$$

where

$$v_{ITB}=1.2v_M+v_{TB} \tag{4.60}$$

and

$$v_{TB}=\left((0.351\sin\theta+0.541\cos\theta)\sqrt{gd(\rho_L-\rho_G)/\rho_L}\right) \tag{4.61}$$

Liquid velocities in the liquid slug and Taylor bubble regions are given by

$$v_M=v_{SL}+v_{SG}=v_{LLS}H_{LLS}+v_{GLS}(1-H_{LLS}) \quad \text{(slug)} \tag{4.62}$$

and

$$v_M=v_{SL}+v_{SG}=v_{LTB}H_{LTB}+v_{GTB}(1-H_{LTB}) \quad \text{(Taylor bubble)} \tag{4.63}$$

The liquid film length, L_F, is

$$L_F = L_U - L_S \tag{4.64}$$

The equation for slug unit, L_U, is

$$L_U = L_S \frac{v_{LLS}H_{LLS} - v_{LTB}H_{LTB}}{v_{SL} - v_{LTB}H_{LTB}} \tag{4.65}$$

4.2.3.5 Modification to this Model

A difficulty with the above model is that the model can produce a negative Taylor bubble length. The field example from Hasan and Kabir [2000] yielded such a result. This difficulty might result from the correlation equation (Eq. (4.55)) for liquid holdup in the slug. We examine this below.

Equation (4.64) implies that if $L_U > L_S$, the following inequality must hold:

$$v_{LLS}H_{LLS} < v_{SL} \tag{4.66}$$

From Eq. (4.62), the following equation is obtained

$$v_{LLS}H_{LLS} = v_M - v_{GLS}(1 - H_{LLS}) \tag{4.67}$$

Combining Eqs. (4.66) and (4.67) gives the following inequality:

$$v_{SL} > v_M - v_{GLS}(1 - H_{LLS}) \tag{4.68}$$

Simplifying Eq. (4.68), and replacing v_{GLS} with Eq. (4.56), the following equation is obtained:

$$v_{SG} < \left(1.2v_M + v_{0\infty} \sin\theta\sqrt{H_{LLS}}\right)\left(1 - H_{LLS}\right) \tag{4.69}$$

In the inequality Eq. (4.69), only H_{LLS} is variable as predicted by Eq. (4.55). Other parameters such as v_{SG}, v_M, and $v_{0\infty}$ are constant. Therefore, once the length of the Taylor bubble term is negative, the liquid holdup in slug calculated by Eq. (4.55) must only be approximate. This means that there is limited validity to the correlation for liquid holdup in the slug. The calculation of H_{LLS} needs to be modified. In PAWS, a modifier is given to change the value of H_{LLS} to preserve the inequality in Eq. (4.69).

4.2.4 Unified Annular Flow Model

In this section, the model is described according to the order of calculation in PAWS. We consider pressure gradient, film thickness, entrainment, core velocity and density, shear stress between each phase and wall, and interfacial shear stress between two phases.

Pressure Gradient (Momentum Balance) Equations

The linear momentum balance for the liquid and gas core phases are

$$A_F \frac{dp}{dL} - \tau_{WF} S_F + \tau_I S_I - \rho_L A_F g \sin\theta = 0 \tag{4.70}$$

$$A_C \frac{dp}{dL} - \tau_I S_I - \rho_C A_C g \sin\theta = 0 \tag{4.71}$$

The parameters in the above equations are shown in Figure 4-3

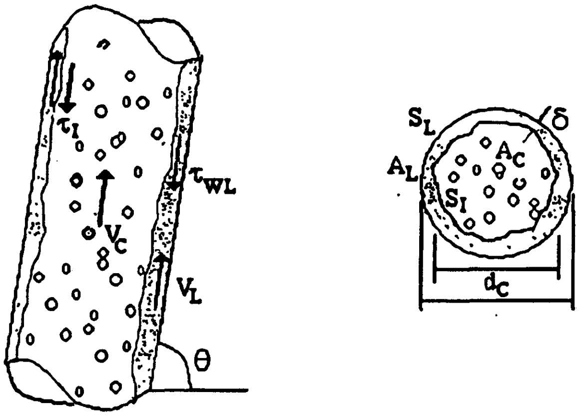


Figure 4-3. Physical Model for Annular Flow (from Gomez, et al. [2000])

Film Thickness Equation

The film thickness equation is obtained by combining the above two equations, thus

$$\tau_{WF}\frac{S_F}{A_F}-\tau_I S_I\left(\frac{1}{A_C}+\frac{1}{A_F}\right)+(\rho_L-\rho_C)g\sin\theta=0 \tag{4.72}$$

Equation (4.69) is an implicit equation for film thickness δ. Film thickness is determined by trial and error.

Entrainment Fraction

The entrainment fraction, E, is calculated by the correlations proposed by Wallis [1969] as follows

$$E=1-e^{-0.125(v_{sgc}-15)} \tag{4.73}$$

where

$$v_{SGC}=\frac{10^4 v_{SG}\mu_G}{\sigma}\sqrt{\rho_G/\rho_L} \tag{4.74}$$

Velocity of Film and Core

Velocities of the liquid film and gas core are determined from mass balance calculations, yielding respectively

$$v_F=v_{SL}\frac{(1-E)d^2}{4\delta(d-\delta)} \tag{4.75}$$

and

$$v_C=\frac{(v_{SG}+v_{SL}E)d^2}{(d-2\delta)^2} \tag{4.76}$$

Core Properties

The gas void fraction in the core is given by

$$\alpha_C=\frac{v_{SG}}{v_{SL}E+v_{SG}} \tag{4.77}$$

The core average density is

$$\rho_C = \rho_G \alpha_C + \rho_L (1 - \alpha_C) \tag{4.78}$$

The core average viscosity is

$$\mu_C = \mu_G \alpha_C + \mu_L (1 - \alpha_C) \tag{4.79}$$

Liquid Wall Shear Stress

The liquid wall shear stress is determined from single-phase flow calculations based on the hydraulic diameter concept similar to the procedure described for stratified flow.

Interfacial Shear Stress

The definition of interfacial shear stress for annular flow is

$$\tau_I = f_I \rho_C \frac{(v_C - v_F)^2}{2} \tag{4.80}$$

The interfacial shear stress suggested by Aveles, et al. [1991] and extended by Gomez et al. [2000] is

$$f_I = f_{CS} I_\theta \tag{4.81}$$

where f_{CS} is the friction factor (of v_{SC}, d, rho$_C$, and mu$_C$) that would be obtained if only the core (gas phase and the entrainment) flows in the pipe. Calculation of f_{CS} should be based on core superficial velocity ($v_{SC}=v_{SG}+Ev_{SL}$), core average density and viscosity given above.

The interfacial correction parameter I_θ accounts for the roughness of the interface and the inclination angle as follows

$$I_\theta = I_H \cos^2\theta + I_V \sin^2\theta \tag{4.82}$$

The horizontal correction parameter given by Henstock and Hanratty [1976] is

$$I_H = 1 + 800 F_A \tag{4.83}$$

where

$$F_A = \frac{\left[\left(0.707 \mathrm{Re}_{SL}^{0.5}\right)^{2.5} + \left(0.0379 \mathrm{Re}_{SL}^{0.9}\right)^{2.5} \right]^{0.4}}{\mathrm{Re}_{SG}^{0.9}} \left(\frac{v_L}{v_G}\right)\left(\frac{\rho_L}{\rho_G}\right)^{0.5} \tag{4.84}$$

The Reynolds numbers Re_{SL} and Re_{SG} are the liquid and gas superficial Reynolds numbers, respectively.

The vertical correction parameter is given by Wallis [1969]

$$I_V = 1 + 300\frac{\delta}{d} \tag{4.85}$$

4.3 Gas Properties

Gas properties change along the pipe in a flowing, multiphase system. In this section, the formulas of gas Z-factor, gas viscosity, and gas density are presented.

4.3.1 Z-factor

There are many correlations for predicting pseudo-critical properties. Among those correlations, the methods proposed by Standing and Sutton are widely accepted in the industry. The Sutton correlation [1985] is

$$P_{pc} = 756.8 - 131.0\gamma_g - 3.6\gamma_g^2 \tag{4.86}$$

$$Tpc = 169.2 + 349.5\gamma_g - 74.0\gamma_g^2 \tag{4.87}$$

The equations above treat natural gas as if it is composed of hydrocarbon components only and without non-hydrocarbons such as CO_2, nitrogen, hydrogen sulfide, and water vapor. However, in many cases, natural gases do contain non-hydrocarbons. To correct the pseudo-critical properties for the CO_2 and H_2S components, Wichard and Aziz [1972] proposed the following correlations:

$$A = yCO_2 + yH_2S \tag{4.88}$$

$$B = yH_2S \tag{4.89}$$

$$\varepsilon = 120(A^{0.9} - A^{1.6}) + 15(B^{0.5} - B^4) \tag{4.90}$$

$$T'pc = Tpc - \varepsilon \tag{4.91}$$

$$p'_{pc} = \frac{p_{pc} T'^{pc}}{T_{pc} + B(1-B)\varepsilon} \tag{4.92}$$

Pseudo-reduced pressure and temperature are

$$p_{pr} = p / p_{pc} \tag{4.96}$$

$$T_{pr} = T / T_{pc} \tag{4.97}$$

The Z-factor is obtained using the Dranchuk and Abou-Kassem [1975]method. The correlation equations are

$$z = 1 + c_1 \rho_{pr} + c_2 \rho_{pr}^2 - c_3 \rho_{pr}^5 + c_4(\rho_{pr}) \tag{4.98}$$

where

$$\rho_{pr} = 0.27 p_{pr/} (T_{pr} z) \tag{4.99}$$

The coefficients c_1, c_2, and c_3 are functions of pseudo-reduced temperature and are constant for a given temperature. The coefficient c_4 is a function of pseudo-reduced temperature and density. The equations for all four coefficients are

$$c_1(T_{pr}) = A_1 + A_2 / T_{pr} + A_3 / T_{pr}^3 + A_4 / T_{pr}^4 + A_5 / T_{pr}^5 \tag{4.100}$$

$$c_2(T_{pr}) = A_6 + A_7 / T_{pr} + A_8 / T_{pr}^2 \tag{4.101}$$

$$c_3(T_{pr}) = A_9 (A_7 / T_{pr} + A_8 / T_{pr}^2) \tag{4.102}$$

$$c_4(\rho_{pr}) = A_{10}(1 + A_{11}\rho_{pr}^2)\frac{\rho_{pr}^2}{T_{pr}^3}\exp(-A_{11}\rho_{pr}^2) \tag{4.103}$$

A1 = 0.3265

A2 = -1.070

A3 = -0.5339

A4 = 0.01569

A5 = -0.05165

A6 = 0.5475

A7 = -0.7361

A8 = 0.1844

A9 = 0.1056

A10 = 0.6134

A11 = 0.7210

4.3.2 Viscosity

The well-known correlation developed by Lee et al. [1966] is used in PAWS to calculate gas viscosity. It is presented below.

$$\mu_g = 10^{-4} K \exp(X\rho^Y) \tag{4.104}$$

$$K(M_w, T) = \frac{9.379 + 0.01607 M_w}{209.2 + 19.26 M_w + (T + 460)} (T + 460)^{1.5} \tag{4.105}$$

$$X(M_w, T) = 3.448 + \frac{986.4}{(T + 460)} + 0.01009 M_w \tag{4.106}$$

$$Y(M_w, T) = 2.447 - 0.2224 X \tag{4.107}$$

$$\rho = 1.4935 \times 10^{-3} \frac{pM_w}{zT} = 4.3267 \times 10^{-2} \frac{p\gamma_g}{z(T + 460)} \tag{4.108}$$

4.3.3 Density

Gas density is

$$\rho = \frac{pM_w}{ZR(T + 460)} \tag{4.109}$$

4. 4 Friction Factor

There are many approaches for calculating friction factor. Based on the characteristics of multiphase flow, the procedure presented by Gomez, et al [2000] is used in PAWS. It is outlined below.

4.4.1 Reynolds Number

The Reynolds Number, Re, is

$$\mathrm{Re} = \frac{\rho v d}{\mu} \tag{4.110}$$

4.4.2 Laminar Flow

When Re is less than 2300, the flow is laminar flow. The friction factor for laminar flow is

$$f = 16/\mathrm{Re} = 16 dv p/\mu \tag{4.111}$$

4.4.3 Turbulent Flow

When Re is more than 2300, the flow is turbulent flow. The friction factor proposed by Liang-Biao and Aziz [1996] is

$$f = 0.001375\left\{1+\left[2\times10^{4}\frac{\varepsilon}{d}+\frac{10^{6}}{\mathrm{Re}}\right]^{\frac{1}{3}}\right\} \tag{4.112}$$

Chapter 5

COMPUTER PROGRAM (PAWS) FLOW CHARTS

The computer code is written using FORTRAN 90. It is applicable to liquid and gas flow for inclination angles ranging from horizontal to vertical. The code is composed of two main parts: determination of flow patterns, and calculation of pressure drop. The procedure to determine the flow patterns is shown is Figure 5-1. The calculation of pressure drop includes four main subroutine programs for the different flow patterns with several subroutine and function programs to calculate Z-factor, friction factor, density, viscosity, surface tension of fluid, and pressure for each segment. Fluid properties are estimated using published correlations

5.1 Flow Chart

The calculation is divided into two parts. First, the wellbore is divided into several segments according to its inclination from the horizontal. Second, the accuracy of the calculation is determined by selecting length intervals that yield pressure loss values that are less than a certain value or tolerance, such as 10 psi pressure loss. Calculations are made for the selected interval starting from the inlet end of the interval, and the resulting outlet pressure is used as input to the next interval. The same procedure is repeated until the total length L of pipe is reached. Figure 5-1 illustrates the procedure.

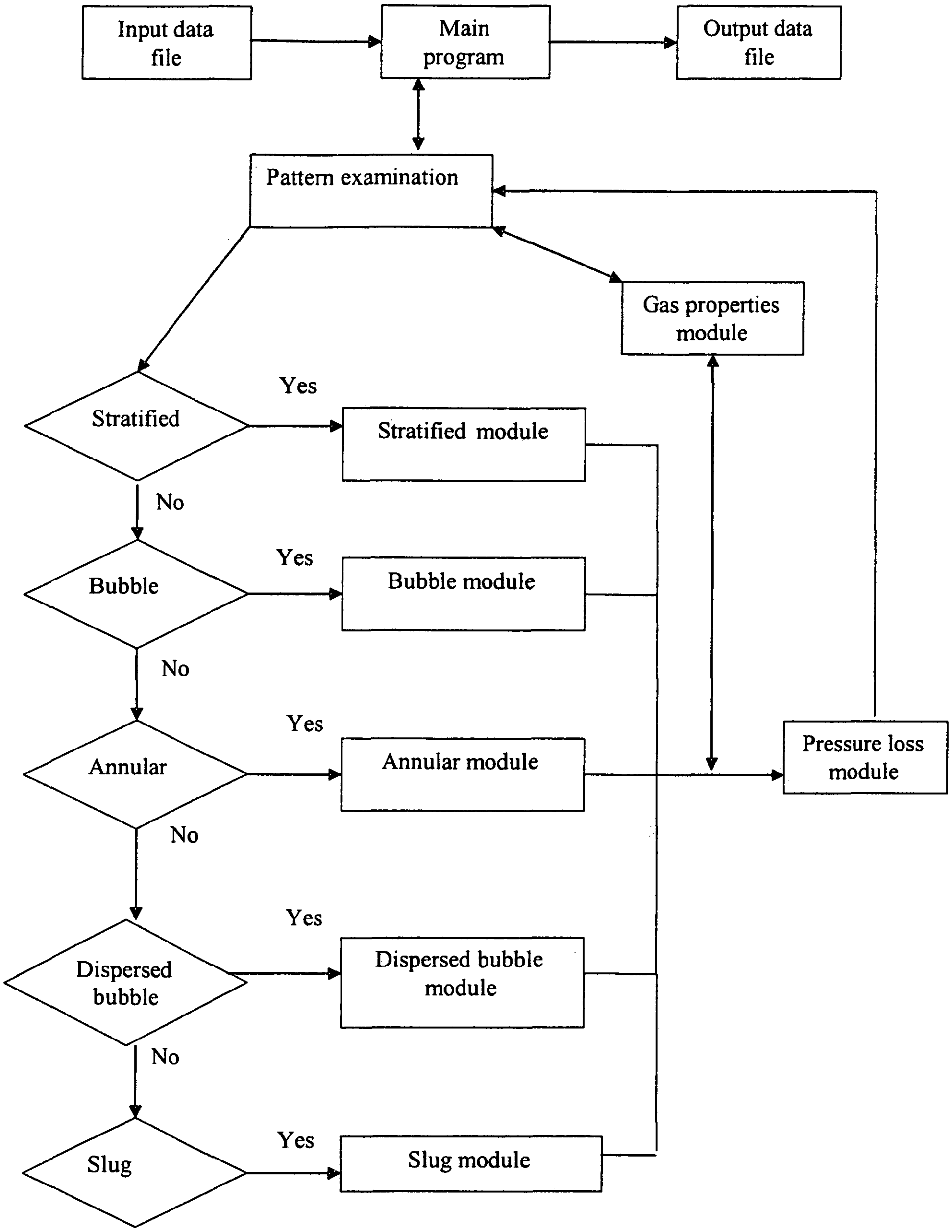


Figure 5-1. Program Flow Chart

5.2 How to Pick Up Interval Length and Include the Acceleration Component

Suppose pressure is P_0, hydraulic pressure gradient is P_{GH}, and frictional pressure gradient is P_{GF}. If the pressure drop is too large over one interval, the properties of fluids might vary so much that the prediction of pressure gradient cannot represent the whole interval. In this case, a maximum pressure drop for all intervals is chosen based on its accuracy. The interval length, L_I, is chosen to be less than the ratio of the maximum pressure drop divided by the total pressure gradient.

The steps for including acceleration component follow:

Step 1. Based on the frictional and hydraulic components, a pressure drop, P_H+P_F, can be calculated. The pressure drop, P_{A1}, for the acceleration component can be calculated between the inlet pressure P_0 and outlet pressure $P_0+P_H+P_F$.

Step 2. If P_{A1} is small enough to be neglected (e.g. less than $0.001L_I/L$), then continue to the next interval; if not, the new outlet pressure is $P_0+P_F+P_H+P_{A1}$.

Step 3. Given the inlet pressure P_0 and the new outlet pressure $P_0+P_F+P_H+P_{A1}$, a new acceleration pressure drop, P_{A2}, can be calculated.

Step 4. Comparing the acceleration pressure drops, if the absolute value of P_{A1} minus P_{A2} is smaller than the tolerance, continue to the next interval. If not, shorten the interval length and repeat the above calculation.

This procedure is sketched in Figure 5-2.

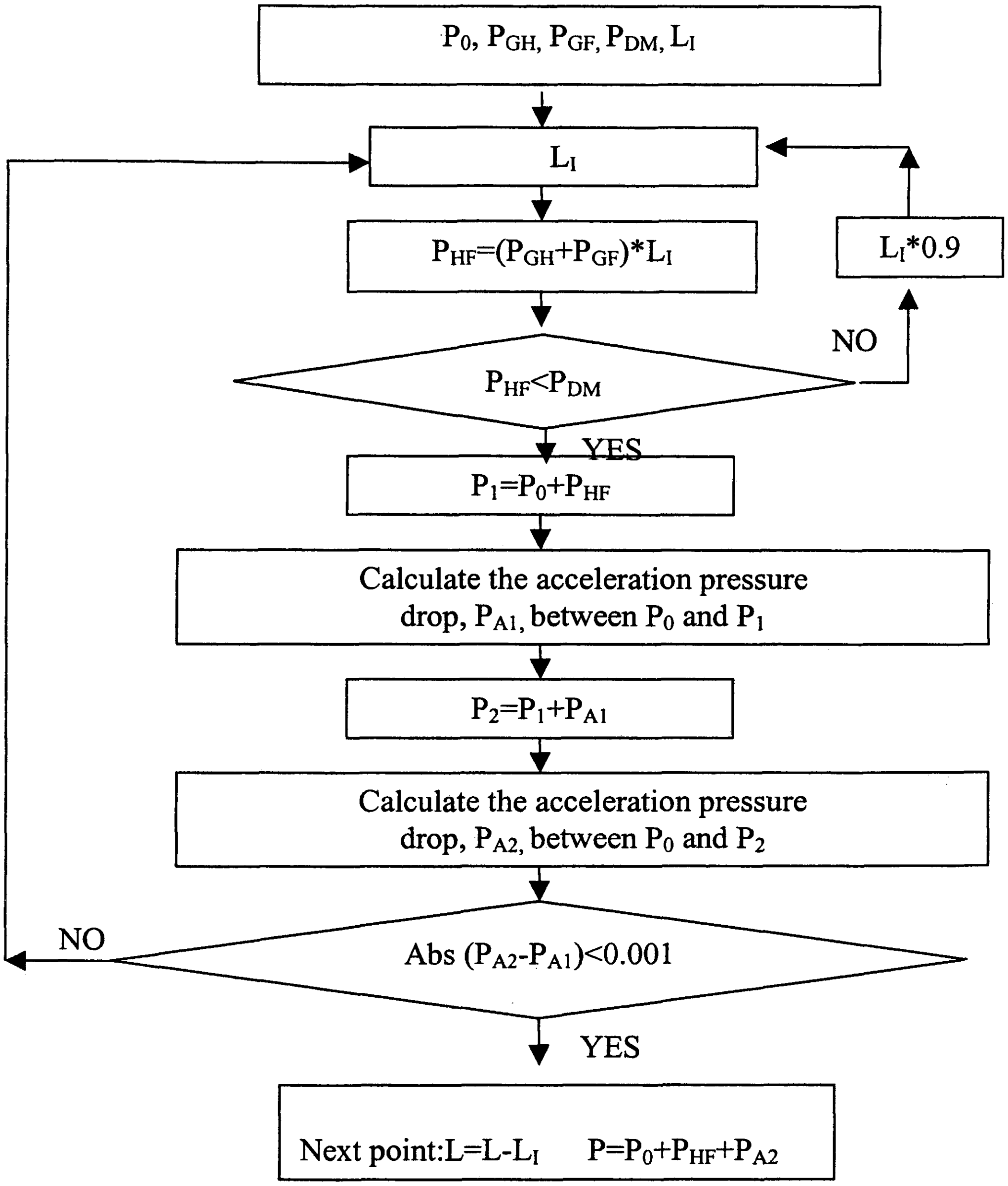


Figure 5-2. Calculation of Acceleration Pressure Drop and Length Interval

Chapter 6

RANGE OF APPLICABILITY OF PAWS

In this chapter, the range of applicability of the computer program PAWS is described. PAWS can be applied to a variety of flow regimes, well inclinations, and pipe diameters. An example of the use of the fuzzy set in the calculation of pressure loss is analyzed.

6.1 Applicability to Various Flow Regimes and Well Inclinations

This computer program can be applied to various conditions. For example it can be used to model pressure profiles in a wellbore with horizontal, inclined, and vertical tubing. It can be applied to different flow regimes in the same wellbore. Furthermore, it is applicable to pipelines with different pipe diameters and pipe roughness. The following example illustrates the type of wellbore conditions that can be modeled using PAWS (Figure 6-1).

Example: A 4500-ft directional well produces 23° API oil through 2.99-in and 2.44-in ID tubing. The tubing consists of four sections with 0°, 30°, 60°, and 90° inclination angles respectively. The wellbore is sketched in Figure 6-1. The gas/oil ratio (GOR) is 450 scf/STB, and the gas gravity is 0.80. The following property values are available at the wellhead where pressure is 505 psi.

V_{SL}=1.201 ft/sec	$\rho_L = 55.042\, lbm/ft^3$	$\mu_L = 13.09\, cp$
V_{SG}=2.824 ft/sec	$\rho_g = 2.19\, lbm/ft^3$	$\mu_g = 0.019\, cp$
		$\sigma = 0.0696\, lbm/s^2$

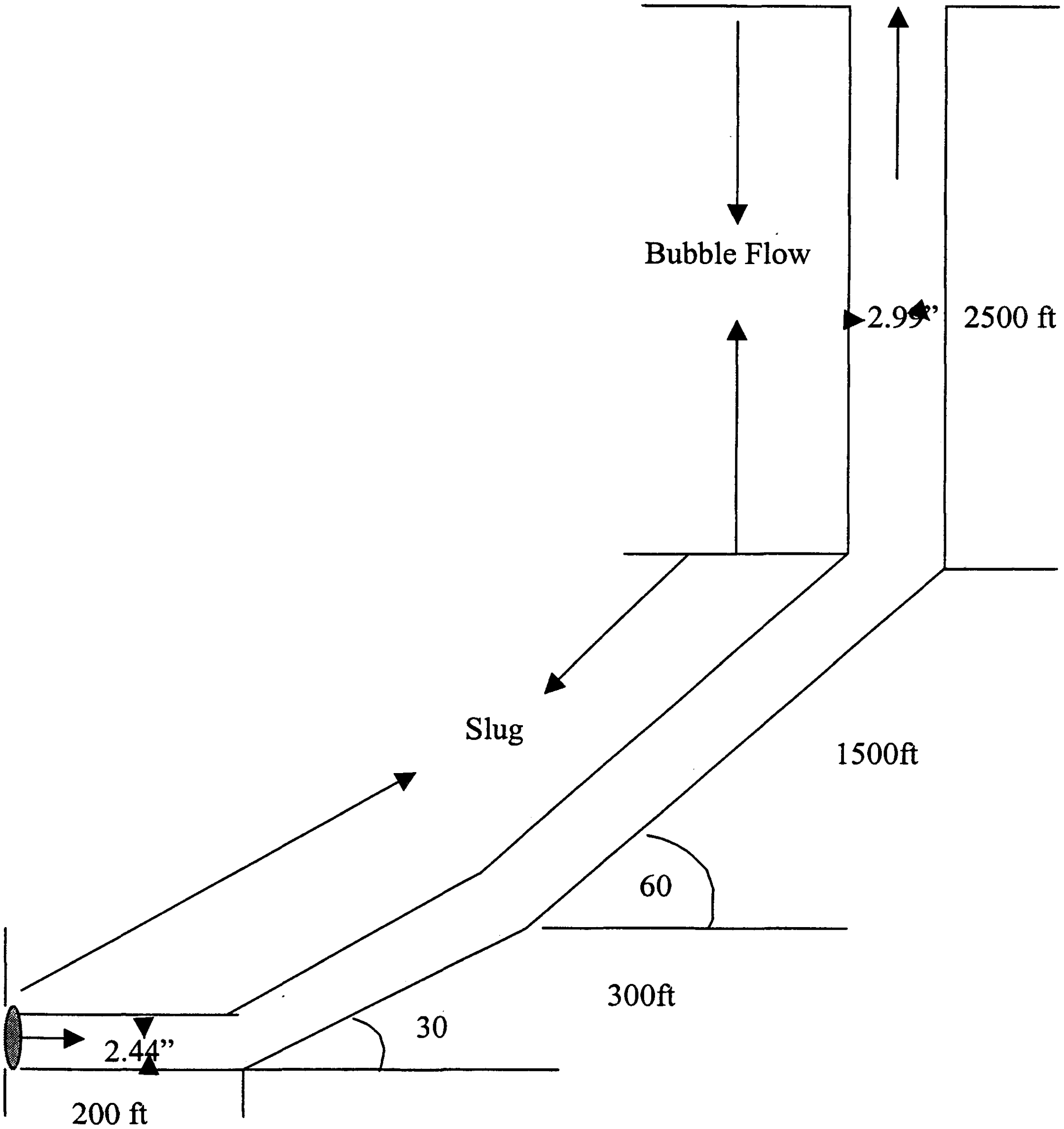


Figure 6-1. Illustration of Wellbore Conditions Suitable for Program Applicabiliry

6.2 Application of the Fuzzy Model for Bubble Flow

The computer program PAWS developed in this study can be used to produce a series of alpha-cuts for pressure prediction by developing a fuzzy set of pressure loss. Suppose alpha can have the values 0.0, 0.1, 0.2, ..., 0.9, 1. The alpha-cuts of pressure loss are shown in Table 6-1.

The alpha-cuts table or the pressure loss fuzzy set can provide a pressure interval for a given possibility. We can use the fuzzy method to calculate pressure. For example, consider a 5000-ft deep oil well in which gas and oil flow with the superficial velocity of 0.5 ft/sec and 1.23 ft/sec respectively. The pressure and temperature at the wellhead are 561 psi and 62 °F. The diameter of the tubing is 2.99-in. Oil and gas properties are the following:

Liquid			Gas		
Density (lbm/ft^3)	Viscosity (cp)	Surface tension (lbm/sec^2)	Density (lbm/ft^3)	Viscosity (cp)	Specific Gravity (lbf/sec^2)
53.36	2.257	0.0696	2.19	0.018	0.6

The produced gas composition contains N_2, H_2S, and CO_2 with volume fractions of 1 percent, 2 percent and 2 percent respectively.

Suppose the distribution coefficient is not well known so that the value listed in the reference is one value from a range of possible values because the gas contains impurities. In such a case, we can use the fuzzy model to evaluate the pressure drop. There are 4 steps to use the fuzzy model.

Step 1. Fuzzify the distribution coefficient given in Chapter 2.

Step 2. Use PAWS to produce the fuzzy set file (shown as output File 3 in Appendix B) and the alpha-cuts file for pressure loss (shown as output File 2 in Appendix B).

Step 3. List the alpha-cuts of pressure loss (as in Table 6-1), and use the alpha-cuts to set up the fuzzy set.

Step 4. Evaluate the prediction of pressure loss. For example, based on studies or experience, we estimate the pressure at the bottom of the well to be between 2114 psi and 2153 psi with the membership of 0.80, while it ranges between 2102 psi and 2212 psi with the membership of 0.3. For comparison, the conventional result can be obtained from the fuzzy set, namely, 2119 psi at vertex point of 1.2.

Table 6-1. Alpha-cuts of Pressure Loss

	Alpha-cuts of C_0		Alpha-cuts of Pressure prediction	
Alpha	lower boundary	upper boundary	lower boundary	upper boundary
0	1.1	2	2094.58	2237.23
0.1	1.11	1.92	2097.42	2229.42
0.2	1.12	1.84	2099.87	2221.01
0.3	1.13	1.76	2102.45	2211.92
0.4	1.14	1.68	2104.99	2202.06
0.5	1.15	1.6	2107.49	2191.34
0.6	1.16	1.52	2109.96	2179.63
0.7	1.17	1.44	2112.39	2166.78
0.8	1.18	1.36	2114.49	2152.63
0.9	1.19	1.28	2117.15	2136.95
1	1.2	1.2	2119.47	2119.47

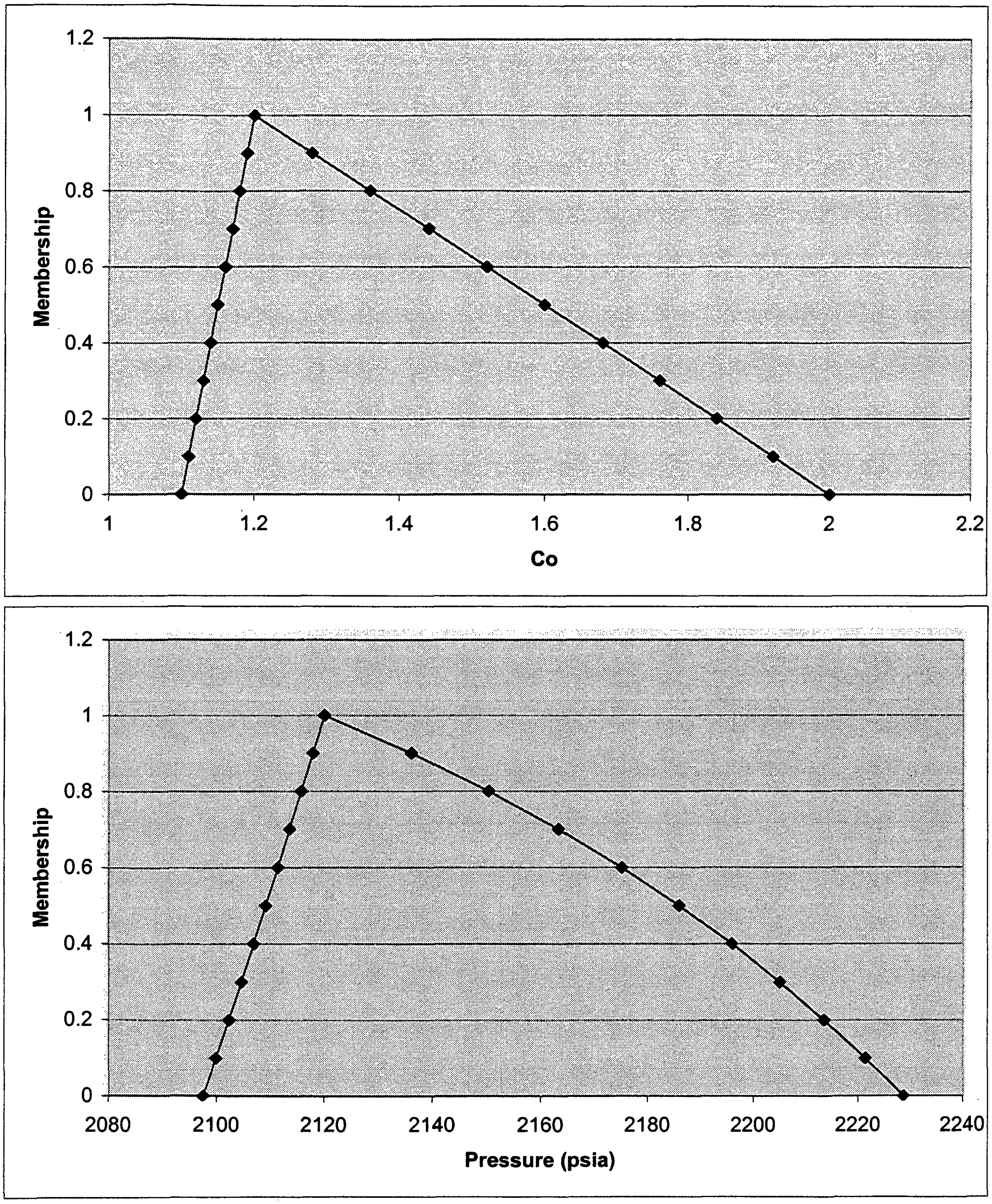


Figure 6-2. Pressure Loss Fuzzy Set

Chapter 7

PAWS VALIDATION AND STUDY OF NOVEL FEATURES

Two field examples (Hasan and Kabir [2002]) are used to evaluate the validity of the modified model and computer program. To quantify the accuracy of different models, an objective function is defined. Results of the validation exercise show that this model is more accurate than some models in this field example. Furthermore, by using this computer program, the effects of acceleration components, fuzzification of velocity distribution coefficient, well deviation, and well diameter are analyzed.

The comparison of models results is quantified using an objective function defined by

$$OB = \frac{1}{N}\sqrt{\sum_{i=1}^{N}(\Delta P_i)^2} \tag{7.1}$$

where Δp_i = pressure deviation from the measured data, and N is the number of measured data.

7.1 Validation Using Field Data

Field example 1 (Hasan and Kabir [2002]): A 5151-ft vertical well produces 23° API dry oil at 1,140 STB/D through 2.99-in. ID tubing. The gas/oil ratio (GOR) is 450 scf/STB, and the gas gravity is 0.80. The following property values are available at the wellhead where pressure is 505 psig:

V_{SL} = 1.61 ft/sec

V_{SG} = 2.284 ft/sec

$\rho_L = 55.042$ lbm/ft^3

$\rho_g = 2.19$ lbm/ft^3

$\mu_L = 13.09$ cp

$\mu_g = 0.019$ cp

$\sigma = 0.0696 \ lbm/s^2$

The pressures calculated by PAWS along the vertical wellbore are shown in the following table. The last five columns represent bubble flow, dispersed bubble flow, slug flow, annular flow, and stratified flow. The flow region is present when the integer values is non-zero.

Table 7-1. Predicted Pressure Along the Vertical Wellbore

```
******************** Output DATA ************************
 # of!pressure! length of!bubble!dis.  !slug!annula!strati!
  cal! (psia) !  pipe(ft)!flow  !bubble!flow!flow  !flow  !
***********************************************************
    1     530.77      50.00      0     0     3     0     0
    2     542.12     100.00      0     0     3     0     0
    3     553.48     150.00      0     0     3     0     0
    4     564.84     200.00      0     0     3     0     0
    5     576.22     250.00      0     0     3     0     0
    6     587.60     300.00      0     0     3     0     0
    7     598.99     350.00      0     0     3     0     0
    8     610.38     400.00      0     0     3     0     0
    9     621.78     450.00      0     0     3     0     0
   10     633.19     500.00      0     0     3     0     0
   11     644.61     550.00      0     0     3     0     0
   12     656.03     600.00      0     0     3     0     0
   13     667.46     650.00      0     0     3     0     0
   14     678.89     700.00      0     0     3     0     0
```

Table 7-1. (cont.) Predicted Pressure Along the Vertical Wellbore

15	690.34	750.00	0	0	3	0	0
16	701.78	800.00	0	0	3	0	0
17	713.24	850.00	0	0	3	0	0
18	724.70	900.00	0	0	3	0	0
19	736.17	950.00	0	0	3	0	0
20	747.64	1000.00	0	0	3	0	0
21	759.12	1050.00	0	0	3	0	0
22	770.60	1100.00	0	0	3	0	0
23	782.09	1150.00	0	0	3	0	0
24	793.59	1200.00	0	0	3	0	0
25	805.09	1250.00	0	0	3	0	0
26	816.60	1300.00	0	0	3	0	0
27	834.94	1350.00	0	0	0	4	0
28	847.18	1400.00	0	0	0	4	0
29	858.38	1450.00	0	0	0	4	0
30	869.16	1500.00	0	0	0	4	0
31	879.76	1550.00	0	0	0	4	0
32	890.31	1600.00	0	0	0	4	0
33	900.89	1650.00	0	0	0	4	0
34	911.54	1700.00	0	0	0	4	0
35	922.30	1750.00	0	0	0	4	0
36	933.18	1800.00	0	0	0	4	0
37	944.21	1850.00	0	0	0	4	0
38	955.40	1900.00	0	0	0	4	0
39	966.77	1950.00	0	0	0	4	0
40	978.32	2000.00	0	0	0	4	0
41	990.07	2050.00	0	0	0	4	0

Table 7-1. (cont.) Predicted Pressure Along the Vertical Wellbore

42	1002.02	2100.00	0	0	0	4	0
43	1014.18	2150.00	0	0	0	4	0
44	1026.56	2200.00	0	0	0	4	0
45	1039.16	2250.00	0	0	0	4	0
46	1051.98	2300.00	0	0	0	4	0
47	1065.04	2350.00	0	0	0	4	0
48	1078.34	2400.00	0	0	0	4	0
49	1091.88	2450.00	0	0	0	4	0
50	1105.66	2500.00	0	0	0	4	0
51	1119.70	2550.00	0	0	0	4	0
52	1133.99	2600.00	0	0	0	4	0
53	1148.53	2650.00	0	0	0	4	0
54	1163.34	2700.00	0	0	0	4	0
55	1178.41	2750.00	0	0	0	4	0
56	1193.74	2800.00	0	0	0	4	0
57	1209.34	2850.00	0	0	0	4	0
58	1225.21	2900.00	0	0	0	4	0
59	1241.36	2950.00	0	0	0	4	0
60	1257.78	3000.00	0	0	0	4	0
61	1274.47	3050.00	0	0	0	4	0
62	1291.45	3100.00	0	0	0	4	0
63	1308.70	3150.00	0	0	0	4	0
64	1326.23	3200.00	0	0	0	4	0
65	1344.03	3250.00	0	0	0	4	0
66	1362.12	3300.00	0	0	0	4	0

Table 7-1. (cont.) Predicted Pressure Along the Vertical Wellbore

67	1380.49	3350.00	0	0	0	4	0
68	1399.14	3400.00	0	0	0	4	0
69	1418.07	3450.00	0	0	0	4	0
70	1437.28	3500.00	0	0	0	4	0
71	1456.76	3550.00	0	0	0	4	0
72	1476.52	3600.00	0	0	0	4	0
73	1496.56	3650.00	0	0	0	4	0
74	1516.87	3700.00	0	0	0	4	0
75	1537.45	3750.00	0	0	0	4	0
76	1558.31	3800.00	0	0	0	4	0
77	1579.43	3850.00	0	0	0	4	0
78	1600.81	3900.00	0	0	0	4	0
79	1622.45	3950.00	0	0	0	4	0
80	1644.36	4000.00	0	0	0	4	0
81	1666.52	4050.00	0	0	0	4	0
82	1688.92	4100.00	0	0	0	4	0
83	1711.58	4150.00	0	0	0	4	0
84	1734.48	4200.00	0	0	0	4	0
85	1757.62	4250.00	0	0	0	4	0
86	1781.00	4300.00	0	0	0	4	0
87	1804.60	4350.00	0	0	0	4	0
88	1828.43	4400.00	0	0	0	4	0
89	1852.48	4450.00	0	0	0	4	0
90	1876.75	4500.00	0	0	0	4	0
91	1901.22	4550.00	0	0	0	4	0

Table 7-1. (cont.) Predicted Pressure Along the Vertical Wellbore

92	1925.90	4600.00	0	0	0	4	0
93	1950.79	4650.00	0	0	0	4	0
94	1975.86	4700.00	0	0	0	4	0
95	2001.13	4750.00	0	0	0	4	0
96	2026.57	4800.00	0	0	0	4	0
97	2052.20	4850.00	0	0	0	4	0
98	2078.00	4900.00	0	0	0	4	0
99	2103.96	4950.00	0	0	0	4	0
100	2130.08	5000.00	0	0	0	4	0
101	2156.36	5050.00	0	0	0	4	0
102	2182.78	5100.00	0	0	0	4	0
103	2209.35	5150.00	0	0	0	4	0
104	2209.89	5151.00	0	0	0	4	0

The pressures calculated by PAWS are compared with measured data and the results from other models (Hasan and Kabir [2000] and Ansari et al.[1994]) in Table 7-2. The objective function values for each model are also listed in Table 7-2. The objective function for PAWS is 22, while the objective function for Ansari is 29 and the objective function for Hasan-Kabir is 17, the lowest value. Figure 7-1 is plotted from the data in Table 7-2. It shows that the PAWS results provide a decent match of the measured data.

Table 7-2. Comparing Calculated and Measured Pressures for a Vertical Well

Depth, ft	Pressure,Psig			
	Data	Hasan-Kabir	Ansari et al.	PAWS
0	505	505	505	505
400	587	593	586	595
650	647	654	641	652
1150	777	781	758	767
1650	920	918	885	886
2150	1074	1063	1021	1026
2650	1237	1212	1165	1133
3150	1407	1369	1316	1294
3650	1582	1530	1473	1482
4150	1850	1695	1634	1697
4650	1960	1864	1799	1936
5151	2105	2034	1968	2194
OB		17.34	29.00	21.87

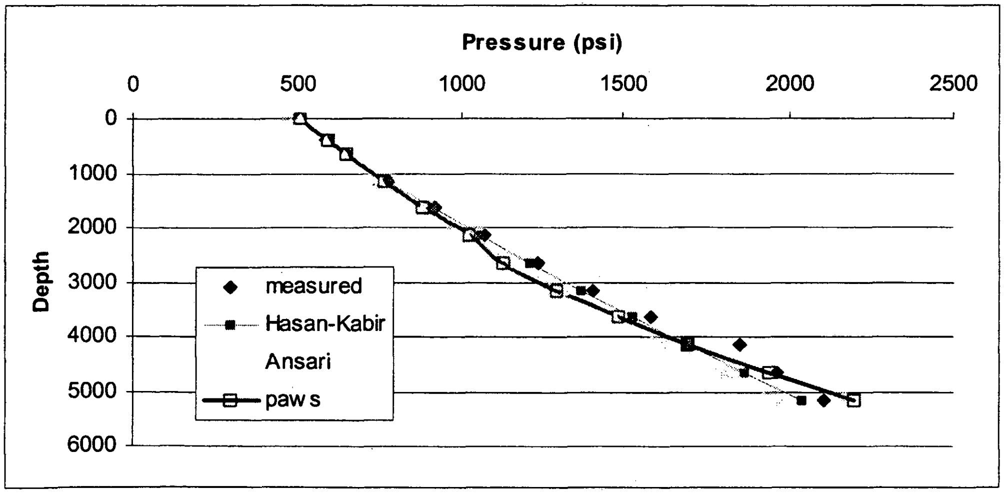


Figure 7-1. Comparing Calculated and Measured Pressures for a Vertical Well

Field example 2 (Hasan and Kabir [2002]): A 17.5° deviated well as Figure 7-2, has measured depth of 6241ft. The well produces 33° API oil at 2922 STB/D with 20.02% water cut through a 2.44-in. ID tubing. The gas/oil ratio (GOR) is 447 scf/STB, and the gas gravity is 0.60. The following property values are available at the wellhead where pressure is 361 psig:

liquid velocity (ft/sec): 6.513
gas velocity (ft/sec): 14.8
liquid density (lbm/ft^3): 53.36
liquid viscosity (cp): 2.25
surface tension (lbm/sec^2): 0.064
gas density (lbm/ft^3): 1.03
gas viscosity(cp): 0.018
gas specific gravity: 0.6

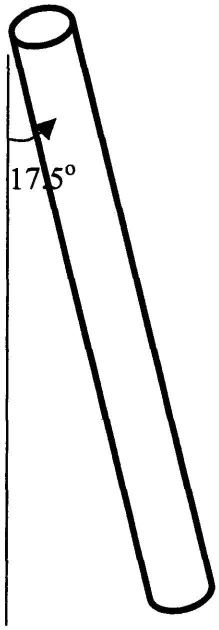


Figure 7-2. Illustration of the Deviated Well

Pressures calculated by PAWS along the wellbore are shown in the following table.

Table 7-3. Predicted Pressure along the Deviated Wellbore

```
******************** Output DATA ************************
 # of!pressure! length of!bubble!dis.  !slug!annula!strati!
  cal! (psia) !  pipe(ft)!flow  !bubble!flow!flow  !flow  !
*********************************************************
    1     389.82      50.00      0     0     3     0     0
    2     403.98     100.00      0     0     3     0     0
    3     418.16     150.00      0     0     3     0     0
    4     432.34     200.00      0     0     3     0     0
    5     446.54     250.00      0     0     3     0     0
    6     460.74     300.00      0     0     3     0     0
    7     474.96     350.00      0     0     3     0     0
    8     489.18     400.00      0     0     3     0     0
    9     503.41     450.00      0     0     3     0     0
   10     517.66     500.00      0     0     3     0     0
   11     531.91     550.00      0     0     3     0     0
   12     546.18     600.00      0     0     3     0     0
   13     560.45     650.00      0     0     3     0     0
   14     574.73     700.00      0     0     3     0     0
   15     589.03     750.00      0     0     3     0     0
   16     603.33     800.00      0     0     3     0     0
   17     617.64     850.00      0     0     3     0     0
   18     631.97     900.00      0     0     3     0     0
   19     646.30     950.00      0     0     3     0     0
   20     660.65    1000.00      0     0     3     0     0
   21     675.00    1050.00      0     0     3     0     0
   22     689.37    1100.00      0     0     3     0     0
```

Table 7-3. (cont'd) Predicted Pressure along the Deviated Wellbore

23	703.74	1150.00	0	0	3	0	0
24	718.13	1200.00	0	0	3	0	0
25	732.52	1250.00	0	0	3	0	0
26	746.93	1300.00	0	0	3	0	0
27	761.35	1350.00	0	0	3	0	0
28	775.78	1400.00	0	0	3	0	0
29	790.21	1450.00	0	0	3	0	0
30	804.66	1500.00	0	0	3	0	0
31	819.12	1550.00	0	0	3	0	0
32	833.59	1600.00	0	0	3	0	0
33	848.07	1650.00	0	0	3	0	0
34	862.57	1700.00	0	0	3	0	0
35	877.07	1750.00	0	0	3	0	0
36	891.58	1800.00	0	0	3	0	0
37	906.10	1850.00	0	0	3	0	0
38	920.64	1900.00	0	0	3	0	0
39	935.18	1950.00	0	0	3	0	0
40	949.74	2000.00	0	0	3	0	0
41	964.31	2050.00	0	0	3	0	0
42	978.88	2100.00	0	0	3	0	0
43	993.47	2150.00	0	0	3	0	0
44	1008.07	2200.00	0	0	3	0	0
45	1022.68	2250.00	0	0	3	0	0
46	1037.30	2300.00	0	0	3	0	0
47	1051.93	2350.00	0	0	3	0	0
48	1066.58	2400.00	0	0	3	0	0

Table 7-3. (cont'd) Predicted Pressure along the Deviated Wellbore

49	1081.23	2450.00	0	0	3	0	0
50	1095.89	2500.00	0	0	3	0	0
51	1110.57	2550.00	0	0	3	0	0
52	1125.26	2600.00	0	0	3	0	0
53	1139.95	2650.00	0	0	3	0	0
54	1154.66	2700.00	0	0	3	0	0
55	1169.38	2750.00	0	0	3	0	0
56	1184.11	2800.00	0	0	3	0	0
57	1198.85	2850.00	0	0	3	0	0
58	1213.61	2900.00	0	0	3	0	0
59	1228.37	2950.00	0	0	3	0	0
60	1243.14	3000.00	0	0	3	0	0
61	1257.93	3050.00	0	0	3	0	0
62	1272.72	3100.00	0	0	3	0	0
63	1287.53	3150.00	0	0	3	0	0
64	1302.35	3200.00	0	0	3	0	0
65	1317.18	3250.00	0	0	3	0	0
66	1332.02	3300.00	0	0	3	0	0
67	1346.87	3350.00	0	0	3	0	0
68	1361.73	3400.00	0	0	3	0	0
69	1376.60	3450.00	0	0	3	0	0
70	1391.49	3500.00	0	0	3	0	0
71	1406.38	3550.00	0	0	3	0	0
72	1421.29	3600.00	0	0	3	0	0
73	1436.20	3650.00	0	0	3	0	0

Table 7-3. (cont'd) Predicted Pressure along the Deviated Wellbore

74	1451.13	3700.00	0	0	3	0	0
75	1466.07	3750.00	0	0	3	0	0
76	1481.02	3800.00	0	0	3	0	0
77	1495.98	3850.00	0	0	3	0	0
78	1510.95	3900.00	0	0	3	0	0
79	1525.93	3950.00	0	0	3	0	0
80	1540.92	4000.00	0	0	3	0	0
81	1555.93	4050.00	0	0	3	0	0
82	1570.94	4100.00	0	0	3	0	0
83	1585.96	4150.00	0	0	3	0	0
84	1601.00	4200.00	0	0	3	0	0
85	1616.04	4250.00	0	0	3	0	0
86	1631.10	4300.00	0	0	3	0	0
87	1646.17	4350.00	0	0	3	0	0
88	1661.25	4400.00	0	0	3	0	0
89	1676.33	4450.00	0	0	3	0	0
90	1691.43	4500.00	0	0	3	0	0
91	1706.54	4550.00	0	0	3	0	0
92	1721.66	4600.00	0	0	3	0	0
93	1736.79	4650.00	0	0	3	0	0
94	1751.93	4700.00	0	0	3	0	0
95	1767.09	4750.00	0	0	3	0	0
96	1782.25	4800.00	0	0	3	0	0
97	1797.42	4850.00	0	0	3	0	0
98	1812.60	4900.00	0	0	3	0	0

Table 7-3. (cont'd) Predicted Pressure along the Deviated Wellbore

99	1827.79	4950.00	0	0	3	0	0
100	1843.00	5000.00	0	0	3	0	0
101	1858.21	5050.00	0	0	3	0	0
102	1873.43	5100.00	0	0	3	0	0
103	1888.67	5150.00	0	0	3	0	0
104	1903.91	5200.00	0	0	3	0	0
105	1919.17	5250.00	0	0	3	0	0
106	1934.43	5300.00	0	0	3	0	0
107	1949.70	5350.00	0	0	3	0	0
108	1964.99	5400.00	0	0	3	0	0
109	1980.28	5450.00	0	0	3	0	0
110	1995.58	5500.00	0	0	3	0	0
111	2010.90	5550.00	0	0	3	0	0
112	2026.22	5600.00	0	0	3	0	0
113	2041.56	5650.00	0	0	3	0	0
114	2056.90	5700.00	0	0	3	0	0
115	2072.25	5750.00	0	0	3	0	0
116	2087.61	5800.00	0	0	3	0	0
117	2102.99	5850.00	0	0	3	0	0
118	2118.37	5900.00	0	0	3	0	0
119	2133.76	5950.00	0	0	3	0	0
120	2149.16	6000.00	0	0	3	0	0
121	2164.57	6050.00	0	0	3	0	0
122	2179.99	6100.00	0	0	3	0	0
123	2195.42	6150.00	0	0	3	0	0
124	2210.86	6200.00	0	0	3	0	0
125	2223.53	6241.00	0	0	3	0	0

For comparison, the pressures calculated by PAWS, measured data, and the calculated pressure by other models are listed in Table 7-4. Objective function values for each model are also listed in Table 7-4. Among the models, PAWS has the second lowest objective function. Figure 7-3 is plotted from the data in Table 7-4. It shows that the results calculated by PAWS provide a good match of the measured.

Table 7-4. Comparing Calculated and Measured Pressures for a Deviated Well

Depth, ft	Pressure, (psi)				
	Data	Hasan-Kabir	Ansari et al.	Beggs-Brill	PAWS
0	361	361	361	361	361
1000	611	615	580	609	645
2000	876	884	810	861	935
3000	1161	1174	1064	1144	1228
4000	1473	1482	1352	1447	1526
5250	1875	1886	1717	1845	1904
5750	2084	2053	1867	2009	2058
6000	2189	2137	1947	2091	2134
6250	2238	2222	2025	2173	2209
OB		7.35	50.35	16.31	14.68

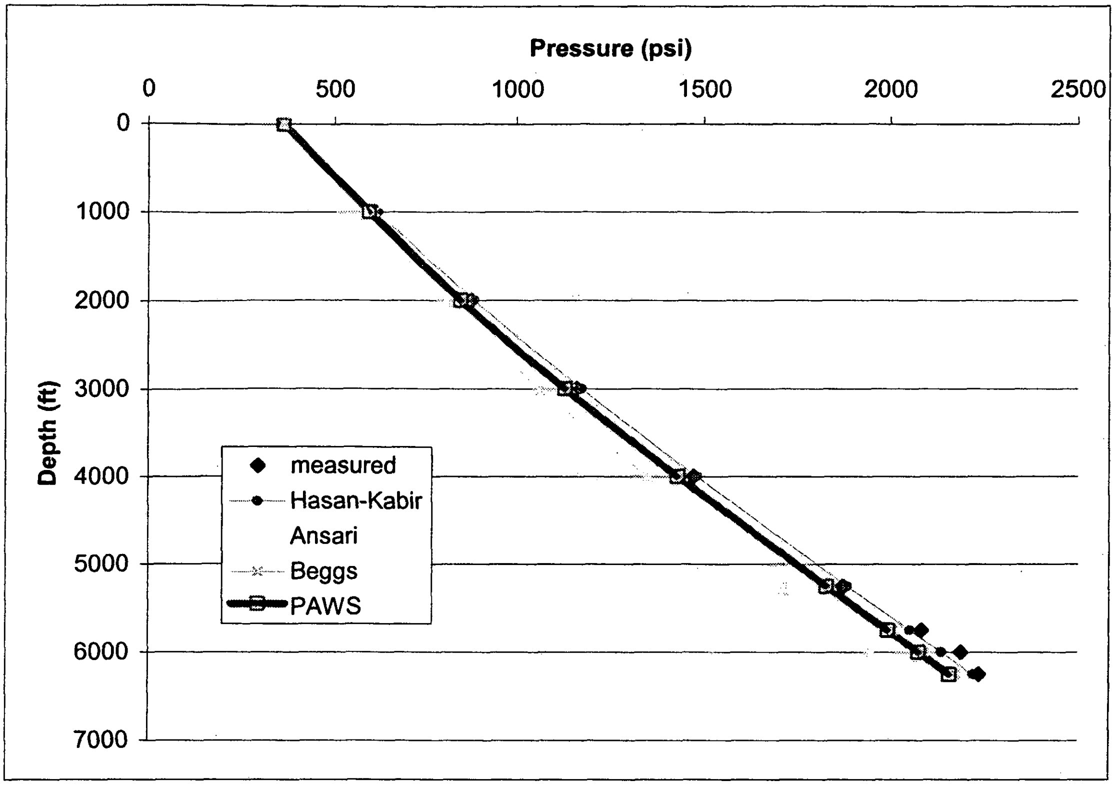


Figure 7-3. Comparing Calculated and Measured Pressure for a Deviated Well

7.2 Effect of Acceleration Component

By running the program, it was found that whether the effect of acceleration component can be neglected depends on different conditions. When the flow pattern along the pipe does not change with a little difference of pressure and the flow rate is not too high, the acceleration component can be neglected in prediction of pressure drop. Otherwise, the effect of acceleration component on pressure drop should be considered.

For the steady-state flow, the pressure drop of the acceleration component mainly results from the big pressure drop between two points of inlet and outlet. The pressure drop leads to the change of gas properties, forming the pressure loss. Because the flow rate of both bubble and stratified flow is very low, the gas properties might vary less than the other flow patterns. Therefore, to compare the effect of acceleration component on pressure drop, only the dispersed bubble, annular and slug flows are chosen in this section.

7.2.1 Neglected Acceleration Component in Prediction of Pressure Drop

Case 1: an oil well with 2.99" ID tubing is producing oil and gas. The superficial velocity of oil and gas are 1.0 ft/sec and 20.824 ft/sec, respectively. The pressure at wellhead is 505 psi. The oil and gas properties are as follows.

Liquid			Gas		
Density (lbm/ft^3)	Viscosity (cp)	Surface tension (lbm/sec^2)	Density (lbm/ft^3)	Viscosity (cp)	Specific Gravity (lbf/sec^2)
55.042	13.09	0.06	2.19	0.019	0.8

The pressure losses are predicted by the PAWS program in both ways of incorporated and non-incorporated acceleration components. They are listed in Table 7-5. The differences between the two series of predicted pressures are also listed in Table 7-5. The difference is less than 0.1 psi along the pipe. The calculated pressures overlap one another in this case.

7.2.2 Include Acceleration Component in Prediction of Pressure Drop

Case 2: Consider another well with the same conditions as in Case 1 except the oil and gas flowrates. In this well, the oil and gas superficial velocity are 4.601 ft/sec and 2.824 ft/sec. The flow in this wellbore is slug flow. And its predicted pressures are listed also in Table 7-5. The difference of predicted pressure between two situations is still trivial, (all of which are less than 0.5 psi), but larger than those of Case 1. This trend shows that the effect of the acceleration component becomes larger as the flow rate increases. Namely, the acceleration component cannot be neglected if the flow rate is too high.

Case 3: consider one more well with the same condition as Case 1 except the flow rates of gas and oil. The oil and gas superficial velocities are 1 ft/sec and 20.84 ft/sec, respectively. The predicted pressures along the well are also listed in Table 7-5. The flow in this well is annular pattern except for the depth range from 2850 ft to 2900 ft, where its pattern becomes dispersed bubble flow. Because of the unstable flow pattern, the difference between two kinds of predicted pressures reaches about 24 psi. Figure 7-4 shows the difference between the two predicted pressure loss calculations. The acceleration component cannot be neglected in this case.

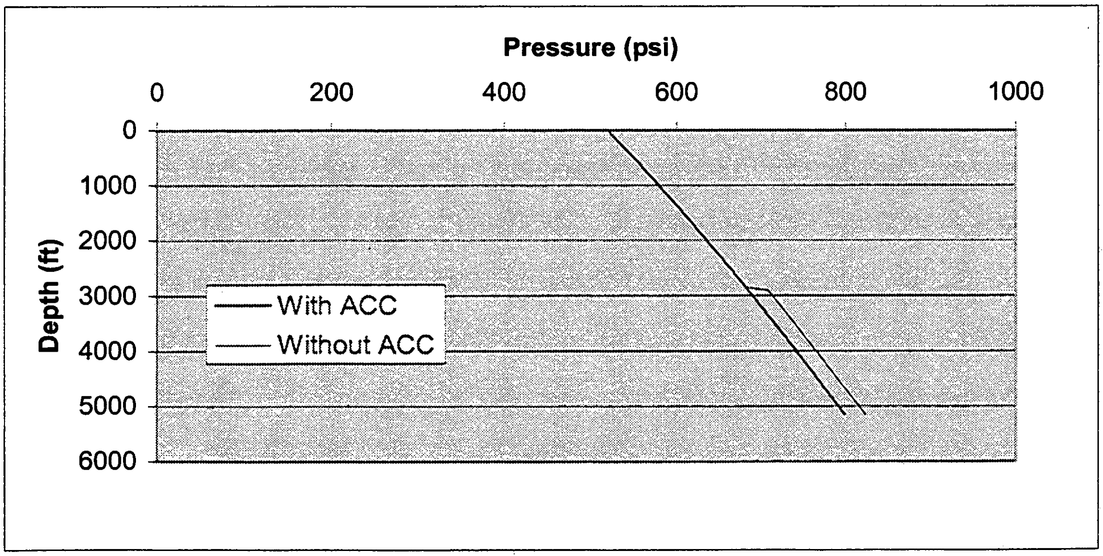


Figure 7-4. Effect of Acceleration Component on Pressure Loss

Table 7-5. Effect of Acceleration Component on Pressure Drop

	Slug Flow			Dispersed Bubble Flow			Annular Flow		
Wellbore Length (ft)	Pressue with ACC. (psia)	Pressue without ACC. (psia)	Difference (psi)	Pressue with ACC. (psia)	Pressue without ACC. (psia)	Difference (psi)	Pressue with ACC. (psia)	Pressue without ACC. (psia)	Difference (psi)
50	533.41	533.41	0.00	535.65	535.65	0.00	522.59	522.59	0.00
100	547.42	547.42	0.00	551.86	551.86	0.00	525.65	525.65	0.00
150	561.44	561.44	0.00	568.08	568.08	0.00	528.70	528.70	0.00
200	575.47	575.47	0.00	584.31	584.31	0.00	531.74	531.74	0.00
250	589.51	589.51	0.00	600.55	600.54	0.01	534.76	534.76	0.00
300	603.57	603.56	0.01	616.79	616.78	0.01	537.78	537.78	0.00
350	617.63	617.63	0.00	633.04	633.03	0.01	540.79	540.78	0.01
400	631.70	631.70	0.00	649.29	649.28	0.01	543.78	543.78	0.00
450	645.79	645.79	0.00	665.55	665.55	0.00	546.77	546.77	0.00
500	659.89	659.88	0.01	681.82	681.81	0.01	549.74	549.74	0.00
550	673.99	673.99	0.00	698.10	698.09	0.01	552.71	552.71	0.00
600	688.11	688.11	0.00	714.38	714.37	0.01	555.66	555.66	0.00
650	702.24	702.23	0.01	730.67	730.66	0.01	558.61	558.61	0.00
700	716.37	716.37	0.00	746.96	746.95	0.01	561.55	561.55	0.00
750	730.52	730.52	0.00	763.26	763.25	0.01	564.47	564.47	0.00
800	744.68	744.67	0.01	779.57	779.56	0.01	567.39	567.39	0.00
850	758.84	758.84	0.00	795.88	795.87	0.01	570.30	570.30	0.00
900	773.02	773.01	0.01	812.20	812.19	0.01	573.20	573.20	0.00
950	787.20	787.20	0.00	828.53	828.52	0.01	576.10	576.10	0.00
1000	801.40	801.39	0.01	844.86	844.85	0.01	578.98	578.98	0.00
1050	815.60	815.60	0.00	861.20	861.18	0.02	581.86	581.86	0.00
1100	829.82	829.81	0.01	877.54	877.53	0.01	584.73	584.72	0.01
1150	844.04	844.03	0.01	893.89	893.87	0.02	587.59	587.58	0.01
1200	858.27	858.26	0.01	910.25	910.23	0.02	590.44	590.44	0.00
1250	872.51	872.50	0.01	926.61	926.59	0.02	593.28	593.28	0.00
1300	886.76	886.75	0.01	942.97	942.95	0.02	596.12	596.12	0.00
1350	901.02	901.01	0.01	959.34	959.32	0.02	598.95	598.95	0.00
1400	915.28	915.28	0.00	975.72	975.70	0.02	601.77	601.77	0.00
1450	929.56	929.55	0.01	992.10	992.08	0.02	604.58	604.58	0.00
1500	943.84	943.83	0.01	1008.49	1008.47	0.02	607.39	607.39	0.00
1550	958.13	958.12	0.01	1024.88	1024.86	0.02	610.19	610.19	0.00
1600	972.43	972.42	0.01	1041.28	1041.26	0.02	612.99	612.98	0.01
1650	986.73	986.73	0.00	1057.68	1057.66	0.02	615.77	615.77	0.00
1700	1001.05	1001.04	0.01	1074.09	1074.06	0.03	618.55	618.55	0.00

Table 7-5. Effect of Acceleration Component on Pressure Drop

	Slug Flow			Dispersed Bubble Flow			Annular Flow		
Wellbore Length (ft)	Pressue with ACC. (psia)	Pressue without ACC. (psia)	Difference (psi)	Pressue with ACC. (psia)	Pressue without ACC. (psia)	Difference (psi)	Pressue with ACC. (psia)	Pressue without ACC. (psia)	Difference (psi)
1750	1015.37	1015.36	0.01	1090.50	1090.48	0.02	621.33	621.33	0.00
1800	1029.70	1029.69	0.01	1106.92	1106.89	0.03	624.09	624.09	0.00
1850	1044.04	1044.03	0.01	1123.34	1123.31	0.03	626.86	626.85	0.01
1900	1058.38	1058.38	0.00	1139.76	1139.74	0.02	629.61	629.61	0.00
1950	1072.73	1072.73	0.00	1156.20	1156.17	0.03	632.36	632.36	0.00
2000	1087.09	1087.09	0.00	1172.63	1172.61	0.02	635.10	635.10	0.00
2050	1101.46	1101.45	0.01	1189.07	1189.05	0.02	637.84	637.84	0.00
2100	1115.83	1115.83	0.00	1205.52	1205.49	0.03	640.57	640.57	0.00
2150	1130.22	1130.21	0.01	1221.96	1221.94	0.02	643.30	643.30	0.00
2200	1144.60	1144.60	0.00	1238.42	1238.39	0.03	646.02	646.02	0.00
2250	1159.00	1158.99	0.01	1254.88	1254.85	0.03	648.73	648.73	0.00
2300	1173.40	1173.39	0.01	1271.34	1271.31	0.03	651.44	651.44	0.00
2350	1187.81	1187.80	0.01	1287.80	1287.78	0.02	654.14	654.14	0.00
2400	1202.22	1202.21	0.01	1304.27	1304.25	0.02	656.84	656.84	0.00
2450	1216.64	1216.63	0.01	1320.75	1320.72	0.03	659.54	659.54	0.00
2500	1231.07	1231.06	0.01	1337.23	1337.20	0.03	662.23	662.22	0.01
2550	1245.50	1245.49	0.01	1353.71	1353.68	0.03	664.91	664.91	0.00
2600	1259.94	1259.93	0.01	1370.19	1370.17	0.02	667.59	667.59	0.00
2650	1274.39	1274.38	0.01	1386.68	1386.65	0.03	670.26	670.26	0.00
2700	1288.84	1288.83	0.01	1403.18	1403.15	0.03	672.93	672.93	0.00
2750	1303.30	1303.29	0.01	1419.68	1419.64	0.04	675.60	675.60	0.00
2800	1317.76	1317.75	0.01	1436.18	1436.15	0.03	678.26	678.26	0.00
2850	1332.23	1332.22	0.01	1452.68	1452.65	0.03	680.91	680.91	0.00
2900	1346.71	1346.70	0.01	1469.19	1469.16	0.03	683.56	706.91	-23.35
2950	1361.19	1361.18	0.01	1485.70	1485.67	0.03	686.21	709.58	-23.37
3000	1375.67	1375.67	0.00	1502.22	1502.18	0.04	688.85	712.23	-23.38
3050	1390.17	1390.16	0.01	1518.73	1518.70	0.03	691.49	714.89	-23.40
3100	1404.66	1404.66	0.00	1535.26	1535.22	0.04	694.13	717.54	-23.41
3150	1419.17	1419.16	0.01	1551.78	1551.75	0.03	696.76	720.19	-23.43
3200	1433.68	1433.67	0.01	1568.31	1568.28	0.03	699.38	722.83	-23.45
3250	1448.19	1448.18	0.01	1584.84	1584.81	0.03	702.01	725.47	-23.46
3300	1462.71	1462.70	0.01	1601.38	1601.34	0.04	704.63	728.11	-23.48

Table 7-5 (cont'd) Effect of Acceleration Component on Pressure Drop

	Slug Flow			Dispersed Bubble Flow			Annula Flow		
Wellbore Length (ft)	Pressue with ACC. (psia)	Pressue without ACC. (psia)	Difference (psi)	Pressue with ACC. (psia)	Pressue without ACC. (psia)	Difference (psi)	Pressue with ACC. (psia)	Pressue without ACC. (psia)	Difference (psi)
3350	1477.23	1477.22	0.01	1617.91	1617.88	0.03	707.24	730.74	-23.50
3400	1491.76	1491.75	0.01	1634.45	1634.42	0.03	709.85	733.37	-23.52
3450	1506.29	1506.28	0.01	1651.00	1650.96	0.04	712.46	736.00	-23.54
3500	1520.83	1520.82	0.01	1667.55	1667.51	0.04	715.07	738.62	-23.55
3550	1535.38	1535.37	0.01	1684.10	1684.06	0.04	717.67	741.24	-23.57
3600	1549.93	1549.92	0.01	1700.65	1700.61	0.04	720.26	743.86	-23.60
3650	1564.48	1564.47	0.01	1717.21	1717.17	0.04	722.86	746.47	-23.61
3700	1579.04	1579.03	0.01	1733.76	1733.73	0.03	725.45	749.08	-23.63
3750	1593.60	1593.59	0.01	1750.33	1750.29	0.04	728.04	751.69	-23.65
3800	1608.17	1608.16	0.01	1766.89	1766.85	0.04	730.62	754.29	-23.67
3900	1637.32	1637.30	0.02	1800.03	1799.99	0.04	735.78	759.49	-23.71
3950	1651.90	1651.89	0.01	1816.60	1816.56	0.04	738.35	762.09	-23.74
4000	1666.48	1666.47	0.01	1833.18	1833.14	0.04	740.93	764.68	-23.75
4050	1681.07	1681.06	0.01	1849.75	1849.72	0.03	743.49	767.27	-23.78
4100	1695.66	1695.65	0.01	1866.33	1866.30	0.03	746.06	769.86	-23.80
4150	1710.26	1710.25	0.01	1882.92	1882.88	0.04	748.62	772.44	-23.82
4200	1724.86	1724.85	0.01	1899.50	1899.46	0.04	751.18	775.02	-23.84
4250	1739.47	1739.46	0.01	1916.09	1916.05	0.04	753.74	777.60	-23.86
4300	1754.08	1754.07	0.01	1932.68	1932.64	0.04	756.30	780.18	-23.88
4350	1768.69	1768.68	0.01	1949.27	1949.23	0.04	758.85	782.75	-23.90
4400	1783.31	1783.30	0.01	1965.87	1965.83	0.04	761.40	785.33	-23.93
4450	1797.93	1797.92	0.01	1982.47	1982.43	0.04	763.94	787.89	-23.95
4500	1812.56	1812.55	0.01	1999.07	1999.03	0.04	766.49	790.46	-23.97

7.3 Effect of Fuzzification of Velocity Distribution Coefficient

Figure 7-4 based on Table 6-1 illustrates that the fuzzification of velocity distribution coefficient plays a significant part in the pressure drop. The difference of 0.9 in distribution coefficient can result in 200 psi change in pressure drop.

Comparing the fuzzy results and non-fuzzy result in the figure, the former describes the uncertainty of distribution coefficient by the fuzzy set, while the latter just gives us a single value for the pressure drop. With the fuzzy set of pressure drop, we can, based on the literature or our experience, evaluate and find a robust pressure drop for well management or design. But, the non-fuzzy model cannot give us such kind of solution.

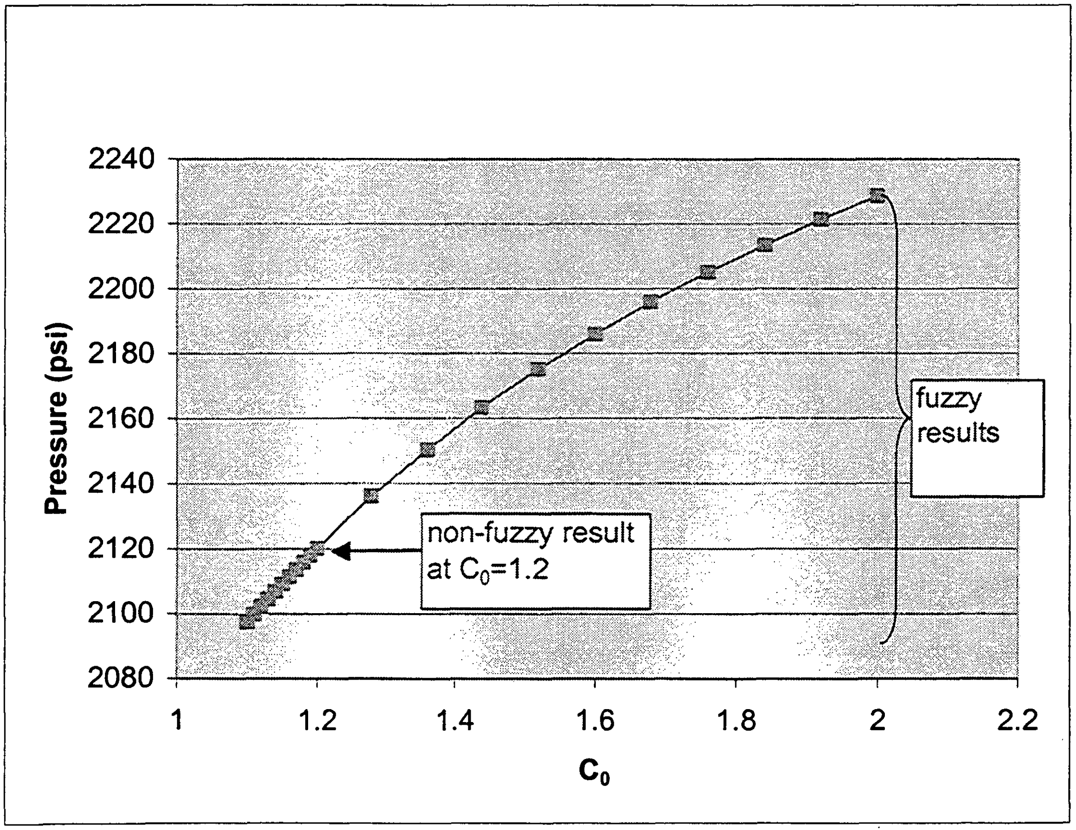


Figure 7-5. Effect of Fuzzification of Velocity Distribution Coefficient

7.4 Effect of Wellbore Deviation

Wellbore deviation plays a significant role in multiphase flow. Pressure drop increases with an increase of inclination angle relative to the horizontal plane. For example, a 3000-ft vertical well with 2.99-in ID tubing produces oil and gas with superficial velocities of 1.23 and 0.5 ft/sec. The following property values are available at the wellhead where the pressure is 561 psi.

Liquid			Gas		
Density (lbm/ft^3)	Viscosity (cp)	Surface tension (lbm/sec^2)	Density (lbm/ft^3)	Viscosity (cp)	Specific Gravity (lbf/sec^2)
53.36	2.257	0.0696	2.19	0.018	0.6

Suppose the well inclination angle is changed from 90°, to 60°, to 30°, and to 0°. The change in deviation directly influences the pressure drop. The pressure drop decreases from 926.76 psi for vertical well to 8.79 psi for a horizontal well. Results are shown in Table 7-6 and Figure 7-6.

The change in wellbore deviation changes flow patterns. This example shows that the flow pattern changes from bubble flow in a vertical well, to slug flow in wells with 30° and 60° inclination, and to stratified flow in a horizontal well.

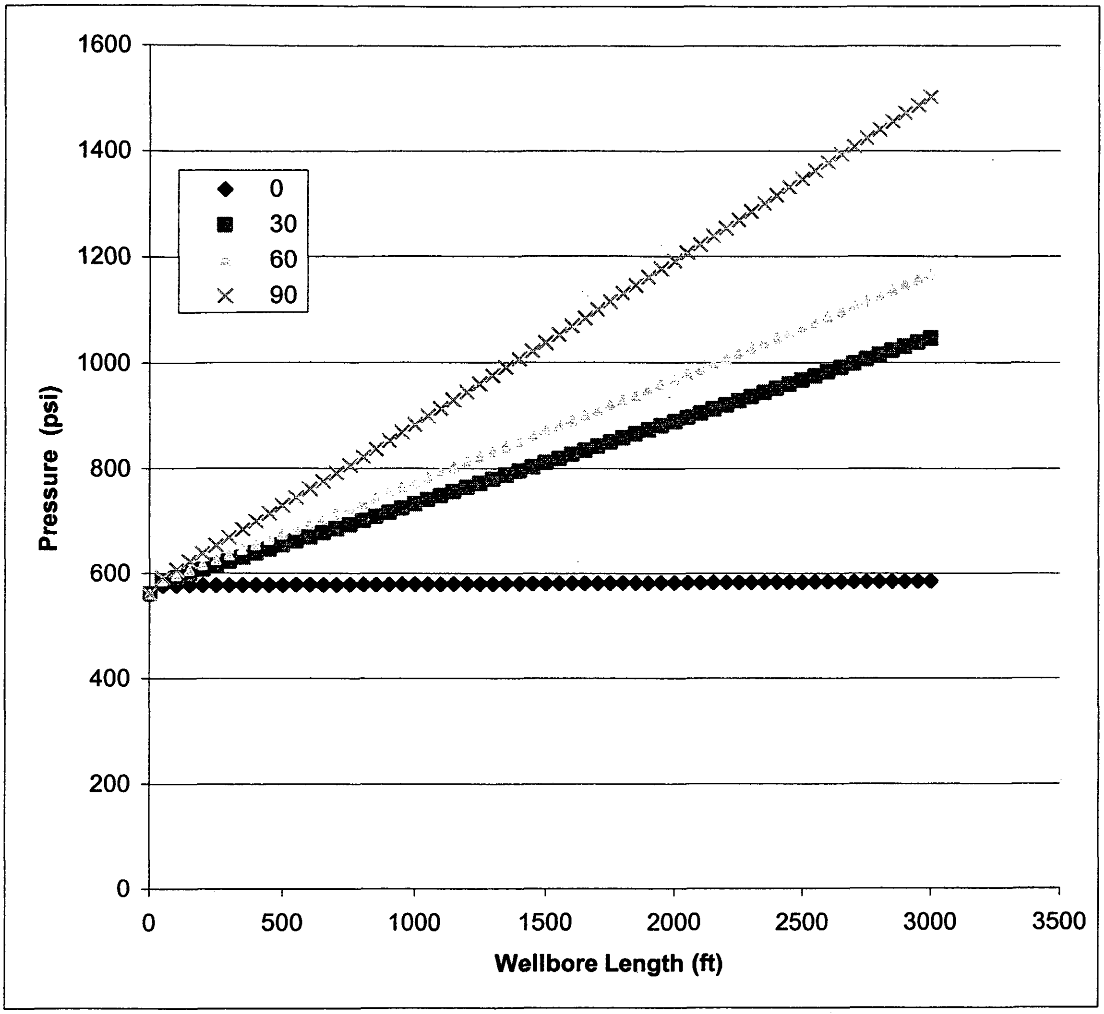


Figure 7-6. Effect of Well Deviation on Pressure Drop

Table 7-6. Effect of Inclination Angle on Pressure Drop

	Pressure (psia)			
Wellbore Length (ft)	Stratified Flow at Inclination Angle of 0°	Slug Flow at Inclination Angle of 30°	Slug Flow at Inclination Angle of 60°	Bubble Flow at Inclination Angle of 90°
0	560.77	560.77	560.77	560.77
100	576.11	591.11	595.09	606.16
200	576.42	606.75	614.71	636.84
300	576.72	622.4	634.34	667.54
400	577.02	638.05	653.98	698.25
500	577.32	653.7	673.64	728.98
600	577.62	669.35	693.31	759.72
700	577.92	685.01	712.99	790.48
800	578.22	700.68	732.69	821.25
900	578.53	716.34	752.41	852.03
1000	578.83	732.01	772.14	882.83
1100	579.13	747.69	791.85	913.65
1200	579.43	763.36	811.52	944.48
1300	579.73	779.03	831.16	975.32
1400	580.03	794.71	850.76	1006.18
1500	580.33	810.38	870.33	1037.06
1600	580.64	826.05	889.87	1067.95
1700	580.94	841.72	909.39	1098.85
1800	581.24	857.39	928.91	1129.77
1900	581.54	873.05	948.46	1160.71
2000	581.84	888.72	968.04	1191.66
2100	582.14	904.4	987.63	1222.63
2200	582.44	920.07	1007.25	1253.62
2300	582.75	935.76	1026.9	1284.62
2400	583.05	951.45	1046.56	1315.64
2500	583.35	967.14	1066.26	1346.67
2600	583.65	982.84	1085.97	1377.72
2700	583.95	998.54	1105.71	1408.79
2800	584.25	1014.25	1125.47	1439.87
2900	584.55	1029.96	1145.26	1470.97
3000	584.86	1045.68	1165.07	1502.09
Pressure Drop	24.09	484.91	604.3	941.32

7.5 Effect of Effect of Diameter

Wellbore diameter influences pressure drop and flow patterns. The pressure drop of the flow decreases with an increase in pipe diameter. For example, consider three 4000 ft deep vertical wells producing gas and oil. Their diameters are 2-inch, 2.44-inch, and 2.99-inch, respectively. Suppose they produce gas and oil with the same properties as follows.

pressure at beginning point (psia) 375.47
temperature (F^o) 62
gas superficial velocity (ft/sec) 7.5
liquid superficial velocity (ft/sec) 12.23
liquid density (lbm/ft^3) 53.36
liquid viscosity (cp) 2.257
Surface tension (lbm/sec^2) 0.06
gas density(lbm/ft^3) 2.19
gas viscosity (cp) 0.018
gas specific gravity 0.6
and gas contains 1 percent N_2, 2 percent H_2S, and 2 percent CO_2.

Using the PAWS program, the pressure drops of the three wells are 2250 psia, 1995 psia, and 1775 psia for 2-inch, 2.44-inch and 2.99-inch wells respectively. The well with the smallest diameter had the largest pressure drop of the three wells. The pressure profiles of the three wells are shown in Figure 7-7.

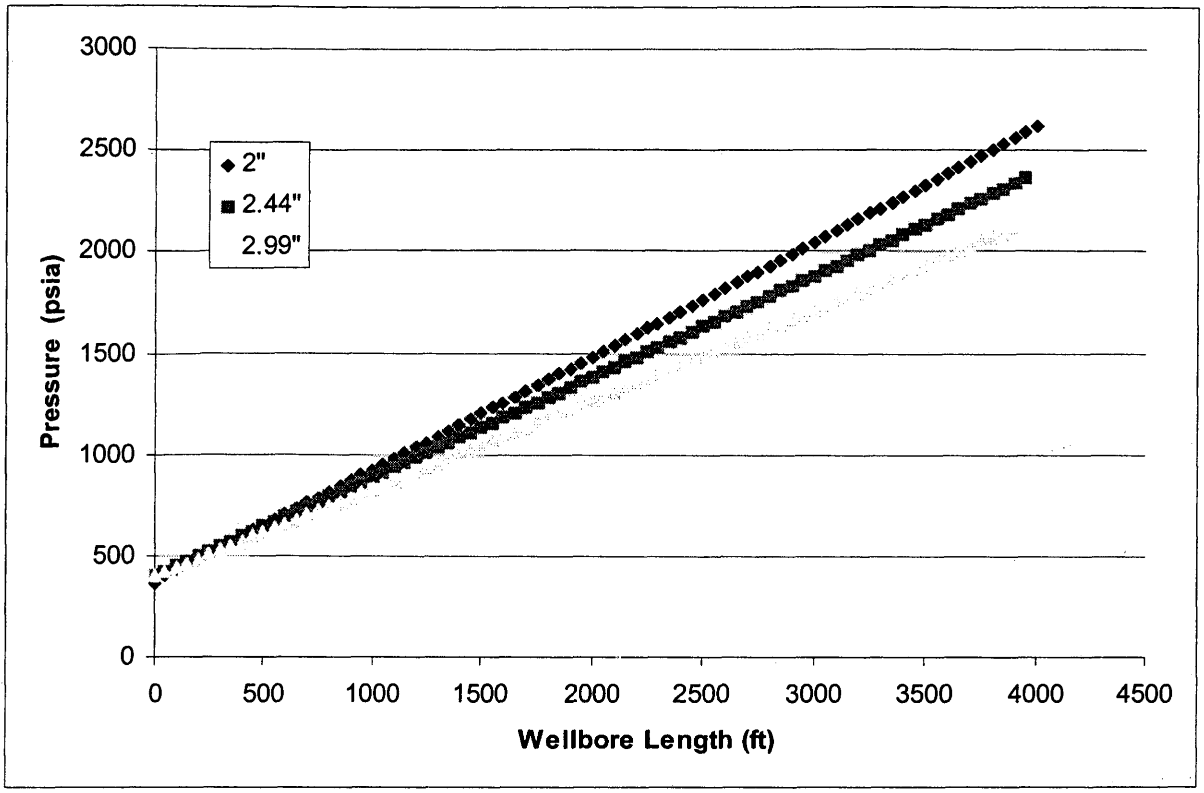


Figure 7-7 Effect of Well Diameter on Pressure

Chapter 8

CONCLUSIONS AND RECOMMENDATIONS

A computer program named PAWS was developed in this study. The PAWS formulation represents the state-of-the-art of gas-liquid flow mechanistic modeling. It simulates flow in pipes and wells using a formulation based on unified mechanistic models. PAWS neglects the pressure drop at the interface between two pipes with different internal diameters. It allows gas properties to change along the length of the pipe, but assumes liquid properties are constant. PAWS can model fluid flow in pipes and wells for inclination angles that range from horizontal to vertical. A special feature of PAWS is the inclusion of a fuzzy model for bubble flow. Based on the results of this thesis, the following conclusions have been reached.

Fuzzy mathematics was introduced into a two-phase flow model to describe the uncertain velocity distribution coefficient. The fuzzy bubble model was formulated and then used to calculate a pressure drop fuzzy set in terms of alpha-cuts. The fuzzification of the distribution coefficient has a significant impact on the pressure drop. The impact depends on the range of uncertainty of the distribution coefficient.

An upper boundary of high liquid level in pipe for the existence of stratified flow was formulated. The upper boundary algorithm helps determine the existence of stratified flow and improves the identification of the correct flow regime.

The computer program PAWS includes the acceleration component and can determine interval length to improve the accuracy of calculated pressure loss values. The acceleration component can be neglected for stable flow, but should be included if the flow pattern is unstable or the flow rate is very high.

The following recommendations are made for future study. They are designed to improve wellbore-reservoir coupling in reservoir simulation.

Incorporate a pressure gradient term for the pressure drop at the interface between two pipes with different internal diameters.

Allow liquid properties to vary with changes in pressure and temperature.

Now that fuzzy mathematics has been introduced into a mechanistic wellbore model, it could also be used to model uncertain reservoir properties, such as porosity and permeability, in reservoir flow models. Future studies should develop a fuzzy reservoir simulator coupled to a fuzzy wellbore simulator, and study the characterization of reservoir properties using fuzzy math.

NOMENCLATURE

A=area, L^2, ft^2

C_0=flow distribution coefficient

d=diameter, L, ft

E=entrainment fraction

F=dimension group

F_A=annular flow parameter

f_m=Moody friction factor

f= friction factor

g=acceleration due to gravity, L/t^2, ft/sec^2

H=liquid holdup

h=liquid level height, L, ft

I=interfacial annular parameter

L=length of pipe, L, ft

R_e=Reynolds number

P=pressure, M/Lt^2, lbf/ft^2

S=perimeter, L, ft

V=velocity, L/t, ft/sec

$v_{0\infty}$=single bubble terminal-rise velocity, L/t, ft/sec

X=Lockhart and Martinelli parameter

Y=Dimension group

δ=film thickness

μ=viscosity, M/Lt, LBM/ft-sec

ρ=density

π=3.1415926

θ=Inclination angle from horizontal

τ=shear stress, M/L^3

σ=surface tension, M/t^2, lbf/ft

Subscripts

A=acceleration component

C=core

CB=critical buoyancy

CD=critical diameter

F=film

G=gas

GH=hydraulic pressure gradient

GF=frictional pressure gradient

H=horizontal

I=interface

L=liquid

LS=liquid slug

M=mixture

Max=maximum

R=radians

S=slug body

SC=superficial core

SL=superficial liquid

SG=superficial gas

TB=Taylor bubble

U=total slug unit

V=vertical

W=wall

REFERENCES

Ansari, A.M., Sylvester, N.D., Sarica, C., and Shoham, O. Brill, J.P. (1994): "A Comprehensive Mechanistic Model for Upward Two-Phase Flow in Wellbores," Paper SPE 20630, Society of Petroleum Engineers, Richardson, Texas

Alves, I.M., Caetano, E.F., Minami, K., and Shoham, O. (1991): "Modeling of Annular Flow Behavior for Gas Wells," Paper SPE 20384

Aziz, K., Govier, G. M. and Forgarasi, M. (July-September 1972): "Pressure Drop in Wells Producing Oil and Gas," J. Can. Pet. Tech.

Barnea, D. (1985): "A Unified Model for Predicting Flow Pattern Transitions for the Whole Range of Pipe Inclination," Int. J. Multiphase Flow, 13, No 1, 1

Barnea, D., Shoham, O., Taitel, Y., and Dukler, A. E. (1985): "Gas Liquid Flow in Inclined Tubes: Flow Pattern Transition for Upward Flow" CHEM. Eng. Sci., 40, 131

Beggs, H.D. and Brill, J.P. (1973): "A Study of Two-Phase Flow in Inclined Pipes," Paper SPE 4007, Society of Petroleum Engineers, Richardson, Texas

Bendiksen, K. H. (1984): "An Experimental Investigation of the Motion of Long Bubbles in Inclined Tubes," Int. J. Multiphase Flow 10, 467

Bornea, J and Kang S. Y. (1985): "Gas-liquid Flow in Inclined Tubes: Flow pattern Transition for Upward Flow," Chem. Eng. Sci. 40, 31

Brill, J.P. and Mukherjee, H. (1999): **Multiphase Flow in Wells**, Society of Petroleum Engineers, Richardson, Texas

Chokshi, R. N., Schmits, Z, and Doty, D.R. (1996): "Experimental Study and the Development of a Mechanistic Model for Two-Phase Flow Through Vertical Tubing," Paper SPE 35676, Society of Petroleum Engineers, Richardson, Texas

Dranchuk, P. M. and Abou-Kassem, J. H. (July-Sept.1975): "Calculation of z-Factors for Natural Gases Using Equations of State," J. Can. Pet. Tech.

Fanchi, J. R. and Christiansen, R. L. (May 28, 2004): "Locating the End-0f-Tubing for Effective Production of Gas," U.S. Department of Energy Report

Gomez, L.E., Shoham, O. and Schmidt, Z. (2000): "Unified Mechanistic Model for Steady-State Two-Phase Flow: Horizontal to Vertical Upward Flow," Paper SPE 65705, Society of Petroleum Engineers, Richardson, Texas

Harmathy, T. Z. (1960): "Velocity of Large Drops and Bubbles in Media of Infinite or Restricted Extent," AICHE J. 6, 281

Hasan, A. R. and Kabir, C. S. (1988): "A Study of Multiphase Flow Behavior in Vertical Wells," Paper SPE 15138, Society of Petroleum Engineers, Richardson, Texas

Hasan, A. R. and Kabir, C.S. (2002): **Fluid Flow and Heat Transfer in Wellbores,** Society of Petroleum Engineers, Richardson, Texas

Henstock, W. H. and Hanratty, T. J. (1976): "The Interfacial Drag and Height of the Wall Layer in Annular Flow," AICHE. J. 22, No. 6, 990

James, J. B., Esfandiar, E. and Thomas, F. (2002): "**Fuzzy Mathematics in Economic and Engineering,**" Physica-Verlag, Heidelberg, Germany

Lee, A. L., Gonzales, M. H.and Eakin, B.E. (1966): "The Viscosity of Natural Gases," Trans., AIME 237, 997

Ouyang, L., and Aziz, K. (1996): "Development of New Wall Friction Factor and Interfacial Friction Factor Correlation for Gas-liquid Stratified Flow in Wells and Pipelines," Paper SPE 35679, Society of Petroleum Engineers, Richardson, Texas

Ozon, P.M., Ferschneider, G., and Chwetzof, A. (1987): "A New Multiphase Flow Model Predicts Pressure and Temperature Profiles," Paper SPE 16535, Society of Petroleum Engineers, Richardson, Texas

Petalas, N. and Aziz, K. (1996): "Development and Testing of a New Mechanistic Model for Multiphase Flow in Pipes," proceeding ASME, Fluid Eng. Division, 236, No. 1

Petalas, N., and Aziz, K. (2000): "A Mechanistic Model for Multiphase Flow in Pipes," J. Can. Pet. Tec.

Scott, S. L., Shoham, O. and Brill, G. P. (August 1989): "Prediction of Slug Length in Horizontal Large-Diameter Pipes," Paper SPE 15103, Society of Petroleum Engineers, Richardson, Texas

Shi, H., Holmes, J.A., Durlofsky, Aziz, K., Diaz, L.R., Alkaya, B. and Oddie, G. (2005): "Drift-Flux Modeling of Two-Phase flow in Wellbores," Paper SPE 84228

Sutton, R. P. (1985): “Compressibility Factor for High-Molecular-Weight Reservoir Gases,” paper SPE 14265, Society of Petroleum Engineers, Richardson, Texas

Taitel, Y., Barnea, D. and Dukler, A. E. (1980): “Modeling Flow Pattern Transition for Steady Upward Flow in Vertical Tubes,” AICHE J., 26, No. 3, 345

Taitel Y. and Dukler, A. E. (1976): “ A Model for Predicting Flow Regime Transition in Horizontal or Near Horizontal Gas-liquid Pipes,” AICHEJ., 22 No. 1, 47

Wallis, G.B. (1969): **One Dimensional Two Phase Flow**, McGraw-Hill Book Co. Inc., New York City

Wichert, E. and Aziz, K. (1972) : “Calculate z’s for Sour Gases,” Hydrocarbon Processing
(May 1972) 49, 267

Xiao, J. J., Shoham, O. and Brill, J. P. (1990): “A Comprehensive Mechanistic Model for Two-Phase Flow in Pipelines,” Paper SPE 20631, Society of Petroleum Engineers, Richardson, Texas

Zahradnik, J. and Kastanek, F. (1979): “Gas Holdup in Uniformly Aerated Bubble Column Reactors,” Chem. Eng. Comm. 3, 423

Zuber, N. and Findlay, J.A. (1965): “Average Volumetric Concentration in Two-phase Flow System,” J. Heat Transfer, Trans. ASME 87, 453

APPENDIX A. MODULES AND ROUTINES

The program developed in this study is composed of six modules written in FORTRAN90 using Digital Visual Fortran® and the Windows® Operating System. There are a number of routines in each module. In this appendix, all of the routines in each of the six modules are listed, and a brief description of each routine is presented.

A.1 Main Program Module

This module contains one subroutine for pattern examination. From six flow patterns: bubble, annular, slug, dispersed bubble, and stratified bubbles, this subroutine can determine the flow pattern in the calculated interval to predict holdup and pressure drop.

This module also plays a number of other roles. The input and output functions are responsible for reading an input data set and outputting data both to screen console and to files. It also controls access to the fuzzy system. In addition, it outputs a profile of flow patterns along the wellbores.

A.2 Stratified Flow Module

This module is composed of three subroutines. The Stratified_3 subroutine is used to predict the pressure gradient and pressure loss for stratified flow. The Stratified_LHL4 subroutine is used to optimize the loop step to solve the high liquid level in pipe from a nonlinear, implicit equation. The Stratified_Solver5 subroutine is used to calculate cross-sectional areas, perimeter, hydraulic diameters, in-situ velocities, friction factor, and shear stress for both liquid and gas. In addition it calls the function that calculates the high liquid level.

A.3 Bubble Flow Module

This module is responsible for predicting the pressure drop of bubble flow, and providing the fuzzy set of pressure drop for different distribution coefficients. It first solves liquid holdup by trial and error from a nonlinear, implicit equation for liquid holdup. It calculates mixture properties such as density, viscosity, and velocity, and uses values from other modules to calculate friction factor of the mixture. Finally, it predicts pressure drop.

A.4 Annulus Module

There are three subroutines in this module. The Annula_3 subroutine predicts the pressure gradient and pressure loss for annular flow. The Annula_FT4 subroutine optimizes the loop step to determine liquid film thickness along the pipe. The Annula_Solver5 subroutine uses average liquid film thickness from Annula_FT4 to calculate the entrainment of liquid and cross sectional areas. Then it calculates liquid holdup, mixture density, viscosity, velocity, and the liquid friction factor of the liquid film. It calculates interfacial shear stress between core flow and liquid film, and the shear stress between liquid film and pipe wall. Finally, it calculates liquid film thickness.

A.5 Slug Module

There are three subroutines in this module. The Slug_3 subroutine predicts the pressure gradient and pressure loss for the slug flow pattern. The Slug_parameter4 subroutine is responsible for a series of parameters for the slug flow, such as single bubble rise velocity, Taylor bubble velocity, slug body length, holdup, in-situ velocity of both fluids in the slug body, fiction factor, and shear stress between slug and pipe wall. In addition, this subroutine uses the Stratified module to solve for holdup, in-situ velocity and shear stress of both liquid and gas with the pipe wall.

A.6 GASFRICTION Module

The two subroutines Pressloss_ann4 and Pressloss are in this module. Pressloss_ann4 is responsible for annular flow, and Pressloss is responsible for the other three flow patterns. Pressloss can optimize the pipe interval of each step to improve the accuracy of the pressure loss calculation. Furthermore it incorporates the acceleration component in the calculation. The GASFRICTION module is used to calculate gas Z-factor, gas density, gas viscosity, and friction factor for both liquid and gas phases. The routines are listed below.

Routine	Description
F_Ppc	Calculate the pseudo critical pressure
F_Tpc	Calculate the pseudo critical temperature
Ppc_wa	Modify the pseudo critical pressure with the contamination of H_2S and/or CO_2
Tpc_wa	Modify the pseudo critical temperature with the contamination of H_2S and/or CO_2
Gasvis_puri	Calculate gas viscosity
Gasvis_impu	Calculate gas viscosity with N_2, H_2S, or CO_2 impurities
Z_factor	Calculate the Z-factor for gas along the pipe.
Fric_factor	Calculate the friction factor for both liquid and gas
Dens_g	Calculate density of gas with different conditions along the pipe.

APPENDIX B. PROGRAM USER'S MANUAL

This appendix is the user's manual for the computer program. It describes input data and output results.

B.1 Input Record

The input data records are read from both files and the computer screen. Most input data records are read once at the beginning of calculation through the input files in the forms presented below.

There are four input records that are read from the screen. The first record tells the computer whether the pressure drop is predicted from surface to bottom or from bottom to surface. The integer "2" represents from surface to bottom, and "1" represents the reverse direction.

The second record is the maximum value for predicting pressure drop in each calculated step. For example, 50 psi might be used for the value.

The third record controls whether the program provides a non-fuzzy result or fuzzy results. The integer "1" means that the user wants a fuzzy output result, while "0" specifies a regular (non-fuzzy) result.

The last record determines whether the calculation incorporates the acceleration component. The integer "1" means that the calculation incorporates the acceleration component, while "0" means it does not. The example is listed as follows:

```
****************PRESSURE DIRECTION CONTOL ******************

 **** FROM SURFACE TO BOTTOM OR FROM BOTTOM TO SURFACE****
  From surface to bottom, please input---2----Otherwise, ---1---
2
```

```
 In case changing mind, please input the number again!
2
 --------------------------------------------------------
 ****************PREDICTION INTERVAL CONTOL ******************


****** MAXIMUM PRESSURE LOSS IN EACH CALCULATION-STEP ******
 How much do you choose? (50 PSI is suggested)
50
 In case changing mind, please input the number again!
50
 --------------------------------------------------------
 ******************FUZZY CONTOL DATA *******************
 Do you want  FUZZY RESULTS?
 If yes, please input  1  ;   if not, input   0
1
 In case changing mind, please input the number again!
0
 --------------------------------------------------------
 ***************** ACCELERATION CONTOL ********************
 In the pressure prediction, do you want to incorperate
           the acceleration component?
 If yes, please input  1  ;   if not, input   0
1
 In case changing mind, please input the number again!
1
```

Most input data records are read once at the beginning of the calculation through input files such as those illustrated below.

File 1

Input fluid properties
number of pipes with different inclined angle
3
pressure at begining point (psia)
575.7
temperature (F)
62
temperature gradient
0.0
gas superficial velocity (ft/sec)
0.5
liquid superficial velocity (ft/sec)
1.23
liquid density (lbm/ft^3)
53.36
liquid viscosity (cp)
2.257
surface tension (lbf/sec^2)
0.0696
gas density(lbm/ft^3)
2.19
gas viscosity(cp)
0.018
gas specific gravity

0.6

N2

0.01

H2S

0.02

CO2

0.02

File 2

```
# pipe div.  length(ft)   incl. angle (radian)diameter(ft)
roughness(ft)

  1,          3000.0,     1.57,                 0.25,          0.00015
  2,          1000.0,     1.57,                 0.203,         0.00015
  3,          1000.0,     1.57,                 0.166,         0.00015
```

Note that the number of pipes with different angles in File 1 must be equal to the number of records in File 2.

B.2 Output Files

There are three output files. When the fuzzy control data is input, the program produces two output files: one is a series of alpha-cuts for pressure prediction (file 2) while another shows all fuzzy sets (file 3). When a non-fuzzy calculation is requested, regular results are presented (file 1). In file 1, the first item is the number of calculation intervals, the second is the calculated pressure, the third is length of pipe, the fourth shows that the flow is bubble flow if the value is 1, the fifth shows that the flow is dispersed bubble flow if the value is 2, the sixth shows that the flow is slug flow if the value is 3, the seventh shows that the flow is annular flow if the value is 4, and the eighth shows that the flow is stratified flow if the value is 6. File 3 has the same items. File 2 has three items: the first is the value for alpha, the second is the lower boundary of alpha-cuts, and the third is the upper boundary of alpha-cuts. Output file examples are listed below.

File 1: Regular Pressure Drop and Patterns Profile with Depth

```
********************* DATA *************************
 # of!pressure! length of!bubble!dis.  !slug!annula!strati!
  cal! (psia) !  pipe(ft)!flow  !bubble!flow!flow  !flow  !

***********************************************************
    1     590.82      50.00     1     0     0     0     0
    2     606.16     100.00     1     0     0     0     0
    3     621.50     150.00     1     0     0     0     0
    4     636.84     200.00     1     0     0     0     0
    5     652.19     250.00     1     0     0     0     0
    6     667.54     300.00     1     0     0     0     0
    7     682.90     350.00     1     0     0     0     0
    8     698.25     400.00     1     0     0     0     0
    9     713.62     450.00     1     0     0     0     0
   10     728.98     500.00     1     0     0     0     0
   11     744.35     550.00     1     0     0     0     0
   12     759.72     600.00     1     0     0     0     0
   13     775.10     650.00     1     0     0     0     0
   14     790.48     700.00     1     0     0     0     0
   15     805.86     750.00     1     0     0     0     0
   16     821.25     800.00     1     0     0     0     0
   17     836.64     850.00     1     0     0     0     0
   18     852.03     900.00     1     0     0     0     0
   19     867.43     950.00     1     0     0     0     0
   20     882.83    1000.00     1     0     0     0     0
   21     898.24    1050.00     1     0     0     0     0
   22     913.65    1100.00     1     0     0     0     0
   23     929.06    1150.00     1     0     0     0     0
   24     944.48    1200.00     1     0     0     0     0
   25     959.90    1250.00     1     0     0     0     0
```

File 1 (cont'd): Regular Pressure Drop and Patterns Profile with Depth

26	975.32	1300.00	1	0	0	0	0
27	990.75	1350.00	1	0	0	0	0
28	1006.18	1400.00	1	0	0	0	0
29	1021.62	1450.00	1	0	0	0	0
30	1037.06	1500.00	1	0	0	0	0
31	1052.50	1550.00	1	0	0	0	0
32	1067.95	1600.00	1	0	0	0	0
33	1083.40	1650.00	1	0	0	0	0
34	1098.85	1700.00	1	0	0	0	0
35	1114.31	1750.00	1	0	0	0	0
36	1129.77	1800.00	1	0	0	0	0
37	1145.24	1850.00	1	0	0	0	0
38	1160.71	1900.00	1	0	0	0	0
39	1176.19	1950.00	1	0	0	0	0
40	1191.66	2000.00	1	0	0	0	0
41	1207.15	2050.00	1	0	0	0	0
42	1222.63	2100.00	1	0	0	0	0
43	1238.12	2150.00	1	0	0	0	0
44	1253.62	2200.00	1	0	0	0	0
45	1269.12	2250.00	1	0	0	0	0
46	1284.62	2300.00	1	0	0	0	0
47	1300.13	2350.00	1	0	0	0	0
48	1315.64	2400.00	1	0	0	0	0
49	1331.15	2450.00	1	0	0	0	0
50	1346.67	2500.00	1	0	0	0	0
51	1362.19	2550.00	1	0	0	0	0
52	1377.72	2600.00	1	0	0	0	0
53	1393.25	2650.00	1	0	0	0	0
54	1408.79	2700.00	1	0	0	0	0
55	1424.33	2750.00	1	0	0	0	0
56	1439.87	2800.00	1	0	0	0	0
57	1455.42	2850.00	1	0	0	0	0
58	1470.97	2900.00	1	0	0	0	0
59	1486.53	2950.00	1	0	0	0	0
60	1502.09	3000.00	1	0	0	0	0
62	1517.54	3050.00	1	0	0	0	0
63	1532.99	3100.00	1	0	0	0	0
64	1548.45	3150.00	1	0	0	0	0
65	1563.91	3200.00	1	0	0	0	0

File 1 (cont'd): Regular Pressure Drop and Patterns Profile with Depth

```
 66    1579.38    3250.00       1      0      0      0      0
 67    1594.85    3300.00       1      0      0      0      0
 68    1610.33    3350.00       1      0      0      0      0
 69    1625.81    3400.00       1      0      0      0      0
 70    1641.30    3450.00       1      0      0      0      0
 71    1656.79    3500.00       1      0      0      0      0
 72    1672.29    3550.00       1      0      0      0      0
 73    1687.79    3600.00       1      0      0      0      0
 74    1703.29    3650.00       1      0      0      0      0
 75    1718.80    3700.00       1      0      0      0      0
 76    1734.31    3750.00       1      0      0      0      0
 77    1749.83    3800.00       1      0      0      0      0
 78    1765.36    3850.00       1      0      0      0      0
 79    1780.88    3900.00       1      0      0      0      0
 80    1796.42    3950.00       1      0      0      0      0
 81    1811.95    4000.00       1      0      0      0      0
 83    1827.28    4050.00       1      0      0      0      0
 84    1842.62    4100.00       1      0      0      0      0
 85    1857.96    4150.00       1      0      0      0      0
 86    1873.30    4200.00       1      0      0      0      0
 87    1888.65    4250.00       1      0      0      0      0
 88    1904.01    4300.00       1      0      0      0      0
 89    1919.36    4350.00       1      0      0      0      0
 90    1934.73    4400.00       1      0      0      0      0
 91    1950.10    4450.00       1      0      0      0      0
 92    1965.47    4500.00       1      0      0      0      0
 93    1980.85    4550.00       1      0      0      0      0
 94    1996.23    4600.00       1      0      0      0      0
 95    2011.62    4650.00       1      0      0      0      0
 96    2027.01    4700.00       1      0      0      0      0
 97    2042.41    4750.00       1      0      0      0      0
 98    2057.82    4800.00       1      0      0      0      0
 99    2073.22    4850.00       1      0      0      0      0
100    2088.63    4900.00       1      0      0      0      0
101    2104.05    4950.00       1      0      0      0      0
102    2119.47    5000.00       1      0      0      0      0
```

File 2: Alpha-Cuts of Pressure Drop

```
****************************OUTPUT DATA ABLE***************************
  ALPHA !LOWER BOUNDARY PRESSURE (PSIA)!UPPER BOUNDARY PRESSURE (PSIA)!

***********************************************************************
   0.00                     2094.58                      2237.23
   0.10                     2097.24                      2229.42
   0.20                     2099.87                      2221.01
   0.30                     2102.45                      2211.92
   0.40                     2104.99                      2202.06
   0.50                     2107.49                      2191.34
   0.60                     2109.96                      2179.63
   0.70                     2112.39                      2166.78
   0.80                     2114.79                      2152.63
   0.90                     2117.15                      2136.95
   1.00                     2119.47                      2119.47
```

File 3: Fuzzy Sets of Pressure Drop and Pattern Profile with Depth

The following table presents some of the results of the file. The complete file is included with the accompanying CD.

```
********************* DATA AT ALPHA************************
 # of!pressure! length of!bubble!dis.  !slug!annula!strati!
  cal! (psia) !  pipe(ft)!flow  !bubble!flow!flow  !flow  !
***********************************************************
LOWER BOUNDARY OF ALPHA= 0.0AND C0= 1.10
    1     590.58     50.00      1     0     0     0     0
    2     605.69    100.00      1     0     0     0     0
    3     620.79    150.00      1     0     0     0     0
    4     635.90    200.00      1     0     0     0     0
    5     651.01    250.00      1     0     0     0     0
```

6	666.13	300.00	1	0	0	0	0
7	681.25	350.00	1	0	0	0	0
8	696.37	400.00	1	0	0	0	0
9	711.50	450.00	1	0	0	0	0
10	726.63	500.00	1	0	0	0	0
11	741.76	550.00	1	0	0	0	0
12	756.90	600.00	1	0	0	0	0
13	772.04	650.00	1	0	0	0	0
14	787.19	700.00	1	0	0	0	0
15	802.34	750.00	1	0	0	0	0
16	817.49	800.00	1	0	0	0	0
17	832.65	850.00	1	0	0	0	0
18	847.81	900.00	1	0	0	0	0
19	862.98	950.00	1	0	0	0	0
20	878.15	1000.00	1	0	0	0	0
21	893.32	1050.00	1	0	0	0	0
22	908.49	1100.00	1	0	0	0	0
23	923.68	1150.00	1	0	0	0	0
24	938.86	1200.00	1	0	0	0	0
25	954.05	1250.00	1	0	0	0	0
26	969.24	1300.00	1	0	0	0	0
27	984.44	1350.00	1	0	0	0	0
28	999.64	1400.00	1	0	0	0	0
29	1014.84	1450.00	1	0	0	0	0
30	1030.05	1500.00	1	0	0	0	0
31	1045.26	1550.00	1	0	0	0	0
32	1060.48	1600.00	1	0	0	0	0
33	1075.70	1650.00	1	0	0	0	0
34	1090.92	1700.00	1	0	0	0	0
35	1106.15	1750.00	1	0	0	0	0
36	1121.39	1800.00	1	0	0	0	0
37	1136.62	1850.00	1	0	0	0	0
38	1151.86	1900.00	1	0	0	0	0
39	1167.11	1950.00	1	0	0	0	0
40	1182.36	2000.00	1	0	0	0	0
41	1197.61	2050.00	1	0	0	0	0
42	1212.87	2100.00	1	0	0	0	0
43	1228.13	2150.00	1	0	0	0	0
44	1243.40	2200.00	1	0	0	0	0
45	1258.67	2250.00	1	0	0	0	0
46	1273.94	2300.00	1	0	0	0	0
47	1289.22	2350.00	1	0	0	0	0

48	1304.51	2400.00	1	0	0	0	0
49	1319.79	2450.00	1	0	0	0	0
50	1335.09	2500.00	1	0	0	0	0
51	1350.38	2550.00	1	0	0	0	0
52	1365.68	2600.00	1	0	0	0	0
53	1380.99	2650.00	1	0	0	0	0
54	1396.30	2700.00	1	0	0	0	0
55	1411.61	2750.00	1	0	0	0	0
56	1426.93	2800.00	1	0	0	0	0
57	1442.25	2850.00	1	0	0	0	0
58	1457.58	2900.00	1	0	0	0	0
59	1472.91	2950.00	1	0	0	0	0
60	1488.24	3000.00	1	0	0	0	0
62	1503.43	3050.00	1	0	0	0	0
63	1518.61	3100.00	1	0	0	0	0
64	1533.81	3150.00	1	0	0	0	0
65	1549.00	3200.00	1	0	0	0	0
66	1564.20	3250.00	1	0	0	0	0
67	1579.41	3300.00	1	0	0	0	0
68	1594.62	3350.00	1	0	0	0	0
69	1609.84	3400.00	1	0	0	0	0
70	1625.06	3450.00	1	0	0	0	0
71	1640.29	3500.00	1	0	0	0	0
72	1655.52	3550.00	1	0	0	0	0
73	1670.75	3600.00	1	0	0	0	0
74	1685.99	3650.00	1	0	0	0	0
75	1701.24	3700.00	1	0	0	0	0
76	1716.49	3750.00	1	0	0	0	0
77	1731.74	3800.00	1	0	0	0	0
78	1747.00	3850.00	1	0	0	0	0
79	1762.27	3900.00	1	0	0	0	0
80	1777.54	3950.00	1	0	0	0	0
81	1792.81	4000.00	1	0	0	0	0
83	1807.85	4050.00	1	0	0	0	0
84	1822.90	4100.00	1	0	0	0	0
85	1837.95	4150.00	1	0	0	0	0
86	1853.00	4200.00	1	0	0	0	0
87	1868.06	4250.00	1	0	0	0	0
88	1883.13	4300.00	1	0	0	0	0
89	1898.20	4350.00	1	0	0	0	0
90	1913.27	4400.00	1	0	0	0	0
91	1928.35	4450.00	1	0	0	0	0

```
     92    1943.44    4500.00       1       0       0       0       0
     93    1958.53    4550.00       1       0       0       0       0
     94    1973.62    4600.00       1       0       0       0       0
     95    1988.73    4650.00       1       0       0       0       0
     96    2003.83    4700.00       1       0       0       0       0
     97    2018.94    4750.00       1       0       0       0       0
     98    2034.06    4800.00       1       0       0       0       0
     99    2049.18    4850.00       1       0       0       0       0
    100    2064.31    4900.00       1       0       0       0       0
    101    2079.44    4950.00       1       0       0       0       0
    102    2094.58    5000.00       1       0       0       0       0
UPPER BOUNDARY OF ALPHA=  0.0AND C0=  2.00
      1     591.96      50.00       1       0       0       0       0
      2     608.44     100.00       1       0       0       0       0
      3     624.93     150.00       1       0       0       0       0
      4     641.41     200.00       1       0       0       0       0
      5     657.90     250.00       1       0       0       0       0
      6     674.39     300.00       1       0       0       0       0
      7     690.89     350.00       1       0       0       0       0
      8     707.39     400.00       1       0       0       0       0
      9     723.88     450.00       1       0       0       0       0
     10     740.39     500.00       1       0       0       0       0
     11     756.89     550.00       1       0       0       0       0
     12     773.40     600.00       1       0       0       0       0
     13     789.91     650.00       1       0       0       0       0
     14     806.42     700.00       1       0       0       0       0
     15     822.94     750.00       1       0       0       0       0
     16     839.45     800.00       1       0       0       0       0
     17     855.97     850.00       1       0       0       0       0
     18     872.50     900.00       1       0       0       0       0
     19     889.02     950.00       1       0       0       0       0
     20     905.55    1000.00       1       0       0       0       0
     21     922.08    1050.00       1       0       0       0       0
     22     938.61    1100.00       1       0       0       0       0
     23     955.15    1150.00       1       0       0       0       0
     24     971.69    1200.00       1       0       0       0       0
     25     988.23    1250.00       1       0       0       0       0
     26    1004.78    1300.00       1       0       0       0       0
     27    1021.32    1350.00       1       0       0       0       0
     28    1037.87    1400.00       1       0       0       0       0
     29    1054.43    1450.00       1       0       0       0       0
     30    1070.98    1500.00       1       0       0       0       0
```

31	1087.54	1550.00	1	0	0	0	0
32	1104.10	1600.00	1	0	0	0	0
33	1120.66	1650.00	1	0	0	0	0
34	1137.23	1700.00	1	0	0	0	0
35	1153.80	1750.00	1	0	0	0	0
36	1170.37	1800.00	1	0	0	0	0
37	1186.95	1850.00	1	0	0	0	0
38	1203.53	1900.00	1	0	0	0	0
39	1220.11	1950.00	1	0	0	0	0
40	1236.69	2000.00	1	0	0	0	0
41	1253.28	2050.00	1	0	0	0	0
42	1269.87	2100.00	1	0	0	0	0
43	1286.46	2150.00	1	0	0	0	0
44	1303.06	2200.00	1	0	0	0	0
45	1319.65	2250.00	1	0	0	0	0
46	1336.25	2300.00	1	0	0	0	0
47	1352.86	2350.00	1	0	0	0	0
48	1369.47	2400.00	1	0	0	0	0
49	1386.08	2450.00	1	0	0	0	0
50	1402.69	2500.00	1	0	0	0	0
51	1419.30	2550.00	1	0	0	0	0
52	1435.92	2600.00	1	0	0	0	0
53	1452.55	2650.00	1	0	0	0	0
54	1469.17	2700.00	1	0	0	0	0
55	1485.80	2750.00	1	0	0	0	0
56	1502.43	2800.00	1	0	0	0	0
57	1519.06	2850.00	1	0	0	0	0
58	1535.70	2900.00	1	0	0	0	0
59	1552.34	2950.00	1	0	0	0	0
60	1568.98	3000.00	1	0	0	0	0
62	1585.68	3050.00	1	0	0	0	0
63	1602.38	3100.00	1	0	0	0	0
64	1619.08	3150.00	1	0	0	0	0
65	1635.79	3200.00	1	0	0	0	0
66	1652.50	3250.00	1	0	0	0	0
67	1669.21	3300.00	1	0	0	0	0
68	1685.93	3350.00	1	0	0	0	0
69	1702.64	3400.00	1	0	0	0	0
70	1719.37	3450.00	1	0	0	0	0
71	1736.09	3500.00	1	0	0	0	0
72	1752.82	3550.00	1	0	0	0	0
73	1769.55	3600.00	1	0	0	0	0

```
      74    1786.29   3650.00       1       0       0       0       0
      75    1803.03   3700.00       1       0       0       0       0
      76    1819.77   3750.00       1       0       0       0       0
      77    1836.51   3800.00       1       0       0       0       0
      78    1853.26   3850.00       1       0       0       0       0
      79    1870.01   3900.00       1       0       0       0       0
      80    1886.77   3950.00       1       0       0       0       0
      81    1903.52   4000.00       1       0       0       0       0
      83    1920.18   4050.00       1       0       0       0       0
      84    1936.83   4100.00       1       0       0       0       0
      85    1953.50   4150.00       1       0       0       0       0
      86    1970.16   4200.00       1       0       0       0       0
      87    1986.83   4250.00       1       0       0       0       0
      88    2003.50   4300.00       1       0       0       0       0
      89    2020.17   4350.00       1       0       0       0       0
      90    2036.85   4400.00       1       0       0       0       0
      91    2053.53   4450.00       1       0       0       0       0
      92    2070.21   4500.00       1       0       0       0       0
      93    2086.90   4550.00       1       0       0       0       0
      94    2103.59   4600.00       1       0       0       0       0
      95    2120.28   4650.00       1       0       0       0       0
      96    2136.98   4700.00       1       0       0       0       0
      97    2153.68   4750.00       1       0       0       0       0
      98    2170.38   4800.00       1       0       0       0       0
      99    2187.09   4850.00       1       0       0       0       0
     100    2203.80   4900.00       1       0       0       0       0
     101    2220.51   4950.00       1       0       0       0       0
     102    2237.23   5000.00       1       0       0       0       0
LOWER BOUNDARY OF ALPHA= 0.1AND C0= 1.11
       1     590.61     50.00       1       0       0       0       0
       2     605.74    100.00       1       0       0       0       0
       3     620.87    150.00       1       0       0       0       0
       4     636.00    200.00       1       0       0       0       0
```

APPENDIX C. FORTRAN 90 SOURCE CODE

This source code for the FORTRAN 90 program is included with the accompanying CD. The program is written using Digital Visual Fortran® and the Windows® Operating System. The code is divided into six modules. The first module is the main program and incorporates subroutines that identify flow patterns. The second module is the stratified flow module. The third module is the bubble flow module. The fourth module is the annular flow module. The fifth module is the slug flow module. The sixth module contains the functions that calculate gas properties, friction factors, and two types of pressure prediction subroutines.

```
!*********************************************************************
!*                                                                   *
!*         ######## MAIN PROGRAM---PAWS#########                     *
!*                                                                   *
!*********************************************************************
!*********************************************************************
!* GAS AND LIQUID PROPERTIES                                         *
!* rhoG        gas density  (lbm/ft3)                                *
!* rhoL        liquid density  (lbm/ft3)                             *
!* rhoM        mixture density                                       *
!* muG         gas viscosity (cp)                                    *
!* muL         liquid viscosity  (cp)                                *
!* muM         mixture viscosity  (cp)                               *
!* sigma       face tension  (lbm/sec2)                              *
!* Sgas        gas specific gravity                                  *
!*-------------------------------------------------------------------*
!*PRESSURE AND TEMPERATUE                                            *
!* P           pressure (psia)                                       *
!* T           temperature (R)                                       *
!* Ppc         psuedo critical pressure (psi)                        *
!* Tpc         psuedo critical temperature (R)                       *
!* Ppr         reduced pressure                                      *
!* Tpr         reduced temperature                                   *
!* Tgrad       temperature gradient(R/ft)                            *
!* Ploss       prediction of pressure loss (psi)                     *
!* PlossA      the pressure loss results from acceleartion compo.   *
!* z           z_factor                                              *
!*-------------------------------------------------------------------*
!* VELOCITY                                                          *
!* vG          in-situ gas velocity  (ft/sec)                        *
!* vL          in-situ liquid velocity  (ft/sec)                     *
!* vSG         superficial gas velocity   (ft/sec)                   *
!* vSL         superficial liquid velocity  (ft/sec)                 *
!*-------------------------------------------------------------------*
!* VARIABLES ABOUT PIPE                                              *
!* L           wellbore length (ft)                                  *
!* d           pipe diameter (ft)                                    *
!* rough       pipe roughness (ft)                                   *
!* theta       pipe inclined angle from horizontal plane (radian)    *
!* Step        interval length (ft)                                  *
!* ACL         accumulative length of calculation (ft)               *
!* N           Total number of different pipes                       *
!*-------------------------------------------------------------------*
!* GAS MIXTURE                                                       *
!* N2          fraction in gas (%)                                   *
!* H2S         fraction in gas (%)                                   *
!* CO2         friction in gas (%)                                   *
!*-------------------------------------------------------------------*
```

```
!*-------------------------------------------------------------------*
!*  CONTROL DATA
!* DI           presssure from surface to bottom or reconverse      *
!* ACL          control length  (ft)                                *
!* KCA          control data for including acceleration component   *
!* KCF          control output fuzzy or not                         *
!* Maxip        control prediction pressure in each interval(ft)    *
!* Maxi         maximum number of loop                              *
!*-------------------------------------------------------------------*
!* CONSTANT VALUE                                                   *
!* PI=3.141592653589793                                             *
!* g=32.2       gravity (ft/sec2)                                   *
!* Ps=14.7      standart pressure (psi)                             *
!* Tsc=60       standart pressure (F)                               *
!*-------------------------------------------------------------------*
!* FUZZY VARIBLES and OTHEER VARIABLES                              *
!* regime(5)   represent patterns                                   *
!* alpha                                                            *
!* aa, bb, cc  parameter of fuzzy set                               *
!* C0          velocity distribution coefficient                    *
!********************************************************************

PROGRAM MULTIPHASE

USE GASFRICTION
USE SLUG
USE STRATIFIED
USE BUBBLE
USE ANNULA

IMPLICIT NONE

Real(8)::vSG
Real(8)::vSL
Real(8)::vSG0
Real(8)::vSL0


Real(8)::rhoG
Real(8)::rhoL
Real(8)::muG
Real(8)::muL
Real(8)::rhoG0
Real(8)::rhoGR
Real(8)::muG0
Real(8)::muGR
Real(8)::sigma
Real(8)::theta
Real(8)::Sgas
```

```
Real(8)::T0         !temperature at begining point
Real(8)::P0         !pressure at begining point
Real(8)::T
Real(8)::Tgrad
Real(8)::Tpc, Ppc, Tpr, Ppr
Real(8)::P
Real(8)::Ploss
real(8)::Z
Real(8):: Step
Real(8)::d
Real(8)::rough
Real(8):: L
Real(8):: ACL

Real(8), parameter::PI=3.141592653589793
Real(8), parameter::g=32.2
Real(8), parameter::Ps=14.7
Real(8), parameter::Tsc=60
Integer, parameter::maxi=20

Integer::numb
Integer::N
Real(8), dimension(:), allocatable::L0, theta0, d0, rough0
Real(8), dimension(:)::PP(10000), LL(10000)
Integer, dimension(:,:)::Pat(1:5, 1:10000)
Real(8), dimension(:,:)::PF(1:2, 0:10)
Integer::ind, boundb

Real(8)::rho
Real(8)::rhoM
Real(8)::muM


!gas mixture
Real(8)::N2
Real(8)::H2S
Real(8)::CO2

Integer::K,  NS, NR  !loop--number
Integer, dimension(:)::regime(5)!represent patterns


!CONTROL VARIABLES
Integer::KCA, KCF, DI
Real(8)::KCP, Maxip



Real(8)::C0
```

```
Integer::bound
real(8)::alpha
real(8)::aa, bb, cc   !parameter of fuzzy set

Integer::IO

real(8)::deriFG
Real(8)::P1, P2      !intermediate value for calculation of pressure
Real(8):: IV1, IV2, IV3, IV4, IV5 !intermediate variable
Real(8):: R1, R2, R3, R4, R5, R6, R7, R8, R9, R10 !replacing variable
!--------------------------------------------------------------------

!--------------------------------------------------------------------
!Read data from file 1
OPEN(UNIT=100, file="Fluid_P.DAT",action="read", iostat=io,
status="old" )

If(IO>0) stop "can not open file"

read(100, *)
!the number of pipes with different inclined angles
read(100, *)
read(100, *)N
!pressure
read(100, *)
read(100, *)p0
!temperature
read(100, *)
read(100, *)T0
!temperature gradient
read(100, *)
read(100, *)Tgrad

!gas superfacial velocity
read(100, *)
read(100, *)vSG0

!liquid superfacial velocity
read(100, *)
read(100, *)vSL0
!liquid properties
read(100, *)
read(100, *)rhoL
read(100, *)
read(100, *)muL
read(100, *)
read(100, *)sigma

!Gas properties
read(100, *)
```

```
read(100, *)rhoG0
read(100, *)
read(100, *)muG0
read(100, *)
read(100, *)Sgas
read(100, *)
read(100, *)N2
read(100, *)
read(100, *)H2S
read(100, *)
read(100, *)CO2
close (unit=100)
!-------------------------------------------------------------------


!-------------------------------------------------------------------
!allocate array

allocate(L0(0:N))
allocate(theta0(0:N))
allocate(d0(0:N))
allocate(rough0(0:N))
!-------------------------------------------------------------------




!-------------------------------------------------------------------
!Read data from File 2 about pipe information

OPEN(UNIT=200, file="pipe.DAT",action="read", iostat=io, status="old" )

If(IO>0) stop "can not open pipe file"

read(200, *)

Do k=1, N

   read(200, *)IV1, L0(k), theta0(k), d0(k),  rough0(k)

Enddo

Close (unit=200)
!-------------------------------------------------------------------


!unit converstion of temperature and viscosity

T0=T0+460           !from F to R
```

```
muL=0.00672*muL     !from cp to lbm/sec.ft
muG0=0.00672*muG0
!-------------------------------------------------------------------


!define the fuzzy set of velocity distribution coefficient
c0=1.2
aa=1.1
bb=1.2
cc=2.0
!-------------------------------------------------------------------


!-------------------------------------------------------------------
!control number input
!PRESSURE LOSS FROM SURFACE TO BOTTOM OR OPPOSITE
WRITE(*, *) "---------------------------------------------------------"
WRITE(*, *) "****************PRESSURE DIRECTION CONTOL
******************"
WRITE(*,*)
WRITE(*, *) "**** FROM SURFACE TO BOTTOM OR FROM BOTTOM TO SURFACE****"
WRITE(*, *) " From surface to bottom, input---2----,Otherwise, ---1---
"
Read(*,*)     DI
WRITE(*, *) "In case changing mind, please input the number again!"
Read(*,*)     DI
WRITE(*, *) "---------------------------------------------------------"



!-------------------------------------------------------------------
!MAXIMUM PRESSURE DROP IN EACH STEP
WRITE(*, *) "---------------------------------------------------------"
WRITE(*, *) "****************PREDICTION INTERVAL CONTOL
******************"
WRITE(*,*)
WRITE(*, *) "****** MAXIMUM PRESSURE LOSS IN EACH CALCULATION-STEP
******"
WRITE(*, *) " How much do you choose? (50 PSI is suggested)"
Read(*,*)     MAXIP
WRITE(*, *) " In case changing mind, please input the number again!"
Read(*,*)     MAXIP
WRITE(*, *) "---------------------------------------------------------"

!-------------------------------------------------------------------
!REQUIRE FUZZY RESULT OR NOT

WRITE(*, *) "*****************FUZZY CONTOL DATA ******************"
WRITE(*, *) " Do you want  FUZZY RESULTS?"
WRITE(*, *) " If yes, please input  1  ;   if not, input   0"
```

```
Read(*,*) KCF
WRITE(*, *) " In case changing mind, please input the number again!"
Read(*,*) KCF
WRITE(*, *) "-------------------------------------------------------"

!-------------------------------------------------------------------




!INCORPORATE ACCELERTION COMPONENET OR NOT
WRITE(*, *) "***************** ACCELERATION CONTOL
*********************"
WRITE(*, *) "In the pressure prediction, do you want to incorporate"
WRITE(*, *) "            the acceleration component?"
WRITE(*, *) " If yes, please input  1  ;   if not, input   0"
Read(*,*) KCA
WRITE(*, *) " In case changing mind, please input the number again!"
Read(*,*) KCA
WRITE(*, *) "-------------------------------------------------------"




!-------------------------------------------------------------------
!calculate psuedo critical pressure and temperature

     Ppc = f_Ppc(Sgas)
     Tpc = f_Tpc(Sgas)


  If ((H2S>0).or.(CO2>0)) then
    Ppc=Ppc_wa(Tpc, Ppc, CO2, H2S)
    Tpc=Tpc_wa(Tpc,  CO2, H2S)

  Endif
!-------------------------------------------------------------------



!initialize the pattern
  pat=0
  d0(0)=d0(1)
  NS=0
  T=T0          !temperature at beginning point
  L0(0)=0.0    !length for each angle
  ACL=0.0      !cumulative length
```

```
!--------------------------------------------------------------------

!calculate z-factor
  Ppr=p0/Ppc
  Tpr=T0/Tpc

  z=Z_factor(Ppr, Tpr)


 !calculate gas_viscosity
  If(((N2>0).or.(H2S>0).or.(CO2>0)).and.(T>560).and.(T<760)) then
      muG=Gasvis_Impu(T, Sgas, Ppr, Tpr, N2, CO2, H2S)

  Else
   muG=Gasvis_Puri(P0, T0, Sgas, Z)
  End if

  mugR=mug0/mug
!--------------------------------------------------------------------



 ! calculate density
    rhoG=dens_g(P0, T0 , Z, Sgas)
    rhogR=rhog0/rhog
    rhogr=1
!--------------------------------------------------------------------


!output file
OPEN(400, FILE="OUTPUT.DAT", ACTION="WRITE")
WRITE(400, *) "********************* DATA AT
ALPHA*************************"
WRITE(400, *) "# of!pressure! length of!bubble!dis.  !slug
!annula!strati!"
WRITE(400, *) " cal! (psia) !  pipe(ft)!flow  !bubble!flow  !flow
!flow  !"
WRITE(400, *)
"************************************************************"

     if(KCF==0) then
   alpha=1
     else
   alpha=0
     end if

 IV1=1.1
```

```
 boundb=2

 if(alpha==1)then
      boundb=1
  iv1=1.0
     endif


  DO          !loop 1 for calculating the fuzzy set

   DO BOUND=1, boundb     !loop 2 for calculating the upper and lower
boundary
   ACL=0.0
   L=0.0
   p=p0
   NS=0
   T=T0
   muG=muG0
   rhoG=rhoG0


 IF (BOUND==1) THEN
      c0=aa+alpha*(bb-aa)
      else
      c0=cc-alpha*(cc-bb)
 ENDIF
   If(kcf==1)then
    IF (BOUND==1) THEN
         WRITE(400,fmt="(A24, F4.1, a7, F5.2)")&
      "LOWER BOUNDARY OF ALPHA=", ALPHA, "AND C0=", C0
     ELSE
      WRITE(400,fmt="(A24, F4.1, a7, F5.2)")&
    "UPPER BOUNDARY OF ALPHA=", ALPHA, "AND C0=", C0
     ENDIF
    endif

   vSG=vSG0
   vSL=vSL0
       DO K=1, N       !loop3 for calculating the different pipe

 ACL=ACL+L0(k)
         theta=theta0(k)
         d=d0(k)
         rough=rough0(k)
 vSG=vSG*d0(k-1)**2/d0(k)**2
 vSL=vSL*d0(k-1)**2/d0(k)**2


     do                      ! loop 4 for calculating the pressure drop
      NS=NS+1
```

```
         regime=0

      if (L>=ACL) exit

       call patterns_2(KCA, maxip, c0, d, rough, vSG, vSL, rhoG,&
    rhoL, muG, muL, sigma, theta, Sgas, Z, T,Tgrad,Tpc, P,&
  Ppc, Ploss, L, step, ACL,regime, DI)


!SAVE RESULT
       L=L+Step
       p=p+Ploss
       T=T+Tgrad*step

!CALCULATE THE FLUID PLROPERTIES OF NEW POINT FOR NEXT STEP.
   Ppr=p/Ppc
   Tpr=T/Tpc
!calculate z-factor
       z=Z_factor(Ppr, Tpr)

!calculate gas_viscosity

    if(((N2>0).or.(H2S>0).or.(CO2>0)).and.(T>100).and.(T<300)) then
    muG=Gasvis_Impu(T, Sgas, Ppr, Tpr, N2, CO2, H2S)
    else
muG=Gasvis_Puri(P, T, Sgas, Z)
    end if
    mug=mugR*muG

    rhoG=dens_g(P, T, Z, Sgas)
    rhog=rhog*rhogR


!record pressure, length
pp(ns)=p
ll(ns)=L

!record pattern
do nr=1, 5
pat(nr, ns)=regime(NR)
enddo


  WRITE(400,fmt="(I5, 2f10.2, 5I6)")NS, pp(ns), LL(ns), &
            pat(1,ns), pat(2,ns), pat(3,ns),pat(4,ns),pat(5,ns)


       enddo
   end do
```

```
  !  IF(ALPHA>1) EXIT

 IND=INT(10*ALPHA)

   IF(ind>10) EXIT


 PF(BOUND, IND)=P


   ENDDO

    alpha=alpha+0.1


if(alpha>=iv1) exit

   ENDDO
    PF(2,10)=PF(1,10)


IF(PF(2, 1)/=0.0) THEN

OPEN(300, FILE="FUZZY_RESULTS_PIPE_END.DAT", ACTION="WRITE")
WRITE(300, *) "****************************OUTPUT DATA TABLE&
                ***************************"
WRITE(300, *) " ALPHA !LOWER BOUNDARY PRESSURE (PSIA)!&
                     UPPER BOUNDARY PRESSURE (PSIA)!"
WRITE(300, *) "****************************************&
                    ********************************"


DO K=0, 10
iv1=k/10.
WRITE(300, fmt="(f7.2, 2f29.2)") iv1, PF(1, k), PF(2, K)
enddo
close(300)

ENDIF


DEALLOCATE(L0)
DEALLOCATE(ROUGH0)
DEALLOCATE(THETA0)
DEALLOCATE(D0)
write(*,*) "********PREDICTION OF PRESSUR LOSS IS COMPLETED!!!!&
                               *********************"

contains
!---------------------------------------------------------------
```

```
!@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@


!*******************************************************************
!*                       *
!* ######## FIGURE OUT PATTERN #########                      *
!*                   *
!*******************************************************************
Subroutine PATTERNS_2(KCA,maxip, c0, d, rough, vSG, vSL, rhoG,&
           rhoL, muG, muL, sigma, theta, Sgas, Z, T,Tgrad,Tpc,&
             P, Ppc, Ploss, L, step, ACL, regime, DI)
implicit none


!bubble flow

real(8)::Maxip   !maximum of pressure drop
Real(8)::d             !pipe diameter
Real(8)::rough         !pipe roughness
Real(8)::vSG           !superficial gas velocity
Real(8)::vSL           !superficial liquid velocity

Real(8)::rhoG          !gas density
Real(8)::rhoL          !liquid density
Real(8)::muG           !gas viscosity
Real(8)::muL           !liquid viscosity
Real(8)::sigma         !interficial force
Real(8)::theta         !pipe inclined angle from horizontal plane
Real(8)::Sgas          !gas specific gravity
Real(8)::T             !temperature (F)
Real(8)::Tgrad         !temperature gradient (F/ft)
Real(8)::Tpc           !Psuedo critical temperature
Real(8)::P             !pressure (psia)
Real(8)::Ppc           !Psuedo critical pressure
Real(8)::Ploss         !pressure loss
Real(8)::Pgrad         !pressure loss gradient
Real(8)::Z
Real(8)::C0            !velocity distribution coefficient
Real(8):: Step         !calculating interval length
Real(8):: L            !accumulative length calculated so far
Real(8):: ACL          !calculating the length of pipe divisions.
real(8)::deri, func    !intermediate variables used for solving roots
Real(8), parameter::PI=3.141592653589793
Real(8), parameter::g=32.2
Integer::numb
```

```
real(8):: IV1, IV2, IV3, IV4, IV5 ! simplification

real(8):: RR1, RR2, RR3, RR4, RR5, RR6 !simplification


Real(8)::vIN           !bubble terminal rise velocity
Real(8)::VmaxB         !maximum gas velocity
Real(8)::dmin          !minimum diameter of bubble flow
Real(8)::IV            !Intermedate value used
Real(8)::thetamin
Real(8)::RS            !superfacial velocity ration
Real(8)::fM            !frictional facotr of mixture velocity
Real(8)::dMax          !critical diameter of dispersed bubble
Real(8)::dCD           !critical deformed diameter
Real(8)::dCB           !critical buoyancy diameter


!stratified flow
Real(8)::AL, AG, A     !area of liquid, gas, and the whole tube
Real(8)::SL, SG, S     !perimeter of liquid, gas, and the whole tube
Real(8)::dL, dG        !diameter of liquid, gas, and the whole tube
Real(8)::tauL, tauG, tauI !shear stress of liquid, gas
Real(8)::h             !liquit level
Real(8)::X, Y          !parameters
Real(8)::dAdl          !the derivative of gas area respet to liquid high
level


!annula flow

Real(8)::vG            !in-situ gas velocity
Real(8)::vL            !in-situ liquid velocity
Real(8)::vM            !mixture velocity
Real(8)::vBR           !bubble rise velocity
Real(8)::HL            !liquid holdup

Real(8)::Ppr
Real(8)::Tpr

Real(8)::ReSG         !Gas Reynolds number of superficial velocity
Real(8)::ReSL         !Liquid Reynolds number of superficial velocity
Real(8)::rhoM         !mixture density

!gas mixture
Real(8)::N2           !included in gas (%)
Real(8)::H2S          !included in gas (%)
Real(8)::CO2          !included in gas (%)

Real(8)::Lf
```

```
Real(8)::Angl
Real(8)::st, rhoL1,rhoL2, rhoG1,rhoLG2
Real(8)::mu
Real(8)::tauWL, tauWG
Real(8)::fG, fL, fI
real(8):: fmG, fmL    !gas and liquid friction factor
Real(8):: deriHA
Real(8)::deriFL,deriFG
Real(8)::delta
INTEGER::DI
Integer, dimension(:)::regime(5)!represent patterns
Integer::KCA
 regime(3)=0



!examine the patterns, first suppose the flow is not slug flow

regime(5)=0

!*******************************************************************
!Statified flow pattern
!@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
    RR1=P
    RR2=T
RR3=rhoG
RR4=muG
RR5=L


Call stratified_3(KCA, maxip, h, d, rough, vSG, vSL, rhoG, rhoL, &
     muG, muL, sigma, theta, Sgas, Z, T,Tgrad,Tpc, P, Ppc, Ploss,&
    L, step, ACL, DI)


 if(h>=d) goto 11
  IV1=2.*h/d-1.
  IV2=(1-IV1**2)**0.5

  dadl=d*IV2      !E35
  AG=(d**2/4.0)*(acos(IV1)-IV1*IV2)      !E36
  vG=vSG*pi*d**2/4./AG
  IV3=(1.-h/d)
  IV4=g*cos(theta)*(rhoL-rhoG)*AG
  IV5=IV3*(IV4/(rhoG*dadl))**0.5

  11  IF((vG<IV5).and.(h<d)) then!E34

   regime(5)=5
   goto 100
```

```
   ELSE
    p=RR1
    T=RR2
rhoG=RR3
    muG=RR4
    L=RR5


  END IF
!------------------------------------------------------------------



!@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
! bubble flow pattern
!@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@



!1. calculate terminal rise velocity

10 regime(1)=0

vIN=1.53*(g*(rhoL-rhoG)*sigma/rhoL**2)**0.25


!criterion 1: the maximum velocity for bubble flow
VmaxB=(0.43*vSL+0.375*vIN)*sin(theta)


if (vSG>VmaxB) go to 20  !not bubble flow, go to dispersed bubble
criteria

!criterion 2: the minimum diameter of pipeline for bubble flow

dmin=19.1*(sigma/(g*(rhoL-rhoG)))**0.5
if (d<dmin)  go to 20  !not bubble, so go to stratified flow

!Criterion 3: Minimum inclination angle for bubble flow

!IV1=3./4.*cos(pi*45/180)*(vIN/g)*(0.8*1.3/d)

!thetamin=acos((-1.+(1.+4.*IV1**2)**0.5)/2.)

!if (theta<thetamin) goto 20 !not bubble, go to next criterion


call bubble_3(KCA,maxip,c0, d, rough, vSG, vSL, rhoG, rhoL, muG, &
```

```
muL, sigma, theta, Sgas, Z, T,Tgrad,Tpc, P, Ppc, Ploss, L, step, ACL,
DI)

regime(1)=1

goto 100

!-----------------------------------------------------------------------


!@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
!annula flow
!@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@

20  regime(4)=0


fmG=Fric_factor(d,rough, rhoG, muG, vSG)


deriFG=fmG*rhoG*vSG**2/(2.*d)  !Gas frictional pressure gradient

fmL=Fric_factor(d,rough, rhoL, muL, vSL)


deriFL=fmL*rhoL*vSL**2/(2.*d)          !liquid frictional pressure
gradient


X=deriFL/deriFG

Y=(rhoL-rhoG)*g*sin(theta)/deriFG

!solve the HL


HL=0.25   !guess value

numb=0
do

   !function value
    IV1=(1-HL)**2.5*HL

    IV2=(1.+75.*HL)/IV1-X/HL**3

    func=-Y+IV2

    !Derivative
```

```
        IV2=(1.+75.*HL)*((1.-HL)**2.5-2.5*(1.-HL)**1.5*HL)

      deri=(75.0*(1.-HL)**2.5*HL-IV2)/IV1**2+3*X/HL**4

     !new HL

      HL=HL-func/deri
      numb=numb+1
          If((abs(func/deri)<0.00001).or.(numb>maxi)) exit

enddo


!Step 1: Wave bridge criteria

if(HL>=0.24) goto 30  !it is not annular flow because of the wave
bridge,

!Step 2: Instability of film criteria

IV1=(2.-1.5*HL)*X/(HL**3*(1-1.5*HL))

if (Y>IV1)  goto 30 !the film is instable so there is no annular flow.



  call annula_3(KCA, maxip, d, rough, vSG, vSL, rhoG, rhoL,&
               muG, muL,sigma, theta, Sgas, Z, T,Tgrad,Tpc, P,&
    Ppc, Ploss, L, step, ACL, DELTA, DI)
IF(DELTA>=D/2)     GOTO 30
   regime(4)=4

go to 100



!@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
! dispersed bubble pattern

!@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@

 30 regime(2)=0

!Step 1: transiton boundary


   vM=vSG+vSL
   RS=vSG/vM     !E28
```

```
   if(RS>0.52) goto 40  !no dispersed bubble flow because of too much
gas
!step2


   fm=Fric_factor(d,rough, rhoL, muL, vM)

   !calculate the critical bubble dimeter
   IV1=(sigma/rhoL)**0.6/((2.*fm*vM**3/d)**0.4)

   dMax=(4.15*(vSG/vM)**0.5+0.725)*IV1                !E29

   !calculate the critical deformed dimeter

    IV1=0.4*sigma/((rhoL-rhoG)*g)
    dCD=2.*IV1**0.5

!if turbulent force cannot break the large bubble to small bubble.

if(dMax>dCD) goto 40

!step 3
dCB=(3./8.)*(rhoL/(rhoL-rhoG))*fM*vM**2/(g*cos(theta))      !E30

if((dMax>dCB).and.(theta<0.174)) goto 40  !no dispersed bubble because
b

regime(2)=2
call bubble_3(KCA,maxip,c0, d, rough, vSG, vSL, rhoG, rhoL, muG,&
       muL, sigma,theta, Sgas, Z, T,Tgrad,Tpc, P, Ppc, Ploss,&
    L, step, ACL, DI)

goto 100


!@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
!slug flow
!@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
40 regime(3)=3

    RR1=P
    RR2=T
RR3=rhoG
RR4=muG
RR5=L


call slug_3(KCA, maxip, d, rough, vSG, vSL, rhoG, rhoL, muG,&
           muL, sigma, theta,Sgas, Z, T,Tgrad,Tpc, P, Ppc, Ploss,&
    L, step, ACL, DI, Lf)
```

```
if(lf>0) then
goto 100
else
regime(3)=0
   p=RR1
   T=RR2
   rhoG=RR3
    muG=RR4
    L=RR5
 call bubble_3(KCA,maxip,c0, d, rough, vSG, vSL, rhoG, rhoL, muG, &
            muL, sigma, theta, Sgas, Z, T,Tgrad,Tpc, P, Ppc, Ploss,&
 L, step, ACL, DI)
regime(1)=1

Endif

100 return

END SUBROUTINE PATTERNS_2


End program multiphase
!@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
```

```
!@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@

MODULE GASFRICTION

IMPLICIT NONE

CONTAINS

!******************************************************************
!* To calculate pseudo critical pressure                          *
!* Sgas is the gas specific gravity from 0.57 to 1.68             *
!* Corr = 1  Sutton correlation                                   *
!******************************************************************
Function f_Ppc(Sgas)
Real (8) ::Sgas,  f_Ppc

 f_Ppc =756.8-131.*Sgas-3.6*Sgas**2


End Function f_Ppc
!@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@



!******************************************************************
!* To calculate critical temperature                              *
!* Sgas is the gas specific gravity from 0.57 to 1.68             *
!* Sutton correlation                                             *
!******************************************************************
Function f_Tpc(Sgas)

Real(8) :: Sgas, f_Tpc


    f_Tpc =169.2+349.5*Sgas-74.0*Sgas**2


End Function f_Tpc
!@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
```

```
!*******************************************************************
!* To modified critical temperature with CO2 and/or H2S present    *
!*  by using Wichert and Aziz correction for calculated pseudo     *
!* Ppc -  psuedo critical pressure                                 *
!* Tpc -  psuedo citical temperture                                *
!* SPg -  gas specific gravity                                     *
!* CO2 -  mole fraction of CO2                                     *
!* H2S -  mole fraction of H2S                                     *
!*******************************************************************

Real(8) Function Tpc_Wa(Tpc, CO2, H2S)

Real(8)::Tpc, CO2, H2S
Real(8)::E

   E=120.*(CO2+H2S)**0.9-120.*(CO2+H2S)**1.6+15.*&
        (H2S ** 0.5-H2S ** 4)

   Tpc_wa=Tpc-E

End Function Tpc_wa
!@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@


!*******************************************************************
!* To modified critical pressure with CO2 and/or H2S present       *
!*  by using Wichert and Aziz correction for calculated pseudo     *
!* Ppc -  psuedo critical pressure                                 *
!* Tpc -  psuedo citical temperture                                *
!* SPg -  gas specific gravity                                     *
!* CO2 -  mole fraction of CO2                                     *
!* H2S -  mole fraction of H2S                                     *
!*******************************************************************

Real (8) Function Ppc_wa(Tpc, Ppc, CO2, H2S)

Real (8) :: Tpc, Ppc, CO2, H2S

Real (8) :: E

E=120.0*((CO2+H2S)**0.9-(CO2+H2S)**1.6)+15.0*&
             (H2S**0.5-H2S**4)

Ppc_wa=Ppc*(Tpc-E)/(Tpc+H2S*(1.0-H2S)*E)

End Function Ppc_wa
!@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
```

```
!********************************************************************
!*                                                                  *
!* ########1  Correlation  for purity gas viscosity#########        *
!*                                                                  *
!* To calculate gas viscosity (cp) by using Lee,et al.              *
!* P -   pressure (psia)                                            *
!* T -   temperature (F)                                            *
!* Sgas - gas specific gravity                                      *
!* Z -   Z factor                                                   *
!********************************************************************
Function Gasvis_Puri(P, T, Sgas, Z)

Real (8) :: P, T, Sgas, Z, gasvis_puri
Real (8) :: rho                !gas density
Real (8) :: A1, A2, A3, A4
Real (8) :: MW          !Molecular Weight

   MW=Sgas * 28.9625
   rho=0.0014935 * P * MW / (Z *T )
   A2=3.448 + 986.4 /T + 0.01009 * MW
   A3=2.447 - 0.2224 * A2
   A1=(9.379+0.01607*MW)*T**1.5/(209.2+19.6*MW+T)
   Gasvis_puri = 10.0 ** (-4) * A1 * exp(A2 * rho ** A3)*0.00672

End Function Gasvis_Puri
!@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@


!********************************************************************
!*                                                                  *
!* ######## 2    Correlation for impurity gas viscosity#########    *
!*                                                                  *
!* To calculate gas viscosity by for impurity gas  at atmospheric   *
!* Ppr - psuedo relative pressure                                   *
!* Tpr - psuedo relative temperture                                 *
!* T -   temperature (F)  (100F<t<300F)                             *
!* Sgas - gas specific gravity  (0.55<SPg<1.55)                     *
!* N2 -  nitrogen mole fraction content                             *
!* CO2 - carbon dioxide mole fraction content                       *
!* H2S - hydrogen sulfide mole fraction content                     *
!********************************************************************

Real(8) Function Gasvis_Impu(T, Sgas, Ppr, Tpr, N2, CO2, H2S)

Real (8) :: T, Sgas, Ppr, Tpr, N2, CO2, H2S
Real (8) :: A1, A2, A3, A4, A5
Real (8) :: inter
```

```
 A1 = (1.709 * 10 ** (-5) - 2.062 * 10 ** (-6) * Sgas) * T
 A3 = N2 * (0.00848 * log10(Sgas) + 0.00959)
 A4 = CO2 * (0.00908 * log10(Sgas) + 0.00624)
 A5 = H2S * (0.00849 * log10(Sgas) + 0.00373)

 inter=A1 + A2 + A3 + A4 + A5

 A1 = -2.4621182 + 2.97054714*Ppr-0.286264054*Ppr**2+&
     0.00805420522 * Ppr ** 3

 A2 = Tpr * (2.80860949 - 3.49803305 * Ppr + 0.36037302 *&
          Ppr ** 2 -0.0104432413 * Ppr ** 3)

 A3 = Tpr ** 2 * (-0.793385684 + 1.39643306 * Ppr-0.149144925*&
          Ppr ** 2 +0.00441015512 * Ppr ** 3)

 A4 = Tpr ** 3 * (0.0839387178 - 0.186408848 * Ppr +&
        0.0203367881 * Ppr ** 2-0.000609579263 * Ppr ** 3)

 gasvis_impu=0.00672*Exp(A1+A2+A3+A4)*inter/Tpr

End Function Gasvis_Impu
!@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@


!*******************************************************************
!*                                                                 *
!* ######## Correlation for z-factor#########                       *
!*                                                                 *
!* Correlation: Dranchuk and Abou-Kassem                           *
!* Calculation method: Newton iterative technique                  *
!* maximum time of iterative: 20; if more than it, then z=1.0      *
!* Ppr -  psuedo relative pressure                                 *
!* Tpr -  psuedo relative temperture                               *
!*******************************************************************
Real(8) Function Z_factor(Ppr, Tpr)

Real (8) :: Ppr, Tpr
Real (8), PARAMETER :: A1 = 0.3265
Real (8), PARAMETER :: A2 = -1.070
Real (8), PARAMETER :: A3 = -0.5339
Real (8), PARAMETER :: A4 = 0.01569
Real (8), PARAMETER :: A5 = -0.05165
Real (8), PARAMETER :: A6 = 0.5475
Real (8), PARAMETER :: A7 = -0.7361
Real (8), PARAMETER :: A8 = 0.1844
Real (8), PARAMETER :: A9 = 0.1056
Real (8), PARAMETER :: A10 = 0.6134
Real (8), PARAMETER :: A11 = 0.7210
```

```
Real (8) ::rhor
Real (8) ::C1, C2, C3, C4, C5
Integer :: numb
Real (8) ::Z
Real (8) ::func, deri, ind, DERI1, DERI2, DERI3
integer::maxi


  maxi=40
  numb=0


! guess a z-factor
  Z=0.1

  C1=A1+A2/Tpr+A3/Tpr**3+A4/Tpr**4+A5/Tpr**5
  C2=A6+A7/Tpr+A8/Tpr**2
  C3=A9*(A7/Tpr+A8/Tpr**2)
  C4=0.27*Ppr/Tpr
!-------------------------------------------------------------------
    Do
      numb=numb+1

      rhor =C4/Z

      C5=A10*(1.0+A11*rhor**2)*(rhor**2/Tpr**3)*Exp(-A11*rhor**2)

      func=Z-(1.0+C1*rhor+C2*rhor**2-C3*rhor**5+C5)


  DERI1=1.0+(C1*rhor+2.*C2*rhor**2-5*C3*rhor**5)/Z


  DERI2=2*(A10/Tpr**3)*rhor**2*(1+A11*rhor**2-A11**2*rhor**4)*&
            exp(-1*A11*rhor**2)/Z


  DERI=DERI1+DERI2

  IF(deri==0.0) EXIT

  Z=Z-func/deri

  IF ((Abs(func/deri)<0.0001).or.(numb>= MAXI)) EXIT

    End Do
!-------------------------------------------------------------------

If ((numB>=MAXI).or.(deri==0.0)) Then
```

```
        Z_factor =1.0

Else
        Z_factor = Z

    EndIf

End Function Z_factor
!@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@



!*****************************************************************
!* To calculate friction factor                                  *
!* rho is the fluid density (lb/ft3)                             *
!* d   is diameter of pipe                                       *
!* v   is velocity(ft/sec)                                       *
!* mu  is viscosity(cp)                                          *
!* rough  absolute roughness of pipe (ft)                        *
!*****************************************************************

Real(8) Function Fric_factor1(d,rough, rho, mu, v)

Real(8):: rho, v, d, mu, rough
Real(8):: Re, IV1, IV2,IV3, x, func, deri


  IV1=rough/d
  Re=d*v*rho/mu

  If (Re<2100.0) then

     fric_factor1=16.0/Re

  Else
     !guess number
     x=(0.02)**0.5

  Do
    IV2=2.*IV1+18.7/(Re*x)
    func=1./x-1.74+2.*log10(IV2)

    deri=(-1./x**2)*(1+37.4/(log(10.)*IV2*Re))

    x=x-func/deri

if(abs(func/deri)<0.00001)  exit

  Enddo
```

```
    fric_factor1=x**2
  End if
End Function fric_factor1
!@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@


!*******************************************************************
!* To calculate friction factor                                    *
!* rho is the fluid density (lb/ft3)                               *
!* d   is diameter of pipe                                         *
!* v   is velocity(ft/sec)                                         *
!* mu  is viscosity(cp)                                            *
!* rough  absolute roughness of pipe (ft)                          *
!*******************************************************************

Real(8) Function Fric_factor(d,rough, rho, mu, v)

Real(8):: rho, v, d, mu, rough
Real(8):: Re, IV1, IV2,IV3, x, func, deri

IV1=rough/d
Re=d*v*rho/mu

   IF (Re<2300) THEN
       fric_factor=16./Re

   Else
        fric_factor=0.001375*(1.+(20000.*rough/d+1000000/Re)**(1/3))

   END IF

End Function fric_factor
!@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@


!*******************************************************************
!* To calculate gas density(lbm/ft3)                               *
!* p     is the fluid density (psia)                               *
!* T     is temperature (R)                                        *
!* z     is z_factor                                               *
!* Sgas  is gas gravity                                            *
!*******************************************************************
Real (8) Function dens_g(P, T, Z, Sgas)

Real (KIND = 8) :: P, T, Z, Sgas, MW

  MW = Sgas * 28.9625
```

```
  dens_g=P * MW / (10.732*Z *T)

End Function dens_g
!@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@



!*******************************************************************
!* To predict pressure loss for stratified, bubble, and slug flow  *
!* Pgrad     is the pressure gradient (psi/ft)                     *
!* Ploss     is prediction of pressure loss (psi)                  *
!* PlossA    is the pressure loss results from acceleartion compo. *
!* P         is pressure (psia)                                    *
!* T         is temperature (R)                                    *
!* Ppc       is psuedo critical pressure (psi)                     *
!* Tpc       is psuedo critical temperature (R  )                  *
!* T1        is temperature (R)                                    *
!* Tgrad     is temperature gradient(R/ft)                         *
!* z         is z_factor                                           *
!* Sgas      is gas speific gravity                                *
!* vG        is in-situ gas velocity                               *
!* rhoG      is gas density  (lbm/ft3)                             *
!* vG        is in-situ gas velocity (lbm/ft3)                     *
!* L        wellbore length (ft)                                   *
!* ACL      control length  (ft)                                   *
!* KCA      control data for including acceleration component      *
!* Maxip    control prediction pressure in each interval(ft)       *
!*******************************************************************
Subroutine Pressloss(KCA, maxip, P, Ppc, Pgrad, T,Tpc, Tgrad, Sgas,&
                     vG,rhoG, ACL, L, step,Ploss)

Implicit none

Real(8)::Pgrad
Real(8)::Ploss
Real(8)::PlossA

Real(8)::P
Real(8)::P1
Real(8)::T
Real(8)::T1
Real(8)::Tgrad
Real(8)::Ppc
Real(8)::Tpc
Real(8)::Ppr         !reduced pressure
Real(8)::Tpr         !relative temperature
Real(8)::Ppr1        !relative pressure
Real(8)::Tpr1        !relative temperature
Real(8)::Z, Z1       !Z-factor
Real(8)::rhoG        !gas density
```

```
Real(8)::rhoL         !gas density
Real(8)::rhoG1        !gas density
Real(8)::vG           !gas in-situ velocity
Real(8):: Step        !calculating interval length
Real(8):: L           !accumulative length calculated so far
Real(8):: ACL         !calculating the length of pipe divisions.
Real(8)::MAXIP
Real(8)::Sgas
Real(8)::IV1
Integer::KCA
Real(8)::min


  !in case transition from one dividion pipe to another

  Step=min(50.0, ACL-L)

  Ploss=Pgrad*step
  !in case infinite loop
  if(maxip==0) stop

!-----------------------------------------------------------------
  Do
    if(Ploss<maxip) exit
    step=step*0.9
    Ploss=Pgrad*step

  Enddo

!----------------------------------------------------------
!calculate the pressure loss resulted from the acceleration
 IF(KCA==1) THEN
   p1=p+ploss
   T1=T+step*Tgrad
   Ppr1=p1/Ppc
   Tpr1=T1/Tpc
   z1=z_factor(Ppr1, Tpr1)
   rhoG1=dens_g(P1, T1, Z1, Sgas)
   PlossA=0.5*rhoG*vG**2*(rhoG/rhoG1-1.)/(144.*32.2)
   Ploss=Ploss+PlossA
 ENDIF
!-----------------------------------------------------------------

End subroutine pressloss
!@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
```

```
!********************************************************************
!* To predict pressure loss for annula flow                         *
!* Pgrad   is the pressure gradient (psi/ft)                        *
!* Ploss    is prediction of pressure loss (psi)                    *
!* PlossA    is the pressure loss results from acceleartion compo. *
!* P         is pressure (psia)                                     *
!* T         is temperature (R)                                     *
!* Ppc       is psuedo critical pressure (psi)                      *
!* Tpc       is psuedo critical temperature (R  )                   *
!* T1        is temperature (R)                                     *
!* Tgrad     is temperature gradient(R/ft)                          *
!* z         is z_factor                                            *
!* Sgas      is gas speific gravity                                 *
!* vG        is in-situ gas velocity                                *
!* rhoG      is gas density  (lbm/ft3)                              *
!* L         is wellbore length (ft)                                *
!* d         is pipe diameter (ft)                                  *
!* rough     is pipe roughness (ft)                                 *
!* ACL       control length  (ft)                                   *
!* KCA       control data for including acceleration component     *
!* Maxip     control prediction pressure in each interval(ft)       *
!********************************************************************

!-------------------------------------------
Subroutine Pressloss_ann4(KCA, maxip, P, Ppc, Pgrad, T,Tpc, Tgrad,&
                   Sgas,  rhoL, HGC, vC,rhoC, ACL, L, step,Ploss)
Implicit none

Real(8)::Maxip
Real(8)::vSG
Real(8)::vSL

Real(8)::rhoG        !gas density
Real(8)::rhoL        !liquid density
Real(8)::muG         !gas viscosity
Real(8)::muL         !liquid viscosity
Real(8)::sigma       !interficial force
Real(8)::theta       !pipe inclined angle from horizontal plane
Real(8)::Sgas        !gas specific gravity


Real(8)::d
Real(8)::rough
Real(8):: Step         !calculating interval length
Real(8):: L             !accumulative length calculated so far
Real(8):: ACL          !calculating the length of pipe divisions.
real(8)::deri, func  !intermediate variables used for solving roots
Real(8), parameter::PI=3.141592653589793
Real(8), parameter::g=32.2
Integer::numb
```

```
Integer::KCA

Real(8)::T              !temperature (R)
Real(8)::Tgrad          !temperature gradient (R/ft)
Real(8)::Tpc            !Psuedo critical temperature
Real(8)::T1              !temperature (R)
Real(8)::Tpr1
Real(8)::P              !pressure (psia)
Real(8)::Ppc            !Psuedo critical pressure
Real(8)::Ploss          !pressure loss
Real(8)::PlossA         !pressure loss
Real(8)::Pgrad           !pressure loss gradient
Real(8)::P1              !pressure (psia)
Real(8)::Ppr
Real(8)::Tpr
Real(8)::Ppr1

Real(8)::Z1                 !Z-factor
Real(8)::rhoC               !gas density
Real(8)::rhoC1              !gas density
Real(8)::rhoG1              !gas density
Real(8)::vC                 !gas in-situ velocity in core
Real(8)::HGC                !Gas holdup in core
Real(8):: IV1, IV2, IV3, IV4, IV5 !for simplification
Real(8)::min

  Step=min(50.0, ACL-L)    !in case transition from one dividion pipe
to another
  pgrad=pgrad
    Ploss=Pgrad*step


if(maxip==0) stop
!----------------------
 do
  if(Ploss<maxip) exit
    step=step*0.9
    Ploss=Pgrad*step

enddo
!calculate the pressure loss resulted from the acceleration

IF(KCA==1) THEN

   p1=p+ploss
   T1=T+step*Tgrad
   Ppr1=p1/Ppc
   Tpr1=T1/Tpc
   z1=z_factor(Ppr1, Tpr1)
   rhoG1=dens_g(P1, T1, Z1, Sgas)
```

```
   rhoCl=HGC*rhoG1+(1-HGC)*rhoL
   PlossA=0.5*rhoC*vC**2*(rhoC/rhoCl-1)/(144.*32.2)
   Ploss=Ploss+PlossA

ENDIF

end subroutine pressloss_ann4
!-----------------------------------------------------------------

END MODULE GASFRICTION
!@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@


!******************************************************************
!*                                                                *
!* ######## STATIFIED FLOW#########                                *
!*                                                                *
!******************************************************************
!******************************************************************
!* Whatthe vairables mean are seen in the main program            *
!* This modules are used to calculate                             *
!* the pressure gradient of straatified flow                      *
!******************************************************************


MODULE STRATIFIED
USE GASFRICTION
IMPLICIT NONE
CONTAINS


Subroutine Stratified_3(KCA, maxip,h, d, rough, vSG, vSL, rhoG,&
      rhoL,muG, muL, sigma, theta, Sgas,Z, T,Tgrad,Tpc, P, Ppc,&
   Ploss, L, step, ACL, DI)

Implicit none

reaL(8)::Maxip
Real(8)::d
Real(8)::rough
Real(8)::vSG
Real(8)::vSL
Real(8)::rhoG
Real(8)::rhoL
Real(8)::muG
Real(8)::muL
Real(8)::sigma
Real(8)::theta
Real(8)::Sgas
```

```
Real(8)::T
Real(8)::Tgrad
Real(8)::Tpc
Real(8)::P
Real(8)::Ppc
Real(8)::Ploss
Real(8)::Pgrad
Real(8):: Step
Real(8):: L
Real(8):: ACL
real(8)::deri, func  !intermediate variables used for solving roots
Real(8), parameter::PI=3.141592653589793
Real(8), parameter::g=32.2
Integer:: numb
real(8):: IV1, IV2, IV3, IV4, IV5 !for simplification
real(8):: R1, R2, R3, R4, R5, R6, R7, R8, R9, R10 !for replacment


Real(8)::vG     !in-situ gas velocity
Real(8)::vL     !in-situ liquid velocity
Real(8)::vM     !mixture velocity
Real(8)::vBR    !bubble rise velocity
Real(8)::HL      !liquid holdup

Real(8)::P1              !pressure at new point (psia)
Real(8)::T1              !temperature at new point(F)
Real(8)::Ppr
Real(8)::Tpr
Real(8)::Ppr1
Real(8)::Tpr1
Real(8)::Z

Real(8)::ReSG          !Gas Reynolds number of superficial velocity
Real(8)::ReSL          !Liquid Reynolds number of superficial velocity
Real(8)::rho           !density
Real(8)::rhoM          !mixture density
Real(8)::muM           !mixture viscosity


Real(8)::A, AL, AG     !section area of total, liquid, and gas
Real(8)::Angl,SL, SG, SI  !angles and peremeters of fluid
Real(8)::dL, dG, h        !hydraulic diameter
Real(8)::st, rhoL1,rhoL2, rhoG1,rhoLG2
Real(8)::mu
Real(8)::tauWL, tauWG, tauI  !Shear strsses
Real(8)::fG, fL, fI          !friction factor
Real(8)::x, y
Real(8):: deriHA
Real(8)::Z1
Integer::KCA           !Control the acceleration component
```

```
Integer::DI           !Contol the direction for pressure prediction


Call STRATIFIED_LHL4(h,d, rough,vSG, vSL,rhoG, rhoL, muG, muL,sigma,&
                     theta, p, AL, SL,SG, SI, tauwL,TauWG, tauI)

!-------------------------------------------------------------------
!Examine the liquid high level in pipe
IF(H>=D) GOTO 3


!Examine if it is stratified flow

A=PI*D**2/4
x=2.*h/d-1.
Angl=acos(x)
HL=AL/A
AG=A-AL
deriHA=d*(1-x**2)**0.5
vG=vSG/(1-HL)

y=((1-x)/2.)*(g*cos(theta)*(rhoL-rhoG)*AG/(rhoG*deriHA))**0.5

If (vG<=y) then
  !calculate the pressure gradient from ghydraulic and frictional
component


  Pgrad=(-1)**DI*(tauWL*SL/AL-tauI*SI/AL+rhoL*g*sin(theta))&
                  /(32.2*144.)

  !calculate pressure loss
  CALL Pressloss(KCA, maxip, P, Ppc, Pgrad, T,Tpc, Tgrad, Sgas,&
                 vG,rhoG, ACL, L, step,Ploss)
Else

End if


3 RETURN

END Subroutine Stratified_3

!@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@



!******************************************************************
Subroutine STRATIFIED_LHL4(h,d, rough,vSG, vSL,rhoG, rhoL, muG, muL,&
                   sigma,theta, p, AL, SL,SG, SI, tauwL,TauWG, tauI)
```

```
Implicit none

Real(8)::Maxip    !maximum of pressure drop
Real(8)::d             !pipe diameter
Real(8)::rough         !pipe roughness
Real(8)::vSG           !superficial gas velocity
Real(8)::vSL           !superficial liquid velocity

Real(8)::rhoG         !gas density
Real(8)::rhoL         !liquid density
Real(8)::muG          !gas viscosity
Real(8)::muL          !liquid viscosity
Real(8)::sigma        !interficial force
Real(8)::theta        !pipe inclined angle from horizontal plane
Real(8)::Sgas         !gas specific gravity
Real(8)::T              !temperature (R)
Real(8)::Tgrad          !temperature gradient (R/ft)
Real(8)::Tpc            !Psuedo critical temperature
Real(8)::P              !pressure (psia)
Real(8)::Ppc            !Psuedo critical pressure
Real(8)::Ploss          !pressure loss
Real(8)::Pgrad          !pressure loss gradient

Real(8):: Step          !calculating interval length
Real(8):: L              !accumulative length calculated so far
Real(8):: ACL           !calculating the length of pipe divisions.
real(8)::deri, func  !intermediate variables used for solving roots
Real(8), parameter::PI=3.141592653589793
Real(8), parameter::g=32.2
Integer::numb, K

Real(8):: x1, x2, x0
Real(8):: y1, y2, y0
Real(8)::A, AL, AG, HL
Real(8)::Angl,SL, SG, SI
Real(8):: dL, dG, h
Real(8)::st,rho, rhoL1,rhoL2, rhoG1,rhoLG2
Real(8)::tauWL, tauWG, tauI

Real(8)::vG, vL
Real(8)::fG, fL, fI
```

```
!********************************************************************
!figure out the liquid level by error and trail method
!********************************************************************


x0=0.0001*d
call  stratified_solver5(x0,d, rough,vSG, vSL,rhoG, rhoL, muG,&
                          muL,sigma,theta, p, AL, SL,SG, SI,&
   tauwL,TauWG, tauI, y0)

x1=x0+0.0002*d
Call Stratified_solver5(x1,d, rough,vSG, vSL,rhoG, rhoL, muG,&
                      muL,sigma,theta, p, AL, SL,SG, SI, tauwL,&
  TauWG, tauI,y1)


Do K=1, 2000

    if (y0*y1<=0) then
x2=(x0+x1)/2
call Stratified_solver5(x2,d, rough,vSG, vSL,rhoG,&
 rhoL, muG, muL,sigma,theta, p, AL, SL,SG, SI,&
  tauwL,TauWG, tauI, y2)
if (ABS(y2)<=0.0001)then
    H=x2
else
   if (y0*y2<0) THEN
     x1=x2
     y1=y2
   else
     x0=x2
     y0=y2
   endif
   H=X0
            end if
    else
    x0=x1
    y0=y1
    x1=x1+0.002*d


call Stratified_solver5(x1,d, rough,vSG, vSL,rhoG,&
 rhoL, muG, muL,sigma,theta, p, AL, SL,SG, SI,&
  tauwL,TauWG, tauI, y1)

endif


IF(ABS(Y1)<0.001) EXIT
    If(x1>=d)   EXIT
```

```
Enddo
!-----------------------------------------------------------------


!examine the solution of liqiud high level

if (ABS(Y0)>1) then
WRITE(*,*) "there is no solution of liquid level"
H=D
else
    call Stratified_solver5(x0,d, rough,vSG, vSL,rhoG, rhoL,&
 muG, muL,sigma,theta, p, AL, SL,SG, SI, tauwL,TauWG, tauI, y0)
    H=X0
end if

return
END SUBROUTINE STRATIFIED_LHL4
!@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@




!*******************************************************************
!subroutine for calculating the value for implicit funtion
!*******************************************************************

Subroutine Stratified_solver5(h,d, rough,vSG, vSL,rhoG, rhoL,&
 muG, muL,sigma,theta,p, AL, SL,SG, SI, tauwL,TauWG, tauI, y)

Implicit none
real(8)::Maxip   !maximum of pressure drop
Real(8)::d           !pipe diameter
Real(8)::rough       !pipe roughness
Real(8)::vSG         !superficial gas velocity
Real(8)::vSL         !superficial liquid velocity

Real(8)::rhoG       !gas density
Real(8)::rhoL       !liquid density
Real(8)::muG        !gas viscosity
Real(8)::muL        !liquid viscosity
Real(8)::sigma      !interficial force
Real(8)::theta      !pipe inclined angle from horizontal plane
Real(8)::Sgas      !gas specific gravity
Real(8)::T            !temperature (F)
Real(8)::Tgrad        !temperature gradient (F/ft)
Real(8)::Tpc          !Psuedo critical temperature
Real(8)::P            !pressure (psia)
Real(8)::Ppc          !Psuedo critical pressure
```

```
Real(8)::Ploss        !pressure loss
Real(8)::Pgrad       !pressure loss gradient

Real(8):: Step         !calculating interval length
Real(8):: L             !accumulative length calculated so far
Real(8):: ACL          !calculating the length of pipe divisions.
real(8)::deri, func  !intermediate variables used for solving roots
Real(8), parameter::PI=3.141592653589793
Real(8), parameter::g=32.2
Integer::numb
Real(8):: IV1, IV2, IV3, IV4, IV5 !intermediate variables used for
simplification


Real(8):: Re, ReL, ReG, ReI
Real(8)::A, AL, AG, HL
Real(8)::Angl,SL, SG, SI
Real(8)::dL, dG, h
Real(8)::st,  rho
Real(8)::mu
Real(8)::tauWL, tauWG, tauI

Real(8)::vG, vL
Real(8)::fG, fL, fI
Real(8)::x, y
Real(8):: deriHA
Real(8)::vSGT
Real(8)::roughI  !the wave roughness

!calculate the geometry parameters

IV1=2.*h/d-1.
Angl=ACOS(IV1)  !unit is radia

SL=Angl*d

SG=(pi-Angl)*d

AL=(d**2/4.)*(pi-Angl+IV1*(1.-IV1**2)**0.5)

AG=pi*d**2/4.0-AL

SI=d*(1-IV1**2)**0.5

DL=4.0*AL/SL

DG=4.0*AG/(SG+SI)

A=pi*d**2/4.0  !pipe section area
```

```
!insitu velocity

VL=VSL*A/AL
VG=VSG*A/AG



!Roynolds number

ReL=DL*VL*rhoL/muL
ReG=DG*VG*rhoG/muG


!frictional factor of gas

  If (ReG<=2300) then

      fG=16.0/ReG
   Else
      fG=0.001375*(1.0+(20000.*rough/d+10**6/ReG)**(1./3.))

  End if


! fricational factor of liquid
fL=(1.6291/ReL**0.5161)*(vSG/vSL)**0.0926



!Interfacial frictional factor
 !critical superficial velocity for the transition from smooth flow to
waxy

vSGT=5.*(14.7/P)**0.5
st=(rhoG*vL**2*muL**2)/(sigma**2*rhoL)    !E63


If (d<0.5/12.)   then    !(unit inch)
   if (vSG<=vSGT) then
     fI=fG
   else
     fI=fG*(1.0+15.*(vSG-vSGT)/vSGT*(h/d)**0.5)

   end if
Else
   if(st>0.005) then
     roughI=34.*sigma/(rhoL*vL**2)

 fI=fric_factor(d, roughI, rhoG, muG, vG)
   else
```

```
     roughI=(170.*sigma/(rhoG*vL**2))*st**0.3

 fI=fric_factor(d,roughI,rhoG, muG, vG)

   end if
End if


!shear stress


tauWG=fG*rhoG*vG**2/2.0       !shear stress between gas and pipe

tauWL=fL*rhoL*vL**2/2.0       !shear stress between liqid and pipe

tauI=fI*rhoG*(vG-vL)**2/2.0   !shear stress between gas and liqid


y=tauWL*SL/AL-tauWG*SG/AG-tauI*(1./AL+1./AG)+(rhoL-rhoG)*g*sin(theta)


End subroutine Stratified_solver5
END MODULE STRATIFIED


!@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
```

```
!*******************************************************************
!*            *
!* ######## BUBBLE FLOW#########                              *
!*       *
!*******************************************************************
MODULE BUBBLE
USE GASFRICTION
IMPLICIT NONE
CONTAINS


SUBROUTINE BUBBLE_3(KCA,maxip, C0, d, rough, vSG, vSL, rhoG, rhoL,&
                  muG, muL, sigma, theta, Sgas, Z, T,Tgrad,Tpc, P,&
   Ppc, Ploss, L, step, ACL, DI)
IMPLICIT NONE

real(8)::Maxip   !maximum of pressure drop
Real(8)::d            !pipe diameter
Real(8)::rough        !pipe roughness
Real(8)::vSG          !superficial gas velocity
Real(8)::vSL          !superficial liquid velocity

Real(8)::rhoG        !gas density
Real(8)::rhoL        !liquid density
Real(8)::muG         !gas viscosity
Real(8)::muL         !liquid viscosity
Real(8)::sigma       !interficial force
Real(8)::theta       !pipe inclined angle from horizontal plane
Real(8)::Sgas       !gas specific gravity
Real(8)::T             !temperature (F)
Real(8)::Tgrad         !temperature gradient (F/ft)
Real(8)::Tpc           !Psuedo critical temperature
Real(8)::P             !pressure (psia)
Real(8)::Ppc           !Psuedo critical pressure
Real(8)::Ploss        !pressure loss
Real(8)::Pgrad       !pressure loss gradient

Real(8):: Step         !calculating interval length
Real(8):: L             !accumulative length calculated so far
Real(8):: ACL          !calculating the length of pipe divisions.
real(8)::deri, func  !intermediate variables used for solving roots
Real(8), parameter::PI=3.141592653589793
Real(8), parameter::g=32.2
Integer::KCA          !CONTOL NUMBER FOF ACCELERATION COMPONENT

Integer::numb
real(8):: IV1, IV2, IV3, IV4, IV5 !for simplification
```

```
Real(8)::Ppr1, Tpr1  !relative pressure and temperature at the new
point
Real(8):: T1       !temperature at old and new points
Real(8)::HL          !liquid holdup
Real(8)::vG, vL, vM                !velocity
Real(8)::vBR                                 !bubble rise velocity
Real(8)::f, fM      !friction fractor
Real(8)::muM!viscosity
Real(8)::rhoM!mixture density
Real(8)::Z1      !z-fractor
Real(8):: P1          !pressure at new point
Real(8):: C0           !distribution coefficient
integer::maxi
real(8):: Z
integer::DI

maxi=20
!calculate mixture velocity
vM=vSG+vSL
!-----------------------------------------------------------

! calculate bubble rise velocity
IV1=g*sigma*(rhoL-rhoG)/rhoL**2   !IS  unit
vBR=1.53*IV1**0.25

!-----------------------------------------------------------
!solve the liquid holdup

numb=1
Hl=0.1  !guess value for liquid holdup

Do

     func=1-HL-vSG/(C0*vM+vBR*sin(theta)*HL**0.5)

     deri=(vSG/(c0*vM-vBR*sin(theta)*HL**0.5)**2)*&
      (vBR*sin(theta)/(2.*HL**0.5))-1


     HL=HL-func/deri

    if((abs(func/deri)<0.0001).or.(numb>maxi)) exit
    numb=numb+1

End do

!------------------------------------------------------------------
!calculate mixture density, mixture viscosity,
rhoM=HL*rhoL+(1.0-HL)*rhoG
```

```
muM=HL*muL+(1.0-HL)*muG

!-------------------------------------------------------------------

!calculate in-situ gas velocity
vG=vSG/(1.0-HL)

!-------------------------------------------------------------------
!calculate friction factor


f=Fric_factor(d,rough, rhoM, muM, vM)


!-------------------------------------------------------------------

!the friction factor is Fanning friction factor, while here is Moody
one
f=4*f

Pgrad=(-1)**DI*(g*rhoM*sin(theta)+f*vM**2*rhoM/(2*d))/(32.2*144)


CALL Pressloss(KCA, maxip, P, Ppc, Pgrad, T,Tpc, Tgrad, Sgas,&
                        vG,rhoG, ACL, L, step,Ploss)



end subroutine bubble_3

End MODULE bubble
!@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
```

```
!*****************************************************************
!*            *
!* ######## ANNULA FLOW#########                              *
!*        *
!*****************************************************************

Module annula

use gasfriction

implicit none


contains

SUBROUTINE ANNULA_3(KCA, maxip, d, rough, vSG, vSL, rhoG, rhoL,&
                    muG, muL,sigma, theta, Sgas, Z, T,Tgrad,Tpc,&
 P, Ppc, Ploss, L,step, ACL, DELTA, DI)
implicit none
real(8)::Maxip  !maximum of pressure drop
Real(8)::d            !pipe diameter
Real(8)::rough        !pipe roughness
Real(8)::vSG          !superficial gas velocity
Real(8)::vSL          !superficial liquid velocity

Real(8)::rhoG        !gas density
Real(8)::rhoL        !liquid density
Real(8)::muG         !gas viscosity
Real(8)::muL         !liquid viscosity
Real(8)::sigma       !interficial force
Real(8)::theta       !pipe inclined angle from horizontal plane
Real(8)::Sgas         !gas specific gravity
Real(8)::T             !temperature (F)
Real(8)::Tgrad         !temperature gradient (F/ft)
Real(8)::Tpc           !Psuedo critical temperature
Real(8)::P             !pressure (psia)
Real(8)::Ppc           !Psuedo critical pressure
Real(8)::Ploss        !pressure loss

Real(8):: Step         !calculating interval length
Real(8):: L             !accumulative length calculated so far
Real(8):: ACL          !calculating the length of pipe divisions.
Real(8)::PI=3.141592653589793
Real(8)::g=32.2
Real(8)::Z


Real(8)::vC          !core velocity
Real(8)::rhoC        !core density
Real(8)::muC          !core viscosity
```

```
Real(8)::A, AC  !total,liquid, gas section area
Real(8):: SI !perimeter
Real(8):: tauI  !shear stress
Real(8):: HGC
Real(8)::Pgrad
Integer::KCA           !CONTOL NUMBER FOF ACCELERATION COMPONENT
Integer::DI            !CONTOL PREDICTION DIRECTION
Real(8)::DELTA



Call annula_FT4(DELTA, D,rough, VSG, VSL, rhoL, rhoG,muL, muG,sigma,&
                              theta,HGC, vC,rhoC, SI, AC, TauI)



IF(DELTA==D/2) GOTO 31

Pgrad=(-1)**DI*(g*rhoC*sin(theta)+tauI*SI/AC)/(32.2*144)

call Pressloss_ann4(KCA, maxip, P, Ppc, Pgrad, T,Tpc, Tgrad, Sgas,&
                   rhoL, HGC,vC,rhoC, ACL, L, step,Ploss)

31 RETURN

End subroutine ANNULA_3

!@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@



!*******************************************************************


SUBROUTINE annula_FT4(DELTA, d,rough, VSG, VSL, rhoL, rhoG,muL,&
                 muG,sigma, theta, HGC,vC,rhoC, SI, AC, TauI)
implicit none

reaL(8)::Maxip   !maximum of pressure drop
Real(8)::d             !pipe diameter
Real(8)::rough         !pipe roughness
Real(8)::vSG           !superficial gas velocity
Real(8)::vSL           !superficial liquid velocity

Real(8)::rhoG          !gas density
Real(8)::rhoL          !liquid density
Real(8)::muG           !gas viscosity
Real(8)::muL           !liquid viscosity
Real(8)::sigma         !interficial force
Real(8)::theta         !pipe inclined angle from horizontal plane
```

```
Real(8)::Sgas          !gas specific gravity
Real(8)::T             !temperature (F)
Real(8)::Tgrad         !temperature gradient (F/ft)
Real(8)::Tpc           !Psuedo critical temperature
Real(8)::P             !pressure (psia)
Real(8)::Ppc           !Psuedo critical pressure
Real(8)::Ploss         !pressure loss
Real(8)::Pgrad         !pressure loss gradient

Real(8):: Step         !calculating interval length
Real(8):: L            !accumulative length calculated so far
Real(8):: ACL          !calculating the length of pipe divisions.
real(8)::deri, func    !intermediate variables used for solving roots
Integer::numb
real(8):: IV1, IV2, IV3, IV4, IV5 !for simplification


Real(8):: delta!film thickness
Real(8):: vM!mixture velocity
Real(8):: vSGC          !critical gas velocity for calculating
entrainment
Real(8):: E             !liquid entrainment
Real(8):: vF            !liquid film velocity
Real(8):: vC            !core velocity
Real(8):: rhoC          !core density
Real(8):: muC           !core viscosity
Real(8):: HGC           !gas fraction in core
Real(8):: AC            !core cross section area
Real(8):: AF            !liquid film cross section area
Real(8):: dF            !liquid film hydraulic diameter

Real(8):: SF            !liquid film perimeter
Real(8):: SI            !core perimeter

Real(8):: fF            !liquid film friction factor
Real(8):: fI            !core friction factor
Real(8):: fSC           !friction factor
Real(8):: I             !correction parameter for friction factor
Real(8):: Iv            !correction parameter of vertical
Real(8):: Ih            !correction parameter for horizontal
Real(8):: FA            !correction parameter
real(8)::tauWF          !liquid film shear stress
real(8)::tauI           !core shear stress
Integer::k

Real(8):: x1, x2, x0
Real(8):: y1, y2, y0
```

```
!*********************************************************************
!figure out the film thickness by error and trail method
!*********************************************************************

x0=0.0001*d
call  annula_solver5(x0,d,rough, VSG, VSL, rhoL, rhoG,muL, muG,sigma,&
                          theta,HGC, vC,rhoC, SI, AC, TauI, y0, e)

x1=x0+0.001*d
Call annula_solver5(x1,d,rough, VSG, VSL, rhoL, rhoG,muL, muG,sigma,&
                   theta,HGC,vC,rhoC, SI, AC, TauI, y1, e)


Do k=1, 1000

    if (y0*y1<0) then
x2=(x0+x1)/2.
call annula_solver5(x2,d,rough, VSG, VSL, rhoL, rhoG,&
muL, muG,sigma,theta,HGC, vC,rhoC, SI, AC, TauI, y2,e)
if (abs(y2)<=0.0001)then
    delta=x2
else
   if (y0*y2<=0) then
     x1=x2
     y1=y2
   else
     x0=x2
     y0=y2
   endif
            delta=x0
end if

else
    x0=x1
    y0=y1
    x1=x1+0.001*d

     call annula_solver5(x1,d,rough, VSG, VSL, rhoL, rhoG,&
muL, muG,sigma,theta,HGC, vC,rhoC, SI, AC, TauI, y1, e)
endif
    If((x0>=0.5*d).or.(e<=0.0)) exit

Enddo

!-----------------------------------------------------------------
!examine the solution of liqiud high level

  if ((abs(y0)>0.1).or.(e<=0.0)) then
print*, "there is no solution of liquid film thickness"
DELTA=D/2.
```

```
  else
    call annula_solver5(deltA,d,rough, VSG, VSL, rhoL, rhoG,muL,&
 muG,sigma, theta,HGC,vC,rhoC, SI, AC, TauI, y0, e)
  endif


END SUBROUTINE annula_FT4

!@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@


!*******************************************************************

Subroutine annula_solver5(delta,d,rough, VSG, VSL, rhoL, rhoG,muL,&
                   muG,sigma,theta,HGC,vC,rhoC, SI, AC, TauI, y, E)
implicit none
Real(8)::d              !pipe diameter
Real(8)::rough          !pipe roughness
Real(8)::vSG            !superficial gas velocity
Real(8)::vSL            !superficial liquid velocity

Real(8)::rhoG           !gas density
Real(8)::rhoL           !liquid density
Real(8)::muG            !gas viscosity
Real(8)::muL            !liquid viscosity
Real(8)::sigma          !interficial force
Real(8)::theta          !pipe inclined angle from horizontal plane
Real(8)::Sgas           !gas specific gravity

real(8)::deri, func     !intermediate variables used for solving roots
Real(8), parameter::PI=3.141592653589793
Real(8), parameter::g=32.2
Integer::numb
real(8):: IV1, IV2, IV3, IV4, IV5 !for simplification



Real(8):: delta!film thickness
Real(8):: vM!mixture velocity
Real(8):: vSGC            !critical gas velocity for calculating
entrainment
Real(8):: E               !liquid entrainment
Real(8):: vF              !liquid film velocity
Real(8):: vC              !core velocity
Real(8):: rhoC            !core density
Real(8):: muC             !core viscosity
```

```
Real(8):: HGC           !gas fraction in core
Real(8):: A             !pipe cross section area
Real(8):: AC            !core cross section area
Real(8):: AF            !liquid film cross section area
Real(8):: dF            !liquid film hydraulic diameter
Real(8):: dc            !liquid film hydraulic diameter

Real(8):: SF            !liquid film perimeter
Real(8):: SI            !core perimeter

Real(8):: fF            !liquid film friction factor
Real(8):: fI            !core friction factor
Real(8):: fC            !core friction factor
Real(8):: fCS           ! friction factor
Real(8):: I             ! correction parameter for friction factor
Real(8):: Iv            ! correction parameter of vertical
Real(8):: Ih            ! correction parameter for horizontal
Real(8):: FA            ! correction parameter
real(8)::tauWF          !liquid film shear stress
real(8)::tauI           !core shear stress
real(8)::y              !function value for figure out the film
thickness
real(8)::ReSG           !gas Reynolds number
real(8)::ReSL           !gas Reynolds number
real(8)::vSC            !core superficial velocity

!calculate mixture velocity
vM=vSG+vSL
!------------------------------------------------------------

! critical gas velocity for entrainment fractor.

vSGC=10000.*(vSG*muG/sigma)*(rhoG/rhoL)**0.5

!solve the entrainment fraction

E=1.-exp(-0.125*(vSGC-15))


!------------------------------------------------------------
!Liquid film velocity
vF=vSL*(1.-E)*d**2/(4.*delta*(d-delta))

!gas core velocity
vC=(vSL+vSL*E)*d**2/(d-2*sigma)**2

!the properties of core
!gas fraction in the core
HGC=vSG/(vSL*E+vSG)
```

```
!the core average density
rhoC=rhoG*HGC+rhoL*(1.-HGC)

!the core average viscosity

muC=muG*HGC+muL*(1.-HGC)

!diameter of gas core

dC=d-2.*delta

!To calculate the friction factor, solve the hydraulic diameter

!Section area of liquid film and gas core
AF=pi*(d**2/4.-dC**2/4.)
AC=pi*dC**2/4.

!Perimeter of liquid film and gas core
SF=pi*d
SI=pi*(d-2.*delta)

!hydraulic diameter of liquid film

dF=11.*AF/SF

!calculate the friction factor of liquid film and core


fF=Fric_factor(df,rough, rhoL, muL, vF)


fC=Fric_factor(dC,rough, rhoC, muC, vC)


!the following is about interficial friction fractor

!vSC=the core superficial velocity
vSC=vSG+E*vSL

!superfacial core frction factor

fCS=Fric_factor(d,rough, rhoC, muC, vSC)

 ! fCS=Fric_factor1(d,rough, rhoC, muC, vSC)


 !vertical correction parameter,  Iv, E96

Iv=1+300*delta/d
```

```
!The following is calculation of the horizontal correction parameter


!superfacial gas and liquid Reynolds Numbers
ReSG=d*rhoG*vSG/muG

ReSL=d*rhoL*vSL/muL

IV1=((0.707*ReSL**0.5)**2.5+(0.0379*ReSL**0.9)**2.5)**0.4

FA=(IV1/ReSG**0.9)*(vSL/vSG)*(rhoL/rhoG)**0.5
Ih=1.+800.0*FA

!the correction of interfacial friction factor is

I=Iv*(sin(theta))**2+Ih*(cos(theta))**2

!the interfacial friction factor is
fI=fCS*I

!shear stress


tauWF=fF*rhoL*vF**2/2.0       !shear stress between liqid film and pipe
wall

tauI=fI*rhoC*(vC-vF)**2/2.0  !shear stress between gas core and liqid

y=tauWF*SF/AF-tauI*SI*(1./AF+1./AC)+(rhoL-rhoG)*g*sin(theta)

return

End Subroutine annula_solver5
!-----------------------------------------------------------------------
----


END MODULE

!@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
```

```
!*******************************************************************
!*                                                                 *
!* ######## SLUG FLOW#########                                     *
!*                                                                 *
!*******************************************************************

MODULE SLUG
USE GASFRICTION
USE STRATIFIED

implicit none
contains



SUBROUTINE slug_3(KCA, maxip, d, rough, vSG, vSL, rhoG, rhoL, muG,&
                    muL, sigma,theta, Sgas, Z, T,Tgrad,Tpc, P, Ppc,&
 Ploss, L, step, ACL, DI, Lf)

implicit none

real(8)::Maxip  !maximum of pressure drop
Real(8)::d            !pipe diameter
Real(8)::rough        !pipe roughness
Real(8)::vSG          !superficial gas velocity
Real(8)::vSL          !superficial liquid velocity

Real(8)::rhoG         !gas density
Real(8)::rhoL         !liquid density
Real(8)::muG          !gas viscosity
Real(8)::muL          !liquid viscosity
Real(8)::sigma        !interficial force
Real(8)::theta        !pipe inclined angle from horizontal plane
Real(8)::Sgas         !gas specific gravity
Real(8)::T            !temperature (R)
Real(8)::Tgrad        !temperature gradient (R/ft)
Real(8)::Tpc          !Psuedo critical temperature
Real(8)::P            !pressure (psia)
Real(8)::Ppc          !Psuedo critical pressure
Real(8)::Ploss        !pressure loss
Real(8)::Pgrad        !pressure loss

Real(8):: Step        !calculating interval length
Real(8):: L           !accumulative length calculated so far
Real(8):: ACL         !calculating the length of pipe divisions.
Real(8), parameter::PI=3.141592653589793
Real(8), parameter::g=32.2
real(8)::z
```

```
Real(8)::vG           !in-situ gas velocity
Real(8)::vL           !in-situ liquid velocity
Real(8)::vM           !mixture velocity
Real(8)::vBR          !bubble rise velocity

Real(8)::HLSU         !liquid holdup slug unit
Real(8)::HLTB         !liquid holdup in Taylor bubble body
Real(8)::HLLS         !liquid holdup  in slug



Real(8)::rhoU         !density
Real(8)::muU          !mixture viscosity

Real(8)::A, AL, AG
Real(8)::Angl,SF, SG, SI
Real(8)::dL, dG, h
Real(8)::tauWF, tauWG, tauI

! slug part
Real(kind=8)::rhoS, muS !density and viscosity in slug
Real(8):: fS            !friction factor of slug
Real(8):: tauS          !slug shear stress


Real(8)::x, x1, x2, x0
Real(8)::IV1, IV2, IV3


Real(8):: Re, ReL, ReG, ReI

!In-situ Velocity in slug body and Taylor bubble.
Real(8)::vLLS, vGLS, vLTB, vGTB

!Velosity of bubble, Taylor bubble velocity, and the insitu taylor
bubble
Real(8)::vBB, vBT, vITB
!slug unit length, slug length, Taylor bubble length
Real(8)::Lsh, Lsv, Ls, Lu,  Lf

Integer::KCA           !CONTOL NUMBER FOF ACCELERATION COMPONENT
Integer::DI            !CONTOL NUMBER FOF PREDICITON DIRECTION



Call SLUG_Parameter4(d, rough, vSG, vSL, rhoG, rhoL, muG, muL,&
                    sigma, theta,LS,LF, HLLS, HLTB, SF, SG, tauWF,&
 tauWG, tauS)
```

```
If(ls<=0)  goto 1
!***********************************************************************
 A=pi*d**2/4.

 Lu=LS+LF
 HLSU=(HLLS*LS+HLTB*LF)/LU

 vG=vSG/(1-HLSU)
 rhoU=HLSU*rhoL+(1.-HLSU)*rhoG
 IV1=rhoU*sin(theta)*g
 IV2=(tauS*pi*d/A)*Ls/Lu
 IV3=((tauWF*SF+tauWG*SG)/A)*LF/Lu

 Pgrad=(IV1+IV2+IV3)/(32.2*144)


CALL Pressloss(KCA, maxip, P, Ppc, Pgrad, T,Tpc, Tgrad, Sgas,&
                          vG,rhoG, ACL, L, step,Ploss)

1 return

END Subroutine slug_3
!@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@



!*******************************************************************
Subroutine SLUG_Parameter4(d, rough, vSG, vSL, rhoG, rhoL, muG,&
                           muL, sigma, theta,LS, LF, HLLS, HLTB,&
    SF, SG, tauWF, tauWG, tauS)

implicit none
Real(8)::vSG           !superficial gas velocity
Real(8)::vSL           !superficial liquid velocity
Real(8)::vG            !in-situ gas velocity
Real(8)::vL            !in-situ liquid velocity
Real(8)::vM            !mixture velocity
Real(8)::vBR           !bubble rise velocity
Real(8)::vTB           !Taylor bubble rise velocity

Real(8)::HU            !liquid holdup
Real(8)::HLTB          !liquid holdup
Real(8)::HLLS          !liquid holdup
Real(8)::HLSU          !liquid holdup

Real(8)::T             !temperature (R)
Real(8)::Tgrad         !temperature (R)
Real(8)::T1            !temperature at new point(R)
Real(8)::P             !pressure (psia)
```

```
Real(8)::Ppc            !Psuedo critical pressure
Real(8)::Tpc            !Psuedo critical temperature
Real(8)::Ppr            !relative pressure
Real(8)::Tpr            !relative temperature
Real(8)::Ppr1           !relative pressure
Real(8)::Tpr1           !relative temperature

Real(8)::ReSG           !Gas Reynolds number of superficial velocity
Real(8)::ReSL           !Liquid Reynolds number of superficial velocity
Real(8)::rho            !density
Real(8)::rhoG           !gas density
Real(8)::rhoL           !liquid density
Real(8)::rhoM           !mixture density
Real(8)::muG            !gas viscosity
Real(8)::muL            !liquid viscosity
Real(8)::muM            !mixture viscosity
Real(8)::sigma          !interficial force
Real(8)::g=32.2         !interficial force
Real(8), parameter::PI=3.141592653589793

Real(8)::rough          !pipe roughness
Real(8)::theta          !pipe inclined angle from horizontal plane



Real(8)::A, ALTB
Real(8)::Angl,SF, SG, SI
Real(8)::d, dL, dG, h
Real(8)::tauWF, tauWG, tauI
Real(8)::y
Real(8):: Re, ReL, ReG, ReI
!In-situ Velocity in slug body and Taylor bubble.
Real(8)::vLLS, vGLS, vLTB, vGTB
!velocity of bubble, Taylor bubble, and the insitu taylor bubble
Real(8)::vBB, vBT, vITB
Real(8)::fG, fL, fI
!slug unit length, slug length, Taylor bubble length
Real(8)::Lsh, Lsv, Ls, Lu, LF
! slug part
Real(8)::rhoS, muS       !density and viscosity in slug
Real(8):: fS             !friction factor of slug
Real(8):: tauS           !slug shear stress


Real(kind=8)::IV1, IV2, IV3
```

```
!calculate the mixture velocity, single bubble rise velocity,,
!Taylor bubble velocity E76-2, and in-situ Taylor bubble velocity,

vM=vSG+vSL

vBR=1.53*(g*sigma*(rhoL-rhoG)/rhoL**2)**0.25

vTB=(0.351*sin(theta)+0.541*cos(theta))*(g*d*(rhoL-rhoG)/rhoL)**0.5



vITB=1.2*vM+vTB


!************************************************
!calculate the slug length
!1. calculate the vertical slug length
Lsv=30.0*d   !d is in ft unit

!2. Calculate horizontal length
if (d<2.0/12.0) then

       Lsh=20*d     !d is in ft unit
 else
       Lsh=exp(-25.4+28.5*(log(d*12))**0.1)

 end if

!3. calculate the length of slug
Ls=Lsv*(sin(theta))**2+Lsh*(cos(theta))**2



!***********************************************
!Calculate the liquid holdup in slug body E71
!@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
IV1=rhoL*vm*d/muL
!IV1=rhoL*vSL*d/muL
IV2=-(0.45*theta+0.00000248*IV1)

HLLS=exp(IV2)

!control HLLS to be in the reasonable area for slug flow
    do
     IV1=vSG/(1-HLLS)
 IV2=1.2*vM+vBR*HLLS**0.5*sin(theta)
 HLLS=HLLS*1.001
 if(iv1>IV2) exit
 if(HLLS>=1.) stop "HLLS is exceed the 1"
```

```
enddo


!Calculate gas flow rate in slug body, vGLS, equ.72

!vGLS=1.2*vM+vBR*sin(theta)*HLLS**0.5
vGLS=1.2*vM+vBR*HLLS**0.5*sin(theta)

!Calculate liquid flow rate in slug body, vLLS, Equ.77

vLLS=(vM-vGLS*(1-HLLS))/HLLS

!calcualte shear stress in slug body, TauS

rhoS=rhoL*HLLS+rhoG*(1.-HLLS)

muS=muL*HLLS+muG*(1.-HLLS)



!write(*,*)"d*vm*rhos/mus",d*vm*rhos/mus


fS=Fric_factor(d,rough, rhoS, muS, vM)


tauS=fs*rhoS*vM**2/2.


!------------------------------------------------------------------
!determine the HLTB, vLTB, vGTB, SF, SG, tauWF, tauWG
Call  STRATIFIED_LHL4(h,d, rough,vSG, vSL,rhoG, rhoL, muG, muL,&
                 sigma,theta, p,ALTB, SF, SG,SI, tauWF, tauWG, tauI)


!holdup in Taylor bubble, HLTB
A=pi*d**2/4.

HLTB=ALTB/A

! calculate liquid flow rate in Taylor bubble, vLTB, E75


vLTB=(vITB-vLLS)*HLLS/HLTB-vITB
```

```
!calculate gas flow rate in Taylor bubble, vGTB, E76

vGTB=(vM-vLTB*HLTB)/(1.-HLTB)


!calculate the length of slug unit, E65

Lu=Ls*(vLLS*HLLS-vLTB*HLTB)/(vSL-vLTB*HLTB)

LF=Lu-Ls
!calculate the average liquid holdup in the slug unit, E66

HLSU=(HLLS*Ls+HLTB*LF)/Lu

 1 return

End subroutine SLUG_Parameter4
!@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@

end module slug

!@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
```