CHAPTER VI

APPLICATION AND IMPROVEMENT OF GUO'S FOUR-PHASE FLOW MODEL

In this chapter, the application of Guo's four-phase flow model is discussed. Then, the modifications of the Guo's original model are presented. After that, these modified Guo's models are tested. The comparison of the modified Guo's models against six other multiphase flow correlations is then made by statistical analysis, and the results are finally discussed.

6.1 Application of Guo's four-phase flow model

In order to evaluate the application of Guo's four-phase flow model, several data sets were collected from published SPE papers as shown in Table 6.1.

Table 6.1: Data sets from published SPE papers.

	Number of data set	Source	Type of fluid	Well status
1	20	SPE 1546	2-phase	Vertical
2	18	SPE 1657 G	2-Phase	Vertical
3	27	SPE 4316	2-Phase, 3-Phase	Vertical
4	89	SPE 12989	2-Phase	Vertical & Inclined
5	54	SPE 16880	2-Phase, 3-Phase	Vertical & Inclined
Total	**208**			

After the data sets had been collected, they were grouped as shown in Table 6.2, 6.3, 6.4, 6.5, and 6.6.

Table 6.2: Data sets grouped by tubing diameter.

Group	Tubing Diameter (I.D, inch)	Number of data set
1	1.995	19
2	2.441	38
3	2.764 & 2.992	50
4	3.958	56
5	4.494 & 4.892	13
6	6.184	30
7	8.76	2
	Total	**208**

Table 6.3: Data sets grouped by gas-liquid ratio.

Group	Gas-liquid ratio (GLR) (scf/stb)	Number of data set
1	≤ 1000	130
2	> 1000	78
	Total	**208**

Table 6.4: Data sets grouped by liquid flow rate.

Group	Liquid flow rate (Q_L) (stb/d)	Number of data set
1	≤ 350	46
2	$350 < Q_L \leq 5{,}000$	74
3	> 5,000	88
	Total	**208**

Table 6.5: Data sets grouped by gas flow rate.

Group	Gas flow rate (Q_g) (Mscf/d)	Number of data set
1	≤ 1,000	73
2	1,000 < Qg ≤ 5,000	72
3	> 5,000	63
	Total	**208**

Table 6.6: Data sets grouped by oil specific gravity.

Group	Oil Specific Gravity (γ_o) (°API)	Number of data set
1	≤ 20	54
2	20 < °API ≤ 45	99
3	> 45	55
	Total	**208**

Guo's four-phase flow model was then coded as a computer program on a Microsoft Excel Worksheet. The parameters required as to input in Guo's four-phase flow model are shown in Table 6.7.

Table 6.7: Input data required in Guo's four-phase flow model.

	Parameter	Units
1	Volumetric flow rate of solid	ft^3/d
2	Water production rate	bbl/d
3	Oil production rate	stb/d
4	Gas-liquid ratio	scf/stb
5	Specific gravity of solid	dimensionless
6	Specific gravity of produced water	dimensionless
7	Specific gravity of oil	dimensionless
8	Specific gravity of gas	dimensionless
9	Surface temperature	°F
10	Bottom hole temperature	°F
11	Wellhead flowing pressure	psia
12	Well depth	ft
13	Tubing size, I.D	in
14	Tubing wall roughness	ft

Then, all 208 data sets were used to calculate the bottomhole flowing pressure using Guo's four-phase flow model and six other multiphase flow correlations which are Duns and Ros (modified), Hagedorn and Brown, Fancher and Brown, Beggs and Brill, Orkiszewski, Duns and Ros (original). For calculations of these six multiphase flow correlations, the program PROSPER was utilized. The input data used in PROSPER are same as input data used in Guo's four-phase flow model (shown in Table 6.7). For both programs, tubing wall roughness is 0.00015 feet (for new commercial steel tubing).

Then, these calculated bottomhole flowing pressures were compared with the measured bottomhole flowing pressures. Statistical values such as the average absolute error and standard deviation as shown in Figure 6.1 were determined. The average relative error (ARE) , the average absolute error (AAE), and standard deviation (SD) of 208 data sets are as shown in Table 6.8 (see Appendix A4 for determination of statistical parameters). In the statistical analysis, the average absolute error is used as an important and good indicator of the accuracy.

Table 6.8: Statistical parameters for Guo's model and six other multiphase flow correlations for 208 data sets.

Statistical parameter	Guo	Duns & Ros (Modified)	Hagedorn & Brown	Fancher & Brown	Beggs & Brill	Orkiszewski	Duns&Ros(Original)
Avg: relative error	2.7	0.8	3.9	14.9	-11.2	-1.9	-1.1
Avg: absolute error	38.5	17.3	19.9	22.1	19.7	18.1	14.9
Std: deviation	46.8	25.6	28.7	29.1	26.2	26.6	21.9

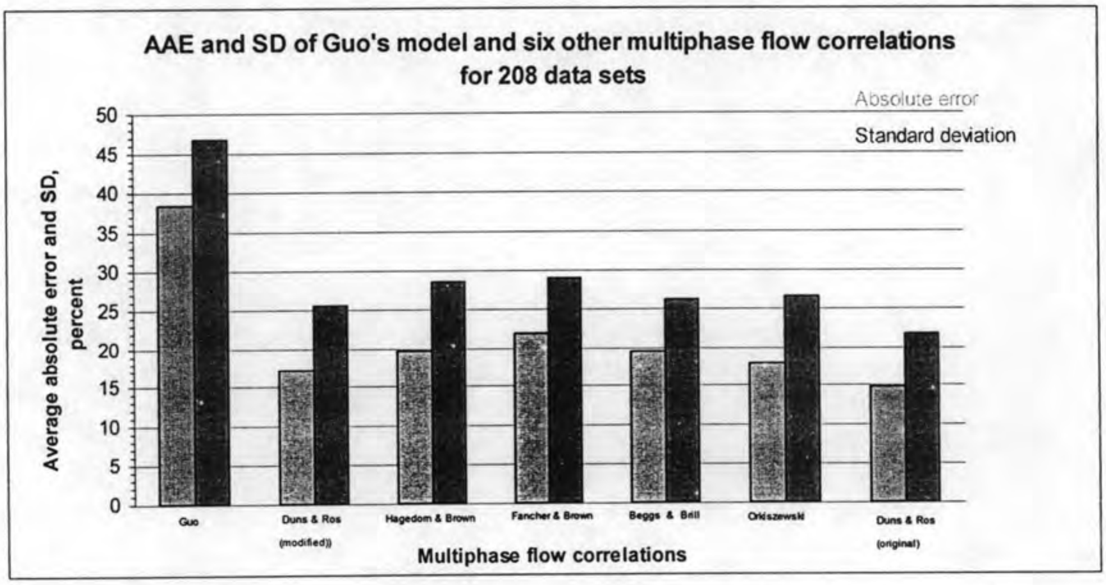


Figure 6.1: Comparison of Guo's model and six other multiphase flow correlations for 208 data sets.

From Table 6.8 and Figure 6.1, it can be seen that the average absolute error and standard deviation of Guo's four-phase flow model are significantly higher than the other six multiphase flow correlations. Therefore, it is clearly seen that this model must be improved for its accuracy.

6.2 Improvement of Guo's four-phase flow model

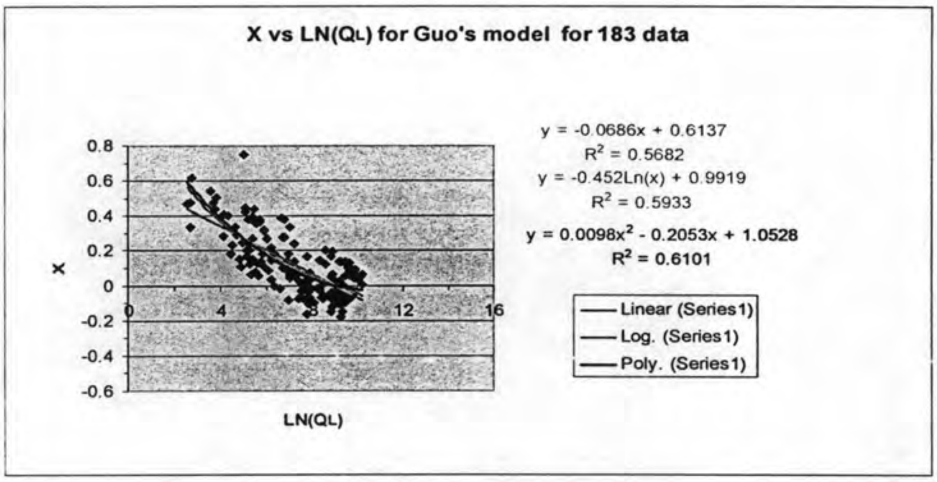
To improve Guo's four-phase flow model, five modifications were considered. These modifications are

1) modification of Guo's four-phase flow model with tuning factor
2) modification of Guo's four-phase flow model with Z factor (with and without tuning factor)
3) modification of Guo's four-phase flow model with R_s and B_o factor (with and without tuning factor)
4) modification of Guo's four-phase flow model with Z, R_s and B_o factor (with and without tuning factor)
5) modification of Guo's four-phase flow model with incremental calculation (with and without tuning factor)

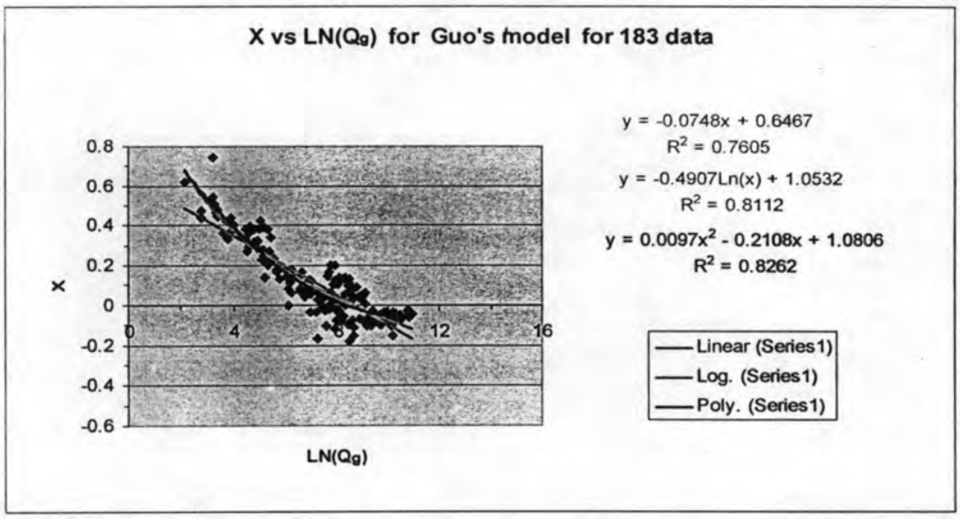
6.2.1 Modification of Guo's four-phase flow model (original) with tuning factor

The procedure for determining the tuning factor for liquid holdup (F_{LHU}) has been expressed in Section 4.1. Using this procedure, 208 data sets acquired from the SPE papers were used to calculate the tuning factor for liquid holdup (F_{LHU}). In Step 1 of this procedure (back calculation of F_{LHU}), 25 data sets were discarded since they yield negative values of F_{LHU}. Therefore, 183 data sets were used to determine the X values in Step 2 of the procedure.

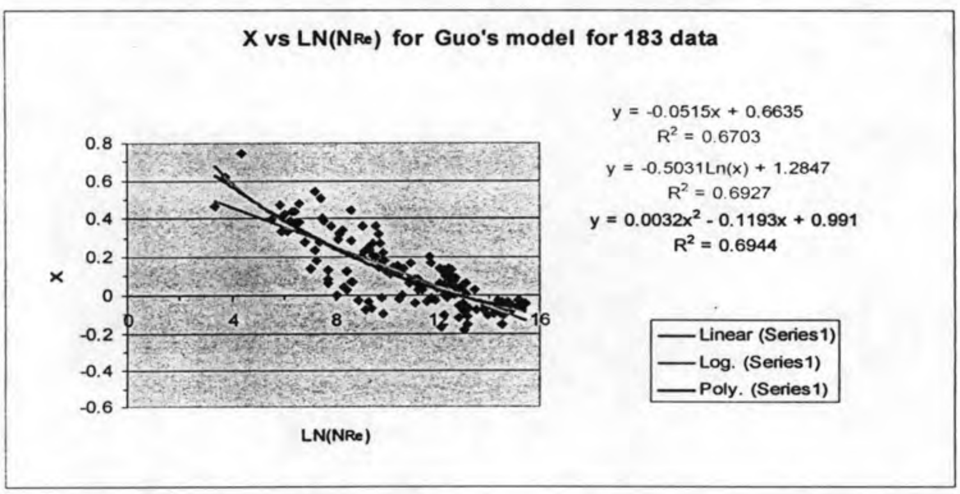
Then, the X value for each data set was plotted against natural logarithms of liquid flow rate (Q_L), gas flow rate (Q_g) and Reynolds number (N_{Re}) (Step 3 of the procedure in Section 4.1). These plots are shown in Figure 6.2. In Figure 6.2, the green lines represent linear trend lines, the red lines represent logarithm trend lines, and the black lines represent polynomial trend lines. Each trend line has its relationship and coefficient of determination (R^2). The maximum value of R^2 must be chosen for each plot. It can be seen that R^2 value of the polynomial trend line is maximum for each plot. Therefore, the relationships of the polynomial trend lines were chosen to calculate X value for each plot (Step 4 in Section 4.1).



(a) Plot of X versus natural logarithm of liquid flow rate.



(b) Plot of X versus natural logarithm of gas flow rate.



(c) Plot of X versus natural logarithm of Reynolds number.

Figure 6.2: Plot of X versus well parameters for Guo's model (original).

The selected relationships can be summarized as follows:

For X vs. LN(Q_L) plot,

$$X = 0.0098(LN(Q_L))^2 - 0.2053LN(Q_L) + 1.0528 \qquad (6.1)$$

For X vs. LN(Q_g) plot,

$$X = 0.0097(LN(Q_g))^2 - 0.2108LN(Q_g) + 1.0806 \qquad (6.2)$$

For X vs. LN (N_{Re}) plot,

$$X = 0.0032(LN(N_{\mathrm{Re}}))^2 - 0.1193LN(N_{\mathrm{Re}}) + 0.991 \qquad (6.3)$$

Equations 6.1, 6.2 and 6.3 can be used to determine the X value for each data set (Step 5 of Section 4.1). After the X value is obtained, tuning factor for liquid holdup (F_{LHU}) can be calculated from Equation 4.2 for each data set (Step 6 in Section 4.1). In Equation 4.2, the Y value is assumed to be zero.

These calculated tuning factors for liquid holdup (F_{LHU}) were then used to correct the friction factors (i.e. F_{LHU} was multiplied to the friction factor). These corrected friction factors were utilized to calculate the bottomhole flowing pressures by Guo's four-phase flow model. These calculated bottomhole flowing pressures were compared with the measured bottomhole flowing pressures. Statistical values such as the average absolute error and standard deviation are determined and shown in Figure 6.2. The average relative error, the average absolute error, and standard deviation of 183 data sets are shown in Table 6.9.

Table 6.9: Statistical parameters for Guo's model (original) with and without the tuning factor for 183 data sets.

No. of data set	Statistical parameter	Guo's model (original)			
		Without tuning	Tuning for Q_L	Tuning for Q_g	Tuning for N_{Re}
183	Avg relative error	6.4	-46.3	-4.8	-15.9
	Avg absolute error	37.6	67.9	24.0	42.7
	SD	44.1	178.9	32.8	86.1

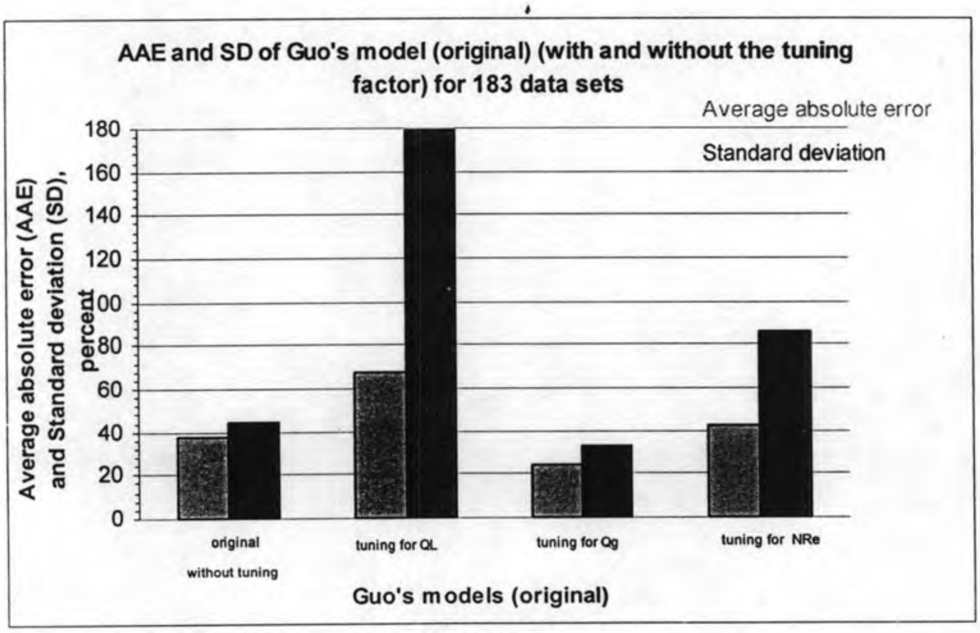


Figure 6.3: Comparison of Guo's model (original) with and without the tuning factor for 183 data sets.

From Figure 6.3 and Table 6.9, the average absolute error and standard deviation obtained from Guo's model (original) tuning for gas flow rate (Q_g) is the lowest. Its average absolute error and standard deviation are 24.0% and 32.8%, respectively.

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

In this section, Guo's original model is modified by the Z factor with and without the tuning factor. For the case without the tuning factor, Equations 4.3 through 4.7 are used instead of Equation 3.8, and 3.11 through 3.14. For the case with the tuning factor, Equations 4.3 through 4.7 are also used to back calculate the tuning factor for liquid holdup (F_{LHU}). After F_{LHU} is backed calculated, the X value is determined from Equation 4.2 for the Y value is assumed to be zero.

Then, the X values were plotted against natural logarithms of liquid flow rate (Q_L), gas flow rate (Q_g) and Reynolds number (N_{Re}). These plots are shown in Figure 6.4. In Figure 6.4, the green lines represent linear trend lines, the red lines represent logarithm trend lines, and the black lines represent polynomial trend lines. Each trend line has its relationship and coefficient of determination (R^2). The maximum value of R^2 must be chosen for each plot. It can be seen that R^2 value of the polynomial trend line is maximum for each plot. Therefore, the relationships of the polynomial trend lines were chosen to calculate X value for each plot. The selected relationships are summarized as follows:

For X vs. LN(Q_L) plot,

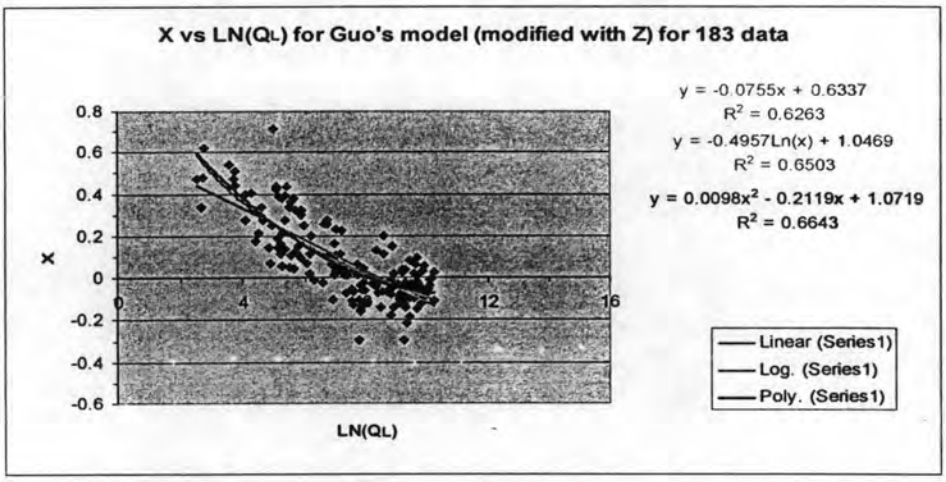
$$X = 0.0098(LN(Q_L))^2 - 0.2119LN(Q_L) + 1.0719 \qquad (6.4)$$

For X vs. LN(Q_g) plot,

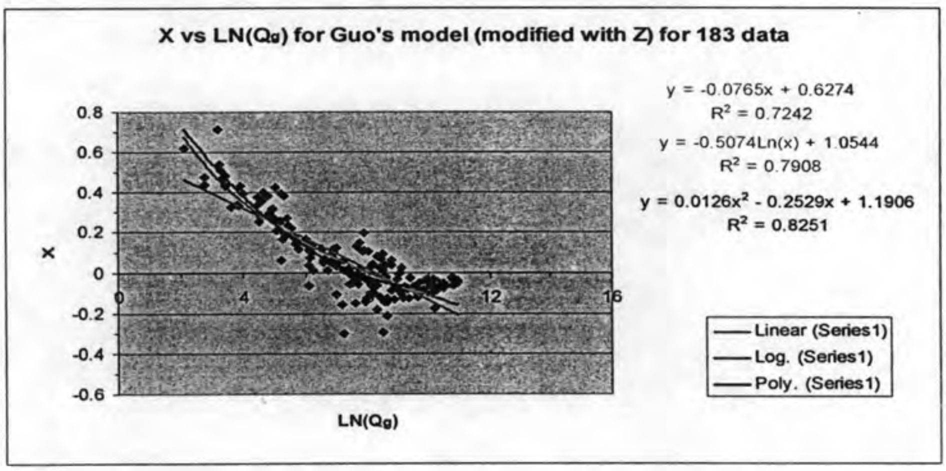
$$X = 0.0126(LN(Q_g))^2 - 0.2529LN(Q_g) + 1.1906 \qquad (6.5)$$

For X vs. LN (N_{Re}) plot,

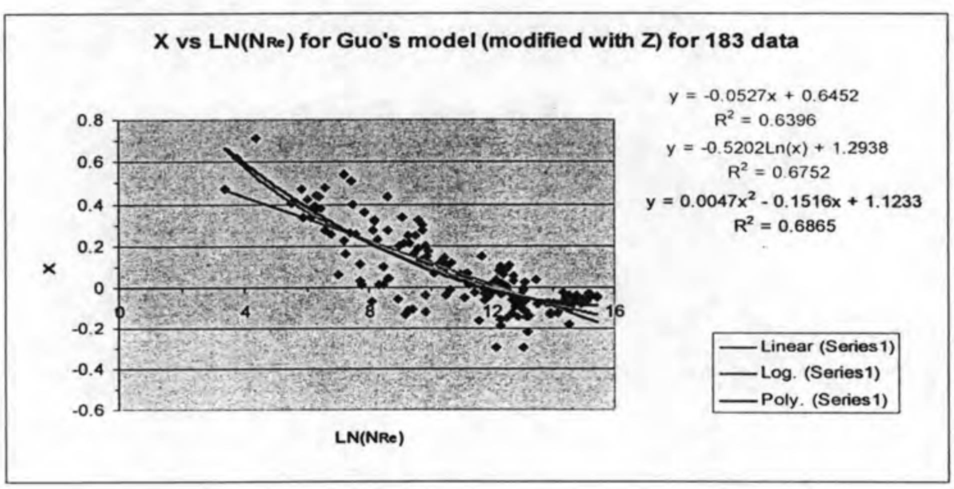
$$X = 0.0047(LN(N_{Re}))^2 - 0.1516LN(N_{Re}) + 1.1233 \qquad (6.6)$$



(a) Plot of X versus natural logarithm of liquid flow rate.



(b) Plot of X versus natural logarithm of gas flow rate.



(c) Plot of X versus natural logarithm of Reynolds number.

Figure 6.4: Plot of X versus well parameters for Guo's model modified with Z.

The determination of the X value for each data set is the same procedure expressed in Step 4 of Section 4.1. After the X value was obtained, the tuning factor for liquid holdup (F_{LHU}) was calculated using Equation 4.2. These calculated tuning factors for liquid holdup (F_{LHU}) were then used to calculate the bottomhole flowing pressures by Guo's four-phase flow model modified with the Z factor. These calculated bottomhole flowing pressures were compared, then, with the measured bottomhole flowing pressures. Statistical values such as the average absolute error and standard deviation are compared and shown in Figure 6.5. The average relative error, the average absolute error, and standard deviation of 183 data sets are as shown in Table 6.10.

Table 6.10: Statistical parameters for Guo's model modified with the Z factor with and without the tuning factor for 183 data sets.

No. of data set	Statistical parameter	Guo's model modified with the Z factor			
		Without tuning	Tuning for Q_L	Tuning for Q_g	Tuning for N_{Re}
183	Avg relative error	-1.2	-30.7	0.2	-8.8
	Avg absolute error	32.9	48.4	17.2	33.7
	SD	41.6	159.6	28.8	89.9

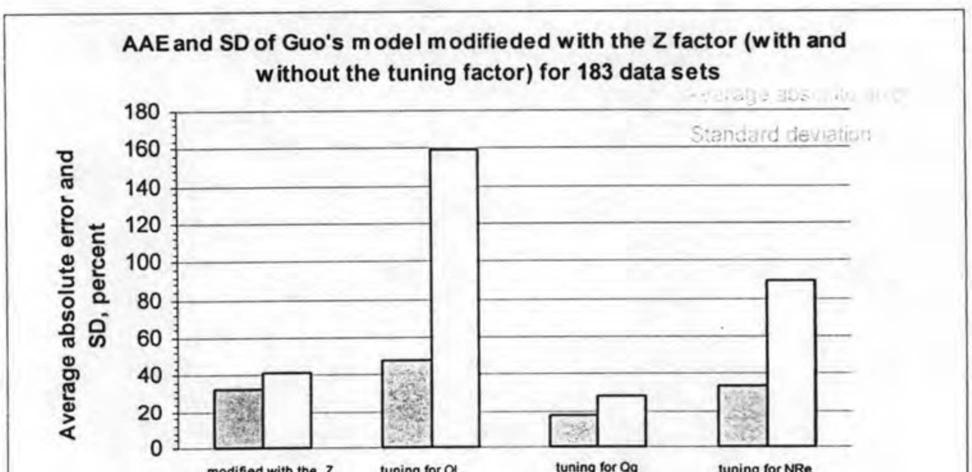


Figure 6.5: Comparison of Guo's model modified with the Z factor with and without tuning factor for 183 data sets.

From Figure 6.5 and Table 6.10, the average absolute error and standard deviation obtained from Guo's model modified with the Z factor tuning for gas flow rate (Q_g) is the lowest. Its average absolute error and standard deviation are 17.2% and 28.8%, respectively.

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

When Guo's four-phase flow model is modified with solution or dissolved gas-oil ratio (R_s) and oil formation volume factor (B_o), Equations 4.8, 4.9, and 4.11 through 4.16 from Section 4.3 are used instead of Equations 3.6 through 3.9, 3.11, 3.12, 3.14, and 3.15 that are used in Guo's original model. This modified model is used in the case of with and without the tuning factor.

The determination of F_{LHU}, X, and the relationships of X with well parameters are the same as the one in Section 6.2.2 except for the equations. In this part, equations from Section 4.3 are used. But, in the case that solution gas-oil ratio (R_s) calculated from the correlation at the bottomhole is higher than the actual total gas-oil ratio (R), F_{LHU} cannot be back calculated from Guo's model. In this study, 85 data sets have solution gas-oil ratio (R_s) at the bottomhole higher than total gas-oil ratio (R). Therefore, only 98 data sets were used to determine F_{LHU}, X, and the relationships of X with well parameters.

Then, the X values for 98 data sets were plotted with natural logarithms of liquid flow rate (Q_L), gas flow rate (Q_g), and Reynolds number (N_{Re}). These plots are shown in Figure 6.6. It can be seen that R^2 value of the polynomial trend lines are maximum for each plot. Therefore, the selected relationships for each plot are

For X vs. LN(Q_L) plot,

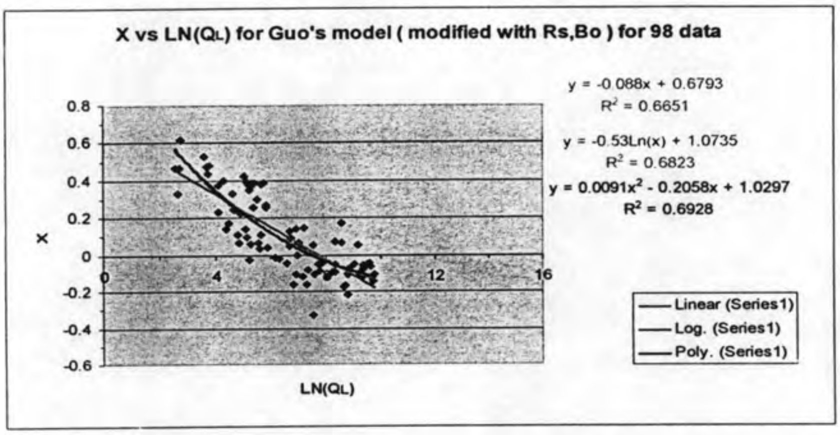
$$X = 0.0091(LN(Q_L))^2 - 0.2058LN(Q_L) + 1.0297 \quad (6.7)$$

For X vs. LN(Q_g) plot,

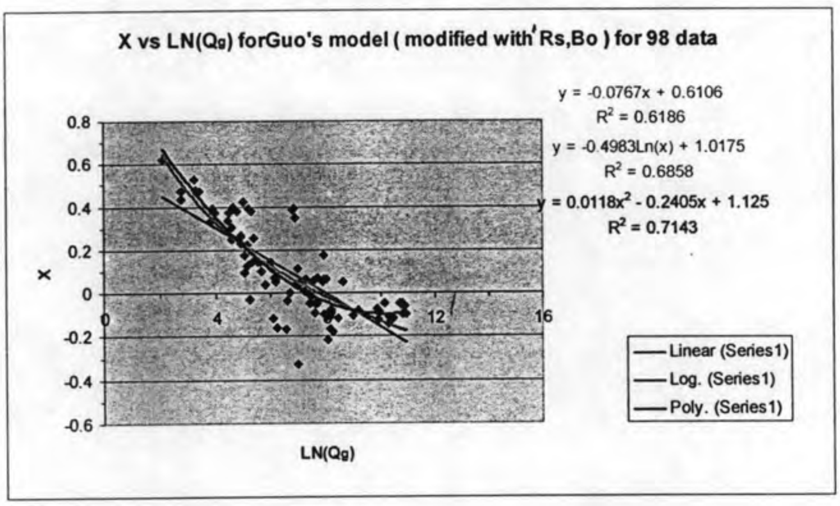
$$X = 0.0118(LN(Q_g))^2 - 0.2405LN(Q_g) + 1.125 \quad (6.8)$$

For X vs. LN (N_{Re}) plot,

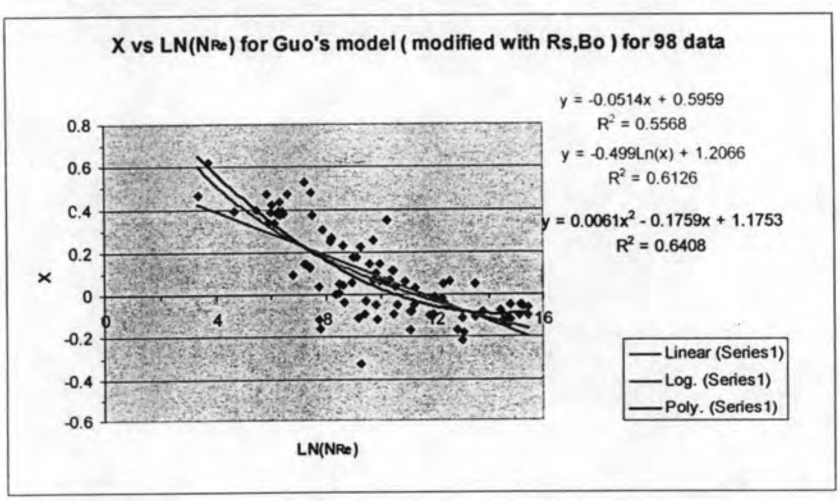
$$X = 0.0061(LN(N_{Re}))^2 - 0.1759LN(N_{Re}) + 1.1753 \quad (6.9)$$



(a) Plot of X versus natural logarithm of liquid flow rate.



(b) Plot of X versus natural logarithm of gas flow rate.



(c) Plot of X versus natural logarithm of Reynolds number.

Figure 6.6: Plot of X versus well parameters for Guo's model modified with R_s and B_o.

Then, the X value for 183 data sets were calculated for each selected relationship. After the X value was calculated, the tuning factor for liquid holdup (F_{LHU}) was calculated from Equation 4.2. These calculated tuning factors for liquid holdup (F_{LHU}) were used to calculate the bottomhole flowing pressure by Guo's four-phase flow model modified with R_s and B_o. These calculated bottomhole flowing pressures were compared, then, with the measured bottomhole flowing pressures. Statistical values such as the average absolute error and standard deviation were computed and are shown in Figure 6.7. The average relative error, the average absolute error, and standard deviation of 183 data sets are shown in Table 6.11.

Table 6.11: Statistical parameters for Guo's model modified with R_s and B_o with and without the tuning factor for 183 data sets.

No. of data set	Statistical parameter	Guo's model modified with R_s and B_o			
		Without tuning	Tuning for Q_L	Tuning for Q_g	Tuning for N_{Re}
183	Avg relative error	-24.2	-36.9	-18.3	-23.2
	Avg absolute error	44.7	49.0	29.8	37.5
	SD	50.3	113.0	35.0	75.8

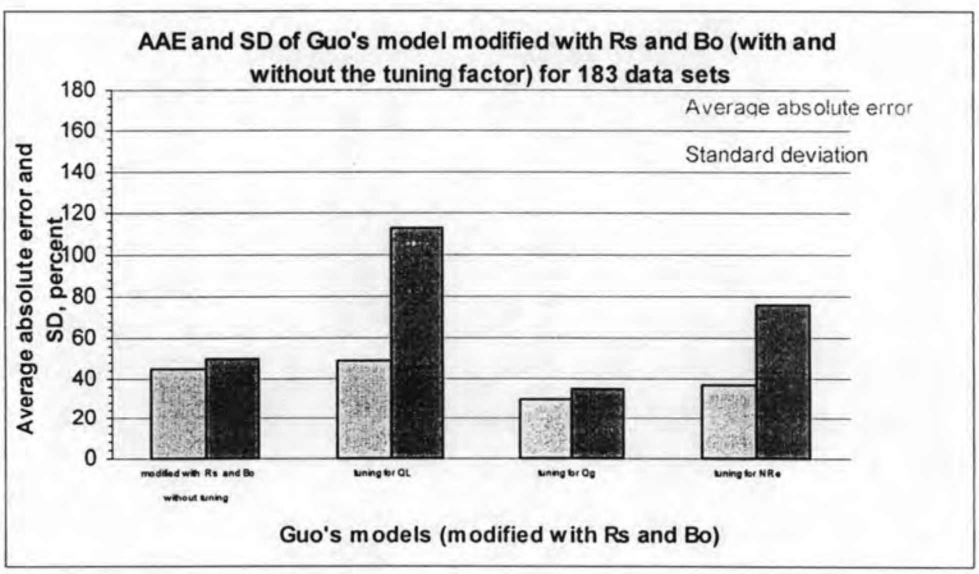


Figure 6.7: Comparison of Guo's model modified with R_s and B_o with and without the tuning factor for 183 data sets.

From Figure 6.7 and Table 6.11, it can be seen that the average absolute error and standard deviation obtained from Guo's model modified with R_s and B_o tuning for gas flow rate (Q_g) is the lowest. Its average absolute error and standard deviation are 29.8% and 35.0%, respectively.

6.2.4 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)

In Section 4.4, Equations 4.18 through 4.25 which are expressed in terms of gas compressibility factor (Z), solution or dissolved gas-oil ratio (R_s), and oil formation volume factor (B_o) are used to modify Guo's original model. This modified model is considered with and without the tunlng factor.

The equations from Section 4.4 are used to determine F_{LHU}, X, and the relationships of X with well parameters. But, F_{LHU} cannot be calculated from Guo's model when solution gas-oil ratio (R_s) calculated from the correlation at the bottomhole is higher than the actual total gas-oil ratio (R). As a result, 85 data sets cannot be used. In addition, 8 data sets that give negative F_{LHU} cannot be used, either. Therefore, a total of 90 data sets were used to determine F_{LHU}, X, and the relationships of X with well parameters.

Then, the X value for 90 data sets were plotted with natural logarithms of liquid flow rate (Q_L), gas flow rate (Q_g), and Reynolds number (N_{Re}). These plots are shown in Figure 6.8. It can be seen that R^2 value of the polynomial trend lines are maximum for each plot. Therefore, the selected relationships for each plot are:

For X vs. LN(Q_L) plot,

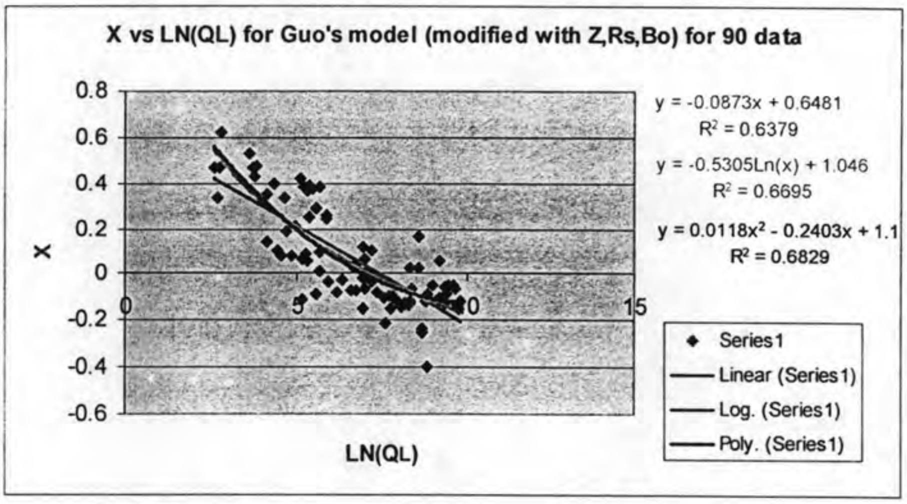
$$X = 0.0118(LN(Q_L))^2 - 0.2403LN(Q_L) + 1.1 \qquad (6.10)$$

For X vs. LN(Q_g) plot,

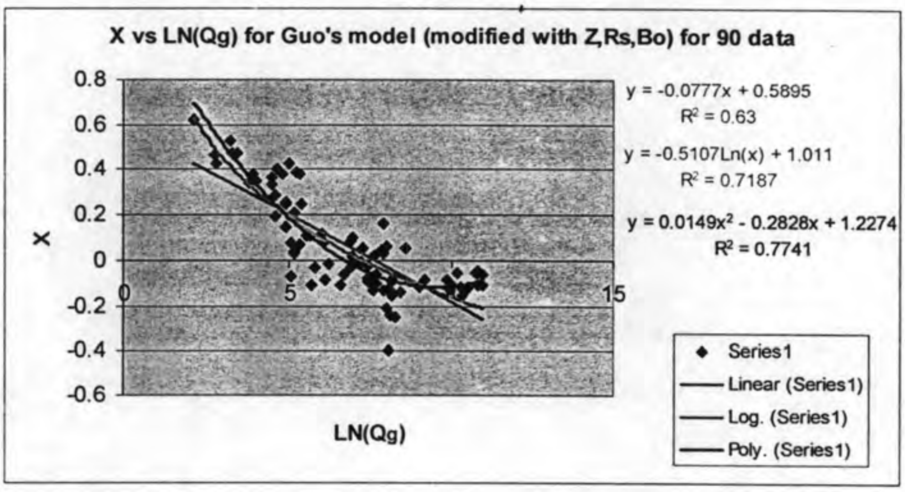
$$X = 0.0149(LN(Q_g))^2 - 0.2828LN(Q_g) + 1.2274 \qquad (6.11)$$

For X vs. LN (N_{Re}) plot,

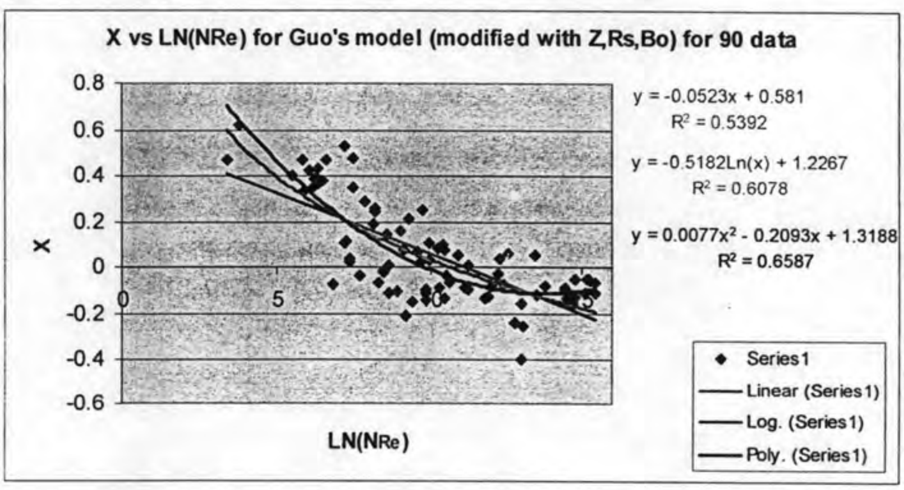
$$X = 0.0077(LN(N_{Re}))^2 - 0.2093LN(N_{Re}) + 1.3188 \qquad (6.12)$$



(a) Plot of X versus natural logarithm of liquid flow rate.



(b) Plot of X versus natural logarithm of gas flow rate.



(c) Plot of X versus natural logarithm of Reynolds number.

Figure 6.8: Plot of X versus well parameters for Guo's model modified with Z, R_s, and B_o.

Then, the X value for 183 data sets were calculated for each selected relationship. After the X value was calculated, the tuning factor for liquid holdup (F_{LHU}) was calculated from Equation 4.2. These calculated tuning factors for liquid holdup (F_{LHU}) were used to calculate the bottomhole flowing pressure by Guo's four-phase flow model modified with Z, R_s, and B_o. These calculated bottomhole flowing pressures were compared, then, with the measured bottomhole flowing pressures. Statistical values such as the average absolute error and standard deviation were computed and are shown in Figure 6.9. The average relative error, the average absolute error, and standard deviation of 183 data sets are shown in Table 6.12.

Table 6.12: Statistical parameters for Guo's model modified with Z, R_s, and B_o with and without the tuning factor for 183 data sets.

No. of data set	Statistical parameter	Guo's model modified with Z, R_s, and B_o			
		Without tuning	Tuning for Q_L	Tuning for Q_g	Tuning for N_{Re}
183	Avg relative error	-28.1	-31.7	-18.3	-24.7
	Avg absolute error	44.6	42.0	29.1	39.6
	SD	47.2	97.5	35.1	122.7

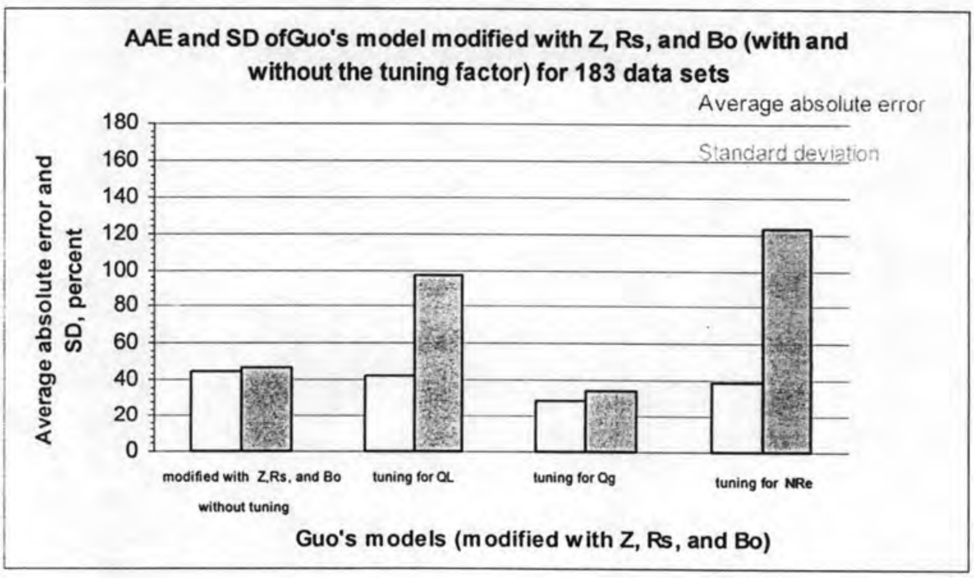


Figure 6.9: Comparison of Guo's model modified with Z, R_s, and B_o with and without the tuning factor for 183 data sets.

From Figure 6.9 and Table 6.12, it can be seen that the average absolute error and standard deviation that obtained from Guo's model modified with Z, R_s, and B_o tuning for gas flow rate (Q_g) is the lowest. Its average absolute error and standard deviation are 29.8% and 35.0%, respectively.

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

The procedure for the incremental calculation of this study has been expressed in Section 4.5. The calculation is started from the measured wellhead flowing pressure ($p_1 = p_{wh}$) at wellhead (L_1=0). Then, a pressure is assumed and a pressure increment $\Delta p_{guessed}$ corresponding to the length increment (ΔL =100 feet for each) is estimated. In this study, temperature at each length increment is determined, and then the average pressure and the average temperature in the length increment ΔL are calculated (see in Appendix A6 for temperature determination).

The necessary fluid and PVT properties at conditions of the average pressure and the average temperature are also determined using empirical correlations. The pressure at the selected depth for the average pressure and the average temperature is calculated and then the pressure increment $\Delta p_{calculated}$ corresponding to the selected length increment is also calculated. This calculated pressure increment $\Delta p_{calculated}$ is compared with the estimated pressure increment Δp_{gussed}. If they are not sufficiently close, estimate a new pressure increment and iteratively repeat until the estimated and calculated values are sufficiently close.

From Sections 6.2.1 through 6.2.4, we can see that the modified Guo's models tuning for gas flow rate (Q_g) give the best result over the other modified Guo's models. Among the modified Guo's models, the modification by Z factor with tuning for gas flow rate is the best. Therefore, this model was chosen for incremental calculation.

Incremental calculations with and without the tuning factor were considered. For modification with the tuning factor, the X value obtained from Guo's model modified by the Z factor with tuning for gas flow rate was used to calculate F_{LHU}.

The calculated F_{LHU} values were used to calculate the flowing pressure at the selected length by Guo's four-phase flow model modified with the Z factor. This procedure was used to calculate the flowing pressure until total length is reached. The pressure at total length is the bottomhole flowing pressure. This calculated bottomhole flowing pressure was compared, then, with the measured bottomhole flowing pressure. Statistical values such as the average absolute relative error and standard deviation were determined. The average relative error, the average absolute relative error, and standard deviation of 183 data sets are shown in Figure 6.10 and Table 6.13.

Table 6.13: Statistical parameters for Guo's model modified with the Z with and without the tuning factor for incremental calculation for 183 data sets.

No. of data	Statistical parameter	Guo's model			
		Modified by Z without tuning factor	Modified by Z without tuning factor using incremental calculation	Modified by Z with tuning factor	Modified by Z with tuning factor using incremental calculation
183	Avg relative error	-1.2	-362.8	-0.2	-256.1
	Avg absolute error	32.9	375.7	17.2	258.7
	SD	41.6	513.4	28.8	258.1

From Figure 6.10 and Table 6.13, it can be seen that the average absolute error and standard deviation obtained from Guo's model modified with the Z factor tuning for gas flow rate is the lowest. Its average absolute relative error and standard deviation are 17.2% and 28.8%, respectively. The average absolute errors of incremental calculation are 375.7% and 258.7% where there is no tuning factor and with tuning factor, respectively. Such a large error may come from the fact that the original Guo's model was derived for the whole tubing length. Thus, it is not appropriate to perform calculations for small tubing sections.

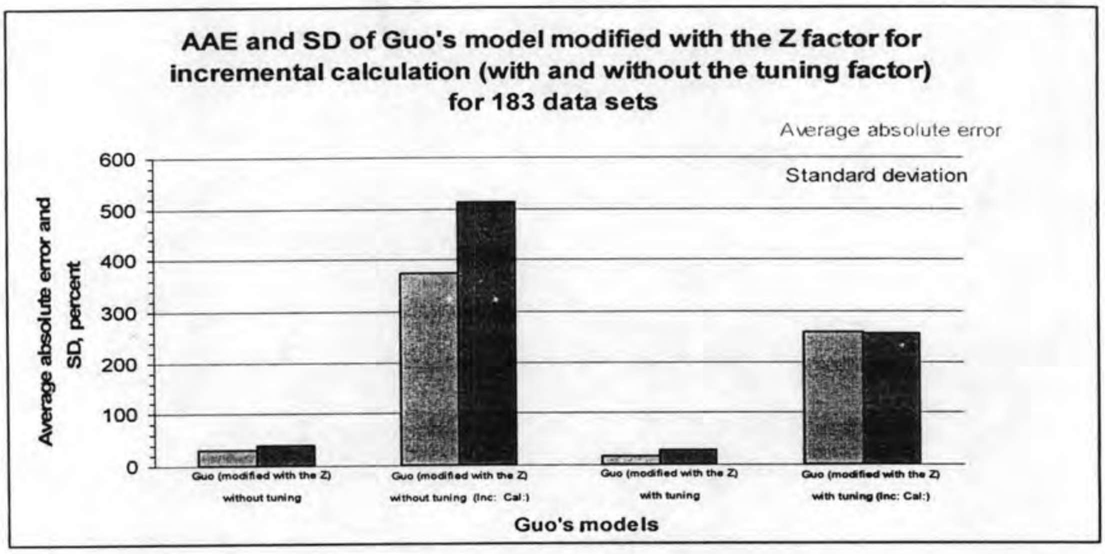


Figure 6.10: Comparison of Guo's model modified with the Z factor for incremental calculation with and without the tuning factor for 183 data sets.

6.3 Testing of the modified Guo's four-phase flow models

According to Sections 6.2.1 through 6.2.4, we can see that the modified Guo's model tuning for gas flow rate (Q_g) gives the best result over the other modified Guo's models. Among the modified Guo's models, the modification by Z factor with tuning for gas flow rate is the best. Therefore, this model was chosen for testing of the modified Guo's four-phase flow model.

According to Table 6.10, it can be clearly seen that, if we use 183 data sets available in the process of determining the tuning factor, the results is always satisfactory since we are tuning for this specific data set. In order to illustrate that the method works, we determined the tuning factor from 90 sets of data instead of using the whole set of data available for Guo's model modified with the Z factor tuning for gas flow rate. Then, this tuning factor was used to compute the pressure.

The same procedures were used to determine F_{LHU}, X, and the relationships of X as in Guo's model modified with the Z factor tuning for gas flow rate. Table 6.14 shows the comparison of the relationships determined from 183 data sets and the relationships determined from 90 data sets.

The relationships determined from 90 data sets were used to calculate the bottomhole flowing pressures by Guo's model modified with the Z factor tuning for gas flow rate. These calculated bottomhole pressures were compared with the measured bottomhole flowing pressures. Statistical parameters such as the average absolute error (AAE) and standard deviation (SD) were determined.

Then, the average absolute errors (AAE) for the case in which the tuning factor was determined from 183 data sets are compared with the average absolute errors (AAE) for the case in which the tuning factor was determined from 90 data sets. This comparison is shown in Table 6.15.

From Table 6.15, it can be seen that AAE for the two cases are not significantly differed. As a result, we can say that the modifications we made are not sensitive to the number of data sets.

Table 6.14: Comparison of the relationships determined from 183 data sets between the relationships determined from 90 data sets.

No. of data set	Relationship
90	$X = 0.0109(LN(Q_g))^2 - 0.2274LN(Q_g) + 1.1232$
183	$X = 0.0126(LN(Q_g))^2 - 0.2529LN(Q_g) + 1.1906$

Table 6.15: Comparison of the average absolute error (AAE) determined from 183 data sets and 90 data sets.

Guo's model	AAE determined from 183 data (%)	AAE determined from 90 data (%)	Deviation AAE from 183 data (%)
Modified with Z tuning for Qg	17.2	20.4	-3.2

6.4 Comparison of the modified Guo's four-phase flow models against six other multiphase flow correlations

In this section, the comparisons of modified Guo's four-phase flow models against six other multiphase flow correlations which are Duns and Ros (modified), Hagedorn and Brown, Fancher and Brown, Beggs and Brill, Orkiszewski, Duns and Ros (original) are expressed. From Sections 6.2.1 through 6.2.4, we can see that the modified Guo's model tuning for gas flow rate (Q_g) gives the best result over the other modified Guo's models for each section. Therefore, these modified Guo's models tuning for gas flow rate (Q_g) are chosen to compare with six other multiphase flow correlations.

In the comparison, statistical parameters such as the average relative error, the average absolute error and standard deviation are analyzed in different groupings based on gas-liquid ratio (GLR), tubing ID, API gravity, liquid flow rate, and gas flow rate. However, the average absolute error is used as an important and good indicator of the accuracy in this study. Therefore, it is important to be sure that the average absolute error is within certain limits. To clarify this, the models and correlations are ranked according to the percentage of the results within certain error limits. In this study, the models and correlations are ranked in three error limit ranges as 0 -10% of AAE (good), 10- 20% of AAE (fair), and greater than 20% of AAE (poor).

The following symbols are used in tables of statistical analysis:

ARE = Average relative error

AAE = Average absolute error

SD = Standard deviation

$G(O)Q_g$ = Guo's model (original) tuning for Q_g

$G(Z)Q_g$ = Guo's model (modified with the Z factor) tuning for Q_g

$G(ZRB)Q_g$ = Guo's model (modified with Z, R_s, and B_o factor) tuning for Q_g

$G(RB)Q_g$ = Guo's model (modified with R_s, and B_o factor) tuning for Q_g

DR(M) = Duns and Ros (modified) multiphase correlation

HB = Hagedorn and Brown multiphase correlation

FB = Fancher and Brown multiphase correlation

BB = Beggs and Brill multiphase correlation

OKZS = Orkiszewski multiphase correlation

DR(O) = Duns and Ros (original) multiphase correlation

According to Table 6.16 and Figure 6.11, it can be seen that AAE of Guo's model modified with Z factor tuning for gas flow rate is better than other modified Guo's models and multiphase flow correlations except Duns and Ros (modified) correlation and Duns and Ros (original) correlation. The other modified Guo's models have higher AAE values than the other multiphase flow correlations.

Table 6.16: Statistical parameters of the modified Guo's models and six other multiphase flow correlations for 183 data.

Statistical parameter	G(O)Qg	G(Z)Qg	G(ZRB)Qg	G(RB)Qg	DR(M)	HB	FB	BB	OKZS	DR(O)
ARE	-4.8	-0.2	-18.1	-18.3	3.3	5.4	17.6	-9.1	0.3	1.6
AAE	24.0	17.2	29.5	29.8	16.7	19.6	21.9	18.6	18.0	14.0
SD	32.8	28.8	34.5	35.0	24.8	28.2	27.2	25.0	26.5	20.2

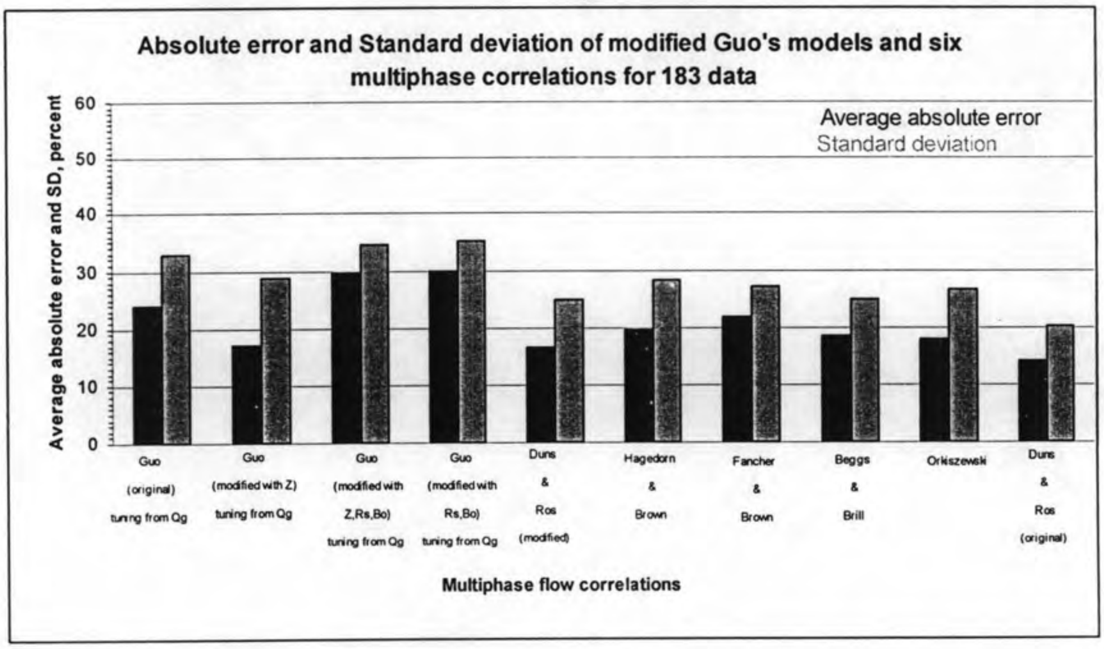


Figure 6.11: Comparison of the modified Guo's models and six other multiphase flow correlations for 183 data.

Tables 6.17 through 6.38 and Figures 6.12 through 6.28 show the comparison of statistical parameters and ranking for different groupings based on gas-liquid ratio (GLR), tubing ID, API gravity, liquid flow rate (Q_L), and gas flow rate (Q_g) for modified Guo's four-phase flow models against six other multiphase flow correlations.

6.4.1 Comparison of statistical parameters and ranking for different groupings based on gas-liquid ratio (GLR)

In the grouping based on gas-liquid ratio (GLR), Duns and Ros (original) correlation performs well in both GLR less than or equal to 1,000 scf/stb and greater than 1,000 scf/stb. However, the AAE for cases with lower GLR is less than that of the high GLR, indicating that the correlation is more accurate for low GLR wells. From Figures 6.12 and 6.13 and Tables 6.17 and 6.18, it can be seen that AAE of Guo's model modified with the Z factor tuning for gas flow rate is better than the other modified Guo's models, Hagedorn and Brown correlation, and Fancher and Brown correlation for both GLR less than or equal to 1,000 scf/stb and greater than 1,000 scf/stb. We can see that the accuracy of Guo's model modified with the Z factor tuning for gas flow rate is about the same for low and high GOR.

Table 6.17: Statistical parameters of the modified Guo's models and six other multiphase flow correlations for GLR ≤ 1,000 scf/stb (112 data sets).

Statistical parameter	G(O)Qg	G(Z)Qg	G(ZRB)Qg	G(RB)Qg	DR(M)	HB	FB	BB	OKZS	DR(O)
ARE	-3.5	-2.2	-20.5	-21.0	0.8	3.4	17.8	-6.9	3.6	-2.9
AAE	24.8	17.1	30.5	30.6	15.9	17.6	20.8	14.0	13.7	12.4
SD	33.0	30.6	31.1	30.7	24.3	25.2	25.7	19.3	20.1	18.7

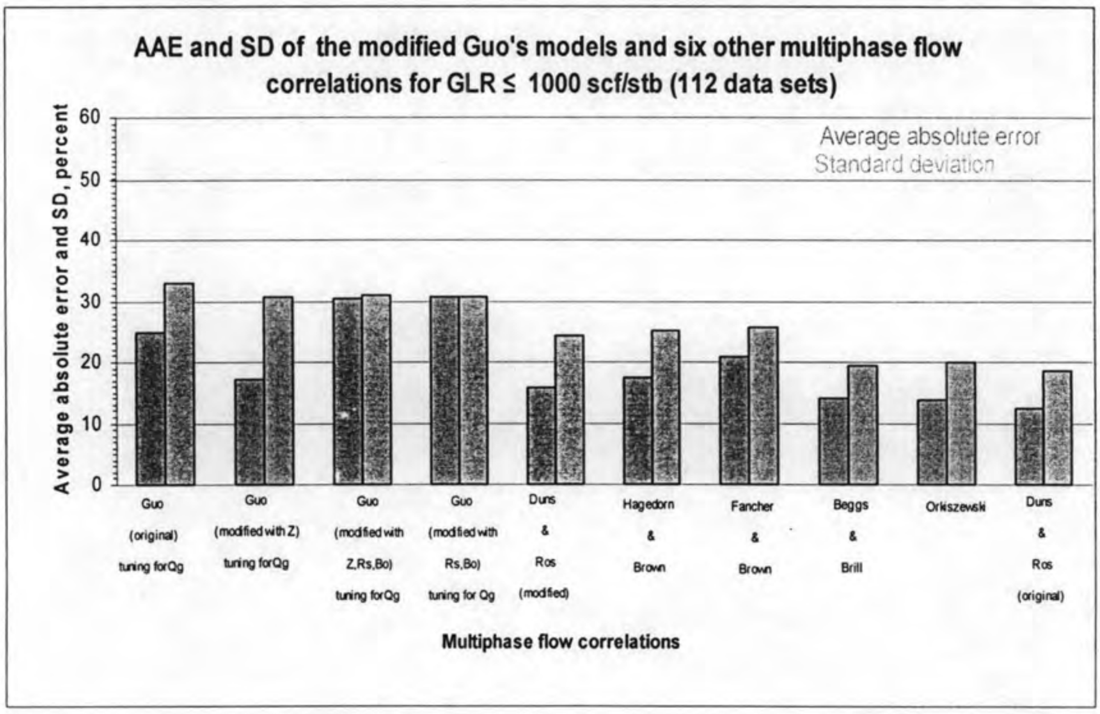


Figure 6.12: Comparison of the modified Guo's models and six other multiphase flow correlations for GLR ≤ 1,000 scf/stb (112 data sets).

Table 6.18: Statistical parameters of the modified Guo's models and six other multiphase flow correlations for GLR > 1,000 scf/stb (71 data sets).

Statistical parameter	G(O)Qg	G(Z)Qg	G(ZRB)Qg	G(RB)Qg	DR(M)	HB	FB	BB	OKZS	DR(O)
ARE	-7.0	3.0	-14.2	-14.0	7.3	8.6	17.1	-12.4	-4.9	8.8
AAE	22.8	17.2	28.2	28.5	17.9	22.8	23.8	25.9	24.8	16.5
SD	32.7	25.8	39.7	40.6	25.1	32.3	29.4	31.9	33.7	20.4

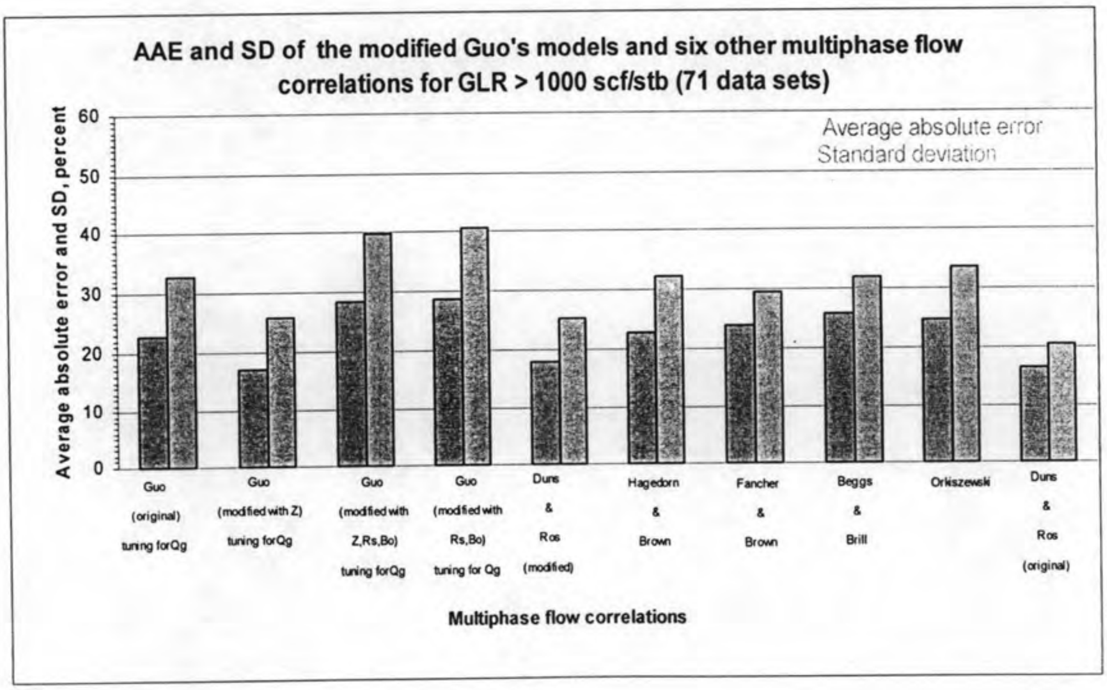


Figure 6.13: Comparison of the modified Guo's models and six other multiphase flow correlations for GLR > 1000 scf/stb (71 data sets).

Ranking of the modified Guo's models and six other multiphase flow correlations for grouping of GLR is shown in Table 6.19. From this table, we can see that Guo's model modified with the Z factor tuning for gas flow rate, Duns and Ros (modified) correlation, and Duns and Ros (original) correlation give fair accuracy for any gas-liquid ratio (GLR) while Hagedorn and Brown correlation, Beggs and Brill correlation, and Orkiszewski correlation give also fair accuracy for gas-liquid ratio less than 1,000 scf/stb because of 10-20% of their AAE range.

Table 6.19: Ranking of the modified Guo's models and six other multiphase flow correlations for grouping of GLR.

Models	GLR ≤ 1,000 scf/stb			GLR > 1,000 scf/stb		
	0-10%	10-20%	> 20%	0-10%	10-20%	> 20%
$G(O)Q_g$			√			√
$G(Z)Q_g$		√			√	
$G(ZRB)Q_g$			√			√
$G(RB)Q_g$			√			√
DR(M)		√			√	
HB		√				√
FB			√			√
BB		√				√
OKZS		√				√
DR(O)		√			√	

6.4.2 Comparison of statistical parameters and ranking for different groupings based on tubing ID

In Tables 6.20 through 6.25 and Figures 6.14 through 6.19 which show the results from the grouping based on tubing ID, Duns and Ros (original) correlation performs well for 2.441" and 6.184" tubing ID, while Hagedorn and Brown correlation works well for 3.812", 3.826", and 3.958" tubing ID, and Beggs and Brill correlation works well for 1.995" tubing ID. Duns and Ros (modified) correlation performs well for 4.494" and 4.892" tubing ID, while Guo's model modified with the Z factor tuning for gas flow rate works well for 2.764" and 2.992" tubing ID.

In this grouping, we can see the accuracy of Guo's model modified with the Z factor tuning for gas flow rate is the best over the other modified Guo's models for all tubing diameter ID except 1.995" tubing ID. Besides, Guo's model (original) modified with the tuning factor for gas flow rate can be utilized for 2.441", 3.812", 3.826", 3.958", 4.494", and 4.892" tubing ID while Guo's model modified with Z, R_s, and B_o tuning for gas flow rate and Guo's model modified with R_s, and B_o tuning for gas flow rate can be used for 2.441", 4.494", and 4.892" tubing ID.

Table 6.20: Statistical parameters of the modified Guo's models and six other multiphase flow correlations for 1.995"tubing ID (19 data sets).

Statistical parameter	G(O)Qg	G(Z)Qg	G(ZRB)Qg	G(RB)Qg	DR(M)	HB	FB	BB	OKZS	DR(O)
ARE	-41.8	-34.3	-22.5	-22.6	25.6	30.9	41.9	8.8	16.4	12.2
AAE	42.1	39.7	29.2	28.3	32	34	43.8	16.2	21.3	18.3
SD	49.5	56.8	31.8	33.4	30.5	25.9	33.8	20.2	20.1	17.8

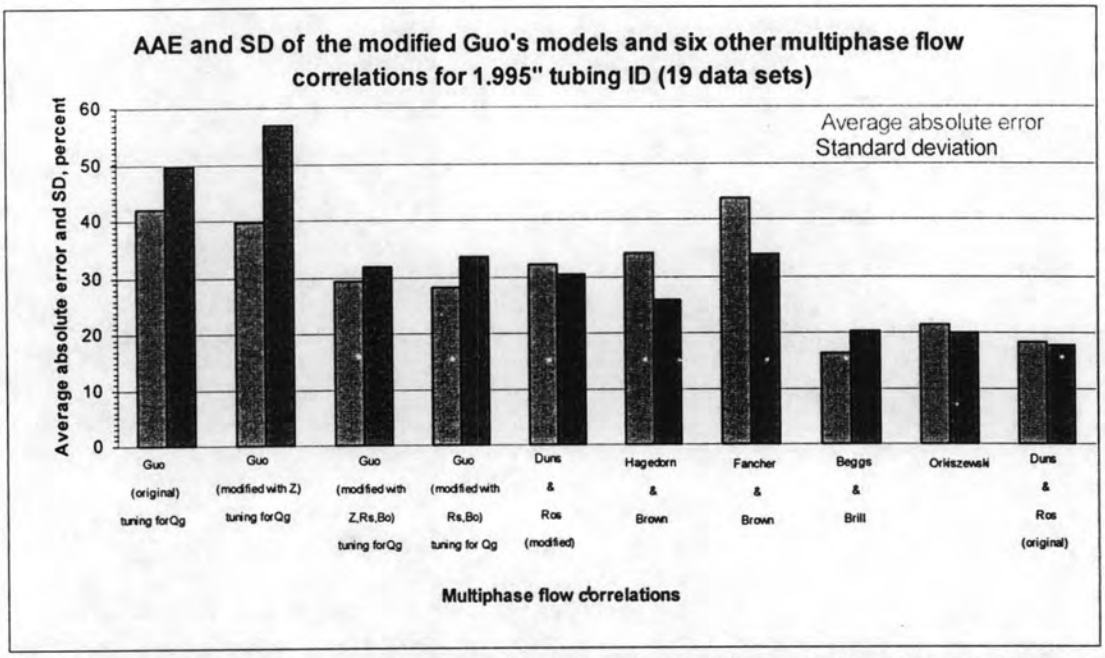


Figure 6.14: Comparison of the modified Guo's models and six other multiphase flow correlations for 1.995"tubing ID (19 data sets).

Table 6.21: Statistical parameters of the modified Guo's models and six other multiphase flow correlations for 2.441"tubing ID (38 data sets).

Statistical parameter	G(O)Qg	G(Z)Qg	G(ZRB)Qg	G(RB)Qg	DR(M)	HB	FB	BB	OKZS	DR(O)
ARE	2.5	8.9	0.6	0.2	14.4	15.5	29.8	-2.5	10.9	3.6
AAE	19.8	13.9	19.6	19.8	19.8	21.6	33.2	15.9	18.4	12.9
SD	25	18.2	25	24.4	23.9	23.1	29.7	23.7	22.1	18.2

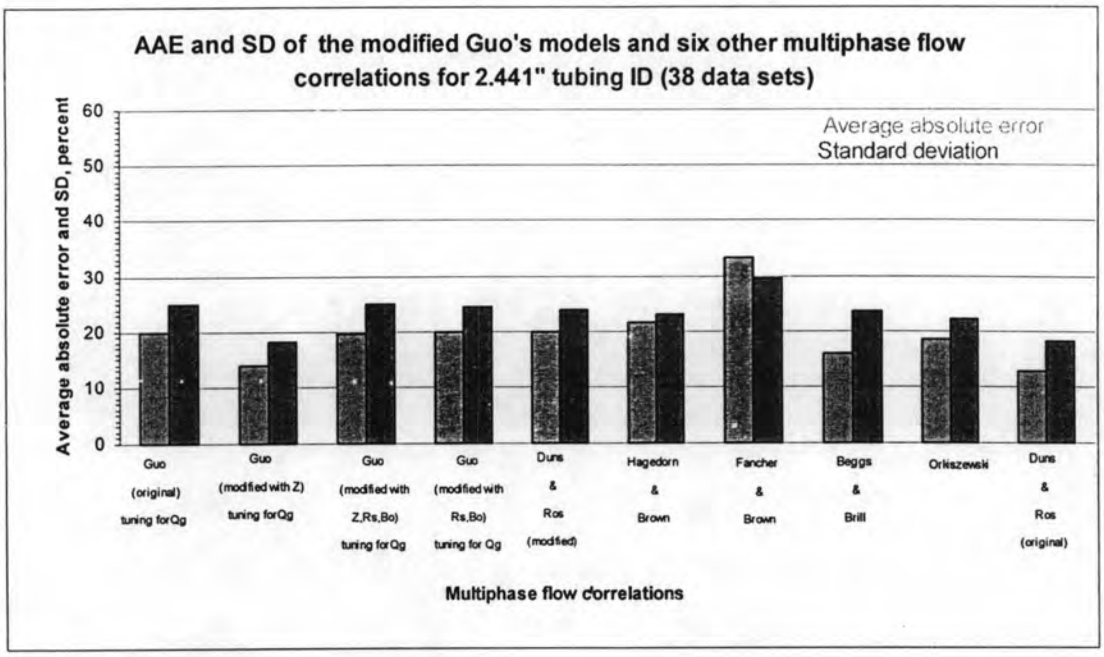


Figure 6.15: Comparison of the modified Guo's models and six other multiphase flow correlations for 2.441"tubing ID (38 data sets).

Table 6.22: Statistical parameters of the modified Guo's models and six other multiphase flow correlations for 2.764" and 2.992"tubing ID (49 data sets).

Statistical parameter	G(O)Qg	G(Z)Qg	G(ZRB)Qg	G(RB)Qg	DR(M)	HB	FB	BB	OKZS	DR(O)
ARE	-14.2	-0.9	-9.4	-10.1	-2.3	-6.1	23	-16.4	-2.1	-6.2
AAE	30.4	19.9	26.5	26.4	22.1	31.2	25.4	28	24.7	22.8
SD	34.5	28	40.5	40	30.5	41	26.3	32.3	35	28.9

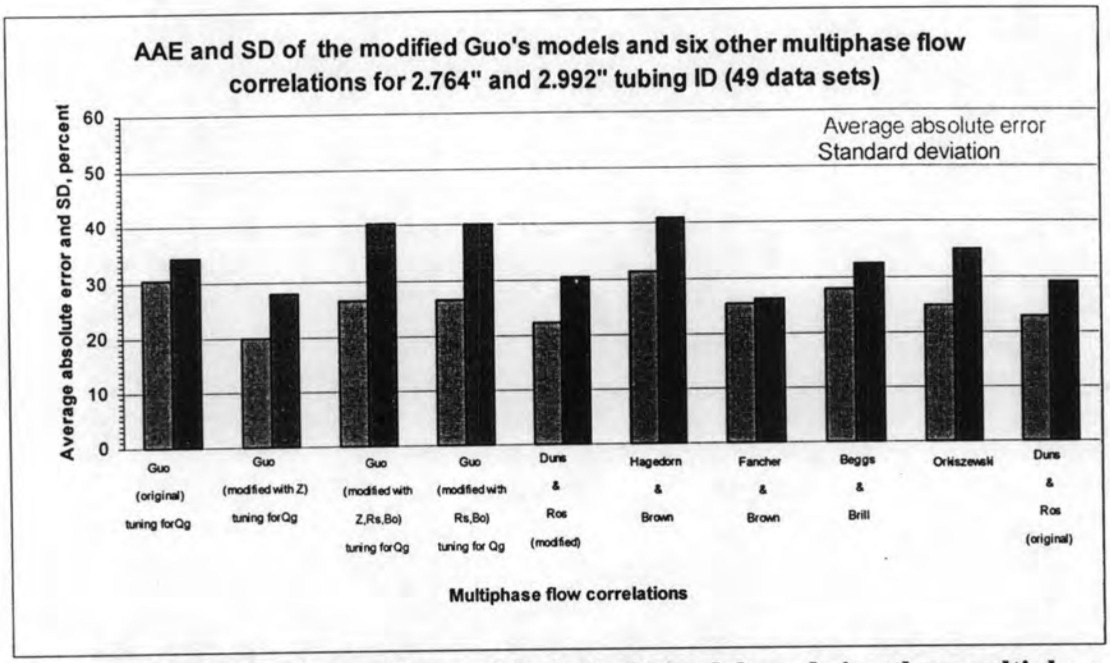


Figure 6.16: Comparison of the modified Guo's models and six other multiphase flow correlations for 2.764" and 2.992"tubing ID (49 data sets).

Table 6.23: Statistical parameters of the modified Guo's models and six other multiphase flow correlations for 3.812", 3.826", and 3.958"tubing ID (43 data sets).

Statistical parameter	G(O)Qg	G(Z)Qg	G(ZRB)Qg	G(RB)Qg	DR(M)	HB	FB	BB	OKZS	DR(O)
ARE	-4.5	1.2	-30.2	-30.6	-7.6	-2.9	-3.2	-20.9	-13.5	2.1
AAE	15	12.9	37	38.1	9.7	7.8	8.6	21.4	16.6	9.7
SD	18.3	16.7	34.8	35.9	11.2	9.6	10.8	18.2	21.4	13.1

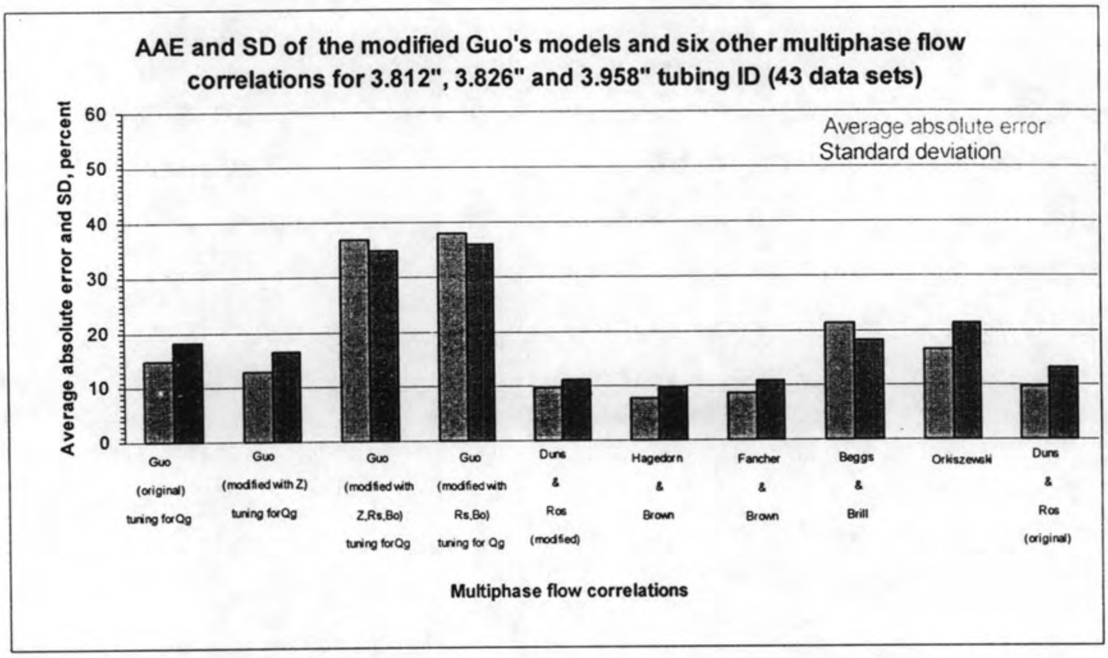


Figure 6.17: Comparison of the modified Guo's models and six other multiphase flow correlations for 3.812", 3.826", and 3.958" tubing ID (43 data sets).

Table 6.24: Statistical parameters of the modified Guo's models and six other multiphase flow correlations for 4.494" and 4.892" tubing ID (9 data sets).

Statistical parameter	G(O)Qg	G(Z)Qg	G(ZRB)Qg	G(RB)Qg	DR(M)	HB	FB	BB	OKZS	DR(O)
ARE	18.5	13.4	-6.2	-4	9.4	11	17.2	5.2	12	10.7
AAE	20	14.2	14.7	15.9	10	12.2	17.2	11.5	18	11.7
SD	17.6	17.1	24.1	25.8	11.7	13.7	18.2	16.9	23.6	16.1

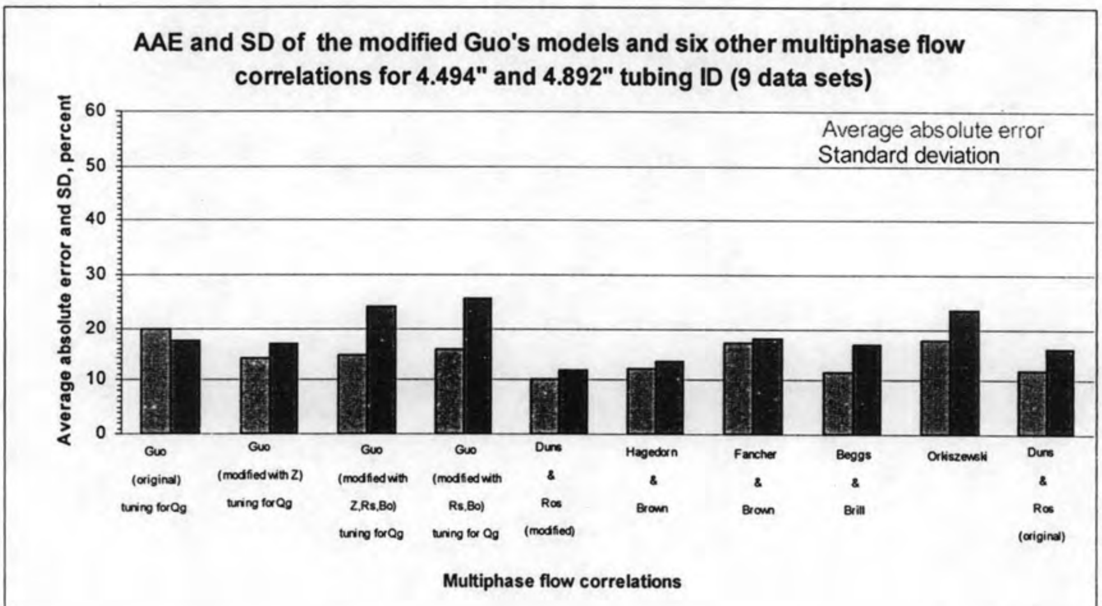


Figure 6.18: Comparison of the modified Guo's models and six other multiphase flow correlations for 4.494" and 4.892" tubing ID (9 data sets).

Table 6.25: Statistical parameters of the modified Guo's models and six other multiphase flow correlations for 6.184" tubing ID (25 data sets).

Statistical parameter	G(O)Qg	G(Z)Qg	G(ZRB)Qg	G(RB)Qg	DR(M)	HB	FB	BB	OKZS	DR(O)
ARE	21.3	6.2	-43.6	-43.4	-2.7	5.5	5.7	-3	-3.5	1.9
AAE	21.3	8	43.6	43.4	4.1	6	6.2	4	4.2	3.2
SD	6.9	8.1	11.4	11.4	5.5	4.4	4.4	4.1	4.5	4.1

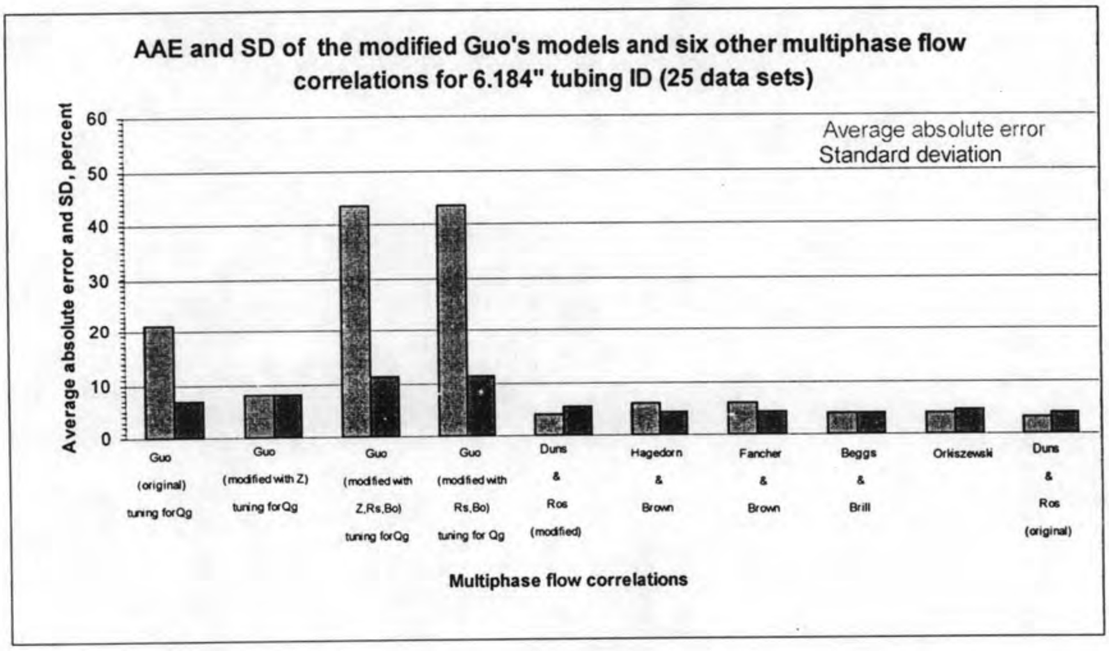


Figure 6.19: Comparison of the modified Guo's models and six other multiphase flow correlations for 6.184" tubing ID (25 data sets).

Table 6.26 (a): Ranking of the modified Guo's models and six other multiphase flow correlations for grouping of tubing ID.

Models	1.995" Tubing			2.441" Tubing			2.764", 2.992" Tubing		
	0-10%	**10-20%**	**> 20%**	**0-10%**	**10-20%**	**> 20%**	**0-10%**	**10-20%**	**> 20%**
G(O)Q_g			√		√				√
G(Z)Q_g			√		√			√	
G(ZRB)Q_g			√		√				√
G(RB)Q_g			√		√				√
DR(M)			√		√				√
HB			√			√			√
FB			√			√			√
BB		√			√				√
OKZS			√		√				√
DR(O)		√			√				√

Table 6.26 (b): Ranking of the modified Guo's models and six other multiphase flow correlations for grouping of tubing ID.

Models	3.812", 3.826", 3.958" Tubing			4.494", 4.892" Tubing			6.184" Tubing		
	0-10%	**10-20%**	**> 20%**	**0-10%**	**10-20%**	**> 20%**	**0-10%**	**10-20%**	**> 20%**
G(O)Q_g		√			√				√
G(Z)Q_g		√			√		√		
G(ZRB)Q_g			√		√				√
G(RB)Q_g			√		√				√
DR(M)	√			√			√		
HB	√				√		√		
FB	√				√		√		
BB			√		√		√		
OKZS		√			√		√		
DR(O)	√				√		√		

In Table 6.26 (a) and 6.26 (b), it can be seen that Duns and Ros (modified) correlation is good for 3.812", 3.826", 3.958", 4.494", 4.892", and 6.184" tubing ID because of its 0-10% of AAE range. Hagedorn and Brown correlation, Fancher and Brown correlation, and Duns and Ros (original) correlation can be used with good accuracy for 3.812", 3.826", 3.958", and 6.184" tubing ID while Guo's model modified with the Z factor tuning for gas flow rate, Beggs and Brill correlation and Orkiszewski correlation can be used with good accuracy for 6.184" tubing ID due to 0-10% of their AAE range. Guo's model modified with the Z factor tuning for gas flow rate fairly works for 2.441" through 4.892" tubing ID due to its 10-20% of AAE range. Guo's model (original) modified with the tuning factor for gas flow rate is fair for 2.441", 3.812",3.826",3.958", 4.494", and 4.892" tubing ID due to its 10-20% of AAE range.

We can also see that Duns and Ros (original) correlation and Beggs and Brill correlation fairly work for 1.995", 2.441", 4.494", and 4.892" tubing ID and Orkiszewski correlation can be used with fair accuracy for 2.441" through 4.892" tubing ID because of their 10-20% of AAE range. For Guo's model modified with Z, R_s, B_o tuning for gas flow rate and Guo's model modified with R_s, B_o tuning for gas flow rate, both fairly works for 2.441", 4.494", and 4.892" tubing ID due to their 10-20% of AAE range. Besides, Hagedorn and Brown correlation and Fancher and Brown correlation faifly work for 4.494", 4.892" tubing ID and Duns and Ros (modified) correlation is fair for 2.441" tubing ID due to their 10-20% of AAE range.

6.4.3 Comparison of statistical parameters and ranking for different groupings based on API gravity

In the grouping based on API gravity, Orkiszewski correlation performs well in API gravity less than or equal to 20°API, Guo's model modified with the Z factor tuning for gas flow rate works well in 20° to 45° API gravity range, Duns and Ros (modified) correlation performs well in 20° to 45° API gravity and API gravity greater than 45°. (Figures 6.20 through 6.22 and Tables 6.27 through 6.29)

For the grouping based on API gravity, Guo's model modified with the Z factor tuning for gas flow rate performs well over the other modified Guo's models for any API gravity except in the case of API gravity less than or equal to 20°. However, Guo's model (original) modified with the tuning factor for gas flow rate can only be employed for API gravity greater than 45°. The other modified Guo's models have the high AAE values for any API gravity.

Table 6.27: Statistical parameters of the modified Guo's models and six other multiphase flow correlations for API ≤ 20° (48 data sets).

Statistical parameter	G(O)Qg	G(Z)Qg	G(ZRB)Qg	G(RB)Qg	DR(M)	HB	FB	BB	OKZS	DR(O)
ARE	-13	-6.9	-2.7	-3.5	6.5	-3.6	31.1	-8.5	10.6	-7.3
AAE	35	29.2	23.3	24	28.6	36	34.3	23.3	21.9	24
SD	48.1	47.9	34.3	34.9	36.9	44.4	34.1	31.3	27.2	27.9

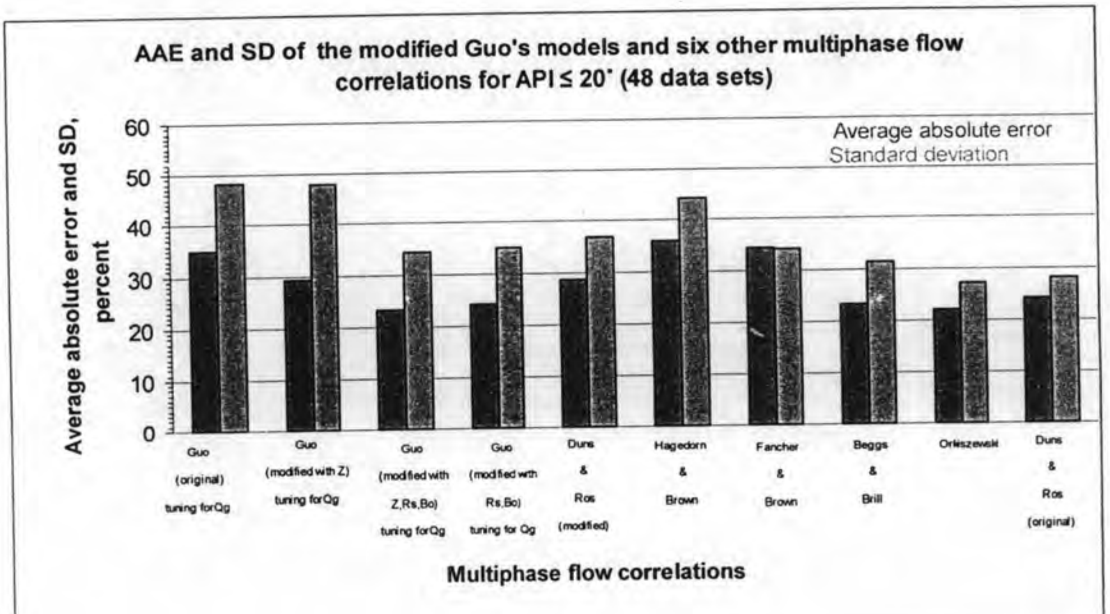


Figure 6.20: Comparison of the modified Guo's models and six other multiphase flow correlations for API ≤ 20° (48 data sets).

Table 6.28: Statistical parameters of the modified Guo's models and six other multiphase flow correlations for 20° < API ≤ 45° (87 data sets).

Statistical parameter	G(O)Qg	G(Z)Qg	G(ZRB)Qg	G(RB)Qg	DR(M)	HB	FB	BB	OKZS	DR(O)
ARE	-3	-0.6	-23.9	-24.2	2.6	10.6	16.6	-7.2	-1.1	2.3
AAE	22.8	12.7	31.6	31.5	12.7	14	19.4	14.3	14.8	8.6
SD	27.6	17.2	27.2	26.9	19	17.8	22.9	19.7	23.1	13.9

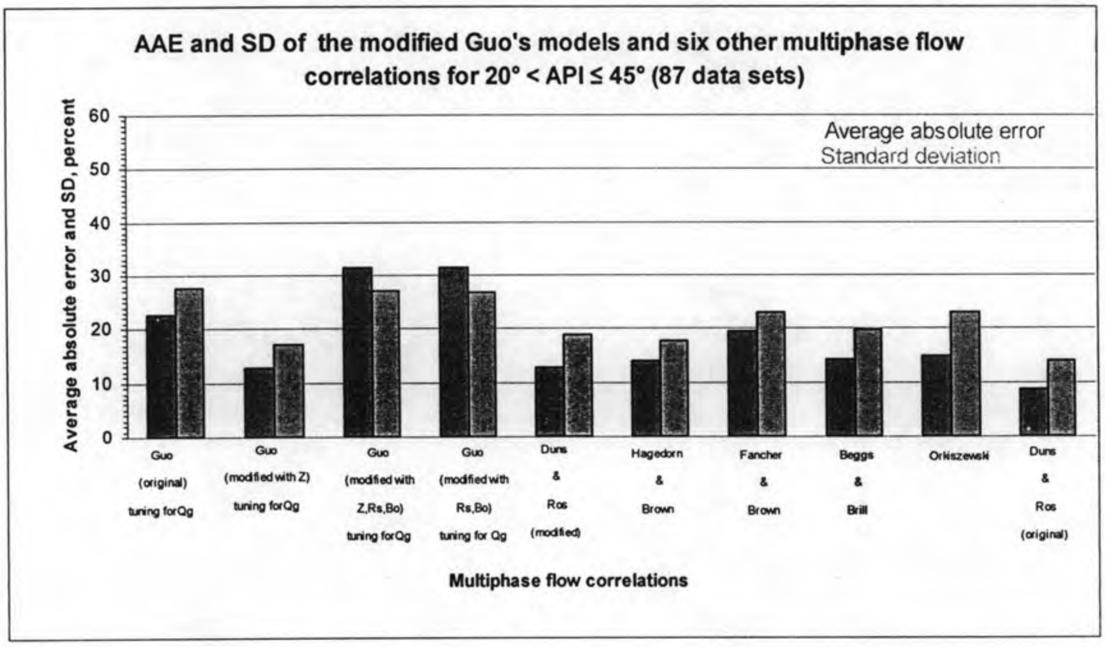


Figure 6.21: Comparison of the modified Guo's models and six other multiphase flow correlations for 20° < API ≤ 45° (87 data sets).

Table 6.29: Statistical parameters of the modified Guo's models and six other multiphase flow correlations for API > 45° (48 data sets).

Statistical parameter	G(O)Qg	G(Z)Qg	G(ZRB)Qg	G(RB)Qg	DR(M)	HB	FB	BB	OKZS	DR(O)
ARE	-0.1	7.3	-22.9	-22.4	1.6	5.1	5.7	-12.9	-7.4	9.3
AAE	15.3	13.2	32.1	32.4	12	13.4	14.2	21.9	20.1	13.6
SD	19.2	16.7	42.7	43.4	18.3	19.9	20.5	26.6	28.6	17.3

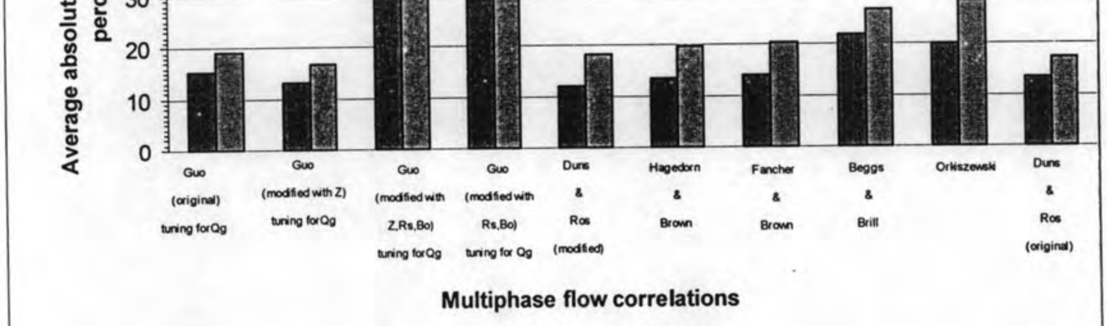


Figure 6.22: Comparison of the modified Guo's models and six other multiphase flow correlations for API > 45° (48 data sets).

Ranking of the modified Guo's models and six other multiphase flow correlations are shown in Table 6.30. In this table, Duns and Ros (original) is good for API gravity 20°-45° due to 0-10% of AEE range while Guo's model modified with the Z factor tuning for gas flow rate, Duns and Ros (modified) correlation, Hagedorn and Brown correlation, and Fancher and Brown correlation are fair for over 20° API gravity because of their 10-20% of AAE range. Besides, it can be seen that Guo's original model modified with the tuning factor for gas flow rate and Duns and Ros correlation are fair for over 45° API gravity because of their 10-20% AEE range. It can also be seen that Orkiszewski correlation and Beggs and Brill correlation fairly work for API gravity 20°-45° due to 10-20% of their AAE range.

Table 6.30: Ranking of the modified Guo's models and six other multiphase flow correlations for grouping of API gravity.

Models	API ≤ 20			20< API ≤ 45			API > 45		
	0-10%	**10-20%**	**> 20%**	**0-10%**	**10-20%**	**> 20%**	**0-10%**	**10-20%**	**> 20%**
G(O)Q_g			√			√		√	
G(Z)Q_g			√		√			√	
G(ZRB)Q_g			√			√			√
G(RB)Q_g			√			√			√
DR(M)			√		√			√	
HB			√		√			√	
FB			√		√			√	
BB			√		√				√
OKZS			√		√				√
DR(O)			√	√				√	

6.4.4 Comparison of statistical parameters and ranking for different groupings based on liquid flow rate

Statistical parameters of different liquid flow rate groups are expressed in Tables 6.31 through 6.33 and Figures 6.23 through 6.25. In this statistical analysis, Beggs and Brill correlation gives the best result for liquid flow rate less than or equal to 350 stb/d , Guo's model modified with the Z factor tuning for gas flow rate performs well in 350 to 5,000 stb/d liquid rate, and Duns and Ros (modified) correlation and Hagedorn and Brown correlation obtains the best result in liquid rate greater than 5,000 stb/d.

In the different liquid flow rate groups, we can say that Guo's model modified with the Z factor tuning for gas flow rate gives the best results over the other modified Guo's models for liquid flow rate greater than 350 stb/d. Guo's model (original) modified with the tuning factor for gas flow rate can be utilized for liquid rate greater than 5,000 stb/d. However, the other modified Guo's models have the high AAE values for all liquid flow rate groups.

Table 6.31: Statistical parameters of the modified Guo's models and six other multiphase flow correlations for $Q_L \leq$ 350 stb/d (44 data sets).

Statistical parameter	G(O)Qg	G(Z)Qg	G(ZRB)Qg	G(RB)Qg	DR(M)	HB	FB	BB	OKZS	DR(O)
ARE	-4.2	-1.4	1.2	2.2	28.4	29.7	46.9	3.1	16.3	11.7
AAE	32.3	30.7	28.5	28	31	31.6	47.7	16.7	22.1	16.3
SD	49	50.1	37.5	37.7	26.8	24.9	30.7	23.6	24.5	16.8

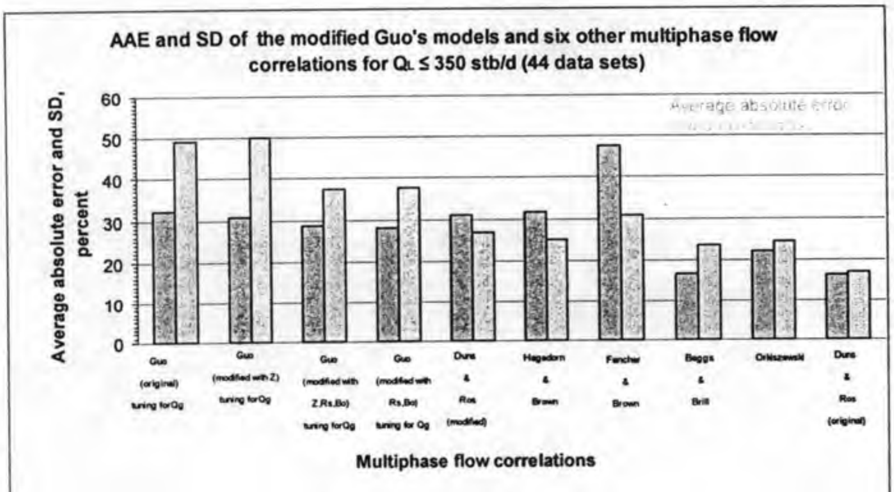


Figure 6.23: Comparison of the modified Guo's models and six other multiphase flow correlations for $Q_L \leq$ 350 stb/d (44 data sets).

Table 6.32: Statistical parameters of the modified Guo's models and six other multiphase flow correlations for 350 < $Q_L \leq$ 5,000 stb/d (64 data sets).

Statistical parameter	G(O)Qg	G(Z)Qg	G(ZRB)Qg	G(RB)Qg	DR(M)	HB	FB	BB	OKZS	DR(O)
ARE	-14.4	-4.2	-18.1	-18.4	-5.2	-4.8	17.8	-11.5	-1.8	-5.6
AAE	22.5	12.9	22.4	21.6	15.4	23.4	18.1	21	20.5	17
SD	24.8	17.9	30.4	29.2	21.1	32.6	15.9	26.9	29.8	23

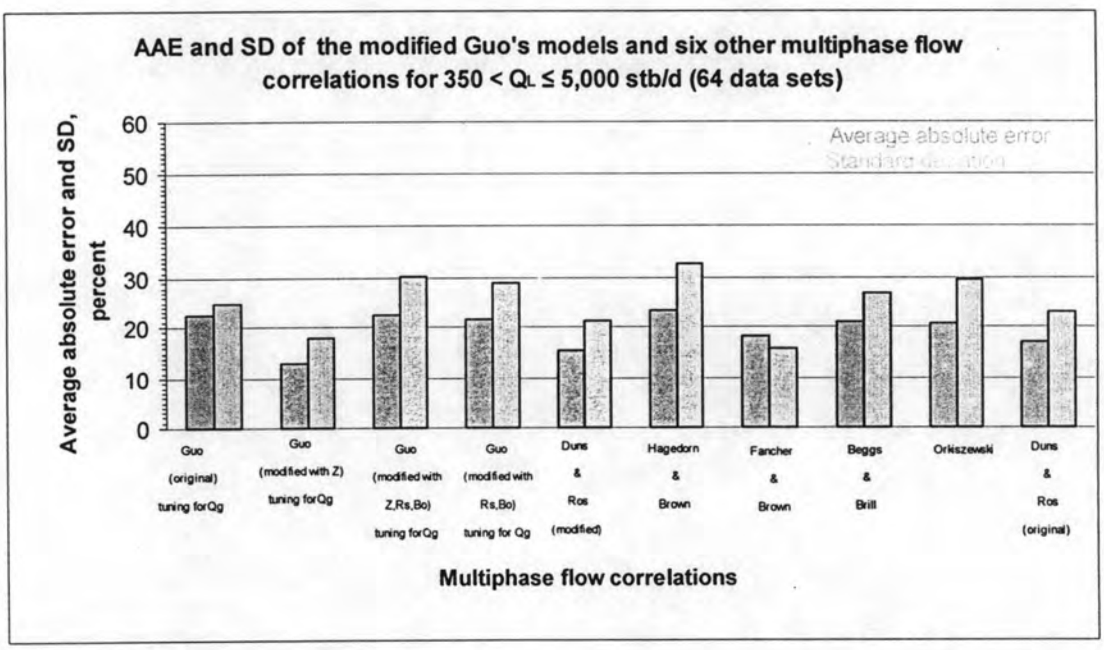


Figure 6.24: Comparison of the modified Guo's models and six other multiphase flow correlations for 350 < $Q_L \leq$ 5,000 stb/d (64 data sets).

Table 6.33: Statistical parameters of the modified Guo's models and six other multiphase flow correlations for $Q_L > 5{,}000$ stb/d (75 data sets).

Statistical parameter	G(O)Qg	G(Z)Qg	G(ZRB)Qg	G(RB)Qg	DR(M)	HB	FB	BB	OKZS	DR(O)
ARE	2.9	4	-29.3	-30.3	-4.1	-0.1	0.2	-14.1	-7.2	1.9
AAE	20.5	12.9	36.3	37.7	9.4	9.4	10.1	17.8	13.6	10.1
SD	24.4	16.8	31.9	32.6	14.7	14.7	15.6	21.9	20.2	16.8

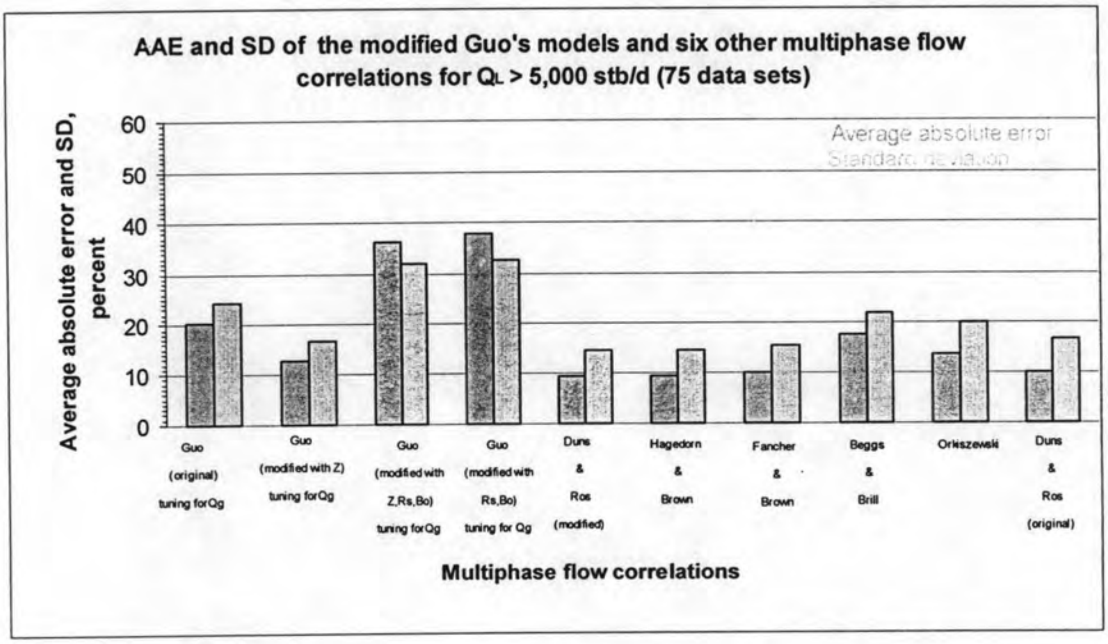


Figure 6.25: Comparison of the modified Guo's models and six other multiphase flow correlations for $Q_L > 5{,}000$ stb/d (75 data sets).

In Table 6.34, Duns and Ros (modified) correlation and Hagedorn and Brown correlation are good for above 5,000 stb/d of liquid flow rate because of their 0-10% AAE range. Besides, Duns and Ros (original) correlation fairly works for any liquid flow rate while Guo's model modified with the Z factor tuning for gas flow rate is fair for above 350 stb/d of liquid flow rate due to their 10-20% of AAE range. It can also be seen that, Beggs and Brill correlation fairly works for liquid flow rate less than or equal to 350 stb/d and greater than 5,000 stb/d due to 10-20% of its AAE range. Moreover, Fancher and Brown correlation is fair for liquid flow rate above 350stb/d while Duns and Ros (modified) correlation fairly works for liquid flow rate 350-5,000 stb/d and Orkiszewski correlation is fair for above 5,000 stb/d of liquid flow rate due to their 10-20% of AAE range.

Table 6.34: Ranking of the modified Guo's models and six other multiphase flow correlations for grouping of liquid flow rate.

Models	$Q_L \leq 350$ stb/d			$350 < Q_L \leq 5{,}000$ stb/d			$Q_L > 5{,}000$ stb/d		
	0-10%	**10-20%**	**> 20%**	**0-10%**	**10-20%**	**> 20%**	**0-10%**	**10-20%**	**> 20%**
G(O)Q_g			√			√			√
G(Z)Q_g			√		√			√	
G(ZRB)Q_g			√			√			√
G(RB)Q_g			√			√			√
DR(M)			√		√		√		
HB			√			√	√		
FB			√		√			√	
BB		√				√		√	
OKZS			√			√		√	
DR(O)		√			√			√	

6.4.5 Comparison of statistical parameters and ranking for different groupings based on gas flow rate

For the grouping based on gas flow rate, Beggs and Brill correlation obtains the best result for gas flow rate less than or equal to 1,000 Mscf/d group, the modified Guo's model with the Z factor tuning for gas flow rate performs the best in 1,000 to 5,000 Mscf/d gas rate group, and Duns and Ros (modified) correlation and Hagedorn and Brown correlation performs well in gas rate greater than 5,000 Mscf/d group. (Figures 6.26 through 6.28 and Tables 6.35 through 6.37)

For the different gas flow rate groups, it can be seen that Guo's model modified with the Z factor tuning for gas flow rate has the best results over the other modified Guo's models for gas flow rate greater than 1,000 Mscf/d. Guo's model (original) modified with the tuning factor for gas flow rate can be used for gas flow rate greater than 5,000 Mscf/d. However, the other modified Guo's models have the high AAE values for all gas flow rate groups.

Table 6.35: Statistical parameters of the modified Guo's models and six other multiphase flow correlations for Qg ≤ 1,000 Mscf/d (69 data sets).

Statistical parameter	G(O)Qg	G(Z)Qg	G(ZRB)Qg	G(RB)Qg	DR(M)	HB	FB	BB	OKZS	DR(O)
ARE	-4.2	-1.9	-6.8	-5.8	14.1	17.2	35.4	1	12.1	3.8
AAE	25.5	22.7	24.4	23.8	23.8	26.2	36	13.8	17.3	15.1
SD	40.1	40.4	31.9	32	29.3	28.9	29.4	19.4	20.7	19.4

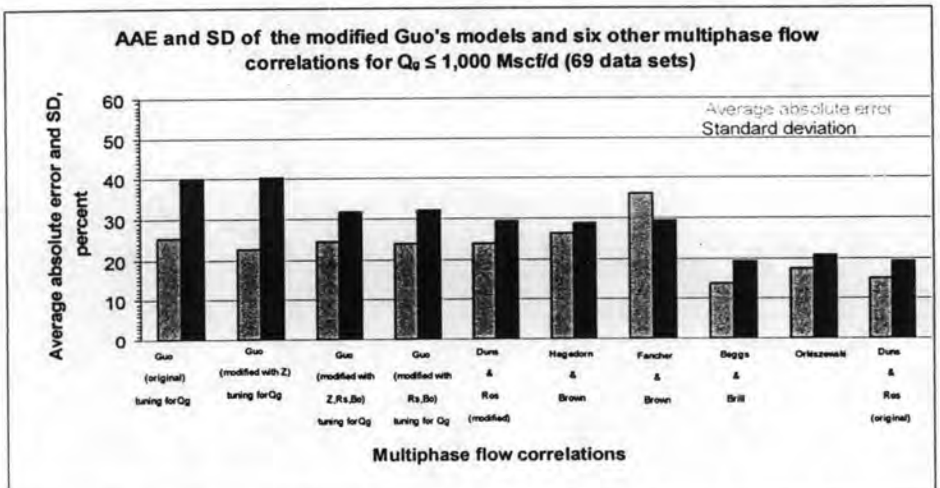


Figure 6.26: Comparison of the modified Guo's models and six other multiphase flow correlations for Qg ≤ 1,000 Mscf/d (69 data sets).

Table 6.36: Statistical parameters of the modified Guo's models and six other multiphase flow correlations for 1,000 < Qg ≤ 5,000 Mscf/d (58 data sets).

Statistical parameter	G(O)Qg	G(Z)Qg	G(ZRB)Qg	G(RB)Qg	DR(M)	HB	FB	BB	OKZS	DR(O)
ARE	-11.4	-2.3	-20	-21.1	-4.1	-3.3	13.6	-14.3	-2.8	-5
AAE	29.2	15.6	26.9	27.7	16.8	23.2	18.1	24.1	20.4	16.1
SD	32.7	21.3	26.4	26.1	23.2	33.2	21.0	29.7	28.2	23.3

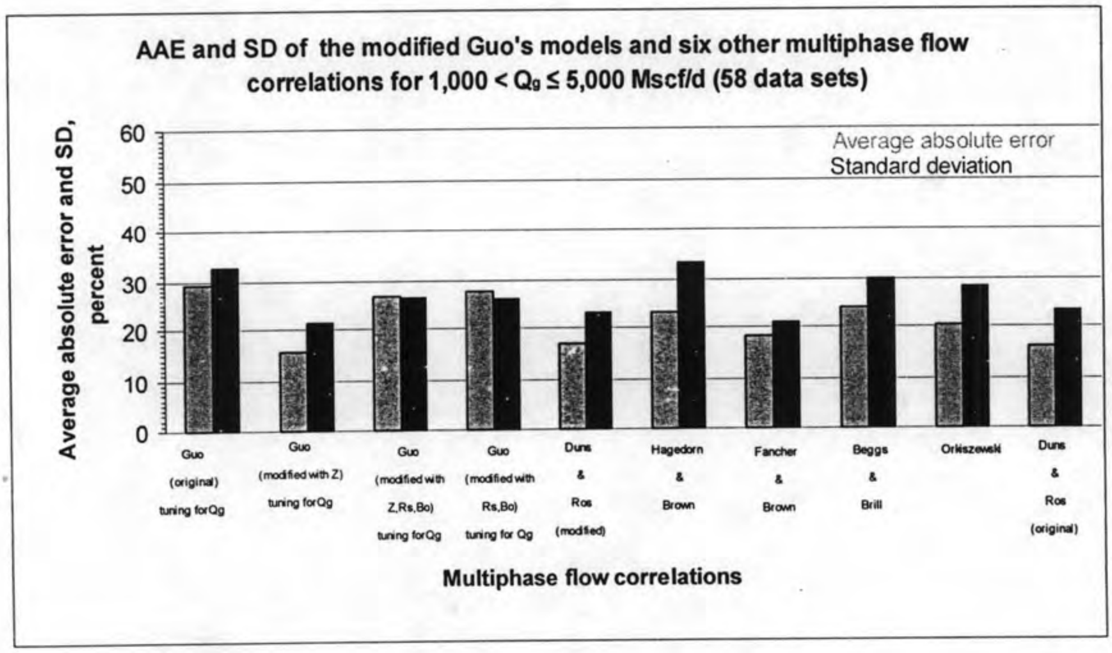


Figure 6.27: Comparison of the modified Guo's models and six other multiphase flow correlations for 1,000 < Q_g ≤ 5,000 Mscf/d (58 data sets).

Table 6.37: Statistical parameters of the modified Guo's models and six other multiphase flow correlations for Qg > 5,000 Mscf/d (56 data sets).

Statistical parameter	G(O)Qg	G(Z)Qg	G(ZRB)Qg	G(RB)Qg	DR(M)	HB	FB	BB	OKZS	DR(O)
ARE	1.1	4.2	-30.1	-30.8	-2.1	0	-0.3	-16.0	-11.0	5.8
AAE	16.9	12	38.6	39.3	7.8	7.8	8.6	18.9	16.5	10.4
SD	19.9	15.4	41.3	41.3	13.3	12.9	13.7	22.0	25.5	15.8

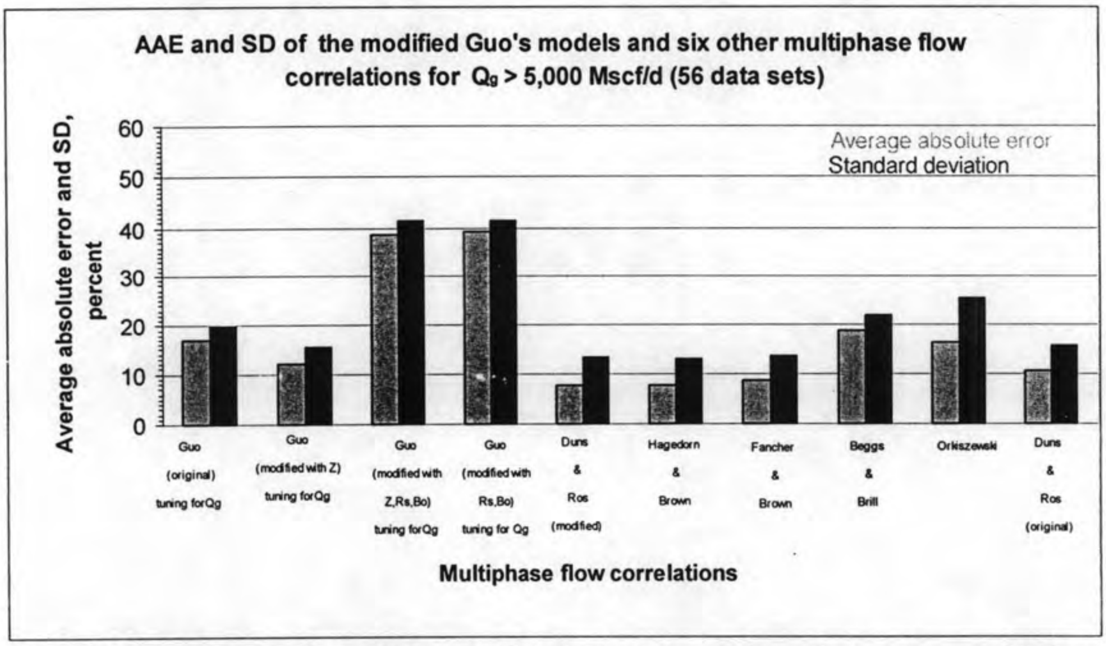


Figure 6.28: Comparison of the modified Guo's models and six other multiphase flow correlations for Qg > 5,000 Mscf/d (56 data sets).

Ranking of the modified Guo's models and six other multiphase flow correlations for grouping of gas flow rate are shown in Table 6.38. According to this table, we can see that Duns and Ros (modified) correlation, Hagedorn and Brown correlation, and Fancher and Brown correlation are good for above 5,000 Mscf/d of gas flow rate due to their 0-10% of AAE range. Duns and Ros (original) correlation fairly works for any gas flow rate while Beggs and Brill correlation and Orkiszewski correlation are fair for gas flow rate less than or equal to 1,000 Mscf/d and greater than 5,000 mscf/d because of their 10-20% of AAE range. Besides, Guo's model modified with the Z factor tuning for gas flow rate is fair for above 1,000 Mscf/d of gas flow rate while Duns and Ros (modified) correlation and Fancher and Brown correlation fairly work for 1,000-5,000 Mscf/d of gas flow rate and Guo's model (original) modified with tuning for gas flow rate is also fair for gas flow rate above 5,000 Mscf/d due to their 10-20 % of AAE range.

Table 6.38: Ranking of the modified Guo's models and six other multiphase flow correlations for grouping of gas flow rate.

Models	$Q_g \leq 1,000$ Mscf/d			$1,000 < Q_g \leq 5,000$ Mscf/d			$Q_g > 5,000$ Mscf/d		
	0-10%	**10-20%**	**> 20%**	**0-10%**	**10-20%**	**> 20%**	**0-10%**	**10-20%**	**> 20%**
$G(O)Q_g$			√			√		√	
$G(Z)Q_g$			√		√			√	
$G(ZRB)Q_g$			√			√			√
$G(RB)Q_g$			√			√			√
DR(M)			√		√		√		
HB			√			√	√		
FB			√		√		√		
BB		√				√		√	
OKZS		√				√		√	
DR(O)		√			√			√	

According to tables for ranking of Guo's modified models and six other multiphase flow correlations, we can analyze the AAE limit range of model or correlation for each different grouping. For each model or correlation, its AEE limit range can be expressed as follows:

Guo's model (original) tuning for gas flow rate can be used with fair accuracy for 2.441", 3.812", 3.826", 3.958", 4.494", and 4.892" tubing ID, over 45°API gravity, and over 5,000 Mscf/d gas flow rate due to 10-20% range of AAE range.

For Guo's model (modified with the Z factor) tuning for gas flow rate, it is good in 6.184" tubing due to 0-10% of AAE range and fair for any gas-liquid ratio (GLR), 2.441" through 4.892" tubing ID, over 20°API gravity, over 350 stb/d of liquid flow rate, and over 5,000 Mscf/d gas flow rate due to 10-20% range of AAE.

For Guo's model (modified with Z, R_s, and B_o) tuning for gas flow rate and Guo's model (modified with R_s, and B_o) tuning for gas flow rate, both models fairly works for 2.441" and 4.494", 4.892" tubing ID because of 10-20% of their AAE range.

Duns and Ros (modified) correlation is good for 3.812" through 6.184" tubing ID, and over 5,000 stb/d liquid flow rate because of 0-10% of AAE range. This correlation is fair for any gas-liquid ratio, 2.441" tubing ID , over 20°API gravity, 350-5,000 stb/d liquid flow rate, and over 1,000 Mscf/d gas flow rate due to 10-20% range of AAE.

For Hagedorn and Brown correlation, it is good in over 5,000 stb/d liquid flow rate group, over 5,000 Mscf/d gas flow rate group, 3.812", 3.826", 3.958" and 6.184" tubing ID groups due 0-10% of their AAE range. And, it is fair in GLR less than 1,000 scf/stb group, 4.494", 4.892" tubing ID group, and over 20°API gravity groups because of their 10-20% AAE range.

For Fancher and Brown correlation, , it is good for over 5,000 Mscf/d gas flow rate, 3.812", 3.826", 3.958", and 6.184" tubing ID due to 0-10% of their AAE range. This correlation is fair for 4.494", 4.892" tubing ID, over 350 stb/d liquid flow rate, 1,000-5,000 Mscf/d gas flow rate, and over 20°API gravity due to their 10-20% AAE range.

Beggs and Brill correlation is good for 6.184" tubing ID because of its 0-10% of AAE range, while it is fair for GLR less than 1,000 scf/stb, 1.995", 2.441", 4.494", and 4.892" tubing ID, 20-45°API gravity, liquid flow rate less than or equal to 350 stb/d and liquid flow rate greater than 5,000 stb/d, gas flow rate less than or equal to 1,000 Mscf/d and gas flow rate greater than 5,000 Mscf/d due to their 10-20% AAE range.

For Orkiszewski correlation, it is good for 6.184" tubing ID because of its 0-10% of AAE range and fairly works for 2.441", 3.812", 3.826", 3.958", 4.494", and 4.892" tubing ID, 20-45°API gravity, liquid flow rate greater than 5,000 stb/d, gas flow rate less than or equal to 1,000 Mscf/d and gas flow rate greater than 5,000 Mscf/d due to their 10-20% AAE range.

For Duns and Ros (original) correlation, it is good for 20-45°API gravity, 3.812", 3.826", 3.958", and 6.184" tubing ID because of their 0-10% of AAE range. This correlation is fair for 1.995", 2.441", 4.494", and 4.892" tubing ID, over 45°API gravity, all liquid flow rates and all gas flow rates due to their 10-20% AAE range.