Research Article
Improved Lifetime Pressure Drop Management for Subsurface Safety Valves in Oil and Gas Wells

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Abstract: Pressure losses occur in restriction, especially in the Subsurface Safety Valve (SSSV) might not be major but can be significant in some wells. As we could not always predict the behavior of the dynamic entity such as the reservoir and the flow of fluid, the production system could exceeds the expected performance, which then could affect the SSSV. Therefore, a proper management of SSSV could help overcome this problem. This project attempts to develop a numerical model which could predict the pressure drops in the SSSV in single and two-phase, subcritical flow as a part of the SSSV proper management program. The project also had done several sensitivities analysis on the parameters that could affect the pressure drops in SSSV which are presented in this paper. The knowledge on the parameters affecting the pressure drop can be used in designing an efficient and optimized SSSV. It is also hope that a proper and dynamic control over the SSSV could be achieved by using this model.

Keywords: Pressure drops, sensitivity analysis, subcritical flow, subsurface safety valve

INTRODUCTION

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 (Hargrove and Raulins, 1976).

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 (Beggs *et al*., 1977). 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. By working properly when other system fails, the SSSV is the final defense against the uncontrolled flow from a well (James Garner, 2002).

The first safety device to control subsurface flow was used during the mid-1940s in US inland water (James Garner, 2002). 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 slick line 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.

A proper management of SSSV is required in order to have a dynamic control over the SSSV. With proper management of SSSV we are able to design an optimize SSSV and predict the required pressure drop or flow rate for valve closure. 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. The prediction method can also be used in determining the correct sizing for the choke.

This project has developed a numerical model to predict the pressure drops across the SSSV for single and two-phase, subcritical flow by using the developed correlations. The sensitivity analysis is done on several parameters to observe its effect towards the pressure drop in the SSSV.

LITERATURE REVIEW

The principle work of SSSV: 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. SSSV is categorized into Surface-Controlled SSSV (SCSSV)

and Subsurface Controlled SSSV (SSCSV) (Purser, 1977).

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. SCSSV can be categorized into tubing retrievable and wire line retrievable (Brown, 1984). 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 wire line 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 slick line.

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 bottom hole 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.

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 (Beggs *et al.*, 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 flow behavior: In compressible flow, there are 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 Sachdeva *et al.* (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 Surbey *et al.* (1988) and Brill (1999).

Surbey *et al.* (1988) 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.

Pressure drops across SSSV: Pressure losses occur throughout the whole production systems but the principal losses usually occur in the reservoir, the tubing and the flow line. Even though the pressure loss in the restriction is minor but it could be significant in some well too. The three main types of restrictions are SSSV, surface or bottom hole 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:

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

METHODOLOGY

This project will focus on developing the computer codes for predicting the pressure drops in SSSV for single and two-phase, subcritical flow. The calculation procedures used in the model are as follow:

Single-phase flow calculation procedures:
The equation used for single-phase flow is published by API[65]:

$$P_1 - P_2 = \frac{1.048\times10^{-6}\gamma_g Z_1 T_1 q_{sc}^2(1-\beta^4)}{P_1 d^4 C_d^2 Y^2} \tag{1}$$

In Eq. (1), the API suggested the value for discharged coefficient, C_d is 0.9. While for the expansion factor, Y the default value of 0.85 can be used for quick estimation.

Beta ratio is the ratio of the bean diameter over the pipe ID. The equation is as follow:

$$\beta = \frac{d}{D} \tag{2}$$

For gas compressibility factor, if it is not given by the user, the model will calculate it by using Brill and Beggs (1974) correlations. The methods to calculate using the correlations are as follow:

Two-phase flow calculation procedures: 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 single equation for discharged coefficient will give reasonable results for any type of SSSV are as follow:

$$P_1 - P_2 = \frac{1.078\times10^{-4}\rho_n V_m^2}{C_d} \tag{3}$$

To calculate the pressure drops by using Equation 4, the parameters involved are needed to be calculated first. The steps are as follow:

- Find Producing Gas Oil Ratio, R:

Table 1: Values of constant depending on API gravity for Rs

Constant	API≤30	API>30
C_1	0.03620	0.01780
C_2	1.09370	1.18700
C_3	25.7240	23.9310

Table 2: Values of constant depending on API gravity for Bo

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}

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

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

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

$$D = 10^F \tag{2.31}$$

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

$$F = 0.3106 - 0.49T_{pr} + 0.1824T_{pr}^2 \tag{2.33}$$

and

$$z = A + \frac{1-A}{e^B} + Cp_{pr}^D \tag{2.34}$$

Fig. 1: Excerpt of Brill and Beggs (1974) correlation from (Boyun Guo, 2005)

$$R = \frac{q_g}{q_o} \tag{4}$$

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

$$R_s = C_1\gamma_{gc}P^{C_2}\text{EXP}\left[\frac{C_3(API)}{T+460}\right] \tag{5}$$

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 (Table 1).

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

$$B_0 = 1 + C_1R_s + C_2(T - 60)\left(\frac{API}{\gamma_{gc}}\right) + C_3R_s(T - 60)\left(\frac{API}{\gamma_{gc}}\right) \tag{6}$$

The constants are determined in Table 2.

- Gas compressibility factor, Z used in the numerical model is by using Brill and Beggs (1974) and Boyun Guo (2005) correlation. For equations, refer Fig. 1.

- Calculate Gas Formation Volume Factor, B_g at standard conditions of $P_{sc} = 14.7$ psia and $T_{sc} = 520°R$:

$$B_g = \frac{0.0283ZT}{P} \qquad (7)$$

- Find in-situ Oil Flow Rate, q_o':

$$q_o' = 6.5 \times 10^{-5} q_o B_0 \qquad (8)$$

- Find in-situ Gas Flow Rate, q_g':

$$q_g' = \frac{q_o(R - R_s)B_g}{86400} \qquad (9)$$

- Find No-Slip Liquid Holdup, λ_L:

$$\lambda_L = \frac{q_o'}{q_o' + q_g'} \qquad (10)$$

- Find Density of Oil, ρ_o:

$$\rho_o = \frac{350\gamma_o + 0.0764\gamma_g R_s}{5.615 B_O} \qquad (11)$$

- Find Density of Gas, ρ_g:

$$\rho_g = \frac{2.7\gamma_g P}{ZT} \qquad (12)$$

- Calculate No-Slip Density, ρ_n:

$$\rho_n = \rho_o \lambda_L + \rho_g(1 - \lambda_L) \qquad (13)$$

- Calculate Area of SSSV, A in ft^2:

$$A = \left(\frac{\pi}{4}\right)\left(\frac{d}{12}\right)^2 \qquad (14)$$

- Calculate Mixture Velocity, V_m:

$$V_m = \frac{q_o' + q_g'}{A} \qquad (15)$$

- Calculate Number of Void Space, N_v:

$$N_v = \frac{q_g'}{q_o'} \qquad (16)$$

- Calculate Beta Ratio, β. Refer to Eq. (2).
- Calculate Discharged Coefficient, C_d:

$$C_d = C_1 + C_2 N_v + C_3\beta + C_4\beta^2 \qquad (17)$$
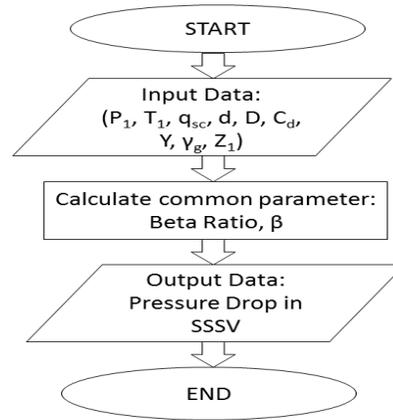
Fig. 2: Flow chart for single phase flow program
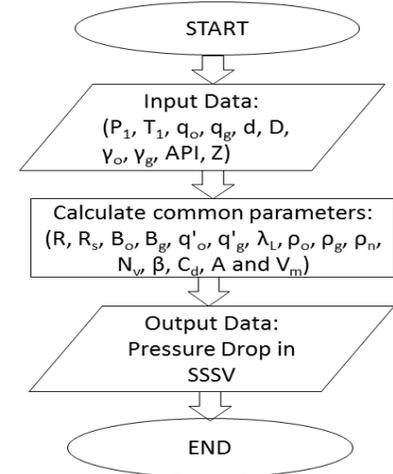
Fig. 3: Flow chart for two-phase flow program

With all parameters calculated, the pressure drop in two-phase flow can be calculated by using Eq. (3).

RESULTS AND DISCUSSION

Computation algorithm: The computer codes for both single and two-phase flow were developed by using Wolfram Mathematica software. For each phases, two computer codes were developed. The first code for given input of gas compressibility factor and for the second code, the gas compressibility factor is calculated by using the Brill and Beggs (1974) and Boyun Guo (2005) correlations. Data in Table 1 and 2 were used to calculate pressure drop across subsurface safety valve and data in Table 3 and 4 shows the range of acceptable thermo-physical properties of fluids in utilized model.

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

Table 3: Base case and sensitivity range for single-phase flow

1P flow base case					
P_1	1000.00		Psia		
T_1	176.000		F		
d	0.78125		in		
D	2.60200		in		
C_d	0.90000				
Y	0.85000				
Y_g	0.70000				
Z_1	0.91340				
q_{sc}	800.000		Mscfd		
Sensitivity range					
	1	2	3	4	5
P_1	600.00	800.00	*1000.00*	1200.00	1400
T_1	130.00	150.00	*176.000*	200.000	220.0
q_g	100.00	300.00	500.00	*800.000*	1100
d	0.5625	0.6875	*0.78125*	0.90625	1.000
D	1.8150	2.1500	*2.6020*	2.76400	3.340
Y_g	0.5000	0.6000	*0.7000*	0.80000	0.900

Italic values: Base case

Table 4: Base case and sensitivity range for two-phase flow

2P flow base case					
P_1	615.000		Psia		
T_1	170.000		F		
Q_{op}	800.000		Stb/d		
Q_{gp}	250000		Scf/d		
d	0.78125		in		
D	2.60200		in		
Y_o	0.85000				
Y_g	0.65000				
Apl	35.0000				
Z	0.95340				
Sensitivity range					
	1	2	3	4	5
P_1	200.00	400.000	*615.000*	800.000	1000.0
T_1	130.00	150.000	*170.000*	190.000	210.00
q_o	200.00	500.000	*800.000*	1000.00	1500.0
q_g	170000	200000	*250000*	280000	350000
d	0.5625	0.6875	*0.78125*	0.90625	1.0000
D	1.8150	2.1500	*2.60200*	2.76400	3.3400
Y_o	0.7500	0.8000	*0.85000*	0.90000	0.9500
Y_g	0.5000	*0.6500*	0.70000	0.80000	0.9000
Apl	10.000	20.000	*35.0000*	45.0000	60.000

Italic values: Base case

Mscfd, the gas specific gravity, the bean diameter and pipe ID in inch. With this input, the common parameter of Z and β are calculated. The programs will then proceed with calculating the pressure drops in SSSV.

For two-phase flow, 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. Common parameters to be calculated from the input datas are Z, 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. The programs will then proceed with calculating the pressure drops in SSSV.

The computer programs flow chart are attached in the Fig 2 and 3.

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 pseudo critical pressure and temperature can be determined from the simple correlation mention below where it only requires the gas specific gravity:

$$P_{pc} = 709.604 - 58.718\gamma_g \qquad (18)$$

$$T_{pc} = 170.491 + 307.344\gamma_g \qquad (19)$$

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 and 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.

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 sensitivity range is as mention in Table 3 and 4.

Figure 4 shows the sensitivity results for pipe ID and bean diameter with pressure drops. From the figure, we can observe that as the pipe ID increases, the

pressure drop in 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. We can also see that as bean diameter increases, the pressure drops decreases. This phenomenon happened because as the bean diameter increases, the restriction for fluid to flow in the SSSV is less therefore decreases the friction losses. Hence the pressure drops across the SSSV decreases.

Based on Fig. 5, as the upstream pressure increases, the pressure drops in SSSV will decrease. For single phase gas flow, this phenomenon can be explained by the decreasing in density as the pressure increases, assuming the temperature across the SSSV is
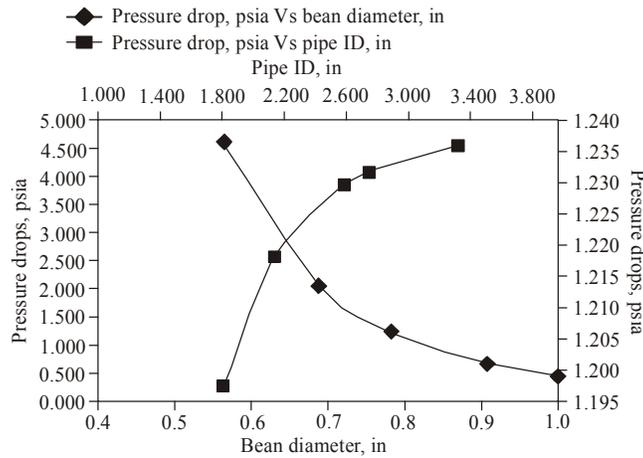
Fig. 4: Pressure drops with bean diameter and pipe ID sensitivity for single-phase flow
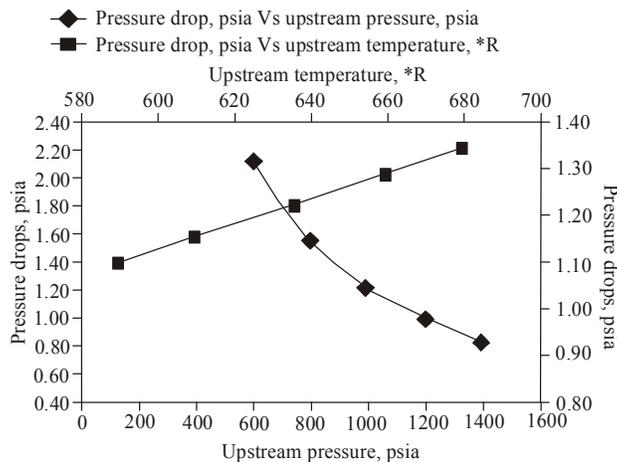
Fig. 5: Pressure drops with upstream pressure and temperature sensitivity for single-phase flow
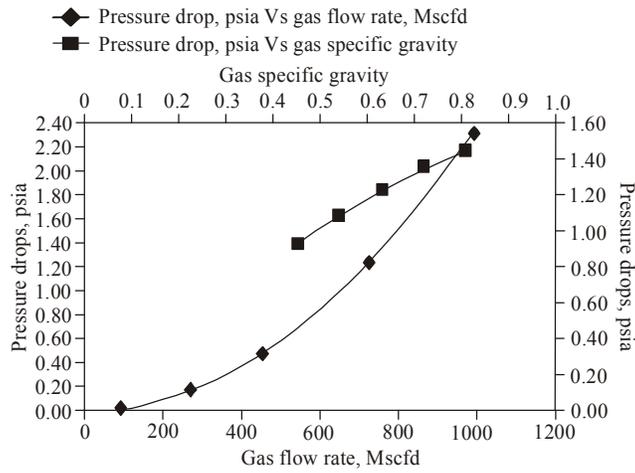
Fig. 6: Pressure drops with gas flow rate and gas specific gravity sensitivity for single-phase flow
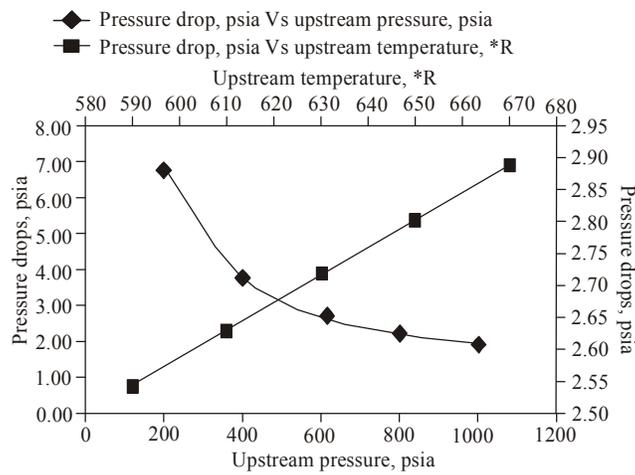
Fig. 7: Pressure drops with upstream pressure and temperature sensitivity for two-phase flow
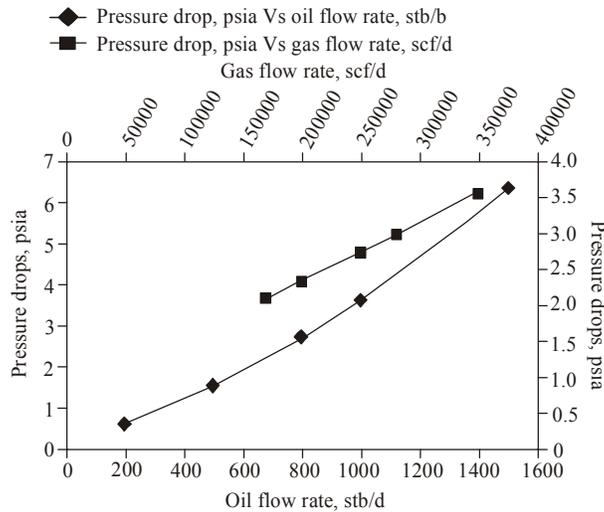
Fig. 8: Pressure drops with oil and gas flow rate sensitivity for two-phase flow
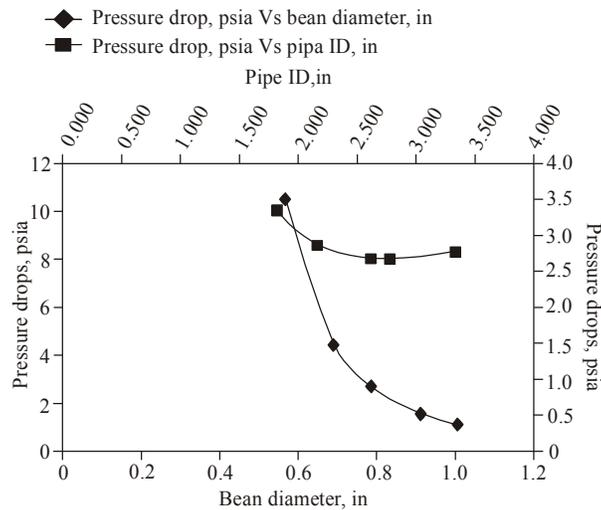
Fig. 9: Pressure drops with bean diameter and pipe id sensitivity for two-phase Flow
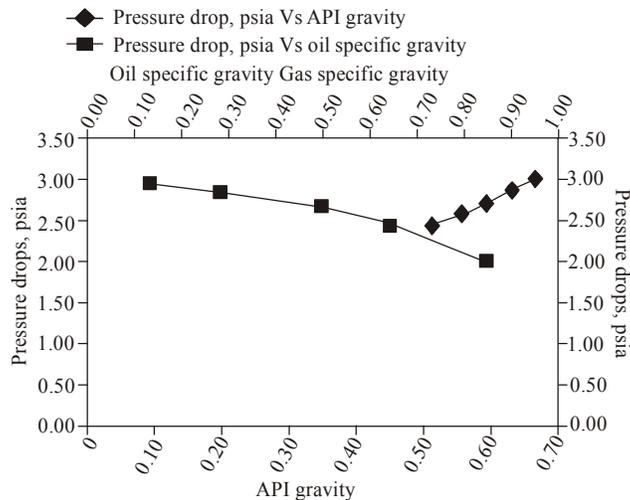
Fig. 10: Pressure drops with API gravity, oil and gas specific gravity sensitivity

constant. The less dense gas will reduced the friction losses along the pipe therefore decreases the pressure drops in SSSV. We can also see that as the temperature increases, the pressure drops will also increase. This is due to the effect of the viscosity of gas which will become more viscous as the temperature increases. This will lead to more resistance for gas to flow, increase of friction loss and increasing of pressure drops.

Figure 6 shows that as the gas flow rate increase, the pressure drops will also increase. 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. We can also observe 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. As the gas density increases, it will also increase the friction losses. Therefore, the pressure drops across the SSSV also increases.

Pressure drops with upstream pressure and temperature for two-phase flow as shown in Fig. 7 displays the same trend as the single-phase flow. The gas flow rate sensitivity for two phase flow in Fig. 8 also display the same trend as the single-phase flow. The increase of oil flow rate would mean the velocity increase of flow which will increase the friction. Hence the increase of pressure drops in SSSV.

Pressure drops with bean diameter for both phases of flow displays the same trend as shown in Fig. 9. We can see some difference in the trend for the pipe ID parameter. Based on Fig. 9 can see that as the pipe ID increasing, the pressure drop across SSSV decreases
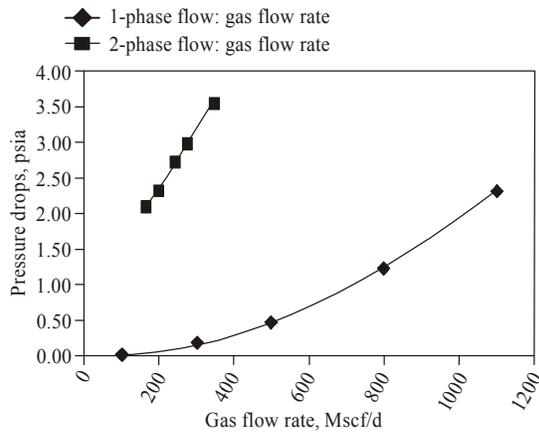
Fig. 11: Sensitivity result comparison: flow rate
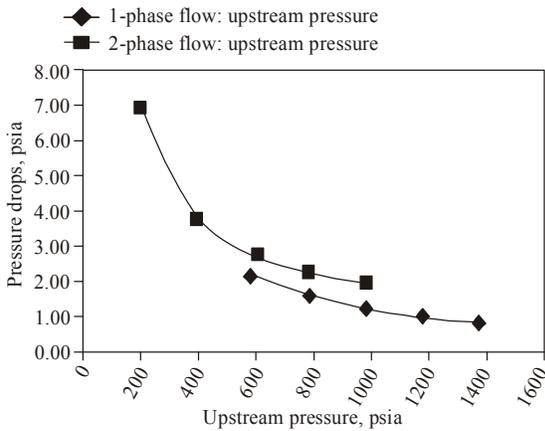
Fig. 12: Sensitivity result comparison: upstream pressure
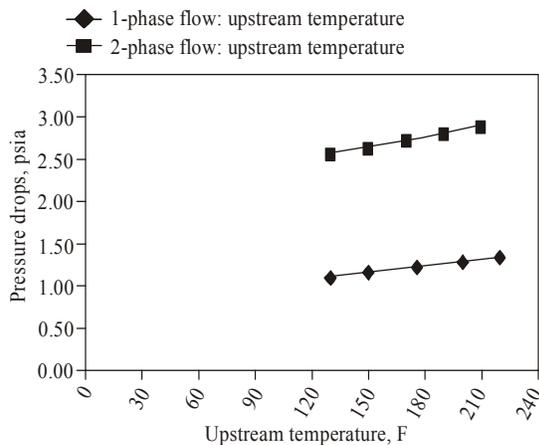
Fig. 13: Sensitivity result comparison: upstream temperature

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.

Based on Fig. 10, we can observe that as API gravity increases, the pressure drops decreases. 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 figure, 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.

Based on Fig. 10, it can also 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.

The results from sensitivity analysis for both phases are then compared. Based on the graph plotted from Fig. 11 to 16, 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.
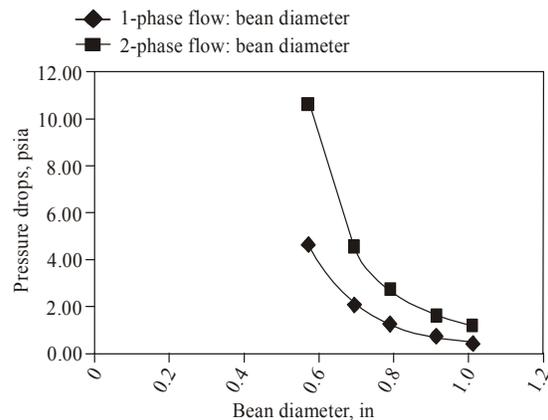
Fig. 14: Sensitivity result comparison: bean diameter
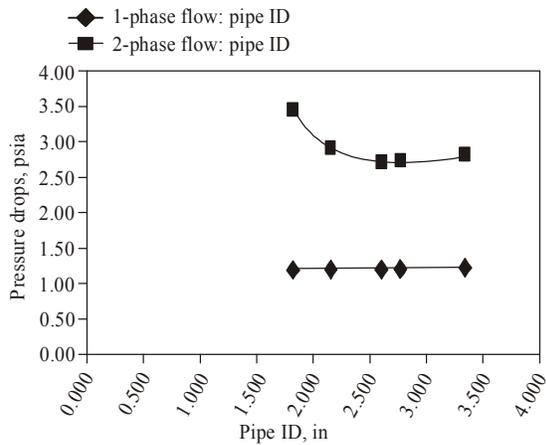
Fig. 15: Sensitivity result comparison: pipe ID
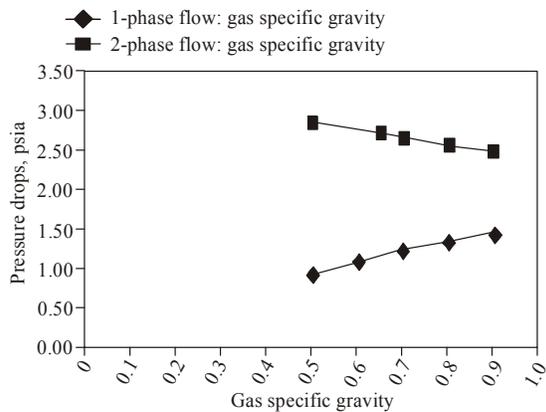
Fig. 16: Sensitivity result comparison: gas specific gravity

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.

CONCLUSION

As a result of the analysis done on pressure drops in SSSV, it can be conclude that:

- The numerical model to predict the pressure drop across the SSSV for single and two-phase flow for subcritical flow has been developed.
- The sensitivities on several parameters had been done to analyze the effect of the parameters towards the pressure drop across 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. We are also able to know the range of sensitivity for each parameter that is affecting the SSSV so that the SSSV would not be under-design or over-design.
- It is hope that this project is beneficial and can be applied in the industry for a better management of the SSSV.

ACKNOWLEDGMENT

NOMENCLATURE

P_1 : Upstream pressure
N_v : Void space
P_2 : Downstream pressure
k : Ratio of specific heat of gas
P : Pressure
γ_g : Gas gravity
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
D : Tubing ID, in
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

REFERENCES

Ahmed, T., 1989. Hydrocarbon Phase Behavior. Gulf Publishing Company, Houston.

Beggs, H.D., J.P. Brill, E.A. Proaiio and C.E. Roman-Lazo, 1977. Study of Pressure Drop and Closure Forces in Velocity-type Subsurface Safety Valves. University of Tulsa, Okla.

Beggs, H., 1991. Production Optimization: Using NODAL Analysis. 2nd Edn., OGCI Publications, Tulsa, Oklahoma, pp: 411, ISBN: 0930972147.

Boyun Guo, D.A., 2005. Natural Gas Engineering Handbook. Gulf Publishing Company, Houston, pp: 446, ISBN: 0976511339.

Brill, J.P. and H.D. Beggs, 1974. Two-Phase Flow in Pipes. INTER-COMP Course, The Hague.

Brill, H.M., 1999. Chapter 5: Flow Through Restrictions and Piping Components. In: Brill, J.P. and H. Mukherjee (Ed.), Multiphase Flow in Well. Henry L. Doherty Memorial Fund of AIME, Richardson, pp: 156, ISBN: 1555630804.

Brown, K.E., 1984. The Technology of Artificial Lift Methods. PPC Books, Tulsa, Vol. 2.

Hargrove, D.N. and G.M. Raulins, 1976. Surface Subsurface Safety Systems. Offshore South East Asia Conference, 17-20 February, Singapore, ISBN: 978-1-55563-745-3.

James Garner, K.M., 2002. At the Ready: Subsurface Safety Valves. Oilfield Rev., 14(4): 52-64.

Purser, P.E., 1977. Review of reliability and performance of subsurface safety valves. Offshore Technology Conference, 2-5 May, Houston, Texas.

Sachdeva, R., Z. Schmidt, J.P. Brill and R.M. Blais, 1986. Two-phase flow through chokes. SPE Annual Technical Conference and Exhibition, 5-8 October, New Orleans, Louisiana, ISBN: 978-1-55563-607-4.

Surbey, D.W., B.G. Kelkar and J.P. Brill, 1988. Study of subcritical flow through multiple-orifice valves. Soc. Prod. Esng., 3(1): 103-108.

Wichert, E. and K. Aziz, 1972. Calculate Zs for sour gases. Hydrocar-bon Process., 51(May): 119.