NUMERICAL MODELING OF PRESSURE DROP IN SUBSURFACE SAFETY VALVES

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Dissertation submitted to the Petroleum Engineering Programme
in Partial Fulfilment of the Requirements
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CERTIFICATION OF APPROVAL

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Approved by,

____

(Mohammad Amin Shoushtari)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

MAY 2012

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgement, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

JAMALIATUL MUNAWWARAH MOHD ALISJABANA

ABSTRACT

This report will present on the research done for the project entitle “Numerical Modeling of Pressure Drop in Subsurface Safety Valves.” The project objective is to develop a numerical model that could determine the pressure changes across the Subsurface Safety Valve (SSSV) by using Wolfram Mathematica software. By having this numerical model, we are also able to run sensitivities on the parameters that could affect the pressure drop. It is hope by having this project, a dynamic control over the SSSV can be achieved as a function of fluid flow parameters. In this report, literature review is done on the introduction to SSSV and how it is operated, the flow behavior and also on the concept of pressure drop in SSSV. Project methodology and activities have been designed and the milestone for this project has been planned. The mathematical procedures and the program code flow chart are also included in the report. This report also presents the single and two phase flow computer code that has been completed and also the results and analysis of the sensitivities run on the parameters that could affect the pressure drop across the SSSV. In conclusion, the project has been successfully completed and it is hope that this project is able to be applied in the industry.

ACKNOWLEDGEMENT

First and foremost, praise to the Almighty God for giving an utmost opportunity for me to complete this final year project successfully as part of the requirement for Bachelors of Engineering (Hons.) in Petroleum Engineering at Universiti Teknologi PETRONAS.

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ABBREVIATION & NOMENCLATURES

SSSV	Subsurface Safety Valve	λ_L	No-slip liquid holdup
SCSSV	Surface-Controlled SSSV	ρ_o	Density of oil
SSCSV	Subsurface-Controlled SSSV	A	Area of SSSV
API	American Petroleum Institute	D	Tubing ID, in
P_1	Upstream pressure	N_v	Void space
P_2	Downstream pressure	k	Ratio of specific heat of gas
P	Pressure	C_p	Specific heat at constant pressure
γ_g	Gas gravity	C_v	Specific heat at constant volume
Z	Gas compressibility factor		
T_1	Upstream temperature		
T	Temperature		
q_{sc}	Gas flow rate, Mscfd		
β	Beta ratio		
d	Bean diameter, in		
C_d	Discharged coefficient		
Y	Expansion factor, dimensionless		
ρ_g	Density of gas		
ρ_n	No-slip density, lbm/ft^3		
V_m	Mixture velocity through choke, ft/sec		
R	Producing Gas Oil Ratio		
q_g	Produced gas flow rate, scf/d		
q_o	Produced oil flow rate, stb/d		
R_s	Solution Gas Oil Ratio		
γ_{gc}	Corrected gas gravity		
B_o	Oil Formation Volume Factor		
B_g	Gas Formation Volume Factor		
q'_o	In-situ oil flow rate, ft^3/sec		
q'_g	In-situ gas flow rate, ft^3/sec		

CHAPTER 1

INTRODUCTION

1.1 Background of Study

In every field either offshore or onshore, it is necessary to have an adequate and reliable safety system. A good safety system will protect the increasingly high capital investment in equipment and structure, protect the environment against ecological damages which could occur, prevent the unnecessary waste of our natural resources, and most important of all, to protect the lives of people working in the area itself, (D.N.Hargrove).

In most offshore producing well, Subsurface Safety Valve (SSSV) is installed as per required by law and is one of many devices available for well fluid containment. SSSV is designed to prohibit the flow of the producing well in the event of disasters such as explosions or fires, excessive pressure in and flow from the producing zone, leaks or tubing failure above well completion zone or failure of surface safety system. As (James Garner, 2002) says that by working properly when other system fail, SSSV is the final defense against the disaster of uncontrolled flow from a well.

According to (James Garner, 2002), the first safety device to control subsurface flow was used during the mid-1940s in US inland water. The valve was deployed only when needed that is when a storm was expected. The valve was dropped into the wellbore and acted as a check valve to shut off the flow if the rate exceeded a predetermined value. It was then retrieved by using a slickline unit. The use of SSSV only become prominent when the state of Louisiana passed a law in 1949 which requires an automatic shut-off device below the wellhead in every producing well in its inland water.

'Modeling' is defined by (Taitel, 1995) as a kind of approximations in which the physics of the problem is approximated and formulated in a format tractable by analytical or numerical means. By using modeling, one tries to simplify the problem to the extent that it could be analyzed with reasonable efforts. The more elaborate the description of the problem, the more elaborate and difficult the formulation is. In solving engineering problems, one will usually choose the least elaborate model that could still satisfy the requirement for accuracy.

1.2 Problem Statement

In oil and gas industry, it is important to have an optimized production of oil and gas wells. Production optimization can be defined as an optimum analysis and comprehensive investigation of well production systems to maximized hydrocarbon recovery while minimizing the operating cost. In order to have an optimize production; the whole production systems are needed to be optimized, so that they could perform efficiently. This can be done by performing production optimization at different levels such as well level, platform / facility level or field level. This project will focus on optimizing one of the components in the well level which is the SSSV.

The SSSV must function properly throughout the exposure to a wide range of temperature and pressures. As the reservoir and the flow is a dynamic entity, we would not be able to predict its behavior all the time. At times, the production conditions may exceed expected performance, (James Garner, 2002) which then will affect the SSSV. Therefore, a proper management of SSSV is required to overcome this problem.

A proper management of SSSV should start in the beginning of designing the SSSV so that the SSSV could work efficiently from the first day of its installation. Through proper management of SSSV, it allows us to estimate the pressure traverse across the valve as well as the well production rates that are necessary for SSSV valve closure. The consequences of improper management of SSSV are significance as it could cause the lost in production and also loss of well protection.

At the moment, there is no unique method in having a good management of the SSSV. However, the correlations that could be used in predicting pressure drop across a SSSV in single and multiphase flow have been developed. This prediction method can also be used in determining the correct sizing for the choke.

This project aims to develop a numerical model by using the developed correlation to determine the pressure changes across the SSSV with hopes to have a better management of the SSSV.

1.3 Objectives

The objectives of this study are:

- To develop a numerical model that could determine the pressure changes in single and two phase flow in SSSV by using Wolfram Mathematica software.
- To run sensitivities on the parameters that could affect the pressure changes in SSSV.

1.4 Scope of Study

The scope of study includes:

- Understanding of SSSV and how it works
- Understanding the concept of flow behavior – critical and subcritical flow
- Understanding the concept of pressure drops
- Deeper understanding on the developed mathematical correlations in calculating the pressure changes in SSSV
- Familiarization with Wolfram Mathematica software in order to develop the computer code for the model.

1.5 Relevancy of the Project

The study will produce a numerical model that could calculate the pressure drop in SSSV focusing on subcritical flow in single or two phase flow. With the model, determination of the pressure changes across the SSSV in different phases of flow can be done easily. Besides, the parameters that could affect the pressure drop across the SSSV can be determined. Furthermore, this model can also be used during the designing part of the SSSV. Through this modeling work, it is hope that a better management of SSSV can be achieved.

1.6 Feasibility of the Project within the Scope and Time Frame

With careful planning and full dedication in conducting this research, the project are able be completed within the given times of 8 months. During FYP 1, it is required for the student to complete the research on the project topic, the understanding on the mathematical formulation and the familiarization of the Wolfram Mathematica software. For FYP 2, the focus should be on developing the numerical model and to run sensitivities on the parameters that could affect the pressure drop across the SSSV. Following is the analysis and interpretation of the results. The cost for this project is affordable as the student only have to purchase Wolfram Mathematica to complete the project.

CHAPTER 2

LITERATURE REVIEW

In order to complete the project, it is important to understand the mechanism of the SSSV, the flow behavior and the concept of pressure drop.

2.1 The Principle Work of SSSV

2.1.1 Categorization of SSSV

According to (James Garner, 2002), safety valve is a simple device that most of the time it is open to allow the flow of produced fluid but in an emergency situation it is automatically closes and stops the flow. (Purser, 1977) has categorized SSSV into Surface-Controlled SSSV (SCSSV) and Subsurface Controlled SSSV (SSCSV). Figure 1 summarized the categorization of SSSV.

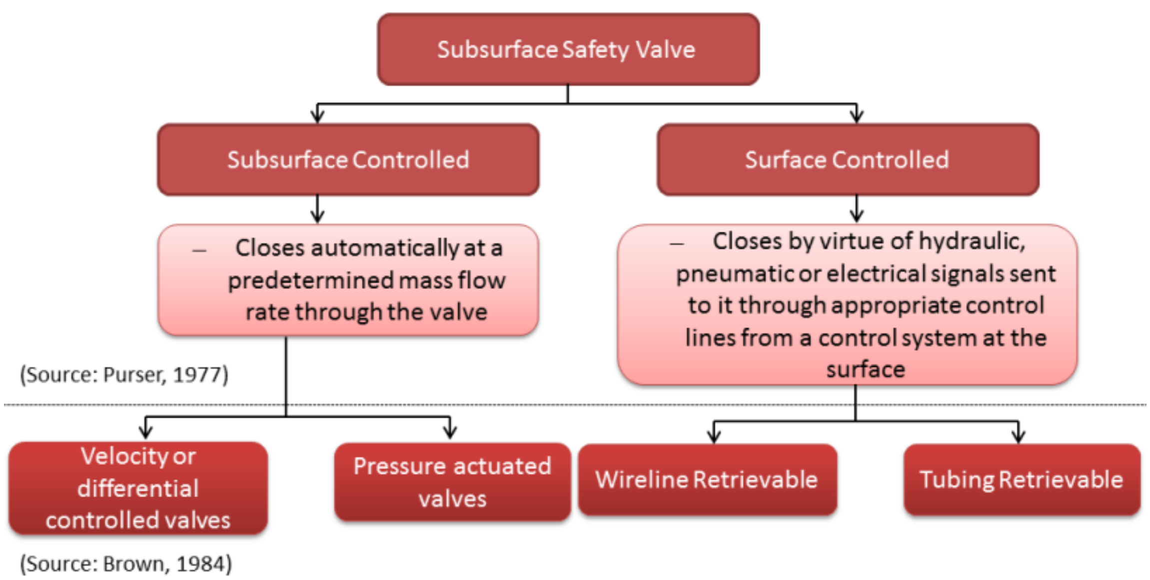


Figure 1 Categorization of SSSV

SCSSV is operated from the surface facilities through a control line that is tie in to the external surface of the production tubing. It is the most widely used as it is a more reliable method. SCSSV operates in a fail-safe mode with hydraulic control pressure used to hold open a ball or flapper assembly that will close if the control pressure is lost. From Figure 1, the two basic types of SCSSV are tubing retrievable and wireline retrievable. In tubing retrievable, the entire safety-valve component is run as an integral part of the tubing string and can only be retrieved by pulling the tubing. While in wireline retrievable, the valve nipple is run as an integral part of the tubing and the internal valve assembly can be subsequently run and retrieved by using slickline.

SSCSV is designed to remain open provided either a pre-set differential pressure occurring through a fixed size orifice in the valve is not exceeded or the flowing bottomhole pressure is maintained above a pre-set value. The valve will close when there is any increase in the differential pressure which causes the force of the spring to close the valve. There are two basic operating mechanism of SSCSV. There are velocity- or differential-controlled valves and pressure-actuated valves, (Brown, 1984). Velocity- or differential-controlled valves are operated by an increase in fluid flow while pressure-actuated valves are operated by a decrease in ambient pressure.

2.1.2 Valve Closure Mechanism

Valve closure mechanism is based on a simple force balance principle. The safety valve is held open by the spring and seal gripping forces which together are greater than the opposing resultant well fluid forces generated by normal production rates, (H.D.Beggs, 1977). When the production rate is higher than normal and the net well fluid forces become great enough to overcome the spring and seal gripping forces it will then actuate the valve closure. The mechanism will be explained in more details at the end of this section.

The common key feature of early subsurface safety valve is the use of different valve closure mechanism design such as ball and flapper valves. A ball valve is a sphere with a hole through it which allows the flow of fluid through the valve when the hole is aligned with the tubing. The flow of fluid will stop when the ball is rotated 90° which places the solid part of the ball in the flow stream. Figure 2 shows the schematic diagram and a real ball-type safety valve.

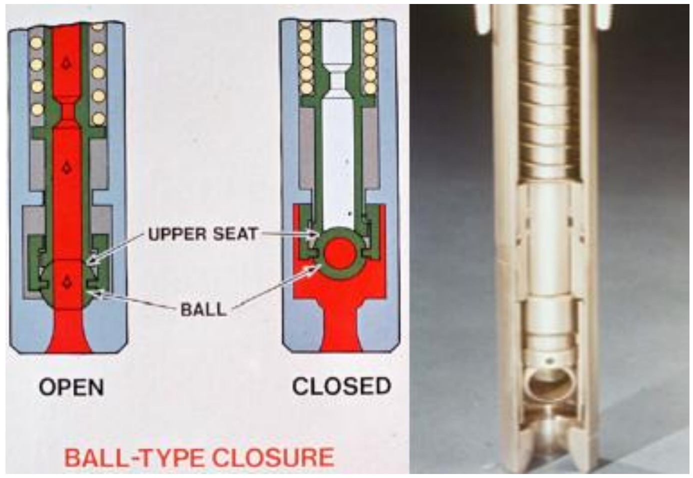


Figure 2 Schematic diagram and picture of Ball-type valve

While the more common flapper-valve design acts like a door. A flow tube moves in one direction to push the flapper open to allow flow through the valve. Moving the flow tube back from the flapper allows a torsion spring to close the valve and block the flow. Figure 3 shows the schematic diagram and a real flapper-type safety valve.

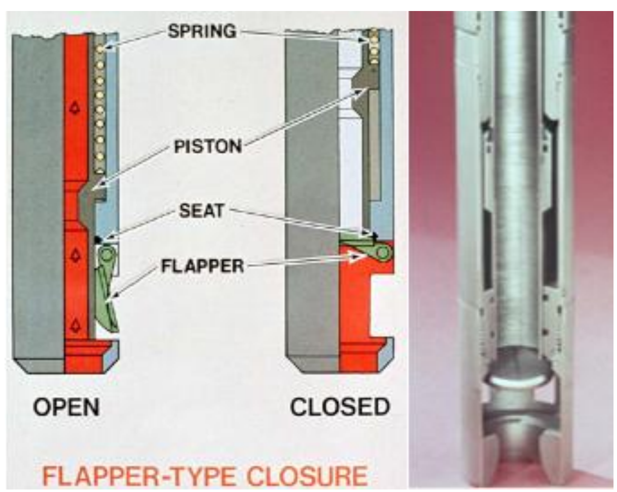


Figure 3 Schematic diagram and picture of Flapper-type valve

In SSCSV, the restriction in the flow path is held open by a spring. The pressure below the restriction is P_1 and that above is P_2. These pressures act on the exposed faces of the piston, creating a pressure drop to close the valve. When the fluid flows upward, the constriction creates a pressure differential that increases the closure force. As the spring is pre-set for a specific flow rate, when the flow rates reaches the critical rate, the piston will moves up, releasing the flapper to close and stop the fluid flow. The mechanism explained above is illustrated in Figure 4.

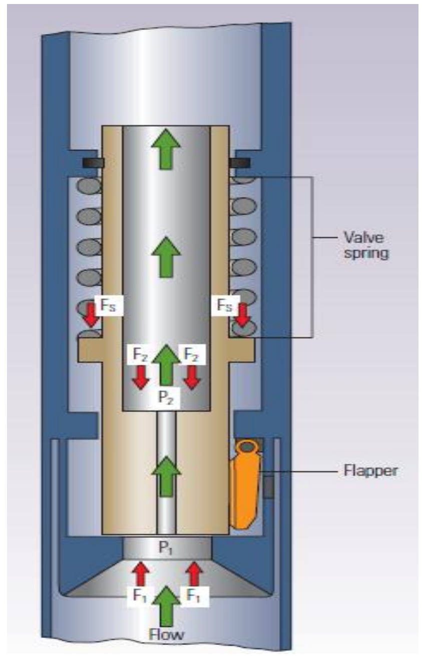


Figure 4 Typical subsurface-controlled safety valve operation, (James Garner, 2002)

For a SCSSV, the activation is no longer depends on downhole flow conditions. It is design normally as a closed valve with the spring force, F_s acting to push the piston upward and release the flapper to close the valve. Control pressure that is transmitted from surface through a hydraulic-control line act against the spring to keep the flapper valve open during production. The opening force F_H is generated by the ring-shaped area between the piston and the valve body that the hydraulic pressure acts upon. The mechanism explained above is illustrated in Figure 5.

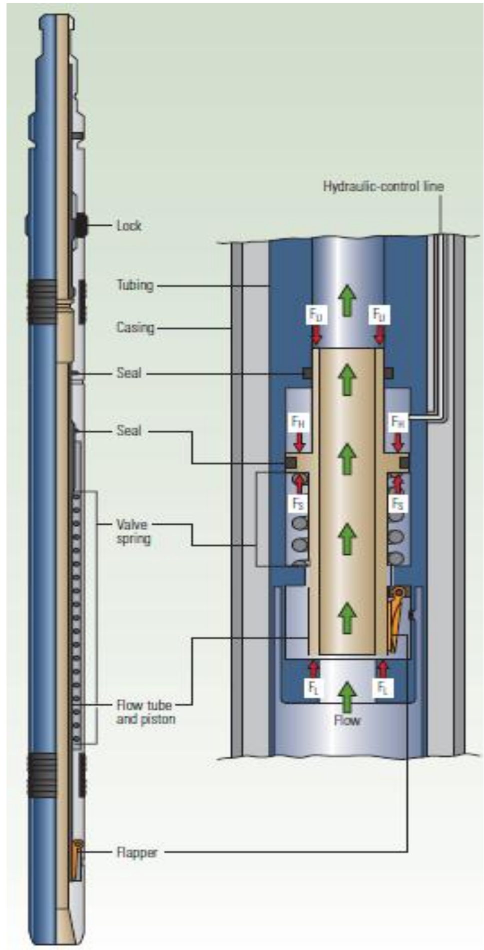


Figure 5 SCSSV Operation, (James Garner, 2002)

2.2 The Flow Behaviors

In compressible flow, we can recognize two regions of different behavior depending on the Mach number. The Mach number, M is defined as the ratio of the fluid speed to the local speed of sound. When the flow velocity is smaller than the local speed of sound and the Mach number is smaller than unity ($M < 1$), this flow region is called subsonic (or subcritical). Meanwhile, if the flow velocity is greater than the local speed of sound and the Mach number is greater than unity ($M > 1$); the flow region is defined as supersonic (or supercritical). Sonic (or critical) flow region is the limiting condition that separating the two flow regions which happened when the velocity of gas is approximately equal to the local speed of sound and the Mach number is equal to unity ($M = 1$).

There are two types of two-phase flow that can exist in a restriction. There are critical and subcritical flows. In a report by (R.Sachdeva, 1986) stated that when the flow rate through choke reaches a maximum value and the velocity of fluids reaches sonic velocity, the flow behavior will become independent of conditions downstream from the choke. This situation can be demonstrated by the changes or disturbance in downstream condition such as decreasing the downstream pressure will not change the condition in the upstream where it does not increase the flow rate. This statement is also supported by (D.W.Surbey) and (J.P Brill, 1999).

(D.W.Surbey) defined subcritical flow as flow across the choke where the flow rate is affected by both the upstream pressure and the pressure drop across the choke. The velocity of the fluids through the choke is less than the sonic velocity. This condition can be demonstrated by increasing the downstream pressure which then will affect the flow rate and upstream pressure.

According to (Beggs, 1991), in order to distinguish between critical and subcritical flow, the rule-of-thumb which states that if the ratio of downstream pressure to upstream pressure is less than or equal to 0.5, then the flow will be critical can be used. This is a closer approximation for single-phase gas than for two-phase flow. Usually the critical pressure ratio in two phase flow used by engineer is either 0.6 or 0.7. However, the research done at Tulsa University has shown that the ratio must be as low as 0.3 before the flow is considered critical.

The main purpose of choke is to control flow rate, therefore choke will usually be sized so that critical flow will exist. As for SSSV which its main task is to shut in the well when the wellhead pressure becomes too low, it is designed and sized for minimum pressure drop so that it will be operating in subcritical flow. This project is also focusing on subcritical flow in a SSSV.

2.3 The Concept of Pressure Drop

This section will explain the concept of pressure drop in production system and pressure drop in SSSV.

2.3.1 Pressure Drops in Production System

The production system is referred to as the combined system of the reservoir, the wellbore and the surface treatment facilities. To produce the oil from the reservoir to the storage tank, the oil has to flow through a variety of restrictions which will consume some of the energy stored within the compressed fluids. These energy losses can be represented by the pressure losses.

A loss in pressure will occur within the fluid firstly when the oil has to flow through the reservoir rock to the drainage area of the individual wells. This pressure loss is known as reservoir pressure drop or drawdown. Reservoir pressure drop is principally dependent upon the reservoir rock and fluid characteristic such as reservoir's porosity, permeability and the fluid viscosity.

The fluid then has to be able to leave the formation and enter the wellbore at the junction between the reservoir and the individual wellbore. Therefore, a major completion decision on how the fluid connectivity between formation and wellbore is to be provided has to be made. In some cases, the fluid will be produced through open hole, while others through perforated liners. The pressure drop generated by the perforations and other near wellbore completion equipment is known as the bottomhole completion pressure drop. This pressure drops will be dependent on the number, location and characteristics of these perforations that will influence the fluid flow.

Once inside the wellbore, the fluid will need to flow upward in the production tubing string through various sizes of tubing and restrictions that is caused by other completion string components resulting in pressure losses of the fluid between the bottomhole location and surface. This pressure drop is referred to as completion string or vertical lift pressure drop. This pressure loss is attributable to 3 primary sources which are frictional pressure loss, hydrostatic head pressure loss and kinetic energy losses.

Frictional pressure loss is causes by the loss associated with viscous drag. While hydrostatic head pressure loss is due to the density of the fluid column in the production tubing. Kinetic energy losses are due to expansion and contraction in the fluid flow area and also the acceleration or deceleration of the fluid as it flows through the restrictions.

Once the fluid arrives at the surfaces, it will then flow through the surface equipment and flowline giving rise to additional pressure loss. The extent of these pressure losses is depending upon the operating system being minimal for a small platform with small flowline lengths or being significant for offshore wells or onshore wells that have great distance from the production gather stations.

Figure 6 summarized the pressure losses that occur in a complete production system.

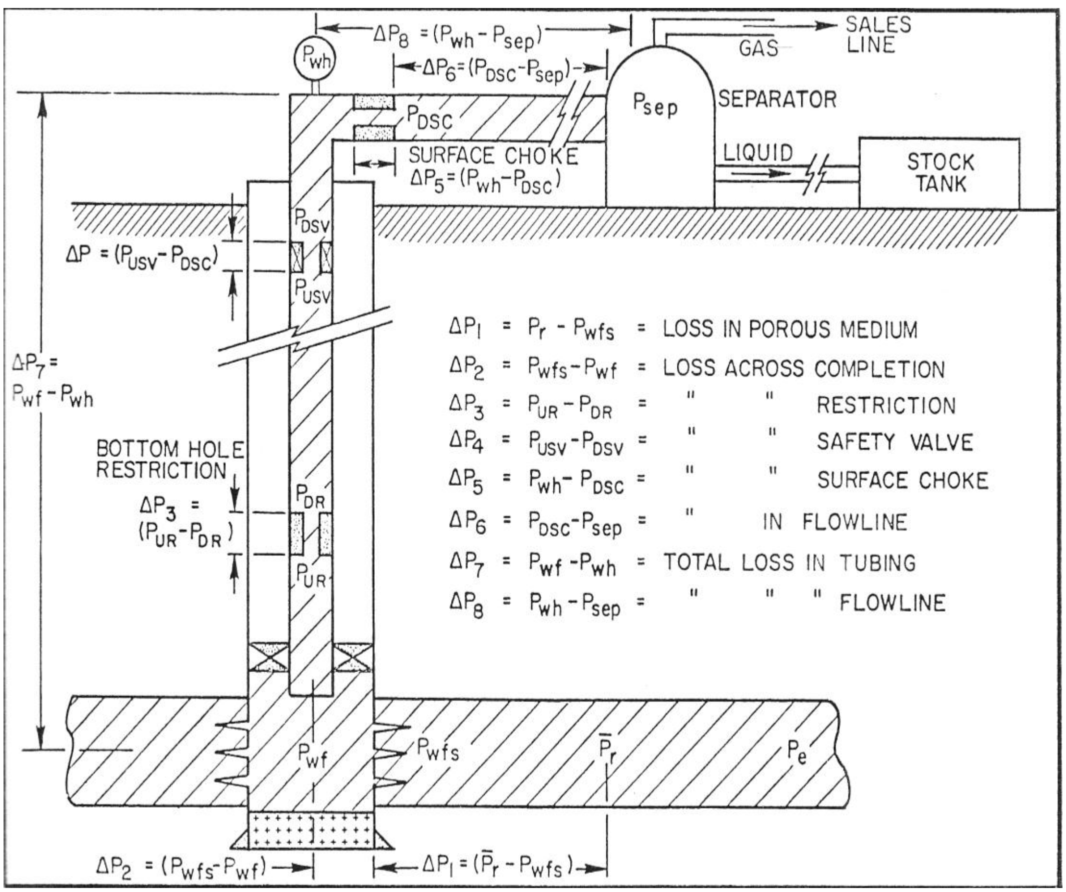


Figure 6 Pressure losses in complete production system

2.3.2 Pressure Drops across SSSV

The principal losses in the well system do not usually occur in the restriction but it could be significant in some well too. The three main types of restrictions are SSSV, surface or bottomhole chokes and valves and fittings.

When SSSV is chosen as a node in the nodal analysis, the upstream of the SSSV is a combination of the Inflow Performance (IPR) curve and the vertical multiphase pressure drop from the bottom of the well to the bottom of the SSSV. While the downstream of the SSSV will include the horizontal and vertical multiphase pressure drops from the separator to the top of the SSSV. According to (Beggs, 1991), the inflow and outflow expressions are:

Inflow:

$$P_R - \Delta P_{res} - \Delta P_{tubing\ below} - \Delta P_{SSSV} = P_{node}$$

Outflow:

$$P_{sep} + \Delta P_{flowline} + \Delta P_{tubing\ above} = P_{node}$$

The pressure loss across a restriction in subcritical flow such as choke or bean in SSSV is proportional to the flow rate of fluids through the restriction, (H.D.Beggs, 1977). Therefore, the higher the flow rate, the greater the pressure loss.

2.3.3 Research Works Done on SSSV

According to (J. David Lawson, 1974), the API computer programs are able to predict the pressure drops but only for single phase gas or single phase liquid flow as it uses the pressure drops correlations based on single phase theory. However, most SSSV will be operating under multiphase flow conditions. Therefore, it is needed to develop the pressure drop correlations that are valid for multiphase flow.

As a result the API Offshore Safety and Anti-Pollution Research (OSAPR) Committee has therefore funded a few projects at the University of Tulsa dealing with the determination of SSSV behavior in the presence of multiphase fluid flow. The purpose of this research is to develop correlations for predicting pressure drop across SSSV occurring during multiphase flow as a function of variables such as gas and liquid flow rate, bean or choke size, gas-liquid ratio and average pressure, (H.D.Beggs, 1977).

This Final Year Project (FYP) will be focusing on the development of numerical model of the pressure drops across the SSSV by using the correlations from the researches done by University of Tulsa. Besides that, this project will also analyze the parameters that could results in the changes in pressure drops which will be discussed in more details in Chapter 4.

CHAPTER 3

METHODOLOGY

3.1 Research Methodology

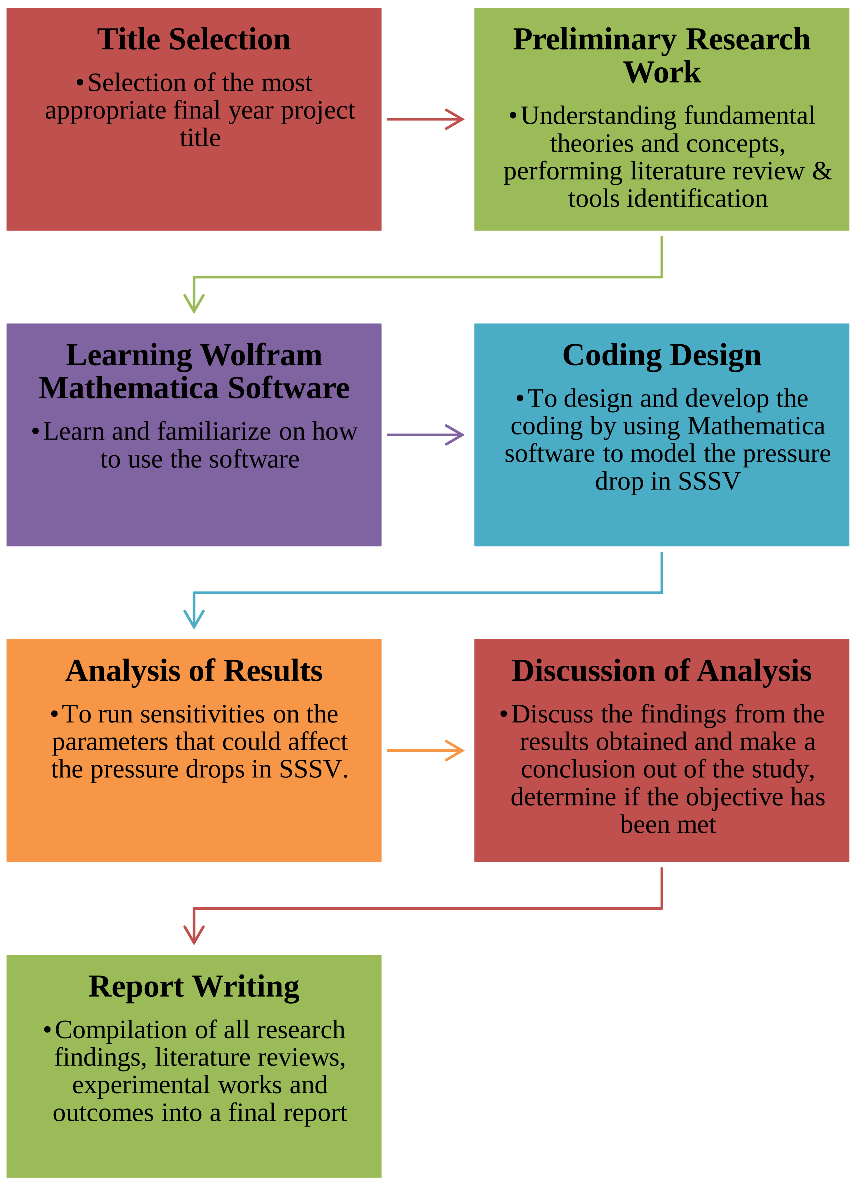


Figure 7 Research Methodology Flow chart

3.2 Key Milestone and Project Activities Gantt chart

Table 1 Gantt Chart of FYP 1 Project Implementation

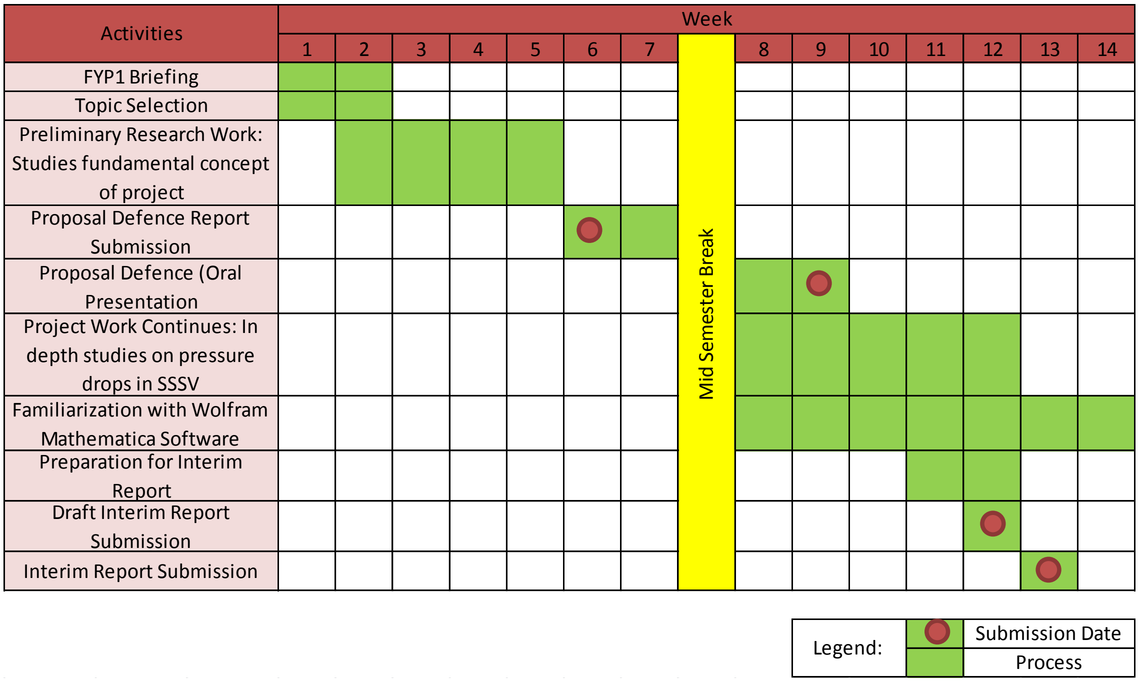
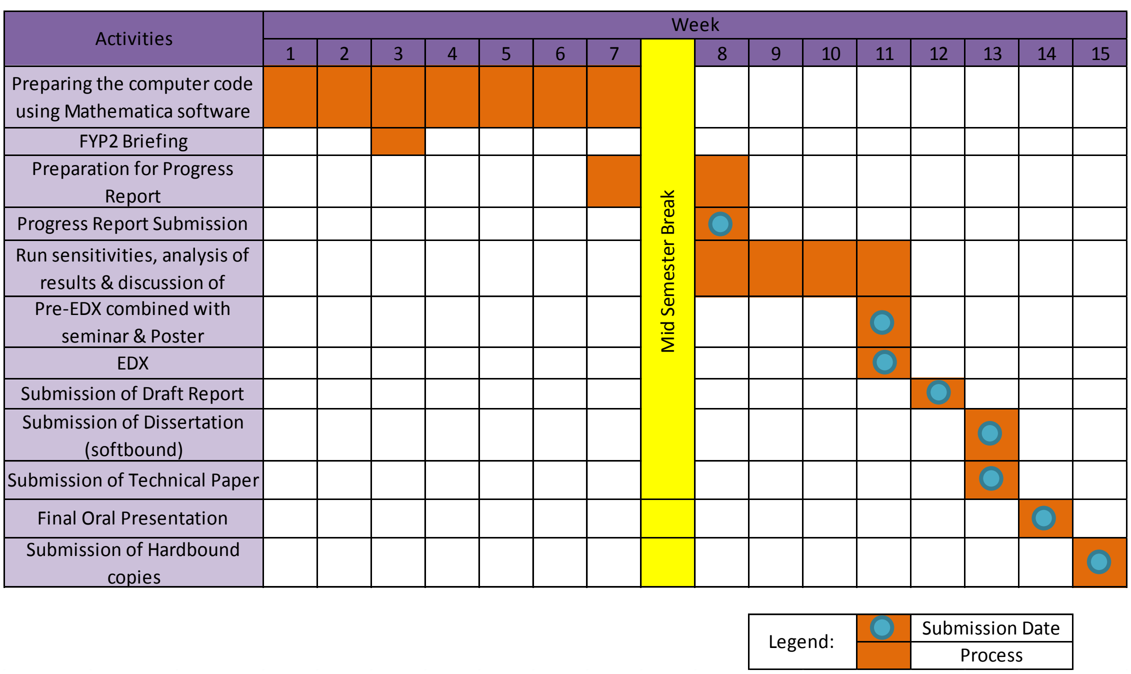


Table 2 Gant Chart of FYP 2 Project Implementation



3.3 Calculation Procedures

The project will be focusing on the calculation of pressure drop in SSSV in single-phase and two-phase in subcritical flow. Below are the calculation procedures for both phases of flow:

3.3.1 Single-Phase Flow

The equation was published by the API[65] for gas flow (single phase):

$$\boldsymbol{P_1 - P_2 = \frac{1.048 \times 10^{-6} \gamma_g Z_1 T_1 q_{sc}^2 (1 - \beta^4)}{P_1 d^4 C_d^2 Y^2}}$$

Equation 1

API suggested using the discharged coefficient, C_d at 0.9.

The equations for all parameters in Equation 1 are as follow:

I. Equation for gas specific gravity, γ_g:

$$\boldsymbol{\gamma_g = \frac{\rho_g Z T}{2.7 P}}$$

Equation 2

II. Equation for gas compressibility factor, Z_1

There are a few methods that can be used to estimates gas compressibility factor namely Standing and Katz chart and Brill and Beggs (1974) correlation. For developing the numerical model in this project, the Brill and Beggs correlation is to be used.

$$A = 1.39(T_{pr} - 0.92)^{0.5} - 0.36T_{pr} - 0.10 \quad \textbf{(2.28)}$$

$$B = (0.62 - 0.23T_{pr})p_{pr} + \left(\frac{0.066}{T_{pr} - 0.86} - 0.037\right)p_{pr}^2 + \frac{0.32p_{pr}^6}{10^E} \quad \textbf{(2.29)}$$

$$C = 0.132 - 0.32\log(T_{pr}) \quad \textbf{(2.30)}$$

$$D = 10^F \quad \textbf{(2.31)}$$

$$E = 9(T_{pr} - 1) \quad \textbf{(2.32)}$$

$$F = 0.3106 - 0.49T_{pr} + 0.1824T_{pr}^2 \quad \textbf{(2.33)}$$

and

$$z = A + \frac{1 - A}{e^B} + Cp_{pr}^D \quad \textbf{(2.34)}$$

Figure 8 Excerpt of Brill and Beggs (1974) correlation from (Dr. Boyun Guo, 2005)

III. Equation for Beta Ratio, β:

$$\boldsymbol{\beta = \frac{d}{D}}$$

Equation 3

IV. Equation for expansion factor, Y:

$$\boldsymbol{Y = 1 - [0.41 + 0.35\beta^4]\left[\frac{P_1 - P_2}{kP_1}\right]}$$

Equation 4

Determination of expansion factor is iterative. The value ranges between 0.67 and 1.0. For quick estimates, the default value of 0.85 is often used.

V. The equation for ratio of specific heat of gas, k:

$$k = \frac{C_p}{C_v}$$

Equation 5

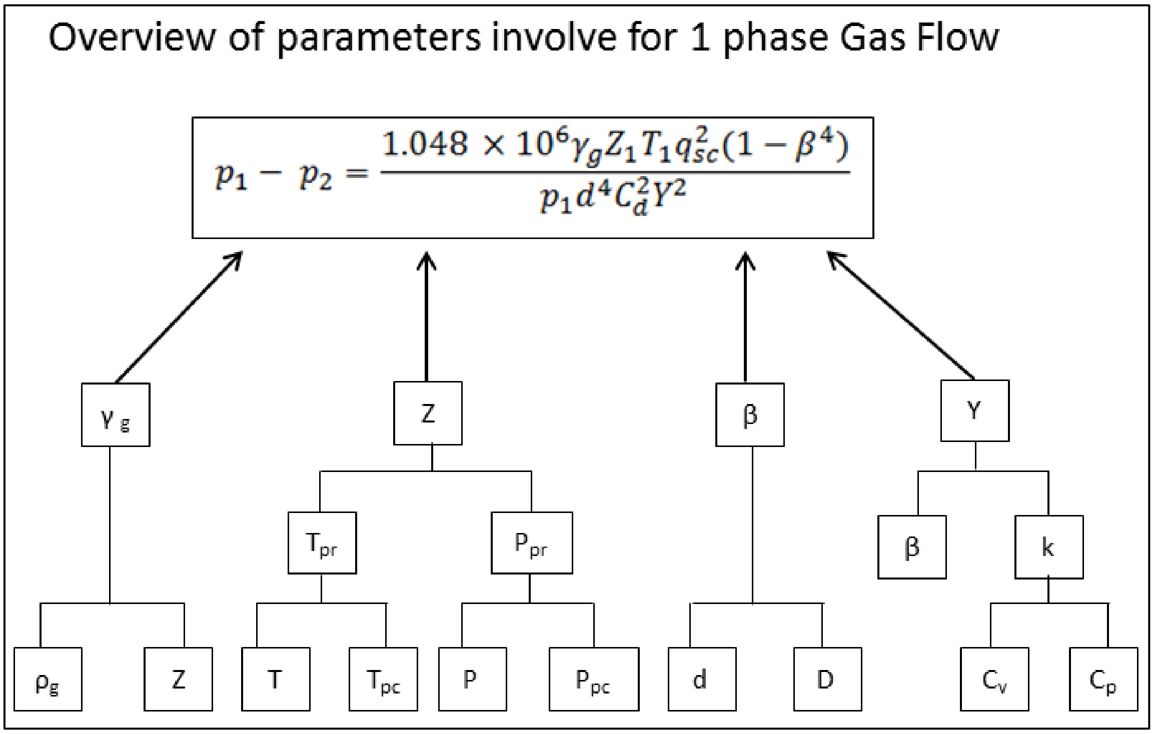


Figure 9 Overview of parameters involve for 1 phase Gas Flow

3.3.2 Two-Phase Flow

A research project sponsored by the API at University of Tulsa that was designed to improve the equation for sizing SSSV's operating in two-phase subcritical flow. The equation for pressure drop is:

$$P_1 - P_2 = \frac{1.078 \times 10^{-4} \rho_n V_m^2}{C_d}$$

Equation 6

The equation can be used for all type of SSSV. In order to use Equation 6, we need to calculate the parameters involved in the equation. Listed below are the parameters that need to be calculated.

I. To calculate No-Slip Density, ρ_n:

a) Find Producing Gas Oil Ratio, R:

$$R = \frac{q_g}{q_o}$$

Equation 7

b) Find Solution Gas Oil Ratio, R_s at any pressure less than or equal to bubble point pressure:

$$R_s = C_1 \gamma_{gc} P^{C_2} EXP\left[\frac{C_3(API)}{T + 460}\right]$$

Equation 8

If separator conditions are unknown, the uncorrected gas gravity may be used in the correlations for R_s and B_o. The values of the constant are depending on the API gravity of the oil and are given by:

Table 3 Values of constant depending on API gravity for R_s

Constant	API ≤ 30	API > 30
C_1	0.0362	0.0178
C_2	1.0937	1.1870
C_3	25.7240	23.9310

c) Estimate Oil Formation Volume Factor, B_o by using Vasquez and Beggs method:

$$B_0 = 1 + C_1 R_s + C_2 (T - 60)\left(\frac{API}{\gamma_{gc}}\right) + C_3 R_s (T - 60)\left(\frac{API}{\gamma_{gc}}\right)$$

Equation 9

The constants are determined from:

Table 4 Values of constant depending on API gravity for B_o

Constant	API ≤ 30	API > 30
C_1	4.677×10^{-4}	4.670×10^{-4}
C_2	1.751×10^{-5}	1.100×10^{-5}
C_3	-1.811×10^{-8}	1.337×10^{-9}

d) Gas compressibility factor, Z used in the numerical model is by using Brill and Beggs (1974) correlation. For equations, refer **Figure 8**.

e) Calculate Gas Formation Volume Factor, B_g at standard conditions of Psc=14.7 psia and T_{sc}=520°R:

$$\boldsymbol{B_g = \frac{0.0283ZT}{P}}$$

Equation 10

f) Find in-situ Oil Flow Rate, q_o'

$$\boldsymbol{q_o' = 6.5 \times 10^{-5} q_o B_0}$$

Equation 11

g) Find in-situ Gas Flow Rate, q_g'

$$\boldsymbol{q_g' = \frac{q_o(R - R_s)B_g}{86400}}$$

Equation 12

h) Find No-Slip Liquid Holdup, λ_L:

No-Slip Liquid Holdup is defined as the ratio of the volume of liquid in a pipe element that would exist if the gas and liquid traveled at the same velocity divided by the volume of the pipe element.

$$\boldsymbol{\lambda_L = \frac{q_o'}{q_o' + q_g'}}$$

Equation 13

i) Find Density of Oil, ρ_o:

$$\boldsymbol{\rho_o = \frac{350\gamma_o + 0.0764\gamma_g R_s}{5.615B_o}}$$

Equation 14

j) Find Density of Gas, ρ_g:

$$\boldsymbol{\rho_g = \frac{2.7\gamma_g P}{ZT}}$$

Equation 15

k) By using all the parameters calculated above, calculate No-Slip Density, ρ_n:

$$\boldsymbol{\rho_n = \rho_o\lambda_L + \rho_g(1 - \lambda_L)}$$

Equation 16

II. To calculate Mixtures Velocity, V_m:

a. Calculate Area of SSSV, A in ft^2:

$$\boldsymbol{A = \left(\frac{\pi}{4}\right)\left(\frac{d}{12}\right)^2}$$

Equation 17

b. Calculate Mixture Velocity, V_m:

$$\boldsymbol{V_m = \frac{q'_o + q'_g}{A}}$$

Equation 18

III. To calculate Discharged Coefficient, C_d:

a. Calculate Number of Void Space, N_v:

$$\boldsymbol{N_v = \frac{q'_g}{q'_o}}$$

Equation 19

b. Calculate Beta Ratio, β. Refer to Equation 3.

c. Calculate Discharged Coefficient, C_d:

$$C_d = C_1 + C_2 N_v + C_3 \beta + C_4 \beta^2$$

Equation 20

Once all parameters have been calculated, the pressure drop in two phase flow can be calculated by using Equation 6.

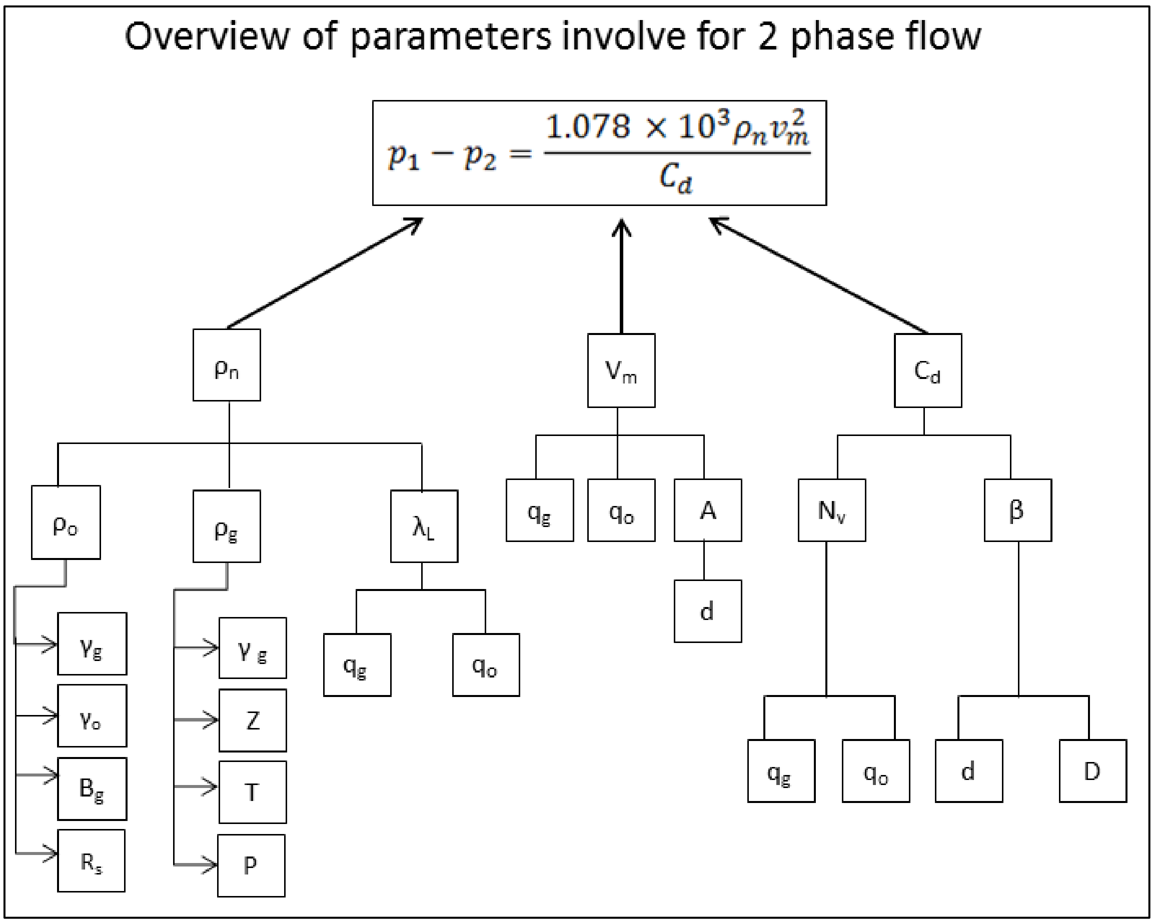


Figure 10 Overview of parameters involve for two-phase flow

3.4 Program Flow Chart

3.4.1 Program Flow Chart for Single-Phase Flow

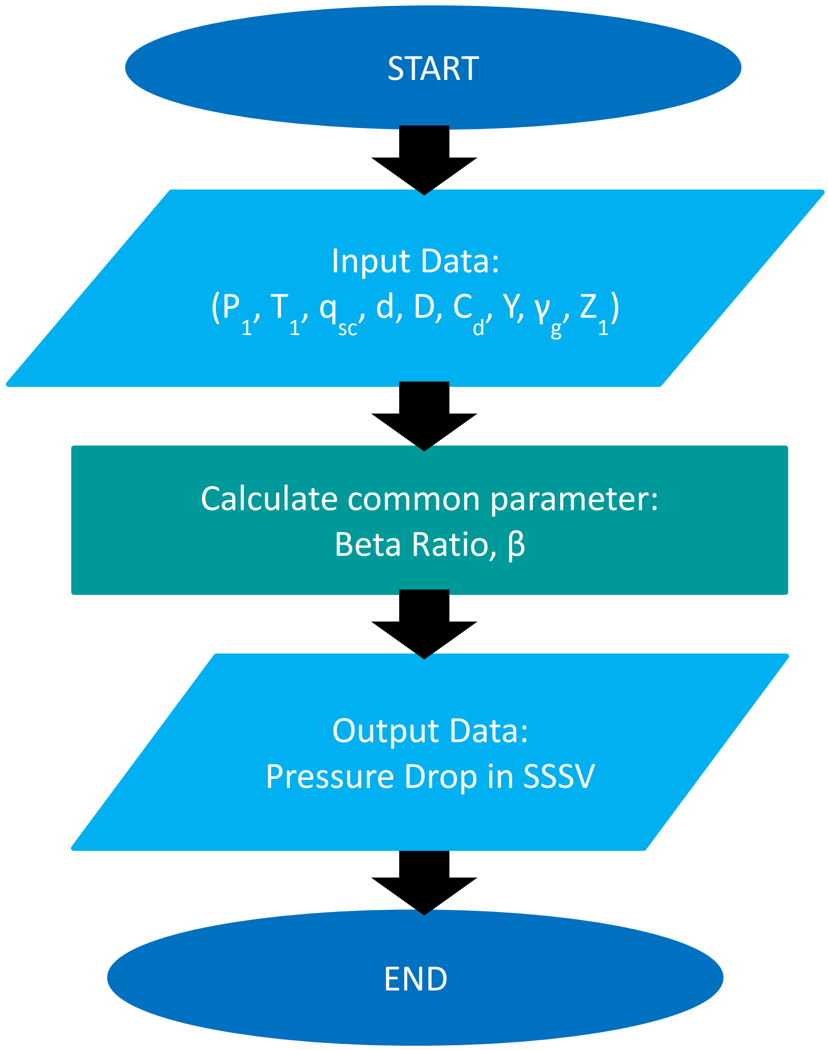


Figure 11 Flow chart for Single-Phase flow program

3.4.2 Program Flow Chart for Two-Phase Flow

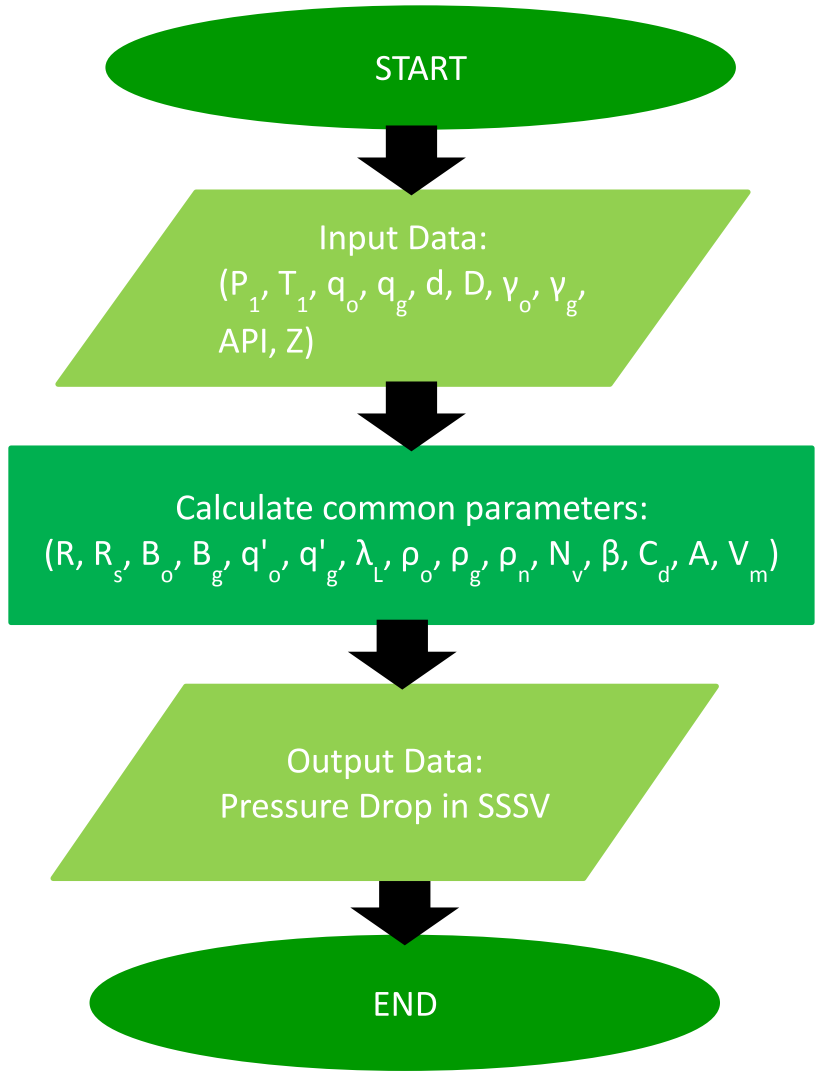


Figure 12 Flow chart for Two-Phase flow program

3.5 Tools / Software

This project only requires the use of Wolfram Mathematica software to develop the numerical model of pressure drop across the SSSV.

Wolfram Mathematica 8

Figure 13 Wolfram Mathematica logo

Wolfram Mathematica is a computational software program that is used in scientific, engineering and mathematical fields and other areas of technical computing. It was conceived by Stephen Wolfram and is developed by Wolfram Research of Champaign, Illinois.

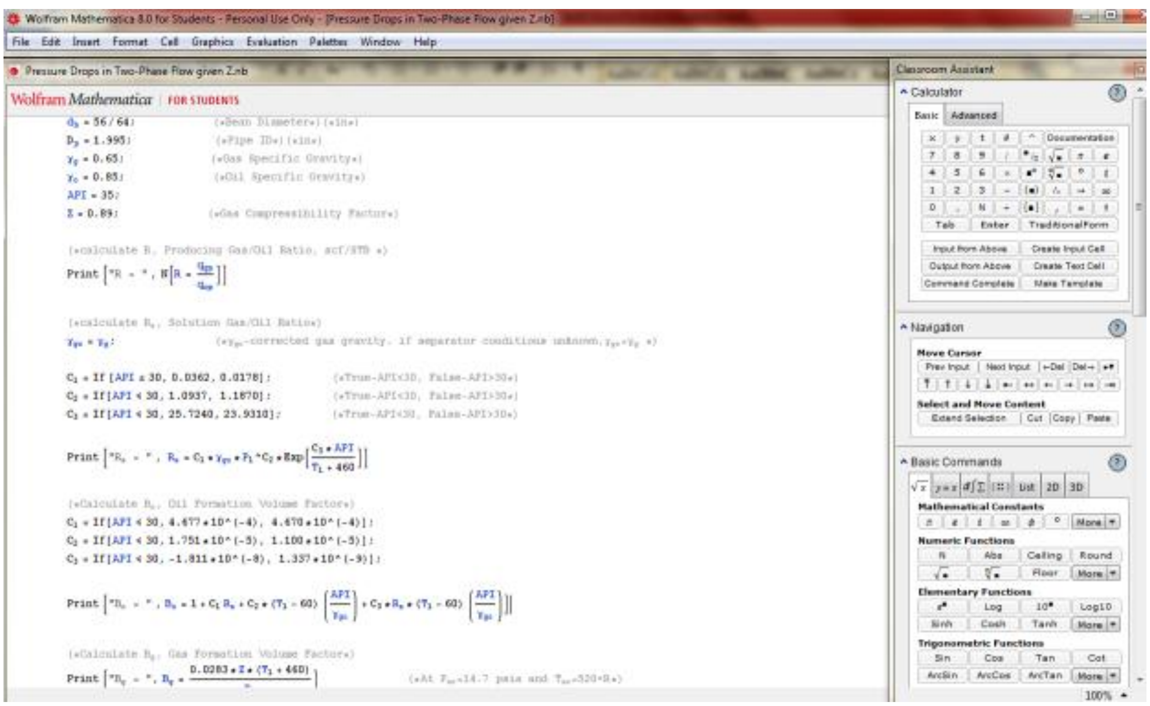


Figure 14 Wolfram Mathematica interface

CHAPTER 4

RESULTS & DISCUSSION

This chapter will discuss on the results for both objectives of the project which are firstly, to develop numerical model of pressure drop of SSSV for single and two phase flow and secondly, to run sensitivity on several parameters to find their effect towards the pressure drop in SSSV.

4.1 Computation Algorithm

For this project, four (4) computer programs that can be used to predict the pressure drops in SSSV have been developed. The first program is for single phase, subcritical flow with given gas compressibility factor by the user. The second program is for single phase, subcritical flow and calculated gas compressibility factor by using Brill and Beggs (1974) correlations. While the third program is for two phase, subcritical flow with given gas compressibility factor that can be input by the user. The last and fourth program is for two phase, subcritical flow and calculated gas compressibility factor by using Brill and Beggs (1974) correlations. The computer codes are as attached in Appendix 1 to Appendix 4.

The calculation procedure for the first and second computer programs are done by using the equation published by API[65] has been translated into the computer codes by using the Wolfram Mathematica software. The input data needed to predict the single phase pressure drops are the upstream pressure in psia, upstream temperature in Rankine, the gas flow rate in Mscfd, the gas specific gravity, the bean diameter and pipe ID in inch. For the discharge coefficient, the value 0.9 is used as suggested by the API while the default value of 0.85 for expansion factor is used for quick estimation.

The difference in the first and second computer programs is only on the gas compressibility factor, Z where in the first program, the value of Z is given by the user while in the second program, Z is calculated by using the Brill and Beggs (1974) correlations. Common parameters will be calculated once all data has been input into the programs. The parameters mentioned are the beta ratio and Z (for second program only). The final computation of the program will be on the calculation of the pressure drops in single phase flow.

For the third and fourth computer programs, the calculation procedure is done by using the equation that was developed by the research done by Universiti of Tulsa. The input data required for the programs are upstream pressure in psia, upstream temperature in Rankine, produced oil flow rate in stb/d, produced gas flow rate in scf/d, oil and gas specific gravity, API gravity, bean diameter and pipe ID in inch and Z (for third program only). Common parameters to be calculated from the input datas are Z (for fourth program only), producing GOR, solution GOR, oil FVF, gas FVF, in-situ oil flow rate, in-situ gas flow rate, liquid holdup, density of oil and gas, no-slip density, void space, beta ratio, discharged coefficient, area of SSSV and mixture velocity. With the common parameters calculated, the pressure drops for two phase flow will then be calculated.

4.2 The Assumptions Used in the Model

For the numerical model, it is assume that the composition of gas of hydrogen sulfide (H_2S) is less than 3%, nitrogen (N_2) is less than 5% and total content of inorganic compounds is less than 7%. This assumption is made so that the calculation of pseudocritical pressure and temperature can be determined from the simple correlation mention below where it only required the gas specific gravity.

$$P_{pc} = 709.604 - 58.718\gamma_g$$

Equation 21

$$T_{pc} = 170.491 + 307.344\gamma_g$$

Equation 22

If there are impurities in the gases, it will require some corrections that can be made by using either charts or correlations such as Wichert-Aziz (1972) and Ahmad (1989).

For the model, the kinetic energy change or acceleration component is assumed to be zero for constant area and incompressible flow.

4.3 Sensitivity Analysis

Sensitivities on several parameters had been run in order to determine how the parameters will affect the pressure drops in the SSSV. When one variable is changed, the others are kept constant and the effect of changes towards the pressure drops is analyzed. Before running the sensitivities, the base case for both single and two phase flow are needed to be set up. This is done so that we could compare the results for several ranges of values of the parameter's data. The sensitivity range is also decided. The base case and the sensitivity range for both single and two phase flow are as follow:

Table 5 Base Case and Sensitivity Range for 1-Phase Flow

1P Flow Base Case

P_1	1000	*psia*
T_1	176	*F*
d	0.78125	*in*
D	2.602	*in*
C_d	0.9	
Y	0.85	
γ_g	0.7	
Z_1	0.9134	
q_{sc}	800	*Mscfd*

Sensitivity Range

	1	2	3	4	5
P_1	600	800	1000	1200	1400
T_1	130	150	176	200	220
q_g	100	300	500	800	1100
d	0.5625	0.6875	0.78125	0.90625	1
D	1.815	2.150	2.602	2.764	3.340
γ_g	0.5	0.6	0.7	0.8	0.9

Base Case

Table 6 Base Case and Sensitivity Range for 2-Phase Flow

2-P Flow Base Case

P_1	615	psia
T_1	170	F
q_{op}	800	stb/d
q_{gp}	250000	scf/d
d	0.78125	in
D	2.602	in
γ_o	0.85	
γ_g	0.65	
API	35	
Z	0.9534	

Sensitivity Range

	1	2	3	4	5
P_1	200	400	615	800	1000
T_1	130	150	170	190	210
q_o	200	500	800	1000	1500
q_g	170000	200000	250000	280000	350000
d	0.5625	0.6875	0.78125	0.90625	1
D	1.815	2.150	2.602	2.764	3.340
γ_o	0.75	0.80	0.85	0.90	0.95
γ_g	0.5	0.65	0.7	0.8	0.9
API	10	20	35	45	60

The sensitivities results are plotted on the graph against the pressure drops to show the relationship between the particular parameter and pressure drops. The results will be discussed next.

4.4 Sensitivity Results for Single-Phase Flow

4.4.1 Effect of Gas Flow Rate on Pressure Drop

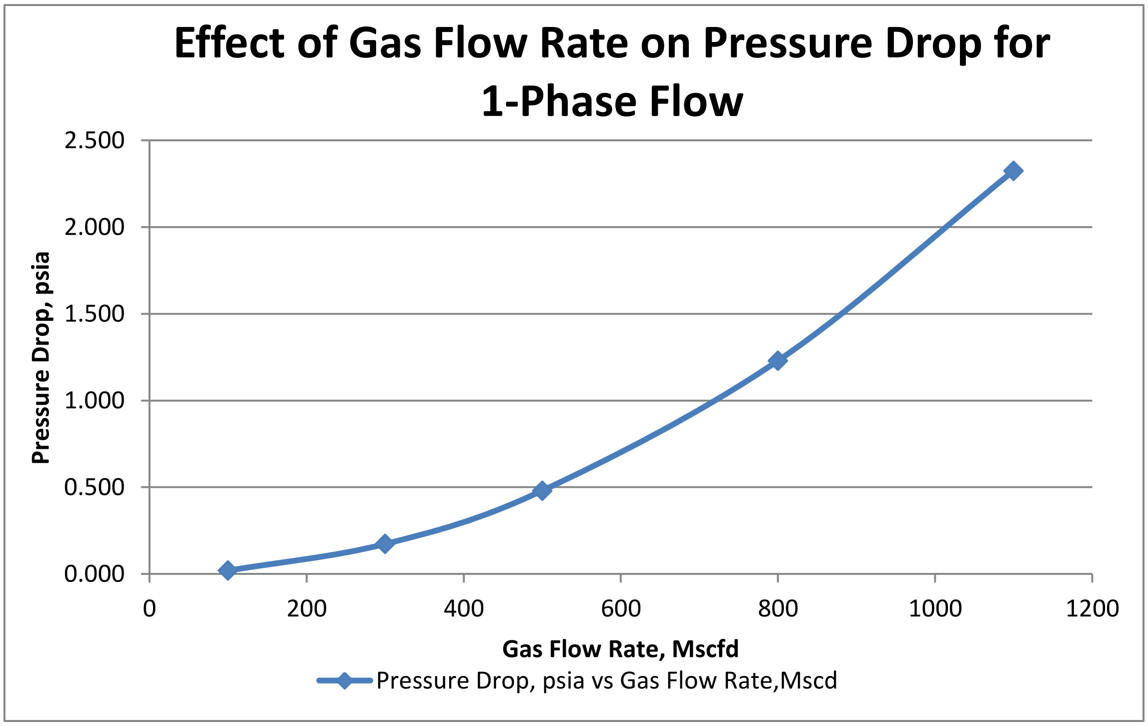


Figure 15 Effect of Gas Flow Rate on Pressure Drop for 1-Phase Flow

Based on the graph obtained by plotting various gas flow rate with pressure drop for single phase flow, it can be seen that as the gas flow rate increases, the pressure drop increases. This phenomenon can be explained by saying that as the gas flow rate increases; the gas velocity will also increase. This will cause an increase in the friction loss which causes the pressure drop to increase as well. Besides, from the single phase pressure drop equation, we can see that the gas flow rate is proportional to the pressure drop.

4.4.2 Effect of Pipe ID on Pressure Drop

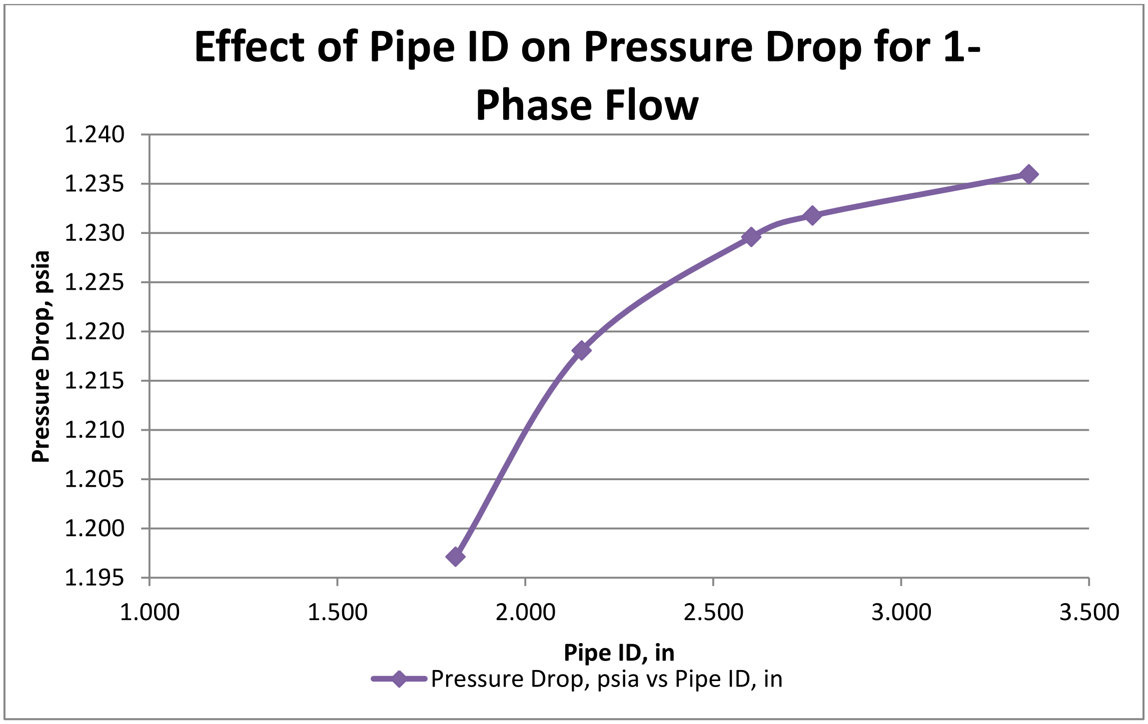


Figure 16 Effect of Pipe ID on Pressure Drop for 1-Phase Flow

The sensitivity is then done on several values of Pipe ID. The pipe ID is referring to the tubing ID before and after the SSSV. Based on the graph plotted for pipe ID with pressure drops, we can observe that as the pipe ID increases in size, the pressure drops across the SSSV increases. When there is an increased in the pipe ID, the restriction for fluid to flow in the pipe will decrease. Hence it will reduce the friction in pipe which then will decrease the pressure drops across SSSV. However in this case, we can observe that the pressure drop is increasing. This phenomenon is happening because of the fluid from the pipe entering the small entry of the SSSV at higher flow rate which then increases the pressure drops.

4.4.3 Effect of Bean Diameter on Pressure Drop for 1-Phase Flow

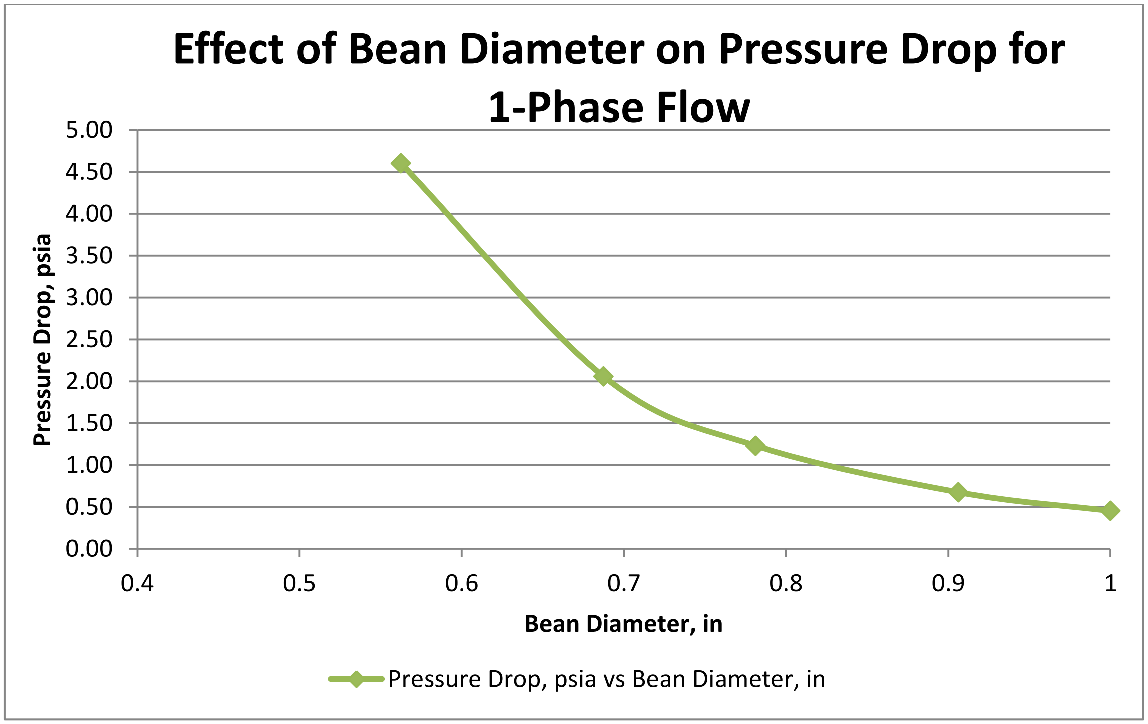


Figure 17 Effect of Bean Diameter on Pressure Drop for 1-Phase Flow

Several values of bean diameter which is the size of SSSV have been used in order to analyze the effect of bean diameter towards the pressure drop across the SSSV. The range is from 36/64 opening to fully open, 64/64. Based on the graph above, it can be seen that as the bean diameter size increases, the pressure drop across the SSSV decreases. This is because as the bean diameter increases, the restriction for fluid to flow in the SSSV is less and therefore decreases the friction losses. Hence the pressure drops across the SSSV decreases.

4.4.4 Effect of Upstream Pressure on Pressure Drop for 1-Phase Flow

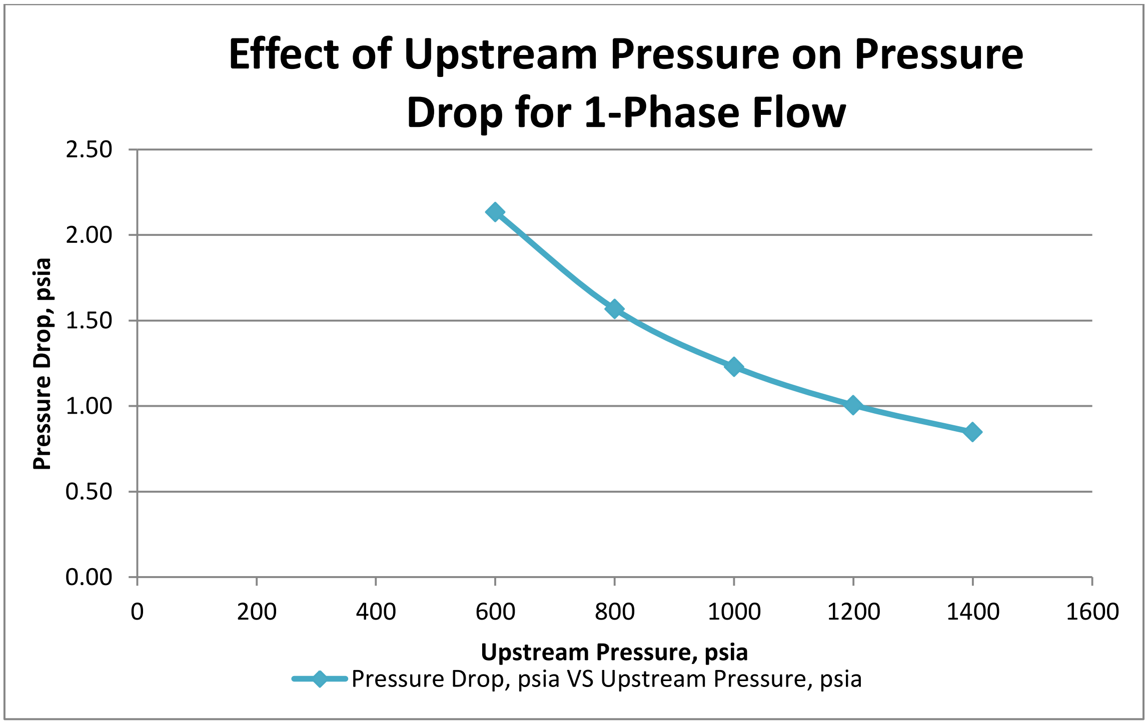


Figure 18 Effect of Upstream Pressure on Pressure Drop for 1-Phase Flow

The upstream pressure is referring to the pressure entering the SSSV. Based on the graph plotted on upstream pressure with pressure drop, we can observe that as the upstream pressure increases, the pressure drop across the SSSV decreases. For a single phase gas flow which is a compressible flow, when the pressure increases, it will decrease the density of the gas assuming the temperature is constant. Lesser density of gas will reduced the friction losses along the pipe. Therefore, decreases the pressure drop across the SSSV.

4.4.5 Effect of Upstream Temperature on Pressure Drop for 1-Phase Flow

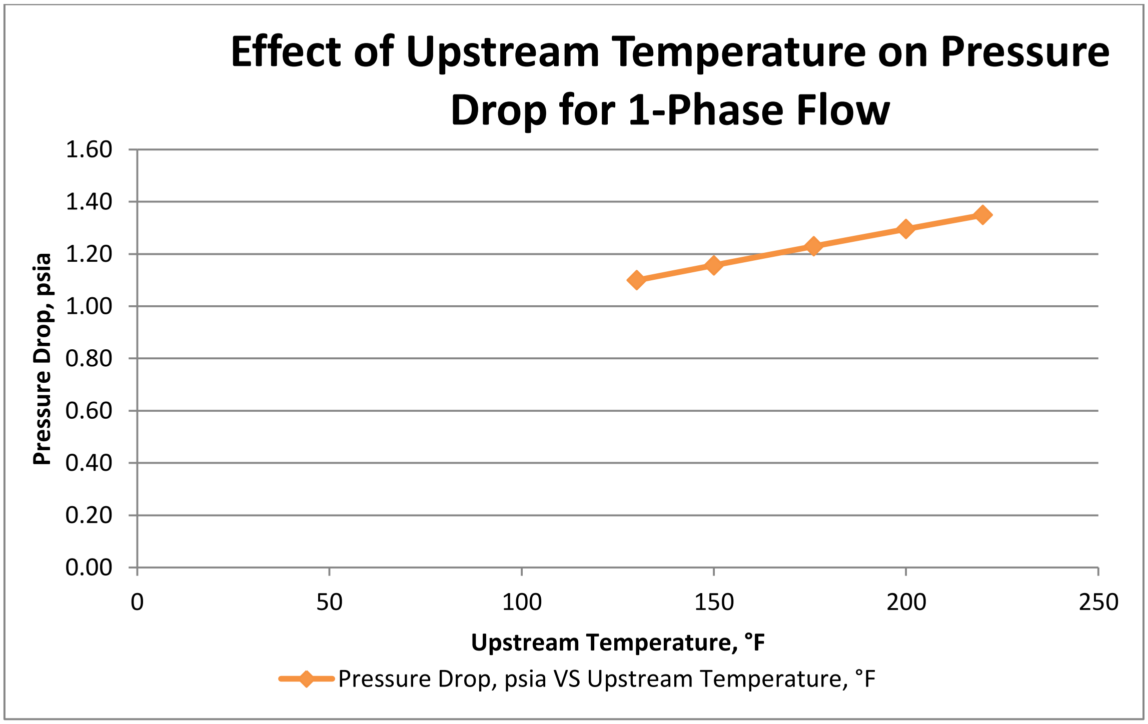


Figure 19 Effect of Upstream Temperature on Pressure Drop for 1-Phase Flow

Based on the graph plotted on upstream temperature with pressure drop, it can be seen that as the temperature increases, the pressure drop across the SSSV increases. This is due to the effect of the viscosity of the gas. When temperature increases the gas will become more viscous, this will cause more resistance for the gas to flow. Hence, the friction losses increase which then causes the pressure drop across the SSSV to increase.

4.4.6 Effect of Gas Specific Gravity on Pressure Drop for 1-Phase Flow

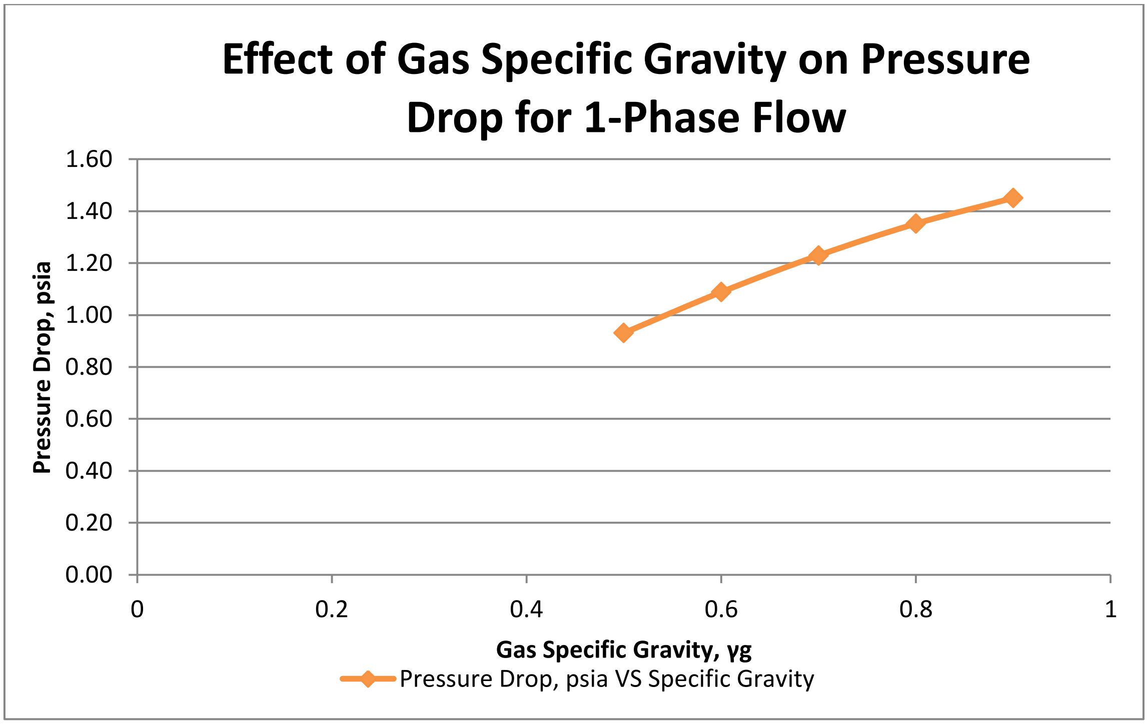


Figure 20 Effect of Gas Specific Gravity on Pressure Drop for 1-Phase Flow

Based on the graph plotted on gas specific gravity with pressure drop, it can be seen that when the gas specific gravity increases, the pressure drop across the SSSV also increases. This phenomenon can be explained with the density of gas. As the gas specific gravity increases, the density of gas also increases which also increase the friction losses. Therefore, the pressure drops across the SSSV also increases.

4.5 Sensitivity Results for Two-Phase Flow

4.5.1 Effect of Upstream Pressure on Pressure Drop

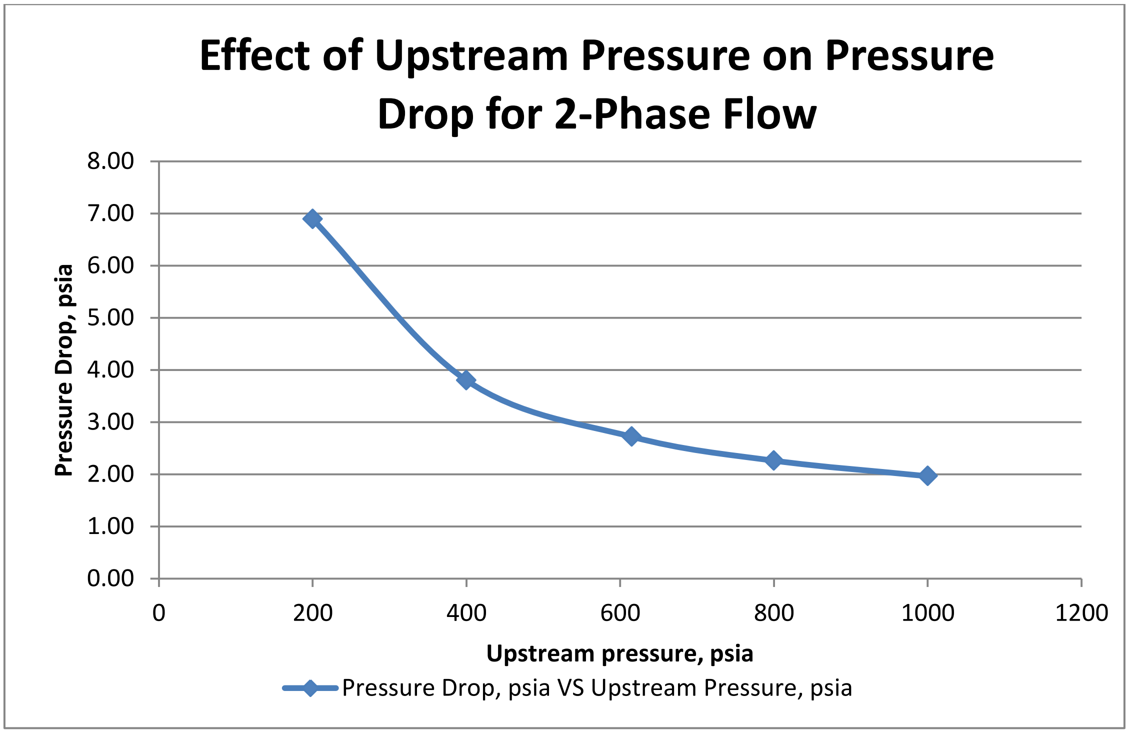


Figure 21 Effect of Upstream Pressure on Pressure Drop for 2-Phase Flow

The upstream pressure is referring to the pressure entering the SSSV. Based on the graph plotted on upstream pressure with pressure drop, we can observe that as the upstream pressure increases, the pressure drop across the SSSV decreases. This phenomenon can be explained through the density effect. As the upstream pressure increase, the density which is dependent on the pressure will decrease. The less dense fluid will be able to move more easily through the SSSV. This could also means, the friction losses is reduced as the upstream pressure increases. Therefore, the pressure drop decreases.

4.5.2 Effect of Upstream Temperature on Pressure Drop

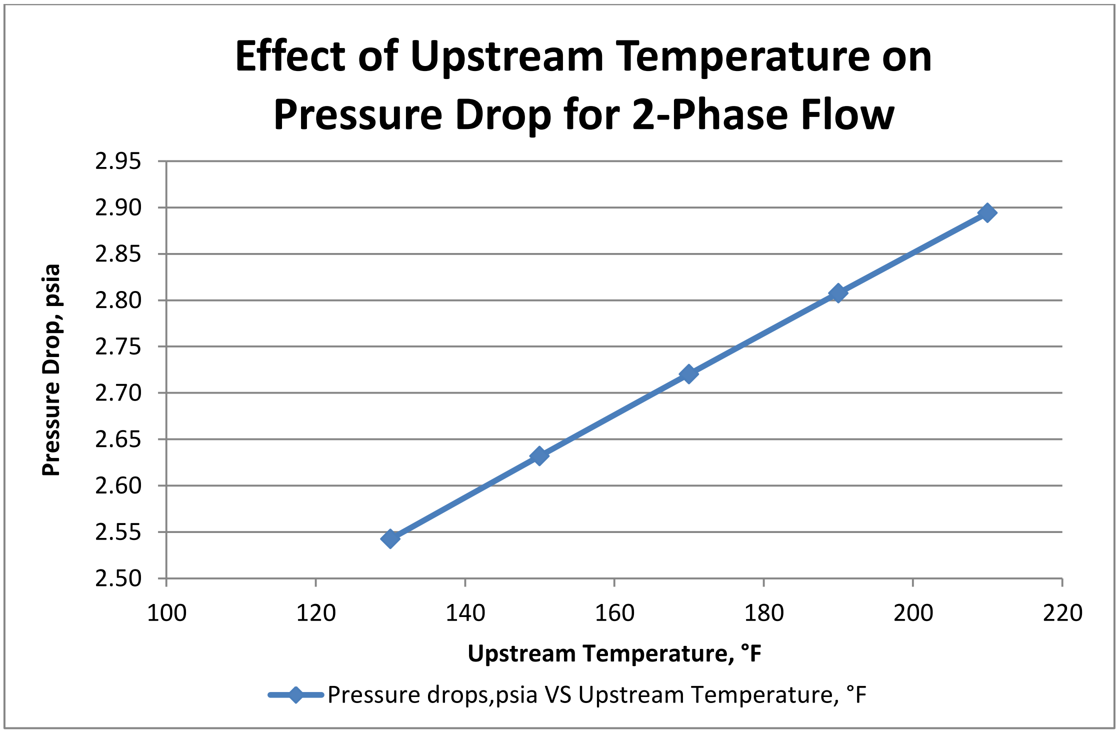


Figure 22 Effect of Upstream Temperature on Pressure Drop for 2-Phase Flow

Based on the graph plotted on upstream temperature with pressure drop, it can be seen that as the temperature increases, the pressure drop across the SSSV increases. This is due to the effect of the viscosity of the two-phase flow. The viscosity of liquid will decrease as the temperature increases. The viscosity of gas will increase with when the temperature increases. As the two-phase fluid will have different viscosity, it will move at different velocity. The different in velocity increases slippage between the gas liquid phases which then increases the pressure drop.

4.5.3 Effect of Oil Flow Rate on Pressure Drop

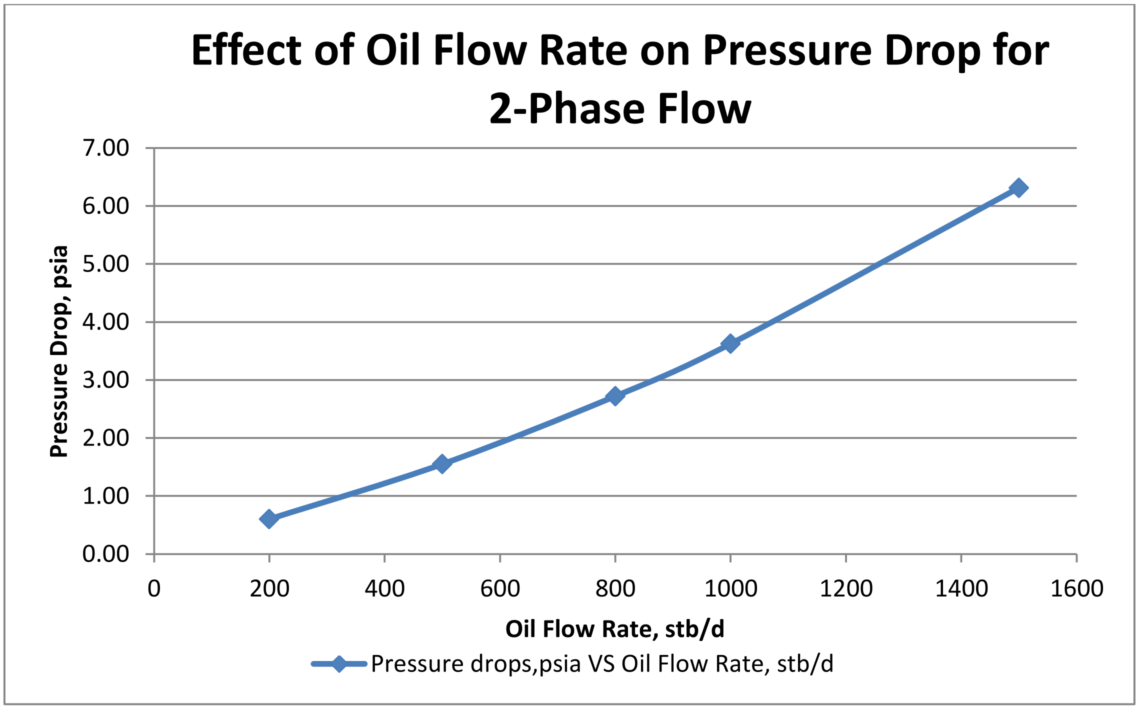


Figure 23 Effect of Oil Flow Rate on Pressure Drop for 2-Phase Flow

Based on the graph obtained by plotting various oil flow rate with pressure drop for two phase flow, it can be observed that as the oil flow rate increases, the pressure drop increases. This phenomenon can be explained by saying that as the oil flow rate increases; the liquid holdup and oil velocity will also increase. This will cause an increase in both the hydrostatic and friction loss which causes the pressure drop to increase as well.

4.5.4 Effect of Gas Flow Rate on Pressure Drop

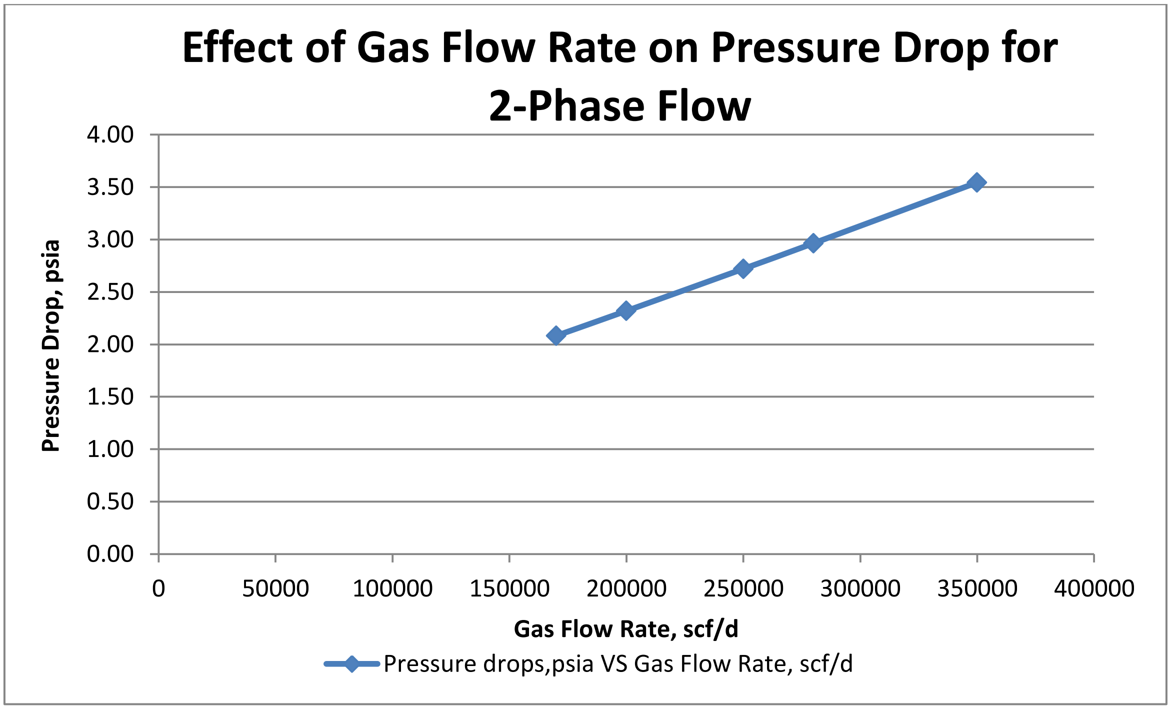


Figure 24 Effect of Gas Flow Rate on Pressure Drop for 2-Phase Flow

Based on the graph obtained by plotting various gas flow rate with pressure drop for two-phase flow, it can be seen that as the gas flow rate increases, the pressure drop increases. This phenomenon can be explained by saying that as the gas flow rate increases; the gas velocity will also increase. This will cause an increase in the friction loss which causes the pressure drop to increase as well.

4.5.5 Effect of Bean Diameter on Pressure Drop

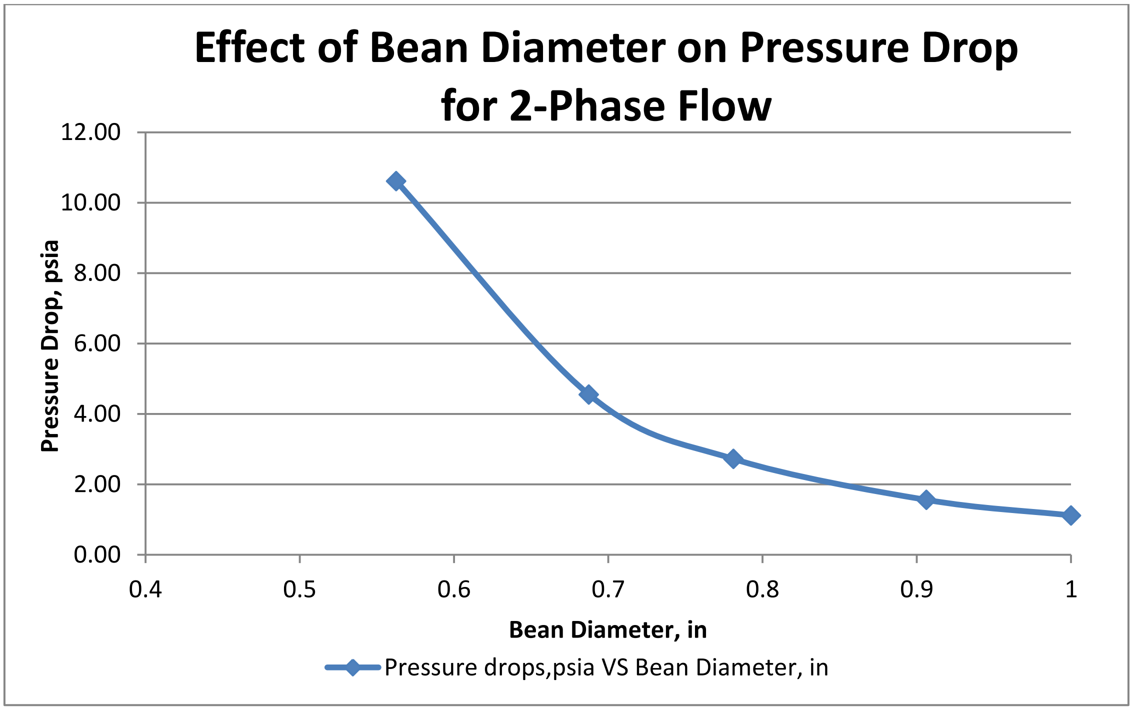


Figure 25 Effect of Bean Diameter on Pressure Drop for 2-Phase Flow

Several values of bean diameter which is the size of SSSV have been used in order to analyze the effect of bean diameter towards the pressure drop across the SSSV. The range is from 36/64 opening to fully open, 64/64. Based on the graph above, it can be seen that as the bean diameter size increases, the pressure drop across the SSSV decreases. This is because as the bean diameter increases, the restriction for fluid to flow in the SSSV is less and therefore decreases the friction losses. Hence the pressure drops across the SSSV decreases.

4.5.6 Effect of Pipe ID on Pressure Drop

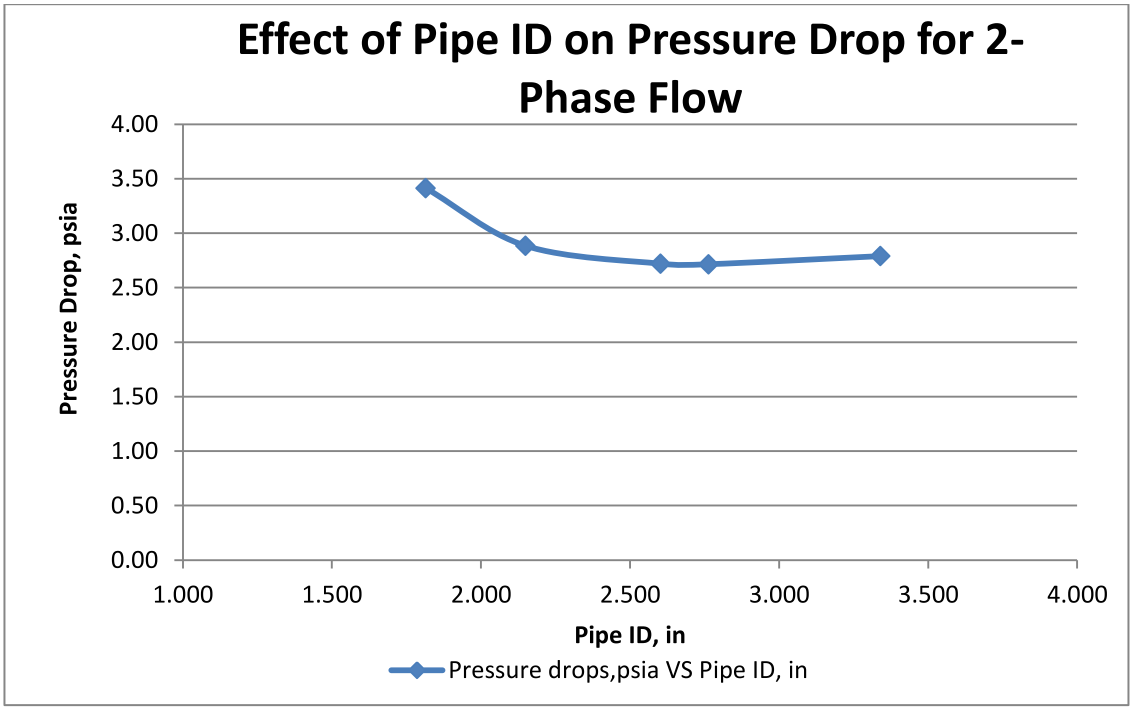


Figure 26 Effect of Pipe ID on Pressure Drop for 2-Phase Flow

Based on the graph plotted for pipe ID with pressure drop, we can see that as the pipe ID increasing, the pressure drop across SSSV decreases only until the pipe ID of 2.764 in. At pipe ID of 3.340 in and above, the pressure drop started to increased. This phenomenon can be explained by saying as the pipe ID increases, the friction loss and the total pressure gradient will decrease up to a certain point. However, as the pipe ID increases above the maximum, the velocity of the mixture decreases and the fluid will be more in contact with the pipe wall which will increase the friction losses. Therefore, the pressure drop started to increase above 3.340 in.

4.5.7 Effect of API Gravity on Pressure Drop

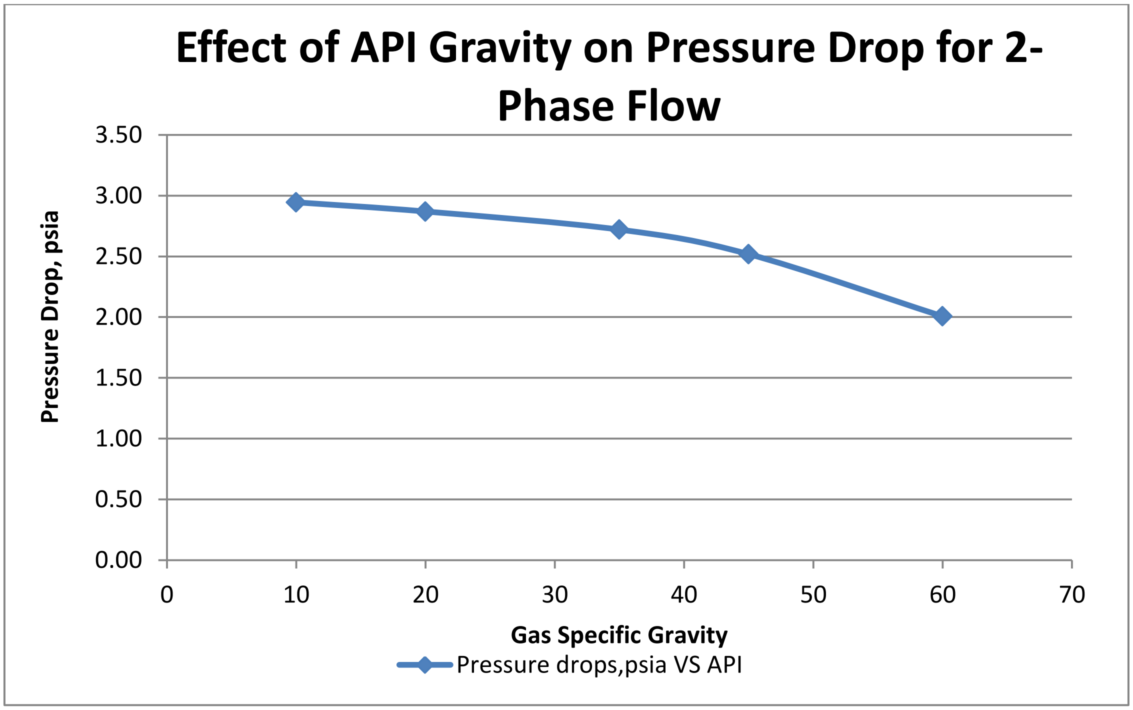


Figure 27 Effect of API Gravity on Pressure Drop for 2-Phase Flow

Based on the graph plotted for API Gravity with pressure drop, we can see that as the API gravity increases, the pressure drop increases. API gravity is a measured of how heavy or light a petroleum liquid is compared to water. The lower the API gravity, the heavy the liquid is. From the trend in the above graph, it can be explained that the lighter the liquid, it is much easier for the fluid to move across the SSSV. This also means, less restriction and reduced friction loss which results to less pressure drop.

4.5.8 Effect of Oil Specific Gravity on Pressure Drop

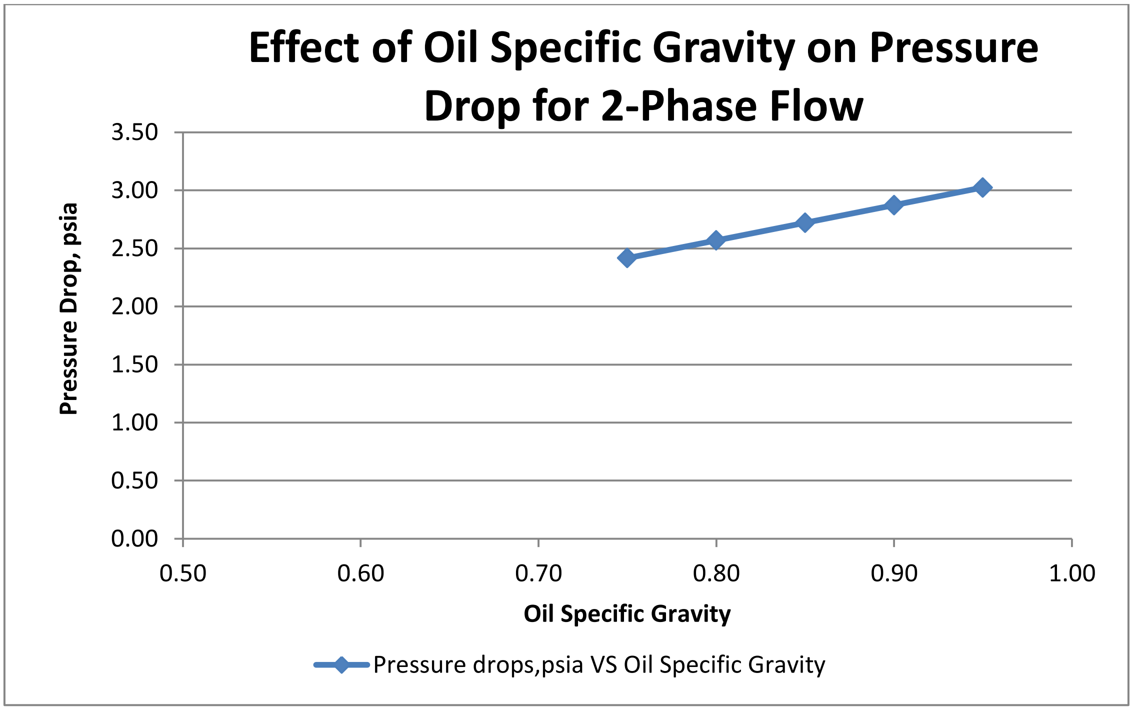


Figure 28 Effect of Oil Specific Gravity on Pressure Drop for 2-Phase Flow

Based on the graph plotted on oil specific gravity with pressure drop, it can be seen that when the oil specific gravity increases, the pressure drop across the SSSV also increases. This phenomenon can be explained with the density of oil. As the oil specific gravity increases, the density of oil also increases. As the oil density increases, it will also increase the friction losses. Therefore, the pressure drops across the SSSV also increases.

4.6 Sensitivity Results Comparison

In this section, the results from sensitivity analysis for both phases will be compared.

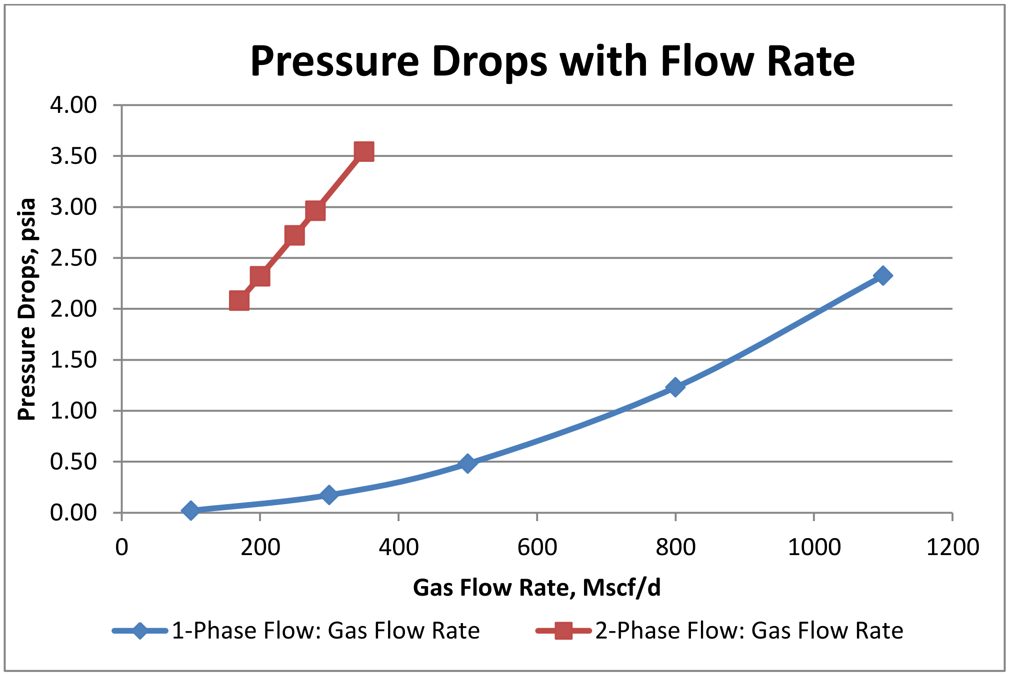


Figure 29 Sensitivity Result Comparison: Flow Rate

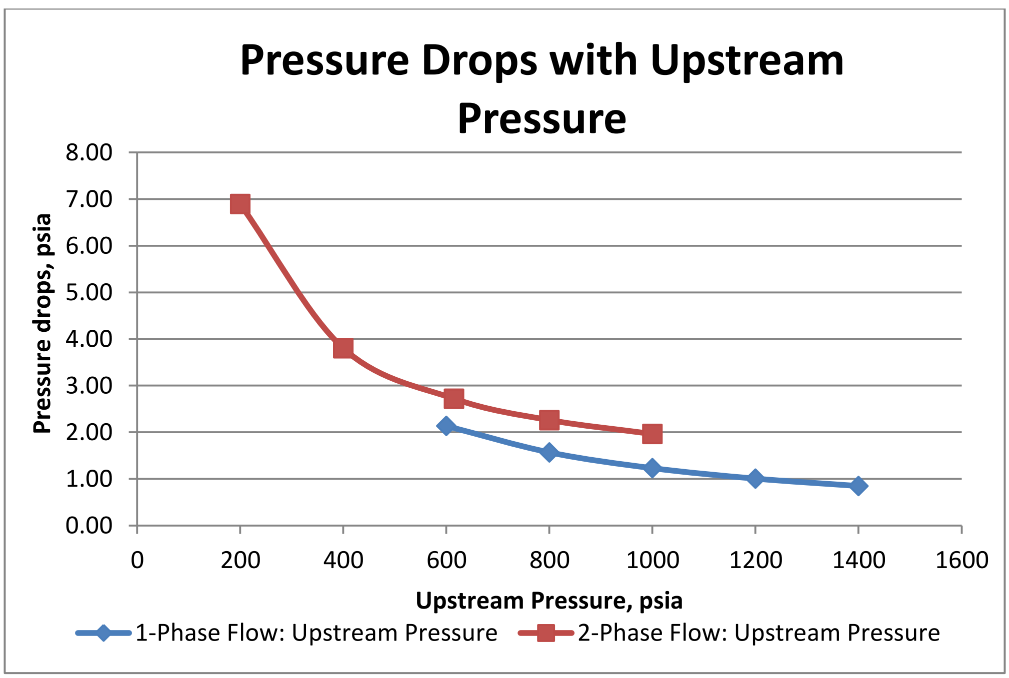


Figure 30 Sensitivity Result Comparison: Upstream Pressure

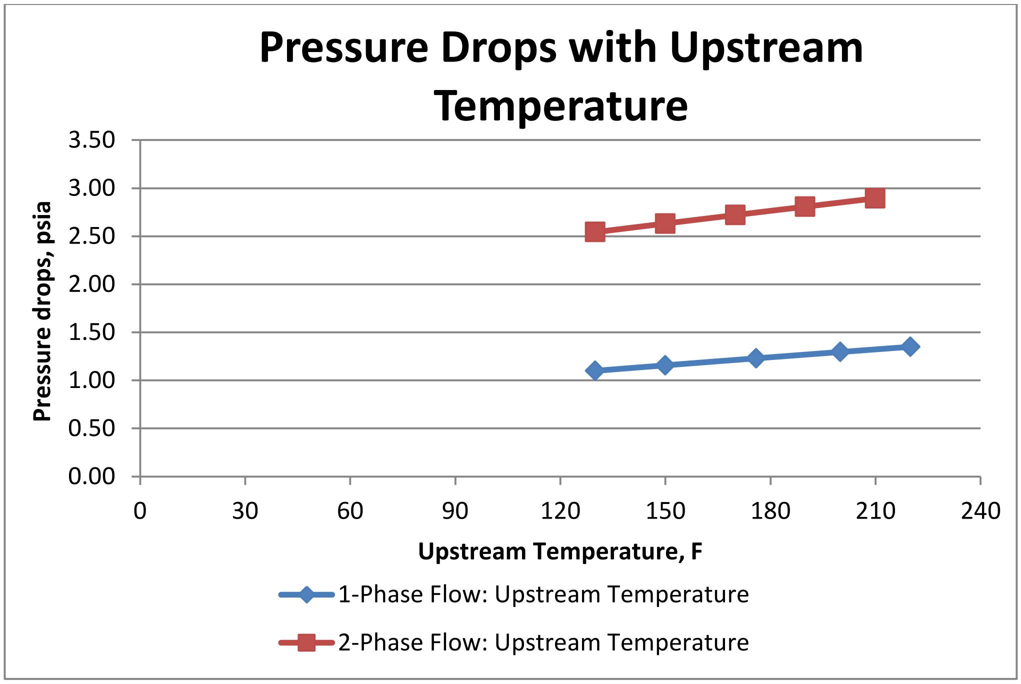


Figure 31 Sensitivity Result Comparison: Upstream Temperature

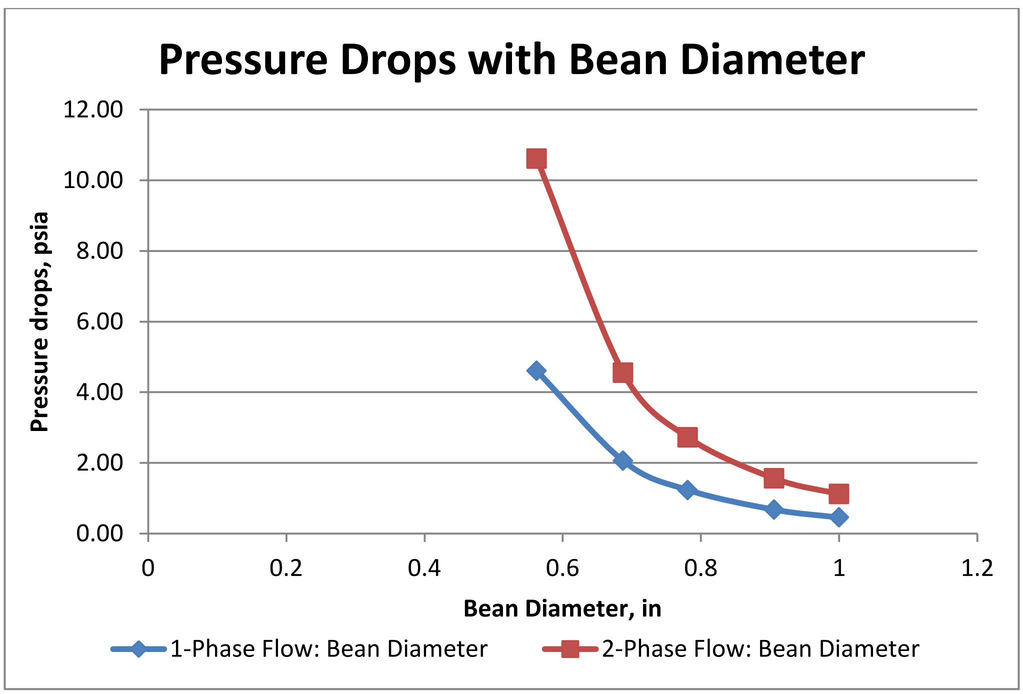


Figure 32 Sensitivity Result Comparison: Bean Diameter

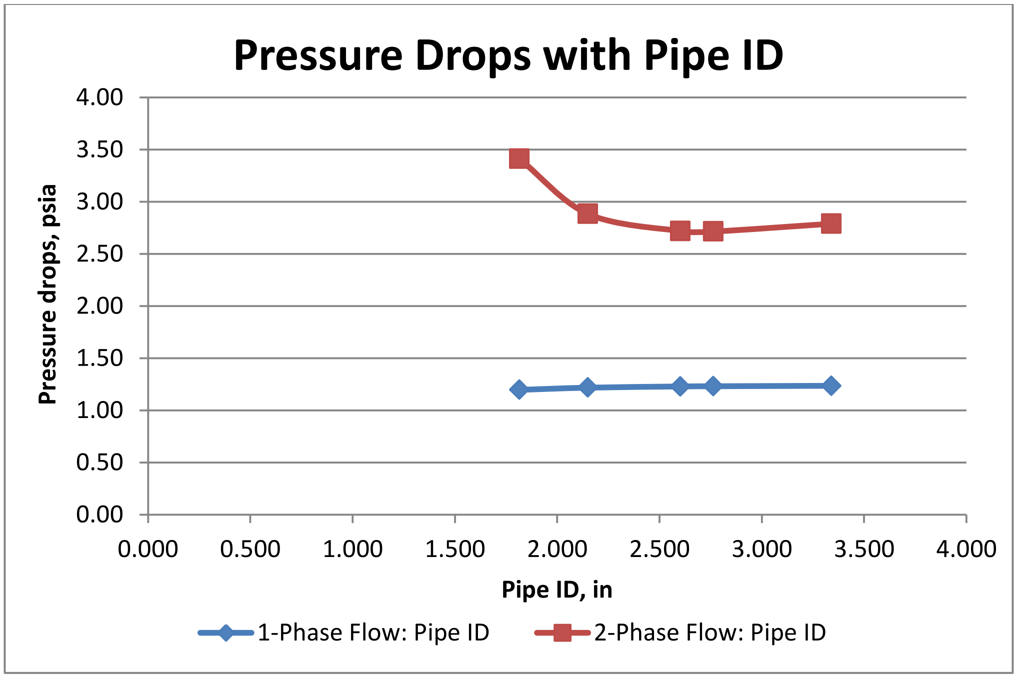


Figure 33 Sensitivity Result Comparison: Pipe ID

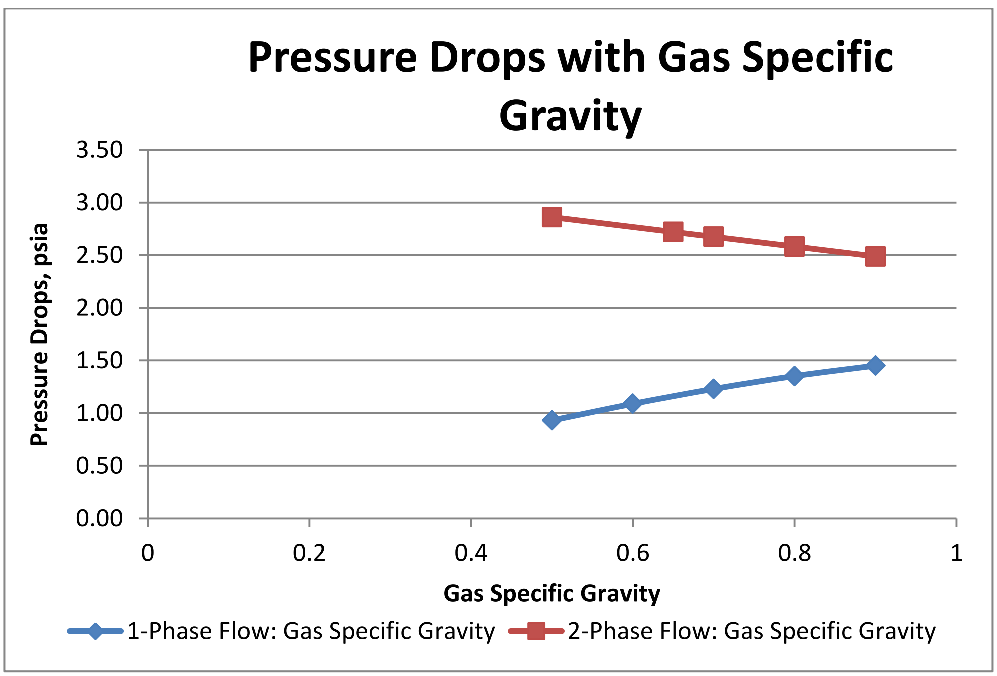


Figure 34 Sensitivity Result Comparison: Gas Specific Gravity

Based on the graph plotted from Figure 29 to Figure 34, we could observe the trend of behavior for each parameter on single and two-phase flow. It can be seen that the pressure drop for 2-phase flow for every parameters is higher than the pressure drop for single-phase flow. The higher pressure drop for 2-phase flow is due to the interaction of the phases in the SSSV which will increase the friction losses. The friction losses in 2-phase flow are higher than single-phase flow hence higher pressure drop as well.

The sensitivity results comparison is important especially during the designing of the SSSV. In order to have an optimized and efficient SSSV, we should not under-design or over-design it. Since it is possible to have both single and two-phase flow in the SSSV, we are able to know the gap between the single and two-phase flow SSSV competencies through this comparison. Therefore, this knowledge can be used to design the efficient and optimized SSSV.

CHAPTER 5

CONCLUSIONS & RECOMMENDATIONS

5.1 Conclusions

The whole project can be summarized as follow:

- The numerical model to predict the pressure drop across the SSSV for single and two-phase flow for subcritical flow has been developed.
- In the model, the gas compressibility factor is calculated by using Brill and Beggs (1974) correlations.
- It is also assumed that the acceleration component is zero for constant area and incompressible flow.
- The sensitivity analysis on several parameters had been done to analyze the effect of the parameters towards the pressure drop in the SSSV.
- It is important to know the effect of each parameter towards the pressure drop across the SSSV as the knowledge can be used in designing an efficient and optimized SSSV.
- With a good understanding on the sensitivity analysis done, we are able to know the range of sensitivity for each parameter that is affecting the SSSV so that we would not under design or over design the SSSV.
- It is hope that through this project, a better management of the SSSV can be achieved. Hopefully the project will be beneficial and can be applied in the industry.
- The objectives of the project have been achieved. Therefore, the project can be considered as successfully completed.

5.2 Recommendations

The following are the recommendations suggested in order to improve the project:

- The developed numerical model can be further improved by adding the calculation for spring force to determine the forces tending for valve closure.

- More in depth study and analysis on the SSSV. For example, pressure drop in SSSV for 3-phase flow.

- All study and computer codes done on SSSV should be compiled in one integrated computer programs that could be used as a standard for a better management of the SSSV.

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APPENDIX 1

The numerical model for **Pressure Drop in SSSV for Single-Phase Flow –Given Z**

Pressure Drops in SSSV for Single-Phase Flow

Given Z

```
In[1]:= Clear["Global`*"];

(*input parameters*)
P1 = 1000;            (*Pressure Upstream*)(*psia*)
T1 = 176 + 460;       (*Upstream Temperature*)(*°R*)
qsc = 800;            (*Gas Flow Rate*)(*Mscfd*)
db = 50 / 64;         (*Bean Diameter*)(*in*)
Dp = 2.602;           (*Pipe ID*)(*in*)
Cd = 0.9;             (*Discharge coefficient*)(*suggested by API*)
Y = 0.85;             (*Expansion Factor*)(*Default value for quick estimation*)
γg = 0.7;             (*Gas Specific Gravity*)
Z1 = 0.9051;

(*calculating Beta Ratio,β*)
Print["β = ", β = db/Dp]


(*To calculate pressure drop, ΔP*)
Print["ΔP = ", ΔP = ((1.048*10^(-6))*γg*Z1*T1*(qsc)^2*(1 - β^4))/(P1*db^4*(Cd)^2*Y^2)]

Manipulate[Plot[((1.048*10^(-6))*γg*Z1*T1*(qsc)^2*(1 - β^4))/(P1*db^4*(Cd)^2*Y^2),
  {qsc, 200, 1000}, AxesLabel → {"Gas Flow Rate, Mscfd", "Pressure Drop,psia"},
  PlotLabel → "Pressure Drop,psi vs. Gas Flow Rate"] ]
```

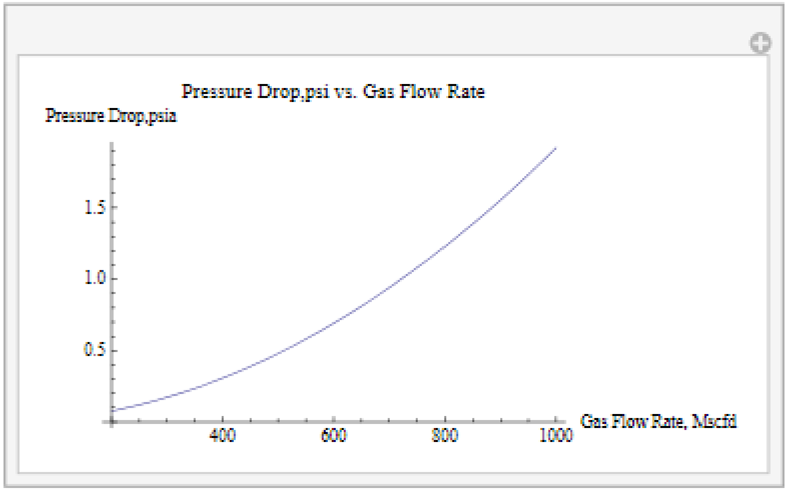
$$\beta = \frac{d_b}{D_p}$$

$$\Delta P = \frac{(1.048 \times 10^{-6})\, \gamma_g Z_1 T_1 (q_{sc})^2 (1-\beta^4)}{P_1 d_b^4 (C_d)^2 Y^2}$$

$\beta = 0.30025$

$\Delta P = 1.22961$

Out[13]=



APPENDIX 2

The numerical model for **Pressure Drop in SSSV for Single-Phase Flow –Calculating Z using Brill and Beggs (1974) correlations**

Pressure Drops in SSSV for Single-Phase Flow

with Z calculation using Brill & Beggs(1974)

```
In[14]:= Clear["Global`*"];

(*Input Parameters*)
P1 = 1000;              (*Pressure Upstream*)(*psia*)
T1 = 176 + 460;          (*Upstream Temperature*)(*°R*)
qsc = 800;               (*Gas Flow Rate*)(*Mscfd*)
db = 50 / 64;             (*Bean Diameter*)(*in*)
Dp = 2.602;               (*Pipe ID*)(*in*)
Cd = 0.9;               (*Discharge coefficient*)(*suggested by API*)
Y = 0.85;               (*Expansion Factor*)(*Default value for quick estimation*)
γg = 0.7;              (*Gas Specific Gravity*)

(*Calculating Beta Ratio,β*)
Print["β = ", β = db/Dp]

(*Calculating Gas Compressibility Factor, Z*)
(*For Ppc and Tpc formula, assume that the composition of gas H2S < 3%,
N2 <5% and total content of inorganic compound < 7% *)

Ppc = 709.604 - 58.718 * γg;    (*Pseudocritical Pressure*)
Ppr = P1/Ppc;                   (*Pseudoreduced Pressure*)
Tpc = 170.491 + 307.344 * γg;   (*Pseudocritical Temperature*)
Tpr = T1/Tpc;                     (*Pseudoreduced Temperature*)
```

```
(*Brill and Beggs - Z Factor*)
Print["Aconstant = ", Aconstant = 1.39 (Tpr - 0.92)^0.5 - 0.36 * Tpr - 0.10]
Print["Econstant = ", Econstant = 9 (Tpr - 1)]
Print["Bconstant = ",
 Bconstant = (0.62 - 0.23 * Tpr) * Ppr + (0.066/(Tpr - 0.86) - 0.037) * (Ppr)^2 + (0.32 * (Ppr)^6)/10^Econstant]
Print["Cconstant = ", Cconstant = 0.132 - 0.32 * Log10[Tpr]]
Print["Fconstant = ", Fconstant = 0.3106 - 0.49 * Tpr + 0.1824 * (Tpr)^2]
Print["Dconstant = ", Dconstant = 10^Fconstant]

Print["Z1 = ", Z1 = Aconstant + (1 - Aconstant)/Exp[Bconstant] + Cconstant * (Ppr)^Dconstant]


(*To calculate pressure drop, ΔP*)
Print["ΔP = ", ΔP = ((1.048 * 10^(-6)) * γg * Z1 * T1 * (qsc)^2 * (1 - β^4))/(P1 * db^4 * (Cd)^2 * Y^2)]
```

β = 0.30025

$A_{constant}$ = 0.493272

$E_{constant}$ = 5.84317

$B_{constant}$ = 0.464356

$C_{constant}$ = 0.062469

$F_{constant}$ = -0.00140078

$D_{constant}$ = 0.99678

Z_1 = 0.905096

ΔP = 1.2296

APPENDIX 3

The numerical model for **Pressure Drop in SSSV for Two-Phase Flow –Given Z**

Pressure Drops in SSSV for Two-Phase Flow

Given Z

```
In[36]:= Clear["Global`*"];
(*given parameters*)
P1 = 615;                (*Pressure Upstream*)(*psia*)
T1 = 170;                (*Upstream Temperature*)(*oF*)
qop = 800;               (*Produced Oil Flow Rate*)(*STB/D*)
qgp = 250000;            (*Produced Gas Flow Rate*)(*scfd*)
db = 50 / 64;            (*Bean Diameter*)(*in*)
Dp = 2.602;              (*Pipe ID*)(*in*)
γg = 0.65;               (*Gas Specific Gravity*)
γo = 0.85;               (*Oil Specific Gravity*)
API = 35;
Z = 0.9534;              (*Gas Compressibility Factor*)

(*calculate R, Producing Gas/Oil Ratio, scf/STB *)
Print["R = ", N[R = qgp/qop]]

(*calculate Rs, Solution Gas/Oil Ratio*)
γgc = γg;
(*γgc-corrected gas gravity. if separator conditions unknown,γgc=γg *)

C1 = If [API ≤ 30, 0.0362, 0.0178];          (*True-API≤30, False-API>30*)
C2 = If[API ≤ 30, 1.0937, 1.1870];           (*True-API≤30, False-API>30*)
C3 = If[API ≤ 30, 25.7240, 23.9310];         (*True-API≤30, False-API>30*)

Print["Rs = ", Rs = C1 * γgc * P1^C2 * Exp[(C3 * API)/(T1 + 460)]]

(*Calculate Bo, Oil Formation Volume Factor*)
C1 = If[API ≤ 30, 4.677 * 10^(-4), 4.670 * 10^(-4)];
C2 = If[API ≤ 30, 1.751 * 10^(-5), 1.100 * 10^(-5)];
C3 = If[API ≤ 30, -1.811 * 10^(-8), 1.337 * 10^(-9)];

Print["Bo = ", Bo = 1 + C1 Rs + C2 * (T1 - 60) (API/γgc) + C3 * Rs * (T1 - 60) (API/γgc)]

(*Calculate Bg, Gas Formation Volume Factor*)
Print["Bg = ", Bg = (0.0283 * Z * (T1 + 460))/P1]
```

(*At P_{sc}=14.7 psia and T_{sc}=520∘R*)

(*Calculate $q_o^{'}$, in-situ Oil Flow Rate*)(*ft^3/sec*)

$$\text{Print}\left["q_o\ =\ ",\ q_o = 6.5 * 10\text{^}(-5) * q_{op} * B_o\right]$$

(*Calculate $q_g^{'}$, in-situ Gas Flow Rate*)(*ft^3/sec*)

$$\text{Print}\left["q_g\ =",\ q_g = \frac{q_{op} * (R - R_s) * (B_g)}{86400}\right]$$

(*Calculate Liquid Holdup,λ_1*)

$$\text{Print}\left["\lambda_1\ =\ ",\ \lambda_1 = \frac{q_o}{q_o + q_g}\right]$$

(*Calculate Density of oil, ρ_o*)(*lbm/ft^3*)

$$\text{Print}\left["\rho_o\ =\ ",\ \rho_o = \frac{350 * \gamma_o + 0.0764 * \gamma_g * R_s}{5.615 * B_o}\right]$$

(*Calculate Density of gas, ρ_g*)(*lbm/ft^3*)

$$\text{Print}\left["\rho_g\ =\ ",\ \rho_g = \frac{2.7 * \gamma_g * P_1}{Z * (T_1 + 460)}\right]$$

(*Calculate No-Slip Density, ρ_n*)(*lbm/ft^3*)

$$\text{Print}\left["\rho_n\ =\ ",\ \rho_n = \rho_o * \lambda_1 + \rho_g * (1 - \lambda_1)\right]$$

(*Calculate number of Void Space, N_v*)

$$\text{Print}\left["N_v\ =\ ",\ N_v = \frac{q_g}{q_o}\right]$$

(*Calculate Beta Ratio, β*)

$$\text{Print}\left["\beta\ =\ ",\ \beta = \frac{d_b}{D_p}\right]$$

(*Calculate Discharge Coefficient, C_d*)

C_1 = 0.233; (*Constant Value*)

C_2 = 8.4 * 10^(-4); (*Constant Value*)

C_3 = 6.672; (*Constant Value*)

C_4 = -11.661; (*Constant Value*)

$$\text{Print}\left["C_d\ =\ ",\ C_d = C_1 + C_2 * N_v + C_3 * \beta + C_4 * \beta\text{^}2\right]$$

(*Calculate Area of SSSV, A*)(*ft^2*)

$$\text{Print}\left["A\ =\ ",\ N\left[A = \left(\frac{\pi}{4}\right) * \left(\frac{d_b}{12}\right)^2\right]\right]$$

(*Calculate Mixture Velocity, V_m*)(*ft/sec*)

$$\text{Print}\left["V_m\ =\ ",\ V_m = \frac{q_o + q_g}{A}\right]$$

```
(*Calculate Pressure Drop*)(*psia*)
Print["ΔP = ", ΔP = (1.078*10^(-4)*ρn*(Vm)^2)/Cd]

(*To find Downstream pressure, P2*)(*psia*)
Print["P2 = ", P2 = P1 - ΔP]

Manipulate[Plot[(1.078*10^(-4)*ρn*(Vm)^2)/Cd, {Vm, 0, 30},
  AxesLabel → {"Mixture Velocity, ft/sec", "Pressure Drop,psia"},
  PlotLabel → "Pressure Drop,psi vs. Mixture Velocity"]]
```

$R = 312.5$

$R_s = 89.3558$

$B_o = 1.10759$

$B_g = 0.0276393$

$q_o = 0.0575947$

$q_g = 0.0571069$

$\lambda_1 = 0.502126$

$\rho_o = 48.5499$

$\rho_g = 1.79695$

$\rho_n = 25.2728$

$N_v = 0.991531$

$\beta = 0.30025$

$C_d = 1.18586$

$A = 0.00332895$

$V_m = 34.4558$

$\Delta P = 2.72749$

$P_2 = 612.273$

APPENDIX 4

The numerical model for **Pressure Drop in SSSV for Two-Phase Flow –Calculating Z using Brill and Beggs (1974) correlations**

Pressure Drops in SSSV for Two-Phase Flow

with Z calculation using Brill & Beggs(1974)

```
In[76]:= Clear["Global`*"];
(*given parameters*)
P1 = 615;              (*Pressure Upstream*) (*psia*)
T1 = 170;              (*Upstream Temperature*) (*°F*)
qop = 800;             (*Produced Oil Flow Rate*) (*STB/D*)
qgp = 250 000;         (*Produced Gas Flow Rate*) (*scfd*)
db = 50 / 64;          (*Bean Diameter*) (*in*)
Dp = 2.602;            (*Pipe ID*) (*in*)
γg = 0.65;             (*Gas Specific Gravity*)
γo = 0.85;             (*Oil Specific Gravity*)
API = 35;

(*Calculating Gas Compressibility Factor, Z*)
(*For Ppc and Tpc formula, assume that the composition of gas H2S < 3%,
N2 <5% and total content of inorganic compound < 7% *)

Ppc = 709.604 - 58.718 * γg;       (*Pseudocritical Pressure*)
Ppr = P1 / Ppc;                    (*Pseudoreduced Pressure*)
Tpc = 170.491 + 307.344 * γg;      (*Pseudocritical Temperature*)
Tpr = (T1 + 460) / Tpc;            (*Pseudoreduced Temperature*)

(*Brill and Beggs - Z Factor*)
Aconstant = 1.39 (Tpr - 0.92)^0.5 - 0.36 * Tpr - 0.10;
Econstant = 9 (Tpr - 1);
```

$$B_{constant} = (0.62 - 0.23 * T_{pr}) * P_{pr} + \left(\frac{0.066}{T_{pr} - 0.86} - 0.037\right) * (P_{pr})^2 + \frac{0.32 * (P_{pr})^6}{10^{E_{constant}}};$$

$$C_{constant} = 0.132 - 0.32 * \mathrm{Log10}[T_{pr}];$$

$$F_{constant} = 0.3106 - 0.49 * T_{pr} + 0.1824 * (T_{pr})^2;$$

$$D_{constant} = 10^{F_{constant}};$$

$$\mathrm{Print}\left["Z = ",\ Z = A_{constant} + \frac{1 - A_{constant}}{\mathrm{Exp}[B_{constant}]} + C_{constant} * (P_{pr})^{D_{constant}}\right]$$

```
(*Calculate R, Producing Gas/Oil Ratio, scf/STB *)
```

```
Print ["R = ", N[R = q_gp/q_op]]

(*Calculate R_s, Solution Gas/Oil Ratio*)
γgc = γg;
(*γgc-corrected gas gravity. if separator conditions unknown,γgc=γg *)

C1 = If [API ≤ 30, 0.0362, 0.0178];          (*True-API≤30, False-API>30*)
C2 = If[API ≤ 30, 1.0937, 1.1870];           (*True-API≤30, False-API>30*)
C3 = If[API ≤ 30, 25.7240, 23.9310];         (*True-API≤30, False-API>30*)
```

$$\text{Print}\left[\text{"}R_s = \text{"},\ R_s = C_1 * \gamma_{gc} * P_1 \,\hat{}\, C_2 * \text{Exp}\left[\frac{C_3 * \text{API}}{T_1 + 460}\right]\right]$$

```
(*Calculate B_o, Oil Formation Volume Factor*)
C1 = If[API ≤ 30, 4.677 * 10^(-4), 4.670 * 10^(-4)];
C2 = If[API ≤ 30, 1.751 * 10^(-5), 1.100 * 10^(-5)];
C3 = If[API ≤ 30, -1.811 * 10^(-8), 1.337 * 10^(-9)];
```

$$\text{Print}\left[\text{"}B_o = \text{"},\ B_o = 1 + C_1 R_s + C_2 * (T_1 - 60)\left(\frac{\text{API}}{\gamma_{gc}}\right) + C_3 * R_s * (T_1 - 60)\left(\frac{\text{API}}{\gamma_{gc}}\right)\right]$$

(*Calculate B_g, Gas Formation Volume Factor*)

$$\text{Print}\left[\text{"}B_g = \text{"},\ B_g = \frac{0.0283 * Z * (T_1 + 460)}{P_1}\right]$$

(*At P_{sc}=14.7 psia and T_{sc}=520∘R*)

(*Calculate q_o', in-situ Oil Flow Rate*)(*ft^3/sec*)

$$\text{Print}\left[\text{"}q_o = \text{"},\ q_o = 6.5 * 10\,\hat{}\,(-5) * q_{op} * B_o\right]$$

(*Calculate q_g', in-situ Gas Flow Rate*)(*ft^3/sec*)

$$\text{Print}\left[\text{"}q_g = \text{"},\ q_g = \frac{q_{op} * (R - R_s) * (B_g)}{86400}\right]$$

(*Calculate Liquid Holdup,λ_1*)

$$\text{Print}\left[\text{"}\lambda_1 = \text{"},\ \lambda_1 = \frac{q_o}{q_o + q_g}\right]$$

(*Calculate Density of oil, ρ_o*)(*lbm/ft^3*)

$$\text{Print}\left[\text{"}\rho_o = \text{"},\ \rho_o = \frac{350 * \gamma_o + 0.0764 * \gamma_g * R_s}{5.615 * B_o}\right]$$

(*Calculate Density of gas, ρ_g*)(*lbm/ft^3*)

$$\text{Print}\left[\text{"}\rho_g = \text{"},\ \rho_g = \frac{2.7 * \gamma_g * P_1}{Z * (T_1 + 460)}\right]$$

(*Calculate No-Slip Density, ρ_n*)(*lbm/ft^3*)

```
Print["ρ_n = ", ρ_n = ρ_o * λ_1 + ρ_g * (1 - λ_1)]

(*Calculate number of Void Space, N_v*)
Print["N_v = ", N_v = q_g/q_o]

(*Calculate Beta Ratio, β*)
Print["β = ", β = d_b/D_p]

(*Calculate Discharge Coefficient, C_d*)
C_1 = 0.233;            (*Constant Value*)
C_2 = 8.4 * 10^(-4);    (*Constant Value*)
C_3 = 6.672;            (*Constant Value*)
C_4 = -11.661;          (*Constant Value*)

Print["C_d = ", C_d = C_1 + C_2 * N_v + C_3 * β + C_4 * β^2]

(*Calculate Area of SSSV, A*) (*ft^2*)
Print["A = ", N[A = (π/4) * (d_b/12)^2]]

(*Calculate Mixture Velocity, V_m*) (*ft/sec*)
Print["V_m = ", V_m = (q_o + q_g)/A]

 (*Calculate Pressure Drop*) (*psia*)
 Print["ΔP = ", ΔP = (1.078 * 10^(-4) * ρ_n * (V_m)^2)/C_d]

 (*To find Downstream pressure, P_2*) (*psia*)
 Print["P_2 = ", P_2 = P_1 - ΔP]

 Manipulate[Plot[(1.078 * 10^(-4) * ρ_n * (V_m)^2)/C_d, {V_m, 0, 50},
   AxesLabel → {"Mixture Velocity, ft/sec", "Pressure Drop,psia"},
   PlotLabel → "Pressure Drop,psi vs. Mixture Velocity"]]
```

$Z = 0.948382$

$R = 312.5$

$R_s = 89.3558$

$B_o = 1.10759$

$B_g = 0.0274938$

$q_o = 0.0575947$

$q_g = 0.0568063$

$\lambda_1 = 0.503446$

ρ_o = 48.5499

ρ_g = 1.80646

ρ_n = 25.3392

N_v = 0.986312

β = 0.30025

C_d = 1.18586

A = 0.00332895

V_m = 34.3655

ΔP = 2.72035

P_2 = 612.28

Out[125]=