COMPARATIVE AND SENSITIVITY STUDY OF THE EFFECTS OF FLOW PARAMETERS ON PRESSURE DROP IN VERTICAL TUBING

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Abstract

Two-phase gas-liquid flow occurs in vertical pipes during the production of reservoir fluids. The two most common flow patterns that are observed during oil production are the Bubble and Slug flows. Determination of pressure drop in two-phase flow is more complicated than single-phase flow because two fluids with different densities flow in the tubing at different velocities. Using two multiphase correlations (Hagedorn and Brown, and Duns and Ros), the effect of fluid properties variation at different flow conditions on pressure drop were studied. Fluid data developed with correlations and West Sak fluid data were used for the analysis. Plots showing the relationship between pressure drop and different fluid properties were made. From the analysis, it was concluded that oil density, oil viscosity and oil flow rate are the three factors that influence pressure drop in vertical pipes the most. The Hagedorn and Brown correlation was shown to be able to compute pressure drop for high-viscosity oil.

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Chapter 1

Introduction

Multiphase flow is a rule rather than an exception in oil and gas production and transport. Petroleum engineers encounter vertical two-phase flow in wellbore tubing during the production of oil and gas. Proper modeling of pressure transverse is important in various designs in the petroleum industry. In vertical multiphase flow, it is useful for the following (Brown and Beggs 1977):

a) Selecting correct tubing sizes.
b) Predicting when the well will quit flowing and hence predicting times for artificial lift.
c) Designing artificial lift installations.
d) Determining the productivity index of wells.
e) Predicting maximum flow rates.

The hydrodynamics of single-phase flow is better understood than that of two-phase flow. There are different analytical solutions for single-phase flow developed from the fundamental fluid flow equations. These fundamental equations for single-phase flow are not applicable to two-phase flow because of a number of reasons (Govier and Aziz 1972):

a) The flow of multiphase mixture may not be characterized merely as laminar, or as a combination of laminar and turbulent flow, but the relative quantities and distribution of the phases (known as the flow pattern) must be considered.
b) Because of the differences in phase densities normally encountered, the flow pattern in horizontal, vertical or inclined flow is not symmetrical about the flow axis.
c) The presence of an interface between the phases itself adds to the complexity of the problem, and the fundamental equation must be written for it as well as for the individual phases.
d) The separate phases move at different average velocities and the in situ concentrations are not the same as the concentrations in which the phases are introduced. This is known as slippage.

Four flow patterns have been observed in two-phase vertical flow. They are bubble flow, slug flow, transition flow and mist flow. These different flow patterns can occur at different flow conditions in the well bore. For example, the reservoir fluid could be in single phase at the prevailing pressure and temperature at the bottom hole. As the fluid flows upwards, the pressure continuously drops. When it is below the bubble point pressure, gas will begin to come out of solution in form of bubbles. At this point, bubble flow pattern is said to have occurred. Due to additional pressure drop in the system as the fluid continues to flow upwards, the population of the bubbles increases and starts to coalesce to form larger bubbles of a diameter approximately equal to the pipe diameter. At this point we have slug flow. With continued decrease in pressure and accompanying libration of gas, the transition and mist flow pattern could possibly occur in the system. In most oil wells, bubble and slug flow are the two main flow patterns that are observed. The remaining two flow patterns are usually observed in wellbores producing condensate and natural gas.

The total pressure drop has been identified to be the combination of the elevation component, the friction component, and the acceleration component. In vertical two-phase flow, the elevation component contributes the major part of the total pressure drop. The friction component contributes a little, except at a very high oil and gas flow rates, where it becomes more pronounced. In most cases, the effect of the acceleration component is assumed to be negligible.

Presently, different correlations are available for the determination of pressure drop during two-phase flow. Each of these correlations uses fluid physical properties such as viscosity, gas-oil ratio, density, and surface tension for predicting the pressure drop. Vertical two-phase flow is a transient phenomenon because the different thermodynamic properties of the fluids are rarely in equilibrium. In order to simplify the problem, the flow conduit is divided into segments and a steady state condition is assumed in each segment. Fluid properties are usually measured at the surface; therefore, in order to determine them at different depths, fluid property correlations must be used for their estimation.

The objective of this work is to critically evaluate how various fluid and operational properties like oil density, oil viscosity, gas-oil ratio, oil flow rate, and gas flow rate contribute to the outcome of the pressure drop in a vertical circular flow conduit. Two types of fluid data were used:

1) The fluid data developed using appropriate correlations

2) Actual fluid data from West Sak Reservoir

Pressure drop for each fluid type was predicted at different oil and gas flow rates. Two vertical multiphase correlations, the Hagedorn and Brown correlation (1964) and the Duns and Ros correlation (1963) were used to determine the pressure drop. The Hagedorn and Brown (1964) correlation had been shown in the literature to perform best at a wide range of fluid properties variations. However, this correlation does not predict the flow pattern in the well bore. In order to know the flow pattern under any condition, the Duns and Ros correlation (1963) was also used. Parametric analysis was then carried out to observe the effect operational parameters and fluid properties have on pressure drop.

Chapter 2

Literature Review

Two-phase flow occurs in the petroleum industry during the production and transportation of oil and gas. During production, the accurate knowledge of pressure gradient is particularly useful in the optimum selection of flow string dimensions. Also, during gas lift operation, the determination of optimum injection depth, optimum gas injection rate, and optimum gas injection pressure lies in the knowledge of the pressure gradient. Another useful application of pressure transverse in the wellbore can be found in the area of pump selection, where the hydraulic horsepower of the pump should be capable of bringing the produced hydrocarbon to the surface.

2.1 Basic Terms in Gas-Liquid Two-Phase Flow

2.1.1 Flow Pattern

In two-phase gas-liquid flow in pipes or channels, an interface exists between the phases. The phase boundary can take a variety of configurations, known as the flow pattern. The existing flow pattern in a given two-phase flow system depends on the operational parameters (gas and liquid flow rates), the geometrical variables (pipe diameter and pipe inclination angle), and the physical properties of both phases (gas and liquid densities, viscosities, and surface tension).

In vertical two-phase flow, four different flow patterns have been identified, according to Orkiszewski (1967). They are bubble flow, slug flow, transition flow, and annular-mist flow patterns (see Figure 2.1).

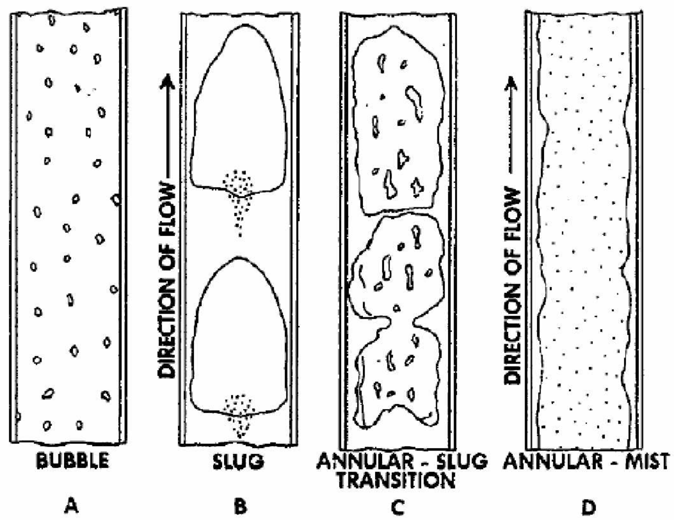

Figure 2.1 Vertical Pipe Flow Pattern (Orkiszewski 1967)

According to Brill and Beggs (1994), the different flow patterns can be described as follows;

Bubble flow pattern: In the bubble flow pattern, the pipe is almost completely filled with liquid and the free gas phase is small. The gas is present as small bubbles, randomly distributed, whose diameters also vary randomly. The bubbles move at different velocities, depending upon their respective diameters. Bubble flow occurs at relatively low liquid rates, with low turbulence.

Slug flow pattern: In the slug flow pattern, the gas phase is more pronounced. Although the liquid phase is still continuous, the gas bubbles coalesce to form stable bubbles of approximately the same size and shape which are nearly the diameter of the pipe. These bubbles are called Taylor-Bubbles. The flow consists of successive Taylor-Bubbles and liquid slugs, which bridge the entire pipe cross section. A thin liquid film flows downward between the Taylor-Bubbles and the pipe wall. The film penetrates into the following liquid slug and creates a mixing zone aerated by small gas bubbles.

Transition (annular-slug transition) flow pattern: The change from a continuous liquid phase to a continuous gas phase occurs in this region. The gas bubbles may join and liquid may be entrained in the bubbles. Although liquid effects are significant, the gas phase effects are predominant.

Mist (annular-mist) flow pattern: In the mist flow pattern, the gas phase is continuous and the bulk of the liquid is entrained as droplets in the gas phase. The pipe wall is coated with a liquid film, but the gas phase predominantly controls the pressure gradient.

2.1.2 Liquid Holdup, H_L, and Gas Void Fraction, α

The liquid holdup, H_L, is the fraction of volume element occupied by the liquid phase. Similarly, the gas void fraction, α, is the fraction of the volume element occupied by the gas phase. Liquid holdup, H_L, is a fraction which varies from zero for all gas flow to one for all liquid flow. The relationship between the liquid holdup and gas void fraction is given as (Shoham 2006):

$$\alpha = 1 - H_L. \quad (2.1)$$

2.1.3 No-Slip Liquid Holdup, λ_L

The no-slip liquid holdup, sometimes called the input liquid content, is defined as the ratio of the volume of liquid in a pipe segment divided by the volume of the pipe segment which would exist if the gas and liquid traveled at the same velocity (no slippage). It is a dimensionless quantity and can be calculated directly from the known gas and liquid flow rates given by equation 2.2 (Brill and Beggs 1994):

$$\lambda_L = \frac{q_L}{q_L + q_g}. \quad (2.2)$$

2.1.4 Superficial Velocities (V_{SL} and V_{Sg}) and Mixture Velocity, V_m

The superficial velocity of a phase is the volumetric flux of the phase, which represents the volumetric flow rate per unit area. In other words, the superficial velocity of a phase is the velocity of the fluid, assuming it flows alone in the pipe. The superficial velocities of liquid and gas can be determined from equation 2.3 (Brill and Beggs 1994):

$$V_{SL} = \frac{Q_L}{A}; \; V_{Sg} = \frac{Q_g}{A}. \tag{2.3}$$

The mixture velocity V_m is the total volumetric flow rate of both phases per unit area, which is referred to as the center of volume velocity. It can be obtained by the following relationship (Brill and Beggs 1994):

$$V_m = \frac{Q_L + Q_g}{A} = V_{SL} + V_{Sg}. \tag{2.4}$$

2.1.5 Two-Phase Density, ρ_m

The two-phase density, also known as the mixture density, is the average density of the two-phase mixtures. It is determined from the liquid holdup and gas void fraction and the densities of oil and gas. It is given by equation 2.5 (Brill and Beggs 1994):

$$\rho_m = \rho_L H_L + \rho_g H_g. \tag{2.5}$$

2.2 General Pressure Gradient Equation

Three components make up the general pressure gradient equation: the elevation component, the friction component, and the acceleration component. The right-hand side of equation 2.6 shows these three components of pressure drop (Brill and Beggs 1994):

$$\left(\frac{dp}{dL}\right) = \frac{g}{g_c} \rho_m sin\theta + \frac{f \rho_f V_m^2}{2 g_c d} + \frac{\rho V_m}{g_c} \frac{d V_m}{dL}. \tag{2.6}$$

The pressure drop caused by elevation depends on the densities of the phases and the liquid holdup. This is represented by the first group of terms in the right-hand side of equation 2.6. In vertical two-phase flow, 90%-98% of the pressure gradient is caused by this component. The second group of terms in equation 2.6 is the friction component. The variable 'f' in the equation is the two-phase friction factor and ρ_f is a density term used in determining the friction pressure drop. The third group of terms is the acceleration component of the pressure gradient equation.

2.3 Vertical Two-Phase Flow Correlations

Over the past decades, researchers have presented several correlations that are used to predict pressure drop for multiphase flow in vertical circular pipes. Up till now, there has not been any correlation that has been generally accepted to give accurate results over a whole range of flow conditions obtainable in the oil industry. The complexity of multiphase flow is due to the presence of more than one phase that flow at different velocities. This results in the formation of different flow patterns at different points along the pipe. Each flow pattern is governed by different hydrodynamic principles which affect the in situ liquid holdup and pressure gradient.

Multiphase correlations can be classified into two groups: empirical models and mechanistic models. The early method used in solving multiphase flow problems was through the empirical approach. The investigators used physical models and many simplifying assumptions based on field and laboratory experimental data. Mechanistic modeling was a later approach and this technique is based on a comprehensive description of the basic mechanism occurring in multiphase flow.

2.3.1 Empirical Models

The empirical two-phase correlation was first classified into three groups by Orkiszewski in 1967 based on to the following criteria:

Group 1: Correlations in this group do not consider slip between phases; both phases are assumed to travel at the same velocity. Flow patterns are not distinguished and general formulas are given for mixture density and frictional factor determination. Pressure losses are described by a single energy loss factor. Some correlations in this group are discussed below.

In 1952, Poettmann and Carpenter developed what became the earliest widely accepted correlation for calculating pressure drop during vertical two-phase flow The correlation was developed from data taken from natural flowing and gas-lift wells. The flow string sizes were 2 in, 2 ½ in, and 3 in. Pressure was measured at both the well head and the bottom hole. The gas–liquid ratios used were less than 1500 scf/bbl and the flow rates, Q_L, were greater than 420 bbl/d. Poettmann and Carpenter (1952) used an energy balance equation to show that the total energy loss was composed of elevation loss and friction loss. The multiphase fluids were treated as a homogeneous mixture of gas, oil and water when determining the mixture density. Also, because a no-slip condition was assumed, mixture velocity was taken to be the average velocity in the tubing. Friction loss was calculated using a Fanning-type friction factor, which was assumed to be constant over the entire flow string for a particular set of flow conditions. The viscosity effect was assumed to be negligible since the two phases were in turbulent flow in all their tests. Also, kinetic energy effect was neglected in their correlation.

In 1961, Baxendall and Thomas applied the Poetmann and Carpenter (1952) approach to data taken in Lake Maracaibo wells with tubing sizes of 2 ½ in and 3 ½ in. They observed that a more accurate result would be achieved by developing their own frictional factor correlation. The frictional factor was found to be almost constant at high flow rates. They attributed this phenomenon to the fact that the flow was in a high degree of turbulence.

In 1963, Fancher and Brown reported the results of their experiments conducted with data taken from an 8000 ft well. The well was equipped with pressure gauges at various depths and a wide range of flow rates were used. The tubing size was 2 3/8 in. Liquid holdup was not measured and pressure loss not accounted for by the no-slip density, which was attributed to friction.

Group 2: In this group, liquid holdup is considered in the computation of mixture density and no attempt is made to make distinctions among flow regimes. The liquid holdup is either correlated separately or combined in some form with the wall friction losses. The friction losses are based on the composite properties of the liquid and gas. A correlation in this is discussed below.

In 1964, Hagedorn and Brown developed one of the most celebrated empirical correlations for vertical two-phase flow. It was developed using experimental data from a 1500 ft. test well in Dallas, Texas, for three pipe sizes of 1 in, 1 ¼ in and 1 ½ in. Liquids used were water, with a viscosity of 0.86 cP, and oils, with viscosities of 10, 35, and 110 cP. The effect of liquid viscosity was studied and it was concluded that for a liquid viscosity of less than 12 cp, viscosity had little effect on pressure drop. Hagedorn and Brown (1964) used the Moody Friction Factor obtained by using a two-phase Reynolds number. Their Reynolds number was defined as (Hagedorn and Brown 1964):

$$N_{Retp} = \frac{\{\rho_L H_L + \rho_g (1-H_L) V_m^2}{\mu_L{}^{H_L} . \mu_g{}^{(1-H_L)}} \quad (2.7)$$

Where,

N_{Retp} is the two-phase Reynolds number and is dimensionless,

ρ_L is the liquid density in lb/cu.ft,

ρ_g is the gas density in lb/cu.ft,

V_m is the mixture velocity in ft/cu.ft,

H_L is the liquid Holdup and is dimensionless,

μ_L and μ_g are the liquid and gas viscosity, respectively, in cP.

Liquid holdup is required for this Reynolds number and for determining the two-phase density. Liquid holdup was not measured, but was back calculated through trial and error so that it would fit their definition of friction factor and experimental pressure drop measurements. They showed, using dimensional analysis, that liquid holdup is related principally to four dimensionless numbers: the liquid velocity number, the gas velocity number, the pipe diameter number, and the liquid viscosity number. These same dimensionless numbers had been derived earlier by Duns and Ros (1963).

Group 3: Correlations in this group consider both slip effect and flow regime in their pressure drop predictions. Calculation of friction factor and mixture density varied with flow regime. Correlations in this group are discussed below.

In 1963, Duns and Ros developed a correlation for all pipe sizes. In their experimental setup, the measuring section was a transparent 10-meter tubing. The pressure was measured using a differential manometer, and the liquid holdup was obtained using a radioactive tracer technique. Using π-theorem on 13 variables, they came up with 10 dimensionless groups. Of these 10 dimensionless groups, four were chosen. They are the same as those used by Hagedorn and Brown (1964). Duns and Ros (1963) developed a correlation for dimensionless slip velocity from which the actual slip velocity is calculated. The actual slip velocity is then used in computing the liquid holdup. A different dimensionless slip velocity was developed for the bubble and slug flow patterns. In the mist flow pattern, a no-slip condition was assumed. Therefore, the slip velocity is zero and the mixture density is calculated using a no-slip holdup.

In 1967, Orkeszewski published a pressure-drop correlation based on literature data. After testing numerous published correlations, he concluded that the Griffith and Wallis (1961) procedure could be modified to cover all ranges of two-phase flow. Orkeszewski (1967) developed a correlation for two-phase density and a frictional factor for each of these three flow patterns: bubble flow, slug flow, and mist flow. A transition zone between slug and mist flow was also defined, in which the friction factor was weighted averages of those calculated in the bounding zones. In the slug flow pattern, a liquid distribution coefficient was developed that was used in both the mixture density and friction factor calculation. The liquid distribution coefficient was a function of liquid viscosity, hydraulic diameter, and mixture velocity. The friction factor was correlated with the liquid Reynolds number. In the bubble flow pattern, an expression was given for liquid holdup, and the friction component of the pressure gradient was calculated using the actual liquid velocity and the single-phase friction factor. For the mist flow pattern, it was assumed that there was no slippage between phases, and the friction gradient was determined using the gas velocity.

In 1973, Beggs and Brill developed a correlation that computed the pressure gradient in all ranges of pipe inclination. The correlation was developed from experimental data obtained from a small-scale test facility consisting of 1 in. and 1.5 in. sections of acrylic pipe, 90 ft. in length. The gas flow rate was varied between 0 and 300 Mscf/d, the liquid flow rate between 0 and 30 gal/min, and the average system pressures were between 35 and 95 psia. Fluids used were air and water. Horizontal flow regimes were used in developing this correlation. Different correlations for liquid holdup are presented for each flow pattern. The liquid holdup that would exist if the pipe were horizontal was first calculated and then corrected for the actual pipe inclination angle. A two-phase friction factor was calculated using equations that are independent of flow regime but dependent on holdup.

2.3.2 Mechanistic Models

The continuous efforts of researchers and practicing engineers to improve the accuracy of pressure drop predictions have indicated that empirical calculation methods, by their nature, can never cover all of the parameter ranges that may exist in the operations. This is the reason why the modeling approach is exclusively utilized in current research of multiphase flow behavior. Investigators adopting this approach model the basic physics of multiphase flow and develop appropriate fundamental relationships between the basic parameters. At the same time, they try to eliminate the use of empirical correlations in order to widen the ranges of applicability of their correlations.

In 1972, Aziz et al., in their pioneering work, developed a mechanistic correlation for vertical two-phase flow. Their model involved the prediction of actual flow patterns based on a simplified flow pattern map. Then, the multiphase two-phase density, frictional factor, and pressure gradient were evaluated from comprehensive equations valid for each flow pattern. New correlations for bubble and slug flow were developed, but the Duns and Ros (1963) correlation was used for the mist flow pattern. For the transition flow regime Aziz et al. (1972) used the interpolation method proposed by Duns and Ros (1963).

It was discovered that the failure of empirical models could be partly attributed to features of the flow pattern maps they employ. These maps use arbitrarily dimensionless groups as coordinates and are limited in their applicability by the experimental data used in their construction. In 1980, Taitel et al. developed a mechanistic model for flow pattern determination. They suggested physical mechanisms for the transition boundaries between the various flow patterns and modeled each transition boundary on the basis of the mechanism by which it occurs. They identified four distinct flow patterns, bubble, slug, churn, and annular (see Figure 2.2).

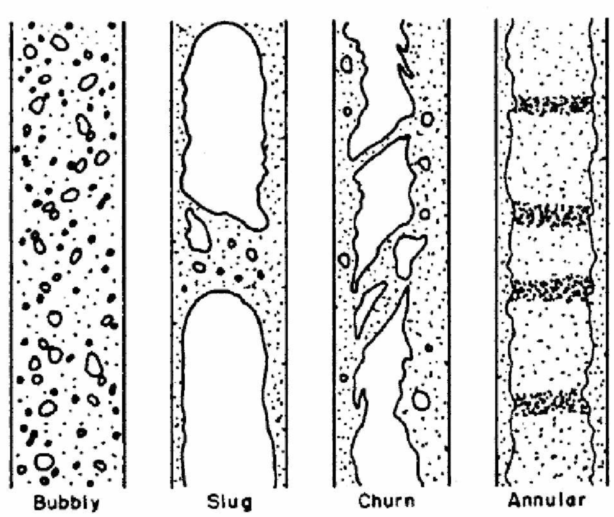

Figure 2.2 Vertical Pipe Flow Regime (Taitel et al. 1980)

In 1988, Hassan and Kabir developed a mechanistic model for multiphase flow in a vertical tube. They examined the transition boundaries individually and developed criteria valid for each of them. The four different transition boundaries were identified as the bubble-slug flow transition boundary, the transition-dispersed bubble flow transition boundary, the slug-churn flow transition boundary, and the transition-annular flow transition boundary. The bubble-slug flow transition was determined from literature and experimental data to occur at a void fraction of 0.25. They related this to measurable variables using the following equation:

$$V_{gs} = 0.429V_{Ls} + 0.357V_{\infty} \qquad (2.8)$$

where

V_{∞} is the terminal velocity of bubble in ft/sec

V_{gs} is the superficial gas velocity in ft/sec

V_{Ls} is the superficial liquid velocity in ft/sec

They also figured that since transition is a gradual process, it is better to use the terminal velocity of Taylor bubbles in slug flow for determining the bubble-slug flow transition boundary. The terminal velocity of Taylor bubbles is dependent on the pipe diameter:

$$V_{\infty T} = 0.35\sqrt{\frac{gd(\rho_L-\rho_g)}{\rho_L}} \approx 0.35\sqrt{gd} \qquad (2.9)$$

where

$V_{\infty T}$ is the Taylor bubble velocity, in ft/sec

ρ_L and ρ_g are the liquid and gas densities, respectively, in lb/cu ft

g is the acceleration due to gravity in ft/sq sec

d is the tubing diameter, in inches

The transition to dispersed bubble flow pattern is attributed to the breakdown of larger bubbles in the liquid due to high flow rates. Hassan and Kabir (1988) used the Taitel et al. (1980) equation for mixture velocity and related it to the maximum bubble diameter possible under turbulent conditions. They presented the following expression for mixture velocity:

$$V_M^{1.12} = 4.68d^{0.48}[\frac{g(\rho_L-\rho_g)}{\sigma}]^{0.5}(\frac{\sigma}{\rho_L})^{0.6}(\frac{\rho_M}{\mu_L})^{0.08} \qquad (2.10)$$

where

V_M is the mixture velocity in ft/sec

σ is the interfacial tension in dynes/cm

μ_L is liquid viscosity in cP

ρ_L and ρ_g are the liquid and gas density in lb/cu ft

g is the acceleration due to gravity in ft/sq ft

ρ_M is the mixture density in ft/sec

d is the tubing diameter, in inches

If mixture velocity, V_m, is greater than the value calculated from the equation 2.10, then the bubble flow will persist even if the void fraction is above 0.52. For the slug-churn transition boundary, they agreed to use Hewitt-Robert's map (1969) to predict this transition at pressures higher than 10atm. In transition to the annular flow pattern, the void fraction approaches unity and an expression for superficial gas velocity was derived.

In 1990, Ansari et al. published a comprehensive mechanistic model that first predicts the transition boundary of different flow regimes and then calculates pressure drop for bubble, slug and annular flow regimes. An implicit equation was developed for calculating liquid holdup in the bubble flow pattern. They divided the slug flow pattern into fully developed and developing slug flow.

Chapter 3

PVT and Fluid Properties

During production, as oil and gas flow upwards in the tubing, the initial temperature and pressure reduce to a lower value. Because the physical properties of the reservoir fluids are both functions of temperature and pressure, they also change during production. Due to the constant change in fluid properties during production, the tubing is usually divided into segments for ease of calculation. Within each segment, the fluid properties are assumed to be constant, and the pressure drop is calculated by integrating the pressure gradient equation along the pipe length as shown in Figure 3.1. The pipe between A and B is divided into 'n' segments. The pressure changes from one segment to another, but for each segment the pressure is assumed to be constant at the average flow conditions along the segment.

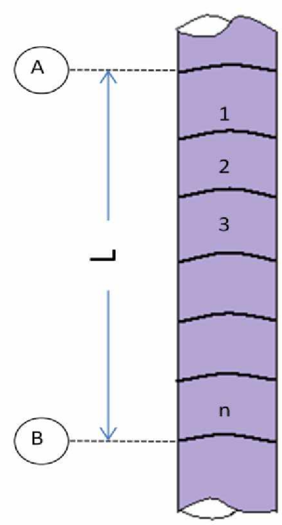

Figure 3.1: Schematics of Calculation Increments in Vertical Two-Phase Flow in Pipes (Shoham 2006)

In most cases, the actual values of the fluid properties are measured at surface conditions. The values at intermediate points in the tubing are obtained using fluid property correlations. The fluid properties required for the calculation of pressure drop are pressure, temperature, oil and gas viscosities, solution gas-oil ratio, oil and gas formation volume factors, oil and gas densities, interfacial tension, and oil and gas specific gravities. The different fluid properties correlations used for the analysis are discussed below.

3.1 Solution Gas-Oil Ratio, R_s

Solution gas-oil ratio, R_s, is defined as the quantity of gas dissolved in oil at reservoir pressure and temperature (Dake 1978). The significance of R_s is best illustrated by considering a typical gas-oil ratio curve for black oil as a function of pressure at a constant reservoir pressure as shown in Figure 3.2. At all pressures above the bubble point pressure, the gas-oil ratio is constant because no gas is evolved. However, as the reservoir pressure falls below the bubble point pressure, the oil is saturated and cannot contain all gas in solution, resulting in the release of some gas and consequently leaving less gas dissolved in oil. From basic thermodynamics, the following solubility behavior may be expected (Asheim Harald 2006):

(a) Solubility is proportional to pressure (Henry's law).
(b) Solubility is inversely proportional to the exponential of 1/T (after Clausius-Clapeyron's law).
(c) Heavy gas is more soluble than light gas. Heavy oil dissolves less gas than light oil (molecular similarity).

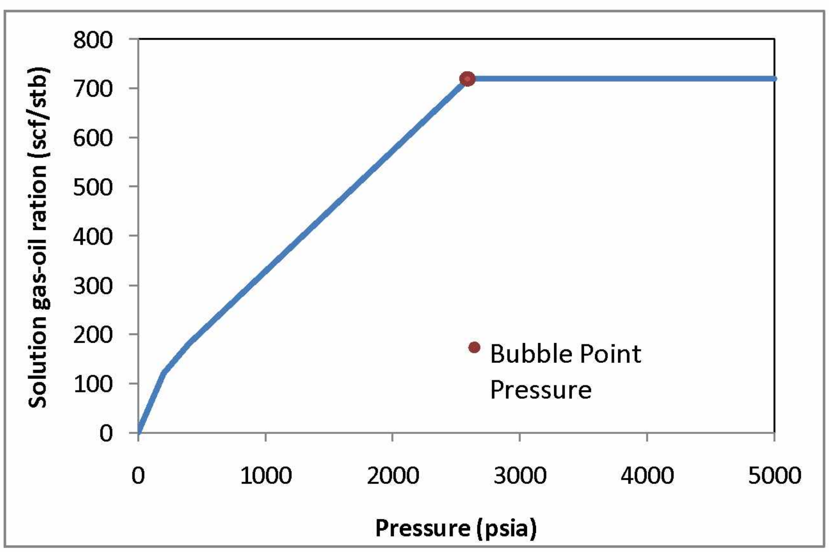

Figure 3.2: Variation of Solution Gas-Oil Ratio with Pressure at Constant Reservoir Temperature for Black Oil (Dandekar 2006)

Many empirical correlations have been developed for estimating the solution gas-oil ratio. One of the most widely used in the petroleum industry is Standing's Correlation, developed in 1947 using California crude data.

$$R_s = \gamma_g [\left(\frac{P}{18.2} + 1.4\right) 10^x]^{1.208} \quad (3.1)$$

$$x = 0.0125API - 0.00091(T - 460) \quad (3.2)$$

where

R_s is the solution gas-oil ratio in scf/stb

T is Temperature in degree-Rankin

P is pressure in psia

Other correlations for estimating the solution gas-oil ratio are Glasø (1980) and Lasater (1958).

3.2 Oil Volume Factor, B_o:

The oil formation volume factor is the volume in barrels occupied in the reservoir, at the prevailing pressure and temperature, by one stock tank barrel of oil plus its dissolved gas (Dake 1978).

When gas dissolves in oil, the mass contained in the oil phase increases. This makes the pressure-volume behavior of liquid below the saturation pressure fundamentally different from the behavior from above the saturation pressure. Figure 3.3 shows a typical variation of the formation volume factor with pressure.

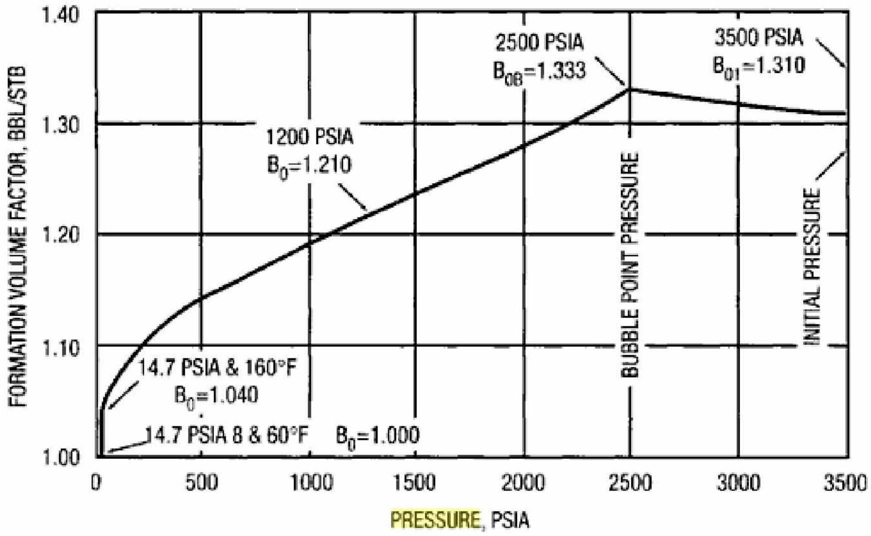

Figure 3.3: Effect of Pressure on Oil Formation Volume Factor

At all times, it was assumed in this work that the reservoir pressure is below the bubble point pressure (the oil is saturated). The reservoir fluid in this condition (below bubble point pressure) is in two-phase and is characterized with the following behaviors:

(a) The liquid volume expands as gas dissolves in it. The increment in volume will be roughly proportional to the amount of gas and the molecular size of the gas that dissolves in it.

(b) The liquid volume expands as its temperature increases. However, increased temperature will also reduce gas solubility.

(c) When pressure is increased, the liquid volume reduces (is compressed), but gas solubility goes up.

The overall effect of pressure increase at a constant temperature will be increased liquid volume because an increase in volume due to increased solubility surpasses the reduction in volume due to compression. Temperature increase at constant pressure will result in reduced liquid volume, caused by vaporization. Different correlations have been developed for the estimation of the oil formation volume factor. Some of the well-known correlations are by Standing (1947), Glasø (1980), and Vazquez and Beggs (1980).

Vazquez and Beggs (1980) developed a correlation based on 6000 measurements of B_o at various pressures. They reported an average error of 4.7% when their correlation was tested against measured field data. The coefficients in their correlation are different for oil API≤30 and API>30, as shown in equations 3.3 and 3.4.

For API ≤ 30

$$B_o = 1 + (4.677 \times 10^{-4})R_s + (0.1751 \times 10^{-4})(T - 40)\left(\frac{\gamma_{API}}{\gamma_{gc}}\right) - (1.8106 \times 10^{-8})R_s(T - 60)\left(\frac{\gamma_{API}}{\gamma_{gc}}\right) \quad (3.3)$$

For API >30

$$B_{0b} = 1 + (4.67 \times 10^{-4})R_s + (0.11 \times 10^{-4})(T - 60)\left(\frac{\gamma_{API}}{\gamma_{gc}}\right) - (0.1337 \times 10^{-8})R_s(T - 60)\left(\frac{\gamma_{API}}{\gamma_{gc}}\right) \quad (3.4)$$

where

γ_{gc} is the modified specific gravity and is computed as follows:

$$\gamma_{gc} = \gamma_g\left[1 + (0.5912 \times 10^{-4})\gamma_{API}T_{sp}LOG\left(\frac{P_{sp}}{114.7}\right)\right] \quad (3.5)$$

The units of the parameters in equation 3.4 are as follows:

B_{ob} is the formation volume factor in bbl/stb

R_s is the solution gas-oil ratio in scf/stb

γ_{API} is the API gravity of the oil

P is the pressure in psia

T is the temperature in degrees Rankin

Parameters in equation 3.5 are as follows:.

P_{sp} is the separator pressure in psia

T_{sp} is the separator temperature in degrees Fahrenheit

3.3 Gas Volume Factor, B_g

This is the volume in barrels that one standard cubic foot of gas will occupy as free gas in the reservoir at the prevailing reservoir pressure and temperature (Dake 1978). At surface conditions, natural hydrocarbon gas behaves like an ideal gas, that is, Z=1. But at downhole conditions, the Z factor is in the order of 0.7-0.9. Therefore, another way to define the gas volume factor, $B_{g,,}$ is "it is the ratio of gas volume at specific pressure and temperature to the ideal gas volume at standard condition." From real-gas law, the equation for gas volume factor is given as follows:

$$B_g = 0.02827 \frac{ZT}{P} \tag{3.6}$$

where

B_g is the gas volume factor in cu ft/scf

T is the temperature in degrees Rankin

P is pressure in psia

3.4 Oil Viscosity μ_o

Oil viscosity is defined as the internal resistance of fluid to flow. It is a strong function of temperature, pressure, oil gravity, gas gravity, and solution gas-oil ratio. The oil field unit for viscosity is centipoise. Estimation of the oil viscosity at temperatures equal to or below the bubble point pressure is usually a two-step procedure:

Step 1: Calculate the viscosity of the oil without dissolved gas (dead oil) at reservoir temperature.

Step 2: Adjust the dead oil viscosity to account for the effect of gas solubility at the pressure of interest.

Some available correlations for the estimation of oil viscosity are Beal (1946), Beggs and Robinson (1975), and Glasø (1980). The Beggs and Robinson correlation (1975) for oil viscosity was developed using data obtained from Core Laboratories, Inc. The range of data used for development of the correlation is given in Table 3.1. Their correlation shows oil viscosity to be a function of API. But, oil viscosity, actually, is dependent on its composition and oil of different composition can have the same API. However, their correlation is easy to use and produces fair accuracy and precision over a wide range of APIs. Just as with any other empirical correlation, best results are obtained when they are used within the range of data used for its development. The correlation is given in the following equations:

Table 3.1: Data Range for Beggs and Robinson Correlation (1975)

Variables	Range
Solution gas oil ratio scf/stb	20 to 2070
Oil API gravity	16 to 58
Pressure, psig	0 to 5250
Temperature, ˚F	70 to 295
Number of oil systems = 600 Number of dead oil observations = 460 Number of live oil observations = 2073	

$$\mu_{OD} = 10^{x} - 1 \tag{3.7}$$

where

μ_{OD} is the dead oil viscosity

Other variables in equation 3.7 are obtained using the following relationships:

$$x = Y(T - 460)^{-1.163} \tag{3.8}$$

where

$$Y = 10^{Z} \tag{3.9}$$

and

$$Z = 3.0324 - 0.02023API \tag{3.10}$$

where

T is temperature in degrees Rankin

Using the dead oil viscosity, the saturated oil viscosity can then be calculated with equation 3.11:

$$\mu_{ob} = a(\mu_{OD})^b \tag{3.11}$$

where

$$a = 10.715(R_s + 100)^{-0.515} \tag{3.12}$$

and

$$b = 5.44(R_s + 150)^{-0.338} \tag{3.13}$$

where

R_s is the solution gas-oil ratio in scf/stb.

3.5 Gas Viscosity, μ_g:

The viscosity of gas, μ_g, is a function of pressure and temperature. It decreases with decreasing reservoir pressure at all temperatures. However, at low pressure, it increases as temperature increases, while at high pressures it decreases as temperature increases. The Lee-Gonzalez-Eakin Correlation (1966) used to estimate the viscosity of gas is shown below:

$$\mu_g = A_1 \times 10^{-4} \exp\left(A_2 \rho_g{}^{A_3}\right) \tag{3.14}$$

where

$$A_1 = \frac{(9.379 + 0.01607\, M_g)^{1.5}}{209.2 + 19.26 M_g + T} \tag{3.15}$$

$$A_2 = 3.448 + \left(\frac{986.4}{T}\right) + 0{,}01009 M_g \tag{3.16}$$

$$A_3 = 2.447 - 0.222 A_2 \tag{3.17}$$

and

$$M_g = 28.97 \gamma_g \tag{3.18}$$

where

μ_g is the viscosity of gas in centipoise

T is the temperature in degrees Rankin

ρ_g is the density of gas in g/cu cm

3.6 Oil and Gas Densities

Oil density, ρ_o, is defined as mass per unit volume of the oil at a given temperature and pressure. The density of oil based on black oil properties is given by (Whitson and Brulé 2000) the following:

$$\rho_o = \frac{62.4\gamma_o + 0.0136\gamma_g R_s}{B_o} \tag{3.19}$$

where

γ_o is the specific gravity of oil, which can be obtained using equation 3.20:

$$\gamma_o = \frac{141.5}{\gamma_{API} + 131.5} \tag{3.20}$$

and

γ_g, is the specific gravity of gas and was assumed to be 0.6.

The density of gas, ρ_g, can be estimated from the following equation:

$$\rho_g = 28.97 \frac{P\gamma_g}{ZRT} \tag{3.21}$$

where

Temperature, T, and Pressure, P, are in degrees Rankin and psia, respectively.

The z-factor can be calculated using the Standing-Katz (1942) Correlation.

3.7 Oil and Gas Flow Rates (Q_o, Q_g):

The underground withdrawal of hydrocarbon associated with surface production is obtained from the following relationships (Dake 1978):

$$(underground\ withdrawal)/stb = B_o + (R_p - R_s)B_g \tag{3.22}$$

where

R_p is the produced gas-oil ratio (the ratio of gas flow rate at the surface condition, $q_g^{'}$, and the oil flow rate at surface condition, $q_o^{'}$) in scf/stb

R_s is the solution gas-oil ration in scf/stb

B_g is the gas volume factor in bbl/scf

B_o is the formation volume factor in bbl/stb

From equation 3.23, the oil flow rate, Q_o, at reservoir condition is obtained (Brill and Beggs 1994) as follows:

$$Q_o = q_o^{'} B_o (5.614)/86400 \tag{3.23}$$

where

Q_o is the downhole flow rate of oil in cu ft/sec

$q_o^{'}$ is the surface flow rate of oil in bbl/day

B_o is the oil formation volume factor in bbl/stb

The volume flow rate of gas, Q_g, is obtained from equation 3.24 (Brill and Beggs 1994):

$$Q_g = q_o^{'} \left(R_p - R_s\right) B_g/86400 \tag{3.24}$$

where

Q_g is the downhole gas flow rate in cu ft./sec

$q_o^{'}$ is the oil surface flow rate in stb/day

R_p and R_s are the produced gas-oil ratio and the solution gas-oil ratio in scf/stb

B_g is the gas volume factor in cu ft/scf

3.8 Multiphase Flow Correlations

The literature is rich in correlations for estimation of pressure drop in vertical pipe during the simultaneous flow of oil and gas. Each of the correlations has a range of conditions in which it performs well. According to Takacs (2001), none of the available vertical multiphase pressure drop calculation models are generally applicable because their prediction errors may considerably vary in the different ranges of the flow parameters.

As an effort to find the most accurate correlation for predicting a multiphase pressure drop in a vertical pipe, various authors conducted statistical analysis with the available correlations using field and laboratory data. Lawson and Brill (1974) tested six different correlations against 726 well tests from field and experimental wells. One of their conclusions was that no single correlation was found to be superior to all of the others considered for all ranges of producing well flow variables. Overall, the Hagerdorn and Brown correlation (1964) performed best. In their analysis, two flow regime dependent correlations were used. They were Duns and Ros (1963) and Orkisziwski (1967). The Hagedorn and Brown Correlation (1964) is the industry choice correlation for predicting pressure drop. Its application can be found in the pressure transverse curves used in different artificial lift problems. For these reasons, the correlation was chosen in the present study for computing the pressure gradient. Because the Hagedorn and Brown correlation does not predict the flow pattern at any given condition, the Duns and Ros correlation (1963) was used as a supporting correlation to give the prevailing flow pattern in the tubing and also to compare the predicted pressure.

The general pressure gradient equation is divided into three components: elevation, friction, and acceleration (Brill and Beggs 1994);

$$\frac{dp}{dL} = \left(\frac{dp}{dz}\right)_{elevation} + \left(\frac{dp}{dz}\right)_{friction} + \left(\frac{dp}{dz}\right)_{acceleration} \tag{3.25}$$

$$\left(\frac{dp}{dz}\right)_{elevation} = \frac{g}{g_c}\rho_m sin\theta;$$

$$\left(\frac{dp}{dz}\right)_{friction} = \frac{f\rho_f V_m^2}{2g_c d};$$

$$\left(\frac{dp}{dz}\right)_{acceleration} = \frac{\rho V_m}{g_c}\frac{dV_m}{dL} \tag{3.26}$$

where, θ is the inclination angle of the pipe. For vertical flow, θ=90°, and, therefore, sin 90°=1. Determination of some parameters in equation 4-2 varies for different correlations. This can be observed in the Duns and Ros (1963) and Hagedorn and Brown (1964) correlations.

3.8.1 Duns and Ros Correlation (1963)

The stepwise procedure for calculating pressure drop along flow direction using the Duns and Ros correlation (1963) is presented below:

1) The oil flow rate, Q_o, in ft/sec was first determined by assuming the surface flow rate, q_0', is available and equation 3.27 was used. The oil formation volume factor, B_o, is a variable in this equation and it was estimated from equations 3.3 and 3.4.
2) The producing gas-oil ratio, R_p, was also determined from the surface flow rate of oil and gas ($q_o'$and q_g') from equation 3.27.

$$R_p = \frac{q_g'}{q_o'} \tag{3.27}$$

3) The next variable determined was the gas flow rate, Q_g, from equation 3-24. Two variables were needed in this equation: the gas formation volume factor, B_g, and the solution gas-oil ratio, R_s. They were calculated from equations 3.6 and 3.1, respectively. The unit of the calculated gas flow rate was in cu ft/sec.
4) Using the oil and gas flow rates calculated from steps 1 and 3, the superficial oil and gas velocities were determined from equation 3.28:.

$$V_{sl} = \frac{Q_L}{A}; \qquad V_{sg} = \frac{Q_g}{A} \tag{3.28}$$

where 'A' is the area of the pipe in sq ft

5) Four dimensionless numbers were used for predicting the flow pattern in this correlation. These dimensionless numbers are the liquid velocity number, N_{LV}, the

gas velocity number, N_{gv}, the pipe diameter number, N_d, and the liquid viscosity number, N_L. They were computed from equation 3.29:

$$N_{LV} = 1.938V_{SL}\sqrt[4]{\frac{\rho_L}{\sigma_L}}$$

$$N_{gv} = 1.938V_{sg}\sqrt[4]{\frac{\rho_L}{\sigma_L}}$$

$$N_d = 120.872d\sqrt{\frac{\rho_L}{\sigma_L}}$$

$$N_L = 0.15726\mu_L\sqrt[4]{\frac{1}{\rho_L\sigma_L^3}} \quad (3.29)$$

where σ_L is interfacial tension in dynes/cm

6) Four other dimensionless numbers were also needed for determining the limits of the flow regime. The first two dimensionless numbers, L_1 and L_2, are obtained from the correlating chart in appendix 'A' using the value of pipe diameter number, N_d. The remaining two flow-regime dimensionless numbers, L_s and L_m, were determined from equation 3.30:

$$L_s = 50 + 36N_{LV}$$

$$L_m = 75 + 84{N_{LV}}^{0.75} \quad (3.30)$$

7) The flow patterns were predicted using the following limiting conditions:
    a. Bubble flow : $0 \le N_{gv} \le L_1 + L_2N_{LV}$
    b. Slug flow: $L_1 + L_2N_{LV} \le N_{gv} \le L_S$
    c. Mist flow: $N_{gv} > L_m$
    d. Transition flow: $L_s < N_{gv} < L_m$
8) Nine dimensionless numbers were used to predict the slip factor. Seven of these numbers, F_1, F_2, F_3, F_4, F_5, F_6, and F_7, were obtained from the correlation chart in

appendix 'A' using the liquid viscosity number, N_L. The remaining two, F_3' and F_6', were determined from equation 3.31:

$$F_3' = F_3 - \frac{F_4}{N_d}$$
$$F_6' = 0.029N_d + F_6 \qquad (3.31)$$

9) Using the appropriate dimensionless numbers in step 8, the slip factor was determined for the in-situ flow pattern from equation 3.32:

a. Bubble flow: $S = F_1 + F_2N_{LV} + F_3'(\frac{N_{gv}}{1+N_{LV}})^2$
b. Slug flow: $S = (1 + F_5)\frac{(N_{gv})^{0.982}+F_6'}{(1+F_7N_{LV})^2}$ (3.32)
c. Mist flow: the slip velocity is assumed to be zero.
d. Transition flow: Duns and Ros (1963) suggested an interpolation method between the flow regime boundaries to obtain the pressure drop.

10) The actual slip velocity, V_s, was then computed with the slip factor (step 9) using equation 3.33:

$$V_s = \frac{S}{(\rho_L/\sigma_L g)^{0.25}} \qquad (3.33)$$

The parameter, g, is the acceleration due to gravity. The dimensional analysis for the denominator of equation 3.34 is shown below:

$$(\rho_L/\sigma_L g)^{0.25} = (\frac{lb}{ft^3} * \frac{1}{0.002205}\frac{cm.s^2}{lb.cm} * \frac{1}{32.2}\frac{s^2}{ft})^{0.25} \qquad (3.34)$$

where, in field units, equation 3.35 becomes

$$V_s = \frac{S}{1.938}(\frac{\sigma_L}{\rho_L})^{\frac{1}{4}} \qquad (3.35)$$

11) Then the liquid holdup, H_L, is determined using equation 3.36:

$$H_L = \frac{V_s - V_m + [(V_m - V_s)^2 + 4V_s V_{sL}]^{0.5}}{2V_s} \quad (3.36)$$

The parameter V_m is the mixture velocity. The mixture velocity, V_m, can be determined from equation 3.37:

$$V_m = V_{sL} + V_{sg} \quad (3.37)$$

12) The mixture density, ρ_m, of the two-phase fluid was then determined from equation 3.38 and the elevation pressure drop was computed using equation 3.26. This equation is only valid for bubble flow and slug flow regimes:

$$\rho_m = \rho_L H_L + \rho_g (1 - H_L) \quad (3.38)$$

In the mist flow regime, no-slip flow is assumed by the authors. Therefore, the mixture density, ρ_n, is determined with the no-slip liquid holdup, λ_L.

$$\rho_n = \rho_L \lambda_L + \rho_g (1 - \lambda_L) \quad (3.39)$$

$$\lambda_L = \frac{Q_L}{Q_L + Q_g} \quad (3.40)$$

13) The Moody frictional factor, f_1, could be obtained from the Moody diagram, in Figure 3.4. Chen's equation (1979) could also be used for all ranges of Reynolds numbers, and it is given in equation 3.41:

$$f = 8((\frac{8}{R_e})^{12} + \frac{1}{(A+B)^{1.5}})^{\frac{1}{2}} \quad (3.41)$$

where

$$A = (-2.457LN\left((^7/_{Re})^{0.9} + 0.27\, ^{\epsilon}/_{d}\right)\Big) \quad (3.42)$$

$$B = (\frac{37530}{16})^{16}$$

The parameter N_{Re_L} is the Reynolds number, and it can be determined from equation 3.43:

$$N_{Re_L} = \frac{\rho_L V_{SL} d}{\mu_L} \quad (3.43)$$

where ε is the roughness factor of the pipe wall. It was assumed to be 0.0006 ft.

14) Another friction factor parameter, f_2, is obtained from the chart in Appendix A using the term in equation 3.44:

$$\frac{f_1 V_{sg} N_d^{2/3}}{V_{sL}} \quad (3.44)$$

where, f_3 , also a friction factor parameter, was determined using equation 3.45:

$$f_3 = 1 + f_1\sqrt{\frac{V_{sg}}{50V_{SL}}} \quad (3.45)$$

15) The two-phase frictional factor, f_m, was then determined using equation 3.46:

$$f_m = \frac{f_1 f_2}{f_3} \quad (3.46)$$

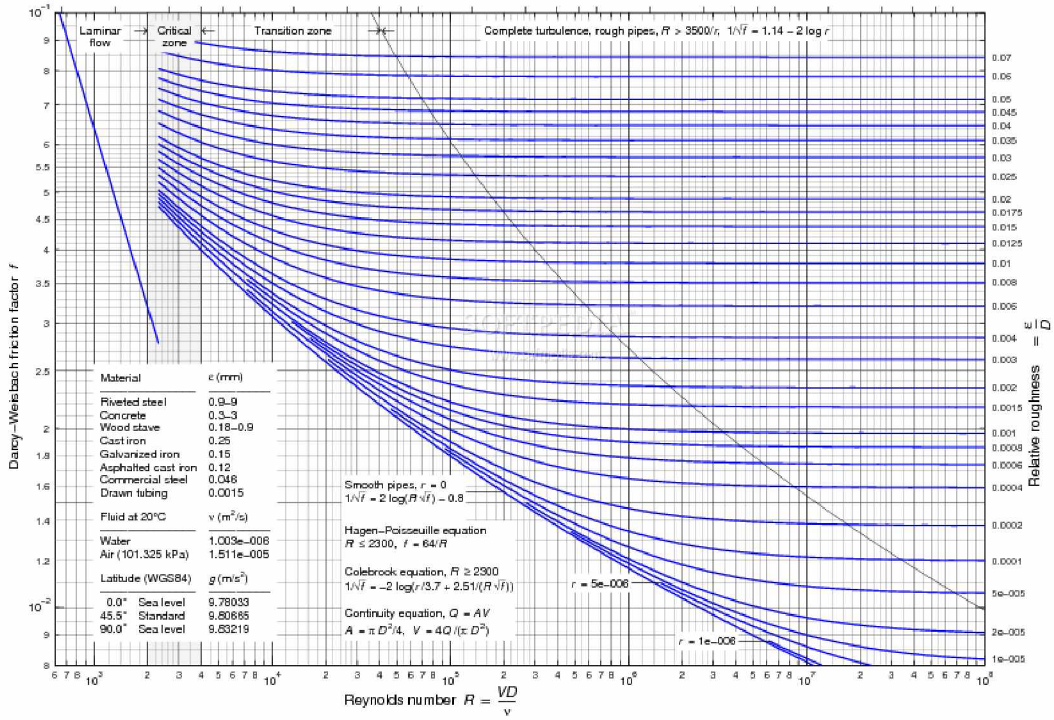

Figure 3.4: Moody Diagram (Govier and Aziz 1972)

16) Then, the pressure drop due to friction was determined from equation 3.47:

$$\left(\frac{dp}{dz}\right)_f = \frac{f_m \rho_L V_{SL} V_m}{2gd} \tag{3.47}$$

17) The total pressure drop was determined by summing the results in step 12 and step 16. Pressure drop due to elevation was assumed to be negligible.

The flow chart for slug and bubble flow patterns is given in Figure 3.5:

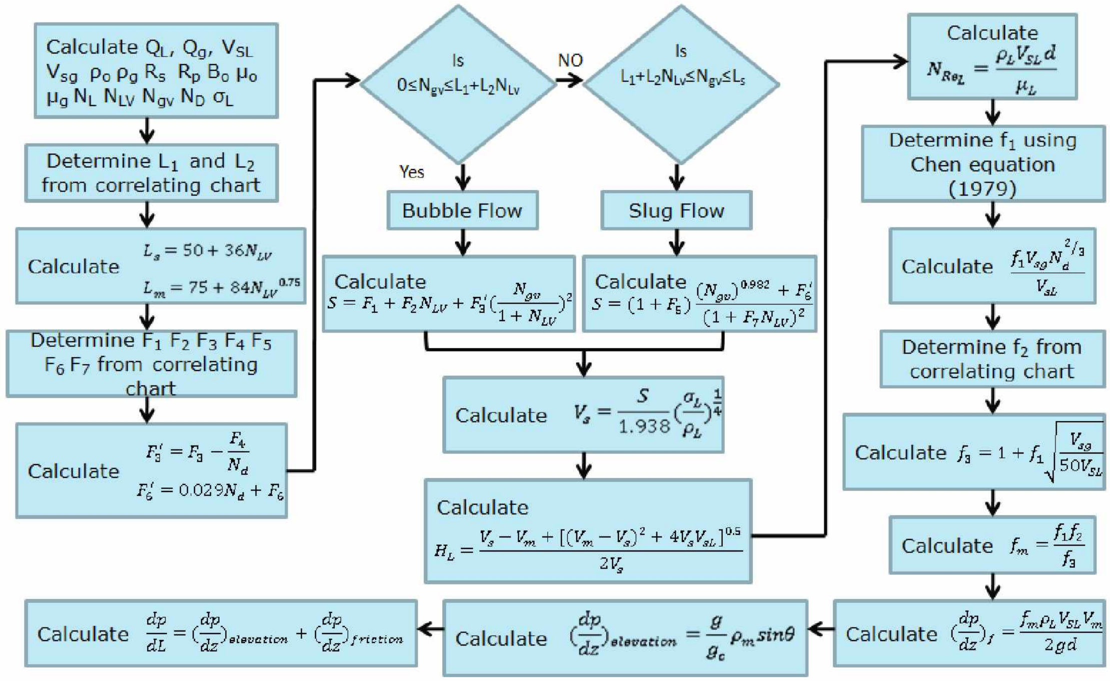

Figure 3.5: Flow Chart for Duns and Ros Correlation

3.8.2 Hagedorn and Brown Correlation (1964)

The stepwise procedure for calculating pressure transverse in a vertical pipe during simultaneous flow of oil and gas, using the Hagedorn and Brown (1964) correlation, is given below:

1) The oil and gas flow rates (Q_L and Q_g) were first determined by using equations 3.23 and 3.24. The correlations used for estimating, B_O, B_g, and R_s, are also given in equations 3.3, 3.6, and 3.1, respectively.
2) Using the values of oil and gas flow rates (Q_L and Q_g), the liquid superficial velocity, V_{SL}, and the gas superficial velocity, V_{Sg}, were determined from equation 3.28.
3) The four dimensionless numbers, liquid velocity number, N_{LV}; gas velocity number, N_{gV}; pipe diameter number, N_d; and liquid viscosity number, N_L, were determined from equation 3.29.
4) Then, the viscosity number coefficient, CN_L, was determined from the correlating chart in Appendix B, using the liquid velocity number, N_L.

5) Also, the holdup factor, H_L/ψ, was obtained from a correlating chart in Appendix B, using the following term:

$$\frac{N_{Lv}P^{0.1}CN_L}{N_g^{0.575}P_a^{0.1}N_d} \tag{3.48}$$

where P_a is the atmospheric pressure in psia and P is the prevailing pressure psia at that condition.

6) The correlating term for the secondary correlation factor, ψ, was also obtained from a correlating chart in the Appendix B, using the term in equation 3.49:

$$\frac{N_{gv}N_L^{0.38}}{N_d^{2.14}} \tag{3.49}$$

7) Then, the liquid holdup, H_L, was obtained as shown in equation 3.50:

$$H_L = \frac{H_L}{\psi} * \psi \tag{3.50}$$

8) Using equation 3.38, the two-phase density, ρ_m, was determined and then the elevation pressure drop was calculated from equation 3.26.
9) The Reynolds number, N_{Re}, was determined from equation 3.51:

$$N_{Re} = \frac{\rho_n V_s d}{\mu_s} \tag{3.51}$$

where ρ_n is the no-slip two-phase density and μ_s is the two-phase viscosity. These two parameters can be determined from equation 3.52:

$$\mu_s = \mu_s^{H_L} \times \mu_g^{(1-H_L)}$$

$$\rho_n = \frac{\rho_L V_{SL} + \rho_g V_{sg}}{V_m} \tag{3.52}$$

10) Using either the Moody Diagram in Figure 3.4 or equation 3.41, the Moody friction factor, f_m, can be determined.

11) The friction component of the pressure drop was then computed from equation 3.53:

$$\left(\frac{dp}{dz}\right)_f = \frac{f_m \rho_f V_m^2}{2gd} \tag{3.53}$$

12) To obtain the total pressure drop, the elevation and friction components of the pressure drop were summed. The acceleration term was assumed to be negligible.

The flow chart for the stepwise procedure for the prediction of pressure drop using the Hagedorn and Brown correlation (1964) can be seen in Figure 3.6.

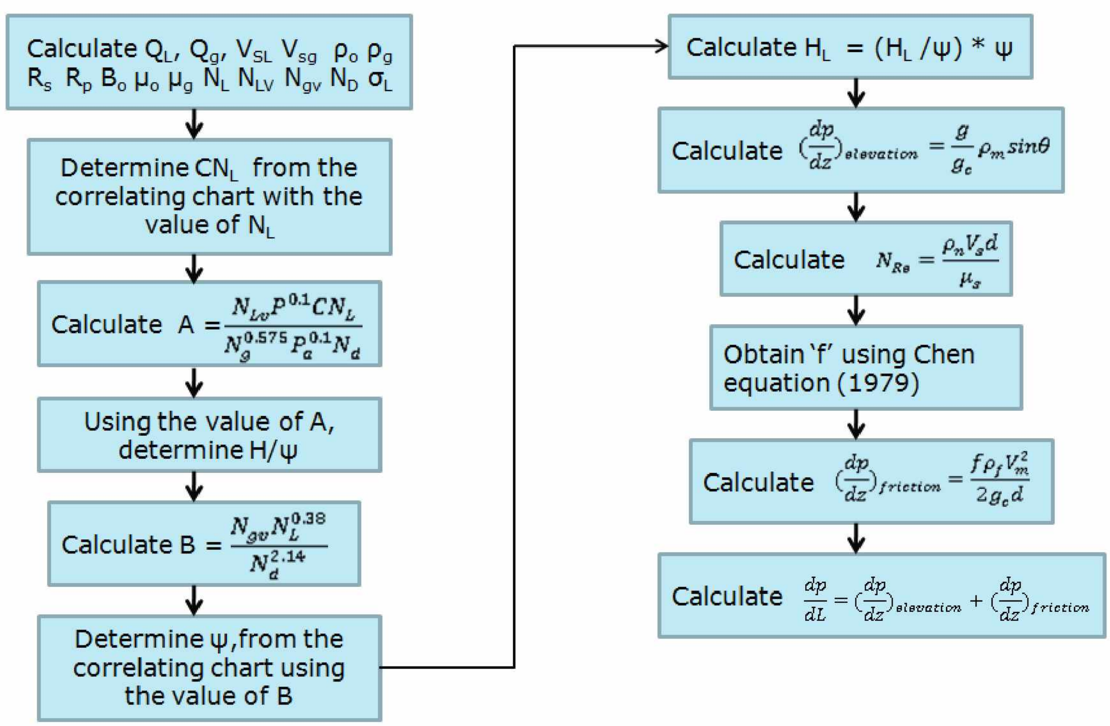

Figure 3.6: Flow Chart for Hagedorn and Brown Correlation

Chapter 4

Methodology and Results

4.1 Development of Fluid Data Using Correlations

As discussed in Chapter 3, the pressure and temperature of produced hydrocarbons are constantly changing as they flow upwards in the production tubing. This results in continuous change in the fluid's physical properties in the tubing during production. In order to cover all possible ranges of variation in the physical properties of the reservoir fluids, the relevant fluid physical property correlations were used to develop fluid data.

The fluid physical properties correlations discussed in Chapter 3 were used at different assumed temperatures and pressures to develop fluid data. Pressure was varied between 100 and 4000 psia and temperature between 70 and 120 °F. An example of fluid data developed at a given temperature and pressure condition using fluid physical property correlations is shown in Table 4.1. In all cases, the interfacial tension, σ, and the gas-specific gravity were assumed to be a constant value. The interfacial tension was assumed to be 30 dynes/cm, and the specific gravity of gas γ_g, was assumed to be 0.6. The interfacial tension is in metric units because an appropriate conversion factor was already incorporated in all equations.

Table 4.1: Fluid Data Developed Using Correlations

API	16
Gas specific graviey	0.6
Downhole temperature ˚F	80
Pressure,psia	3000
Oil viscosity, cP @ 3000 psia	61
Oil formation volume factor, bbl/stb	1.2
Oil density, Ib/cu.ft.	52.8

The oil API gravity was varied from 16 to 45. The lower limit of oil API gravity was chosen to be 16 API because it was the lowest value of oil API gravity in the data used in the development of the Beggs-Robinson correlation (1975) for saturated oil viscosity. Within this range of API gravity, pressure and temperature were assumed to be constant at 3000 psia and 70˚F, respectively. Appropriate fluid physical property correlations were used to calculate each fluid property at this pressure and temperature. The fluid data obtained are shown in Table 4.2.

From Table 4.2, it can be observed that the solution gas-oil ratio increases as the API of the oil increases. This consistent with the fact that heavier oil has lesser gas solubility than lighter oil. Also, as expected, the oil formation volume factor increases as the API of oil increases. Even though the viscosity of oil is a function of the composition of the oil, lower API oils are associated with high viscosity and density, as shown in Table 4.2.

The effect of temperature on the properties of the fluid was studied by varying temperature from 70˚F to 120˚F for oil API of 16 and 25, with pressure constant at 3000 psi. The fluid data developed are shown on Tables 4.3 and 4.4 below.

Table 4.2: Effect of API on Reservoir Fluid Physical Properties

API	Temperature, R	specific gravity of gas	Pressure, psia	Solution GOR, scf/stb	Dead oil viscosity, cP	saturated oil viscosity, cP	Oil FVF, bbl/stb	Oil Density, lb/cu.ft	z-factor	Gas Density, lb/cu.ft
16.00	530.00	0.60	3000.00	422.12	4516.12	90.23	1.20	52.75	0.79	11.61
17.00	530.00	0.60	3000.00	437.05	3078.77	66.68	1.21	52.20	0.79	11.61
18.00	530.00	0.60	3000.00	452.52	2135.71	50.01	1.21	51.67	0.79	11.61
19.00	530.00	0.60	3000.00	468.53	1506.29	38.05	1.22	51.13	0.79	11.61
20.00	530.00	0.60	3000.00	485.10	1079.31	29.34	1.23	50.60	0.79	11.61
21.00	530.00	0.60	3000.00	502.27	785.11	22.92	1.24	50.08	0.79	11.61
22.00	530.00	0.60	3000.00	520.04	579.36	18.12	1.25	49.55	0.79	11.61
23.00	530.00	0.60	3000.00	538.44	433.43	14.49	1.26	49.04	0.79	11.61
24.00	530.00	0.60	3000.00	557.49	328.50	11.72	1.26	48.52	0.79	11.61
25.00	530.00	0.60	3000.00	577.21	252.08	9.57	1.27	48.01	0.79	11.61
26.00	530.00	0.60	3000.00	597.63	195.73	7.89	1.28	47.51	0.79	11.61
27.00	530.00	0.60	3000.00	618.78	153.70	6.57	1.29	47.01	0.79	11.61
28.00	530.00	0.60	3000.00	640.67	121.98	5.52	1.30	46.51	0.79	11.61
29.00	530.00	0.60	3000.00	663.34	97.79	4.67	1.31	46.02	0.79	11.61
30.00	530.00	0.60	3000.00	686.81	79.15	3.99	1.32	45.53	0.79	11.61
31.00	530.00	0.60	3000.00	711.11	64.66	3.43	1.34	44.95	0.79	11.61
32.00	530.00	0.60	3000.00	736.27	53.27	2.97	1.35	44.46	0.79	11.61
33.00	530.00	0.60	3000.00	762.32	44.25	2.58	1.36	43.97	0.79	11.61
34.00	530.00	0.60	3000.00	789.29	37.04	2.27	1.37	43.49	0.79	11.61
35.00	530.00	0.60	3000.00	817.21	31.24	2.00	1.39	43.01	0.79	11.61
36.00	530.00	0.60	3000.00	846.13	26.52	1.77	1.40	42.53	0.79	11.61
37.00	530.00	0.60	3000.00	876.06	22.67	1.58	1.42	42.06	0.79	11.61
38.00	530.00	0.60	3000.00	907.06	19.49	1.41	1.43	41.59	0.79	11.61
39.00	530.00	0.60	3000.00	939.15	16.86	1.27	1.45	41.12	0.79	11.61
40.00	530.00	0.60	3000.00	972.38	14.67	1.15	1.46	40.66	0.79	11.61
41.00	530.00	0.60	3000.00	1006.78	12.82	1.04	1.48	40.20	0.79	11.61
42.00	530.00	0.60	3000.00	1042.40	11.26	0.95	1.49	39.74	0.79	11.61
43.00	530.00	0.60	3000.00	1079.28	9.94	0.87	1.51	39.29	0.79	11.61
44.00	530.00	0.60	3000.00	1117.47	8.81	0.80	1.53	38.84	0.79	11.61
45.00	530.00	0.60	3000.00	1157.00	7.84	0.73	1.55	38.40	0.79	11.61

Table 4.3: Effect of Temperature on the Physical Properties of Oil of API 16

API	Temperature, R	specific gravity of gas	pressure, Psia	Solution GOR, scf/cu.ft.	Dead oil viscisity, cP	saturated oil viscosity,	Oil FVF, bbl/stb	Oil Density, lb/cu.ft.	z-factor	Gas Density, lb/cu.ft.
16.00	530.00	0.60	3000.00	422.12	4516.12	90.23	1.20	52.75	0.79	11.61
16.00	535.00	0.60	3000.00	416.81	2359.79	60.97	1.20	52.76	0.79	11.50
16.00	540.00	0.60	3000.00	411.57	1345.32	43.44	1.20	52.77	0.79	11.39
16.00	545.00	0.60	3000.00	406.39	823.37	32.32	1.20	52.77	0.79	11.29
16.00	550.00	0.60	3000.00	401.28	534.27	24.93	1.20	52.78	0.79	11.18
16.00	555.00	0.60	3000.00	396.24	363.99	19.80	1.20	52.78	0.80	11.01
16.00	560.00	0.60	3000.00	391.25	258.36	16.13	1.19	52.78	0.81	10.71
16.00	565.00	0.60	3000.00	386.33	189.87	13.42	1.19	52.78	0.82	10.55
16.00	570.00	0.60	3000.00	381.47	143.75	11.37	1.19	52.77	0.82	10.40
16.00	575.00	0.60	3000.00	376.68	111.66	9.78	1.19	52.77	0.83	10.24
16.00	580.00	0.60	3000.00	371.94	88.68	8.53	1.19	52.76	0.83	10.16

Table 4.4: Effect of Temperature on the Physical Properties of Oil of API 25

API	Temperature, °F	specific gravity of gas	Pressure, Psia	Solution GOR, scf/stb	Dead oil viscisity, cP	saturated oil viscosity, cP	oil FVF, bbl/scf	Oil Density, lb/cu.ft	z-factor	Gas density, cP
25.00	530.00	0.60	3000.00	577.21	252.08	9.57	1.27	48.01	0.79	11.61
25.00	535.00	0.60	3000.00	569.95	164.18	7.56	1.27	48.03	0.79	11.50
25.00	540.00	0.60	3000.00	562.78	113.18	6.17	1.27	48.05	0.79	11.39
25.00	545.00	0.60	3000.00	555.71	81.70	5.16	1.27	48.06	0.79	11.29
25.00	550.00	0.60	3000.00	548.72	61.26	4.41	1.27	48.07	0.79	11.18
25.00	555.00	0.60	3000.00	541.82	47.40	3.84	1.27	48.07	0.80	11.01
25.00	560.00	0.60	3000.00	535.00	37.66	3.39	1.26	48.08	0.81	10.71
25.00	565.00	0.60	3000.00	528.28	30.60	3.03	1.26	48.08	0.82	10.55
25.00	570.00	0.60	3000.00	521.63	25.35	2.74	1.26	48.07	0.82	10.40
25.00	575.00	0.60	3000.00	515.07	21.34	2.50	1.26	48.07	0.83	10.24
25.00	580.00	0.60	3000.00	508.59	18.23	2.30	1.26	48.06	0.83	10.16

For both API oils, the viscosity reduces as the temperature increases, while the oil density remains approximately constant. Also, a reduction in the solubility of gas in the oil can be observed in Tables 4.3 and 4.4. This is possible because heavier gas dissolves more readily in oil than lighter gas, and, from Tables 3.3 and 3.4, it is evident that the densities of gas decreased as temperature increased.

Finally, the impact pressure has on fluid properties was studied by varying the pressure from 100psi to 4000 psi. Oil API 16 was used at the temperature of 70°F. The results are shown in Table 4.5.

Table 4.5: Effect of Pressure on Fluid Properties

API	Temperature, °F	Gas specific gravity	pressure, psia	Solution GOR, scf/stb	Dead oil viscosity, cP	saturated oil viscosity, cP	Oil FVF, bbl/stb	Oil density, lb/cu.ft	z-factor	Gas density, lb/cu.ft.
16.00	530.00	0.60	100.00	9.03	4516.12	3669.21	1.01	59.40	0.99	0.31
16.00	530.00	0.60	200.00	18.33	4516.12	3006.57	1.01	59.22	0.97	0.63
16.00	530.00	0.60	500.00	50.94	4516.12	1657.22	1.03	58.61	0.91	1.69
16.00	530.00	0.60	1000.00	114.24	4516.12	705.14	1.06	57.47	0.85	3.60
16.00	530.00	0.60	1500.00	184.58	4516.12	357.54	1.09	56.29	0.80	5.73
16.00	530.00	0.60	2000.00	259.97	4516.12	206.90	1.13	55.09	0.76	8.04
16.00	530.00	0.60	2500.00	339.36	4516.12	131.84	1.16	53.90	0.76	10.05
16.00	530.00	0.60	3000.00	422.12	4516.12	90.23	1.20	52.75	0.79	11.61
16.00	530.00	0.60	3500.00	507.78	4516.12	65.21	1.24	51.62	0.82	13.04
16.00	530.00	0.60	4000.00	596.01	4516.12	49.16	1.28	50.54	0.86	14.21

The viscosity of oil approaches the dead oil viscosity as the pressure approaches atmospheric pressure. This is because most of the dissolved gas will come out of solution at very low pressures. Therefore, the solution gas-oil ratio is low and the formation volume factor approaches unity. Also, observable from the table is the remarkable reduction in gas density at low pressures.

4.2 Methodology for Sensitivity Analysis

Pressure drop was calculated with Microsoft Excel spreadsheets using both Hagedorn and Brown (1964) and Duns and Runs (1963) correlations. To check the accuracy of the spreadsheet results, "DPDL", a multiphase-flow pressure-loss code developed by Gomez (2005) was used. The results for the Hagedorn and Brown (1964) correlation obtained from Excel spreadsheets matched closely with those from the computer code as shown in Table 4.6. Also, a close match was obtained between the results of Duns and Ros (1963) in Excel spreadsheets and the computer code, except with the predicted flow pattern at the flow rate of 2000stb/d (see Table 4.7). This disparity in flow regime prediction was resolved by using the Ansari et al. (1990) correlation, also available in the computer code, and the results showed that the flow regime was slug, just as predicted using Excel spreadsheets. One factor that was suspected to be the cause of error in the flow pattern prediction was the interfacial tension. Constant value was assumed for our case, and this is not the same case in the DPDL program.

Table 4.6: Results from Microsoft Excel and Computer Code for Hagedorn and Brown

	using microsoft Excel							using DPDL computer code					
Q	VSL	VSG	ρL	μL	HL	ΔP		VSL	VSG	ρL	μL	HL	ΔP
1000	3.57	7.49	52.7	90.2	0.83	0.36		3.57	7.35	52.84	92.347	0.675	0.3
2000	7.15	6.6	52.7	90.2	0.94	0.52		7.13	6.49	52.84	92.352	0.852	0.5
3000	10.72	5.72	52.7	90.2	0.98	0.52		10.7	5.64	52.84	92.358	0.917	0.7

Table 4.7: Results from Microsoft Excel and Computer Code for Duns and Ros

	Using Microsoft Excel								using DPDLcomputer code						
Q	VSL	VSG	Flow regime	ρL	μL	HL	ΔP		VSL	VSG	Flow regime	ρL	μL	HL	ΔP
1000	3.57	7.49	slug	52.7	90.2	0.45	0.3		3.57	7.35	SLUG	52.84	92.35	0.443	0.3
2000	7.15	6.6	slug	52.7	90.2	0.59	0.45		7.13	6.49	BUBL	52.84	92.35	0.631	0.5
3000	10.72	5.72	bubble	52.7	90.2	0.77	0.57		10.7	5.64	BUBL	52.84	92.36	0.752	0.6

Using the fluid variables developed in the previous section, pressure drops in psi/ft, were calculated for oil flow rates between 100 stb/d and 3000 stb/d, and gas flow rates of

4MMscf/d and 2MMscf/d. A pipe of 2in diameter of was used with a roughness factor, ε, of 0.0006ft. The transition from laminar flow to turbulent flow was taken to occur at a Reynolds number of 2000. That is, up to a Reynolds number equal to 2000, laminar flow prevails, while above this there is turbulent flow.

4.3 Effect of Oil Flow Rate on Pressure Drop

Oil flow rate was varied from 100 stb/d to 3000 stb/d for oils of API gravity from 16 to 45. The gas flow rate was kept constant at 4MMscf/d with the fluid temperature and pressure also constant at 70 °F and 3000 psia. Pressure drops were then calculated using both correlations for the range of oil flow rate. The results are graphically shown in Figures 4.1 and 4.2.

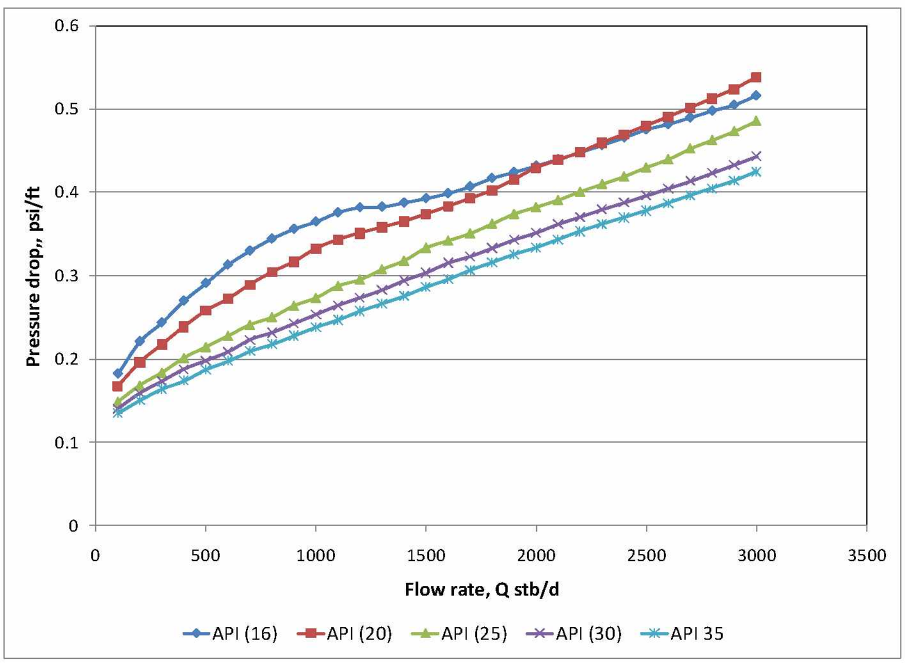

Figure 4.1: Effect of Flow Rate on Pressure Drop at Constant Temperature and Pressure (Hagedorn and Brown Correlation 1964)

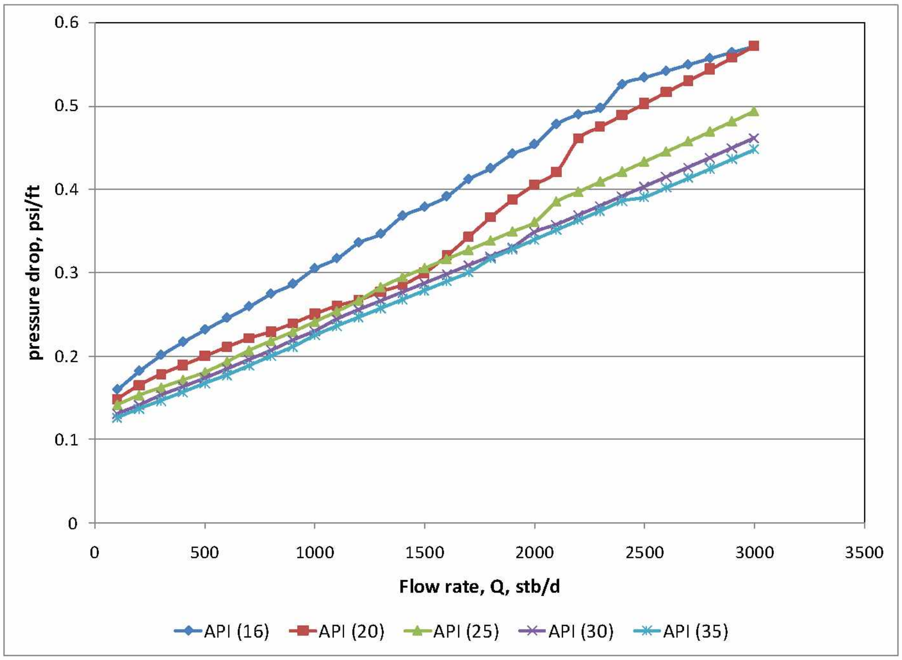

Figure 4.2: Effect of Flow Rate on Pressure Drop at Constant Temperature and Pressure (Duns and Ros Correlation 1963)

The results from both correlations show that pressure drop increases with oil flow rate and oil of lower API gravity has more pressure drop than that of higher API gravity. From the result of the Hagedorn and Brown correlation, it can be observed that at oil flow rate of about 2000 stb/d, the pressure drop for oil of API gravity 20 was equal to that of the oil of 16 API. The same behavior was also observed in Duns and Ros, but at a later flow rate of about 3000 stb/d. This is caused by lower values of the Moody friction factor estimated by Chen's equation (1979) at Reynolds numbers between 2000 and 3000 compared to the actual value on the Moody chart. The lower estimated value of the Moody friction factor reduces the predicted friction pressure drop in both correlations. This is not an expected result because according to Stokes' Law (equation 4.1), higher viscosity should result in a higher friction factor.

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$$f_d = 6\pi\mu V d \tag{4.1}$$

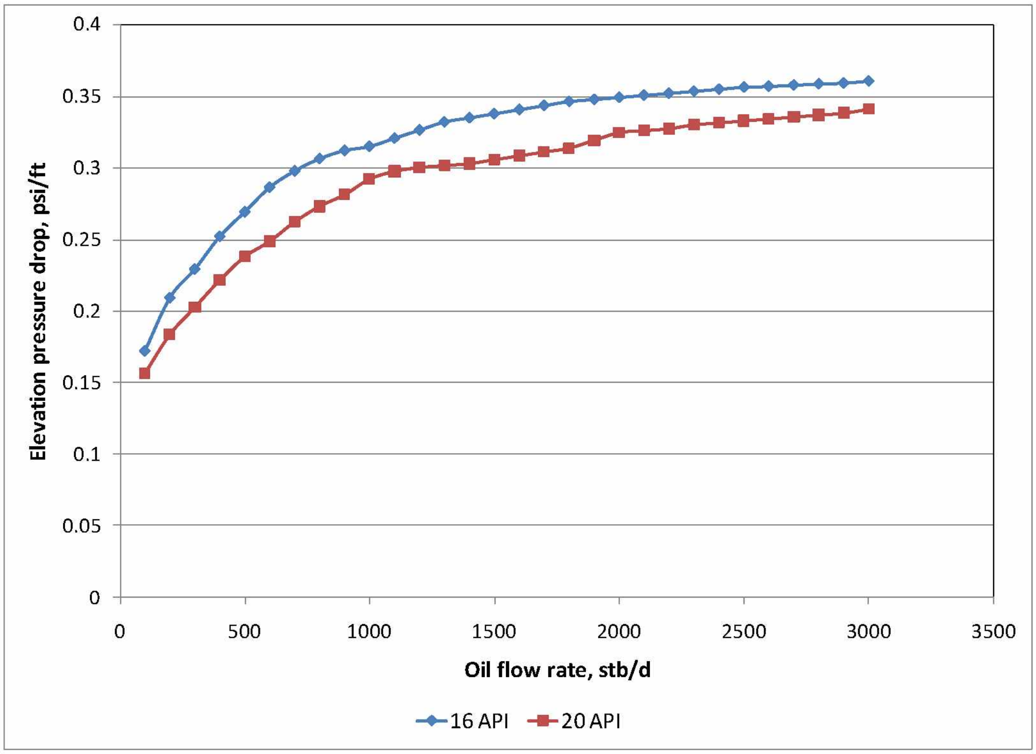


Figure 4.3: Elevation Pressure Drop for 16 API and 20 API Oil (Hagedorn and Brown Correlation 1964)

Figure 4.3 shows only the elevation pressure drop obtained using the Hagedorn and Brown correlation. It can be seen that at all flow rates the pressure drop due to elevation for 16 API oil is greater than that of 20 API oil. The effect of the lower estimated value of the Moody friction factor was observed when only the friction pressure drop was plotted in Figure 4.4. At the bump seen in the graph, the Reynolds number was between 2000 and 3000.

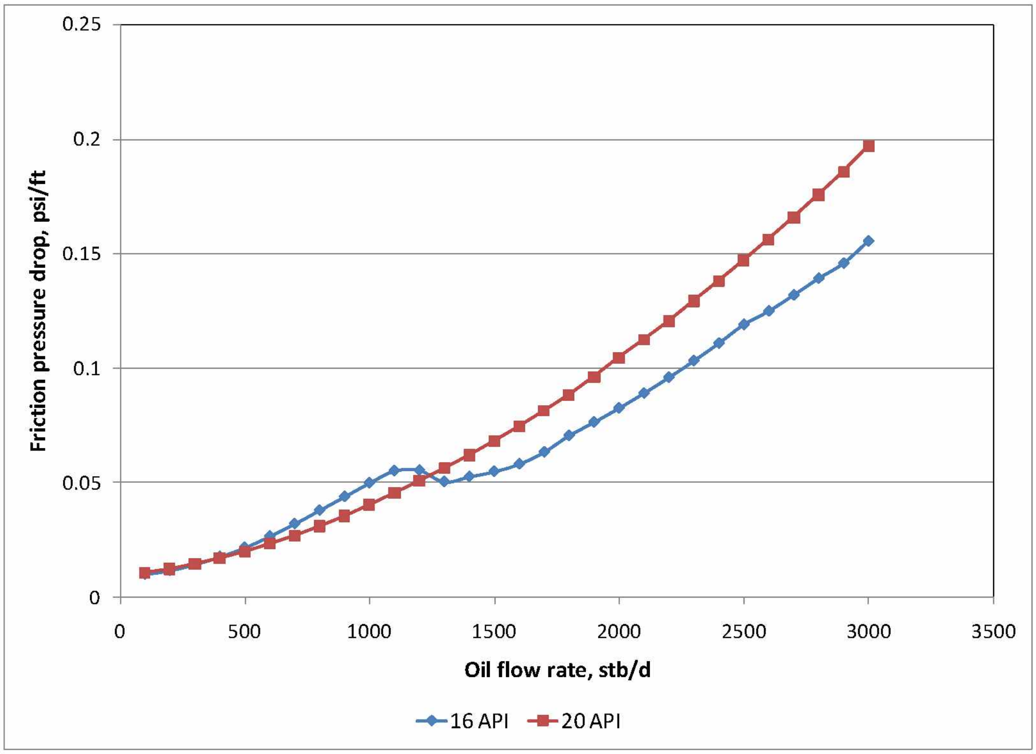


Figure 4.4: Friction Component of the Pressure Drop Equation (Hagedorn and Brown Correlation 1964)

The plot of only the elevation pressure drop against flow rate for the Duns and Ros correlation is shown in Figure 4.5. The bump in the graph occurred at the same oil flow rate at which the flow pattern changed from bubble to slug flow. Figure 4.6 shows the friction pressure drop. For 16 API oil, the Reynolds number was all laminar (<2000). The Reynolds number for 20 API oil falls within 2000 and 3000 between oil flow rates of 1300 stb/d and 1900 stb/d.

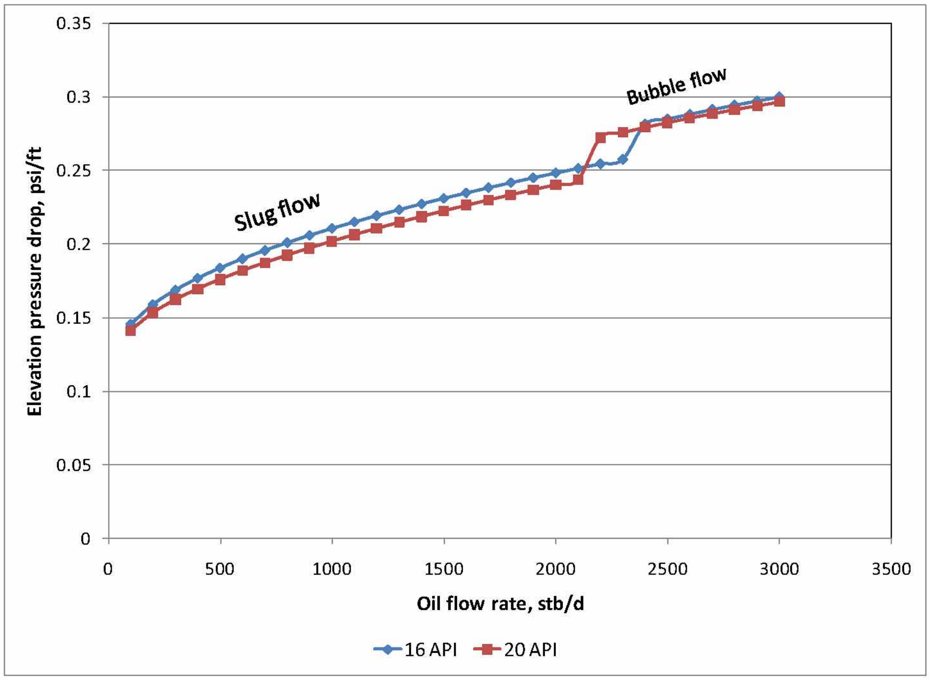


Figure 4.5: Elevation Pressure Drop for 16 and 20 API Oil (Duns and Ros Correlation 1963)

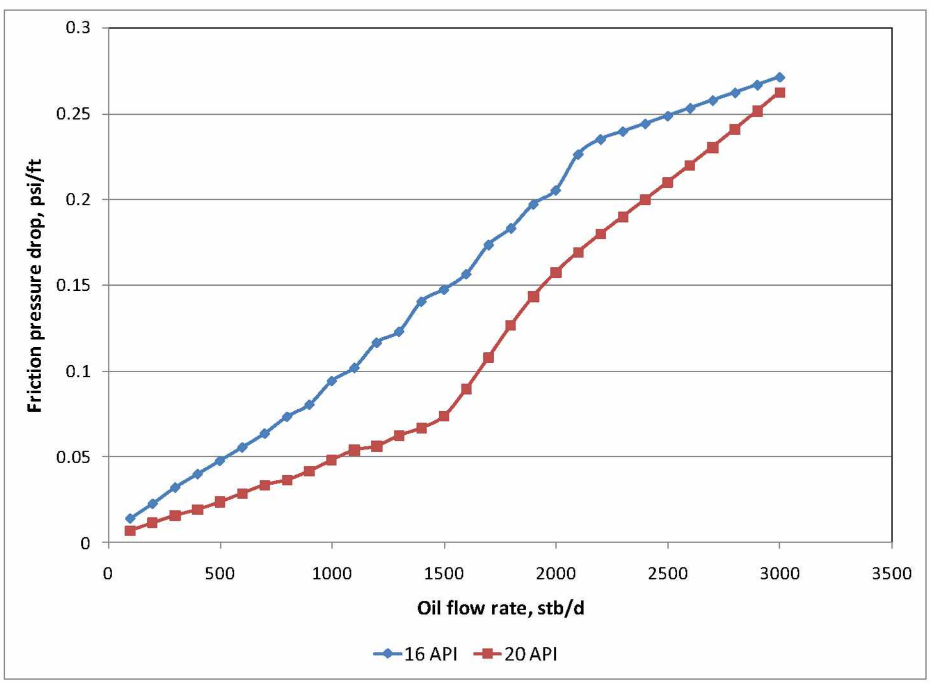


Figure 4.6: Friction Pressure Drop for 16 and 20 API Oil (Duns and Ros Correlation 1963)

Another factor that contributes to pressure drop during simultaneous flow of liquid and gas is the slip between the phases. Liquid holdup increases as slip between the phases increases and so does the pressure drop due to elevation. The slip velocity (equation 4.2) is a measure of slip between the liquid and gas phase.

$$V_{SLIP} = V_g - V_L = \frac{V_{sl}}{H_L} - \frac{V_{sg}}{1-H_L} \tag{4.2}$$

where

V_{SLIP} is the slip velocity in ft/sec

V_g and V_L are the gas and liquid actual velocities, respectively, in ft/sec

V_{sg} and V_{sl} are the gas and liquid superficial velocities, respectively, in ft/sec

H_L is the liquid holdup and it is dimensionless

Figure 4.7 shows that when oil flow rate is increased at a constant gas flow rate, slip reduces as the oil flow rate is increased if the flow pattern is slug flow. But the reverse is observed in the bubble flow pattern. It also shows that the lower API gravity oil has larger slip in slug flow pattern than the higher API gravity oil and, in the bubble flow pattern, the reverse is observed. This observation is in line with the Harmathy (1960) equation for bubble rise velocity in liquid, as shown in equation 4.3. From the equation it can be seen that increase in oil density slows down the terminal velocity of the bubble; thus heavier oils have lower slip velocity in the bubble flow pattern.

$$V_{0\infty} = 1.53\left[\frac{g(\rho_L - \rho_g)\sigma}{\rho_L^2}\right]^{0.25} \tag{4.3}$$

where

$V_{0\infty}$ is the terminal velocity of the bubble in ft/sec

ρ_L and ρ_g are the liquid and gas densities, respectively, in lb/cu.ft.

σ is the interfacial tension in lbm/sq sec

g is the acceleration due to gravity in ft/sq sec

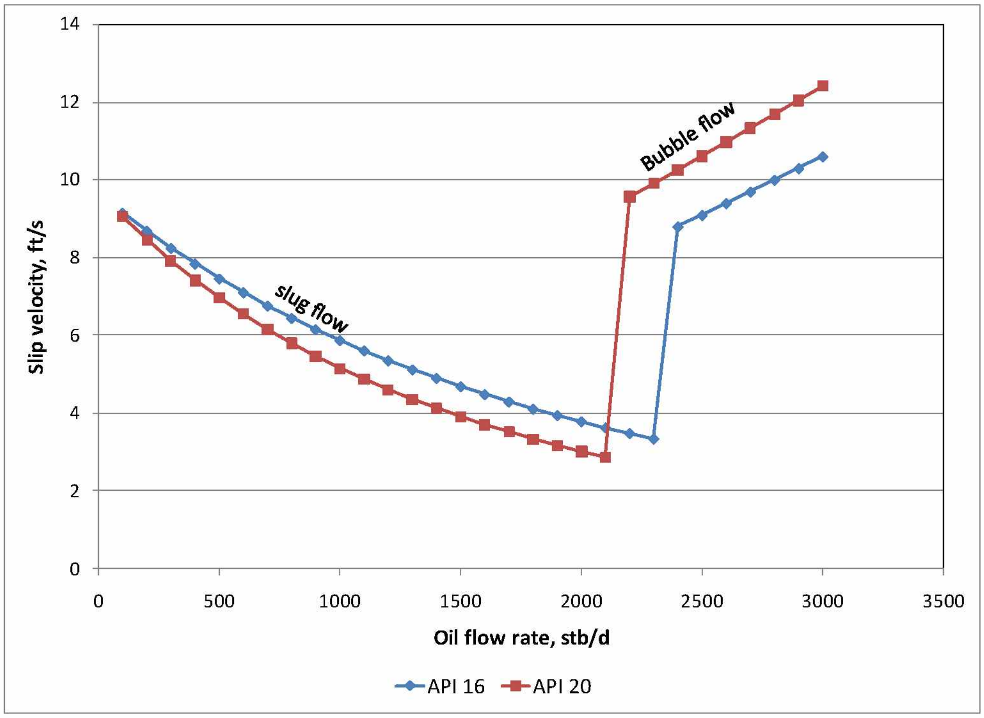


Figure 4.7: The Effect of Flow Regime Change on Slip Velocity

4.4 Effect of Temperature and Viscosity on Pressure Drop

When the temperatures of the fluids were increased in step from 70˚F to 120˚F, the viscosity of oil significantly reduced from 90.2 cP to 8.5 cP. There was a slight increase in gas viscosity from 0.021 cP to 0.022 cP. The other parameters that changed were oil and gas densities, but their changes were negligible. Therefore, viscosity of the crude oil is the only parameter in the pressure gradient equation that is a strong function of temperature. The behavior of pressure drop with change in temperature is identical to that of viscosity shown in Figures 4.8 and 4.9 for the two correlations. From the figure, it can be observed that increase in the viscosity of crude oil increases the pressure drop in the well bore. The anomaly seen in the Duns and Ros correlation at oil flow rate of 2000stb/d is due to the Moody friction factor predicted for the transition from laminar to turbulent flow regimes.

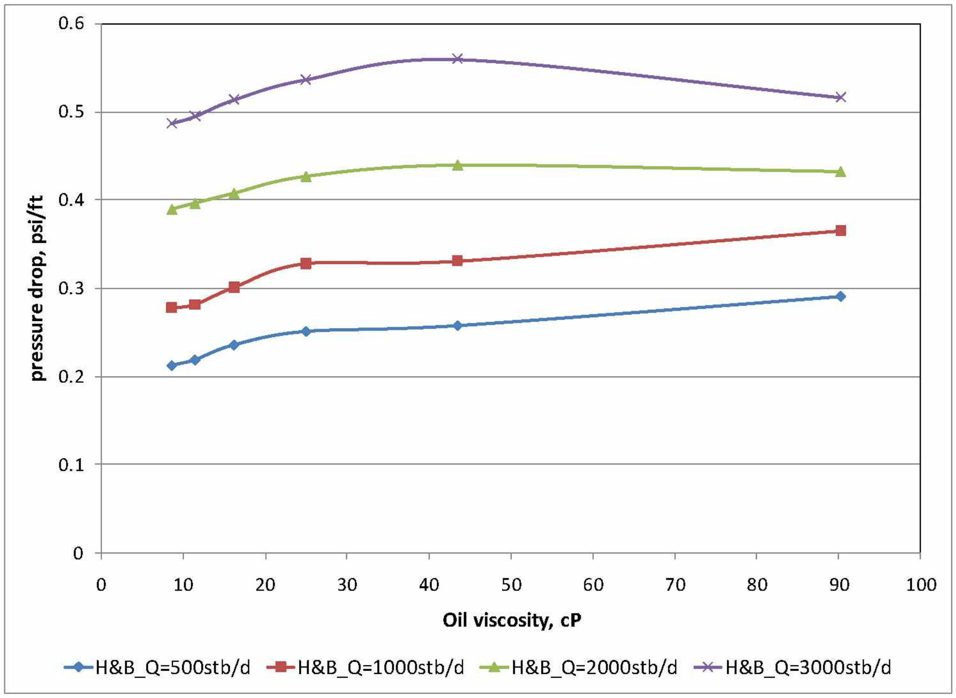


Figure 4.8: Effect of Viscosity on Pressure Drop (Hagedorn and Brown Correlation--1964)

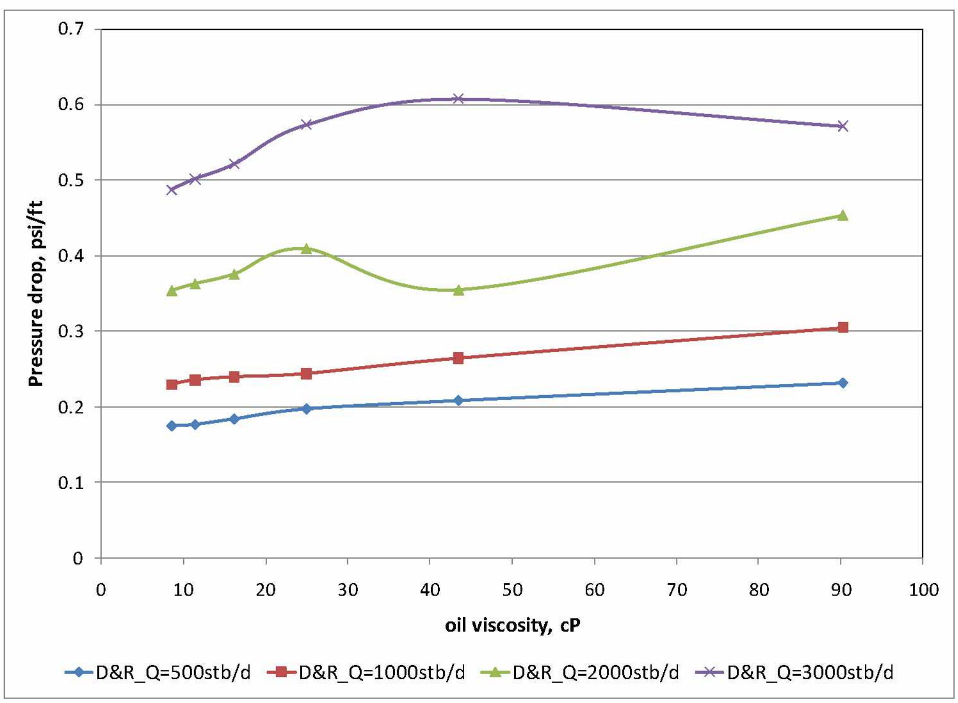


Figure 4.9: The Effect of Viscosity on Pressure Drop (Duns and Ros Correlation--1963)

Temperature increase also affects the slip velocity in such a way that it tends to make the flow pattern more slug than bubble. This is shown in Figure 4.10.

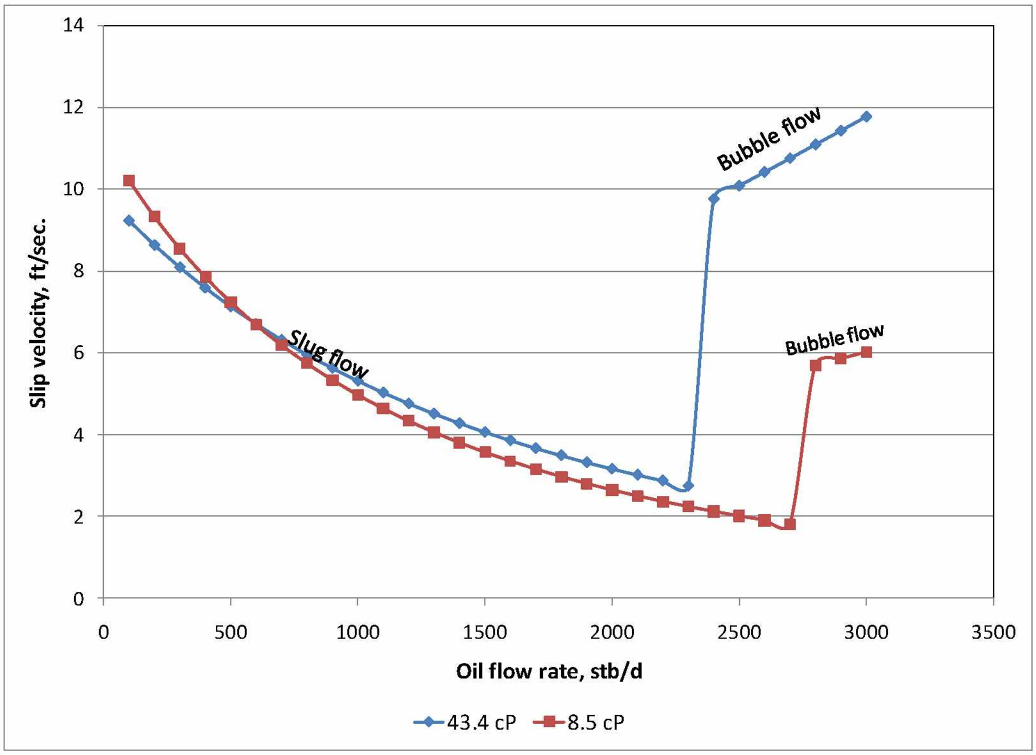


Figure 4.10: Effect of Temperature on Slip Velocity

4.5 Effect of Initial Pressure of the Fluid

The density and viscosity of oil depends on pressure, basically because the solution gas-oil ratio, R_s, on which they both depend, is a function of pressure. At high pressure, more gas is dissolved in the oil, and the gas solubility reduces with pressure reduction. The gas volume factor, B_g, increases with a reduction in pressure. This has an overall effect of increasing the gas flow rate and, thus, the mixture velocity V_M as shown in Table 4.8. Increase in mixture velocity affects the pressure drop in a well by increasing the friction pressure drop.

Table 4.8: Change in Mixture Density with Pressure

Q, Stb/d	Vm at 2000psi	Vm at 3000psi	Vm at 4000psi
1000	24.499	30.302	32.286
2000	29.516	35.728	40.961
3000	33.489	43.169	44.976

Gas density also increases with an increase in pressure, while oil density decreases with an increase in pressure. Thus, reduction in pressure will ultimately cause an increase in pressure drop, as shown in Figure 4.11 below.

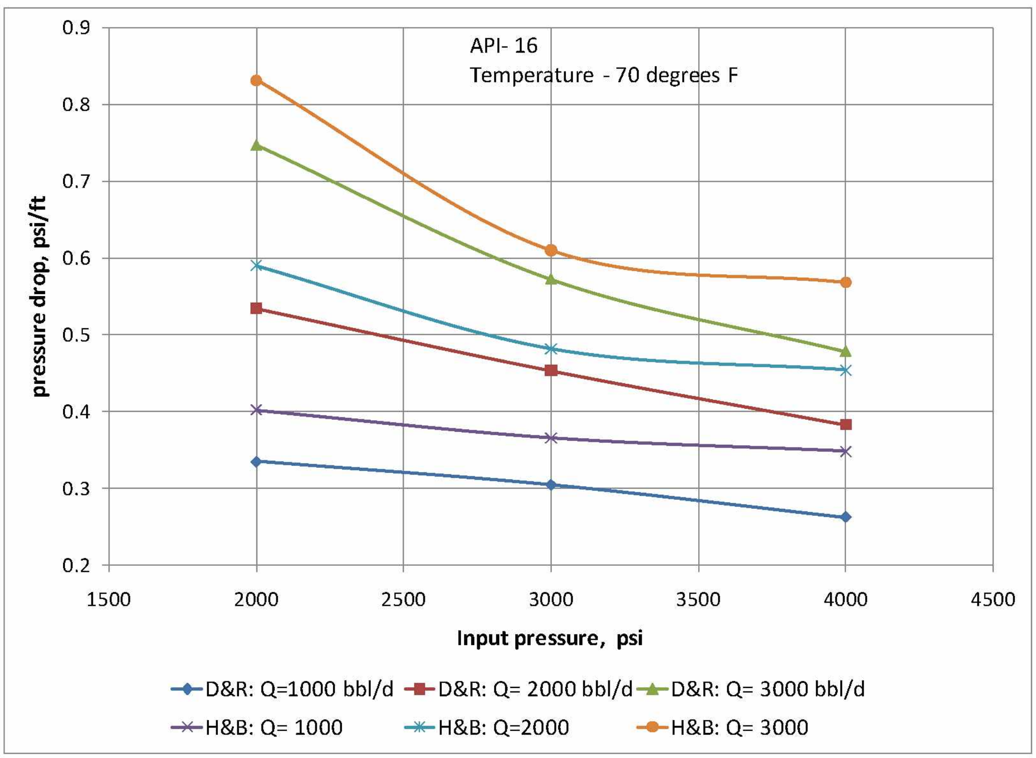


Figure 4.11: Effect of Down-Hole Pressure on Total Pressure Drop in the System

The effect pressure change has on the prevailing flow pattern at a given condition is shown in Figure 4.12 below. It shows that when pressure was reduced to 2000 psia in 16 API gravity oil, the flow pattern was all slug flow. But at 4000 psia, a bubble flow pattern persisted more than it did at 3000 psia.

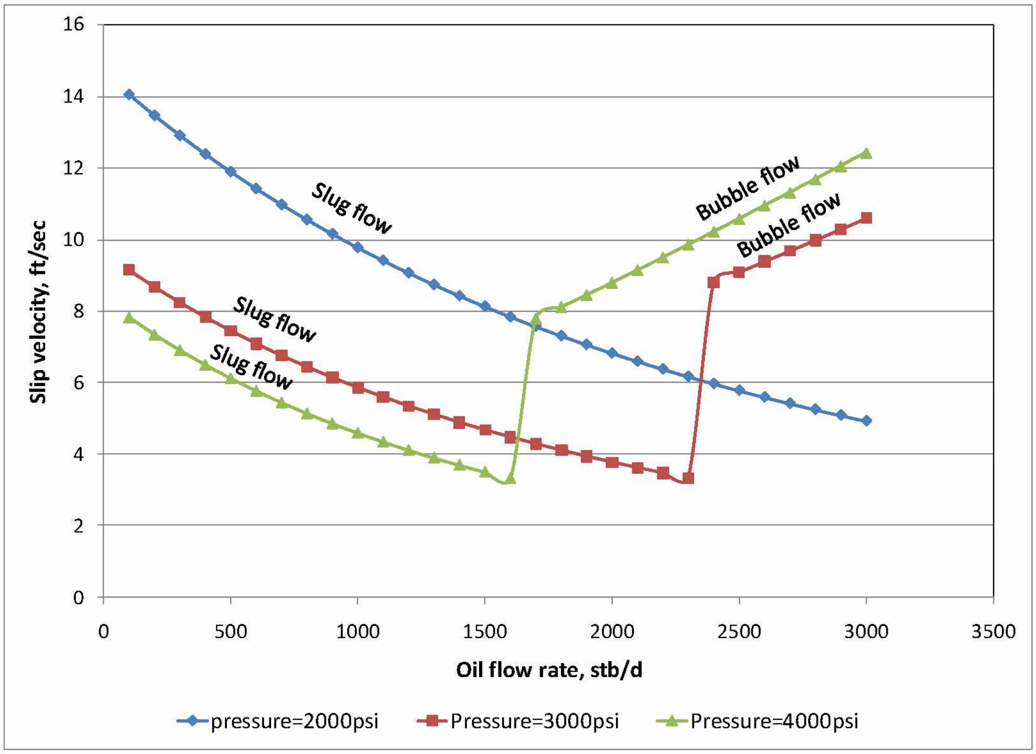


Figure 4.12: The Effect of Pressure Drop on Slip Velocity

4.6 Effect of Gas Flow Rate

The gas flow rate was reduced to 2MMscf/d, and all other variables were kept constant. It was observed in both correlations that the total pressure drop was higher at a lower gas flow rate than at a higher gas flow rate, as shown in Figures 4.13 and 4.14.

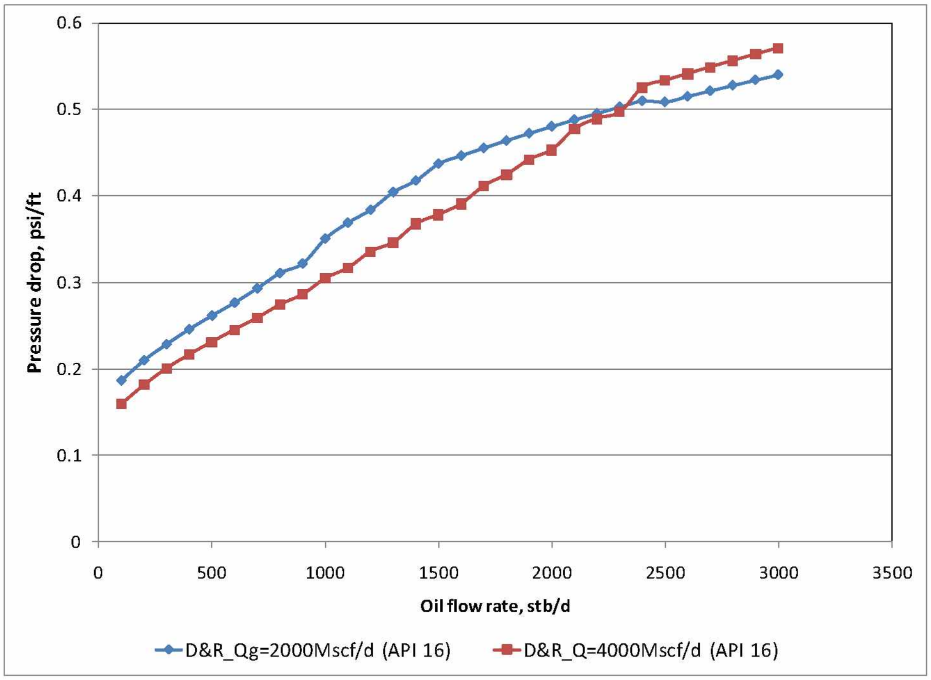


Figure 4.13: Effect of Change in Gas Flow Rate on Pressure Drop (Duns and Ros Correlation--1963)

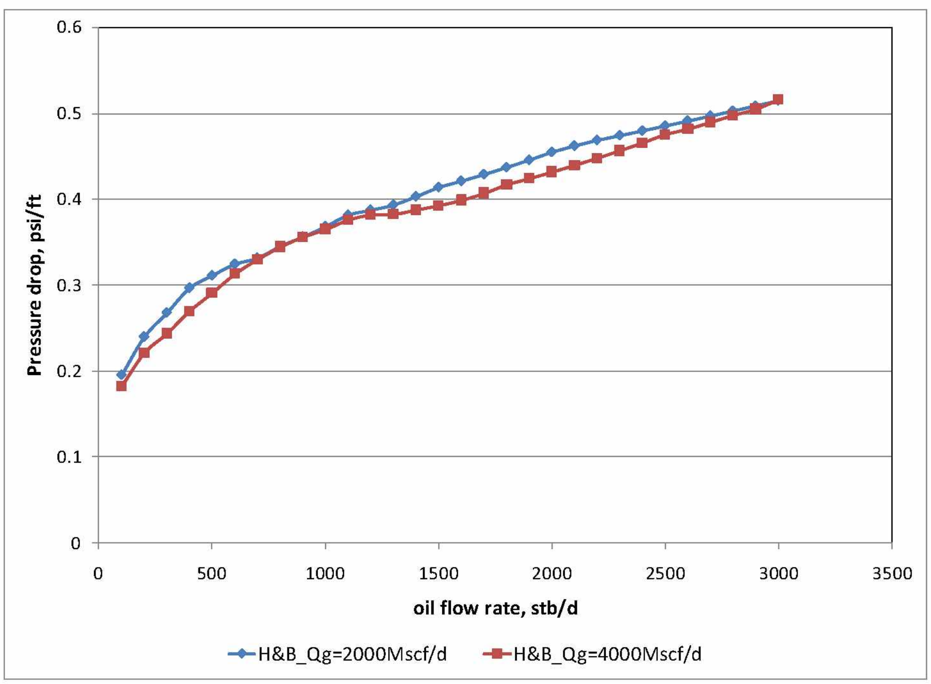


Figure 4.14: The Effect of Change in Gas Flow Rate on Pressure Drop (Hagedorn and Brown--1964)

When the gas flow rate is reduced, pressure drop due to friction also reduces because the gas superficial velocity that determines the mixture velocity is lower. Also, because the gas velocity is lower, the slip between the phases is also lower, resulting in higher liquid holdup. The elevation pressure drop at gas flow rate of 2MMscf/d is greater than the value at a gas flow rate of 4MMscf/d for both correlations.

Furthermore, reduction in gas flow rate results in a bubble flow pattern persisting at a larger range of oil flow rates, as shown in Figure 4.15. The slip velocity of the fluids when the gas flow rate is 2MMscf/d is much lower compared to when it is 4MMscf/d if the flow is in slug flow pattern. However, the difference is not much in a bubble flow pattern.

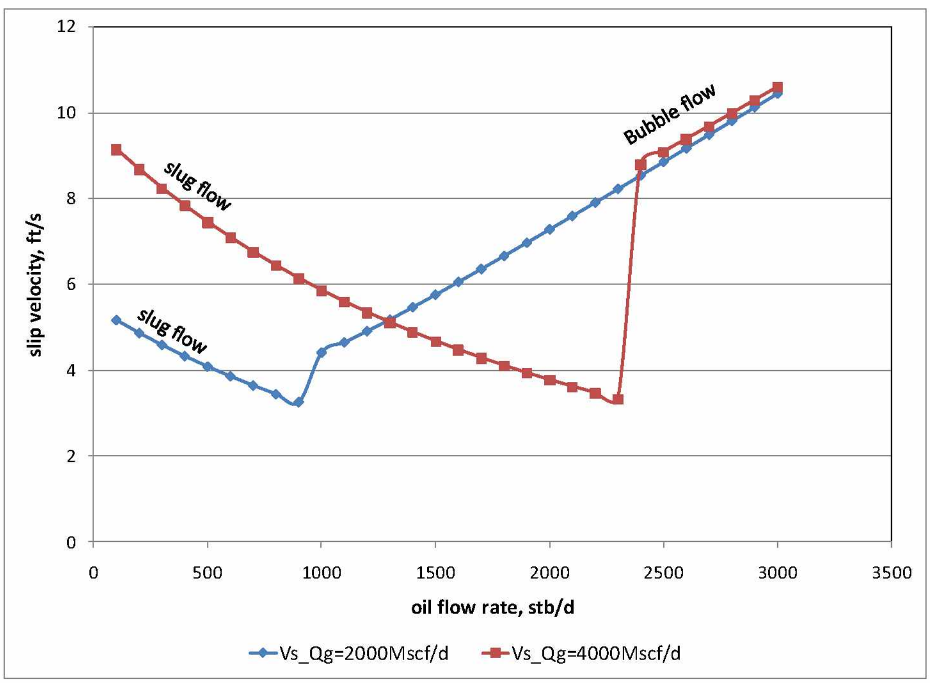


Figure 4.15: Slip Velocities at Different Gas Flow Rates

Chapter 5

Comparison of Results to Field Data

5.1 Field Data

Data used in Chapter 4 were developed using fluid properties correlation. Inasmuch as care was taken to use the correlation within the limits of its accuracy, it could never accurately represent field data. This is because these correlations do not take into account the molecular composition of the crude oil and natural gas. The only way to validate the behaviors observed in the last chapter is to use real field data. A search of literature produced physical properties of oil samples from the West Sak Reservoir.

5.2 A Brief Description of West Sak Reservoir

West Sak is a heavy oil accumulation within the Kuparuk River unit on the North Slope of Alaska. These deposits are part of a larger oil belt that includes the Orion and Polaris fields within the Prudhoe Bay unit, and the Schrader Bluff and Ugnu heavy oil sands within the Milne Point unit. The estimated total oil in place is between 20 and 25 billion barrels. The West Sak core area (Figure 5.1) is the warmest and has the best oil quality. It is located at the eastern edge of the Kuparuk field. It contains about 2.5 billion barrels of oil with oil gravities ranging from 16 to 22 degrees at a reservoir temperature of about 75°F.

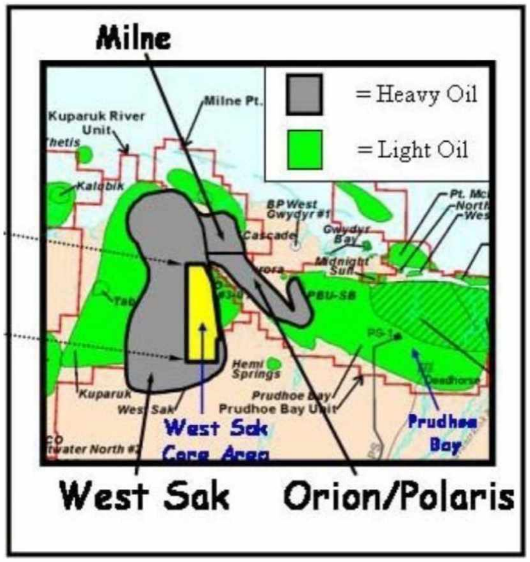


Figure 5.1: West Sak Field (Targac et al. 2005)

5.3 Fluid Data from West Sak

Physical properties of three live oil samples were obtained from Gondouin and Fox (1991). The fluid samples are labeled A, B, and C. Available fluid data for each oil sample are given in Tables 5.1, 5.2 and 5.3. Table 5.1 compares real values of fluid properties to estimated values using correlations at the same temperature and pressure.

Table 5.1: Physical Properties of West Sak Oil Sample A (Gondouin and Fox 1991)

	Actual	Estimated
sample depth, ft	4,603	4,603
Reservoir Temperature, F	80	80
Bubble point pressure, psi	1690	1690
API	19.2	19.2
Oil density, lb/cu.ft	56.4	54.5
solution gas-oil ratio, scf/stb	210	212.5
viscosity at bubble point,cP	35.4	55.66
oil FVF, bbl/stb	1.069	1.1

Table 5.2: Physical Properties of West Sak Oil Sample B (Gondouin and Fox 1991)

West Sak Oil Sample B	
API	18.5
oil viscosity, cP (Live oil)	256 @ 75˚F
solution GOR @ bubble point	167
Bubble Point Pressure, psi	1318
Oil formation volume factor, bbl/stb	1.053
Oil Density, lb/cu.ft.	58.86

Table 5.3: Physical Properties of West Sak Oil Sample C (Gondouin and Fox 1991)

West Sak Oil Sample C	
API	14
oil viscosity, cP (Live oil)	5392 @ 75˚F
solution GOR @ bubble point	126
Bubble Point Pressure, psi	1234
Oil formation volume factor, bbl/stb	1.035
Oil Density, lb/cu.ft.	60.684

Because the gas is 98% methane, physical properties of methane were used. Since the interfacial tension was not given, it was assumed to be 30 dynes/cm. The oil flow rate was varied from 100 to 3000 stb/d and the gas flow rates of 2MMscf/d and 4MMscf/d were used. The results of pressure drop calculated using both correlation are shown in Figures 5.2 through 5.6.

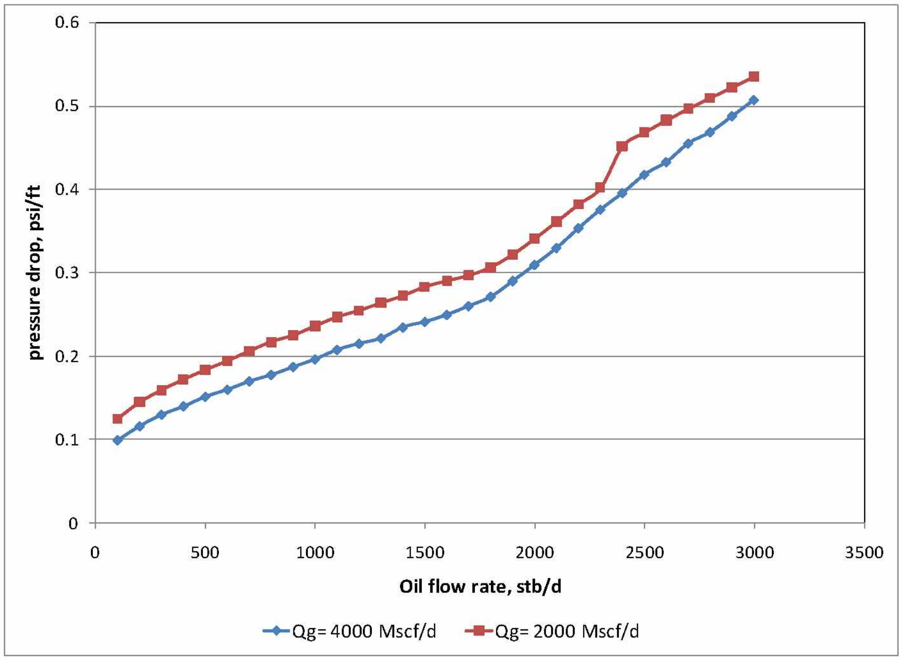


Figure 5.2: Pressure Drop vs Oil Flow Rate for West Sak Oil Sample A (Duns and Ros Correlation--1963)

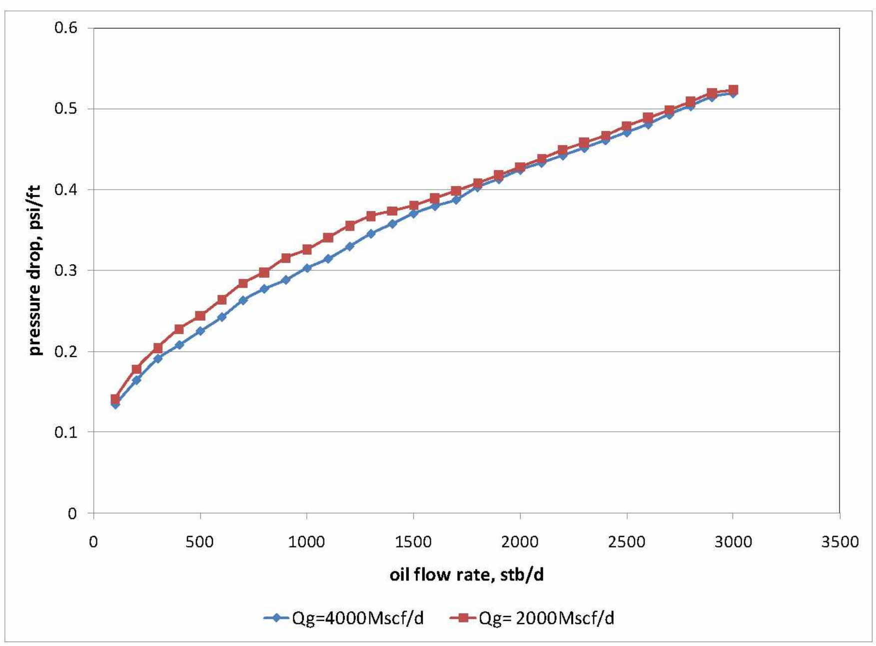


Figure 5.3: Pressure Drop vs Oil Flow Rate for West Sak Oil Sample A (Hagedorn and Brown Correlation--1964)

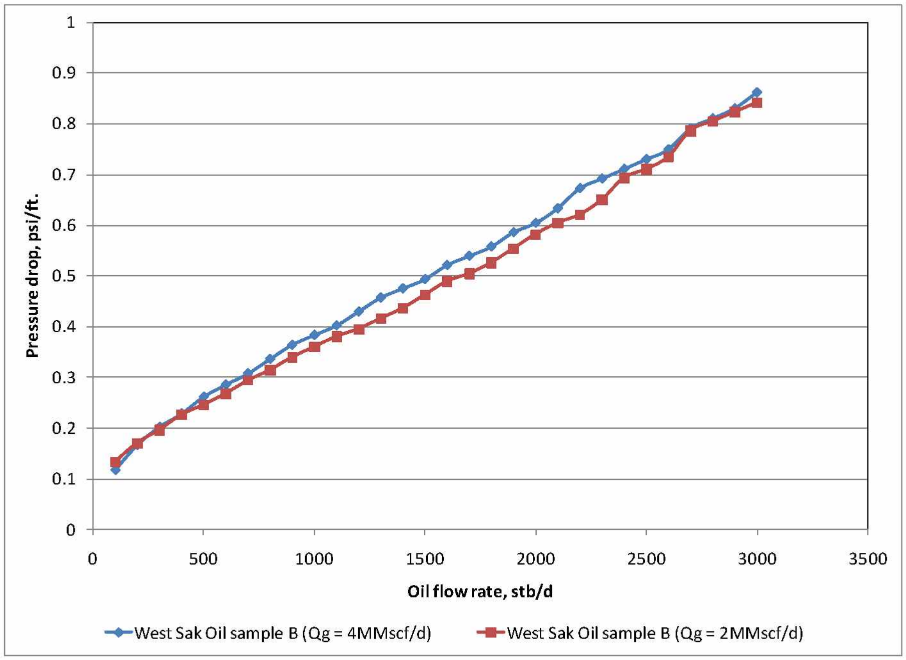


Figure 5.4: Pressure Drop vs Oil Flow Rate for West Sak Oil Sample B (Duns and Ros Correlation--1963)

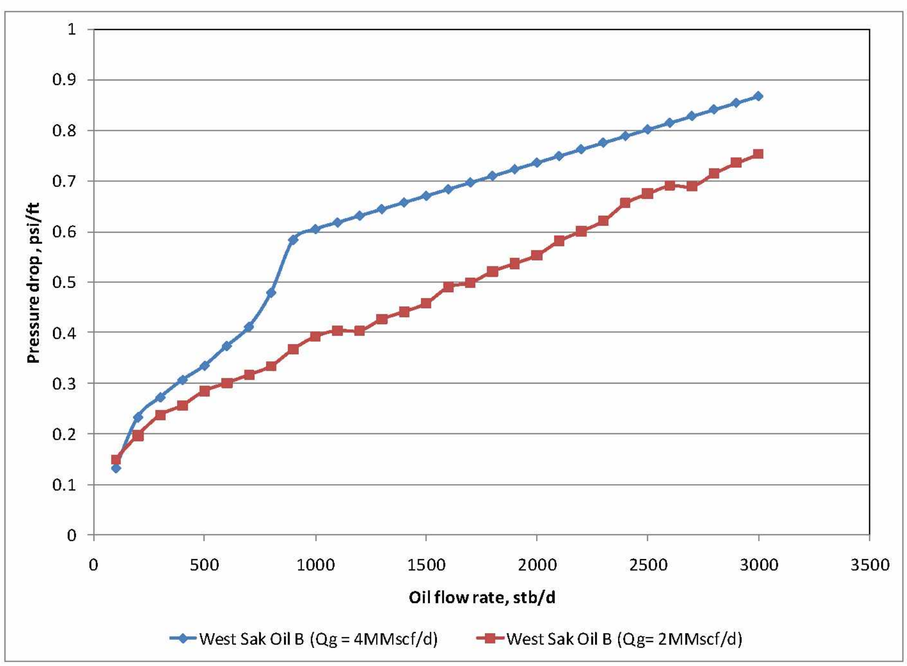


Figure 5.5: Pressure Drop vs Oil Flow Rate for West Sak Oil Sample B (Hagedorn and Brown Correlation--1964)

The viscosity of West Sak oil sample C was too high for the Duns and Ros correlation to calculate; therefore, only the Hagedorn and Brown correlation was used.

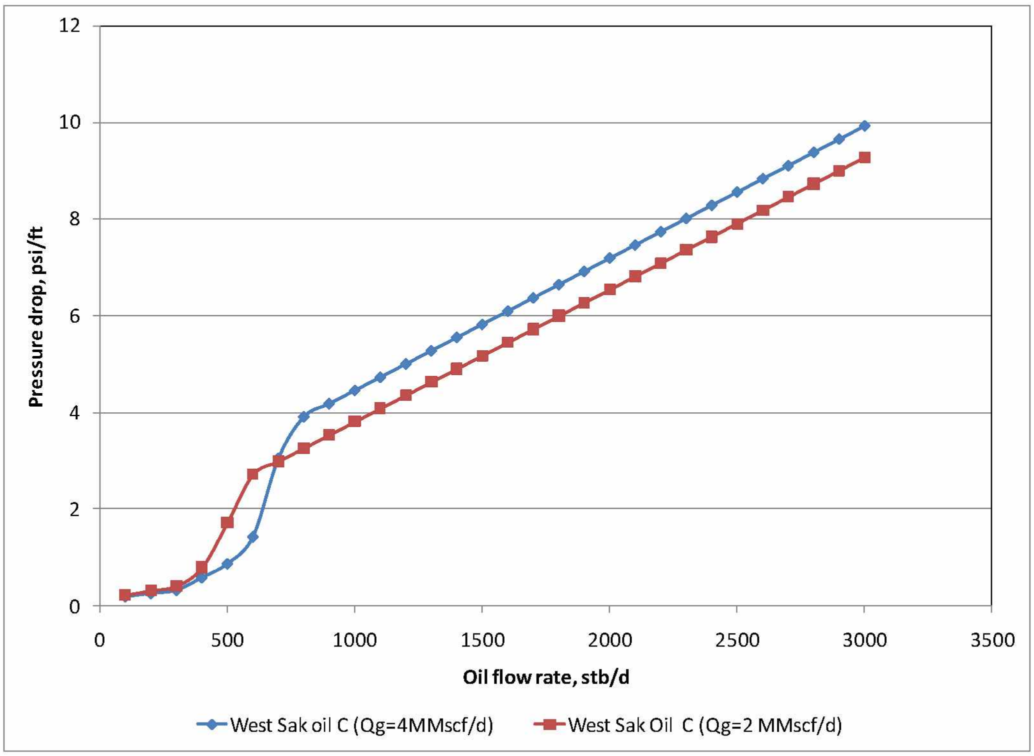


Figure 5.6: Pressure Drop vs Oil Flow Rate for West Sak Oil Sample C (Hagedorn and Brown Correlation--1964)

5.4 Comparison between Results of West Sak Fluid Data and Fluid Data Developed with Correlation.

1) In both West Sak oil and the fluid data developed from correlations, increase in oil flow rate with every other variable constant results in an increase in pressure drop.

2) Increase in both oil density and viscosity is associated with an increase in pressure drop for both cases (West Sak oil sample and fluid data developed from correlations).
3) The results of oil sample developed from correlations shows that in situations where the gas flow rate is varied, reduction of gas flow rate is associated with an increase in pressure drop. The result from West Sak oil showed the same behavior for sample A only. But West Sak oil B and C (lower API oils) showed the opposite behavior.

5.5 Hydraulic Horsepower

Hydraulic horsepower is a measure of the energy requirement of a pump to lift fluid from one point to another. The use of bottom hole pumps (beams pump and electric submersible pumps) as an artificial lift is a common practice in the oil industry. The choice of pump usually takes into account the type of fluid to be lifted (density, viscosity, etc.) and the distance the fluid is to be moved. Hydraulic horsepower relates the pressure drop to the expected flow rate. This is given in equation 5.1:

$$HHP = \frac{\Delta PQ}{1714} \tag{5.1}$$

where

HHP is the hydraulic horsepower

Q is the oil flow rate in gal/min

ΔP is pressure drop in psi

Using the pressure drop calculated from the two multiphase correlations, the horsepower requirements for West Sak fluid samples were calculated. The depth of oil sample A is known, but depth is not available for oil samples B and C. The depth of West Sak Reservoir is between 2500 ft and 4600 ft (Gondouin and Fox 1991). The minimum depth was assumed for West Sak oil samples B and C while calculating the Hydraulic horsepower. The hydraulic horsepower for West Sak oils A, B and C are graphically shown in Figures 5.7 through 5.11.

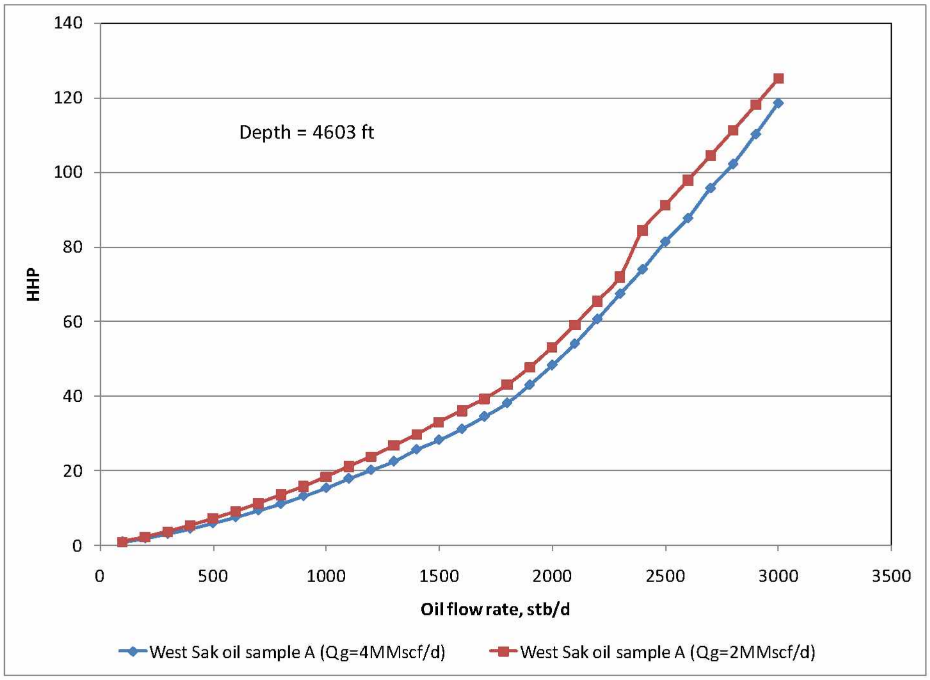


Figure 5.7: Hydraulic Horsepower Requirement for West Sak Fluid Sample A (Duns and Ros Correlation--1963)

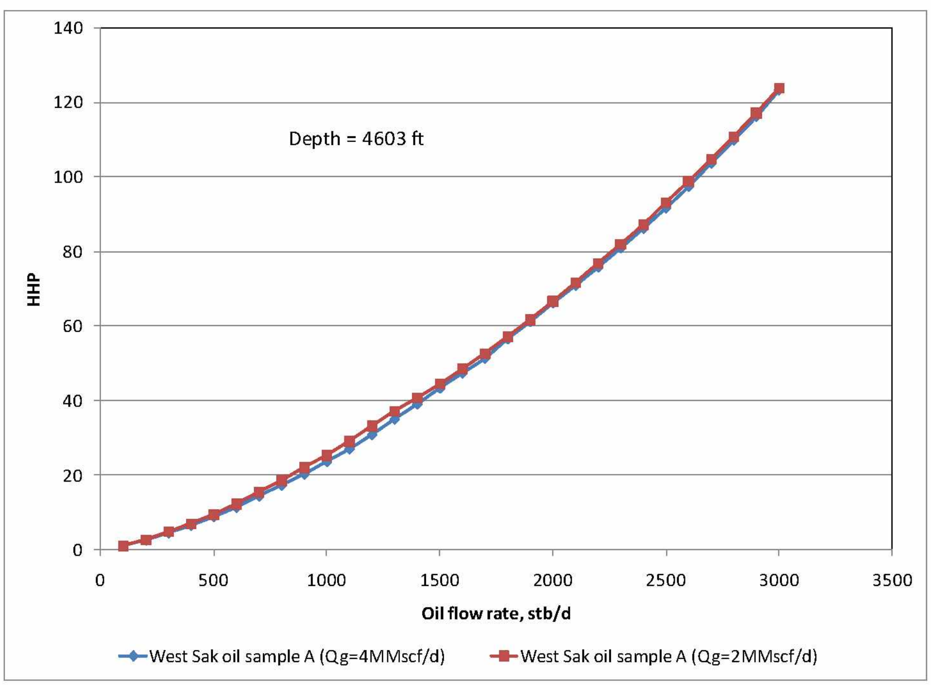


Figure 5.8: Hydraulic Horsepower Requirement for West Sak Fluid Sample A (Hagedorn and Brown Correlation--1964)

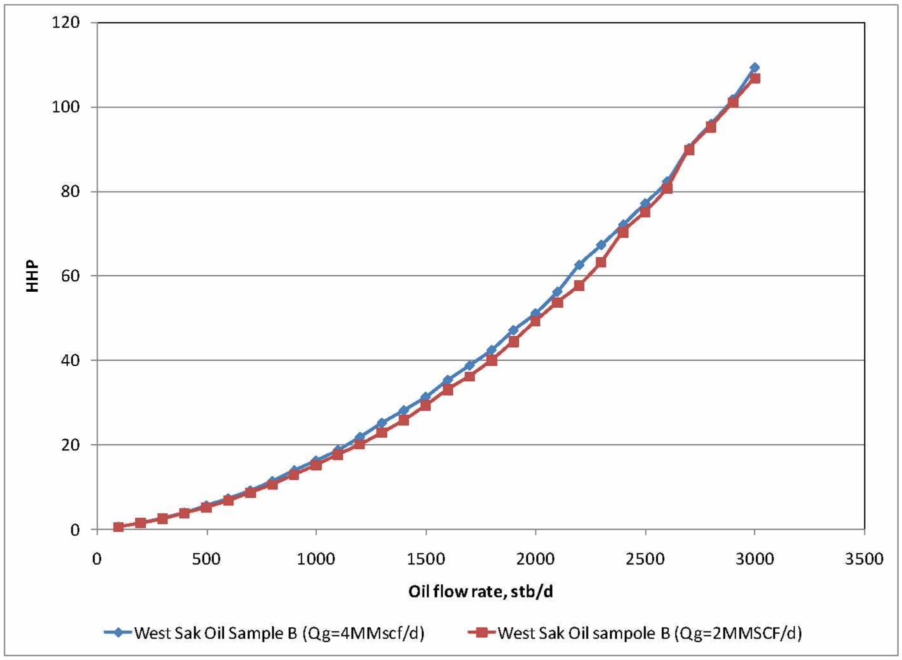


Figure 5.9: Hydraulic Horsepower Requirement for West Sak Fluid Sample B (Duns and Ros Correlation--1963)

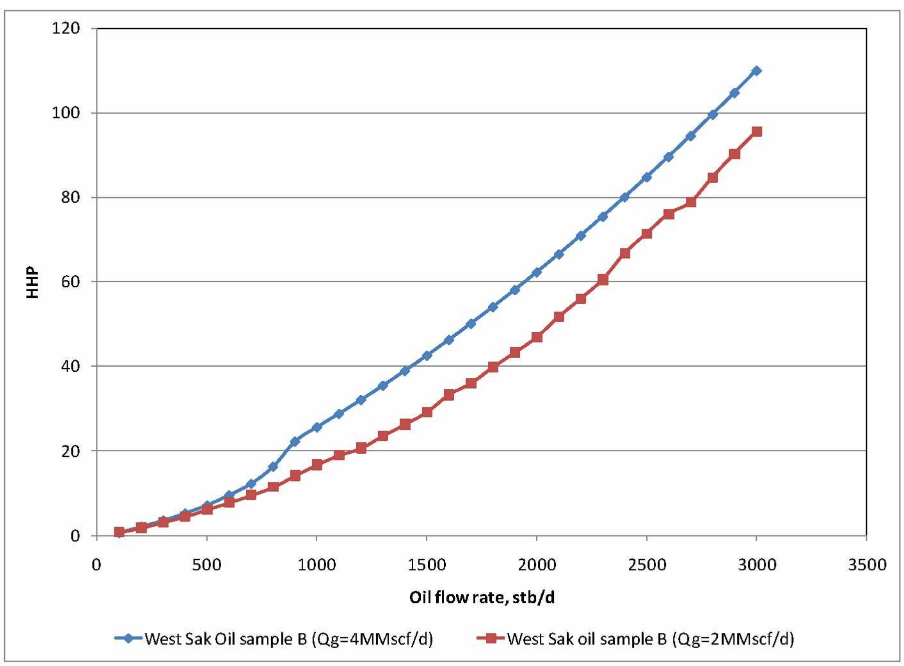


Figure 5.10: Hydraulic Horsepower Requirement for West Sak Fluid Sample B (Hagedorn and Brown Correlation--1964)

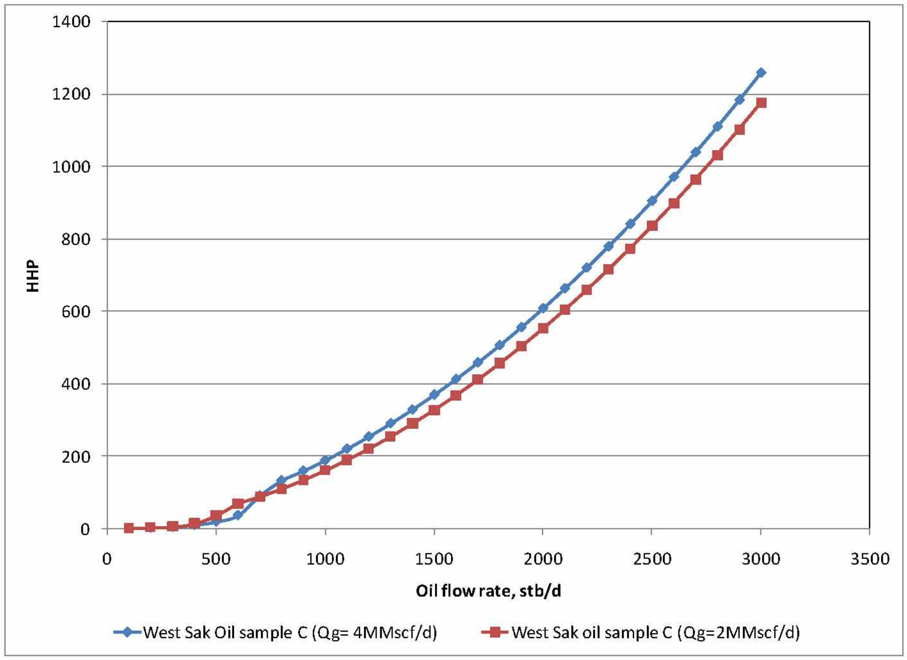


Figure 5.11: Hydraulic Horsepower Requirement for West Sak Fluid Sample C (Hagedorn and Brown Correlation--1964)

5.6 Comparison of the Two Correlations

A comparison was made between Hagedorn and Brown correlation (1964) and the Duns and Ros correlation (1963) using data from literature (Thompson 1982). Table 5.4 shows measured pressure drop and estimated pressure drop using correlations. Positive % error shows an overestimation of pressure drop by the correlation, while negative % error shows an underestimation. From the data in Table 5.4, the Hagedorn and Brown correlation has a standard deviation of 10.4, while that of Duns and Ros correlation has a standard deviation of 17. Therefore, the Hagedorn and Brown correlation performed better than the Duns and Ros correlation.

$$\%Error\ (x_i) = \frac{\Delta P_{estimatied} \ -\Delta P_{measured}}{\Delta P_{measured}} * 100 \tag{5.2}$$

$$x = (\sum_{i=1}^{N} x_i)/N$$

$$STDEV = \sum_{i=1}^{N} \sqrt{\frac{(x_i - x)^2}{N - 1}}$$

where

x is the average error

N is the number of cases

STDEV is standard deviation

Table 5.4: Comparison of the Two Correlation to Measured Pressure Drop (Thompson 1982)

Measured	H&B	% Error	D&R	%Error
1248	1257.4	0.8	1279.4	2.5
2178	2391.2	9.8	2281.7	4.8
2300	2148.8	-6.6	2333	1.4
1580	1437.5	-9.0	1804.3	14.2
1601	1567.2	-2.1	1710.7	6.9
1730	1582.8	-8.5	1810	4.6
2343	2603.3	11.1	2492.1	6.4
2531	2223	-12.2	2375.3	-6.2
2571	2713.9	5.6	2563.7	-0.3
1872	1785.7	-4.6	1865.5	-0.3
1840	1838.9	-0.1	1898.3	3.2
1670	1568.4	-6.1	1698.1	1.7
1845	1762.1	-4.5	1845.7	0.0
1823	1734.2	-4.9	1844.3	1.2
1655	1197	-27.7	1411.2	-14.7
1655	1183.2	-28.5	1355.1	-18.1
1910	1515	-20.7	1632	-14.6
1157	1124.2	-2.8	1216.1	5.1
2200	2138.8	-2.8	2221.6	1.0
1680	1417.6	-15.6	1571.7	-6.4
1890	1380.1	-27.0	1557.8	-17.6
1880	1643.9	-12.6	1804.8	-4.0
1970	1709.5	-13.2	1839.8	-6.6
2030	1862.6	-8.2	1936	-4.6
1770	1837.2	3.8	1813.4	2.5
1605	1291.2	-19.6	1506.8	-6.1
1180	1201.5	1.8	1440.9	22.1
1595	1446.1	-9.3	1699.8	6.6
1124	1145.1	1.9	1177.7	4.8
440	423.3	-3.8	378.4	-14.0
425	488.8	15.0	460.6	8.4
405	422.4	4.3	0	-100.0
555	572	3.1	579.6	4.4
580	623.3	7.5	571.9	-1.4
273	276.4	1.2	316.2	15.8
455	492.9	8.3	452.1	-0.6
485	540.4	11.4	515.6	6.3
355	364.8	2.8	394.8	11.2
240	240.6	0.2	257.7	7.4
342	336.8	-1.5	346	1.2
348	343.4	-1.3	367.1	5.5
456	493.5	8.2	466.6	2.3
464	496.3	7.0	437	-5.8
330	346	4.8	361	9.4
300	318.9	6.3	308.6	2.9

5.7 Limitations of the Two Correlations

The Hagedorn and Brown correlation (1964) was developed using 3 pipe diameters, 1 ¼ in, 1 ½ in, and 2 in . Liquid viscosity ranges of 0.86 – 110 cp were used. The Duns and Ros correlation (1963) was developed for all ranges of pipe sizes, and the liquid viscosity range was between 1cP and 316 cP.

It was observed that when the viscosity of the oil was increased to around 705 cP (corresponding to a reduction of prevailing pressure of 16 API oil to 1000 psi at 70°F), the Duns and Ros Correlation would not be able to calculate the pressure drop in the system. This is because the correlating chart stopped at a liquid viscosity number of 2 and extrapolating it results to huge errors. But the Hagedorn and Brown correlation could be used at this condition.

Chapter 6

Conclusions and Recommendation

The following conclusions can be drawn from the analysis conducted in this study:

1. Based on the graphical analysis of the data obtained from the two correlations, one can make an informed decision on the correlation that is better suited for predicting pressure drop using available field data.
2. Based on the results of the hydraulic horsepower requirement of three West Sak oil samples, one can make an informed decision on the amount of energy that would be expended to lift the reservoir fluid in the West Sak field.
3. Pressure drop prediction is dependent on fluid properties. The value of a measured fluid property can vary considerably from estimated ones. This can cause error in pressure drop prediction.
4. Oil flow rate, oil density, and oil viscosity are the three parameters that have the most effect on pressure drop.
5. Chen's equation for estimating the Moody friction factor yields lower values at Reynolds numbers between 2000 and 3000. For both gas-liquid two-phase correlations, this results in a lower friction pressure drop component prediction.
6. The Hagedorn and Brown correlation can be used at a higher oil viscosity than the Duns and Ros correlation.

Recommendation

(1) Interfacial tension was kept constant throughout the analysis. In the literature, the effect of this parameter is not well known, therefore, more investigation should be performed to study the effect of this parameter on pressure drop.

References

Ansari, A. M., Sylvester, N. D., Shoham, O., and Brill, J. P.: "A Comprehensive Mechanistic Model for Upward Two-Phase Flow in Wellbores", SPE Paper 20630 Presented at the 65th Annual Technical Conference and Exhibition of Society of Petroleum Engineers held in New Orleans, September 23-26, 1990.

Asheim, Harald: "Fluid Properties" Published by Norwegian University of Science and Technology, 2006.

Aziz, K., Govier, G. W. and Fogarasi, M., "Pressure Drops in Vertical Pipe," J. Cdn. Pet. Tech. (July-Sept., 1972) 38-48.

Baxendell P. B. and Thomas R.: "The Calculation of Pressure Gradients in High-Rate Flowing Wells", Presented at Joint AICHE-SPE Symposium, Tulsa, Oklahoma, September 25-28, 1961.

Beal, C.: "The Viscosity of Air, Water, Natural Gases and Crude Oil and its Associated Gases at Oil Field Temperature and Pressures," Trans. AIME, 165, 94 (1946)

Beggs, Dale H. and Brill, J. P. "A Study of Two-Phase Flow in Inclined Pipes", SPE Paper 4007, Presented at SPE-AIME 47th Annual Fall Meeting held in San Antonio, Texas, October 8-11, 1973.

Beggs H. D. and Robinson J. R.:"Estimating the Viscosity of Crude Oil Systems", Journal of Petroleum Technology Forum Articles, September 1975.

Brennen, Christopher E.: "Fundamental of Multiphase Flow", Published by Cambridge Press, 2005.

Brill, James P. and Beggs, Dale H.: "Two-Phase Flow in Pipes" Sixth Edition, Published by S.N. April 1994.

Brown, Kermit E., and Beggs, Dale H.: "The Artificial Lift Methods", Volume 1, Published by PennWell books Publishing Company, 1977.

Chen, N. H.: "An Explicit Equation for Friction Factor in pipe" Ind. Eng. Chem. Fund., 18, 296, 1979.

Dake, L. P.: "Fundamentals of Reservoir Engineering", Published by Elsevier Science B. V., 1978.

Dandekar, Abhijit Y.: "Petroleum Reservoir Rock and Fluid Properties", Published by CRC Press, Taylor and Francis Group, 2006.

Duns, H. Jr. and Ros, N. C. J.: "Vertical Flow of Gas and Liquid Mixtures in Wells," Proc., Sixth World Petroleum Congress, Frankfurt, Germany (1963) 451-465.

Fancher, JR., George H., Brown, Kermit: "Prediction of Pressure Gradient for Multiphase Flow in Tubing", Paper presented at the 37th Annual Fall Meeting of Society of Petroleum Engineers, Los Angeles, California, October 7-10, 1963.

GlasØ, O.: "Generalized Pressure-Volume-Temperature Correlations," JPT May 1980, p. 784-795.

Gomez, L. E.: "DPDL-Computer Program for Pressure Loss Calculation in Gas-Liquid Two-Phase Flow Pipeline," Computer Code vx. 1.0, U. of Tulsa, Tulsa, Oklahama (2005).

Gondouin, M. and Fox, J. M.: "The Challenge of West Sak Heavy Oil: Analysis of an Innovative Approach," SPE Paper 22077, Presented at the International Arctic Technology Conference, Anchorage, Alaska, May 1991.

Govier, G. W. and Aziz, K.: "The Flow of Complex Mixtures in Pipes", Published by Van Nostrand Reinhold Co., 1972.

Griffith, P. and Wallis, G. B.: "Two-Phase Slug Flow," Journal of Heat Transfer; Trans., ASME, August 1961.

Hagedorn, Alton R. and Brown, Kemit E.: "Experimental Study of Pressure Gradient Occurring During Continuous Two-Phase Flow in Small Diameter Vertical Conduits", Presented at the Society of Petroleum Engineers' 30th Annual Fall Meeting, Houston Texas, October 11-14, 1964.

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

Hassan, Rashid A. and Kabir, Shah C.:"A Study of Multiphase Flow Behavior in Vertical Wells", SPE Paper 15138, Presented at Society of Petroleum Engineering California Regional Meeting, Oakland, April 2-4, 1988.

Hewitt, G. F. and Roberts, D. N.: "Studies of Two-Phase Flow Patterns by Simultaneous X-Ray and Flash Photography," AERE-M 2159, Her Majesty's Stationary Office, London (1969).

Lasater, J. A.: "Bubble Point Pressure Correlation," Trans. AIME, 213, 1958, p. 379-381.

Lawson, David J. and Brill, James P.: "A Statistical Evaluation of Methods Used To Predict Pressure Losses for Multiphase Flow in Vertical Oilwell Tubing", SPE Paper 4257, Presented at the SPE-AIME 48th Annual Fall Meeting, Las Vegas, Nevada, September 30 – October 3, 1974.

Lee, L. A., Gonzalez, Mario H. and Eakin, Bertram E.: "The Viscosity of Natural Gases", Journal of Petroleum Technology, August 1966.

Orkiszewski, J.: "Predicting Pressure Drops in Vertical Pipe", SPE Paper 1546, Presented at the 41st Society of Petroleum Engineers' Annual Fall Meeting held in Dallas, Texas, October 2-5, 1967.

Poettmann, F. H. and Carpenter, P. G.: "The Multiphase Flow of Gas, Oil, and Water through Vertical Flow Strings with Application to the Design of Gas Lift Installations," Drilling and Production Practice (1952), 257.

Pucknell J. K., Mason, J. N. E. and Vervest, E. G.:"An Evaluation of Recent 'Mechanistic' Models of Multiphase Flow for Predicting Pressure Drops in Oil and Gas Wells", SPE Paper 26682, Presented at the Offshore European Conference, Aberdeen, United Kingdom, September 7-10, 1993.

Shi, H., Holmes, J. A., Durlofsky L. J., Aziz K., Diaz L. R., Alkaya, B. and Oddie G.:"Drift-Flux Modeling of Multiphase Flow in Wellbores", Presented at Society of Petroleum Engineers Annual Technical Conference and Exhibition, Denver, Colorado, U.S.A., October 5-8, 2003.

Shoham, Ovadia: "Mechanistic Modeling of Gas and Liquid Two-Phase Flow in Pipes", Published by Society of Petroleum Engineers, 2006.

Standing M. B.: "A Pressure-Volume-Temperature Correlation for Mixtures of California Oils and Gases," API Drilling Production Practices, 1947, p. 247.

Standing, M. B. and Katz, D. L., "Density of Natural Gases," Trans. AIME, 146: 140-149 1942.

Taitel, Y., Barnea, D and Dukler, A. E.: "Modeling Flow Pattern Transition for Steady Upward Gas-Liquid Flow in Vertical Tubes," AIChE J. (1980) 26, No. 3, 345-354.

Takacs, Gabor : "Considerations on the Selection of an Optimum Vertical Multiphase Pressure Drop Prediction Model for Oil Wells", SPE Paper 68361, Presented at SPE Production and Operations Symposium, Oklahoma City, Oklahoma, March 24-27, 2001.

Targac, G. W., Redman, R. S., Davis, E. R., Rennie, S. B., McKeever, S. O. and Chambers, B. C.: "Unlocking the Value of West Sak Heavy Oil," SPE Paper 97856, Presented at International Thermal Operation and Heavy Oil Symposium, Calgary, Alberta Canada, November 2005.

Thompson, L. G.: "Supplementary Data, Calculated Results and Calculation Programs for TUFFP Well Data Bank" Fluid Flow Projects Thirty First Research Report, University of Tulsa Fluid Flow Projects, May 1982.

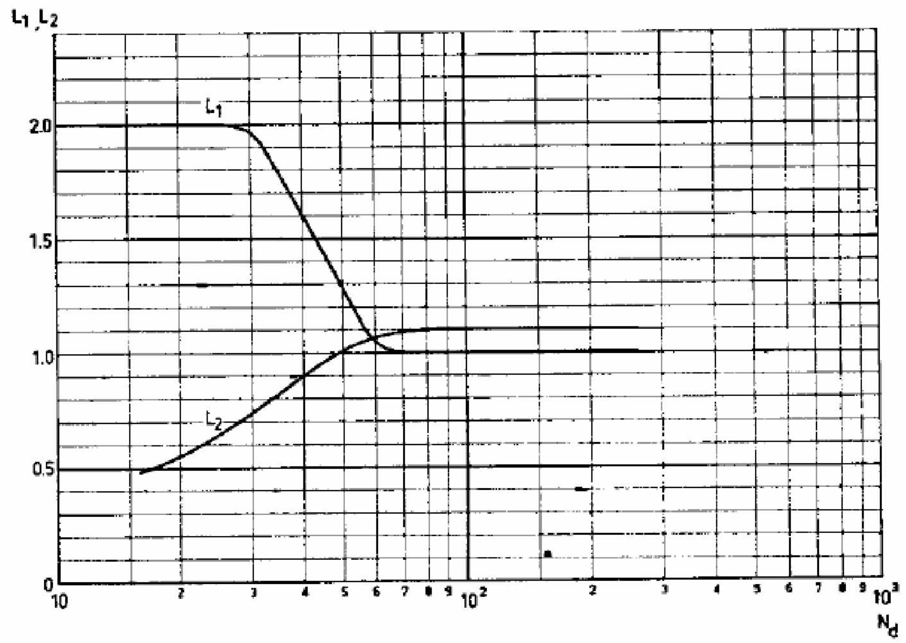
Vazquez, M. and Beggs, H. D.:"Correlation for Fluid Physical Property Predictions," JPT, June 1980, p. 968-970.

White, Frank M.: "Viscous Fluid Flow", Third Edition, Published by McGraw-Hill, 2006.

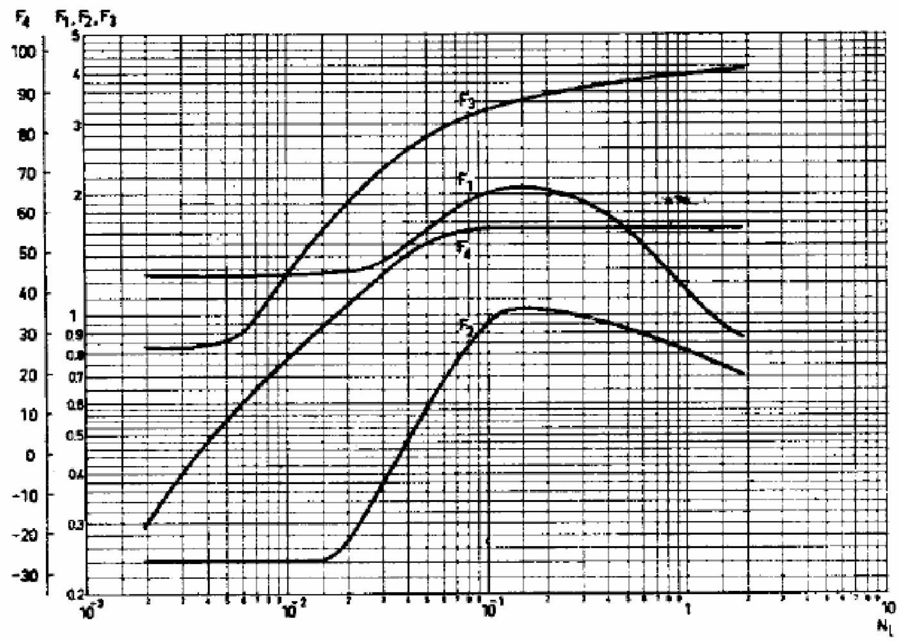
Whitson, Curtis H. and Brulé, Michel R.: "Phase Behavior", Published by Henry L. Doherty Memorial Fund of AIME, Society of Petroleum Engineers Inc., 2000.

Appendix A

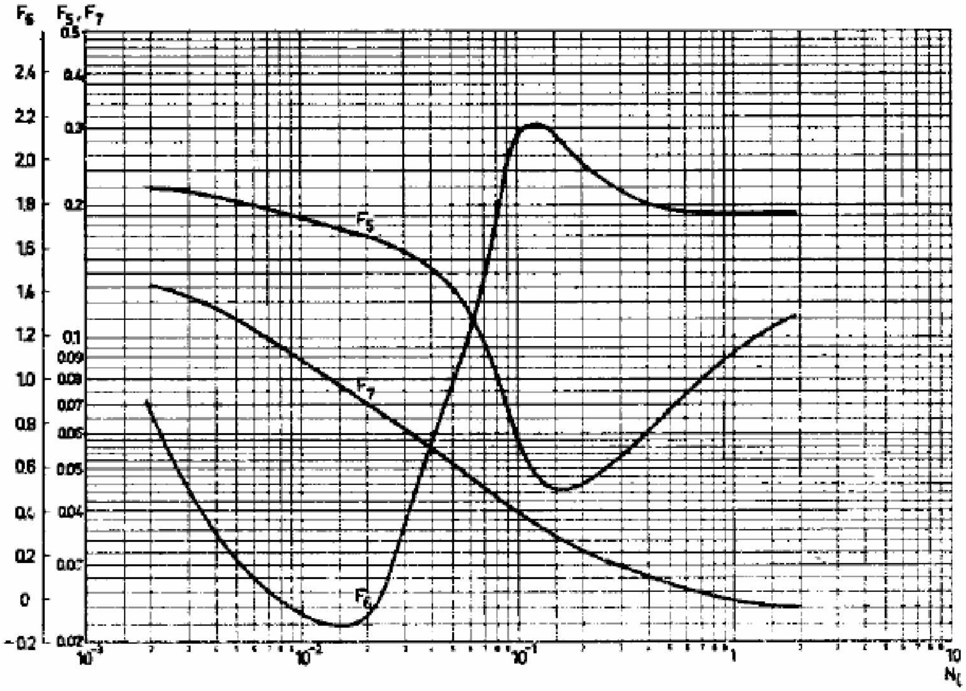
CORRELATING CHARTS FOR DUNS AND ROS CORRELATION (1963)



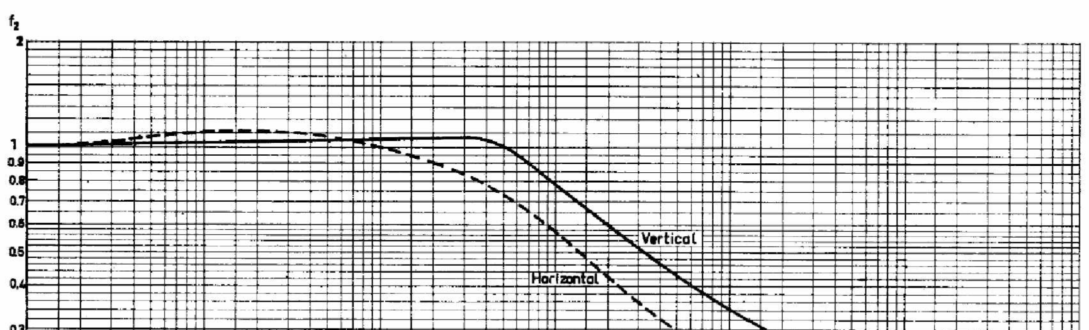
Appendix A Figure 5: L1 and L2 Against Pipe Diameter Number, Nd



Appendix A Figure 6: F1, F2, F3 and F4 Against Viscosity Number NL



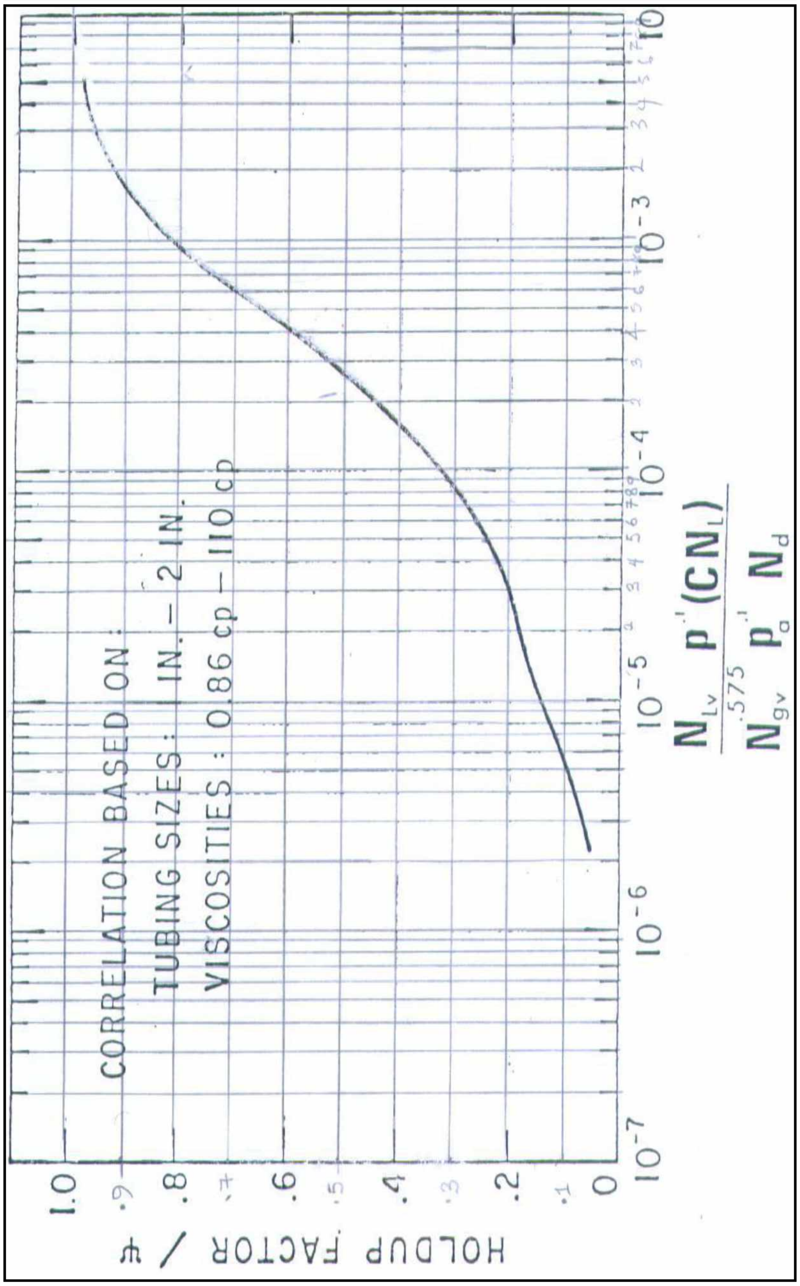
Appendix A Figure 7: F5, F6 and F7 Against Viscosity Number NL



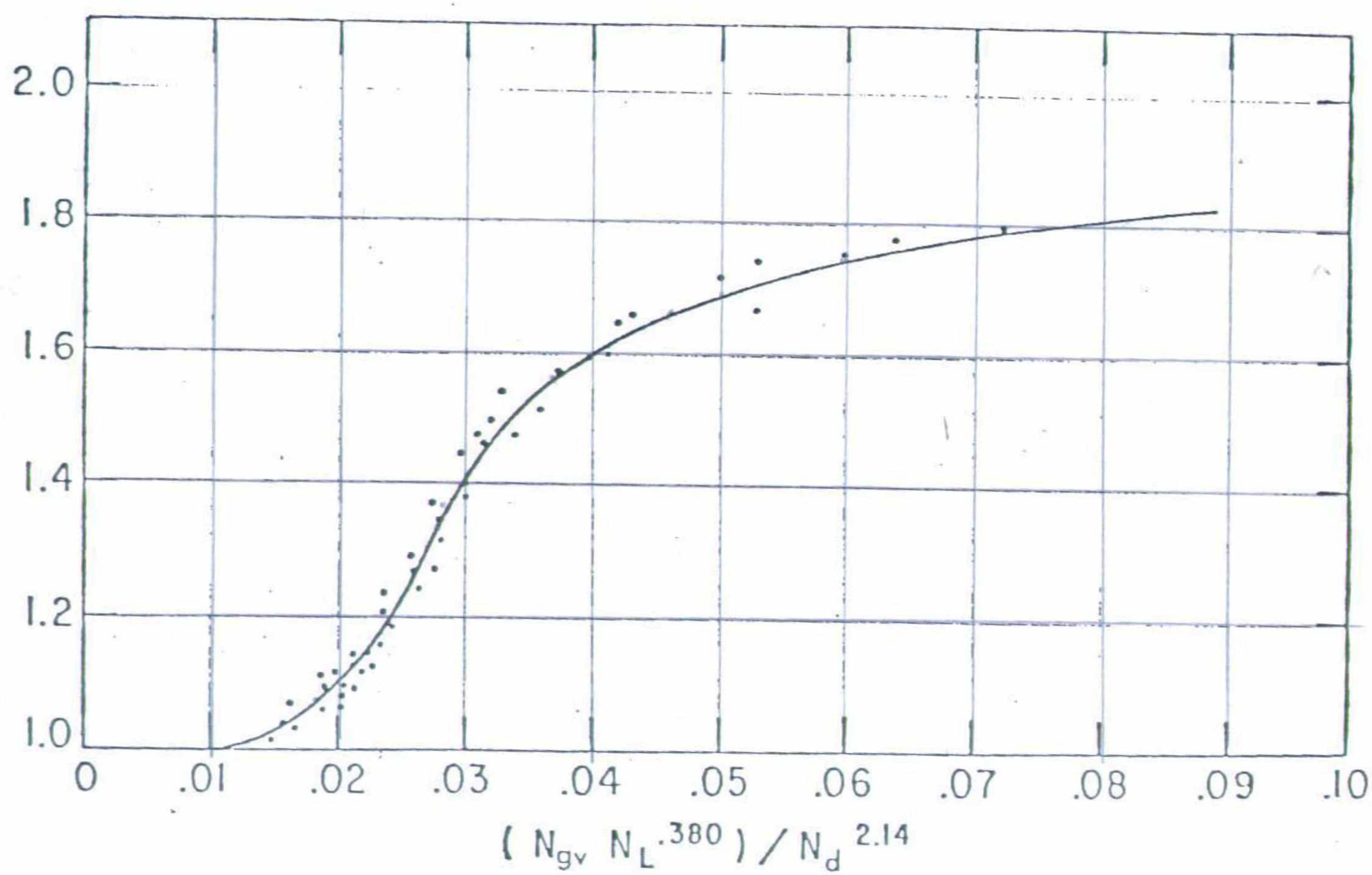
Appendix A Figure 8: f2 Correlation Chart

APPENDIX B

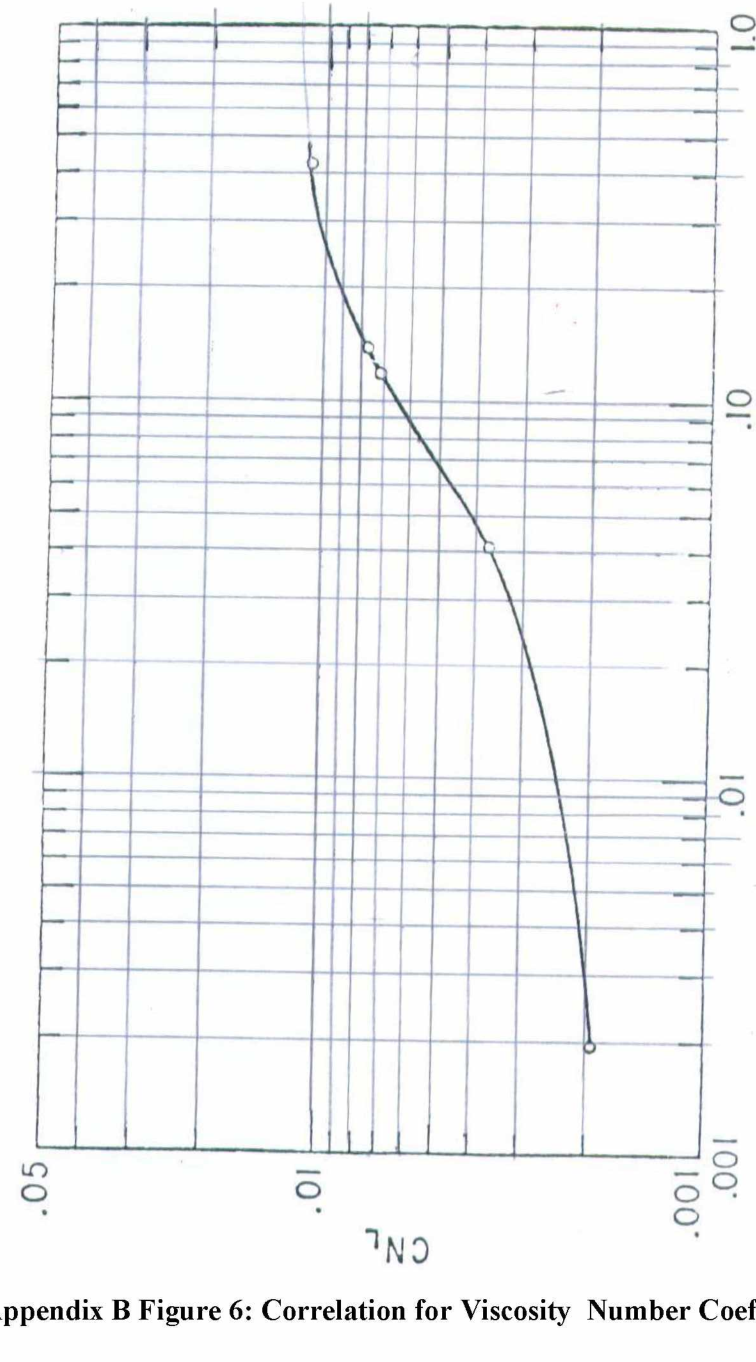
CORRELATING CHARTS OF HAGEDORN AND BROWN (1964)



Appendix B Figure 4: Holdup Factor Correlation



Appendix B Figure 5: Correlation for Secondary Correlation Factor



Appendix B Figure 6: Correlation for Viscosity Number Coefficient

APPENDIX C

HAGEDORN AND BROWN (1964) RESULTS

Appendix C Table 1: Pressure Drop Calculation for Oil of API 16 at Constant Pressure and Temperature

Qo, stb/d	Qg, scf/d	dia., in	ε/d	Temp, R	IFT	Bo	Qo cu.ft/s	Rp, scf/stb	Rs, scf/stb	Z-factor	Bg, cu.ft/scf	Qg, cu.ft/sec	Vsl, ft/s	Vsg, ft/s	Nlv	Ngv	Nd	Nl	μg	CNL	Hl/ψ corr	HL/ψ	ψ corr.	ψ	HL	ρs	ρn	Nre	fm	ρf	Dp	Total DP
100	4000000	2	0.0036	530	30	1.2002	0.0078	40000	422.12	0.79	0.00395	0.180737	0.3573	8.281	0.797	18.48	26.71	0.411	0.021	0.011	0.0001	0.32	0.0117	1	0.32	24.771	13.307	93366	0.029	7.149	1.4437	0.182
200	4000000	2	0.0036	530	30	1.2002	0.0156	20000	422.12	0.79	0.00395	0.178809	0.7146	8.1927	1.595	18.283	26.71	0.411	0.021	0.011	0.0002	0.45	0.0115	1	0.45	30.119	14.906	36347	0.0309	7.377	1.6826	0.2208
300	4000000	2	0.0036	530	30	1.2002	0.0234	13333	422.12	0.79	0.00395	0.176881	1.0719	8.1044	2.392	18.086	26.71	0.411	0.021	0.011	0.0003	0.52	0.0114	1	0.52	32.999	16.411	22953	0.0323	8.162	2.0699	0.2435
400	4000000	2	0.0036	530	30	1.2002	0.03119	10000	422.12	0.79	0.00395	0.174954	1.4292	8.0161	3.19	17.889	26.71	0.411	0.021	0.011	0.0004	0.6	0.0113	1	0.6	36.29	17.831	13145	0.0349	8.761	2.5398	0.2697
500	4000000	2	0.0036	530	30	1.2002	0.03899	8000	422.12	0.79	0.00395	0.173026	1.7866	7.9277	3.987	17.692	26.71	0.411	0.021	0.011	0.0005	0.66	0.0112	1	0.66	38.759	19.172	8799.5	0.0374	9.483	3.117	0.2908
600	4000000	2	0.0036	530	30	1.2002	0.04679	6666.7	422.12	0.79	0.00395	0.171098	2.1439	7.8394	4.784	17.495	26.71	0.411	0.021	0.011	0.0006	0.72	0.011	1	0.72	41.227	20.44	5836.6	0.0407	10.13	3.8286	0.3129
700	4000000	2	0.0036	530	30	1.2002	0.05459	5714.3	422.12	0.79	0.00395	0.169171	2.5012	7.7511	5.582	17.298	26.71	0.411	0.021	0.011	0.0008	0.76	0.0109	1	0.76	42.873	21.642	4541.4	0.0431	10.93	4.6153	0.3298
800	4000000	2	0.0036	530	30	1.2002	0.06239	5000	422.12	0.79	0.00395	0.167243	2.8585	7.6628	6.379	17.1	26.71	0.411	0.021	0.011	0.0009	0.79	0.0108	1	0.79	44.107	22.783	3817.2	0.045	11.77	5.4646	0.3442
900	4000000	2	0.0036	530	30	1.2002	0.07019	4444.4	422.12	0.79	0.00395	0.165315	3.2158	7.5745	7.176	16.903	26.71	0.411	0.021	0.011	0.001	0.81	0.0107	1	0.81	44.93	23.867	3469.2	0.046	12.68	6.3218	0.3559
1000	4000000	2	0.0036	530	30	1.2002	0.07798	4000	422.12	0.79	0.00395	0.163388	3.5731	7.4861	7.974	16.706	26.71	0.411	0.021	0.011	0.0011	0.82	0.0105	1	0.82	45.341	24.898	3411.6	0.0461	13.67	7.1804	0.3647
1100	4000000	2	0.0036	530	30	1.2002	0.08578	3636.4	422.12	0.79	0.00395	0.16146	3.9304	7.3978	8.771	16.509	26.71	0.411	0.021	0.011	0.0012	0.84	0.0104	1	0.84	46.164	25.88	3072.8	0.0458	14.51	7.9472	0.3758
1200	4000000	2	0.0036	530	30	1.2002	0.09358	3333.3	422.12	0.79	0.00395	0.159533	4.2877	7.3095	9.569	16.312	26.71	0.411	0.021	0.011	0.0013	0.86	0.0103	1	0.86	46.987	26.816	2757.4	0.0416	15.3	7.9778	0.3817
1300	4000000	2	0.0036	530	30	1.2002	0.10138	3076.9	422.12	0.79	0.00395	0.157605	4.6451	7.2212	10.37	16.115	26.71	0.411	0.021	0.011	0.0015	0.88	0.0102	1	0.88	47.81	27.71	2466.2	0.0345	16.06	7.2592	0.3824
1400	4000000	2	0.0036	530	30	1.2002	0.10918	2857.1	422.12	0.79	0.00395	0.155677	5.0024	7.1328	11.16	15.918	26.71	0.411	0.021	0.011	0.0016	0.89	0.01	1	0.89	48.221	28.565	2391.3	0.0326	16.92	7.5771	0.3875
1500	4000000	2	0.0036	530	30	1.2002	0.11698	2666.7	422.12	0.79	0.00395	0.15375	5.3597	7.0445	11.96	15.721	26.71	0.411	0.021	0.011	0.0017	0.9	0.0099	1	0.9	48.633	29.382	2312.4	0.0311	17.75	7.9034	0.3926
1600	4000000	2	0.0036	530	30	1.2002	0.12478	2500	422.12	0.79	0.00395	0.151822	5.717	6.9562	12.76	15.524	26.71	0.411	0.021	0.011	0.0018	0.91	0.0098	1	0.91	49.044	30.165	2230.9	0.0302	18.55	8.3752	0.3987
1700	4000000	2	0.0036	530	30	1.2002	0.13257	2352.9	422.12	0.79	0.00395	0.149894	6.0743	6.8679	13.56	15.327	26.71	0.411	0.021	0.011	0.002	0.92	0.0097	1	0.92	49.455	30.915	2147.5	0.0303	19.32	9.1324	0.4069
1800	4000000	2	0.0036	530	30	1.2002	0.14037	2222.2	422.12	0.79	0.00395	0.147967	6.4316	6.7796	14.35	15.129	26.71	0.411	0.021	0.011	0.0021	0.93	0.0095	1	0.93	49.867	31.634	2063.1	0.0311	20.07	10.164	0.4169
1900	4000000	2	0.0036	530	30	1.2002	0.14817	2105.3	422.12	0.79	0.00395	0.146039	6.7889	6.6912	15.15	14.932	26.71	0.411	0.021	0.011	0.0022	0.935	0.0094	1	0.935	50.072	32.325	2063	0.0311	20.87	11.005	0.4241
2000	4000000	2	0.0036	530	30	1.2002	0.15597	2000	422.12	0.79	0.00395	0.144111	7.1462	6.6029	15.95	14.735	26.71	0.411	0.021	0.011	0.0024	0.94	0.0093	1	0.94	50.278	32.989	2059.4	0.0312	21.64	11.893	0.4317
2100	4000000	2	0.0036	530	30	1.2002	0.16377	1904.8	422.12	0.79	0.00395	0.142184	7.5036	6.5146	16.75	14.538	26.71	0.411	0.021	0.011	0.0025	0.945	0.0092	1	0.945	50.484	33.627	2052.6	0.0313	22.4	12.83	0.4397
2200	4000000	2	0.0036	530	30	1.2002	0.17157	1818.2	422.12	0.79	0.00395	0.140256	7.8609	6.4263	17.54	14.341	26.71	0.411	0.021	0.011	0.0027	0.95	0.009	1	0.95	50.69	34.242	2043	0.0314	23.13	13.82	0.448
2300	4000000	2	0.0036	530	30	1.2002	0.17937	1739.1	422.12	0.79	0.00395	0.138328	8.2182	6.338	18.34	14.144	26.71	0.411	0.021	0.011	0.0028	0.955	0.0089	1	0.955	50.895	34.833	2030.6	0.0316	23.84	14.867	0.4567
2400	4000000	2	0.0036	530	30	1.2002	0.18716	1666.7	422.12	0.79	0.00395	0.136401	8.5755	6.2496	19.14	13.947	26.71	0.411	0.021	0.011	0.0029	0.96	0.0088	1	0.96	51.101	35.403	2015.9	0.0318	24.53	15.974	0.4658
2500	4000000	2	0.0036	530	30	1.2002	0.19496	1600	422.12	0.79	0.00395	0.134473	8.9328	6.1613	19.93	13.75	26.71	0.411	0.021	0.011	0.0031	0.965	0.0087	1	0.965	51.307	35.953	1999	0.0321	25.19	17.145	0.4754
2600	4000000	2	0.0036	530	30	1.2002	0.20276	1538.5	422.12	0.79	0.00395	0.132545	9.2901	6.073	20.73	13.553	26.71	0.411	0.021	0.011	0.0032	0.967	0.0086	1	0.967	51.389	36.484	2030.4	0.0316	25.9	17.995	0.4818
2700	4000000	2	0.0036	530	30	1.2002	0.21056	1481.5	422.12	0.79	0.00395	0.130618	9.6474	5.9847	21.53	13.356	26.71	0.411	0.021	0.011	0.0034	0.97	0.0084	1	0.97	51.512	36.996	2043	0.0314	26.57	19.005	0.4897
2800	4000000	2	0.0036	530	30	1.2002	0.21836	1428.6	422.12	0.79	0.00395	0.12869	10.005	5.8963	22.33	13.158	26.71	0.411	0.021	0.011	0.0036	0.973	0.0083	1	0.973	51.636	37.491	2053.8	0.0313	27.22	20.052	0.4978
2900	4000000	2	0.0036	530	30	1.2002	0.22616	1379.3	422.12	0.79	0.00395	0.126762	10.362	5.808	23.12	12.961	26.71	0.411	0.021	0.011	0.0037	0.975	0.0082	1	0.975	51.718	37.969	2080.1	0.0309	27.88	21.007	0.505
3000	4000000	2	0.0036	530	30	1.2002	0.23395	1333.3	422.12	0.79	0.00395	0.124835	10.719	5.7197	23.92	12.764	26.71	0.411	0.021	0.011	0.0039	0.98	0.0081	1	0.98	51.924	38.432	2052.8	0.0313	28.45	22.406	0.5162

Appendix C Table 2: Pressure Drop Calculation for Oil of API 20 at Constant Pressure and Temperature

Qo, stb/d	Qg, scf/d	dia, in	ε/d	Temp, R	IFT	Bo	Qo cu.ft /sec	Rp, scf/stb	Rs, scf/stb	Z-factor	Bg, cu.ft/scf	Qg, cu.ft/sec	Vsl	Vsg	Nlv	Ngv	Nd	Nl	**μg, cP**	CNL	Hl/ψ corr	HL/ψ	ψ corr.	ψ	HL	ρs, lb/cu.ft	ρn	μs, cP	Nre	fm	ρf	Dp,lb/cu.ft	Total DP, psi/ft
100	4E+06	2	0.004	530	30	1.23	0.01	40000	485	0.79	0.004	0.18	0.366	8.268	0.8	18.3	26.2	0.135	0.021	0.008	7E-05	0.28	0.008	1	0.28	22.524	13.259	0.15947	178037	0.0284	7.805	1.54	0.167
200	4E+06	2	0.004	530	30	1.23	0.02	20000	485	0.79	0.004	0.178	0.732	8.166	1.6	18	26.2	0.135	0.021	0.008	1E-04	0.38	0.008	1	0.38	26.424	14.815	0.32896	99386.7	0.02897	8.306	1.775	0.196
300	4E+06	2	0.004	530	30	1.23	0.02	13333	485	0.79	0.004	0.176	1.099	8.065	2.4	17.8	26.2	0.135	0.021	0.008	2E-04	0.45	0.008	1	0.45	29.154	16.28	0.5461	67748.3	0.02952	9.092	2.1	0.217
400	4E+06	2	0.004	530	30	1.23	0.03	10000	485	0.79	0.004	0.174	1.465	7.963	3.2	17.6	26.2	0.135	0.021	0.008	3E-04	0.52	0.008	1	0.52	31.884	17.664	0.90658	45556.8	0.0303	9.786	2.455	0.238
500	4E+06	2	0.004	530	30	1.23	0.04	8000	485	0.79	0.004	0.172	1.831	7.862	4	17.4	26.2	0.135	0.021	0.008	4E-04	0.58	0.007	1	0.58	34.223	18.972	1.39987	32577.3	0.03116	10.52	2.869	0.258
600	4E+06	2	0.004	530	30	1.23	0.05	6667	485	0.79	0.004	0.169	2.197	7.76	4.9	17.1	26.2	0.135	0.021	0.008	5E-04	0.62	0.007	1	0.62	35.783	20.21	1.87015	26686.2	0.03179	11.41	3.352	0.272
700	4E+06	2	0.004	530	30	1.23	0.06	5714	485	0.79	0.004	0.167	2.563	7.659	5.7	16.9	26.2	0.135	0.021	0.008	5E-04	0.67	0.007	1	0.67	37.733	21.384	2.68604	20182.3	0.03283	12.12	3.874	0.289
800	4E+06	2	0.004	530	30	1.23	0.06	5000	485	0.79	0.004	0.165	2.929	7.557	6.5	16.7	26.2	0.135	0.021	0.008	6E-04	0.71	0.007	1	0.71	39.293	22.499	3.5884	16306.3	0.03378	12.88	4.458	0.304
900	4E+06	2	0.004	530	30	1.23	0.07	4444	485	0.79	0.004	0.163	3.296	7.456	7.3	16.5	26.2	0.135	0.021	0.008	7E-04	0.74	0.007	1	0.74	40.463	23.559	4.45905	14087.5	0.03451	13.72	5.097	0.316
1000	4E+06	2	0.004	530	30	1.23	0.08	4000	485	0.79	0.004	0.161	3.662	7.354	8.1	16.2	26.2	0.135	0.021	0.008	8E-04	0.78	0.007	1	0.78	42.023	24.568	5.95705	11267.3	0.03577	14.36	5.808	0.332
1100	4E+06	2	0.004	530	30	1.23	0.09	3636	485	0.79	0.004	0.158	4.028	7.253	8.9	16	26.2	0.135	0.021	0.008	9E-04	0.8	0.007	1	0.8	42.803	25.53	6.88534	10373.2	0.03628	15.23	6.55	0.343
1200	4E+06	2	0.004	530	30	1.23	0.1	3333	485	0.79	0.004	0.156	4.394	7.151	9.7	15.8	26.2	0.135	0.021	0.008	1E-03	0.81	0.007	1	0.81	43.193	26.447	7.4024	10230	0.03637	16.19	7.314	0.351
1300	4E+06	2	0.004	530	30	1.23	0.1	3077	485	0.79	0.004	0.154	4.76	7.05	11	15.6	26.2	0.135	0.021	0.008	0.001	0.815	0.007	1	0.815	43.388	27.324	7.67531	10426.9	0.03625	17.21	8.105	0.358
1400	4E+06	2	0.004	530	30	1.23	0.11	2857	485	0.79	0.004	0.152	5.127	6.948	11	15.3	26.2	0.135	0.021	0.008	0.001	0.82	0.007	1	0.82	43.583	28.162	7.95828	10596.8	0.03614	18.2	8.935	0.365
1500	4E+06	2	0.004	530	30	1.23	0.12	2667	485	0.79	0.004	0.149	5.493	6.847	12	15.1	26.2	0.135	0.021	0.008	0.001	0.83	0.007	1	0.83	43.973	28.964	8.55592	10359.6	0.03629	19.08	9.821	0.374
1600	4E+06	2	0.004	530	30	1.23	0.13	2500	485	0.79	0.004	0.147	5.859	6.745	13	14.9	26.2	0.135	0.021	0.008	0.001	0.84	0.006	1	0.84	44.362	29.732	9.19843	10103.8	0.03645	19.93	10.75	0.383
1700	4E+06	2	0.004	530	30	1.23	0.14	2353	485	0.79	0.004	0.145	6.225	6.644	14	14.7	26.2	0.135	0.021	0.008	0.001	0.85	0.006	1	0.85	44.752	30.469	9.88919	9833.18	0.03663	20.74	11.72	0.392
1800	4E+06	2	0.004	530	30	1.23	0.14	2222	485	0.79	0.004	0.143	6.591	6.542	15	14.4	26.2	0.135	0.021	0.008	0.002	0.86	0.006	1	0.86	45.142	31.176	10.6318	9551.08	0.03682	21.53	12.74	0.402
1900	4E+06	2	0.004	530	30	1.23	0.15	2105	485	0.79	0.004	0.141	6.957	6.441	15	14.2	26.2	0.135	0.021	0.008	0.002	0.88	0.006	1	0.88	45.922	31.855	12.2886	8613.56	0.03754	22.1	13.87	0.415
2000	4E+06	2	0.004	530	30	1.23	0.16	2000	485	0.79	0.004	0.138	7.324	6.339	16	14	26.2	0.135	0.021	0.008	0.002	0.9	0.006	1	0.9	46.702	32.508	14.2035	7755.24	0.03831	22.63	15.08	0.429
2100	4E+06	2	0.004	530	30	1.23	0.17	1905	485	0.79	0.004	0.136	7.69	6.238	17	13.8	26.2	0.135	0.021	0.008	0.002	0.905	0.006	1	0.905	46.897	33.136	14.7272	7771.67	0.0383	23.41	16.21	0.438
2200	4E+06	2	0.004	530	30	1.23	0.18	1818	485	0.79	0.004	0.134	8.056	6.136	18	13.6	26.2	0.135	0.021	0.008	0.002	0.91	0.006	1	0.91	47.092	33.741	15.2702	7777.14	0.03829	24.17	17.37	0.448
2300	4E+06	2	0.004	530	30	1.23	0.18	1739	485	0.79	0.004	0.132	8.422	6.035	19	13.3	26.2	0.135	0.021	0.008	0.002	0.92	0.006	1	0.92	47.482	34.323	16.4169	7496.02	0.03858	24.81	18.64	0.459
2400	4E+06	2	0.004	530	30	1.23	0.19	1667	485	0.79	0.004	0.129	8.788	5.933	19	13.1	26.2	0.135	0.021	0.008	0.002	0.925	0.006	1	0.925	47.677	34.885	17.0221	7482.28	0.03859	25.53	19.89	0.469
2500	4E+06	2	0.004	530	30	1.23	0.2	1600	485	0.79	0.004	0.127	9.155	5.832	20	12.9	26.2	0.135	0.021	0.008	0.002	0.93	0.006	1	0.93	47.872	35.427	17.6497	7460.04	0.03861	26.22	21.18	0.48
2600	4E+06	2	0.004	530	30	1.23	0.21	1538	485	0.79	0.004	0.125	9.521	5.73	21	12.7	26.2	0.135	0.021	0.008	0.002	0.935	0.005	1	0.935	48.067	35.95	18.3004	7429.93	0.03865	26.89	22.52	0.49
2700	4E+06	2	0.004	530	30	1.23	0.22	1481	485	0.79	0.004	0.123	9.887	5.629	22	12.4	26.2	0.135	0.021	0.008	0.003	0.94	0.005	1	0.94	48.262	36.455	18.9751	7392.52	0.03868	27.54	23.89	0.501
2800	4E+06	2	0.004	530	30	1.23	0.22	1429	485	0.79	0.004	0.121	10.25	5.527	23	12.2	26.2	0.135	0.021	0.008	0.003	0.945	0.005	1	0.945	48.457	36.943	19.6747	7348.38	0.03873	28.16	25.31	0.512
2900	4E+06	2	0.004	530	30	1.23	0.23	1379	485	0.79	0.004	0.118	10.62	5.426	23	12	26.2	0.135	0.021	0.008	0.003	0.95	0.005	1	0.95	48.652	37.415	20.4001	7298.03	0.03879	28.77	26.77	0.524
3000	4E+06	2	0.004	530	30	1.23	0.24	1333	485	0.79	0.004	0.116	10.99	5.324	24	11.8	26.2	0.135	0.021	0.008	0.003	0.96	0.005	1	0.96	49.042	37.871	21.932	6984.46	0.03914	29.25	28.37	0.538

Appendix C Table 3: Pressure Drop Calculation for Oil of API 25 at Constant Pressure and Temperature

Qo, stb/d	Qg, scf/d	dia, in	ε/d	Temp, R	IFT	Bo	Qo cu.ft/sec	Rp, scf/stb	Rs, scf/stb	Z-factor	Bg, cu.ft/scf	Qg, cu.ft/sec	Vsl, ft/s	Vsg, ft/s	Nlv	Ngv	Nd	Nl	μg, cP	CNL	Hl/ψ corr	HL/ψ	ψ corr.	ψ	HL	ρs, lb/cu.ft	ρn, lb/cu.ft	μs, cP	Nre	fm	ρf	Dp, lb/cu.ft	Total DP, psi/ft
100	4E+06	2	0.004	530	30	1.27	0.008	40000	577.2	0.79	0.004	0.18	0.4	8.25	0.8	18	25.5	0.045	0.02	0.0038	4E-05	0.22	0.005	1	0.22	19.61	13.205	0.1	273577	0.0281	8.8896	1.73447	0.14826
200	4E+06	2	0.004	530	30	1.27	0.017	20000	577.2	0.79	0.004	0.177	0.8	8.13	1.7	17.7	25.5	0.045	0.02	0.0038	8E-05	0.29	0.005	1	0.29	22.16	14.711	0.17	189093	0.0284	9.7649	2.03725	0.16806
300	4E+06	2	0.004	530	30	1.27	0.025	13333	577.2	0.79	0.004	0.175	1.1	8.01	2.5	17.5	25.5	0.045	0.02	0.0038	0.00012	0.34	0.005	1	0.34	23.98	16.132	0.25	148571	0.0286	10.852	2.41364	0.18331
400	4E+06	2	0.004	530	30	1.27	0.033	10000	577.2	0.79	0.004	0.172	1.5	7.89	3.3	17.2	25.5	0.045	0.02	0.0038	0.00016	0.4	0.005	1	0.4	26.17	17.476	0.38	107172	0.0289	11.671	2.77618	0.201
500	4E+06	2	0.004	530	30	1.27	0.041	8000	577.2	0.79	0.004	0.169	1.9	7.77	4.1	16.9	25.5	0.045	0.02	0.0038	0.00021	0.44	0.005	1	0.44	27.62	18.747	0.51	88422.1	0.0291	12.723	3.22144	0.2142
600	4E+06	2	0.004	530	30	1.27	0.05	6667	577.2	0.79	0.004	0.167	2.3	7.64	5	16.7	25.5	0.045	0.02	0.0038	0.00025	0.48	0.005	1	0.48	29.08	19.952	0.68	72325.1	0.0294	13.69	3.69086	0.22757
700	4E+06	2	0.004	530	30	1.27	0.058	5714	577.2	0.79	0.004	0.164	2.7	7.52	5.8	16.4	25.5	0.045	0.02	0.0038	0.00029	0.52	0.005	1	0.52	30.54	21.096	0.91	58732.3	0.0298	14.575	4.18715	0.24113
800	4E+06	2	0.004	530	30	1.27	0.066	5000	577.2	0.79	0.004	0.162	3	7.4	6.6	16.1	25.5	0.045	0.02	0.0038	0.00034	0.54	0.005	1	0.54	31.26	22.184	1.05	54789.1	0.0299	15.741	4.7758	0.25028
900	4E+06	2	0.004	530	30	1.27	0.074	4444	577.2	0.79	0.004	0.159	3.4	7.28	7.4	15.9	25.5	0.045	0.02	0.0038	0.00038	0.58	0.005	1	0.58	32.72	23.218	1.4	43987	0.0304	16.476	5.33223	0.26425
1000	4E+06	2	0.004	530	30	1.27	0.083	4000	577.2	0.79	0.004	0.156	3.8	7.16	8.3	15.6	25.5	0.045	0.02	0.0038	0.00043	0.6	0.005	1	0.6	33.45	24.205	1.62	40631	0.0306	17.515	5.98309	0.27383
1100	4E+06	2	0.004	530	30	1.27	0.091	3636	577.2	0.79	0.004	0.154	4.2	7.04	9.1	15.3	25.5	0.045	0.02	0.0038	0.00048	0.64	0.005	1	0.64	34.9	25.145	2.16	32340.7	0.0312	18.115	6.61383	0.28832
1200	4E+06	2	0.004	530	30	1.27	0.099	3333	577.2	0.79	0.004	0.151	4.5	6.92	9.9	15.1	25.5	0.045	0.02	0.0038	0.00053	0.65	0.005	1	0.65	35.27	26.043	2.32	31874	0.0312	19.231	7.35894	0.29602
1300	4E+06	2	0.004	530	30	1.27	0.108	3077	577.2	0.79	0.004	0.148	4.9	6.8	11	14.8	25.5	0.045	0.02	0.0038	0.00058	0.68	0.004	1	0.68	36.36	26.902	2.89	27092.9	0.0317	19.904	8.09388	0.30871
1400	4E+06	2	0.004	530	30	1.27	0.116	2857	577.2	0.79	0.004	0.146	5.3	6.68	12	14.6	25.5	0.045	0.02	0.0038	0.00063	0.7	0.004	1	0.7	37.09	27.724	3.34	24688.2	0.0321	20.724	8.89142	0.31931
1500	4E+06	2	0.004	530	30	1.27	0.124	2667	577.2	0.79	0.004	0.143	5.7	6.56	12	14.3	25.5	0.045	0.02	0.0038	0.00068	0.74	0.004	1	0.74	38.54	28.511	4.46	19414.1	0.033	21.089	9.7175	0.33515
1600	4E+06	2	0.004	530	30	1.27	0.132	2500	577.2	0.79	0.004	0.14	6.1	6.44	13	14	25.5	0.045	0.02	0.0038	0.00073	0.75	0.004	1	0.75	38.91	29.265	4.79	18926.9	0.0331	22.012	10.6099	0.34388
1700	4E+06	2	0.004	530	30	1.27	0.141	2353	577.2	0.79	0.004	0.138	6.4	6.32	14	13.8	25.5	0.045	0.02	0.0038	0.00079	0.76	0.004	1	0.76	39.27	29.989	5.15	18413	0.0332	22.9	11.5403	0.35287
1800	4E+06	2	0.004	530	30	1.27	0.149	2222	577.2	0.79	0.004	0.135	6.8	6.2	15	13.5	25.5	0.045	0.02	0.0038	0.00084	0.78	0.004	1	0.78	40	30.685	5.96	16629.8	0.0337	23.538	12.5183	0.36472
1900	4E+06	2	0.004	530	30	1.27	0.157	2105	577.2	0.79	0.004	0.133	7.2	6.07	16	13.2	25.5	0.045	0.02	0.0038	0.0009	0.8	0.004	1	0.8	40.73	31.353	6.89	14992.7	0.0342	24.135	13.5496	0.37693
2000	4E+06	2	0.004	530	30	1.27	0.165	2000	577.2	0.79	0.004	0.13	7.6	5.95	17	13	25.5	0.045	0.02	0.0038	0.00096	0.81	0.004	1	0.81	40.91	31.995	7.14	15043	0.0342	25.023	14.5926	0.38544
2100	4E+06	2	0.004	530	30	1.27	0.174	1905	577.2	0.79	0.004	0.127	8	5.83	17	12.7	25.5	0.045	0.02	0.0038	0.00102	0.81	0.004	1	0.81	41.09	32.614	7.4	15070.8	0.0342	25.885	15.6725	0.39421
2200	4E+06	2	0.004	530	30	1.27	0.182	1818	577.2	0.79	0.004	0.125	8.3	5.71	18	12.5	25.5	0.045	0.02	0.0038	0.00108	0.82	0.004	1	0.82	41.46	33.21	7.96	14541.5	0.0343	26.603	16.8053	0.4046
2300	4E+06	2	0.004	530	30	1.27	0.19	1739	577.2	0.79	0.004	0.122	8.7	5.59	19	12.2	25.5	0.045	0.02	0.0038	0.00115	0.83	0.004	1	0.83	41.64	33.784	8.25	14529.3	0.0343	27.411	17.9602	0.41388
2400	4E+06	2	0.004	530	30	1.27	0.199	1667	577.2	0.79	0.004	0.119	9.1	5.47	20	11.9	25.5	0.045	0.02	0.0038	0.00121	0.83	0.004	1	0.83	41.82	34.338	8.56	14499.5	0.0344	28.194	19.1521	0.42343
2500	4E+06	2	0.004	530	30	1.27	0.207	1600	577.2	0.79	0.004	0.117	9.5	5.35	21	11.7	25.5	0.045	0.02	0.0038	0.00128	0.84	0.004	1	0.84	42.19	34.873	9.2	13939.5	0.0346	28.828	20.4042	0.43465
2600	4E+06	2	0.004	530	30	1.27	0.215	1538	577.2	0.79	0.004	0.114	9.9	5.23	21	11.4	25.5	0.045	0.02	0.0038	0.00135	0.85	0.003	1	0.85	42.37	35.389	9.54	13880.6	0.0346	29.561	21.672	0.44472
2700	4E+06	2	0.004	530	30	1.27	0.223	1481	577.2	0.79	0.004	0.111	10	5.11	22	11.1	25.5	0.045	0.02	0.0038	0.00142	0.86	0.003	1	0.86	42.91	35.888	10.6	12843.7	0.035	30.014	23.041	0.45802
2800	4E+06	2	0.004	530	30	1.27	0.232	1429	577.2	0.79	0.004	0.109	11	4.99	23	10.9	25.5	0.045	0.02	0.0038	0.00149	0.87	0.003	1	0.87	43.1	36.371	11	12764.9	0.035	30.696	24.3886	0.46864
2900	4E+06	2	0.004	530	30	1.27	0.24	1379	577.2	0.79	0.004	0.106	11	4.87	24	10.6	25.5	0.045	0.02	0.0038	0.00156	0.87	0.003	1	0.87	43.28	36.838	11.4	12675.4	0.0351	31.356	25.774	0.47952
3000	4E+06	2	0.004	530	30	1.27	0.248	1333	577.2	0.79	0.004	0.104	11	4.75	25	10.3	25.5	0.045	0.02	0.0038	0.00164	0.88	0.003	1	0.88	43.64	37.29	12.3	12129	0.0353	31.862	27.2431	0.49225

Appendix C Table 4: Pressure Drop Calculation for Oil of API 30 at Constant Pressure and Temperature

Qo, stb/d	Qg, scf/d	dia, in	ε/d	Temp, R	IFT	Bo, bbl/stb	Qo cu.ft/sec	Rp, scf/stb	Rs, scf/stb	Z-factor	Bg, cu.ft/scf	Qg, cu.ft/sec	Vsl, ft/s	Vsg, ft/s	Nlv	Ngv	Nd	Nl	μg, cP	CNL	Hl/ψ corr	HL/ψ	ψ corr.	ψ	HL	ρs, lb/cu.ft	ρn, lb/cu.ft	μs, cP	Nre	fm	ρf	Dp, lb/cu.ft	Total DP, Psi/ft
100	4E+06	2	0.004	530	30	1.324	0.009	40000	686.8	0.8	0	0.18	0.4	8.23	0.85	17.69	24.8	0.02	0.02	0.003	3E-05	0.2	0.0041	1	0.2	18.389	13.157	0.06	468999	0.027911	9.413	1.8186	0.14
200	4E+06	2	0.004	530	30	1.324	0.017	20000	686.8	0.8	0	0.18	0.8	8.08	1.7	17.38	24.8	0.02	0.02	0.003	7E-05	0.27	0.004	1	0.27	20.764	14.62	0.09	371452	0.027995	10.29	2.1126	0.159
300	4E+06	2	0.004	530	30	1.324	0.026	13333	686.8	0.8	0	0.17	1.2	7.94	2.54	17.08	24.8	0.02	0.02	0.003	1E-04	0.32	0.0039	1	0.32	22.46	16.003	0.11	321598	0.028056	11.4	2.4795	0.173
400	4E+06	2	0.004	530	30	1.324	0.034	10000	686.8	0.8	0	0.17	1.6	7.79	3.39	16.77	24.8	0.02	0.02	0.003	0.0001	0.37	0.0038	1	0.37	24.156	17.312	0.15	274972	0.028132	12.41	2.8559	0.188
500	4E+06	2	0.004	530	30	1.324	0.043	8000	686.8	0.8	0	0.17	2	7.65	4.24	16.46	24.8	0.02	0.02	0.003	0.0002	0.4	0.0038	1	0.4	25.173	18.554	0.17	258492	0.028165	13.67	3.3219	0.198
600	4E+06	2	0.004	530	30	1.324	0.052	6667	686.8	0.8	0	0.16	2.4	7.51	5.09	16.15	24.8	0.02	0.02	0.003	0.0002	0.43	0.0037	1	0.43	26.191	19.732	0.2	240979	0.028204	14.87	3.8069	0.208
700	4E+06	2	0.004	530	30	1.324	0.06	5714	686.8	0.8	0	0.16	2.8	7.36	5.94	15.84	24.8	0.02	0.02	0.003	0.0002	0.48	0.0036	1	0.48	27.887	20.851	0.26	200860	0.028318	15.59	4.2149	0.223
800	4E+06	2	0.004	530	30	1.324	0.069	5000	686.8	0.8	0	0.16	3.2	7.22	6.78	15.53	24.8	0.02	0.02	0.003	0.0003	0.5	0.0036	1	0.5	28.566	21.917	0.29	194796	0.028339	16.82	4.7775	0.232
900	4E+06	2	0.004	530	30	1.324	0.077	4444	686.8	0.8	0	0.15	3.5	7.08	7.63	15.22	24.8	0.02	0.02	0.003	0.0003	0.53	0.0035	1	0.53	29.583	22.933	0.34	178339	0.028403	17.78	5.3093	0.242
1000	4E+06	2	0.004	530	30	1.324	0.086	4000	686.8	0.8	0	0.15	3.9	6.93	8.48	14.91	24.8	0.02	0.02	0.003	0.0004	0.56	0.0034	1	0.56	30.601	23.901	0.4	162544	0.028476	18.67	5.8564	0.253
1100	4E+06	2	0.004	530	30	1.324	0.095	3636	686.8	0.8	0	0.15	4.3	6.79	9.33	14.6	24.8	0.02	0.02	0.003	0.0004	0.59	0.0033	1	0.59	31.618	24.826	0.46	147566	0.028557	19.49	6.4185	0.264
1200	4E+06	2	0.004	530	30	1.324	0.103	3333	686.8	0.8	0	0.15	4.7	6.64	10.2	14.29	24.8	0.02	0.02	0.003	0.0004	0.61	0.0033	1	0.65	33.654	25.711	0.64	114059	0.02881	19.64	6.822	0.281
1300	4E+06	2	0.004	530	30	1.324	0.112	3077	686.8	0.8	0	0.14	5.1	6.5	11	13.98	24.8	0.02	0.02	0.003	0.0005	0.63	0.0032	1	0.63	32.975	26.557	0.57	133730	0.028648	21.39	7.7151	0.283
1400	4E+06	2	0.004	530	30	1.324	0.12	2857	686.8	0.8	0	0.14	5.5	6.36	11.9	13.67	24.8	0.02	0.02	0.003	0.0005	0.66	0.0031	1	0.66	33.993	27.367	0.67	120276	0.028754	22.03	8.3248	0.294
1500	4E+06	2	0.004	530	30	1.324	0.129	2667	686.8	0.8	0	0.14	5.9	6.21	12.7	13.37	24.8	0.02	0.02	0.003	0.0006	0.68	0.0031	1	0.68	34.671	28.144	0.74	113717	0.028814	22.85	9.0187	0.303
1600	4E+06	2	0.004	530	30	1.324	0.138	2500	686.8	0.8	0	0.13	6.3	6.07	13.6	13.06	24.8	0.02	0.02	0.003	0.0006	0.71	0.003	1	0.71	35.689	28.89	0.87	101787	0.028941	23.39	9.6596	0.315
1700	4E+06	2	0.004	530	30	1.324	0.146	2353	686.8	0.8	0	0.13	6.7	5.93	14.4	12.75	24.8	0.02	0.02	0.003	0.0007	0.72	0.0029	1	0.72	36.028	29.606	0.92	100981	0.02895	24.33	10.463	0.323
1800	4E+06	2	0.004	530	30	1.324	0.155	2222	686.8	0.8	0	0.13	7.1	5.78	15.3	12.44	24.8	0.02	0.02	0.003	0.0007	0.74	0.0028	1	0.74	36.706	30.294	1.02	94879.5	0.029027	25	11.213	0.333
1900	4E+06	2	0.004	530	30	1.324	0.163	2105	686.8	0.8	0	0.12	7.5	5.64	16.1	12.13	24.8	0.02	0.02	0.003	0.0008	0.76	0.0028	1	0.76	37.385	30.956	1.13	88991.5	0.029111	25.63	11.982	0.343
2000	4E+06	2	0.004	530	30	1.324	0.172	2000	686.8	0.8	0	0.12	7.9	5.5	17	11.82	24.8	0.02	0.02	0.003	0.0008	0.77	0.0027	1	0.77	37.724	31.593	1.19	87824.5	0.029129	26.46	12.852	0.351
2100	4E+06	2	0.004	530	30	1.324	0.181	1905	686.8	0.8	0	0.12	8.3	5.35	17.8	11.51	24.8	0.02	0.02	0.003	0.0009	0.79	0.0026	1	0.79	38.402	32.207	1.33	82120.3	0.029222	27.01	13.66	0.362
2200	4E+06	2	0.004	530	30	1.324	0.189	1818	686.8	0.8	0	0.11	8.7	5.21	18.7	11.2	24.8	0.02	0.02	0.003	0.0009	0.8	0.0026	1	0.8	38.742	32.798	1.4	80811.9	0.029245	27.77	14.575	0.37
2300	4E+06	2	0.004	530	30	1.324	0.198	1739	686.8	0.8	0	0.11	9.1	5.06	19.5	10.89	24.8	0.02	0.02	0.003	0.001	0.81	0.0025	1	0.81	39.081	33.369	1.47	79422.7	0.02927	28.49	15.514	0.379
2400	4E+06	2	0.004	530	30	1.324	0.206	1667	686.8	0.8	0	0.11	9.5	4.92	20.3	10.58	24.8	0.02	0.02	0.003	0.001	0.82	0.0024	1	0.815	39.25	33.92	1.51	80036.9	0.029259	29.31	16.525	0.387
2500	4E+06	2	0.004	530	30	1.324	0.215	1600	686.8	0.8	0	0.1	9.9	4.78	21.2	10.27	24.8	0.02	0.02	0.003	0.0011	0.82	0.0024	1	0.82	39.42	34.451	1.55	80566	0.02925	30.11	17.565	0.396
2600	4E+06	2	0.004	530	30	1.324	0.224	1538	686.8	0.8	0	0.1	10	4.63	22	9.966	24.8	0.02	0.02	0.003	0.0012	0.83	0.0023	1	0.825	39.59	34.965	1.59	81014.1	0.029242	30.88	18.632	0.404
2700	4E+06	2	0.004	530	30	1.324	0.232	1481	686.8	0.8	0	0.1	11	4.49	22.9	9.657	24.8	0.02	0.02	0.003	0.0012	0.83	0.0022	1	0.83	39.759	35.462	1.64	81384.9	0.029235	31.63	19.727	0.413
2800	4E+06	2	0.004	530	30	1.324	0.241	1429	686.8	0.8	0	0.09	11	4.35	23.7	9.347	24.8	0.02	0.02	0.003	0.0013	0.84	0.0021	1	0.84	40.098	35.943	1.72	79567.1	0.029268	32.22	20.788	0.423
2900	4E+06	2	0.004	530	30	1.324	0.249	1379	686.8	0.8	0	0.09	11	4.2	24.6	9.038	24.8	0.02	0.02	0.003	0.0014	0.85	0.0021	1	0.85	40.438	36.408	1.82	77722.5	0.029303	32.78	21.871	0.433
3000	4E+06	2	0.004	530	30	1.324	0.258	1333	686.8	0.8	0	0.09	12	4.06	25.4	8.729	24.8	0.02	0.02	0.003	0.0015	0.86	0.002	1	0.86	40.777	36.859	1.91	75858.5	0.029339	33.32	22.976	0.443

Appendix C Table 5: Pressure Drop Calculation for Oil of API 35 at Constant Pressure and Temperature

Qo, stb/d	Qg, scf/d	dia, in	ε/d	Temp, R	IFT	Bo, bbl/stb	Qo cu.ft/s	Rp, scf/stb	Rs, scf/stb	Z-factor	Bg, cu.ft/scf	Qg, cu.ft/ sec	Vsl, ft/s	Vsg, ft/s	Nlv	Ngv	Nd	Nl	μg, cP	CNL	Hl/ψ corr	HL/ψ	ψ corr.	ψ	HL	ρs, lb/cu.ft	ρn, lb/cu.ft	μs, cP	Nre	fm	ρf	Dp, lb/cu.ft	Total DP, psi/ft
100	4E+06	2	0.004	530	30	1.388	0.009	40000	817	0.79	0.004	0.18	0.4	8.2	0.9	17.4	24.1	0.01	0.02	0.0023	2.8E-05	0.19	0.0033	1	0.19	17.572	13.11	0.05	561257	0.02786	9.7846	1.8832	0.135
200	4E+06	2	0.004	530	30	1.388	0.018	20000	817	0.79	0.004	0.18	0.8	8	1.8	17	24.1	0.01	0.02	0.0023	5.6E-05	0.25	0.0032	1	0.25	19.457	14.54	0.066	486741	0.0279	10.861	2.2131	0.15
300	4E+06	2	0.004	530	30	1.388	0.027	13333	817	0.79	0.004	0.17	1.2	7.9	2.6	16.7	24.1	0.01	0.02	0.0023	8.5E-05	0.3	0.0031	1	0.3	21.027	15.89	0.082	435143	0.02794	12.002	2.5846	0.164
400	4E+06	2	0.004	530	30	1.388	0.036	10000	817	0.79	0.004	0.17	1.7	7.7	3.5	16.3	24.1	0.01	0.02	0.0023	0.00011	0.33	0.0031	1	0.33	21.969	17.16	0.094	421034	0.02795	13.411	3.0452	0.174
500	4E+06	2	0.004	530	30	1.388	0.045	8000	817	0.79	0.004	0.16	2.1	7.5	4.4	15.9	24.1	0.01	0.02	0.0023	0.00014	0.38	0.003	1	0.38	23.539	18.38	0.119	368298	0.028	14.349	3.4358	0.187
600	4E+06	2	0.004	530	30	1.388	0.054	6667	817	0.79	0.004	0.16	2.5	7.3	5.3	15.6	24.1	0.01	0.02	0.0023	0.00018	0.41	0.0029	1	0.41	24.481	19.53	0.136	350061	0.02802	15.584	3.9256	0.197
700	4E+06	2	0.004	530	30	1.388	0.063	5714	817	0.79	0.004	0.16	2.9	7.2	6.1	15.2	24.1	0.01	0.02	0.0023	0.00021	0.45	0.0029	1	0.45	25.737	20.63	0.163	315756	0.02806	16.538	4.3809	0.209
800	4E+06	2	0.004	530	30	1.388	0.072	5000	817	0.79	0.004	0.15	3.3	7	7	14.8	24.1	0.01	0.02	0.0023	0.00024	0.47	0.0028	1	0.47	26.366	21.68	0.179	310178	0.02807	17.824	4.9531	0.217
900	4E+06	2	0.004	530	30	1.388	0.081	4444	817	0.79	0.004	0.15	3.7	6.8	7.9	14.5	24.1	0.01	0.02	0.0023	0.00028	0.5	0.0027	1	0.5	27.308	22.68	0.205	289675	0.02811	18.832	5.4883	0.228
1000	4E+06	2	0.004	530	30	1.388	0.09	4000	817	0.79	0.004	0.15	4.1	6.7	8.8	14.1	24.1	0.01	0.02	0.0023	0.00031	0.53	0.0027	1	0.53	28.25	23.63	0.235	269349	0.02814	19.768	6.0367	0.238
1100	4E+06	2	0.004	530	30	1.388	0.099	3636	817	0.79	0.004	0.14	4.5	6.5	9.6	13.8	24.1	0.01	0.02	0.0023	0.00035	0.55	0.0026	1	0.55	28.878	24.54	0.257	261118	0.02816	20.859	6.6632	0.247
1200	4E+06	2	0.004	530	30	1.388	0.108	3333	817	0.79	0.004	0.14	5	6.3	11	13.4	24.1	0.01	0.02	0.0023	0.00038	0.58	0.0025	1	0.65	32.018	25.42	0.406	175228	0.02842	20.176	6.7924	0.27
1300	4E+06	2	0.004	530	30	1.388	0.117	3077	817	0.79	0.004	0.13	5.4	6.1	11	13	24.1	0.01	0.02	0.0023	0.00042	0.6	0.0025	1	0.6	30.448	26.25	0.323	232175	0.02823	22.635	7.8981	0.266
1400	4E+06	2	0.004	530	30	1.388	0.126	2857	817	0.79	0.004	0.13	5.8	6	12	12.7	24.1	0.01	0.02	0.0023	0.00046	0.62	0.0024	1	0.62	31.076	27.05	0.354	223024	0.02825	23.553	8.5751	0.275
1500	4E+06	2	0.004	530	30	1.388	0.135	2667	817	0.79	0.004	0.13	6.2	5.8	13	12.3	24.1	0.01	0.02	0.0023	0.0005	0.65	0.0023	1	0.65	32.018	27.82	0.406	204189	0.02831	24.179	9.1878	0.286
1600	4E+06	2	0.004	530	30	1.388	0.144	2500	817	0.79	0.004	0.12	6.6	5.6	14	11.9	24.1	0.01	0.02	0.0023	0.00055	0.67	0.0022	1	0.67	32.646	28.56	0.444	195221	0.02834	24.99	9.8939	0.295
1700	4E+06	2	0.004	530	30	1.388	0.153	2353	817	0.79	0.004	0.12	7	5.5	15	11.6	24.1	0.01	0.02	0.0023	0.00059	0.7	0.0022	1	0.7	33.589	29.27	0.509	177971	0.0284	25.512	10.529	0.306
1800	4E+06	2	0.004	530	30	1.388	0.162	2222	817	0.79	0.004	0.12	7.4	5.3	16	11.2	24.1	0.01	0.02	0.0023	0.00064	0.72	0.0021	1	0.72	34.217	29.96	0.558	169491	0.02844	26.226	11.263	0.316
1900	4E+06	2	0.004	530	30	1.388	0.171	2105	817	0.79	0.004	0.11	7.9	5.1	17	10.9	24.1	0.01	0.02	0.0023	0.00069	0.74	0.002	1	0.74	34.845	30.61	0.611	161138	0.02848	26.897	12.012	0.325
2000	4E+06	2	0.004	530	30	1.388	0.18	2000	817	0.79	0.004	0.11	8.3	4.9	18	10.5	24.1	0.01	0.02	0.0023	0.00074	0.75	0.002	1	0.75	35.159	31.25	0.64	160083	0.02849	27.771	12.872	0.334
2100	4E+06	2	0.004	530	30	1.388	0.189	1905	817	0.79	0.004	0.1	8.7	4.8	18	10.1	24.1	0.01	0.02	0.0023	0.00079	0.77	0.0019	1	0.77	35.787	31.86	0.701	151731	0.02853	28.361	13.653	0.343
2200	4E+06	2	0.004	530	30	1.388	0.198	1818	817	0.79	0.004	0.1	9.1	4.6	19	9.77	24.1	0.01	0.02	0.0023	0.00084	0.79	0.0018	1	0.79	36.415	32.45	0.768	143619	0.02858	28.912	14.449	0.353
2300	4E+06	2	0.004	530	30	1.388	0.207	1739	817	0.79	0.004	0.1	9.5	4.4	20	9.41	24.1	0.01	0.02	0.0023	0.0009	0.8	0.0018	1	0.8	36.729	33.02	0.803	142098	0.02859	29.679	15.366	0.362
2400	4E+06	2	0.004	530	30	1.388	0.216	1667	817	0.79	0.004	0.09	9.9	4.3	21	9.05	24.1	0.01	0.02	0.0023	0.00096	0.81	0.0017	1	0.81	36.886	33.57	0.822	143663	0.02858	30.544	16.363	0.37
2500	4E+06	2	0.004	530	30	1.388	0.225	1600	817	0.79	0.004	0.09	10	4.1	22	8.68	24.1	0.01	0.02	0.0023	0.00103	0.81	0.0016	1	0.81	37.043	34.1	0.841	145085	0.02857	31.384	17.387	0.378
2600	4E+06	2	0.004	530	30	1.388	0.235	1538	817	0.79	0.004	0.09	11	3.9	23	8.32	24.1	0.01	0.02	0.0023	0.00109	0.82	0.0016	1	0.82	37.357	34.61	0.88	143074	0.02858	32.064	18.374	0.387
2700	4E+06	2	0.004	530	30	1.388	0.244	1481	817	0.79	0.004	0.08	11	3.8	24	7.96	24.1	0.01	0.02	0.0023	0.00117	0.83	0.0015	1	0.83	37.671	35.11	0.921	140954	0.0286	32.716	19.381	0.396
2800	4E+06	2	0.004	530	30	1.388	0.253	1429	817	0.79	0.004	0.08	12	3.6	25	7.6	24.1	0.01	0.02	0.0023	0.00124	0.84	0.0014	1	0.84	37.828	35.59	0.942	141936	0.02859	33.479	20.478	0.405
2900	4E+06	2	0.004	530	30	1.388	0.262	1379	817	0.79	0.004	0.07	12	3.4	25	7.23	24.1	0.01	0.02	0.0023	0.00132	0.84	0.0014	1	0.84	37.985	36.05	0.964	142802	0.02859	34.218	21.601	0.414
3000	4E+06	2	0.004	530	30	1.388	0.271	1333	817	0.79	0.004	0.07	12	3.2	26	6.87	24.1	0.01	0.02	0.0023	0.00141	0.86	0.0013	1	0.86	38.613	36.5	1.056	134075	0.02865	34.51	22.522	0.425

Appendix C Table 6: Pressure Drop for West Sak Oil A for Gas Flow Rate of 4MMscf/d

Qo, stb/d	Qg, MM scf/d	diameter, in	IFT, dynes/cm	Qo cu.ft/sec	Qg, cu.ft/sec	Vsl ft/s	Vsg ft/s	Nlv	Ngv	Nd	Nl	CNL	HL/ψ	ψ	HL	ρs lb/cu.ft	ρn ft/cu.ft	μs, cp	Nre	fm	ρf lb/cu.ft	Dp friction lb/cu.ft	Total DP psi/ft
100.00	4.00	2.00	30.00	0.01	0.34	0.32	15.63	0.72	35.47	27.62	0.16	0.01	0.23	1.02	0.23	17.57	6.68	0.09	283678.48	0.03	2.54	1.69	0.13
200.00	4.00	2.00	30.00	0.01	0.34	0.64	15.55	1.44	35.28	27.62	0.16	0.01	0.31	1.02	0.32	21.71	7.67	0.18	175293.58	0.03	2.71	1.88	0.16
300.00	4.00	2.00	30.00	0.02	0.34	0.95	15.46	2.17	35.09	27.62	0.16	0.01	0.38	1.02	0.39	25.33	8.62	0.31	114913.87	0.03	2.93	2.12	0.19
400.00	4.00	2.00	30.00	0.03	0.34	1.27	15.38	2.89	34.91	27.62	0.16	0.01	0.42	1.02	0.43	27.40	9.55	0.42	94067.14	0.03	3.33	2.50	0.21
500.00	4.00	2.00	30.00	0.03	0.33	1.59	15.30	3.61	34.72	27.62	0.16	0.01	0.46	1.02	0.47	29.47	10.45	0.58	76071.55	0.03	3.70	2.89	0.22
600.00	4.00	2.00	30.00	0.04	0.33	1.91	15.22	4.33	34.53	27.62	0.16	0.01	0.50	1.02	0.51	31.54	11.33	0.79	60915.08	0.03	4.07	3.30	0.24
700.00	4.00	2.00	30.00	0.05	0.33	2.23	15.13	5.06	34.34	27.62	0.16	0.01	0.55	1.02	0.56	34.13	12.18	1.17	44699.94	0.03	4.35	3.70	0.26
800.00	4.00	2.00	30.00	0.06	0.33	2.55	15.05	5.78	34.16	27.62	0.16	0.01	0.58	1.02	0.59	35.68	13.01	1.49	38165.23	0.03	4.74	4.21	0.28
900.00	4.00	2.00	30.00	0.06	0.33	2.86	14.97	6.50	33.97	27.62	0.16	0.01	0.60	1.02	0.61	36.72	13.82	1.74	35064.52	0.03	5.20	4.77	0.29
1000.00	4.00	2.00	30.00	0.07	0.32	3.18	14.89	7.22	33.78	27.62	0.16	0.01	0.63	1.02	0.64	38.27	14.60	2.21	29614.06	0.03	5.57	5.33	0.30
1100.00	4.00	2.00	30.00	0.08	0.32	3.50	14.80	7.94	33.60	27.62	0.16	0.01	0.65	1.02	0.66	39.30	15.37	2.59	26952.36	0.03	6.01	5.96	0.31
1200.00	4.00	2.00	30.00	0.08	0.32	3.82	14.72	8.67	33.41	27.62	0.16	0.01	0.68	1.02	0.69	40.86	16.12	3.28	22575.50	0.03	6.36	6.60	0.33
1300.00	4.00	2.00	30.00	0.09	0.32	4.14	14.64	9.39	33.22	27.62	0.16	0.01	0.71	1.02	0.72	42.41	16.85	4.16	18844.71	0.03	6.69	7.28	0.35
1400.00	4.00	2.00	30.00	0.10	0.32	4.46	14.56	10.11	33.03	27.62	0.16	0.01	0.73	1.02	0.74	43.44	17.56	4.88	16974.30	0.03	7.10	8.03	0.36
1500.00	4.00	2.00	30.00	0.10	0.32	4.77	14.47	10.83	32.85	27.62	0.16	0.01	0.75	1.02	0.77	44.48	18.25	5.71	15247.61	0.03	7.49	8.82	0.37
1600.00	4.00	2.00	30.00	0.11	0.31	5.09	14.39	11.56	32.66	27.62	0.16	0.01	0.76	1.02	0.78	45.00	18.93	6.18	14788.15	0.03	7.96	9.65	0.38
1700.00	4.00	2.00	30.00	0.12	0.31	5.41	14.31	12.28	32.47	27.62	0.16	0.01	0.77	1.02	0.78	45.25	19.59	6.43	14888.06	0.03	8.48	10.51	0.39
1800.00	4.00	2.00	30.00	0.13	0.31	5.73	14.23	13.00	32.29	27.62	0.16	0.01	0.79	1.02	0.81	46.55	20.23	7.84	12767.75	0.04	8.79	11.43	0.40
1900.00	4.00	2.00	30.00	0.13	0.31	6.05	14.14	13.72	32.10	27.62	0.16	0.01	0.80	1.02	0.82	47.07	20.86	8.49	12306.77	0.04	9.25	12.38	0.41
2000.00	4.00	2.00	30.00	0.14	0.31	6.37	14.06	14.44	31.91	27.62	0.16	0.01	0.82	1.01	0.83	47.68	21.48	9.33	11659.61	0.04	9.67	13.37	0.42
2100.00	4.00	2.00	30.00	0.15	0.31	6.68	13.98	15.17	31.72	27.62	0.16	0.01	0.83	1.01	0.83	47.94	22.08	9.70	11658.23	0.04	10.17	14.38	0.43
2200.00	4.00	2.00	30.00	0.15	0.30	7.00	13.90	15.89	31.54	27.62	0.16	0.01	0.83	1.01	0.84	48.20	22.67	10.09	11639.73	0.04	10.66	15.43	0.44
2300.00	4.00	2.00	30.00	0.16	0.30	7.32	13.81	16.61	31.35	27.62	0.16	0.01	0.84	1.01	0.84	48.45	23.24	10.50	11605.44	0.04	11.15	16.51	0.45
2400.00	4.00	2.00	30.00	0.17	0.30	7.64	13.73	17.33	31.16	27.62	0.16	0.01	0.84	1.01	0.85	48.71	23.80	10.92	11556.59	0.04	11.63	17.62	0.46
2500.00	4.00	2.00	30.00	0.17	0.30	7.96	13.65	18.06	30.98	27.62	0.16	0.01	0.85	1.01	0.85	48.97	24.35	11.35	11494.35	0.04	12.11	18.77	0.47
2600.00	4.00	2.00	30.00	0.18	0.30	8.27	13.57	18.78	30.79	27.62	0.16	0.01	0.85	1.01	0.86	49.22	24.89	11.81	11419.82	0.04	12.58	19.96	0.48
2700.00	4.00	2.00	30.00	0.19	0.29	8.59	13.48	19.50	30.60	27.62	0.16	0.01	0.86	1.01	0.87	49.73	25.41	12.77	10898.43	0.04	12.99	21.21	0.49
2800.00	4.00	2.00	30.00	0.19	0.29	8.91	13.40	20.22	30.41	27.62	0.16	0.01	0.87	1.01	0.87	49.99	25.93	13.28	10806.07	0.04	13.45	22.47	0.50
2900.00	4.00	2.00	30.00	0.20	0.29	9.23	13.32	20.94	30.23	27.62	0.16	0.01	0.87	1.01	0.88	50.25	26.43	13.81	10704.71	0.04	13.91	23.77	0.51
3000.00	4.00	2.00	30.00	0.21	0.29	9.55	13.24	21.67	30.04	27.62	0.16	0.01	0.86	1.01	0.87	49.73	26.93	12.77	11917.11	0.04	14.58	24.99	0.52

Appendix C Table 7: Pressure Drop for West Sak Oil A for Gas Flow Rate of 2MMscf/d

Qo, stb/d	Qg, MM scf/d	diameter, in	IFT, dynes/cm	Qo cu.ft/sec	Qg, cu.ft/sec	Vsl ft/s	Vsg ft/s	Nlv	Ngv	Nd	Nl	CNL	HL/ψ	ψ	HL	ρs lb/cu.ft	ρn ft/cu.ft	μs, cp	Nre	fm	ρf lb/cu.ft	Dp friction lb/cu.ft	Total DP psi/ft
100.00	2.00	2.00	30.00	0.01	0.17	0.32	7.77	0.72	17.64	27.62	0.16	0.01	0.28	1.00	0.28	19.87	7.67	0.13	116077.11	0.03	2.96	0.52	0.14
200.00	2.00	2.00	30.00	0.01	0.17	0.64	7.69	1.44	17.45	27.62	0.16	0.01	0.38	1.00	0.38	24.95	9.55	0.29	68475.95	0.03	3.65	0.70	0.18
300.00	2.00	2.00	30.00	0.02	0.17	0.95	7.61	2.17	17.27	27.62	0.16	0.01	0.45	1.00	0.45	28.50	11.33	0.50	48520.17	0.03	4.50	0.93	0.20
400.00	2.00	2.00	30.00	0.03	0.16	1.27	7.53	2.89	17.08	27.62	0.16	0.01	0.51	1.00	0.51	31.54	13.01	0.79	35947.38	0.03	5.37	1.20	0.23
500.00	2.00	2.00	30.00	0.03	0.16	1.59	7.44	3.61	16.89	27.62	0.16	0.01	0.55	1.00	0.55	33.57	14.60	1.08	30378.92	0.03	6.35	1.52	0.24
600.00	2.00	2.00	30.00	0.04	0.16	1.91	7.36	4.33	16.70	27.62	0.16	0.01	0.60	1.00	0.60	36.11	16.12	1.59	23339.00	0.03	7.20	1.86	0.26
700.00	2.00	2.00	30.00	0.05	0.16	2.23	7.28	5.06	16.52	27.62	0.16	0.01	0.65	1.00	0.65	38.64	17.56	2.34	17685.09	0.03	7.98	2.24	0.28
800.00	2.00	2.00	30.00	0.06	0.16	2.55	7.20	5.78	16.33	27.62	0.16	0.01	0.68	1.00	0.68	40.17	18.93	2.95	15479.30	0.03	8.92	2.68	0.30
900.00	2.00	2.00	30.00	0.06	0.16	2.86	7.11	6.50	16.14	27.62	0.16	0.01	0.72	1.00	0.72	42.20	20.23	4.03	12424.24	0.04	9.70	3.17	0.32
1000.00	2.00	2.00	30.00	0.07	0.15	3.18	7.03	7.22	15.96	27.62	0.16	0.01	0.74	1.00	0.74	43.21	21.48	4.71	11559.22	0.04	10.68	3.69	0.33
1100.00	2.00	2.00	30.00	0.08	0.15	3.50	6.95	7.94	15.77	27.62	0.16	0.01	0.77	1.00	0.77	44.73	22.67	5.94	9888.16	0.04	11.48	4.27	0.34
1200.00	2.00	2.00	30.00	0.08	0.15	3.82	6.87	8.67	15.58	27.62	0.16	0.01	0.80	1.00	0.80	46.25	23.80	7.50	8412.59	0.04	12.25	4.91	0.36
1300.00	2.00	2.00	30.00	0.09	0.15	4.14	6.78	9.39	15.39	27.62	0.16	0.01	0.82	1.00	0.82	47.27	24.89	8.76	7698.25	0.04	13.10	5.59	0.37
1400.00	2.00	2.00	30.00	0.10	0.15	4.46	6.70	10.11	15.21	27.62	0.16	0.01	0.83	1.00	0.83	47.52	25.93	9.10	7881.53	0.04	14.15	6.27	0.37
1500.00	2.00	2.00	30.00	0.10	0.14	4.77	6.62	10.83	15.02	27.62	0.16	0.01	0.83	1.00	0.83	47.78	26.93	9.46	8039.71	0.04	15.18	6.98	0.38
1600.00	2.00	2.00	30.00	0.11	0.14	5.09	6.54	11.56	14.83	27.62	0.16	0.01	0.84	1.00	0.84	48.28	27.88	10.23	7863.31	0.04	16.10	7.75	0.39
1700.00	2.00	2.00	30.00	0.12	0.14	5.41	6.45	12.28	14.65	27.62	0.16	0.01	0.85	1.00	0.85	48.79	28.80	11.05	7668.42	0.04	17.01	8.56	0.40
1800.00	2.00	2.00	30.00	0.13	0.14	5.73	6.37	13.00	14.46	27.62	0.16	0.01	0.86	1.00	0.86	49.30	29.69	11.94	7458.80	0.04	17.88	9.42	0.41
1900.00	2.00	2.00	30.00	0.13	0.14	6.05	6.29	13.72	14.27	27.62	0.16	0.01	0.87	1.00	0.87	49.81	30.54	12.91	7237.72	0.04	18.72	10.31	0.42
2000.00	2.00	2.00	30.00	0.14	0.14	6.37	6.21	14.44	14.08	27.62	0.16	0.01	0.88	1.00	0.88	50.31	31.36	13.95	7008.06	0.04	19.54	11.25	0.43
2100.00	2.00	2.00	30.00	0.15	0.13	6.68	6.12	15.17	13.90	27.62	0.16	0.01	0.89	1.00	0.89	50.82	32.14	15.07	6772.35	0.04	20.33	12.24	0.44
2200.00	2.00	2.00	30.00	0.15	0.13	7.00	6.04	15.89	13.71	27.62	0.16	0.01	0.90	1.00	0.90	51.33	32.90	16.29	6532.76	0.04	21.09	13.27	0.45
2300.00	2.00	2.00	30.00	0.16	0.13	7.32	5.96	16.61	13.52	27.62	0.16	0.01	0.91	1.00	0.91	51.58	33.63	16.94	6540.12	0.04	21.93	14.30	0.46
2400.00	2.00	2.00	30.00	0.17	0.13	7.64	5.88	17.33	13.34	27.62	0.16	0.01	0.91	1.00	0.91	51.83	34.34	17.61	6537.45	0.04	22.75	15.37	0.47
2500.00	2.00	2.00	30.00	0.17	0.13	7.96	5.79	18.06	13.15	27.62	0.16	0.01	0.92	1.00	0.92	52.34	35.02	19.03	6277.14	0.04	23.44	16.53	0.48
2600.00	2.00	2.00	30.00	0.18	0.12	8.27	5.71	18.78	12.96	27.62	0.16	0.01	0.93	1.00	0.93	52.60	35.68	19.78	6257.42	0.04	24.21	17.68	0.49
2700.00	2.00	2.00	30.00	0.19	0.12	8.59	5.63	19.50	12.77	27.62	0.16	0.01	0.93	1.00	0.93	52.85	36.32	20.56	6230.10	0.04	24.96	18.86	0.50
2800.00	2.00	2.00	30.00	0.19	0.12	8.91	5.55	20.22	12.59	27.62	0.16	0.01	0.94	1.00	0.94	53.10	36.94	21.38	6195.80	0.04	25.69	20.09	0.51
2900.00	2.00	2.00	30.00	0.20	0.12	9.23	5.46	20.94	12.40	27.62	0.16	0.01	0.94	1.00	0.94	53.36	37.54	22.22	6155.09	0.04	26.41	21.36	0.52
3000.00	2.00	2.00	30.00	0.21	0.12	9.55	5.38	21.67	12.21	27.62	0.16	0.01	0.93	1.00	0.93	52.85	38.11	20.56	6862.65	0.04	27.49	22.42	0.52

Appendix C Table 8: Pressure Drop for West Sak Oil B for Gas Flow Rate of 4MMscf/d

Qo, stb/d	Qg, MMscf/d	diameter, in	IFT	Qo cu.ft/sec	Qg, cu.ft/sec	Vsl ft/s	Vsg ft/s	Nlv	Ngv	Nd	Nl	CNL	HL/ψ	ψ	HL	ρs lb/cu.ft	ρn lb/cu.ft	μs, cp	Nre	fm	ρf	Dp friction lb/cu.ft	Total DP, psi
100.00	4.00	2.00	30.00	0.01	0.44	0.31	20.36	0.72	46.70	28.22	1.13	0.01	0.15	1.58	0.24	17.27	5.18	0.20	133735.13	0.03	1.55	1.77	0.13
200.00	4.00	2.00	30.00	0.01	0.44	0.63	20.28	1.44	46.51	28.22	1.13	0.01	0.32	1.58	0.51	31.91	5.99	2.47	12561.06	0.04	1.12	1.61	0.23
300.00	4.00	2.00	30.00	0.02	0.44	0.94	20.19	2.16	46.31	28.22	1.13	0.01	0.38	1.58	0.60	37.08	6.78	6.01	5904.41	0.04	1.24	2.09	0.27
400.00	4.00	2.00	30.00	0.03	0.44	1.25	20.11	2.88	46.11	28.22	1.13	0.01	0.43	1.58	0.68	41.38	7.55	12.63	3167.81	0.05	1.38	2.70	0.31
500.00	4.00	2.00	30.00	0.03	0.44	1.57	20.02	3.60	45.92	28.22	1.13	0.01	0.48	1.58	0.76	45.69	8.31	26.50	1678.21	0.04	1.51	2.50	0.33
600.00	4.00	2.00	30.00	0.04	0.44	1.88	19.93	4.31	45.72	28.22	1.13	0.01	0.52	1.58	0.82	49.14	9.05	47.97	1020.73	0.06	1.67	4.63	0.37
700.00	4.00	2.00	30.00	0.05	0.43	2.19	19.85	5.03	45.53	28.22	1.13	0.01	0.55	1.58	0.87	51.72	9.78	74.85	714.05	0.09	1.85	7.50	0.41
800.00	4.00	2.00	30.00	0.05	0.43	2.51	19.76	5.75	45.33	28.22	1.13	0.01	0.59	1.58	0.93	55.16	10.49	135.47	427.63	0.15	1.99	13.79	0.48
900.00	4.00	2.00	30.00	0.06	0.43	2.82	19.68	6.47	45.14	28.22	1.13	0.01	0.63	1.58	1.00	58.61	11.19	245.18	254.56	0.25	2.13	25.31	0.58
1000.00	4.00	2.00	30.00	0.07	0.43	3.13	19.59	7.19	44.94	28.22	1.13	0.01	0.65	1.58	1.00	58.86	11.87	256.00	261.32	0.24	2.39	28.21	0.60
1100.00	4.00	2.00	30.00	0.08	0.43	3.45	19.51	7.91	44.74	28.22	1.13	0.01	0.71	1.58	1.00	58.86	12.54	256.00	278.84	0.23	2.67	30.10	0.62
1200.00	4.00	2.00	30.00	0.08	0.42	3.76	19.42	8.63	44.55	28.22	1.13	0.01	0.74	1.58	1.00	58.86	13.19	256.00	296.35	0.22	2.96	31.99	0.63
1300.00	4.00	2.00	30.00	0.09	0.42	4.08	19.34	9.35	44.35	28.22	1.13	0.01	0.75	1.58	1.00	58.86	13.84	256.00	313.87	0.20	3.25	33.88	0.64
1400.00	4.00	2.00	30.00	0.10	0.42	4.39	19.25	10.07	44.16	28.22	1.13	0.01	0.76	1.58	1.00	58.86	14.47	256.00	331.38	0.19	3.56	35.77	0.66
1500.00	4.00	2.00	30.00	0.10	0.42	4.70	19.17	10.79	43.96	28.22	1.13	0.01	0.78	1.58	1.00	58.86	15.09	256.00	348.90	0.18	3.87	37.66	0.67
1600.00	4.00	2.00	30.00	0.11	0.42	5.02	19.08	11.50	43.77	28.22	1.13	0.01	0.80	1.58	1.00	58.86	15.70	256.00	366.42	0.17	4.19	39.55	0.68
1700.00	4.00	2.00	30.00	0.12	0.41	5.33	19.00	12.22	43.57	28.22	1.13	0.01	0.81	1.58	1.00	58.86	16.29	256.00	383.93	0.17	4.51	41.44	0.70
1800.00	4.00	2.00	30.00	0.12	0.41	5.64	18.91	12.94	43.37	28.22	1.13	0.01	0.82	1.58	1.00	58.86	16.88	256.00	401.45	0.16	4.84	43.33	0.71
1900.00	4.00	2.00	30.00	0.13	0.41	5.96	18.82	13.66	43.18	28.22	1.13	0.01	0.83	1.58	1.00	58.86	17.45	256.00	418.96	0.15	5.17	45.22	0.72
2000.00	4.00	2.00	30.00	0.14	0.41	6.27	18.74	14.38	42.98	28.22	1.13	0.01	0.83	1.58	1.00	58.86	18.02	256.00	436.48	0.15	5.51	47.12	0.74
2100.00	4.00	2.00	30.00	0.14	0.41	6.58	18.65	15.10	42.79	28.22	1.13	0.01	0.84	1.58	1.00	58.86	18.57	256.00	453.99	0.14	5.86	49.01	0.75
2200.00	4.00	2.00	30.00	0.15	0.41	6.90	18.57	15.82	42.59	28.22	1.13	0.01	0.84	1.58	1.00	58.86	19.11	256.00	471.51	0.14	6.21	50.90	0.76
2300.00	4.00	2.00	30.00	0.16	0.40	7.21	18.48	16.54	42.39	28.22	1.13	0.01	0.85	1.58	1.00	58.86	19.65	256.00	489.03	0.13	6.56	52.79	0.78
2400.00	4.00	2.00	30.00	0.16	0.40	7.52	18.40	17.26	42.20	28.22	1.13	0.01	0.86	1.58	1.00	58.86	20.17	256.00	506.54	0.13	6.91	54.68	0.79
2500.00	4.00	2.00	30.00	0.17	0.40	7.84	18.31	17.98	42.00	28.22	1.13	0.01	0.87	1.58	1.00	58.86	20.69	256.00	524.06	0.12	7.27	56.57	0.80
2600.00	4.00	2.00	30.00	0.18	0.40	8.15	18.23	18.70	41.81	28.22	1.13	0.01	0.87	1.58	1.00	58.86	21.19	256.00	541.57	0.12	7.63	58.46	0.81
2700.00	4.00	2.00	30.00	0.18	0.40	8.46	18.14	19.41	41.61	28.22	1.13	0.01	0.88	1.58	1.00	58.86	21.69	256.00	559.09	0.11	7.99	60.35	0.83
2800.00	4.00	2.00	30.00	0.19	0.39	8.78	18.06	20.13	41.42	28.22	1.13	0.01	0.89	1.58	1.00	58.86	22.18	256.00	576.60	0.11	8.36	62.24	0.84
2900.00	4.00	2.00	30.00	0.20	0.39	9.09	17.97	20.85	41.22	28.22	1.13	0.01	0.90	1.58	1.00	58.86	22.66	256.00	594.12	0.11	8.73	64.13	0.85
3000.00	4.00	2.00	30.00	0.21	0.39	9.40	17.89	21.57	41.02	28.22	1.13	0.01	0.91	1.58	1.00	58.86	23.13	256.00	611.64	0.10	9.09	66.02	0.87

Appendix C Table 9: Pressure Drop for West Sak Oil B for Gas Flow Rate of 2MMscf/d

Qo, stb/d	Qg, MMscf/d	diameter, in	IFT	Qo cu.ft/sec	Qg, cu.ft/sec	Vsl ft/s	Vsg ft/s	Nlv	Ngv	Nd	Nl	CNL	HL/ψ	ψ	HL	ρs lb/cu.ft	ρn lb/cu.ft	μs, cp	Nre	fm	ρf	Dp friction lb/cu.ft	Total DP, psi
100.00	2.00	2.00	30.00	0.01	0.22	0.31	10.14	0.72	23.25	28.22	1.13	0.01	0.28	1.10	0.31	21.14	5.99	0.39	40138.34	0.03	1.69	0.53	0.15
200.00	2.00	2.00	30.00	0.01	0.22	0.63	10.05	1.44	23.06	28.22	1.13	0.01	0.39	1.10	0.43	27.73	7.55	1.20	16616.64	0.03	2.06	0.74	0.20
300.00	2.00	2.00	30.00	0.02	0.22	0.94	9.97	2.16	22.86	28.22	1.13	0.01	0.48	1.10	0.53	33.13	9.05	3.05	8031.76	0.04	2.47	1.04	0.24
400.00	2.00	2.00	30.00	0.03	0.22	1.25	9.88	2.88	22.67	28.22	1.13	0.01	0.52	1.10	0.57	35.53	10.49	4.61	6287.51	0.04	3.10	1.43	0.26
500.00	2.00	2.00	30.00	0.03	0.21	1.57	9.80	3.60	22.47	28.22	1.13	0.01	0.58	1.10	0.64	39.13	11.87	8.56	3907.72	0.04	3.60	1.94	0.29
600.00	2.00	2.00	30.00	0.04	0.21	1.88	9.71	4.31	22.27	28.22	1.13	0.01	0.62	1.08	0.67	40.85	13.19	11.52	3294.07	0.05	4.26	2.47	0.30
700.00	2.00	2.00	30.00	0.05	0.21	2.19	9.63	5.03	22.08	28.22	1.13	0.01	0.67	1.08	0.72	43.79	14.47	19.12	2218.77	0.03	4.78	1.87	0.32
800.00	2.00	2.00	30.00	0.05	0.21	2.51	9.54	5.75	21.88	28.22	1.13	0.01	0.70	1.08	0.76	45.56	15.70	25.91	1809.96	0.04	5.41	2.59	0.33
900.00	2.00	2.00	30.00	0.06	0.21	2.82	9.46	6.47	21.69	28.22	1.13	0.01	0.75	1.08	0.81	48.50	16.88	43.02	1194.48	0.05	5.87	4.42	0.37
1000.00	2.00	2.00	30.00	0.07	0.20	3.13	9.37	7.19	21.49	28.22	1.13	0.01	0.78	1.08	0.84	50.27	18.02	58.31	958.13	0.07	6.46	6.28	0.39
1100.00	2.00	2.00	30.00	0.08	0.20	3.45	9.28	7.91	21.30	28.22	1.13	0.01	0.79	1.08	0.85	50.86	19.11	64.53	935.25	0.07	7.18	7.42	0.40
1200.00	2.00	2.00	30.00	0.08	0.20	3.76	9.20	8.63	21.10	28.22	1.13	0.01	0.80	1.06	0.85	50.57	20.17	61.46	1054.99	0.06	8.05	7.64	0.40
1300.00	2.00	2.00	30.00	0.09	0.20	4.08	9.11	9.35	20.90	28.22	1.13	0.01	0.82	1.06	0.87	51.73	21.19	74.99	924.41	0.07	8.68	9.74	0.43
1400.00	2.00	2.00	30.00	0.10	0.20	4.39	9.03	10.07	20.71	28.22	1.13	0.01	0.83	1.06	0.88	52.31	22.18	82.84	890.99	0.07	9.41	11.33	0.44
1500.00	2.00	2.00	30.00	0.10	0.20	4.70	8.94	10.79	20.51	28.22	1.13	0.01	0.84	1.06	0.89	52.89	23.13	91.50	855.60	0.07	10.12	13.13	0.46
1600.00	2.00	2.00	30.00	0.11	0.19	5.02	8.86	11.50	20.32	28.22	1.13	0.01	0.86	1.06	0.91	54.04	24.06	111.65	741.37	0.09	10.71	16.58	0.49
1700.00	2.00	2.00	30.00	0.12	0.19	5.33	8.77	12.22	20.12	28.22	1.13	0.01	0.87	1.05	0.91	54.14	24.95	113.66	767.72	0.08	11.50	17.76	0.50
1800.00	2.00	2.00	30.00	0.12	0.19	5.64	8.69	12.94	19.92	28.22	1.13	0.01	0.88	1.05	0.92	54.72	25.82	125.43	731.40	0.09	12.18	20.39	0.52
1900.00	2.00	2.00	30.00	0.13	0.19	5.96	8.60	13.66	19.73	28.22	1.13	0.01	0.89	1.05	0.93	55.00	26.65	131.77	730.26	0.09	12.91	22.35	0.54
2000.00	2.00	2.00	30.00	0.14	0.19	6.27	8.52	14.38	19.53	28.22	1.13	0.01	0.89	1.05	0.93	55.29	27.46	138.42	727.54	0.09	13.64	24.44	0.55
2100.00	2.00	2.00	30.00	0.14	0.18	6.58	8.43	15.10	19.34	28.22	1.13	0.01	0.90	1.05	0.95	55.86	28.25	152.76	688.60	0.09	14.29	27.89	0.58
2200.00	2.00	2.00	30.00	0.15	0.18	6.90	8.35	15.82	19.14	28.22	1.13	0.01	0.91	1.05	0.95	56.15	29.01	160.48	683.43	0.09	14.99	30.39	0.60
2300.00	2.00	2.00	30.00	0.16	0.18	7.21	8.26	16.54	18.95	28.22	1.13	0.01	0.91	1.05	0.96	56.43	29.76	168.59	677.17	0.09	15.69	33.06	0.62
2400.00	2.00	2.00	30.00	0.16	0.18	7.52	8.17	17.26	18.75	28.22	1.13	0.01	0.92	1.05	0.97	57.01	30.47	186.05	637.71	0.10	16.29	37.54	0.66
2500.00	2.00	2.00	30.00	0.17	0.18	7.84	8.09	17.98	18.55	28.22	1.13	0.01	0.92	1.05	0.97	57.18	31.17	191.63	642.52	0.10	17.00	40.01	0.67
2600.00	2.00	2.00	30.00	0.18	0.17	8.15	8.00	18.70	18.36	28.22	1.13	0.01	0.93	1.05	0.97	57.29	31.85	195.45	652.92	0.10	17.71	42.21	0.69
2700.00	2.00	2.00	30.00	0.18	0.17	8.46	7.92	19.41	18.16	28.22	1.13	0.01	0.93	1.04	0.97	57.07	32.51	188.16	702.06	0.09	18.52	42.22	0.69
2800.00	2.00	2.00	30.00	0.19	0.17	8.78	7.83	20.13	17.97	28.22	1.13	0.01	0.94	1.04	0.97	57.36	33.15	197.57	691.31	0.09	19.17	45.61	0.72
2900.00	2.00	2.00	30.00	0.20	0.17	9.09	7.75	20.85	17.77	28.22	1.13	0.01	0.94	1.04	0.98	57.53	33.78	203.44	693.39	0.09	19.84	48.37	0.74
3000.00	2.00	2.00	30.00	0.21	0.17	9.40	7.66	21.57	17.58	28.22	1.13	0.01	0.94	1.04	0.98	57.64	34.39	207.45	701.60	0.09	20.52	50.79	0.75

Appendix C Table 10: Pressure Drop for West Sak Oil C for Gas Flow Rate of 4MMscf/d

Qo, stb/d	Qg, MMscf/d	diameter, in	IFT dynes/ cm	Qo cu.ft/sec	Qg, cu.ft/ sec	Vsl ft/s	Vsg ft/s	Nlv	Ngv	Nd	Nl	CNL	HL/ψ	ψ	HL	ρs lb/cu.ft	ρn lb/cu. ft	μs, cp	Nre	fm	ρf lb/cu.ft	Dp friction lb/cu.ft	Total DP, psi/ft
100.00	4.00	2.00	30.00	0.01	0.48	0.31	21.77	0.71	50.32	28.65	23.70	0.01	0.22	1.82	0.40	26.71	4.82	3.12	8467.59	0.04	0.87	1.49	0.20
200.00	4.00	2.00	30.00	0.01	0.47	0.62	21.70	1.42	50.16	28.65	23.70	0.01	0.31	1.82	0.56	35.99	5.59	23.90	1295.77	0.05	0.87	1.99	0.26
300.00	4.00	2.00	30.00	0.02	0.47	0.92	21.63	2.14	50.00	28.65	23.70	0.01	0.36	1.82	0.66	41.15	6.35	74.09	479.60	0.13	0.98	6.20	0.33
400.00	4.00	2.00	30.00	0.03	0.47	1.23	21.56	2.85	49.84	28.65	23.70	0.01	0.44	1.82	0.80	49.40	7.09	452.92	88.54	0.72	1.02	35.65	0.59
500.00	4.00	2.00	30.00	0.03	0.47	1.54	21.49	3.56	49.68	28.65	23.70	0.01	0.47	1.82	0.86	52.49	7.82	893.05	50.02	1.28	1.16	73.68	0.88
600.00	4.00	2.00	30.00	0.04	0.47	1.85	21.43	4.27	49.52	28.65	23.70	0.01	0.50	1.82	0.91	55.59	8.53	1760.87	27.96	2.29	1.31	151.22	1.44
700.00	4.00	2.00	30.00	0.05	0.47	2.16	21.36	4.99	49.36	28.65	23.70	0.01	0.54	1.82	0.98	59.71	9.23	4353.77	12.36	5.18	1.43	380.36	3.06
800.00	4.00	2.00	30.00	0.05	0.46	2.47	21.29	5.70	49.20	28.65	23.70	0.01	0.57	1.82	1.00	60.68	9.91	5392.00	10.83	5.91	1.62	502.85	3.91
900.00	4.00	2.00	30.00	0.06	0.46	2.77	21.22	6.41	49.04	28.65	23.70	0.01	0.61	1.82	1.00	60.68	10.58	5392.00	11.67	5.48	1.84	542.21	4.19
1000.00	4.00	2.00	30.00	0.07	0.46	3.08	21.15	7.12	48.88	28.65	23.70	0.01	0.65	1.00	1.00	60.68	11.23	5392.00	12.52	5.11	2.08	581.56	4.46
1100.00	4.00	2.00	30.00	0.07	0.46	3.39	21.08	7.83	48.73	28.65	23.70	0.01	0.66	1.00	1.00	60.68	11.88	5392.00	13.37	4.79	2.32	620.92	4.73
1200.00	4.00	2.00	30.00	0.08	0.46	3.70	21.01	8.55	48.57	28.65	23.70	0.01	0.68	1.00	1.00	60.68	12.51	5392.00	14.22	4.50	2.58	660.27	5.01
1300.00	4.00	2.00	30.00	0.09	0.46	4.01	20.94	9.26	48.41	28.65	23.70	0.01	0.71	1.00	1.00	60.68	13.13	5392.00	15.06	4.25	2.84	699.63	5.28
1400.00	4.00	2.00	30.00	0.09	0.46	4.31	20.88	9.97	48.25	28.65	23.70	0.01	0.73	1.00	1.00	60.68	13.73	5392.00	15.91	4.02	3.11	738.98	5.55
1500.00	4.00	2.00	30.00	0.10	0.45	4.62	20.81	10.68	48.09	28.65	23.70	0.01	0.75	1.00	1.00	60.68	14.33	5392.00	16.76	3.82	3.38	778.34	5.83
1600.00	4.00	2.00	30.00	0.11	0.45	4.93	20.74	11.39	47.93	28.65	23.70	0.01	0.76	1.00	1.00	60.68	14.91	5392.00	17.60	3.64	3.66	817.69	6.10
1700.00	4.00	2.00	30.00	0.11	0.45	5.24	20.67	12.11	47.77	28.65	23.70	0.01	0.78	1.00	1.00	60.68	15.48	5392.00	18.45	3.47	3.95	857.04	6.37
1800.00	4.00	2.00	30.00	0.12	0.45	5.55	20.60	12.82	47.61	28.65	23.70	0.01	0.79	1.00	1.00	60.68	16.05	5392.00	19.30	3.32	4.24	896.40	6.65
1900.00	4.00	2.00	30.00	0.13	0.45	5.85	20.53	13.53	47.45	28.65	23.70	0.01	0.80	1.00	1.00	60.68	16.60	5392.00	20.15	3.18	4.54	935.75	6.92
2000.00	4.00	2.00	30.00	0.13	0.45	6.16	20.46	14.24	47.29	28.65	23.70	0.01	0.81	1.00	1.00	60.68	17.14	5392.00	20.99	3.05	4.84	975.11	7.19
2100.00	4.00	2.00	30.00	0.14	0.45	6.47	20.39	14.96	47.14	28.65	23.70	0.01	0.82	1.00	1.00	60.68	17.68	5392.00	21.84	2.93	5.15	1014.46	7.47
2200.00	4.00	2.00	30.00	0.15	0.44	6.78	20.33	15.67	46.98	28.65	23.70	0.01	0.83	1.00	1.00	60.68	18.20	5392.00	22.69	2.82	5.46	1053.82	7.74
2300.00	4.00	2.00	30.00	0.15	0.44	7.09	20.26	16.38	46.82	28.65	23.70	0.01	0.83	1.00	1.00	60.68	18.71	5392.00	23.54	2.72	5.77	1093.17	8.01
2400.00	4.00	2.00	30.00	0.16	0.44	7.40	20.19	17.09	46.66	28.65	23.70	0.01	0.84	1.00	1.00	60.68	19.22	5392.00	24.38	2.62	6.09	1132.52	8.29
2500.00	4.00	2.00	30.00	0.17	0.44	7.70	20.12	17.80	46.50	28.65	23.70	0.01	0.84	1.00	1.00	60.68	19.72	5392.00	25.23	2.54	6.41	1171.88	8.56
2600.00	4.00	2.00	30.00	0.17	0.44	8.01	20.05	18.52	46.34	28.65	23.70	0.01	0.85	1.00	1.00	60.68	20.20	5392.00	26.08	2.45	6.73	1211.23	8.83
2700.00	4.00	2.00	30.00	0.18	0.44	8.32	19.98	19.23	46.18	28.65	23.70	0.01	0.85	1.00	1.00	60.68	20.68	5392.00	26.92	2.38	7.05	1250.59	9.11
2800.00	4.00	2.00	30.00	0.19	0.43	8.63	19.91	19.94	46.02	28.65	23.70	0.01	0.86	1.00	1.00	60.68	21.16	5392.00	27.77	2.30	7.38	1289.94	9.38
2900.00	4.00	2.00	30.00	0.20	0.43	8.94	19.84	20.65	45.86	28.65	23.70	0.01	0.86	1.00	1.00	60.68	21.62	5392.00	28.62	2.24	7.70	1329.30	9.65
3000.00	4.00	2.00	30.00	0.20	0.43	9.24	19.77	21.36	45.70	28.65	23.70	0.01	0.87	1.00	1.00	60.68	22.08	5392.00	29.47	2.17	8.03	1368.65	9.93

Appendix C Table 11: Pressure Drop for West Sak Oil C for Gas Flow Rate of 2MMscf/d

Qo, stb/d	Qg, MMscf/d	diameter, in	IFT dynes/ cm	Qo cu.ft/sec	Qg, cu.ft/ sec	Vsl ft/s	Vsg ft/s	Nlv	Ngv	Nd	Nl	CNL	HL/ψ	ψ	HL	ρs lb/cu.ft	ρn lb/cu. ft	μs, cp	Nre	fm	ρf lb/cu.ft	Dp friction lb/cu.ft	Total DP, psi/ft
100.00	2.00	2.00	30.00	0.01	0.24	0.31	10.85	0.71	25.08	28.65	23.70	0.01	0.28	1.75	0.49	31.79	5.59	9.50	1630.03	0.04	0.98	0.45	0.22
200.00	2.00	2.00	30.00	0.01	0.24	0.62	10.78	1.42	24.92	28.65	23.70	0.01	0.38	1.75	0.67	41.70	7.09	83.69	239.58	0.27	1.21	3.90	0.32
300.00	2.00	2.00	30.00	0.02	0.23	0.92	10.71	2.14	24.76	28.65	23.70	0.01	0.43	1.75	0.75	46.66	8.53	248.42	99.10	0.65	1.56	12.71	0.41
400.00	2.00	2.00	30.00	0.03	0.23	1.23	10.64	2.85	24.60	28.65	23.70	0.01	0.50	1.75	0.88	53.60	9.91	1139.51	25.61	2.50	1.83	60.16	0.79
500.00	2.00	2.00	30.00	0.03	0.23	1.54	10.58	3.56	24.44	28.65	23.70	0.01	0.55	1.75	0.96	58.56	11.23	3382.52	9.98	6.41	2.16	189.03	1.72
600.00	2.00	2.00	30.00	0.04	0.23	1.85	10.51	4.27	24.28	28.65	23.70	0.01	0.60	1.75	1.00	60.68	12.51	5392.00	7.11	9.00	2.58	330.14	2.71
700.00	2.00	2.00	30.00	0.05	0.23	2.16	10.44	4.99	24.12	28.65	23.70	0.01	0.54	1.75	1.00	60.68	13.73	5392.00	7.95	8.05	3.11	369.49	2.99
800.00	2.00	2.00	30.00	0.05	0.23	2.47	10.37	5.70	23.97	28.65	23.70	0.01	0.57	1.75	1.00	60.68	14.91	5392.00	8.80	7.27	3.66	408.84	3.26
900.00	2.00	2.00	30.00	0.06	0.22	2.77	10.30	6.41	23.81	28.65	23.70	0.01	0.61	1.75	1.00	60.68	16.05	5392.00	9.65	6.63	4.24	448.20	3.53
1000.00	2.00	2.00	30.00	0.07	0.22	3.08	10.23	7.12	23.65	28.65	23.70	0.01	0.65	1.75	1.00	60.68	17.14	5392.00	10.50	6.10	4.84	487.55	3.81
1100.00	2.00	2.00	30.00	0.07	0.22	3.39	10.16	7.83	23.49	28.65	23.70	0.01	0.66	1.75	1.00	60.68	18.20	5392.00	11.34	5.64	5.46	526.91	4.08
1200.00	2.00	2.00	30.00	0.08	0.22	3.70	10.09	8.55	23.33	28.65	23.70	0.01	0.68	1.75	1.00	60.68	19.22	5392.00	12.19	5.25	6.09	566.26	4.35
1300.00	2.00	2.00	30.00	0.09	0.22	4.01	10.03	9.26	23.17	28.65	23.70	0.01	0.71	1.75	1.00	60.68	20.20	5392.00	13.04	4.91	6.73	605.62	4.63
1400.00	2.00	2.00	30.00	0.09	0.22	4.31	9.96	9.97	23.01	28.65	23.70	0.01	0.73	1.75	1.00	60.68	21.16	5392.00	13.89	4.61	7.38	644.97	4.90
1500.00	2.00	2.00	30.00	0.10	0.22	4.62	9.89	10.68	22.85	28.65	23.70	0.01	0.75	1.75	1.00	60.68	22.08	5392.00	14.73	4.34	8.03	684.33	5.17
1600.00	2.00	2.00	30.00	0.11	0.21	4.93	9.82	11.39	22.69	28.65	23.70	0.01	0.76	1.75	1.00	60.68	22.97	5392.00	15.58	4.11	8.69	723.68	5.45
1700.00	2.00	2.00	30.00	0.11	0.21	5.24	9.75	12.11	22.53	28.65	23.70	0.01	0.78	1.75	1.00	60.68	23.83	5392.00	16.43	3.90	9.36	763.03	5.72
1800.00	2.00	2.00	30.00	0.12	0.21	5.55	9.68	12.82	22.38	28.65	23.70	0.01	0.79	1.75	1.00	60.68	24.67	5392.00	17.27	3.70	10.03	802.39	5.99
1900.00	2.00	2.00	30.00	0.13	0.21	5.85	9.61	13.53	22.22	28.65	23.70	0.01	0.80	1.75	1.00	60.68	25.47	5392.00	18.12	3.53	10.69	841.74	6.27
2000.00	2.00	2.00	30.00	0.13	0.21	6.16	9.54	14.24	22.06	28.65	23.70	0.01	0.81	1.72	1.00	60.68	26.26	5392.00	18.97	3.37	11.36	881.10	6.54
2100.00	2.00	2.00	30.00	0.14	0.21	6.47	9.47	14.96	21.90	28.65	23.70	0.01	0.82	1.72	1.00	60.68	27.02	5392.00	19.82	3.23	12.03	920.45	6.81
2200.00	2.00	2.00	30.00	0.15	0.21	6.78	9.41	15.67	21.74	28.65	23.70	0.01	0.83	1.72	1.00	60.68	27.76	5392.00	20.66	3.10	12.70	959.81	7.09
2300.00	2.00	2.00	30.00	0.15	0.20	7.09	9.34	16.38	21.58	28.65	23.70	0.01	0.83	1.72	1.00	60.68	28.48	5392.00	21.51	2.98	13.36	999.16	7.36
2400.00	2.00	2.00	30.00	0.16	0.20	7.40	9.27	17.09	21.42	28.65	23.70	0.01	0.84	1.70	1.00	60.68	29.17	5392.00	22.36	2.86	14.02	1038.52	7.63
2500.00	2.00	2.00	30.00	0.17	0.20	7.70	9.20	17.80	21.26	28.65	23.70	0.01	0.84	1.70	1.00	60.68	29.85	5392.00	23.21	2.76	14.68	1077.87	7.91
2600.00	2.00	2.00	30.00	0.17	0.20	8.01	9.13	18.52	21.10	28.65	23.70	0.01	0.85	1.70	1.00	60.68	30.51	5392.00	24.05	2.66	15.34	1117.22	8.18
2700.00	2.00	2.00	30.00	0.18	0.20	8.32	9.06	19.23	20.94	28.65	23.70	0.01	0.85	1.70	1.00	60.68	31.15	5392.00	24.90	2.57	15.99	1156.58	8.45
2800.00	2.00	2.00	30.00	0.19	0.20	8.63	8.99	19.94	20.79	28.65	23.70	0.01	0.86	1.70	1.00	60.68	31.77	5392.00	25.75	2.49	16.63	1195.93	8.73
2900.00	2.00	2.00	30.00	0.20	0.19	8.94	8.92	20.65	20.63	28.65	23.70	0.01	0.86	1.70	1.00	60.68	32.38	5392.00	26.60	2.41	17.27	1235.29	9.00
3000.00	2.00	2.00	30.00	0.20	0.19	9.24	8.86	21.36	20.47	28.65	23.70	0.01	0.87	1.70	1.00	60.68	32.96	5392.00	27.44	2.33	17.91	1274.64	9.27

APPENDIX D

Duns and Ros (1963) Results

Appendix D Table 1: Pressure Drop Calculation for Oil of API 16 at Constant Pressure and Temperature

Qo, stb/d	Qg, scf/d	dia, in	Qo, cu.ft/sec	Bg, cu.ft/scf	Qg, cu.ft/sec	Vsl, ft/s	Vsg, ft/s	Nlv	Ngv	Nd	Nl	IFT	L1	L2	Bubble flow	slug flow	Transition	mist flow
100	4E+06	2	0.008	0.0039	0.1807	0.3573	8.28	0.8	18.48	26.7	0.4	30	2	0.7	FALSE	TRUE	FALSE	FALSE
200	4E+06	2	0.016	0.0039	0.1788	0.7146	8.19	1.6	18.28	26.7	0.4	30	2	0.68	FALSE	TRUE	FALSE	FALSE
300	4E+06	2	0.023	0.0039	0.1769	1.0719	8.1	2.4	18.09	26.7	0.4	30	2	0.68	FALSE	TRUE	FALSE	FALSE
400	4E+06	2	0.031	0.0039	0.175	1.4292	8.02	3.2	17.89	26.7	0.4	30	2	0.68	FALSE	TRUE	FALSE	FALSE
500	4E+06	2	0.039	0.0039	0.173	1.7866	7.93	4	17.69	26.7	0.4	30	2	0.68	FALSE	TRUE	FALSE	FALSE
600	4E+06	2	0.047	0.0039	0.1711	2.1439	7.84	4.8	17.49	26.7	0.4	30	2	0.68	FALSE	TRUE	FALSE	FALSE
700	4E+06	2	0.055	0.0039	0.1692	2.5012	7.75	5.6	17.3	26.7	0.4	30	2	0.68	FALSE	TRUE	FALSE	FALSE
800	4E+06	2	0.062	0.0039	0.1672	2.8585	7.66	6.4	17.1	26.7	0.4	30	2	0.68	FALSE	TRUE	FALSE	FALSE
900	4E+06	2	0.07	0.0039	0.1653	3.2158	7.57	7.2	16.9	26.7	0.4	30	2	0.68	FALSE	TRUE	FALSE	FALSE
1000	4E+06	2	0.078	0.0039	0.1634	3.5731	7.49	8	16.71	26.7	0.4	30	2	0.68	FALSE	TRUE	FALSE	FALSE
1100	4E+06	2	0.086	0.0039	0.1615	3.9304	7.4	8.8	16.51	26.7	0.4	30	2	0.68	FALSE	TRUE	FALSE	FALSE
1200	4E+06	2	0.094	0.0039	0.1595	4.2877	7.31	9.6	16.31	26.7	0.4	30	2	0.68	FALSE	TRUE	FALSE	FALSE
1300	4E+06	2	0.101	0.0039	0.1576	4.6451	7.22	10	16.12	26.7	0.4	30	2	0.68	FALSE	TRUE	FALSE	FALSE
1400	4E+06	2	0.109	0.0039	0.1557	5.0024	7.13	11	15.92	26.7	0.4	30	2	0.68	FALSE	TRUE	FALSE	FALSE
1500	4E+06	2	0.117	0.0039	0.1537	5.3597	7.04	12	15.72	26.7	0.4	30	2	0.68	FALSE	TRUE	FALSE	FALSE
1600	4E+06	2	0.125	0.0039	0.1518	5.717	6.96	13	15.52	26.7	0.4	30	2	0.68	FALSE	TRUE	FALSE	FALSE
1700	4E+06	2	0.133	0.0039	0.1499	6.0743	6.87	14	15.33	26.7	0.4	30	2	0.68	FALSE	TRUE	FALSE	FALSE
1800	4E+06	2	0.14	0.0039	0.148	6.4316	6.78	14	15.13	26.7	0.4	30	2	0.68	FALSE	TRUE	FALSE	FALSE
1900	4E+06	2	0.148	0.0039	0.146	6.7889	6.69	15	14.93	26.7	0.4	30	2	0.68	FALSE	TRUE	FALSE	FALSE
2000	4E+06	2	0.156	0.0039	0.1441	7.1462	6.6	16	14.74	26.7	0.4	30	2	0.68	FALSE	TRUE	FALSE	FALSE
2100	4E+06	2	0.164	0.0039	0.1422	7.5036	6.51	17	14.54	26.7	0.4	30	2	0.68	FALSE	TRUE	FALSE	FALSE
2200	4E+06	2	0.172	0.0039	0.1403	7.8609	6.43	18	14.34	26.7	0.4	30	2	0.68	FALSE	TRUE	FALSE	FALSE
2300	4E+06	2	0.179	0.0039	0.1383	8.2182	6.34	18	14.14	26.7	0.4	30	2	0.68	TRUE	FALSE	FALSE	FALSE
2400	4E+06	2	0.187	0.0039	0.1364	8.5755	6.25	19	13.95	26.7	0.4	30	2	0.68	TRUE	FALSE	FALSE	FALSE
2500	4E+06	2	0.195	0.0039	0.1345	8.9328	6.16	20	13.75	26.7	0.4	30	2	0.68	TRUE	FALSE	FALSE	FALSE
2600	4E+06	2	0.203	0.0039	0.1325	9.2901	6.07	21	13.55	26.7	0.4	30	2	0.68	TRUE	FALSE	FALSE	FALSE
2700	4E+06	2	0.211	0.0039	0.1306	9.6474	5.98	22	13.36	26.7	0.4	30	2	0.68	TRUE	FALSE	FALSE	FALSE
2800	4E+06	2	0.218	0.0039	0.1287	10.005	5.9	22	13.16	26.7	0.4	30	2	0.68	TRUE	FALSE	FALSE	FALSE
2900	4E+06	2	0.226	0.0039	0.1268	10.362	5.81	23	12.96	26.7	0.4	30	2	0.68	TRUE	FALSE	FALSE	FALSE
3000	4E+06	2	0.234	0.0039	0.1248	10.719	5.72	24	12.76	26.7	0.4	30	2	0.68	TRUE	FALSE	FALSE	FALSE

Qo, stb/d	F1	F2	F3	F4	F5	F6'	F7	S	Vs	Vm	HL	pm, lb/cu.ft	Nrel	fm	bubble corr. Factor	f2	f3	fm	Dp fric., lb/cu.ft	total DP psi/ft
100	2	0.9	3.8	55	0.06	2.6	0.03	20.4	9.14	8.64	0.227	20.95	51.82	1.23	255.7707	0.2	1.84	0.134	2.035	0.15959
200	2	0.9	3.4	55	0.06	2.6	0.03	19.4	8.67	8.91	0.274	22.87	103.6	0.62	63.26069	0.22	1.3	0.105	3.28	0.18162
300	2	0.9	3.4	55	0.06	2.6	0.03	18.4	8.24	9.18	0.308	24.29	155.5	0.41	27.81276	0.27	1.16	0.096	4.632	0.20082
400	2	0.9	3.4	55	0.06	2.6	0.03	17.5	7.83	9.45	0.336	25.44	207.3	0.31	15.47418	0.31	1.1	0.087	5.755	0.21666
500	2	0.9	3.4	55	0.06	2.6	0.03	16.6	7.45	9.71	0.361	26.45	259.1	0.25	9.794358	0.35	1.07	0.081	6.868	0.23135
600	2	0.9	3.4	55	0.06	2.6	0.03	15.8	7.09	9.98	0.382	27.34	310.9	0.21	6.725862	0.39	1.06	0.076	7.999	0.24542
700	2	0.9	3.4	55	0.06	2.6	0.03	15.1	6.75	10.3	0.402	28.16	362.8	0.18	4.885778	0.43	1.04	0.073	9.158	0.25915
800	2	0.9	3.4	55	0.06	2.6	0.03	14.4	6.44	10.5	0.421	28.92	414.6	0.15	3.69805	0.48	1.04	0.072	10.57	0.27425
900	2	0.9	3.4	55	0.06	2.6	0.03	13.7	6.14	10.8	0.438	29.63	466.4	0.14	2.888238	0.51	1.03	0.068	11.59	0.28624
1000	2	0.9	3.4	55	0.06	2.6	0.03	13.1	5.86	11.1	0.454	30.3	518.2	0.12	2.312193	0.58	1.03	0.07	13.57	0.30465
1100	2	0.9	3.4	55	0.06	2.6	0.03	12.5	5.59	11.3	0.47	30.94	570	0.11	1.888359	0.61	1.02	0.067	14.67	0.31672
1200	2	0.9	3.4	55	0.06	2.6	0.03	11.9	5.34	11.6	0.485	31.55	621.9	0.1	1.567802	0.68	1.02	0.069	16.78	0.33567
1300	2	0.9	3.4	55	0.06	2.6	0.03	11.4	5.11	11.9	0.499	32.14	673.7	0.09	1.319737	0.7	1.02	0.065	17.72	0.34623
1400	2	0.9	3.4	55	0.06	2.6	0.03	10.9	4.89	12.1	0.513	32.7	725.5	0.09	1.124018	0.78	1.01	0.068	20.23	0.36757
1500	2	0.9	3.4	55	0.06	2.6	0.03	10.4	4.67	12.4	0.526	33.25	777.3	0.08	0.967021	0.8	1.01	0.065	21.24	0.37838
1600	2	0.9	3.4	55	0.06	2.6	0.03	9.98	4.47	12.7	0.539	33.78	829.2	0.08	0.839265	0.83	1.01	0.063	22.54	0.39108
1700	2	0.9	3.4	55	0.06	2.6	0.03	9.56	4.28	12.9	0.551	34.29	881	0.07	0.733992	0.9	1.01	0.065	24.99	0.41162
1800	2	0.9	3.4	55	0.06	2.6	0.03	9.16	4.1	13.2	0.563	34.78	932.8	0.07	0.646284	0.93	1.01	0.063	26.38	0.42474
1900	2	0.9	3.4	55	0.06	2.6	0.03	8.78	3.93	13.5	0.575	35.26	984.6	0.06	0.572487	0.98	1.01	0.063	28.39	0.44202
2000	2	0.9	3.4	55	0.06	2.6	0.03	8.42	3.77	13.7	0.586	35.73	1036	0.06	0.50985	1	1.01	0.061	29.57	0.45346
2100	2	0.9	3.4	55	0.06	2.6	0.03	8.07	3.62	14	0.597	36.18	1088	0.06	0.456263	1.08	1.01	0.063	32.58	0.47752
2200	2	0.9	3.4	55	0.06	2.6	0.03	7.74	3.47	14.3	0.608	36.62	1140	0.06	0.410091	1.1	1.01	0.061	33.84	0.48934
2300	2	0.9	3.4	55	0.06	2.6	0.03	7.43	3.33	14.6	0.619	37.06	1192	0.05	0.37005	1.1	1.01	0.059	34.49	0.49688
2400	2	0.9	3.4	55	0.06	2.6	0.03	19.6	8.79	14.8	0.702	40.5	1244	0.05	0.335119	1.1	1.01	0.056	35.15	0.52537
2500	2	0.9	3.4	55	0.06	2.6	0.03	20.3	9.08	15.1	0.715	41.01	1296	0.05	0.304481	1.1	1.01	0.054	35.8	0.53337
2600	2	0.9	3.4	55	0.06	2.6	0.03	20.9	9.38	15.4	0.726	41.48	1347	0.05	0.277474	1.1	1.01	0.052	36.45	0.5412
2700	2	0.9	3.4	55	0.06	2.6	0.03	21.6	9.68	15.6	0.737	41.93	1399	0.05	0.253559	1.1	1.01	0.05	37.1	0.54886
2800	2	0.9	3.4	55	0.06	2.6	0.03	22.3	9.98	15.9	0.748	42.37	1451	0.04	0.232292	1.1	1	0.048	37.75	0.55637
2900	2	0.9	3.4	55	0.06	2.6	0.03	22.9	10.3	16.2	0.758	42.78	1503	0.04	0.213304	1.1	1	0.047	38.4	0.56374
3000	2	0.9	3.4	55	0.06	2.6	0.03	23.6	10.6	16.4	0.767	43.17	1555	0.04	0.19629	1.1	1	0.045	39.05	0.57097

Appendix D Table 2: Pressure Drop Calculation for Oil of API 20 at Constant Pressure and Temperature

Qo, stb/d	Qg, scf/d	dia, in	Qo, cu.ft/sec	Bg, cu.ft/scf	Qg, cu.ft / sec	Vsl	Vsg	Nlv	Ngv	Nd	Nl	IFT	L1	L2	Bubble flow	slug flow	FALSE	mist flow	F1	F2	F3	F4	F5	F6'	F7	S	Vs	Vm	HL	pm	Nrel	fm	bubble corr	f2	f3	fm	DP friction	total DP psi/ft
100	4E+06	2	0.008	0	0.18	0.37	8.27	0.81	18.3	26	0.1	30	2	0.68	FALSE	TRUE	FALSE	FALSE	2.1	1.03	3.4	55	0.05	2.9	0.04	19.97	9.04	8.634	0.225	20.38	156.62	0.409	81.31	0.21	1.275	0.07	1.0035	0.1485
200	4E+06	2	0.016	0	0.18	0.73	8.17	1.62	18	26	0.1	30	2	0.65	FALSE	TRUE	FALSE	FALSE	2.1	1.03	3.4	55	0.05	2.9	0.04	18.66	8.449	8.8987	0.269	22.1	313.25	0.204	20.08	0.29	1.096	0.05	1.6603	0.165
300	4E+06	2	0.024	0	0.18	1.1	8.06	2.43	17.8	26	0.1	30	2	0.65	FALSE	TRUE	FALSE	FALSE	2.1	1.03	3.4	55	0.05	2.9	0.04	17.46	7.908	9.1634	0.3017	23.37	469.87	0.136	8.813	0.37	1.052	0.05	2.2731	0.1781
400	4E+06	2	0.032	0	0.17	1.46	7.96	3.23	17.6	26	0.1	30	2	0.65	FALSE	TRUE	FALSE	FALSE	2.1	1.03	3.4	55	0.05	2.9	0.04	16.37	7.411	9.4281	0.3289	24.43	626.49	0.102	4.895	0.43	1.034	0.04	2.7667	0.1889
500	4E+06	2	0.04	0	0.17	1.83	7.86	4.04	17.4	26	0.1	30	2	0.65	FALSE	TRUE	FALSE	FALSE	2.1	1.03	3.4	55	0.05	2.9	0.04	15.36	6.956	9.6928	0.3527	25.36	783.11	0.082	3.093	0.51	1.024	0.04	3.4056	0.1998
600	4E+06	2	0.048	0	0.17	2.2	7.76	4.85	17.1	26	0.1	30	2	0.65	FALSE	TRUE	FALSE	FALSE	2.1	1.03	3.4	55	0.05	2.9	0.04	14.43	6.536	9.9574	0.3744	26.21	939.74	0.068	2.12	0.6	1.018	0.04	4.1396	0.2107
700	4E+06	2	0.0559	0	0.17	2.56	7.66	5.66	16.9	26	0.1	30	2	0.65	FALSE	TRUE	FALSE	FALSE	2.1	1.03	3.4	55	0.05	2.9	0.04	13.58	6.149	10.222	0.3944	26.99	1096.4	0.058	1.537	0.68	1.014	0.04	4.8345	0.221
800	4E+06	2	0.0639	0	0.16	2.93	7.56	6.47	16.7	26	0.1	30	2	0.65	FALSE	TRUE	FALSE	FALSE	2.1	1.03	3.4	55	0.05	2.9	0.04	12.79	5.791	10.487	0.4132	27.72	1253	0.051	1.161	0.72	1.012	0.04	5.2653	0.2291
900	4E+06	2	0.0719	0	0.16	3.3	7.46	7.28	16.5	26	0.1	30	2	0.65	FALSE	TRUE	FALSE	FALSE	2.1	1.03	3.4	55	0.05	2.9	0.04	12.06	5.459	10.751	0.4311	28.41	1409.6	0.045	0.905	0.8	1.01	0.04	6.0095	0.2391
1000	4E+06	2	0.0799	0	0.16	3.66	7.35	8.09	16.2	26	0.1	30	2	0.65	FALSE	TRUE	FALSE	FALSE	2.1	1.03	3.4	55	0.05	2.9	0.04	11.38	5.152	11.016	0.4481	29.08	1566.2	0.041	0.723	0.9	1.008	0.04	6.9372	0.2501
1100	4E+06	2	0.0879	0	0.16	4.03	7.25	8.9	16	26	0.1	30	2	0.65	FALSE	TRUE	FALSE	FALSE	2.1	1.03	3.4	55	0.05	2.9	0.04	10.75	4.866	11.281	0.4644	29.71	1722.9	0.037	0.59	0.98	1.007	0.04	7.7441	0.2601
1200	4E+06	2	0.0959	0	0.16	4.39	7.15	9.7	15.8	26	0.1	30	2	0.65	FALSE	TRUE	FALSE	FALSE	2.1	1.03	3.4	55	0.05	2.9	0.04	10.16	4.6	11.546	0.4801	30.33	1879.5	0.034	0.488	1	1.006	0.03	8.096	0.2668
1300	4E+06	2	0.1039	0	0.15	4.76	7.05	10.5	15.6	26	0.1	30	2	0.65	FALSE	TRUE	FALSE	FALSE	2.1	1.03	3.4	55	0.05	2.9	0.04	9.614	4.353	11.81	0.4952	30.92	2036.1	0.032	0.411	1.08	1.005	0.03	8.9722	0.277
1400	4E+06	2	0.1119	0	0.15	5.13	6.95	11.3	15.3	26	0.1	30	2	0.65	FALSE	TRUE	FALSE	FALSE	2.1	1.03	3.4	55	0.05	2.9	0.04	9.103	4.122	12.075	0.5099	31.49	2192.7	0.03	0.36	1.1	1.005	0.03	9.6149	0.2854
1500	4E+06	2	0.1199	0	0.15	5.49	6.85	12.1	15.1	26	0.1	30	2	0.65	FALSE	TRUE	FALSE	FALSE	2.1	1.03	3.4	55	0.05	2.9	0.04	8.626	3.906	12.34	0.5241	32.04	2349.3	0.032	0.349	1.1	1.005	0.03	11.099	0.2996
1600	4E+06	2	0.1279	0	0.15	5.86	6.75	12.9	14.9	26	0.1	30	2	0.65	FALSE	TRUE	FALSE	FALSE	2.1	1.03	3.4	55	0.05	2.9	0.04	8.18	3.704	12.604	0.5379	32.58	2506	0.035	0.36	1.1	1.005	0.04	13.509	0.3201
1700	4E+06	2	0.1359	0	0.15	6.23	6.64	13.7	14.7	26	0.1	30	2	0.65	FALSE	TRUE	FALSE	FALSE	2.1	1.03	3.4	55	0.05	2.9	0.04	7.763	3.515	12.869	0.5513	33.1	2662.6	0.039	0.371	1.1	1.006	0.04	16.288	0.343
1800	4E+06	2	0.1439	0	0.14	6.59	6.54	14.6	14.4	26	0.1	30	2	0.65	FALSE	TRUE	FALSE	FALSE	2.1	1.03	3.4	55	0.05	2.9	0.04	7.371	3.337	13.134	0.5643	33.61	2819.2	0.043	0.375	1.1	1.006	0.05	19.111	0.3661
1900	4E+06	2	0.1518	0	0.14	6.96	6.44	15.4	14.2	26	0.1	30	2	0.65	FALSE	TRUE	FALSE	FALSE	2.1	1.03	3.4	55	0.05	2.9	0.04	7.003	3.171	13.398	0.577	34.11	2975.8	0.045	0.368	1.1	1.006	0.05	21.654	0.3872
2000	4E+06	2	0.1598	0	0.14	7.32	6.34	16.2	14	26	0.1	30	2	0.65	FALSE	TRUE	FALSE	FALSE	2.1	1.03	3.4	55	0.05	2.9	0.04	6.657	3.014	13.663	0.5894	34.59	3132.5	0.046	0.351	1.1	1.006	0.05	23.764	0.4052
2100	4E+06	2	0.1678	0	0.14	7.69	6.24	17	13.8	26	0.1	30	2	0.65	FALSE	TRUE	FALSE	FALSE	2.1	1.03	3.4	55	0.05	2.9	0.04	6.332	2.867	13.928	0.6015	35.06	3289.1	0.046	0.331	1.1	1.006	0.05	25.538	0.4208
2200	4E+06	2	0.1758	0	0.13	8.06	6.14	17.8	13.6	26	0.1	30	2	0.65	TRUE	FALSE	FALSE	FALSE	2.1	1.03	3.4	55	0.05	2.9	0.04	21.1	9.554	14.192	0.7071	39.18	3445.7	0.046	0.309	1.1	1.006	0.05	27.133	0.4605
2300	4E+06	2	0.1838	0	0.13	8.42	6.03	18.6	13.3	26	0.1	30	2	0.65	TRUE	FALSE	FALSE	FALSE	2.1	1.03	3.4	55	0.05	2.9	0.04	21.86	9.897	14.457	0.7204	39.7	3602.3	0.046	0.288	1.1	1.005	0.05	28.656	0.4747
2400	4E+06	2	0.1918	0	0.13	8.79	5.93	19.4	13.1	26	0.1	30	2	0.65	TRUE	FALSE	FALSE	FALSE	2.1	1.03	3.4	55	0.05	2.9	0.04	22.63	10.25	14.722	0.7331	40.19	3758.9	0.045	0.269	1.1	1.005	0.05	30.162	0.4886
2500	4E+06	2	0.1998	0	0.13	9.15	5.83	20.2	12.9	26	0.1	30	2	0.65	TRUE	FALSE	FALSE	FALSE	2.1	1.03	3.4	55	0.05	2.9	0.04	23.4	10.6	14.986	0.7451	40.66	3915.6	0.045	0.251	1.1	1.005	0.05	31.675	0.5024
2600	4E+06	2	0.2078	0	0.13	9.52	5.73	21	12.7	26	0.1	30	2	0.65	TRUE	FALSE	FALSE	FALSE	2.1	1.03	3.4	55	0.05	2.9	0.04	24.19	10.95	15.251	0.7565	41.11	4072.2	0.044	0.235	1.1	1.005	0.05	33.207	0.5161
2700	4E+06	2	0.2158	0	0.12	9.89	5.63	21.8	12.4	26	0.1	30	2	0.65	TRUE	FALSE	FALSE	FALSE	2.1	1.03	3.4	55	0.05	2.9	0.04	24.98	11.31	15.516	0.7673	41.53	4228.8	0.044	0.22	1.1	1.005	0.05	34.762	0.5298
2800	4E+06	2	0.2238	0	0.12	10.3	5.53	22.6	12.2	26	0.1	30	2	0.65	TRUE	FALSE	FALSE	FALSE	2.1	1.03	3.4	55	0.05	2.9	0.04	25.77	11.67	15.78	0.7776	41.93	4385.4	0.044	0.207	1.1	1.005	0.05	36.343	0.5436
2900	4E+06	2	0.2318	0	0.12	10.6	5.43	23.5	12	26	0.1	30	2	0.65	TRUE	FALSE	FALSE	FALSE	2.1	1.03	3.4	55	0.05	2.9	0.04	26.57	12.03	16.045	0.7874	42.31	4542.1	0.043	0.194	1.1	1.004	0.05	37.951	0.5574
3000	4E+06	2	0.2398	0	0.12	11	5.32	24.3	11.8	26	0.1	30	2	0.65	TRUE	FALSE	FALSE	FALSE	2.1	1.03	3.4	55	0.05	2.9	0.04	27.37	12.39	16.31	0.7966	42.67	4698.7	0.043	0.183	1.1	1.004	0.05	39.587	0.5712

Appendix D Table 3: Pressure Drop Calculation for Oil of API 25 at Constant Pressure and Temperature

Qo, stb/d	Qg, scf/d	dia, in	Qo, cu.ft /sec	Qg, cu.ft/ sec	Vsl	Vsg	Nlv	Ngv	Nd	Nl	IFT	Bubbl e flow	slug flow	FALSE	mist flow	F1	F2	F3	F4	F5	F6'	F7	S	Vs	Vm	HL	pm	Nrel	fm	f2	f3	fm	DP friction	total DP psi/ft
100	4E+06	2	0.01	0.18	0.4	8.2	0.8	18	25	0.04	30	FALSE	TRUE	FALSE	FALSE	1.59	0.55	2.7	52	0.149	1.55	0.054	19.6	8.993	8.628	0.23	19.86	471.61	0.14	0.27	1.09	0.034	0.492	0.1413
200	4E+06	2	0.02	0.177	0.8	8.1	1.7	17.7	25	0.04	30	FALSE	TRUE	FALSE	FALSE	1.59	0.55	2.7	52	0.149	1.55	0.054	17.8	8.163	8.886	0.26	21.2	943.22	0.07	0.4	1.031	0.026	0.7929	0.1528
300	4E+06	2	0.02	0.175	1.1	8	2.5	17.5	25	0.04	30	FALSE	TRUE	FALSE	FALSE	1.59	0.55	2.7	52	0.149	1.55	0.054	16.2	7.432	9.144	0.29	22.26	1414.8	0.05	0.52	1.017	0.023	1.0758	0.162
400	4E+06	2	0.03	0.172	1.5	7.9	3.3	17.2	25	0.04	30	FALSE	TRUE	FALSE	FALSE	1.59	0.55	2.7	52	0.149	1.55	0.054	14.8	6.787	9.402	0.32	23.17	1886.4	0.03	0.68	1.011	0.023	1.4555	0.171
500	4E+06	2	0.04	0.169	1.9	7.8	4.1	16.9	25	0.04	30	FALSE	TRUE	FALSE	FALSE	1.59	0.55	2.7	52	0.149	1.55	0.054	13.5	6.214	9.661	0.34	24.01	2358.1	0.03	0.76	1.009	0.024	1.9684	0.1804
600	4E+06	2	0.05	0.167	2.3	7.6	5	16.7	25	0.04	30	FALSE	TRUE	FALSE	FALSE	1.59	0.55	2.7	52	0.149	1.55	0.054	12.4	5.704	9.919	0.36	24.79	2829.7	0.04	0.7	1.011	0.03	3.005	0.193
700	4E+06	2	0.06	0.164	2.7	7.5	5.8	16.4	25	0.04	30	FALSE	TRUE	FALSE	FALSE	1.59	0.55	2.7	52	0.149	1.55	0.054	11.4	5.248	10.18	0.38	25.53	3301.3	0.05	0.76	1.011	0.035	4.1989	0.2065
800	4E+06	2	0.07	0.162	3	7.4	6.6	16.1	25	0.04	30	FALSE	TRUE	FALSE	FALSE	1.59	0.55	2.7	52	0.149	1.55	0.054	10.5	4.838	10.44	0.4	26.24	3772.9	0.05	0.81	1.01	0.036	5.1256	0.2178
900	4E+06	2	0.07	0.159	3.4	7.3	7.4	15.9	25	0.04	30	FALSE	TRUE	FALSE	FALSE	1.59	0.55	2.7	52	0.149	1.55	0.054	9.74	4.469	10.69	0.42	26.93	4244.5	0.04	0.85	1.009	0.037	6.0292	0.2289
1000	4E+06	2	0.08	0.156	3.8	7.2	8.3	15.6	25	0.04	30	FALSE	TRUE	FALSE	FALSE	1.59	0.55	2.7	52	0.149	1.55	0.054	9.01	4.135	10.95	0.44	27.59	4716.1	0.04	0.9	1.008	0.038	7.0852	0.2408
1100	4E+06	2	0.09	0.154	4.2	7	9.1	15.3	25	0.04	30	FALSE	TRUE	FALSE	FALSE	1.59	0.55	2.7	52	0.149	1.55	0.054	8.36	3.833	11.21	0.46	28.24	5187.7	0.04	0.95	1.008	0.039	8.2379	0.2533
1200	4E+06	2	0.1	0.151	4.5	6.9	9.9	15.1	25	0.04	30	FALSE	TRUE	FALSE	FALSE	1.59	0.55	2.7	52	0.149	1.55	0.054	7.76	3.558	11.47	0.47	28.86	5659.3	0.04	1	1.007	0.041	9.4916	0.2663
1300	4E+06	2	0.11	0.148	4.9	6.8	11	14.8	25	0.04	30	FALSE	TRUE	FALSE	FALSE	1.59	0.55	2.7	52	0.149	1.55	0.054	7.21	3.308	11.73	0.49	29.47	6131	0.04	1.08	1.007	0.043	11.16	0.2822
1400	4E+06	2	0.12	0.146	5.3	6.7	12	14.6	25	0.04	30	FALSE	TRUE	FALSE	FALSE	1.59	0.55	2.7	52	0.149	1.55	0.054	6.71	3.08	11.98	0.51	30.06	6602.6	0.04	1.1	1.006	0.043	12.317	0.2943
1500	4E+06	2	0.12	0.143	5.7	6.6	12	14.3	25	0.04	30	FALSE	TRUE	FALSE	FALSE	1.59	0.55	2.7	52	0.149	1.55	0.054	6.26	2.871	12.24	0.52	30.64	7074.2	0.04	1.1	1.006	0.043	13.292	0.3051
1600	4E+06	2	0.13	0.14	6.1	6.4	13	14	25	0.04	30	FALSE	TRUE	FALSE	FALSE	1.59	0.55	2.7	52	0.149	1.55	0.054	5.84	2.679	12.5	0.54	31.21	7545.8	0.04	1.1	1.006	0.042	14.292	0.316
1700	4E+06	2	0.14	0.138	6.4	6.3	14	13.8	25	0.04	30	FALSE	TRUE	FALSE	FALSE	1.59	0.55	2.7	52	0.149	1.55	0.054	5.46	2.503	12.76	0.55	31.76	8017.4	0.04	1.1	1.005	0.042	15.317	0.3269
1800	4E+06	2	0.15	0.135	6.8	6.2	15	13.5	25	0.04	30	FALSE	TRUE	FALSE	FALSE	1.59	0.55	2.7	52	0.149	1.55	0.054	5.1	2.341	13.02	0.57	32.29	8489	0.04	1.1	1.005	0.041	16.368	0.3379
1900	4E+06	2	0.16	0.133	7.2	6.1	16	13.2	25	0.04	30	FALSE	TRUE	FALSE	FALSE	1.59	0.55	2.7	52	0.149	1.55	0.054	4.78	2.191	13.28	0.58	32.82	8960.6	0.04	1.1	1.005	0.041	17.444	0.349
2000	4E+06	2	0.17	0.13	7.6	6	17	13	25	0.04	30	FALSE	TRUE	FALSE	FALSE	1.59	0.55	2.7	52	0.149	1.55	0.054	4.47	2.052	13.53	0.6	33.33	9432.2	0.04	1.1	1.005	0.04	18.546	0.3602
2100	4E+06	2	0.17	0.127	8	5.8	17	12.7	25	0.04	30	TRUE	FALSE	FALSE	FALSE	1.59	0.55	2.7	52	0.149	1.55	0.054	11.4	5.253	13.79	0.66	35.72	9903.9	0.04	1.1	1.004	0.04	19.674	0.3847
2200	4E+06	2	0.18	0.125	8.3	5.7	18	12.5	25	0.04	30	TRUE	FALSE	FALSE	FALSE	1.59	0.55	2.7	52	0.149	1.55	0.054	11.9	5.443	14.05	0.68	36.29	10375	0.04	1.1	1.004	0.04	20.827	0.3967
2300	4E+06	2	0.19	0.122	8.7	5.6	19	12.2	25	0.04	30	TRUE	FALSE	FALSE	FALSE	1.59	0.55	2.7	52	0.149	1.55	0.054	12.3	5.637	14.31	0.69	36.84	10847	0.04	1.1	1.004	0.039	22.007	0.4086
2400	4E+06	2	0.2	0.119	9.1	5.5	20	11.9	25	0.04	30	TRUE	FALSE	FALSE	FALSE	1.59	0.55	2.7	52	0.149	1.55	0.054	12.7	5.832	14.57	0.71	37.36	11319	0.04	1.1	1.004	0.039	23.213	0.4206
2500	4E+06	2	0.21	0.117	9.5	5.4	21	11.7	25	0.04	30	TRUE	FALSE	FALSE	FALSE	1.59	0.55	2.7	52	0.149	1.55	0.054	13.1	6.029	14.83	0.72	37.85	11790	0.04	1.1	1.004	0.039	24.445	0.4326
2600	4E+06	2	0.22	0.114	9.9	5.2	21	11.4	25	0.04	30	TRUE	FALSE	FALSE	FALSE	1.59	0.55	2.7	52	0.149	1.55	0.054	13.6	6.227	15.08	0.73	38.33	12262	0.04	1.1	1.004	0.039	25.703	0.4447
2700	4E+06	2	0.22	0.111	10	5.1	22	11.1	25	0.04	30	TRUE	FALSE	FALSE	FALSE	1.59	0.55	2.7	52	0.149	1.55	0.054	14	6.427	15.34	0.75	38.78	12734	0.04	1.1	1.004	0.038	26.988	0.4567
2800	4E+06	2	0.23	0.109	11	5	23	10.9	25	0.04	30	TRUE	FALSE	FALSE	FALSE	1.59	0.55	2.7	52	0.149	1.55	0.054	14.4	6.628	15.6	0.76	39.21	13205	0.03	1.1	1.003	0.038	28.299	0.4688
2900	4E+06	2	0.24	0.106	11	4.9	24	10.6	25	0.04	30	TRUE	FALSE	FALSE	FALSE	1.59	0.55	2.7	52	0.149	1.55	0.054	14.9	6.83	15.86	0.77	39.62	13677	0.03	1.1	1.003	0.038	29.636	0.481
3000	4E+06	2	0.25	0.104	11	4.7	25	10.3	25	0.04	30	TRUE	FALSE	FALSE	FALSE	1.59	0.55	2.7	52	0.149	1.55	0.054	15.3	7.032	16.12	0.78	40.02	14148	0.03	1.1	1.003	0.038	31	0.4932

Appendix D Table 4: Pressure Drop Calculation for Oil of API 30 at Constant Pressure and Temperature

Qo, stb/d	Qg, scf/d	dia, in	Qo, cu.ft/sec	Bg, cu.ft/scf	Qg, cu.ft/sec	Vsl	Vsg	Nlv	Ngv	Nd	Nl	IFT	Bubble flow	slug flow	Transistion	mist flow	F1	F2	F3	F4	F5	F6'	F7	S	Vs	Vm	HL	pm	Nrel	fm	f2	f3	fm	DP friction	total pressure loss psi/ft
100	4E+06	2	0.01	0.0039	0.1795	0.394	8.23	0.85	18	24.8	0.019	30	FALSE	TRUE	FALSE	FALSE	1.3	0.3	1.9	1.1	0.2	0.62	0.07	18.2	8.44	8.62	0.21	18.58	1115.6	0.057	0.35	1.0371	0.0194	0.294	0.131101
200	4E+06	2	0.02	0.0039	0.1764	0.788	8.08	1.7	17	24.8	0.019	30	FALSE	TRUE	FALSE	FALSE	1.3	0.3	1.9	1.1	0.2	0.62	0.07	16	7.45	8.87	0.24	19.86	2231.2	0.03	0.55	1.0137	0.0164	0.512	0.141472
300	4E+06	2	0.03	0.0039	0.1733	1.183	7.94	2.54	17	24.8	0.019	30	FALSE	TRUE	FALSE	FALSE	1.3	0.3	1.9	1.1	0.2	0.62	0.07	14.2	6.6	9.121	0.27	20.87	3346.8	0.046	0.55	1.0169	0.025	1.205	0.153335
400	4E+06	2	0.03	0.0039	0.1701	1.577	7.79	3.39	17	24.8	0.019	30	FALSE	TRUE	FALSE	FALSE	1.3	0.3	1.9	1.1	0.2	0.62	0.07	12.6	5.88	9.371	0.3	21.78	4462.4	0.043	0.62	1.0136	0.0265	1.752	0.163387
500	4E+06	2	0.04	0.0039	0.167	1.971	7.65	4.24	16	24.8	0.019	30	FALSE	TRUE	FALSE	FALSE	1.3	0.3	1.9	1.1	0.2	0.62	0.07	11.3	5.26	9.622	0.32	22.61	5578	0.041	0.7	1.0115	0.0284	2.413	0.173795
600	4E+06	2	0.05	0.0039	0.1638	2.365	7.51	5.09	16	24.8	0.019	30	FALSE	TRUE	FALSE	FALSE	1.3	0.3	1.9	1.1	0.2	0.62	0.07	10.2	4.73	9.872	0.35	23.41	6693.6	0.039	0.78	1.01	0.0305	3.186	0.184681
700	4E+06	2	0.06	0.0039	0.1607	2.759	7.36	5.93	16	24.8	0.019	30	FALSE	TRUE	FALSE	FALSE	1.3	0.3	1.9	1.1	0.2	0.62	0.07	9.16	4.26	10.12	0.37	24.17	7809.2	0.038	0.85	1.0088	0.0322	4.028	0.195833
800	4E+06	2	0.07	0.0039	0.1576	3.153	7.22	6.78	16	24.8	0.019	30	FALSE	TRUE	FALSE	FALSE	1.3	0.3	1.9	1.1	0.2	0.62	0.07	8.28	3.85	10.37	0.39	24.91	8924.8	0.037	0.9	1.008	0.0333	4.871	0.206818
900	4E+06	2	0.08	0.0039	0.1544	3.548	7.08	7.63	15	24.8	0.019	30	FALSE	TRUE	FALSE	FALSE	1.3	0.3	1.9	1.1	0.2	0.62	0.07	7.51	3.49	10.62	0.41	25.63	10040	0.036	0.97	1.0073	0.0351	5.924	0.219104
1000	4E+06	2	0.09	0.0039	0.1513	3.942	6.93	8.48	15	24.8	0.019	30	FALSE	TRUE	FALSE	FALSE	1.3	0.3	1.9	1.1	0.2	0.62	0.07	6.83	3.18	10.87	0.43	26.32	11156	0.036	1	1.0067	0.0356	6.823	0.230188
1100	4E+06	2	0.09	0.0039	0.1482	4.336	6.79	9.33	15	24.8	0.019	30	FALSE	TRUE	FALSE	FALSE	1.3	0.3	1.9	1.1	0.2	0.62	0.07	6.22	2.89	11.12	0.45	27	12272	0.035	1.08	1.0062	0.0378	8.166	0.244227
1200	4E+06	2	0.1	0.0039	0.145	4.73	6.64	10.2	14	24.8	0.019	30	FALSE	TRUE	FALSE	FALSE	1.3	0.3	1.9	1.1	0.2	0.62	0.07	5.68	2.64	11.38	0.47	27.66	13387	0.035	1.1	1.0058	0.038	9.154	0.25568
1300	4E+06	2	0.11	0.0039	0.1419	5.124	6.5	11	14	24.8	0.019	30	FALSE	TRUE	FALSE	FALSE	1.3	0.3	1.9	1.1	0.2	0.62	0.07	5.2	2.42	11.63	0.49	28.31	14503	0.034	1.1	1.0055	0.0376	10.02	0.266141
1400	4E+06	2	0.12	0.0039	0.1388	5.518	6.36	11.9	14	24.8	0.019	30	FALSE	TRUE	FALSE	FALSE	1.3	0.3	1.9	1.1	0.2	0.62	0.07	4.77	2.22	11.88	0.51	28.94	15618	0.034	1.1	1.0052	0.0372	10.9	0.276668
1500	4E+06	2	0.13	0.0039	0.1356	5.913	6.21	12.7	13	24.8	0.019	30	FALSE	TRUE	FALSE	FALSE	1.3	0.3	1.9	1.1	0.2	0.62	0.07	4.38	2.04	12.13	0.53	29.55	16734	0.034	1.1	1.0049	0.0368	11.82	0.287263
1600	4E+06	2	0.14	0.0039	0.1325	6.307	6.07	13.6	13	24.8	0.019	30	FALSE	TRUE	FALSE	FALSE	1.3	0.3	1.9	1.1	0.2	0.62	0.07	4.03	1.87	12.38	0.55	30.15	17850	0.033	1.1	1.0046	0.0365	12.75	0.297932
1700	4E+06	2	0.15	0.0039	0.1293	6.701	5.93	14.4	13	24.8	0.019	30	FALSE	TRUE	FALSE	FALSE	1.3	0.3	1.9	1.1	0.2	0.62	0.07	3.71	1.72	12.63	0.56	30.73	18965	0.033	1.1	1.0044	0.0362	13.72	0.308678
1800	4E+06	2	0.15	0.0039	0.1262	7.095	5.78	15.3	12	24.8	0.019	30	FALSE	TRUE	FALSE	FALSE	1.3	0.3	1.9	1.1	0.2	0.62	0.07	3.42	1.59	12.88	0.58	31.3	20081	0.033	1.1	1.0042	0.036	14.71	0.319503
1900	4E+06	2	0.16	0.0039	0.1231	7.489	5.64	16.1	12	24.8	0.019	30	FALSE	TRUE	FALSE	FALSE	1.3	0.3	1.9	1.1	0.2	0.62	0.07	3.16	1.47	13.13	0.6	31.85	21196	0.033	1.1	1.004	0.0358	15.73	0.330411
2000	4E+06	2	0.17	0.0039	0.1199	7.884	5.5	17	12	24.8	0.019	30	TRUE	FALSE	FALSE	FALSE	1.3	0.3	1.9	1.1	0.2	0.62	0.07	6.68	3.11	13.38	0.64	33.39	22312	0.032	1.1	1.0038	0.0355	16.77	0.348298
2100	4E+06	2	0.18	0.0039	0.1168	8.278	5.35	17.8	12	24.8	0.019	30	TRUE	FALSE	FALSE	FALSE	1.3	0.3	1.9	1.1	0.2	0.62	0.07	6.8	3.16	13.63	0.66	33.96	23428	0.032	1.08	1.0037	0.0347	17.51	0.357443
2200	4E+06	2	0.19	0.0039	0.1137	8.672	5.21	18.7	11	24.8	0.019	30	TRUE	FALSE	FALSE	FALSE	1.3	0.3	1.9	1.1	0.2	0.62	0.07	6.94	3.23	13.88	0.68	34.51	24543	0.032	1.08	1.0035	0.0345	18.59	0.36874
2300	4E+06	2	0.2	0.0039	0.1105	9.066	5.06	19.5	11	24.8	0.019	30	TRUE	FALSE	FALSE	FALSE	1.3	0.3	1.9	1.1	0.2	0.62	0.07	7.09	3.3	14.13	0.69	35.04	25659	0.032	1.08	1.0034	0.0344	19.69	0.380077
2400	4E+06	2	0.21	0.0039	0.1074	9.46	4.92	20.3	11	24.8	0.019	30	TRUE	FALSE	FALSE	FALSE	1.3	0.3	1.9	1.1	0.2	0.62	0.07	7.25	3.37	14.38	0.71	35.55	26774	0.032	1.08	1.0032	0.0342	20.82	0.391457
2500	4E+06	2	0.22	0.0039	0.1043	9.854	4.78	21.2	10	24.8	0.019	30	TRUE	FALSE	FALSE	FALSE	1.3	0.3	1.9	1.1	0.2	0.62	0.07	7.42	3.45	14.63	0.72	36.04	27890	0.032	1.08	1.0031	0.0341	21.97	0.402885
2600	4E+06	2	0.22	0.0039	0.1011	10.25	4.63	22	10	24.8	0.019	30	TRUE	FALSE	FALSE	FALSE	1.3	0.3	1.9	1.1	0.2	0.62	0.07	7.6	3.53	14.88	0.73	36.52	29006	0.032	1.08	1.003	0.0339	23.15	0.414365
2700	4E+06	2	0.23	0.0039	0.098	10.64	4.49	22.9	9.7	24.8	0.019	30	TRUE	FALSE	FALSE	FALSE	1.3	0.3	1.9	1.1	0.2	0.62	0.07	7.78	3.62	15.13	0.75	36.97	30121	0.031	1.08	1.0029	0.0338	24.36	0.425904
2800	4E+06	2	0.24	0.0039	0.0948	11.04	4.35	23.7	9.3	24.8	0.019	30	TRUE	FALSE	FALSE	FALSE	1.3	0.3	1.9	1.1	0.2	0.62	0.07	7.97	3.71	15.38	0.76	37.41	31237	0.031	1.08	1.0028	0.0337	25.59	0.437506
2900	4E+06	2	0.25	0.0039	0.0917	11.43	4.2	24.6	9	24.8	0.019	30	TRUE	FALSE	FALSE	FALSE	1.3	0.3	1.9	1.1	0.2	0.62	0.07	8.17	3.8	15.63	0.77	37.83	32352	0.031	1.08	1.0027	0.0336	26.85	0.449177
3000	4E+06	2	0.26	0.0039	0.0886	11.83	4.06	25.4	8.7	24.8	0.019	30	TRUE	FALSE	FALSE	FALSE	1.3	0.3	1.9	1.1	0.2	0.62	0.07	8.37	3.89	15.88	0.79	38.24	33468	0.031	1.08	1.0026	0.0335	28.13	0.460922

Appendix D Table 5: Pressure Drop Calculation for Oil of API 35 at Constant Pressure and Temperature

Qo, stb/d	Qg, scf/d	dia, in	Qo, cu.ft/sec	Bg, cu.ft/scf	Qg, cu.ft/sec	Vsl	Vsg	Nlv	Ngv	Nd	Nl	IFT	Bubble flow	slug flow	Transition	mist flow	F1	F2	F3	F4	F5	F6'	F7	S	Vs	Vm	HL	pm	Nrel	fm	f2	f3	fm	DP friction	total DP psi/ft
100	4E+06	2	0.009	0.004	0.1789	0.413	8.198	0.9	17	24	0	30	FALSE	TRUE	FALSE	FALSE	1.25	0.24	1.25	24	0.19	0.6	0.09	17.52	8.26	8.61	0.204	18	2205.7	0.03	0.43	1.019	0.0127	0.202	0.1264
200	4E+06	2	0.018	0.004	0.1752	0.827	8.027	1.8	17	24	0	30	FALSE	TRUE	FALSE	FALSE	1.25	0.24	1.25	24	0.19	0.6	0.09	14.94	7.04	8.85	0.237	19.1	4411.5	0.043	0.48	1.019	0.0205	0.67	0.137
300	4E+06	2	0.0271	0.004	0.1715	1.24	7.856	2.6	17	24	0	30	FALSE	TRUE	FALSE	FALSE	1.25	0.24	1.25	24	0.19	0.6	0.09	12.85	6.06	9.1	0.266	20	6617.2	0.04	0.6	1.014	0.0234	1.182	0.1469
400	4E+06	2	0.0361	0.004	0.1677	1.653	7.685	3.5	16	24	0	30	FALSE	TRUE	FALSE	FALSE	1.25	0.24	1.25	24	0.19	0.6	0.09	11.13	5.25	9.34	0.294	20.8	8822.9	0.037	0.7	1.011	0.0259	1.786	0.157
500	4E+06	2	0.0451	0.004	0.164	2.066	7.514	4.4	16	24	0	30	FALSE	TRUE	FALSE	FALSE	1.25	0.24	1.25	24	0.19	0.6	0.09	9.707	4.58	9.58	0.32	21.6	11029	0.036	0.79	1.01	0.0281	2.487	0.1675
600	4E+06	2	0.0541	0.004	0.1603	2.48	7.343	5.3	16	24	0	30	FALSE	TRUE	FALSE	FALSE	1.25	0.24	1.25	24	0.19	0.6	0.09	8.516	4.02	9.82	0.345	22.4	13234	0.035	0.83	1.008	0.0287	3.124	0.1775
700	4E+06	2	0.0631	0.004	0.1565	2.893	7.172	6.1	15	24	0	30	FALSE	TRUE	FALSE	FALSE	1.25	0.24	1.25	24	0.19	0.6	0.09	7.509	3.54	10.1	0.369	23.2	15440	0.034	0.9	1.008	0.0304	3.96	0.1886
800	4E+06	2	0.0722	0.004	0.1528	3.306	7.001	7	15	24	0	30	FALSE	TRUE	FALSE	FALSE	1.25	0.24	1.25	24	0.19	0.6	0.09	6.652	3.14	10.3	0.393	24	17646	0.033	0.96	1.007	0.0319	4.856	0.2001
900	4E+06	2	0.0812	0.004	0.1491	3.719	6.83	7.9	14	24	0	30	FALSE	TRUE	FALSE	FALSE	1.25	0.24	1.25	24	0.19	0.6	0.09	5.917	2.79	10.5	0.417	24.7	19852	0.033	1	1.006	0.0327	5.739	0.2113
1000	4E+06	2	0.0902	0.004	0.1453	4.133	6.659	8.8	14	24	0	30	FALSE	TRUE	FALSE	FALSE	1.25	0.24	1.25	24	0.19	0.6	0.09	5.282	2.49	10.8	0.44	25.4	22057	0.032	1.08	1.006	0.0349	6.958	0.2248
1100	4E+06	2	0.0992	0.004	0.1416	4.546	6.488	9.6	14	24	0	30	FALSE	TRUE	FALSE	FALSE	1.25	0.24	1.25	24	0.19	0.6	0.09	4.731	2.23	11	0.462	26.1	24263	0.032	1.1	1.005	0.0351	7.886	0.2361
1200	4E+06	2	0.1082	0.004	0.1379	4.959	6.317	11	13	24	0	30	FALSE	TRUE	FALSE	FALSE	1.25	0.24	1.25	24	0.19	0.6	0.09	4.25	2	11.3	0.484	26.8	26469	0.032	1.1	1.005	0.0348	8.711	0.2466
1300	4E+06	2	0.1173	0.004	0.1341	5.372	6.146	11	13	24	0	30	FALSE	TRUE	FALSE	FALSE	1.25	0.24	1.25	24	0.19	0.6	0.09	3.827	1.8	11.5	0.506	27.5	28675	0.032	1.1	1.005	0.0345	9.563	0.2572
1400	4E+06	2	0.1263	0.004	0.1304	5.786	5.976	12	13	24	0	30	FALSE	TRUE	FALSE	FALSE	1.25	0.24	1.25	24	0.19	0.6	0.09	3.455	1.63	11.8	0.526	28.1	30880	0.031	1.1	1.005	0.0343	10.44	0.2679
1500	4E+06	2	0.1353	0.004	0.1267	6.199	5.805	13	12	24	0	30	FALSE	TRUE	FALSE	FALSE	1.25	0.24	1.25	24	0.19	0.6	0.09	3.125	1.47	12	0.547	28.8	33086	0.031	1.1	1.004	0.0341	11.35	0.2786
1600	4E+06	2	0.1443	0.004	0.123	6.612	5.634	14	12	24	0	30	FALSE	TRUE	FALSE	FALSE	1.25	0.24	1.25	24	0.19	0.6	0.09	2.832	1.34	12.2	0.567	29.4	35292	0.031	1.1	1.004	0.0339	12.28	0.2894
1700	4E+06	2	0.1533	0.004	0.1192	7.026	5.463	15	12	24	0	30	FALSE	TRUE	FALSE	FALSE	1.25	0.24	1.25	24	0.19	0.6	0.09	2.57	1.21	12.5	0.586	30	37498	0.031	1.1	1.004	0.0337	13.23	0.3003
1800	4E+06	2	0.1624	0.004	0.1155	7.439	5.292	16	11	24	0	30	TRUE	FALSE	FALSE	FALSE	1.25	0.24	1.25	24	0.19	0.6	0.09	5.15	2.43	12.7	0.629	31.3	39703	0.031	1.1	1.004	0.0336	14.22	0.3164
1900	4E+06	2	0.1714	0.004	0.1118	7.852	5.121	17	11	24	0	30	TRUE	FALSE	FALSE	FALSE	1.25	0.24	1.25	24	0.19	0.6	0.09	5.343	2.52	13	0.649	32	41909	0.03	1.1	1.003	0.0334	15.23	0.328
2000	4E+06	2	0.1804	0.004	0.108	8.265	4.95	18	10	24	0	30	TRUE	FALSE	FALSE	FALSE	1.25	0.24	1.25	24	0.19	0.6	0.09	5.538	2.61	13.2	0.669	32.6	44115	0.03	1.1	1.003	0.0333	16.27	0.3395
2100	4E+06	2	0.1894	0.004	0.1043	8.679	4.779	18	10	24	0	30	TRUE	FALSE	FALSE	FALSE	1.25	0.24	1.25	24	0.19	0.6	0.09	5.736	2.71	13.5	0.688	33.2	46320	0.03	1.1	1.003	0.0332	17.33	0.351
2200	4E+06	2	0.1984	0.004	0.1006	9.092	4.608	19	9.8	24	0	30	TRUE	FALSE	FALSE	FALSE	1.25	0.24	1.25	24	0.19	0.6	0.09	5.936	2.8	13.7	0.706	33.8	48526	0.03	1.1	1.003	0.0331	18.43	0.3625
2300	4E+06	2	0.2075	0.004	0.0968	9.505	4.437	20	9.4	24	0	30	TRUE	FALSE	FALSE	FALSE	1.25	0.24	1.25	24	0.19	0.6	0.09	6.138	2.89	13.9	0.723	34.3	50732	0.03	1.1	1.003	0.033	19.55	0.374
2400	4E+06	2	0.2165	0.004	0.0931	9.918	4.266	21	9	24	0	30	TRUE	FALSE	FALSE	FALSE	1.25	0.24	1.25	24	0.19	0.6	0.09	6.341	2.99	14.2	0.74	34.8	52938	0.03	1.1	1.003	0.0329	20.69	0.3856
2500	4E+06	2	0.2255	0.004	0.0894	10.33	4.095	22	8.7	24	0	30	TRUE	FALSE	FALSE	FALSE	1.25	0.24	1.25	24	0.19	0.6	0.09	6.545	3.09	14.4	0.756	35.3	55143	0.03	1.05	1.003	0.0313	20.87	0.3903
2600	4E+06	2	0.2345	0.004	0.0856	10.74	3.924	23	8.3	24	0	30	TRUE	FALSE	FALSE	FALSE	1.25	0.24	1.25	24	0.19	0.6	0.09	6.75	3.18	14.7	0.771	35.8	57349	0.03	1.05	1.003	0.0312	22.02	0.4015
2700	4E+06	2	0.2435	0.004	0.0819	11.16	3.753	24	8	24	0	30	TRUE	FALSE	FALSE	FALSE	1.25	0.24	1.25	24	0.19	0.6	0.09	6.955	3.28	14.9	0.785	36.3	59555	0.03	1.05	1.002	0.0312	23.19	0.4129
2800	4E+06	2	0.2526	0.004	0.0782	11.57	3.582	25	7.6	24	0	30	TRUE	FALSE	FALSE	FALSE	1.25	0.24	1.25	24	0.19	0.6	0.09	7.162	3.38	15.2	0.799	36.7	61761	0.03	1.05	1.002	0.0311	24.39	0.4242
2900	4E+06	2	0.2616	0.004	0.0744	11.98	3.411	25	7.2	24	0	30	TRUE	FALSE	FALSE	FALSE	1.25	0.24	1.25	24	0.19	0.6	0.09	7.368	3.47	15.4	0.813	37.1	63966	0.03	1.05	1.002	0.031	25.61	0.4356
3000	4E+06	2	0.2706	0.004	0.0707	12.4	3.24	26	6.9	24	0	30	TRUE	FALSE	FALSE	FALSE	1.25	0.24	1.25	24	0.19	0.6	0.09	7.576	3.57	15.6	0.826	37.5	66172	0.03	1.05	1.002	0.031	26.86	0.4471

Appendix D Table 6: Pressure Drop Computation for West Sak Oil A for Gas Flow Rate of 4MMscf/d

Qo, stb/d	Qg, MMscf/d	diameter, in	Qo, cu.ft/sec	Qg, cu.ft/sec	Vsl ft/sec	Vsg ft/sec	Nlv	Ngv	Nd	Nl	IFT	L1	L2	L1+(L2.Nlv)	Bubble flow	Ls	LM	slug flow	Transition flow	mist flow	F1	F2	F3	F4	F5	F6'	F7	S	Vs ft/sec	Vm ft/sec	HL	ρm lb/cu.ft	Nrel	f1	f2	f3	fm	DP fric lb/cu.ft	total pressure loss psi/ft
100	4.00	2.00	0.01	0.34	0.32	15.63	0.72	35.47	27.62	0.16	30.00	2.00	0.68	2.49	FALSE	76.00	140.81	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	35.97	15.85	15.95	0.14	12.70	125.75	0.51	0.20	1.50	0.07	1.58	0.10
200	4.00	2.00	0.01	0.34	0.64	15.55	1.44	35.28	27.62	0.16	30.00	2.00	0.68	2.98	FALSE	102.00	185.68	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	34.14	15.04	16.18	0.17	14.36	251.50	0.25	0.23	1.18	0.05	2.35	0.12
300	4.00	2.00	0.02	0.34	0.95	15.46	2.17	35.09	27.62	0.16	30.00	2.00	0.68	3.47	FALSE	128.00	225.01	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	32.44	14.29	16.42	0.19	15.54	377.24	0.17	0.28	1.10	0.04	3.12	0.13
400	4.00	2.00	0.03	0.34	1.27	15.38	2.89	34.91	27.62	0.16	30.00	2.00	0.68	3.96	FALSE	154.00	261.13	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	30.85	13.60	16.66	0.21	16.50	502.99	0.13	0.31	1.06	0.04	3.62	0.14
500	4.00	2.00	0.03	0.33	1.59	15.30	3.61	34.72	27.62	0.16	30.00	2.00	0.68	4.46	FALSE	180.00	295.04	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	29.38	12.95	16.89	0.23	17.33	628.74	0.10	0.37	1.04	0.04	4.45	0.15
600	4.00	2.00	0.04	0.33	1.91	15.22	4.33	34.53	27.62	0.16	30.00	2.00	0.68	4.95	FALSE	206.00	327.29	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	28.00	12.34	17.13	0.24	18.08	754.49	0.08	0.40	1.03	0.03	4.93	0.16
700	4.00	2.00	0.05	0.33	2.23	15.13	5.06	34.34	27.62	0.16	30.00	2.00	0.68	5.44	FALSE	232.00	358.21	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	26.70	11.77	17.36	0.26	18.76	880.24	0.07	0.45	1.03	0.03	5.66	0.17
800	4.00	2.00	0.06	0.33	2.55	15.05	5.78	34.16	27.62	0.16	30.00	2.00	0.68	5.93	FALSE	258.00	388.04	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	25.49	11.23	17.60	0.27	19.40	1005.99	0.06	0.48	1.02	0.03	6.15	0.18
900	4.00	2.00	0.06	0.33	2.86	14.97	6.50	33.97	27.62	0.16	30.00	2.00	0.68	6.42	FALSE	284.00	416.95	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	24.36	10.73	17.83	0.28	20.01	1131.73	0.06	0.53	1.02	0.03	6.91	0.19
1000	4.00	2.00	0.07	0.32	3.18	14.89	7.22	33.78	27.62	0.16	30.00	2.00	0.68	6.91	FALSE	310.00	445.07	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	23.29	10.26	18.07	0.29	20.59	1257.48	0.05	0.58	1.02	0.03	7.68	0.20
1100	4.00	2.00	0.08	0.32	3.50	14.80	7.94	33.60	27.62	0.16	30.00	2.00	0.68	7.40	FALSE	336.00	472.49	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	22.29	9.82	18.31	0.30	21.14	1383.23	0.05	0.65	1.01	0.03	8.74	0.21
1200	4.00	2.00	0.08	0.32	3.82	14.72	8.67	33.41	27.62	0.16	30.00	2.00	0.68	7.89	FALSE	362.00	499.29	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	21.34	9.40	18.54	0.32	21.68	1508.98	0.04	0.68	1.01	0.03	9.27	0.21
1300	4.00	2.00	0.09	0.32	4.14	14.64	9.39	33.22	27.62	0.16	30.00	2.00	0.68	8.38	FALSE	388.00	525.54	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	20.45	9.01	18.78	0.33	22.20	1634.73	0.04	0.70	1.01	0.03	9.68	0.22
1400	4.00	2.00	0.10	0.32	4.46	14.56	10.11	33.03	27.62	0.16	30.00	2.00	0.68	8.88	FALSE	414.00	551.29	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	19.61	8.64	19.01	0.34	22.70	1760.47	0.04	0.79	1.01	0.03	11.08	0.23
1500	4.00	2.00	0.10	0.32	4.77	14.47	10.83	32.85	27.62	0.16	30.00	2.00	0.68	9.37	FALSE	440.00	576.59	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	18.82	8.29	19.25	0.35	23.19	1886.22	0.03	0.81	1.01	0.03	11.51	0.24
1600	4.00	2.00	0.11	0.31	5.09	14.39	11.56	32.66	27.62	0.16	30.00	2.00	0.68	9.86	FALSE	466.00	601.47	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	18.07	7.96	19.48	0.35	23.67	2011.97	0.03	0.85	1.01	0.03	12.25	0.25
1700	4.00	2.00	0.12	0.31	5.41	14.31	12.28	32.47	27.62	0.16	30.00	2.00	0.68	10.35	FALSE	492.00	625.96	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	17.36	7.65	19.72	0.36	24.14	2137.72	0.03	0.90	1.01	0.03	13.30	0.26
1800	4.00	2.00	0.13	0.31	5.73	14.23	13.00	32.29	27.62	0.16	30.00	2.00	0.68	10.84	FALSE	518.00	650.09	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	16.68	7.35	19.96	0.37	24.60	2263.47	0.03	0.91	1.01	0.03	14.44	0.27
1900	4.00	2.00	0.13	0.31	6.05	14.14	13.72	32.10	27.62	0.16	30.00	2.00	0.68	11.33	FALSE	544.00	673.89	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	16.05	7.07	20.19	0.38	25.06	2389.22	0.03	0.92	1.01	0.03	16.70	0.29
2000	4.00	2.00	0.14	0.31	6.37	14.06	14.44	31.91	27.62	0.16	30.00	2.00	0.68	11.82	FALSE	570.00	697.38	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	15.44	6.80	20.43	0.39	25.50	2514.96	0.04	0.90	1.01	0.03	19.05	0.31
2100	4.00	2.00	0.15	0.31	6.68	13.98	15.17	31.72	27.62	0.16	30.00	2.00	0.68	12.31	FALSE	596.00	720.57	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	14.87	6.55	20.66	0.40	25.94	2640.71	0.04	0.88	1.01	0.03	21.55	0.33
2200	4.00	2.00	0.15	0.30	7.00	13.90	15.89	31.54	27.62	0.16	30.00	2.00	0.68	12.80	FALSE	622.00	743.49	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	14.32	6.31	20.90	0.41	26.37	2766.46	0.04	0.88	1.01	0.04	24.52	0.35
2300	4.00	2.00	0.16	0.30	7.32	13.81	16.61	31.35	27.62	0.16	30.00	2.00	0.68	13.30	FALSE	648.00	766.16	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	13.80	6.08	21.13	0.42	26.79	2892.21	0.04	0.88	1.01	0.04	27.31	0.38
2400	4.00	2.00	0.17	0.30	7.64	13.73	17.33	31.16	27.62	0.16	30.00	2.00	0.68	13.79	FALSE	674.00	788.57	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	13.31	5.86	21.37	0.42	27.20	3017.96	0.05	0.88	1.01	0.04	29.74	0.40
2500	4.00	2.00	0.17	0.30	7.96	13.65	18.06	30.98	27.62	0.16	30.00	2.00	0.68	14.28	FALSE	699.99	810.76	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	12.83	5.66	21.61	0.43	27.61	3143.70	0.05	0.90	1.01	0.04	32.50	0.42
2600	4.00	2.00	0.18	0.30	8.27	13.57	18.78	30.79	27.62	0.16	30.00	2.00	0.68	14.77	FALSE	725.99	832.72	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	12.39	5.46	21.84	0.44	28.01	3269.45	0.05	0.90	1.01	0.04	34.29	0.43
2700	4.00	2.00	0.19	0.29	8.59	13.48	19.50	30.60	27.62	0.16	30.00	2.00	0.68	15.26	FALSE	751.99	854.48	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	11.96	5.27	22.08	0.45	28.41	3395.20	0.05	0.93	1.01	0.04	37.09	0.45
2800	4.00	2.00	0.19	0.29	8.91	13.40	20.22	30.41	27.62	0.16	30.00	2.00	0.68	15.75	FALSE	777.99	876.03	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	11.55	5.09	22.31	0.46	28.80	3520.95	0.05	0.93	1.01	0.04	38.65	0.47
2900	4.00	2.00	0.20	0.29	9.23	13.32	20.94	30.23	27.62	0.16	30.00	2.00	0.68	16.24	FALSE	803.99	897.39	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	11.16	4.92	22.55	0.46	29.18	3646.70	0.05	0.95	1.01	0.04	41.03	0.49
3000	4.00	2.00	0.21	0.29	9.55	13.24	21.67	30.04	27.62	0.16	30.00	2.00	0.68	16.73	FALSE	829.99	918.57	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	10.78	4.75	22.78	0.47	29.56	3772.45	0.05	0.97	1.01	0.04	43.45	0.51

Appendix D Table 7: Pressure Drop Computation for West Sak Oil A for Gas Flow Rate of 2MMscf/d

Qo, stb/d	Qg, MMscf/d	diameter, in	Qo, cu.ft/sec	Qg, cu.ft/sec	Vsl ft/sec	Vsg ft/sec	Nlv	Ngv	Nd	Nl	IFT	L1	L2	L1+(L2.Nlv)	Bubble flow	Ls	LM	slug flow	Transition flow	mist flow	F1	F2	F3	F4	F5	F6'	F7	S	Vs ft/sec	Vm ft/sec	HL	ρm lb/cu.ft	Nrel	f1	f2	f3	fm	DP friction lb/cu.ft	total pressure loss psi/ft
100	2.00	2.00	0.01	0.17	0.32	7.77	0.72	17.64	27.62	0.16	30.00	2.00	0.68	2.49	0.00	76.00	140.81	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	19.55	8.61	8.09	0.22	17.08	125.75	0.51	0.20	1.36	0.08	0.89	0.12
200	2.00	2.00	0.01	0.17	0.64	7.69	1.44	17.45	27.62	0.16	30.00	2.00	0.68	2.98	0.00	102.00	185.68	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	18.48	8.14	8.33	0.27	19.29	251.50	0.25	0.27	1.13	0.06	1.49	0.14
300	2.00	2.00	0.02	0.17	0.95	7.61	2.17	17.27	27.62	0.16	30.00	2.00	0.68	3.47	0.00	128.00	225.01	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	17.48	7.70	8.56	0.30	20.92	377.24	0.17	0.33	1.07	0.05	1.97	0.16
400	2.00	2.00	0.03	0.16	1.27	7.53	2.89	17.08	27.62	0.16	30.00	2.00	0.68	3.96	0.00	154.00	261.13	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	16.56	7.30	8.80	0.33	22.27	502.99	0.13	0.39	1.04	0.05	2.45	0.17
500	2.00	2.00	0.03	0.16	1.59	7.44	3.61	16.89	27.62	0.16	30.00	2.00	0.68	4.46	0.00	180.00	295.04	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	15.70	6.92	9.03	0.35	23.45	628.74	0.10	0.45	1.03	0.04	2.93	0.18
600	2.00	2.00	0.04	0.16	1.91	7.36	4.33	16.70	27.62	0.16	30.00	2.00	0.68	4.95	0.00	206.00	327.29	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	14.89	6.56	9.27	0.37	24.50	754.49	0.08	0.51	1.02	0.04	3.44	0.19
700	2.00	2.00	0.05	0.16	2.23	7.28	5.06	16.52	27.62	0.16	30.00	2.00	0.68	5.44	0.00	232.00	358.21	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	14.14	6.23	9.51	0.39	25.47	880.24	0.07	0.60	1.02	0.04	4.17	0.21
800	2.00	2.00	0.06	0.16	2.55	7.20	5.78	16.33	27.62	0.16	30.00	2.00	0.68	5.93	0.00	258.00	388.04	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	13.44	5.92	9.74	0.41	26.38	1005.99	0.06	0.68	1.02	0.04	4.86	0.22
900	2.00	2.00	0.06	0.16	2.86	7.11	6.50	16.14	27.62	0.16	30.00	2.00	0.68	6.42	0.00	284.00	416.95	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	12.78	5.63	9.98	0.43	27.23	1131.73	0.06	0.70	1.01	0.04	5.13	0.22
1000	2.00	2.00	0.07	0.15	3.18	7.03	7.22	15.96	27.62	0.16	30.00	2.00	0.68	6.91	0.00	310.00	445.07	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	12.17	5.36	10.21	0.44	28.04	1257.48	0.05	0.79	1.01	0.04	5.94	0.24
1100	2.00	2.00	0.08	0.15	3.50	6.95	7.94	15.77	27.62	0.16	30.00	2.00	0.68	7.40	0.00	336.00	472.49	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	11.59	5.11	10.45	0.46	28.82	1383.23	0.05	0.87	1.01	0.04	6.70	0.25
1200	2.00	2.00	0.08	0.15	3.82	6.87	8.67	15.58	27.62	0.16	30.00	2.00	0.68	7.89	0.00	362.00	499.29	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	11.04	4.87	10.69	0.47	29.56	1508.98	0.04	0.90	1.01	0.04	7.10	0.25
1300	2.00	2.00	0.09	0.15	4.14	6.78	9.39	15.39	27.62	0.16	30.00	2.00	0.68	8.38	0.00	388.00	525.54	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	10.53	4.64	10.92	0.48	30.27	1634.73	0.04	0.95	1.01	0.04	7.67	0.26
1400	2.00	2.00	0.10	0.15	4.46	6.70	10.11	15.21	27.62	0.16	30.00	2.00	0.68	8.88	0.00	414.00	551.29	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	10.05	4.43	11.16	0.50	30.96	1760.47	0.04	1.00	1.01	0.04	8.25	0.27
1500	2.00	2.00	0.10	0.14	4.77	6.62	10.83	15.02	27.62	0.16	30.00	2.00	0.68	9.37	0.00	440.00	576.59	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	9.59	4.23	11.39	0.51	31.63	1886.22	0.03	1.08	1.01	0.04	9.11	0.28
1600	2.00	2.00	0.11	0.14	5.09	6.54	11.56	14.83	27.62	0.16	30.00	2.00	0.68	9.86	0.00	466.00	601.47	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	9.16	4.04	11.63	0.52	32.28	2011.97	0.03	1.10	1.01	0.03	9.49	0.29
1700	2.00	2.00	0.12	0.14	5.41	6.45	12.28	14.65	27.62	0.16	30.00	2.00	0.68	10.35	0.00	492.00	625.96	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	8.76	3.86	11.86	0.54	32.91	2137.72	0.03	1.10	1.00	0.03	9.80	0.30
1800	2.00	2.00	0.13	0.14	5.73	6.37	13.00	14.46	27.62	0.16	30.00	2.00	0.68	10.84	0.00	518.00	650.09	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	8.37	3.69	12.10	0.55	33.52	2263.47	0.03	1.10	1.00	0.03	10.60	0.31
1900	2.00	2.00	0.13	0.14	6.05	6.29	13.72	14.27	27.62	0.16	30.00	2.00	0.68	11.33	0.00	544.00	673.89	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	8.01	3.53	12.34	0.56	34.11	2389.22	0.03	1.10	1.00	0.04	12.23	0.32
2000	2.00	2.00	0.14	0.14	6.37	6.21	14.44	14.08	27.62	0.16	30.00	2.00	0.68	11.82	0.00	570.00	697.38	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	7.67	3.38	12.57	0.57	34.69	2514.96	0.04	1.10	1.00	0.04	14.37	0.34
2100	2.00	2.00	0.15	0.13	6.68	6.12	15.17	13.90	27.62	0.16	30.00	2.00	0.68	12.31	0.00	596.00	720.57	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	7.34	3.24	12.81	0.58	35.26	2640.71	0.04	1.10	1.01	0.04	16.74	0.36
2200	2.00	2.00	0.15	0.13	7.00	6.04	15.89	13.71	27.62	0.16	30.00	2.00	0.68	12.80	0.00	622.00	743.49	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	7.03	3.10	13.04	0.59	35.81	2766.46	0.04	1.10	1.01	0.05	19.18	0.38
2300	2.00	2.00	0.16	0.13	7.32	5.96	16.61	13.52	27.62	0.16	30.00	2.00	0.68	13.30	0.00	648.00	766.16	TRUE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	6.74	2.97	13.28	0.60	36.35	2892.21	0.04	1.10	1.01	0.05	21.51	0.40
2400	2.00	2.00	0.17	0.13	7.64	5.88	17.33	13.34	27.62	0.16	30.00	2.00	0.68	13.79	13.34	674.00	788.57	FALSE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	20.54	9.05	13.51	0.70	41.41	3017.96	0.05	1.10	1.01	0.05	23.58	0.45
2500	2.00	2.00	0.17	0.13	7.96	5.79	18.06	13.15	27.62	0.16	30.00	2.00	0.68	14.28	13.15	699.99	810.76	FALSE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	21.20	9.34	13.75	0.72	42.02	3143.70	0.05	1.10	1.01	0.05	25.36	0.47
2600	2.00	2.00	0.18	0.12	8.27	5.71	18.78	12.96	27.62	0.16	30.00	2.00	0.68	14.77	12.96	725.99	832.72	FALSE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	21.87	9.64	13.99	0.73	42.60	3269.45	0.05	1.10	1.01	0.05	26.91	0.48
2700	2.00	2.00	0.19	0.12	8.59	5.63	19.50	12.77	27.62	0.16	30.00	2.00	0.68	15.26	12.77	751.99	854.48	FALSE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	22.54	9.93	14.22	0.74	43.16	3395.20	0.05	1.10	1.01	0.05	28.34	0.50
2800	2.00	2.00	0.19	0.12	8.91	5.55	20.22	12.59	27.62	0.16	30.00	2.00	0.68	15.75	12.59	777.99	876.03	FALSE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	23.23	10.24	14.46	0.75	43.68	3520.95	0.05	1.10	1.01	0.05	29.70	0.51
2900	2.00	2.00	0.20	0.12	9.23	5.46	20.94	12.40	27.62	0.16	30.00	2.00	0.68	16.24	12.40	803.99	897.39	FALSE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	23.92	10.54	14.69	0.76	44.19	3646.70	0.05	1.10	1.00	0.05	31.04	0.52
3000	2.00	2.00	0.21	0.12	9.55	5.38	21.67	12.21	27.62	0.16	30.00	2.00	0.68	16.73	12.21	829.99	918.57	FALSE	FALSE	FALSE	2.10	1.02	3.42	55.00	0.04	2.90	0.03	24.61	10.85	14.93	0.77	44.67	3772.45	0.05	1.10	1.00	0.05	32.37	0.54

Appendix D Table 8: Pressure Drop Computation for West Sak Oil B for Gas Flow Rate of 4MMscf/d

Qo, stb/d	Qg, MMscf/d	diameter, in	Qo, cu.ft/sec	Qg, cu.ft/sec	Vsl ft/s	Vsg ft/s	Nlv	Ngv	Nd	Nl	IFT	L1	L2	L1+L2.Nlv	Bubble Flow	Ls	LM	slug flow	Transition Flow	mist flow	F1	F2	F3	F4	F5	F6'	F7	S	Vs ft/s	Vm ft/s	HL	ρm lb/cu.ft	Nrel	f1	f2	f3	fm	Dp friction lb/cu.ft	total DP psi/ft
100.00	4.00	2.00	0.01	0.44	0.31	20.36	0.72	46.70	28.22	1.13	30.00	2.00	0.70	2.50	FALSE	75.89	140.59	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	48.77	21.26	20.68	0.14	11.77	17.88	3.58	0.20	5.08	0.14	5.01	0.12
200.00	4.00	2.00	0.01	0.44	0.63	20.28	1.44	46.51	28.22	1.13	30.00	2.00	0.68	2.98	FALSE	101.77	185.31	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	46.91	20.45	20.90	0.16	13.31	35.75	1.79	0.20	2.44	0.15	10.55	0.17
300.00	4.00	2.00	0.02	0.44	0.94	20.19	2.16	46.31	28.22	1.13	30.00	2.00	0.68	3.47	FALSE	127.66	224.52	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	45.15	19.68	21.13	0.18	14.43	53.63	1.19	0.20	1.78	0.13	14.60	0.20
400.00	4.00	2.00	0.03	0.44	1.25	20.11	2.88	46.11	28.22	1.13	30.00	2.00	0.68	3.96	FALSE	153.54	260.52	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	43.48	18.96	21.36	0.20	15.33	71.50	0.90	0.20	1.51	0.12	17.45	0.23
500.00	4.00	2.00	0.03	0.44	1.57	20.02	3.60	45.92	28.22	1.13	30.00	2.00	0.68	4.44	FALSE	179.43	294.32	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	41.89	18.26	21.59	0.22	16.11	89.38	0.72	0.22	1.36	0.12	21.46	0.26
600.00	4.00	2.00	0.04	0.44	1.88	19.93	4.31	45.72	28.22	1.13	30.00	2.00	0.68	4.93	FALSE	205.31	326.45	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	40.38	17.61	21.82	0.23	16.80	107.25	0.60	0.23	1.27	0.11	24.23	0.28
700.00	4.00	2.00	0.05	0.43	2.19	19.85	5.03	45.53	28.22	1.13	30.00	2.00	0.68	5.42	FALSE	231.20	357.27	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	38.95	16.98	22.04	0.24	17.44	125.13	0.51	0.24	1.22	0.10	26.75	0.31
800.00	4.00	2.00	0.05	0.43	2.51	19.76	5.75	45.33	28.22	1.13	30.00	2.00	0.68	5.91	FALSE	257.08	387.01	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	37.58	16.39	22.27	0.25	18.02	143.00	0.45	0.26	1.18	0.10	30.26	0.34
900.00	4.00	2.00	0.06	0.43	2.82	19.68	6.47	45.14	28.22	1.13	30.00	2.00	0.68	6.40	FALSE	282.97	415.82	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	36.28	15.82	22.50	0.26	18.58	160.88	0.40	0.28	1.15	0.10	33.76	0.36
1000.00	4.00	2.00	0.07	0.43	3.13	19.59	7.19	44.94	28.22	1.13	30.00	2.00	0.68	6.89	FALSE	308.85	443.85	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	35.04	15.28	22.73	0.27	19.10	178.75	0.36	0.29	1.13	0.09	36.01	0.38
1100.00	4.00	2.00	0.08	0.43	3.45	19.51	7.91	44.74	28.22	1.13	30.00	2.00	0.68	7.38	FALSE	334.74	471.18	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	33.86	14.76	22.96	0.28	19.60	196.63	0.33	0.30	1.11	0.09	38.21	0.40
1200.00	4.00	2.00	0.08	0.42	3.76	19.42	8.63	44.55	28.22	1.13	30.00	2.00	0.68	7.87	FALSE	360.63	497.89	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	32.74	14.27	23.18	0.29	20.09	214.51	0.30	0.32	1.10	0.09	41.67	0.43
1300.00	4.00	2.00	0.09	0.42	4.08	19.34	9.35	44.35	28.22	1.13	30.00	2.00	0.68	8.36	FALSE	386.51	524.06	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	31.66	13.80	23.41	0.30	20.55	232.38	0.28	0.34	1.08	0.09	45.16	0.46
1400.00	4.00	2.00	0.10	0.42	4.39	19.25	10.07	44.16	28.22	1.13	30.00	2.00	0.68	8.85	FALSE	412.40	549.72	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	30.63	13.35	23.64	0.31	21.00	250.26	0.26	0.35	1.08	0.08	47.34	0.47
1500.00	4.00	2.00	0.10	0.42	4.70	19.17	10.79	43.96	28.22	1.13	30.00	2.00	0.68	9.33	FALSE	438.28	574.93	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	29.65	12.93	23.87	0.31	21.44	268.13	0.24	0.36	1.07	0.08	49.51	0.49
1600.00	4.00	2.00	0.11	0.42	5.02	19.08	11.50	43.77	28.22	1.13	30.00	2.00	0.68	9.82	FALSE	464.17	599.73	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	28.71	12.52	24.10	0.32	21.87	286.01	0.22	0.38	1.06	0.08	53.08	0.52
1700.00	4.00	2.00	0.12	0.41	5.33	19.00	12.22	43.57	28.22	1.13	30.00	2.00	0.68	10.31	FALSE	490.05	624.14	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	27.81	12.12	24.33	0.33	22.29	303.88	0.21	0.39	1.06	0.08	55.28	0.54
1800.00	4.00	2.00	0.12	0.41	5.64	18.91	12.94	43.37	28.22	1.13	30.00	2.00	0.68	10.80	FALSE	515.94	648.19	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	26.94	11.75	24.55	0.34	22.70	321.76	0.20	0.40	1.05	0.08	57.49	0.56
1900.00	4.00	2.00	0.13	0.41	5.96	18.82	13.66	43.18	28.22	1.13	30.00	2.00	0.68	11.29	FALSE	541.82	671.91	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	26.12	11.39	24.78	0.34	23.10	339.63	0.19	0.42	1.05	0.08	61.17	0.59
2000.00	4.00	2.00	0.14	0.41	6.27	18.74	14.38	42.98	28.22	1.13	30.00	2.00	0.68	11.78	FALSE	567.71	695.32	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	25.33	11.04	25.01	0.35	23.50	357.51	0.18	0.43	1.04	0.07	63.42	0.60
2100.00	4.00	2.00	0.14	0.41	6.58	18.65	15.10	42.79	28.22	1.13	30.00	2.00	0.68	12.27	FALSE	593.59	718.44	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	24.56	10.71	25.24	0.36	23.89	375.38	0.17	0.45	1.04	0.07	67.18	0.63
2200.00	4.00	2.00	0.15	0.41	6.90	18.57	15.82	42.59	28.22	1.13	30.00	2.00	0.68	12.76	FALSE	619.48	741.29	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	23.83	10.39	25.47	0.37	24.27	393.26	0.16	0.48	1.04	0.08	72.50	0.67
2300.00	4.00	2.00	0.16	0.40	7.21	18.48	16.54	42.39	28.22	1.13	30.00	2.00	0.68	13.25	FALSE	645.37	763.87	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	23.13	10.09	25.69	0.37	24.65	411.14	0.16	0.49	1.04	0.07	74.85	0.69
2400.00	4.00	2.00	0.16	0.40	7.52	18.40	17.26	42.20	28.22	1.13	30.00	2.00	0.68	13.73	FALSE	671.25	786.22	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	22.46	9.79	25.92	0.38	25.02	429.01	0.15	0.50	1.03	0.07	77.23	0.71
2500.00	4.00	2.00	0.17	0.40	7.84	18.31	17.98	42.00	28.22	1.13	30.00	2.00	0.68	14.22	FALSE	697.14	808.33	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	21.81	9.51	26.15	0.39	25.38	446.89	0.14	0.51	1.03	0.07	79.62	0.73
2600.00	4.00	2.00	0.18	0.40	8.15	18.23	18.70	41.81	28.22	1.13	30.00	2.00	0.68	14.71	FALSE	723.02	830.22	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	21.19	9.24	26.38	0.39	25.75	464.76	0.14	0.52	1.03	0.07	82.04	0.75
2700.00	4.00	2.00	0.18	0.40	8.46	18.14	19.41	41.61	28.22	1.13	30.00	2.00	0.68	15.20	FALSE	748.91	851.90	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	20.59	8.98	26.61	0.40	26.10	482.64	0.13	0.55	1.03	0.07	87.66	0.79
2800.00	4.00	2.00	0.19	0.39	8.78	18.06	20.13	41.42	28.22	1.13	30.00	2.00	0.68	15.69	FALSE	774.79	873.39	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	20.01	8.73	26.83	0.41	26.45	500.51	0.13	0.56	1.03	0.07	90.16	0.81
2900.00	4.00	2.00	0.20	0.39	9.09	17.97	20.85	41.22	28.22	1.13	30.00	2.00	0.68	16.18	FALSE	800.68	894.68	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	19.46	8.48	27.06	0.41	26.80	518.39	0.12	0.57	1.02	0.07	92.67	0.83
3000.00	4.00	2.00	0.21	0.39	9.40	17.89	21.57	41.02	28.22	1.13	30.00	2.00	0.68	16.67	FALSE	826.56	915.79	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	18.92	8.25	27.29	0.42	27.14	536.26	0.12	0.59	1.02	0.07	96.85	0.86

Appendix D Table 9: Pressure Drop Computation for West Sak Oil B for Gas Flow Rate of 2MMscf/d

Qo, stb/d	Qg, MMscf/d	diameter, in	Qo, cu.ft/sec	Qg, cu.ft/sec	Vsl ft/s	Vsg ft/s	Nlv	Ngv	Nd	Nl	IFT	L1	L2	L1+L2.Nlv	Bubble Flow	Ls	LM
100.00	2.00	2.00	0.01	0.22	0.31	10.14	0.72	23.25	28.22	1.13	30.00	2.00	0.70	2.50	0.00	75.89	140.59
200.00	2.00	2.00	0.01	0.22	0.63	10.05	1.44	23.06	28.22	1.13	30.00	2.00	0.68	2.98	0.00	101.77	185.31
300.00	2.00	2.00	0.02	0.22	0.94	9.97	2.16	22.86	28.22	1.13	30.00	2.00	0.68	3.47	0.00	127.66	224.52
400.00	2.00	2.00	0.03	0.22	1.25	9.88	2.88	22.67	28.22	1.13	30.00	2.00	0.68	3.96	0.00	153.54	260.52
500.00	2.00	2.00	0.03	0.21	1.57	9.80	3.60	22.47	28.22	1.13	30.00	2.00	0.68	4.44	0.00	179.43	294.32
600.00	2.00	2.00	0.04	0.21	1.88	9.71	4.31	22.27	28.22	1.13	30.00	2.00	0.68	4.93	0.00	205.31	326.45
700.00	2.00	2.00	0.05	0.21	2.19	9.63	5.03	22.08	28.22	1.13	30.00	2.00	0.68	5.42	0.00	231.20	357.27
800.00	2.00	2.00	0.05	0.21	2.51	9.54	5.75	21.88	28.22	1.13	30.00	2.00	0.68	5.91	0.00	257.08	387.01
900.00	2.00	2.00	0.06	0.21	2.82	9.46	6.47	21.69	28.22	1.13	30.00	2.00	0.68	6.40	0.00	282.97	415.82
1000.00	2.00	2.00	0.07	0.20	3.13	9.37	7.19	21.49	28.22	1.13	30.00	2.00	0.68	6.89	0.00	308.85	443.85
1100.00	2.00	2.00	0.08	0.20	3.45	9.28	7.91	21.30	28.22	1.13	30.00	2.00	0.68	7.38	0.00	334.74	471.18
1200.00	2.00	2.00	0.08	0.20	3.76	9.20	8.63	21.10	28.22	1.13	30.00	2.00	0.68	7.87	0.00	360.63	497.89
1300.00	2.00	2.00	0.09	0.20	4.08	9.11	9.35	20.90	28.22	1.13	30.00	2.00	0.68	8.36	0.00	386.51	524.06
1400.00	2.00	2.00	0.10	0.20	4.39	9.03	10.07	20.71	28.22	1.13	30.00	2.00	0.68	8.85	0.00	412.40	549.72
1500.00	2.00	2.00	0.10	0.20	4.70	8.94	10.79	20.51	28.22	1.13	30.00	2.00	0.68	9.33	0.00	438.28	574.93
1600.00	2.00	2.00	0.11	0.19	5.02	8.86	11.50	20.32	28.22	1.13	30.00	2.00	0.68	9.82	0.00	464.17	599.73
1700.00	2.00	2.00	0.12	0.19	5.33	8.77	12.22	20.12	28.22	1.13	30.00	2.00	0.68	10.31	0.00	490.05	624.14
1800.00	2.00	2.00	0.12	0.19	5.64	8.69	12.94	19.92	28.22	1.13	30.00	2.00	0.68	10.80	0.00	515.94	648.19
1900.00	2.00	2.00	0.13	0.19	5.96	8.60	13.66	19.73	28.22	1.13	30.00	2.00	0.68	11.29	0.00	541.82	671.91
2000.00	2.00	2.00	0.14	0.19	6.27	8.52	14.38	19.53	28.22	1.13	30.00	2.00	0.68	11.78	0.00	567.71	695.32
2100.00	2.00	2.00	0.14	0.18	6.58	8.43	15.10	19.34	28.22	1.13	30.00	2.00	0.68	12.27	0.00	593.59	718.44
2200.00	2.00	2.00	0.15	0.18	6.90	8.35	15.82	19.14	28.22	1.13	30.00	2.00	0.68	12.76	0.00	619.48	741.29
2300.00	2.00	2.00	0.16	0.18	7.21	8.26	16.54	18.95	28.22	1.13	30.00	2.00	0.68	13.25	0.00	645.37	763.87
2400.00	2.00	2.00	0.16	0.18	7.52	8.17	17.26	18.75	28.22	1.13	30.00	2.00	0.68	13.73	0.00	671.25	786.22
2500.00	2.00	2.00	0.17	0.18	7.84	8.09	17.98	18.55	28.22	1.13	30.00	2.00	0.68	14.22	0.00	697.14	808.33
2600.00	2.00	2.00	0.18	0.17	8.15	8.00	18.70	18.36	28.22	1.13	30.00	2.00	0.68	14.71	0.00	723.02	830.22
2700.00	2.00	2.00	0.18	0.17	8.46	7.92	19.41	18.16	28.22	1.13	30.00	2.00	0.68	15.20	0.00	748.91	851.90
2800.00	2.00	2.00	0.19	0.17	8.78	7.83	20.13	17.97	28.22	1.13	30.00	2.00	0.68	15.69	0.00	774.79	873.39
2900.00	2.00	2.00	0.20	0.17	9.09	7.75	20.85	17.77	28.22	1.13	30.00	2.00	0.68	16.18	0.00	800.68	894.68
3000.00	2.00	2.00	0.21	0.17	9.40	7.66	21.57	17.58	28.22	1.13	30.00	2.00	0.68	16.67	0.00	826.56	915.79

Qo, stb/d	slug flow	Transition Flow	mist flow	F1	F2	F3	F4	F5	F6'	F7	S	Vs ft/s	Vm ft/s	HL	ρm lb/cu.ft	Nrel	f1	f2	f3	fm	Dp friction lb/cu.ft	total DP psi/ft
100.00	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	25.94	11.31	10.45	0.21	15.73	17.88	3.58	0.20	3.88	0.18	3.32	0.13
200.00	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	24.86	10.84	10.68	0.25	17.87	35.75	1.79	0.20	2.01	0.18	6.53	0.17
300.00	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	23.84	10.40	10.91	0.28	19.46	53.63	1.19	0.20	1.55	0.15	8.67	0.20
400.00	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	22.88	9.97	11.14	0.30	20.76	71.50	0.90	0.23	1.36	0.15	11.63	0.22
500.00	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	21.96	9.58	11.36	0.32	21.89	89.38	0.72	0.24	1.25	0.14	13.40	0.25
600.00	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	21.09	9.20	11.59	0.34	22.90	107.25	0.60	0.26	1.19	0.13	15.57	0.27
700.00	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	20.27	8.84	11.82	0.36	23.83	125.13	0.51	0.29	1.15	0.13	18.32	0.29
800.00	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	19.48	8.49	12.05	0.37	24.68	143.00	0.45	0.31	1.12	0.12	20.46	0.31
900.00	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	18.74	8.17	12.28	0.39	25.49	160.88	0.40	0.34	1.10	0.12	23.29	0.34
1000.00	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	18.03	7.86	12.50	0.40	26.25	178.75	0.36	0.36	1.09	0.12	25.48	0.36
1100.00	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	17.35	7.57	12.73	0.42	26.98	196.63	0.33	0.38	1.08	0.11	27.69	0.38
1200.00	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	16.71	7.28	12.96	0.43	27.67	214.51	0.30	0.39	1.07	0.11	29.19	0.39
1300.00	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	16.09	7.02	13.19	0.44	28.34	232.38	0.28	0.41	1.06	0.11	31.45	0.42
1400.00	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	15.51	6.76	13.42	0.45	28.98	250.26	0.26	0.43	1.05	0.10	33.76	0.44
1500.00	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	14.95	6.52	13.65	0.46	29.61	268.13	0.24	0.46	1.05	0.10	36.92	0.46
1600.00	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	14.41	6.28	13.87	0.47	30.21	286.01	0.22	0.49	1.04	0.11	40.15	0.49
1700.00	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	13.90	6.06	14.10	0.49	30.80	303.88	0.21	0.50	1.04	0.10	41.80	0.50
1800.00	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	13.41	5.85	14.33	0.50	31.38	321.76	0.20	0.52	1.03	0.10	44.32	0.53
1900.00	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	12.94	5.64	14.56	0.51	31.94	339.63	0.19	0.55	1.03	0.10	47.75	0.55
2000.00	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	12.50	5.45	14.79	0.52	32.48	357.51	0.18	0.58	1.03	0.10	51.27	0.58
2100.00	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	12.07	5.26	15.01	0.53	33.01	375.38	0.17	0.60	1.03	0.10	53.97	0.60
2200.00	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	11.66	5.08	15.24	0.54	33.54	393.26	0.16	0.61	1.03	0.10	55.82	0.62
2300.00	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	11.26	4.91	15.47	0.54	34.05	411.14	0.16	0.64	1.02	0.10	59.54	0.65
2400.00	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	10.88	4.74	15.70	0.55	34.55	429.01	0.15	0.69	1.02	0.10	65.24	0.69
2500.00	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	10.52	4.59	15.93	0.56	35.04	446.89	0.14	0.70	1.02	0.10	67.24	0.71
2600.00	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	10.17	4.43	16.15	0.57	35.52	464.76	0.14	0.72	1.02	0.10	70.24	0.73
2700.00	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	9.84	4.29	16.38	0.58	35.99	482.64	0.13	0.78	1.02	0.10	77.25	0.79
2800.00	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	9.51	4.15	16.61	0.59	36.45	500.51	0.13	0.79	1.02	0.10	79.41	0.80
2900.00	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	9.20	4.01	16.84	0.60	36.90	518.39	0.12	0.80	1.02	0.10	81.60	0.82
3000.00	TRUE	FALSE	FALSE	1.10	0.80	4.00	55.00	0.10	2.58	0.03	8.91	3.88	17.07	0.61	37.35	536.26	0.12	0.81	1.02	0.10	83.81	0.84