CHAPTER IV

IMPROVING GUO'S FOUR-PHASE FLOW MODEL

In Chapter 3, it can be clearly seen that all terms in Equations 3.2 and 3.3 have been formulated at in-situ conditions. Thus, the liquid flow rate and the gas flow rate should be the actual rates at in-situ conditions. Therefore, there is a need to incorporate the compressibility factor, solution gas-oil ratio, and oil formation volume factor into the equations.

In this study, it contains five modifications to improve this model. These modifications are

1) modifications with tuning factor
2) modifications with Z factor
3) modifications with R_s and B_o
4) modifications with Z, R_s, and B_o
5) modifications with incremental calculation

4.1 Modification of Guo's four-phase flow model with tuning factor

In Guo's method, liquid holdup effects were considered by applying a tuning factor to friction factor. The tuning factor was defined as a function of gas-liquid ratio (GLR) and vertical depth. This tuning factor was used to multiply the friction factor (see Appendix A5 for determination of friction factor) for correcting the friction factor. Guo used the following equation for upward flow of coalbed methane (CBM) gas and water in a 2 ⅞" tubing as tuning factor.

$$F_{LHU} = (GLR)^{0.632447\log(H)-1.6499} \qquad (4.1)$$

where

F_{LHU} = tuning factor for liquid holdup, dimensionless
GLR = gas-liquid ratio, scf / ft^3
H = vertical depth

But, Guo has said that this model remains to be tested and tuned if necessary, for other well conditions. In this part of the study, we tried to improve the multiphase flow equation by modifying the tuning factor. This equation can be rewritten in the following form:

$$F_{LHU} = (GLR)^{X\log(H)-Y} \quad (4.2)$$

where

F_{LHU} = tuning factor for liquid holdup, dimensionless

GLR = gas-liquid ratio, scf / ft^3

H = vertical depth, ft

$X \& Y$ = constants

The procedure for determining the tuning factor for liquid holdup (F_{LHU}) is as follows:

1. Use Guo's four-phase flow model to do the back calculation of tuning factor for liquid holdup (F_{LHU}) when all input data and the measured bottomhole flowing pressure of data set are known.
2. Determine the X value from using Equation 4.2 after F_{LHU} value is obtained. In this study, Y value is assumed zero.
3. Plot the actual X value with liquid flow rate, gas flow rate, and Reynolds number.
4. Determine the relationship between the X value and liquid flow rate, gas flow rate, and Reynolds number from the plot.
5. Calculate the X value using the relationship obtained in step 4 for liquid flow rate, gas flow rate, and Reynolds number for each data set.
6. Use Equation 4.2 to calculate tuning factor for liquid holdup (F_{LHU}) for each calculated X value from step 5.

4.2 Modification of Guo's four-phase flow model with gas compressibility factor (Z)

In Equation 3.8, the in-situ volumetric flow rate of gas $\dot{Q}_g$ is expressed in terms of gas flow rate at standard conditions through gas law for ideal gas. The gas law relating pressure, temperature, and volume for a gas with molecules of zero sizes and without intermolecular forces is known as the *ideal* or *perfect gas law*. For gases near atmospheric pressure, the ideal gas law is accurate within 5 percent. If more precise prediction is necessary or if gases at high pressure are to be treated, the ideal gas equation becomes inadequate. Voluminous data are available of P-V-T relations of pure substances and mixtures of natural gases, from which the deviations from ideal gas laws may be noted. The *real gas law* recognizes that gases are not ideal and utilizes a *compressibility factor* Z to represent the deviation from ideality.

In this study, therefore, gas compressibility factor (Z) is utilized to modify Guo's four-phase flow model for the case with and without the tuning factor. Equations 3.3 through 3.9 are recalled as follows:

$$\gamma_m = \frac{\dot{W}_s + \dot{W}_l + \dot{W}_g}{\dot{Q}_s + \dot{Q}_l + \dot{Q}_g} \quad (3.3)$$

$$\dot{Q}_s = 1.16\times10^{-5} Q_s \quad (3.4)$$

$$\dot{W}_s = 7.2\times10^{-4} S_s Q_s \quad (3.5)$$

$$\dot{Q}_l = 6.5\times10^{-5}(Q_w + Q_o) \quad (3.6)$$

$$\dot{W}_l = 4\times10^{-3}(S_w Q_w + S_o Q_o) \quad (3.7)$$

$$\dot{Q}_g = \frac{4.7\times10^{-5} T Q_{gs}}{P} \quad (3.8)$$

$$W_g = 8.85\times10^{-7} S_g Q_{gs} \quad (3.9)$$

In Equation 3.8, the in-situ volumetric flow rate of gas $\dot{Q}_g$ is expressed in terms of gas flow rate at standard conditions through gas law for ideal gas. The gas compressibility factor (Z) was not considered in this equation.

In this study, the gas compressibility factor (Z) has been considered for improving the accuracy of this model (see Appendix A1 for determination of Z factor). Therefore, Equation 3.8 becomes

$$\dot{Q}_g = \frac{4.7\times10^{-5} T Q_{gs} Z}{P} \quad (4.3)$$

Substituting Equations 3.4 through 3.7, 3.9 and 4.3 into Equation 3.3 becomes

$$\gamma_m = \frac{7.2\times10^{-4} S_s Q_s + 4\times10^{-3}(S_w Q_w + S_o Q_o) + 8.85\times10^{-7} S_g Q_{gs}}{1.16\times10^{-5} Q_s + 6.5\times10^{-5}(Q_w + Q_o) + \dfrac{4.7\times10^{-5} T Q_{gs} Z}{P}}$$

Dividing both sides by $\dfrac{4.7\times10^{-5}TQ_{gs}Z}{P}$,

$$\gamma_m = \frac{(7.2\times10^{-4}S_sQ_s + 4\times10^{-3}(S_wQ_w + S_oQ_o) + 8.85\times10^{-7}S_gQ_{gs})/(\dfrac{4.7\times10^{-5}TQ_{gs}Z}{P})}{(1.16\times10^{-5}Q_s + 6.5\times10^{-5}(Q_w + Q_o) + \dfrac{4.7\times10^{-5}TQ_{gs}Z}{P})/(\dfrac{4.7\times10^{-5}TQ_{gs}Z}{P})}$$

$$\gamma_m = \frac{[\ 15.32S_sQ_s + 85.1(S_wQ_w + S_oQ_o) + 0.019S_gQ_{gs}\ ]\dfrac{P}{TQ_{gs}Z}}{[\ 0.247Q_s + 1.38(Q_w + Q_o)\ ]\dfrac{P}{TQ_{gs}Z} + 1}$$

This can be written in the form of Equation 3.10 as

$$\gamma_m = \frac{a''P}{b''P + 1}$$

where

$$a'' = \frac{15.32S_sQ_s + 85.1(S_wQ_w + S_oQ_o) + 0.019S_gQ_{gs}}{TQ_{gs}Z} \tag{4.4}$$

and

$$b'' = \frac{[0.247Q_s + 1.38(Q_w + Q_o)]}{TQ_{gs}Z} \tag{4.5}$$

Flow velocity can be formulated based on volumetric gas rate given by Equation 4.3, liquid flow rate by Equation 3.6, and flow path cross sectional area as

$$v = \frac{144}{A}\left[6.5\times10^{-5}(Q_w + Q_o) + \frac{4.7\times10^{-5}TQ_{gs}Z}{P}\right]$$

which is rearranged to be

$$v = \frac{6.77\times10^{-3}TQ_{gs}Z}{AP} + \frac{9.4\times10^{-3}(Q_w+Q_o)}{A}$$

or

$$v = \frac{c''}{P} + d''$$

where

$$c'' = \frac{6.77\times10^{-3}TQ_{gs}Z}{A} \quad (4.6)$$

$$d'' = \frac{9.4\times10^{-3}(Q_w+Q_o)}{A} \quad (4.7)$$

Equations 4.3 through 4.7 are used to modify Guo's four-phase flow model with gas compressibility factor (Z) for the case with and without tuning factor.

4.3 Modification of Guo's four-phase flow model with solution gas-oil ratio (R_s) and oil formation volume factor (B_o)

The definition of *solution gas-oil ratio (R_s)* is the volume of gas in standard cubic feet that will dissolve (go into solution) in one stock-tank barrel of oil at a given pressure and temperature, having a unit of *scf/STB*. And, *oil formation volume factor (B_o)* is the volume in barrels (bbl) occupied by one stock-tank barrel (STB) oil and its associated solution gas when recombined to a single-phase liquid at a specific pressure and temperature, having a unit of *bbl/STB*.

In the above definitions, we can see that the amount of gas dissolved in oil at reservoir conditions is dependent on the overall composition of the fluid. The amount of gas remaining in solution at any other condition depends on the prevailing pressure and temperature. The amount and rate of gas liberation therefore depend on the pressure and temperature profile along the flow path. Therefore, solution gas-oil ratio (R_s) and oil formation volume factor (B_o) are function of pressure and temperature.

In this section, we tried to improve Guo's four-phase flow model by accounting for solution gas-oil ratio (R_s) and oil formation volume factor (B_o) (see

Appendix A2 and A3 for determination of R_s and B_o). First, Equations 3.3 through 3.7 are recalled as follows:

$$\gamma_m = \frac{\dot{W}_s + \dot{W}_l + \dot{W}_g}{\dot{Q}_s + \dot{Q}_l + \dot{Q}_g} \tag{3.3}$$

$$\dot{Q}_s = 1.16 \times 10^{-5} Q_s \tag{3.4}$$

$$\dot{W}_s = 7.2 \times 10^{-4} S_s Q_s \tag{3.5}$$

$$\dot{Q}_l = 6.5 \times 10^{-5} (Q_w + Q_o) \tag{3.6}$$

$$\dot{W}_l = 4 \times 10^{-3} (S_w Q_w + S_o Q_o) \tag{3.7}$$

When solution gas-oil ratio (R_s) and oil formation volume factor (B_o) are considered in this study, Equations 3.6 and 3.7 become

$$\dot{Q}_l = 6.5 \times 10^{-5} (Q_w + B_o Q_o) \tag{4.8}$$

$$\dot{W}_l = 4 \times 10^{-3} (S_w Q_w + S_o B_o Q_o) \tag{4.9}$$

The in-situ volumetric flow rate of gas ($\dot{Q}_g$) is expressed in terms of gas flow rate at standard condition through gas law for ideal gas as expressed in Equation 3.8. The weight rate of gas depends on volumetric gas flow rate (Q_{gs}), the specific gravity of gas (S_g) as expressed in Equation 3.9

$$\dot{Q}_g = \frac{4.7 \times 10^{-5} T Q_{gs}}{P} \tag{3.8}$$

$$W_g = 8.85 \times 10^{-7} S_g Q_{gs} \tag{3.9}$$

In the above equations, the volumetric gas flow rate (Q_{gs}) can be written as:

$$Q_{gs} = Q_o (R - R_s) \tag{4.10}$$

where

Q_o = oil production rate, stb/d

R = total gas-oil ratio, scf/stb

R_s = solution gas-oil ratio, scf/stb

The volumetric gas flow rate (Q_{gs}) is the free gas rate in standard conditions. Then, Equation 4.10 is substituted in Equations 3.8 and 3.9. Therefore, Equations 3.8 and 3.9 become

$$\dot{Q}_g = \frac{4.7\times10^{-5} T B_o Q_o (R - R_s)}{P} \tag{4.11}$$

$$W_g = 8.85\times10^{-7} S_g B_o Q_o (R - R_s) \tag{4.12}$$

Substituting Equations 3.4, 3.5, 4.8, 4.9, 4.11, 4.12 into Equation 3.3 becomes

$$\gamma_m = \frac{7.2\times10^{-4} S_s Q_s + 4\times10^{-3}(S_w Q_w + S_o B_o Q_o) + 8.85\times10^{-7} S_g B_o Q_o (R - R_s)}{1.16\times10^{-5} Q_s + 6.5\times10^{-5}(Q_w + B_0 Q_o) + \dfrac{4.7\times10^{-5} T B_o Q_o (R - R_s)}{P}}$$

Dividing both sides by $\dfrac{4.7\times10^{-5} T B_o Q_o (R - R_s)}{P}$,

$$\gamma_m = \frac{[7.2\times10^{-4} S_s Q_s + 4\times10^{-3}(S_w Q_w + S_o B_o Q_o) + 8.85\times10^{-7} S_g B_o Q_o (R - R_s)]/[\dfrac{4.7\times10^{-5} T B_o Q_o (R - R_s)}{P}]}{[1.16\times10^{-5} Q_s + 6.5\times10^{-5}(Q_w + B_o Q_o) + \dfrac{4.7\times10^{-5} T B_o Q_o (R - R_s)}{P}]/[\dfrac{4.7\times10^{-5} T B_o Q_o (R - R_s)}{P}]}$$

$$\gamma_m = \frac{[\ 15.32 S_s Q_s + 85.1(S_w Q_w + S_o B_o Q_o) + 0.019 S_g B_o Q_o (R - R_s)\ ]\dfrac{P}{T B_o Q_o (R - R_s)}}{[\ 0.247 Q_s + 1.38(Q_w + B_o Q_o)\ ]\dfrac{P}{T B_o Q_o (R - R_s)} + 1}$$

This equation can be rearranged as

$$\gamma_m = \frac{a'' P}{b'' P + 1}$$

where

$$a'' = \frac{15.32S_sQ_s + 85.1(S_wQ_w + S_oB_oQ_o) + 0.019S_gB_oQ_o(R - R_s)}{TB_oQ_o(R - R_s)} \tag{4.13}$$

and

$$b'' = \frac{[0.247Q_s + 1.38(Q_w + B_oQ_o)]}{TB_oQ_o(R - R_s)} \tag{4.14}$$

Flow velocity can be formulated based on volumetric gas rate given by Equation 4.11, liquid flow rate by Equation 4.8, and flow path cross sectional area

$$v = \frac{144}{A}\left[6.5\times10^{-5}(Q_w + B_oQ_o) + \frac{4.7\times10^{-5}TB_oQ_o(R - R_s)}{P}\right]$$

which is rearranged to be:

$$v = \frac{6.77\times10^{-3}TB_oQ_o(R - R_s)}{AP} + \frac{9.4\times10^{-3}(Q_w + B_oQ_o)}{A}$$

or

$$v = \frac{c''}{P} + d''$$

where

$$c'' = \frac{6.77\times10^{-3}TB_oQ_o(R - R_s)}{A} \tag{4.15}$$

and

$$d'' = \frac{9.4\times10^{-3}(Q_w + B_oQ_o)}{A} \tag{4.16}$$

Equations 4.8, 4.9, and 4.11 through 4.16 are used to modify Guo's four-phase flow model with solution gas-oil ratio (R_s) and oil formation volume factor (B_o) for the case with and without tuning factor.

But, in cases that the solution gas-oil ratio (R_s) calculated from the correlation at the bottomhole is higher than the actual total gas-oil ratio (R), the following procedure is utilized to calculate bottomhole flowing pressure.

1) Back calculate the depth at the actual total gas-oil ratio (R) equals solution gas-oil ratio (R_s) by Guo's model. At this depth, there is no free gas and therefore it has only liquid phase under this depth.
2) Find the flowing pressure at this depth. This pressure is used as the wellhead flowing pressure of liquid phase.
3) When R = R_s, Equation 4.10 becomes zero and Equations 4.11 and 4.12 also become zero. Therefore, Equation 3.3 becomes

$$r_m = \frac{\dot{W}_s + \dot{W}_l}{\dot{Q}_s + \dot{Q}_l}$$

and then Equations 3.4, 3.5, 4.8, and 4.9 are substituted in the above equation,

$$\gamma_m = \frac{7.2\times10^{-4} S_s Q_s + 4\times10^{-3}(S_w Q_w + S_o B_o Q_o)}{1.16\times10^{-5} Q_s + 6.5\times10^{-5}(Q_w + B_0 Q_o)}$$

the flow velocity equation becomes

$$v = \frac{9.4\times10^{-3}(Q_w + B_o Q_o)}{A}$$

4) Substitute r_m and v in Equation 3.2 and then the bottomhole flowing pressure (p_{wf}) can be determined as follows:

$$dP = \left[\frac{7.2\times10^{-4} S_s Q_s + 4\times10^{-3}(S_w Q_w + S_o B_o Q_o)}{1.16\times10^{-5} Q_s + 6.5\times10^{-5}(Q_w + B_o Q_o)}\right]\left(1 + \frac{f\left[\frac{9.4\times10^{-3}(Q_w + B_o Q_o)}{A}\right]^2}{2gd_H}\right)dh$$

Integrating both sides from the well flowing pressure $p_{wh(R=R_s)}$ at (R = R_s) vertical depth $H_{(R=Rs)}$ to bottomhole flowing pressure P_{wf} at total vertical depth H,

$$\int_{p_{wh(R=R_s)}}^{p_{wf}} dP = \left[\frac{7.2\times10^{-4} S_s Q_s + 4\times10^{-3}(S_w Q_w + S_o B_o Q_o)}{1.16\times10^{-5} Q_s + 6.5\times10^{-5}(Q_w + B_o Q_o)}\right]\left(1 + \frac{f\left[\frac{9.4\times10^{-3}(Q_w + B_o Q_o)}{A}\right]^2}{2gd_H}\right)\int_{H_{(R=R_s)}}^{H} dh$$

then

$$p_{wf} - p_{wh(R=R_s)} = X(H - H_{(R=R_s)})$$

where

$$X = \left[\frac{7.2\times10^{-4}S_sQ_s + 4\times10^{-3}(S_wQ_w + S_oB_oQ_o)}{1.16\times10^{-5}Q_s + 6.5\times10^{-5}(Q_w + B_oQ_o)}\right]\left(1 + \frac{f\left[\frac{9.4\times10^{-3}(Q_w + B_oQ_o)}{A}\right]^2}{2gd_H}\right)$$

and then

$$p_{wf} = p_{wh(R=R_s)} + X(H - H_{(R=R_s)}) \tag{4.17}$$

Equation 4.17 is utilized to calculate the bottomhole flowing pressure in cases that the solution gas-oil ratio (R_s) calculated from the correlation at the bottomhole is higher than the actual total gas-oil ratio (R).

4.4 Modification of Guo's four-phase flow model with gas compressibility factor (Z), solution gas-oil ratio (R_s) and oil formation volume factor (B_o)

As mentioned earlier in this chapter, Guo has expressed the liquid flow rate and the gas flow rate at in-situ conditions in terms of the liquid flow rate and the gas flow rate at standard conditions and gas law for ideal gas. It is necessary to convert the fluid properties at in-situ conditions before a pressure loss can be calculated.

Therefore, gas compressibility (Z), solution gas-oil ratio (R_s), and oil formation volume factor (B_o) are considered to modify Guo's original model in this section.

First, the following equations are recalled:

$$\gamma_m = \frac{\dot{W}_s + \dot{W}_l + \dot{W}_g}{\dot{Q}_s + \dot{Q}_l + \dot{Q}_g} \tag{3.3}$$

$$\dot{Q}_s = 1.16\times10^{-5}Q_s \tag{3.4}$$

$$\dot{W}_s = 7.2\times10^{-4}S_sQ_s \tag{3.5}$$

$$\dot{Q}_l = 6.5\times10^{-5}(Q_w + Q_o) \tag{3.6}$$

$$\dot{W}_l = 4\times10^{-3}(S_wQ_w + S_oQ_o) \tag{3.7}$$

$$\dot{Q}_g = \frac{4.7\times10^{-5}TQ_{gs}}{P} \tag{3.8}$$

$$W_g = 8.85\times10^{-7}S_gQ_{gs} \tag{3.9}$$

$$Q_{gs} = Q_o(R - R_s) \tag{4.10}$$

Equation 4.10 is substituted in Equations 3.8 and 3.9 and then Equations 3.6, through 3.9 can be rewritten in terms of gas compressibility factor (Z), solution gas-oil ratio (R_s), and oil formation volume factor (B_o) as follows:

$$\dot{Q}_l = 6.5\times10^{-5}(Q_w + B_oQ_o) \tag{4.18}$$

$$\dot{W}_l = 4\times10^{-3}(S_wQ_w + S_oB_oQ_o) \tag{4.19}$$

$$\dot{Q}_g = \frac{4.7\times10^{-5}TZB_oQ_o(R - R_s)}{P} \tag{4.20}$$

$$W_g = 8.85\times10^{-7}S_gB_oQ_o(R - R_s) \tag{4.21}$$

Equations 3.4, 3.5, 4.18 through 4.21 are substituted in Equation 3.3 and then Equation 3.3 becomes

$$\gamma_m = \frac{7.2\times10^{-4}S_sQ_s + 4\times10^{-3}(S_wQ_w + S_oB_oQ_o) + 8.85\times10^{-7}S_gB_oQ_o(R - R_s)}{1.16\times10^{-5}Q_s + 6.5\times10^{-5}(Q_w + B_0Q_o) + \dfrac{4.7\times10^{-5}TZB_oQ_o(R - R_s)}{P}}$$

Dividing both sides by $\dfrac{4.7\times10^{-5}TZB_oQ_o(R - R_s)}{P}$,

$$\gamma_m = \frac{[7.2\times10^{-4}S_sQ_s + 4\times10^{-3}(S_wQ_w + S_oB_oQ_o) + 8.85\times10^{-7}S_gB_oQ_o(R - R_s)]/[\dfrac{4.7\times10^{-5}TZB_oQ_o(R - R_s)}{P}]}{[1.16\times10^{-5}Q_s + 6.5\times10^{-5}(Q_w + B_oQ_o) + \dfrac{4.7\times10^{-5}TZB_oQ_o(R - R_s)}{P}]/[\dfrac{4.7\times10^{-5}TZB_oQ_o(R - R_s)}{P}]}$$

$$\gamma_m = \frac{[\ 15.32S_sQ_s + 85.1(S_wQ_w + S_oB_oQ_o) + 0.019S_gB_oQ_o(R - R_s)\ ]\dfrac{P}{TZB_oQ_o(R-R_s)}}{[\ 0.247Q_s + 1.38(Q_w + B_oQ_o)\ ]\dfrac{P}{TZB_oQ_o(R-R_s)} + 1}$$

The above equation can be written as

$$\gamma_m = \frac{a''P}{b''P + 1}$$

where

$$a'' = \frac{15.32S_sQ_s + 85.1(S_wQ_w + S_oB_oQ_o) + 0.019S_gB_oQ_o(R - R_s)}{TZB_oQ_o(R - R_s)} \qquad (4.22)$$

and

$$b'' = \frac{[0.247Q_s + 1.38(Q_w + B_oQ_o)]}{TZB_oQ_o(R - R_s)} \qquad (4.23)$$

Flow velocity can be formulated based on volumetric gas rate given by Equation 4.20, liquid flow rate by Equation 4.18, and flow path cross sectional area as

$$v = \frac{144}{A}\left[6.5\times10^{-5}(Q_w + B_oQ_o) + \frac{4.7\times10^{-5}TZB_oQ_o(R - R_s)}{P}\right]$$

which is rearranged to be

$$v = \frac{6.77\times10^{-3}TZB_oQ_o(R - R_s)}{AP} + \frac{9.4\times10^{-3}(Q_w + B_oQ_o)}{A}$$

or

$$v = \frac{c''}{P} + d''$$

where

$$c'' = \frac{6.77\times10^{-3}TZB_oQ_o(R-R_s)}{A} \tag{4.24}$$

and

$$d'' = \frac{9.4\times10^{-3}(Q_w+B_oQ_o)}{A} \tag{4.25}$$

In cases that the solution gas-oil ratio (R_s) calculated from the correlation at the bottomhole is higher than the actual total gas-oil ratio (R), the same procedure and the same equations expressed in Section 4.3 are utilized to calculate the bottomhole flowing pressure.

4.5 Modification of Guo's four-phase flow model with incremental calculation

In the previous chapter, the original Guo's four-phase flow model is utilized to calculate pressure drop for the whole tubing all at once without accounting for the differences in pressure and temperature at different sections of the tubing.

In this section, Guo's four-phase flow model is modified with incremental calculation by dividing the flow conduit into a number of pressure or length increments. In this study, a calculation starts from a known wellhead flowing pressure and a value for pressure at certain depth increment is assumed. And then, a pressure at selected depth is calculated and compared with an assumed pressure until they are converged. The procedure for the incremental calculation of this study is explained as the following:

1. Starting with the known pressure p_1 at location L_1, select a length increment ΔL. In this study, starting from the measured wellhead flowing pressure ($p_1 = p_{wh}$) at wellhead (L_1=0).
2. Assume a pressure at selected length increment ΔL.
3. Estimate a pressure increment Δp corresponding to the length increment ΔL.
4. Calculate the average pressure and the average temperature in the length increment. Temperature may be a function of location.
5. Determine the necessary fluid and PVT properties at conditions of the average pressure and the average temperature using empirical correlations.

6. Calculate the pressure at the selected depth.
7. Calculate the pressure increment Δp corresponding to the selected length increment.
8. Compare the estimated Δp obtained from step 3 with the calculated Δp obtained from step 7. If they are not sufficiently close, estimate a new pressure increment and go to step 3. Repeat steps 3 through 8 until the estimated and calculated values are sufficiently close.
9. Set $L = L_1 + \Sigma\Delta L$ and $p = p_1 + \Sigma\Delta p$.
10. If $\Sigma\Delta L$ is less than the total conduit length, return to step 3.

In this chapter, Guo's original model is modified with the tuning factor and fluid properties such as gas compressibility factor (Z), solution gas-oil ratio (R_s), and oil formation volume factor (B_o). These tuning factor and fluid properties are used under different combinations of modifications. Besides, the Guo's original model is also modified by incremental calculation. Therefore, it contains total of five modifications to improve the Guo's original model in this study.

The application of these modifications is presented in Chapter 6.