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A Study on Gas Compressibility Factor for Gas-Condensate Systems

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Abstract

Gas compressibility factor is the most important gas property. Its value is required in many petroleum engineering calculations. There are many different sources of gas compressibility factor value such as experimental measurements, equations of state, charts, tables, intelligent approaches and empirical correlations methods. In absence of experimental measurements of gas compressibility factor values, it is necessary for the petroleum engineer to find an accurate, quick and reliable method for predicting these values. This study presents a new gas compressibility factor explicit empirical correlation for gas-condensate reservoir systems above dew point pressure. This new correlation is more robust, reliable and efficient than the previously published explicit empirical correlations. It is also in a simple mathematical form. The predicted value using this new correlation can be used as an initial value of implicit correlations to avoid huge number of iterations. This study also presents evaluation of the new and previously published explicit correlations.

Keywords

Natural Gas,; Compressibility Factor; Empirical Correlation; Validation.

Introduction

Naturally occurring gas has many properties such as compressibility factor, density, specific volume, specific gravity, isothermal compressibility coefficient, formation volume factor, expansion factor, and viscosity. They are required in petroleum engineering calculations such as calculations of gas reserves, gas flow through porous medium, gas pressure gradient in production system, gas metering and gas compression. Gas compressibility factor is the most important gas property as all other gas properties depend directly or indirectly on it. Accurate values of gas compressibility factor are obtained from experimental measurements. These experimental measurements are expensive, time consuming and may be unavailable. They are also not available for all reservoir conditions. It is necessary to find an accurate, quick and reliable method for predicting these values. So, numerical correlation concept is introduced in petroleum industry. Several empirical correlations have been developed to approximately predict accurate values of gas compressibility factor at any pressure and temperature conditions. The main objectives of this study are to summarize all available previously published gas compressibility factor empirical correlations, develop a new, simple and accurate gas compressibility factor explicit empirical correlation for any reservoir conditions and evaluate the new and other explicit correlations.

Gas compressibility factor which is also called gas deviation factor or simply gas Z-factor is the most important property of natural gas. It accounts for how much the real gas behavior deviates from the ideal gas behavior at given condition. According to real gas law, it is expressed as a function of pressure, volume, and temperature as follows:

$$Z = \frac{PV}{nRT} \qquad (1)$$

Since 1942, Standing and Katz [1] gas Z-factor chart has become a standard in petroleum industry which is used to estimate gas compressibility factor. It is based on the principle of corresponding states. This principle states that two substances at the same conditions referenced to critical pressure and critical temperature will have similar properties. According to the principle of corresponding states, gas compressibility factor is expressed as a function of reduced pressure and reduced temperature as follows:

$$Z = f(P_r\,, T_r) \qquad (2)$$

Where: $$P_r = \frac{P}{P_c} \qquad (3)$$

$$T_r = \frac{T}{T_c} \qquad (4)$$

For gas mixture, critical and reduced properties are replaced with pseudo-critical and pseudo-reduced properties. The accuracy of pseudo-critical properties calculation will affect the accuracy of gas Z-factor estimation.

Several methods for calculation of natural gas pseudo-critical pressure and temperature for gas-condensate reservoir systems have been developed.

These methods are divided into two categories. In this study, Sutton (1985) [2] modification to Stewart-Burkhardt-Voo [3] mixing rules (SSBV mixing rules), Corredor et al. (1992) [4] mixing rules, Piper et al. (1993) [5] mixing rules, Al-Sharkawy et al. (2000) [6] mixing rules and Al-Sharkawy (2004) [7] mixing parameters are used when natural gas composition is known while Sutton (1985) [2] empirical correlations, Piper et al. (1993) [5] mixing rules, El-Sharkawy-El-Kamel (2000) [8] empirical correlations and Sutton (2005) [9] empirical correlations used when natural gas composition is unknown. For some of these methods, the critical properties of all components of the gas are required. The critical properties of pure components are well known as given in **Table 1**. Gas-condensate gases contain hydrocarbon-plus fractions such as heptanes-plus (C_{7+}) fraction. So, the critical properties of the hydrocarbon-plus fractions must be estimated. Several correlations have been developed to estimate the critical properties of the hydrocarbon-plus fractions. Kesler and Lee (1976) [10] correlations, Whitson (1987) [11] correlation and Riazi and Daubert (1987) [12] correlations are used in this study. Gas-condensate gases also contain impurities such as hydrogen sulfide (H_2S), carbon dioxide (CO_2), nitrogen (N_2) and water vapor (H_2O) which affect the pseudo-critical pressure and temperature values. Several correlations have been developed to account for the presence of these impurities. Wichert and Aziz (1972) [13] correction method, Modified Wichert and Aziz [9] correction method, Standing (1981) [14] correction method and Casey [15] correction method are used in this study. The corrected pseudo-critical pressure and temperature are used to calculate the pseudo-reduced pressure and temperature which are the parameters of gas compressibility factor empirical correlations. All of the above mentioned methods are summarized in **Appendix A**.

Gas compressibility factor empirical correlations are divided into two categories: implicit and explicit empirical correlations. Implicit empirical correlations require iterative solution methods. The most used implicit empirical correlations are Hankinson Thomas and Phillips (1969) [16], Hall-Yarborough (1973) [17], Dranchuk-Purvis-Robinson (1974) [18], Dranchuk-Abu-Kassem (1975) [19] and Hall and Iglesias-Silva (2007) [20] correlations. But, explicit empirical correlations do not require iterative solution methods. They are used directly to calculate gas compressibility factor. The most used previously published explicit empirical correlations are Papay (1968) [21], Beggs and Brill (1973) [22], Gopal (1977) [23], Burnett (1979) [24], Kumar (2004) [25], Bahadori et al. (2007) [26], Al-Anazi and Al-Quraishi (2010) [27], Azizi et al. (2010) [28], Heidaryan-Salarabadi-Moghadasi (2010) [29], Heidaryan-Moghadasi-Rahimi (2010) [30], Shokir et al. (2012) [31], Sanjari and Nemati Lay (2012) [32], M.A. Mahmoud (2013) [33] and Niger Delta (2013) [34] correlations. These explicit empirical correlations are summarized in **Appendix B**.

Data Acquisition

Huge data points were collected to achieve the main objectives of this study. They were divided into two sets according to the source of data points: general data set and specific data set. General data set consists of five thousand, nine hundred and forty data points of gas Z-factor values as a function of pseudo-reduced pressure and temperature. They were the result of Standing and Katz chart digitization done by Poettmann and Carpenter. Statistical distributions such as maximum, minimum, mean, median and range of this data set are shown in Table 2. Specific data set consists of seven hundred and twenty one data points of gas Z-factor values as a function of pseudo-reduced pressure and temperature. These data points are measured at pressures above the dew point pressures of the gas-condensate reservoir systems. They were prepared from data collected from unpublished gas-condensate gas PVT reports. This collected data was reservoir pressure and temperature, mole fraction of gas chemical composition and gas specific gravity. The statistical distributions such as maximum, minimum, mean, median and range of this collected data are shown in Table 3.

Research Methodology

To achieve the objectives of this study, MATLAB Surface Fitting Tool (sftool) was used to develop a new explicit empirical correlation of gas compressibility factor. EXCEL sheets were used to validate the performance of this new correlation. EXCEL sheets were also used to evaluate and grade the performance of this new and other explicit correlations. These validation and evaluation were performed using statistical error analysis such as average absolute percent relative error (AARE%), residual sum of squares (RSS), root mean square error (RMSE), standard deviation (SD) and coefficient of determination (R2) and also with using graphical analysis such as cross plot parity line.

Results and Discussion

To develop the new explicit empirical correlation, 4000 data points from general data set are entered in MATLAB Surface Fitting Tool (sftool). Fig. 1 shows the surface plot of the new correlation which has the following form:

$$Z = -0.1284 + 0.3098\, T_{pr} + 0.1427\, P_{pr} + 0.3222\, T_{pr}^2 - 0.1571\, T_{pr}\, P_{pr} + 0.009456\, P_{pr}^2 - 0.0963\, T_{pr}^3 + 0.02993\, T_{pr}^2\, P_{pr} - 0.00002458\, T_{pr}\, P_{pr}^2 - 0.0002861\, P_{pr}^3 \quad (5)$$

This new empirical correlation is in a simple mathematical form. In which, the gas compressibility factor is a function of pseudo-reduced pressure and temperature. Figure 2 shows the training of this new empirical correlation using 4000 data points from general data set. The statistical parameters values of this training are: RSS = 0.6429, RMSE = 0.0127, AARE% = 0.904, SD = 1.1631 and R2 = 0.9964.

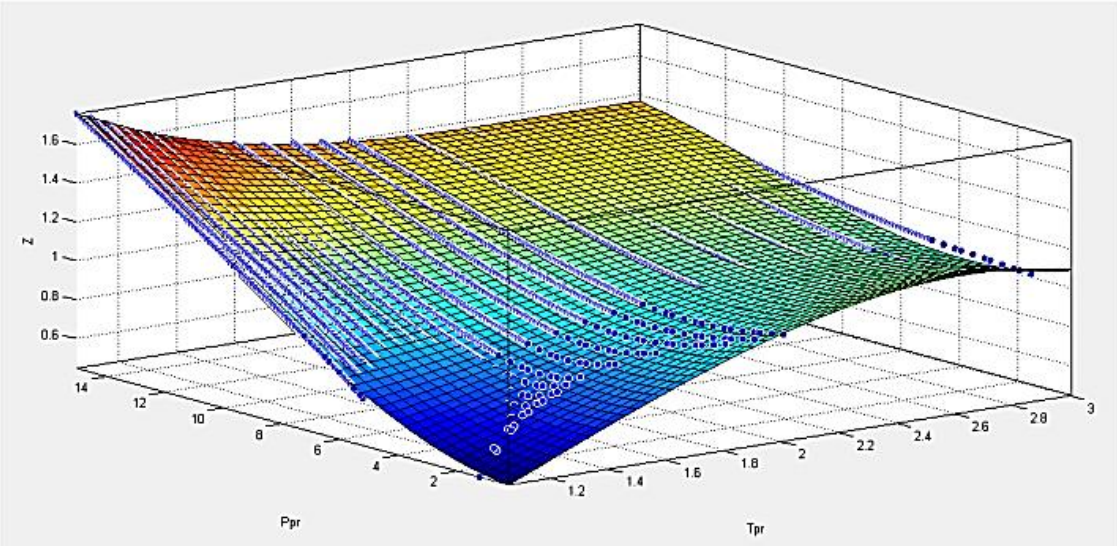

Figure 1 Surface plot of the new proposed Z-factor explicit empirical correlation.

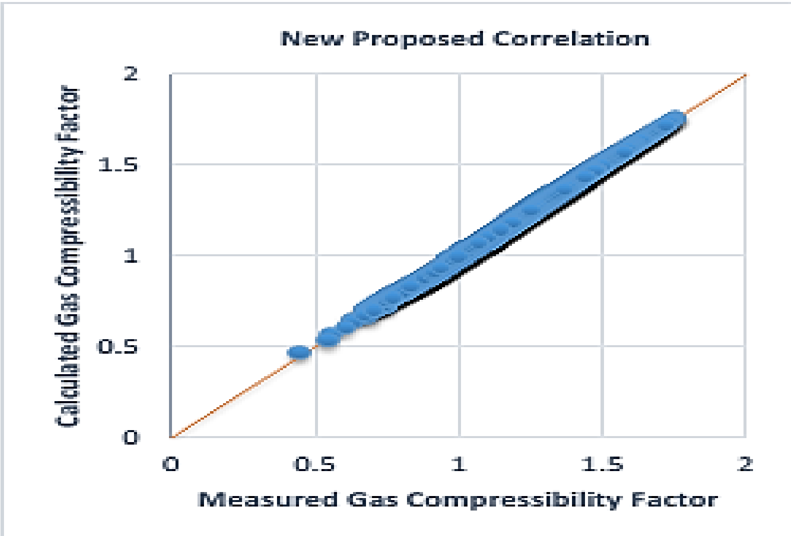

Figure 2 Accuracy of the new proposed Z-factor explicit empirical correlation for training.

Evaluation and Validation

The new and other explicit empirical correlations can be used to predict the Z-factor of gas-condensate gases depending on the choice of the correct gas pseudo-critical pressure and temperature calculation method. There are several methods to calculate gas pseudo-critical pressure and temperature and accessories methods to account for the presence of heptanes-plus fraction and impurities in gas-condensate gases as mentioned above in literature review section. From these methods, twelve methods are formed when gas composition is known and six methods are formed when gas composition is unknown. These methods are evaluated using 721 data points of specific data set. The statistical parameters values of this evaluation are shown in Appendix C from Table C-1 to Table C-18. As shown from these tables, six explicit empirical correlations have high coefficient of determination (R2) values. The cross plots of these correlations when using Sutton (1985), Standing, Wichert & Aziz and Casey method for Ppc and Tpc calculations are shown in Appendix C from Figure C-1 to Figure C-6.

Conclusions

The conclusions emanating from this study are as follows:

- A new explicit empirical correlation for Z-factor is obtained in simple mathematical form.
- The obtained correlation provides better predictions of gas Z-factor values than other explicit empirical correlations. As it gives the highest accuracy when using any method for calculating gas pseudo-critical pressure and temperature either when gas composition is known or unknown except for using El-Sharkawy empirical correlations for calculating gas pseudo-critical pressure and temperature when gas composition is unknown because of the accuracy of these correlations.
- The proposed correlation is recommended for the following pseudo-reduced pressure and temperature ranges for gas-condensate reservoir systems above dew point pressure:

$$1 < P_{pr} \leq 15$$
$$1.05 \leq T_{pr} \leq 3.0$$

- The predicted gas Z-factor value using the new correlation can be used, out of this new correlation recommended ranges, as an initial value of implicit correlations to avoid huge number of iterations.

Table 1 Physical properties of defined components.

Component	Molecular weight	Critical pressure, psia	Critical temperature, °R
H_2s	34.08	1306	1306
Co_2	44.01	1071	1071
N_2	28.0134	493	493
C_1	16.043	667.8	667.8
C_2	30.07	707.8	707.8
C_3	44.097	616.3	616.3
i-C_4	58.123	529.1	529.1
n-C_4	58.123	550.7	550.7
i-C_5	72.15	490.4	490.4
n-C_5	72.15	488.6	488.6
C_6	86.177	436.9	436.9

Table 2 Satistical distributions of general data set.

	Minimum	Maximum	Mean	Median	Range
T_{pr}	1.05	3	1.7375	1.55	1.95
P_{pr}	0.2	15	7.6	7.6	14.8
$Z-factor$	0.251	1.753	1.051966	1.0345	1.502

Table 3 Statistical distributions of specific data set.

	Minimum	Maximum	Mean	Median	Range
T_{res}, °F	147	309	269.27	281	162
P_{res}, psig	2728	9247	7037.85	7593	6519
H_2s	0	5.98	1.65	0.72	5.98
Co_2	0.12	3.93	2.42	2.36	3.81
N_2	0.17	18.29	8.42	9.32	18.12
C_1	65.07	91.7	72.00	69.26	26.63
C_2	3.37	10.5	6.63	5.91	7.13
C_3	1.3	4.97	2.80	2.47	3.67
i-C_4	0.3	0.95	0.55	0.51	0.65
n-C_4	0.31	1.87	1.04	0.95	1.56
i-C_5	0.16	0.77	0.40	0.40	0.61
n-C_5	0.09	0.78	0.41	0.36	0.69
C_6	0.15	1.25	0.55	0.51	1.10
C_{7+}	0.53	7.65	3.14	2.71	7.12
$M_{C_{7+}}$	122	171	146.46	144	49
$\gamma_{C_{7+}}$	0.73	0.81	0.79	0.79	0.08
γ_g	0.67	1.19	0.88	0.86	0.52

Nomenclature

AARE%	=	Average absolute percent relative error, %
E_J	=	Sutton SBV parameter, °R/psia
E_K	=	Sutton SBV parameter, °R/psia$^{0.5}$
J	=	SBV parameter, °R/psia
K	=	SBV parameter, °R/psia$^{0.5}$
M	=	Molecular weight, lb/lb-mole
M_{air}	=	Apparent molecular weight of the air which has the value 28.964 lb/lb-mole
M_{Co_2}	=	Molecular weight of Carbon Dioxide
$M_{C_{7+}}$	=	Molecular weight of heptanes-plus component
M_{H_2S}	=	Molecular weight of Hydrogen Sulfide
M_{N_2}	=	Molecular weight of Nitrogen
N	=	Number of moles of gas, lb-mole
P	=	Absolute pressure, psia
P_c	=	Critical pressure, psia
$P_{c\,Co_2}$	=	Critical pressure of Carbon Dioxide
$P_{c\,H_2S}$	=	Critical pressure of Hydrogen Sulfide
$P_{c\,N_2}$	=	Critical pressure of Nitrogen
P_{pc}	=	Pseudo-critical pressure, psia
$P_{pc\,HC}$	=	Pseudo-critical pressure of hydrocarbon portion
P_{pr}	=	Pseudo-reduced pressure, dimensionless
P_r	=	Reduced pressure, dimensionless
PVT	=	Pressure, volume and temperature
R	=	The universal gas constant which has the value 10.73 psia.ft^3/lb-mole/°R
R^2	=	Coefficient of determination, fraction
RMSE	=	Root mean square error, fraction
RSS	=	Residual sum of squares, fraction
SD	=	Standard deviation, %
T	=	Absolute temperature, °R
T_b	=	Boiling temperature, °R
T_c	=	Critical temperature, °R
$T_{c\,Co_2}$	=	Critical temperature of Carbon Dioxide
$T_{c\,H_2S}$	=	Critical temperature of Hydrogen Sulfide
$T_{c\,N_2}$	=	Critical temperature of Nitrogen
T_{pc}	=	Pseudo-critical temperature, °R
$T_{pc\,HC}$	=	Pseudo-critical temperature of hydrocarbon portion
T_{pr}	=	Pseudo-reduced temperature, dimensionless
T_r	=	Reduced temperature, dimensionless
V	=	Volume, ft^3
W_{HC}	=	Weight fraction of hydrocarbon portion
W_{NHC}	=	Weight fraction of non-hydrocarbon portion
y_{Co_2}	=	Mole fraction of Carbon Dioxide
$y_{C_{7+}}$	=	Mole fraction of heptanes-plus component
y_{HC}	=	Mole fraction of hydrocarbon portion
y_{H_2S}	=	Mole fraction of Hydrogen Sulfide
y_i	=	Mole fraction of component i in the gas mixture
y_{N_2}	=	Mole fraction of Nitrogen
Z	=	Gas deviation factor, dimensionless

Greek symbols

ϵ	=	Wichert and Aziz psudo-critical temperature adjustment parameter, °R
$\gamma_{C_{7+}}$	=	Specific gravity of heptanes-plus component
γ_g	=	Gas specific gravity, dimensionless
$\gamma_{g\,HC}$	=	Specific gravity of hydrocarbon portion

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Appendix A. Pseudo-critical pressure and temperature calculation methods

Sutton Modification to SBV Mixing Rules (SSBV Mixing Rules) (1985)

SBV Mixing rules

$$J = \left(\frac{1}{3}\right)[\textstyle\sum_{i=1}^{n} y_i \left(\frac{T_c}{P_c}\right)_i] + \left(\frac{2}{3}\right)[\textstyle\sum_{i=1}^{n} y_i \left(\sqrt{\frac{T_c}{P_c}}\right)_i]^2$$

$$K = \textstyle\sum_{i=1}^{n} y_i \left(\frac{T_c}{\sqrt{P_c}}\right)_i$$

Sutton Modification

$$F_J = \left(\frac{1}{3}\right)[y\left(\frac{T_c}{P_c}\right)]_{C_{7+}} + \left(\frac{2}{3}\right)[y\left(\sqrt{\frac{T_c}{P_c}}\right)]_{C_{7+}}^2$$

$$E_J = 0.6081\, F_J + 1.1325\, F_J^2 - 14.004\, F_J\, y_{C_{7+}} + 64.434\, F_J\, y_{C_{7+}}^2$$

$$E_K = \left(\sqrt{\frac{T_c}{P_c}}\right)_{C_{7+}} [0.3129\, y_{C_{7+}} - 4.8156\, y_{C_{7+}}^2\ 27.3751\, y_{C_{7+}}^3]$$

$$J' = J - E_J$$

$$K' = K - E_K$$

$$T_{pc} = {K'^2}/{J'}$$

$$P_{pc} = {T_{pc}}/{J'}$$

Corredor et al. Mixing Rules (1992)

$$J = \alpha_0 + \textstyle\sum_{i=1}^{3} \alpha_i\, y_i \left(\frac{T_c}{P_c}\right)_i + \alpha_4 \textstyle\sum_{j=1}^{6} y_j \left(\frac{T_c}{P_c}\right)_j + \alpha_5 [\textstyle\sum_{j=1}^{6} y_j \left(\frac{T_c}{P_c}\right)_j]^2 + \alpha_6 (y_{C_{7+}} M_{C_{7+}}) + \alpha_7 (y_{C_{7+}} M_{C_{7+}})^2$$

$$K = \beta_0 + \sum_{i=1}^{3} \beta_i\, y_i (\tfrac{T_c}{\sqrt{P_c}})_i + \beta_4 \sum_{j=1}^{6} y_j (\tfrac{T_c}{\sqrt{P_c}})_j +$$
$$\beta_5 \,[\sum_{j=1}^{6} y_j (\tfrac{T_c}{\sqrt{P_c}})_j]^{2} + \beta_6 (y_{C_{7+}} M_{C_{7+}}) + \beta_7 (y_{C_{7+}} M_{C_{7+}})^{2}$$

Where $y_i \in \{y_{H_2S}, y_{Co_2}, y_{N_2}\}$ and $y_j \in \{y_{C_1}, y_{C_2}, \dots, y_{C_6}\}$ respectively.

Piper et al. Mixing Rules (1993)

$$J = \alpha_0 + \sum_{i=1}^{3} \alpha_i\, y_i (\tfrac{T_c}{P_c})_i + \alpha_4 \sum_{j=1}^{6} y_j (\tfrac{T_c}{P_c})_j +$$
$$\alpha_5 \,[\sum_{j=1}^{6} y_j (\tfrac{T_c}{P_c})_j]^{2} + \alpha_6 (y_{C_{7+}} M_{C_{7+}}) + \alpha_7 (y_{C_{7+}} M_{C_{7+}})^{2}$$
$$K = \beta_0 + \sum_{i=1}^{3} \beta_i\, y_i (\tfrac{T_c}{\sqrt{P_c}})_i + \beta_4 \sum_{j=1}^{6} y_j (\tfrac{T_c}{\sqrt{P_c}})_j +$$
$$\beta_5 \,[\sum_{j=1}^{6} y_j (\tfrac{T_c}{\sqrt{P_c}})_j]^{2} + \beta_6 (y_{C_{7+}} M_{C_{7+}}) + \beta_7 (y_{C_{7+}} M_{C_{7+}})^{2}$$

Where $y_i \in \{y_{H_2S}, y_{Co_2}, y_{N_2}\}$ and $y_j \in \{y_{C_1}, y_{C_2}, \dots, y_{C_6}\}$ respectively.

Al-Sharkawy et al. Mixing Rules (2000)

$$J = \sum_{i=1}^{6} y_i (\tfrac{T_c}{P_c})_i + \{a_0 + [a_1 (y\, T_c/P_c)]_{C_{7+}} + [a_2 (y\, T_c/P_c)]_{N_2} +$$
$$[a_3 (y\, T_c/P_c)]_{Co_2} + [a_4 (y\, T_c/P_c)]_{H_2S}\}$$
$$K = \sum_{i=1}^{6} y_i (\tfrac{T_c}{\sqrt{P_c}})_i + \{b_0 + [b_1 (y\, T_c/\sqrt{P_c})]_{C_{7+}} +$$
$$[b_2 (y\, T_c/\sqrt{P_c})]_{N_2} + [b_3 (y\, T_c/\sqrt{P_c})]_{Co_2} + [b_4 (y\, T_c/\sqrt{P_c})]_{H_2S}\}$$

Al-Sharkawy Mixing Parameters (2004)

$$J_{inf} = \alpha_0 + \sum_{i=1}^{3} \alpha_i\, y_i (\tfrac{T_c}{P_c})_i + \alpha_4 \sum_{j=1}^{6} y_j (\tfrac{T_c}{P_c})_j +$$
$$\alpha_5 (y_{C_{7+}} M_{C_{7+}})$$
$$K_{inf} = \beta_0 + \sum_{i=1}^{3} \beta_i\, y_i (\tfrac{T_c}{\sqrt{P_c}})_i + \beta_4 \sum_{j=1}^{6} y_j (\tfrac{T_c}{\sqrt{P_c}})_j +$$
$$\beta_5 (y_{C_{7+}} M_{C_{7+}})$$

Where $y_i \in \{y_{H_2S}, y_{Co_2}, y_{N_2}\}$ and $y_j \in \{y_{C_1}, y_{C_2}, \dots, y_{C_6}\}$ respectively.

Sutton Correlations (1985)

$$T_{pc\,HC} = 169.2 + 349.5\,(\gamma_{g\,HC}) - 74\,(\gamma_{g\,HC})^{2}$$
$$P_{pc\,HC} = 756.8 - 131\,(\gamma_{g\,HC}) - 3.6\,(\gamma_{g\,HC})^{2}$$

Where: $y_{HC} = 1 - y_{H_2S} - y_{Co_2} - y_{N_2}$

$$\gamma_{g\,HC} = \frac{\gamma_g - (y_{H_2S} M_{H_2S} - y_{Co_2} M_{Co_2} - y_{N_2} M_{N_2})/M_{air}}{y_{HC}}$$

Piper et al. Mixing Rules (1993)

$$J = 0.11582 - 0.45820\, y_{H_2S} \frac{T_{c\,H_2S}}{P_{c\,H_2S}} - 0.90348\, y_{Co_2} \frac{T_{c\,Co_2}}{P_{c\,Co_2}} -$$
$$0.66026\, y_{N_2} \frac{T_{c\,N_2}}{P_{c\,N_2}} + 0.70729\,(\gamma_g) - 0.099397\,(\gamma_g)^{2}$$
$$K = 3.8216 - 0.06534\, y_{H_2S} \frac{T_{c\,H_2S}}{\sqrt{P_{c\,H_2S}}} - 0.42113\, y_{Co_2} \frac{T_{c\,Co_2}}{\sqrt{P_{c\,Co_2}}} -$$
$$0.91249\, y_{N_2} \frac{T_{c\,N_2}}{\sqrt{P_{c\,N_2}}} + 17.438\,(\gamma_g) - 3.2191 (\gamma_g)^{2}$$

El-Sharkawy-El-Kamel Correlations (2000)

$$T_{pc} = 195.958 + 206.121\,(\gamma_g) + 25.855\,(W_{HC}) -$$
$$6.421 (W_{NHC}) + 9.022\,(W_{HC})^{2} + 163.247\,(W_{NHC})^{2}$$
$$P_{pc} = 193.941 - 131.347\,(\gamma_g) + 217.144 (W_{HC}) +$$
$$1060.349 (W_{NHC}) + 344.573\,(W_{HC})^{2} - 60.591\,(W_{NHC})^{2}$$

Sutton Correlations (2005)

$$T_{pc\,HC} = 164.3 + 357.7\,(\gamma_{g\,HC}) - 67.7\,(\gamma_{g\,HC})^{2}$$
$$P_{pc\,HC} = 744 - 125.4\,(\gamma_{g\,HC}) + 5.9\,(\gamma_{g\,HC})^{2}$$

Kesler and Lee Correlations (1976)

$$T_c = 341.7 + 811\,(\gamma) + (0.4244 + 0.1174\,(\gamma))\, T_b +$$
$$(0.4669 - 3.2623\,(\gamma))\,(10^{5})/T_b$$
$$P_c = exp[8.3634 - 0.0566/\gamma - (0.24244 +$$
$$2.2898/\gamma + 0.11857/\gamma^{2})\,(10^{-3})\, T_b + (1.4685 +$$
$$3.648/\gamma + 0.47227/\gamma^{2})(10^{-7})\, T_b^{2} - (0.42019 +$$
$$1.6977/\gamma^{2})(10^{-10})\, T_b^{3}]$$

Whitson (1987)

$$T_b = (4.5579\,(M)^{0.15178}\,(\gamma)^{0.15427})^{3}$$

Riazi and Daubert Correlations (1987)

$$\theta = a\,(M)^{b}\,(\gamma)^{c}\, exp[d\,(M) + e\,(\gamma) + f\,(M)\,(\gamma)]$$

Wichert and Aziz Correction Method (1972)

$$\epsilon = 120\,(A^{0.9} - A^{1.6}) + 1.5\,(B^{0.5} - B^{4})$$
$$T'_{pc} = T_{pc} - \epsilon$$
$$P'_{pc} = \frac{P_{pc} T'_{pc}}{[T_{pc} + B(1-B)\epsilon]}$$
$$A = y_{H_2S} + y_{Co_2}$$
$$B = y_{H_2S}$$

Modified Wichert and Aziz Correction Method

$$\epsilon = 107.6\,(A - A^{2.2}) + 5.9\,(B^{0.06} - B^{0.68})$$

Standing Correction Method

$$T_{pc} = y_{HC} T_{pc\,HC} + y_{H_2S} T_{c\,H_2S} + y_{Co_2} T_{c\,Co_2} + y_{N_2} T_{c\,N_2}$$
$$P_{pc} = y_{HC} P_{pc\,HC} + y_{H_2S} P_{c\,H_2S} + y_{Co_2} P_{c\,Co_2} + y_{N_2} P_{c\,N_2}$$

Casey Correction Method

$$T''_{pc} = \frac{T'_{pc} - (227.2\, y_{N_2} + 1165\, y_{H_2O})}{1 - (y_{N_2} + y_{H_2O})} - (246.1\, y_{N_2} - 400\; y_{H_2O})$$
$$P''_{pc} = \frac{P'_{pc} - (493.1\, y_{N_2} + 3200\; y_{H_2O})}{1 - (y_{N_2} + y_{H_2O})} - (162\, y_{N_2} - 1270\; y_{H_2O})$$

The coefficients of corredor et al. mixing rules, Piper et al. mixing rules, Al-Sharkawy mixing rules, Al-Sharkawy mixing parameters and Riazi and Daubert correlations are shown in Table A-1 through Table A-5 respectively.

Papay Correlation (1968)

$$Z = 1 - \frac{3.53\, P_{pr}}{10^{0.9813\, T_{pr}}} + \frac{0.274\, P_{pr}^{2}}{10^{0.8157\, T_{pr}}}$$

Beggs and Brill Z-Factor Correlation (1973)

$$Z = A + \frac{1-A}{exp(B)} + C\, P_{pr}^{D}$$

Recommended range: $1.05 < T_{pr} < 2.0$

$P_{pr} < 15$

Where:

$$A = 1.39\,(T_{pr} - 0.92)^{0.5} - 0.36\, T_{pr} - 0.101$$
$$B = (0.62 - 0.23\, T_{pr}) P_{pr} + \left(\frac{0.066}{T_{pr} - 0.86} - 0.037\right) P_{pr}^{2} + \frac{0.32\, P_{pr}^{6}}{10^{(9T_{pr}-9)}}$$
$$C = 0.132 - 0.32\; log\, T_{pr}$$
$$D = 10^{(0.3106\, -\, 0.49\, T_{pr} + 0.1824\, T_{pr}^{2})}$$

Gopal Method (1977)

$$Z = P_{pr}\,(0.711 + 3.66\, T_{pr})^{-1.4667} - 1.6371\,(0.319\, T_{pr} + 0.522) + 2.071$$

Recommended range: $1.05 \le T_{pr} \le 3.0$

$5.4 \le P_{pr} \le 15$

Burnett Correlation (1979)

$$Z = 1 + (Z' - 1)\,(sin\, 90\, U)^{N}$$

Recommended range: $1.3 \le T_{pr} \le 1.85$

$P_{pr} \le P'_{pr}$

Where: $Z' = 0.3379\;\; ln(ln(T_{pr})) + 1.091$

$$P'_{pr} = 21.46\, Z' - 11.9\, z'^{\,2} - 5.9$$
$$U = P_{pr}/P'_{pr}$$
$$N = (1.1 + 0.26\, T_{pr} + (1.04 - 1.42\, T_{pr})\, U)(\frac{exp(U)}{T_{pr}})$$

Shell Oil Company (Kumar) Correlation (2004)

$$Z = A + B\, P_{pr} + (1 - A)\, exp(-C) - D\,(\frac{P_{pr}}{10})^{4}$$

Where: $A = -0.101 - 0.36\, T_{pr} + 1.3868\,\sqrt{T_{pr} - 0.919}$

$$B = 0.021 + \frac{0.04275}{T_{pr} - 0.65}$$
$$C = P_{pr}\,[E + F\, P_{pr} + G\, P_{pr}^{4}]$$
$$D = 0.122\; exp[-11.3\,(T_{pr} - 1)]$$
$$E = 0.6222 - 0.224\, T_{pr}$$

$$F = \frac{0.0657}{T_{pr} - 0.85} - 0.037$$

$$G = 0.32 \exp[-19.53\,(T_{pr} - 1)]$$

Bahadori et al. Correlation (2007)

$$Z = a + b\,P_{pr} + c\,P_{pr}^2 + d\,P_{pr}^3$$

Recommended range: $1.05 \le T_{pr} \le 2.4$

$0.2 \le P_{pr} \le 16$

Where: $a = A_a + B_a\,T_{pr} + C_a\,T_{pr}^2 + D_a\,T_{pr}^3$

$b = A_b + B_b\,T_{pr} + C_b\,T_{pr}^2 + D_b\,T_{pr}^3$

$c = A_c + B_c\,T_{pr} + C_c\,T_{pr}^2 + D_c\,T_{pr}^3$

$d = A_d + B_d\,T_{pr} + C_d\,T_{pr}^2 + D_d\,T_{pr}^3$

Al-Anazi and Al-Quraishi Correlation (2010)

$$Z = \frac{2\,E}{1.0482} + F$$

Where: $A = -0.06708\,P_{pr} + 0.2360$

$$B = \frac{(3\,A)^2 - 1.427}{T_{pr}} + 0.9178$$

$$C = B - (-2\,A)\,(B)$$

$$D = (-2\,A)\,(B)\,(C)$$

$$E = \frac{C + D}{1.0474\,T_{pr}} + 0.9178$$

$$F = \frac{D}{E^2} - E$$

Azizi et al. Correlation (2010)

$$Z = A + \frac{B + C}{D + E}$$

Recommended range: $1.1 \le T_{pr} \le 2.0$

$0.2 \le P_{pr} \le 11$

Where: $A = a\,T_{pr}^{2.16} + b\,P_{pr}^{1.028} + c\,P_{pr}^{1.58}\,T_{pr}^{-2.1} + d\,ln(T_{pr})^{-0.5}$

$$B = e + f\,T_{pr}^{2.4} + g\,P_{pr}^{1.56} + h\,P_{pr}^{0.124}\,T_{pr}^{3.033}$$

$$C = i\,ln(T_{pr})^{-1.28} + j\,ln(T_{pr})^{1.37} + k\,ln(P_{pr}) + l\,ln(P_{pr})^2 + m\,ln(P_{pr})\,ln(T_{pr})$$

$$D = 1 + n\,T_{pr}^{5.55} + o\,P_{pr}^{0.68}\,T_{pr}^{0.33}$$

$$E = p\,ln(T_{pr})^{1.18} + q\,ln(T_{pr})^{2.1} + r\,ln(P_{pr}) + s\,ln(P_{pr})^2 + t\,ln(P_{pr})\,ln(T_{pr})$$

Heidaryan-Salarabadi-Moghadasi Model (2010)

$$Z = \frac{A_1 + A_2\,ln(P_{pr}) + A_3\,[ln(P_{pr})]^2 + A_4\,[ln(P_{pr})]^3 + \frac{A_5}{T_{pr}} + \frac{A_6}{T_{pr}^2}}{1 + A_7\,ln(P_{pr}) + A_8\,[ln(P_{pr})]^2 + \frac{A_9}{T_{pr}} + \frac{A_{10}}{T_{pr}^2}}$$

Recommended range: $1.2 \le T_{pr} \le 3.0$

$0.2 \le P_{pr} \le 15$

Heidaryan-Moghadasi-Rahimi Model (2010)

$$Z = \ln\left(\frac{A_1 + A_3\,\ln(P_{pr}) + \frac{A_5}{T_{pr}} + A_7\,[\ln(P_{pr})]^2 + \frac{A_9}{T_{pr}^2} + \frac{A_{11}}{T_{pr}}\ln(P_{pr})}{1 + A_2\,\ln(P_{pr}) + \frac{A_4}{T_{pr}} + A_6\,[\ln(P_{pr})]^2 + \frac{A_8}{T_{pr}^2} + \frac{A_{10}}{T_{pr}}\ln(P_{pr})}\right)$$

Recommended range: $1.2 \le T_{pr} \le 3.0$

$0.2 \le P_{pr} \le 15$

For more accuracy, two sets of coefficients A_1 through A_{11} values were determined by minimizing the residual sum of squares of this proposed correlation.

Shokir et al. Correlation (2012)

$$Z = A + B + C + D + E$$

Where: $A = 2.679562\,\frac{(2\,T_{pr} - P_{pr} - 1)}{[\frac{(P_{pr}^2 + T_{pr}^3)}{P_{pr}}]}$

$$B = -7.686825\,[\frac{P_{pr}\,T_{pr} + P_{pr}^2}{T_{pr}\,P_{pr} + 2\,T_{pr}^2 + T_{pr}^3}]$$

$$C = -0.000624\,[T_{pr}^2\,P_{pr} - T_{pr}\,P_{pr}^2 + T_{pr}\,P_{pr}^3 + 2\,T_{pr}\,P_{pr} - 2\,P_{pr}^2 + 2\,P_{pr}^3]$$

$$D = 3.067747\,\frac{(T_{pr} - P_{pr})}{(P_{pr}^2 + T_{pr} + P_{pr})}$$

$$E = \frac{0.068059}{T_{pr}\,P_{pr}} + 0.139489\,T_{pr}^2 + 0.081873\,P_{pr}^2 - \frac{0.041098\,T_{pr}}{P_{pr}} + \frac{8.152325\,P_{pr}}{T_{pr}} - 1.63028\,P_{pr} + 0.24287\,T_{pr} - 2.64988$$

Sanjari and Nemati Lay Correlation (2012)

$$Z = 1 + A_1\,P_{pr} + A_2\,P_{pr}^2 + \frac{A_3\,P_{pr}^{A_4}}{T_{pr}^{A_5}} + \frac{A_6\,P_{pr}^{(A_4+1)}}{T_{pr}^{A_7}} + \frac{A_8\,P_{pr}^{(A_4+2)}}{T_{pr}^{(A_7+1)}}$$

Recommended range: $1.01 \le T_{pr} \le 3.0$

$0.01 \le P_{pr} \le 15$

M.A. Mahmoud Correlation (2013)

$$Z = 0.702\,exp(-2.5\,T_{pr})\,P_{pr}^2 - 5.524\,exp(-2.5\,T_{pr})\,P_{pr} + 0.044\,T_{pr}^2 - 0.164\,T_{pr} + 1.15$$

Niger Delta Correlation (2013)

$$Z = 6.41824 - 0.013363\,P_{pr} - 3.351293\,T_{pr}$$

The coefficients of Bahadori et al. correlation, Azizi et al. correlation, Heidaryan-Salarabadi-Moghadasi model, Heidaryan-Moghadasi-Rahimi model and Sanjari and Nemati Lay correlation are shown in Table B-1 through Table B-5 respectively.

Table A-1 Coefficients of Corredor et al. mixing rules

i	α_i	β_i
0	1.5303E-01	2.6662E+00
1	9.0991E-01	9.7778E-01
2	9.5869E-01	9.7607E-01
3	6.6612E-01	7.4161E-01
4	4.7920E-01	5.2672E-01
5	3.4198E-01	1.6886E-02
6	2.0370E-02	4.5333E-01
7	- 8.4700E-05	- 3.1884E-03

Table A-2 Coefficients of Piper et al. mixing rules

i	α_i	β_i
0	5.2073E-02	- 3.9741E-01
1	1.0160E+00	1.0503E+00
2	8.6961E-01	9.6592E-01
3	7.2646E-01	7.8569E-01
4	8.5101E-01	9.8211E-01
5	0.0	0.0
6	2.0818E-02	4.5536E-01
7	- 1.5060E-04	- 3.7684E-03

Table A-3 Coefficients of Al-Sharkawy et al. mixing rules

i	a_i	b_i
0	- 0.040279933	- 0.776423332
1	0.881709332	1.030721752
2	0.800591625	0.734009058
3	1.037850321	0.909963446
4	1.059063178	0.888959152

Table A-4 Coefficients of Al-Sharkawy et al. mixing parameters.

i	α_i	β_i
0	0.036983	- 0.7765003
1	1.043902	1.0695317
2	0.894942	0.9850308
3	0.792231	0.8617653
4	0.882295	1.0127054
5	0.018637	0.4014645

Table A-5 Coefficients of Riazi and Daubert correlations.

θ	a	b	c	d	e	f
T_c, °R	544.4	0.2998	1.0555	$-1.3478*10^{-4}$	-0.61641	0.0
P_c, psia	$4.5203*10^{4}$	-0.8063	1.6015	$-1.8078*10^{-3}$	-0.3084	0.0
T_b, °R	6.77857	0.401673	-1.58262	$3.77409*10^{-3}$	2.984036	$-4.25288*10^{-3}$

Table B-1 Coefficients of Bahadori et al. empirical correlation.

i	A_i	B_i	C_i	D_i
a	0.9694690	- 1.3492380	1.4439590	- 0.3686000
b	- 0.1077830	- 0.1270130	0.1008280	- 0.0123190
c	0.0184810	0.0523405	- 0.0506880	0.0108700
d	- 0.0005840	- 0.0021460	0.0020961	- 0.0004590

Table B-2 Coefficients of Azizi et al. empirical correlation.

a	0.0373142485385592	k	- 24449114791.1531
b	- 0.0140807151485369	l	19357955749.3274
c	0.0163263245387186	m	- 126354717916.607
d	0.0307776478819813	n	623705678.385784
e	13843575480.943800	o	17997651104.3330
f	- 16799138540.763700	p	151211393445.064
g	1624178942.6497600	q	139474437997.172
h	13702270281.086900	r	- 24233012984.0950
i	- 41645509.896474600	s	18938047327.5205
j	237249967625.01300	t	- 141401620722.689

Table B-3 Coefficients of Heidaryan-Salarabadi-Moghadasi model.

A_1	1.11532372699824	A_6	1.15753118672070
A_2	- 0.07903952088760	A_7	- 0.05367780720737
A_3	0.01588138045027	A_8	0.01465569989618
A_4	0.00886134496010	A_9	- 1.80997374923296
A_5	- 2.16190792611599	A_{10}	0.95486038773032

Table B-4 Coefficients of Heidaryan-Moghadasi-Rahimi model.

Coefficient	$0.2 \leq P_{pr} \leq 3$	$3 < P_{pr} \leq 15$
A_1	$2.827793*10^{+00}$	$3.252838*10^{+00}$
A_2	$-4.688191*10^{-01}$	$-1.306424*10^{-01}$
A_3	$-1.262288*10^{+00}$	$-6.449194*10^{-01}$
A_4	$-1.536524*10^{+00}$	$-1.518028*10^{+00}$
A_5	$-4.535045*10^{+00}$	$-5.391019*10^{+00}$
A_6	$6.895104*10^{-02}$	$-1.379588*10^{-02}$
A_7	$1.903869*10^{-01}$	$6.600633*10^{-02}$
A_8	$6.200089*10^{-01}$	$6.120783*10^{-01}$
A_9	$1.838479*10^{+00}$	$2.317431*10^{+00}$
A_{10}	$4.052367*10^{-01}$	$1.632223*10^{-01}$
A_{11}	$1.073574*10^{+00}$	$5.660595*10^{-01}$

Table B-5 Coefficients of Sanjari and Nemati lay empirical correlation.

Coefficient	$0.01 \leq P_{pr} \leq 3.0$	$3.0 \leq P_{pr} \leq 15$
A_1	0.007698	0.015642
A_2	0.003839	0.000701
A_3	- 0.467212	2.341511
A_4	1.018801	- 0.657903
A_5	3.805723	8.902112
A_6	- 0.087361	- 1.136000
A_7	7.138305	3.543614
A_8	0.083440	0.134041

Table C-1 statistical parameters values for explict emperical correlations when using SSBV, Whitson,Kesler&Lee, Wichert&Aziz and Caseymethod for ppe and tpe.

Explicit empirical correlation	Year	RSS	RMSE	AARE %	SD	R^2
New proposed correlation	2018	0.5361	0.0273	1.6484	2.2817	0.9578
Heidaryan-Moghadasi-Rahimi	2010	0.6003	0.0289	1.6938	2.3927	0.9527
Shell Oil Company	2004	0.6080	0.0290	1.7682	2.4726	0.9521
Heidaryan-Salarabadi-Moghadasi	2010	0.7628	0.0325	2.1425	2.8275	0.9399
Beggs and Brill	1973	0.7775	0.0330	2.2082	2.7293	0.9355
Sanjari and Nemati Lay	2012	1.2079	0.0409	2.4920	3.2455	0.9048
Shokir et al.	2012	9.9010	0.1172	7.2638	9.4227	0.2197
Azizi et al.	2010	55.990	0.2787	23.096	23.516	_
M.A. Mahmoud	2013	61.823	0.2928	12.466	21.314	_
Papay	1968	92.456	0.3581	20.715	27.334	_
Gopal	1977	103.38	0.3787	28.380	33.101	_
Bahadori et al.	2007	866.48	1.0963	91.578	92.410	_
Niger Delta	2013	972.80	1.1616	84.401	100.75	_
Al-Anazi and Al-Quraishi	2010	$6.0*10^8$	$9.1*10^2$	$5.2*10^3$	$7.0*10^4$	_
Burnett	1979	_	_	_	_	_

Table C-2 statistical parameters values for explict emperical correlations when using SSBV, Whitson,Kesler&Lee, modified Wichert&Aziz and Caseymethod for ppe and tpe.

Explicit empirical correlation	Year	RSS	RMSE	AARE %	SD	R^2
New proposed correlation	2018	0.5418	0.0274	1.6735	2.2880	0.9573
Heidaryan-Moghadasi-Rahimi	2010	0.6060	0.0289	1.6847	2.3939	0.9522
Shell Oil Company	2004	0.6073	0.0290	1.7650	2.4597	0.9521
Heidaryan-Salarabadi-Moghadasi	2010	0.7539	0.0323	2.1254	2.7986	0.9406
Beggs and Brill	1973	0.7925	0.0334	2.2378	2.7532	0.9342
Sanjari and Nemati Lay	2012	1.2218	0.0412	2.4845	3.2504	0.9037
Shokir et al.	2012	9.6890	0.1159	7.2097	9.3335	0.2364
Azizi et al.	2010	56.125	0.2790	23.125	23.547	_
M.A. Mahmoud	2013	61.822	0.2928	12.479	21.311	_
Papay	1968	92.005	0.3572	20.653	27.269	_
Gopal	1977	102.62	0.3773	28.287	32.977	_
Bahadori et al.	2007	863.70	1.0945	91.414	92.253	_
Niger Delta	2013	960.09	1.1540	83.960	100.09	_
Al-Anazi and Al-Quraishi	2010	$2.2*10^7$	$1.7*10^2$	$1.6*10^3$	$1.4*10^4$	_
Burnett	1979	_	_	_	_	_

Table C-3 statistical parameters values for explict emperical correlations when using SSBV, Riazi &Daubert, Wichert&Aziz and Casey method for ppe and tpe.

Explicit empirical correlation	Year	RSS	RMSE	AARE %	SD	R^2
New proposed correlation	2018	0.5404	0.0274	1.6537	2.2933	0.9574
Heidaryan-Moghadasi-Rahimi	2010	0.5883	0.0286	1.6577	2.3760	0.9536
Shell Oil Company	2004	0.5998	0.0288	1.7381	2.4666	0.9527
Beggs and Brill	1973	0.7341	0.0321	2.1271	2.6586	0.9391
Heidaryan-Salarabadi-Moghadasi	2010	0.7849	0.0330	2.2033	2.8739	0.9381
Sanjari and Nemati Lay	2012	1.1962	0.0407	2.4386	3.2228	0.9057
Shokir et al.	2012	10.098	0.1183	7.3428	9.5204	0.2042
Azizi et al.	2010	55.597	0.2777	23.017	23.439	_
M.A. Mahmoud	2013	64.298	0.2986	12.685	21.736	_
Papay	1968	95.868	0.3646	21.057	27.823	_
Gopal	1977	103.36	0.3786	28.367	33.100	_
Bahadori et al.	2007	874.17	1.1011	91.951	92.799	_
Niger Delta	2013	978.11	1.1647	84.695	101.02	_
Al-Anazi and Al-Quraishi	2010	$9.2*10^{10}$	$1.1*10^4$	$3.3*10^4$	$8.2*10^5$	_
Burnett	1979	_	_	_	_	_

Table C-4 statistical parameters values for explict emperical correlations when using SSBV, Riazi &Daubert, Modified Wichert&Aziz and Casey method for ppe and tpe.

Explicit empirical correlation	Year	RSS	RMSE	AARE %	SD	R^2
New proposed correlation	2018	0.5447	0.0275	1.6824	2.2965	0.9571
Heidaryan-Moghadasi-Rahimi	2010	0.5927	0.0287	1.6517	2.3745	0.9533
Shell Oil Company	2004	0.5976	0.0288	1.7410	2.4508	0.9529
Heidaryan-Salarabadi-Moghadasi	2010	0.7749	0.0328	2.1851	2.8435	0.9389
Beggs and Brill	1973	0.7480	0.0324	2.1524	2.6808	0.9379
Sanjari and Nemati Lay	2012	1.2097	0.0410	2.4287	3.2268	0.9047
Shokir et al.	2012	9.8844	0.1171	7.2889	9.4316	0.2210
Azizi et al.	2010	55.732	0.2780	23.046	23.470	_
M.A. Mahmoud	2013	64.304	0.2986	12.698	21.735	_
Papay	1968	95.408	0.3638	20.994	27.758	_
Gopal	1977	102.60	0.3772	28.274	32.976	_
Bahadori et al.	2007	871.37	1.0993	91.785	92.642	_
Niger Delta	2013	965.35	1.1571	84.251	100.36	_
Al-Anazi and Al-Quraishi	2010	$8.6*10^9$	$3.4*10^3$	$1.6*10^4$	$2.7*10^5$	_
Burnett	1979	_	_	_	_	_

Table C-5 statistical parameters values for explict emperical correlations when using SSBV, Riazi &Daubert, Lee, Wichert&Aziz and Casey method for ppe and tpe.

Explicit empirical correlation	Year	RSS	RMSE	AARE %	SD	R^2
New proposed correlation	2018	0.5356	0.0273	1.6464	2.2799	0.9578
Heidaryan-Moghadasi-Rahimi	2010	0.6068	0.0290	1.7104	2.4032	0.9522
Shell Oil Company	2004	0.6158	0.0292	1.7856	2.4845	0.9515
Heidaryan-Salarabadi-Moghadasi	2010	0.7575	0.0324	2.1243	2.8163	0.9403
Beggs and Brill	1973	0.7952	0.0334	2.2389	2.7569	0.9340
Sanjari and Nemati Lay	2012	1.1965	0.0407	2.5099	3.2402	0.9057
Shokir et al.	2012	9.7668	0.1164	7.2141	9.3599	0.2303
Azizi et al.	2010	56.206	0.2792	23.139	23.556	_
M.A. Mahmoud	2013	59.901	0.2882	12.299	20.985	_
Papay	1968	90.502	0.3543	20.531	27.055	_
Gopal	1977	103.82	0.3795	28.464	33.168	_
Bahadori et al.	2007	863.64	1.0945	91.449	92.271	_
Niger Delta	2013	976.26	1.1636	84.603	100.93	_
Al-Anazi and Al-Quraishi	2010	$3.6*10^8$	$7.1*10^2$	$3.4*10^3$	$5.5*10^4$	_
Burnett	1979	_	_	_	_	_

Table C-6 statistical parameters values for explict emperical correlations when using SSBV, Riazi &Daubert, Kesler & Lee, Modified Wichert&Aziz and Casey method for ppe and tpe.

Explicit empirical correlation	Year	RSS	RMSE	AARE %	SD	R^2
New proposed correlation	2018	0.5416	0.0274	1.6731	2.2869	0.9573
Heidaryan-Moghadasi-Rahimi	2010	0.6129	0.0291	1.7006	2.4051	0.9517
Shell Oil Company	2004	0.6155	0.0292	1.7803	2.4723	0.9515
Heidaryan-Salarabadi-Moghadasi	2010	0.7490	0.0322	2.1080	2.7879	0.9410
Beggs and Brill	1973	0.8105	0.0337	2.2698	2.7809	0.9327
Sanjari and Nemati Lay	2012	1.2100	0.0410	2.5031	3.2448	0.9046
Shokir et al.	2012	9.5539	0.1151	7.1601	9.2699	0.2471
Azizi et al.	2010	56.341	0.2795	23.168	23.587	_
M.A. Mahmoud	2013	59.900	0.2882	12.312	20.983	_
Papay	1968	90.059	0.3534	20.469	26.991	_
Gopal	1977	103.06	0.3781	28.371	33.044	_
Bahadori et al.	2007	860.85	1.0927	91.284	92.114	_
Niger Delta	2013	963.53	1.1560	84.159	100.27	_
Al-Anazi and Al-Quraishi	2010	$1.0*10^7$	$1.2*10^2$	$1.2*10^3$	$9.3*10^3$	_
Burnett	1979	_	_	_	_	_

Table C-7 statistical parameters values for explict emperical correlations when using SSBV, Riazi &Daubert, Kesler & Lee, Corredor et al. mixing rules for ppe and tpe.

Explicit empirical correlation	Year	RSS	RMSE	AARE %	SD	R^2
New proposed correlation	2018	0.5583	0.0278	1.7145	2.3462	0.9560
Heidaryan-Moghadasi-Rahimi	2010	0.6206	0.0293	1.8531	2.5181	0.9511
Shell Oil Company	2004	0.6550	0.0301	1.9205	2.6077	0.9484
Beggs and Brill	1973	0.6552	0.0303	1.9139	2.4991	0.9456
Heidaryan-Salarabadi-Moghadasi	2010	0.9267	0.0359	2.5484	3.2118	0.9270
Sanjari and Nemati Lay	2012	1.0813	0.0387	2.4411	3.2006	0.9148
Shokir et al.	2012	10.693	0.1218	7.4613	9.7395	0.1573
Azizi et al.	2010	55.074	0.2764	22.912	23.312	_
M.A. Mahmoud	2013	59.240	0.2866	12.214	20.925	_
Papay	1968	94.110	0.3613	21.386	27.713	_
Gopal	1977	107.85	0.3868	29.322	33.856	_
Bahadori et al.	2007	892.23	1.1124	93.033	93.837	_
Niger Delta	2013	1045.2	1.2040	88.044	104.25	_
Al-Anazi and Al-Quraishi	2010	$1.5*10^{13}$	$1.5*10^5$	$4.6*10^5$	$1.1*10^7$	_
Burnett	1979	_	_	_	_	_

Table C-8 statistical parameters values for explict emperical correlations when using piper et al. mixing rules for ppe and tpe.

Explicit empirical correlation	Year	RSS	RMSE	AARE %	SD	R^2
New proposed correlation	2018	0.5772	0.0283	1.7721	2.3847	0.9545
Heidaryan-Moghadasi-Rahimi	2010	0.6448	0.0299	1.9131	2.5671	0.9492
Shell Oil Company	2004	0.6698	0.0305	1.9620	2.6276	0.9472
Beggs and Brill	1973	0.6764	0.0308	1.9480	2.5360	0.9439
Heidaryan-Salarabadi-Moghadasi	2010	0.9489	0.0363	2.5803	3.2522	0.9252
Sanjari and Nemati Lay	2012	1.0750	0.0386	2.4648	3.2084	0.9153
Shokir et al.	2012	10.587	0.1212	7.4673	9.7043	0.1657
Azizi et al.	2010	55.111	0.2765	22.921	23.318	_
M.A. Mahmoud	2013	58.121	0.2839	12.223	20.775	_
Papay	1968	93.360	0.3598	21.464	27.661	_
Gopal	1977	106.13	0.3837	29.072	33.589	_
Bahadori et al.	2007	891.60	1.1120	93.027	93.829	_
Niger Delta	2013	1024.4	1.1920	87.102	103.19	_
Al-Anazi and Al-Quraishi	2010	$7.0*10^{11}$	$9.9*10^{3}$	$3.3*10^{4}$	$7.6*10^{5}$	_
Burnett	1979	_	_	_	_	_

Table C-9 statistical parameters values for explict emperical correlations when using Al-Sharkawy et al., Whitson and Kesler & Leemethod for ppe and tpe.

Explicit empirical correlation	Year	RSS	RMSE	AARE %	SD	R^2
New proposed correlation	2018	0.5781	0.0283	1.7583	2.3845	0.9544
Heidaryan-Moghadasi-Rahimi	2010	0.6417	0.0298	1.8426	2.5561	0.9494
Shell Oil Company	2004	0.6792	0.0307	1.9395	2.6953	0.9465
Beggs and Brill	1973	0.6599	0.0304	1.9271	2.5208	0.9452
Heidaryan-Salarabadi-Moghadasi	2010	0.9426	0.0362	2.5646	3.2319	0.9257
Sanjari and Nemati Lay	2012	1.1626	0.0402	2.5012	3.3092	0.9084
Shokir et al.	2012	10.306	0.1196	7.2220	9.5631	0.1878
Azizi et al.	2010	55.643	0.2778	22.991	23.407	_
M.A. Mahmoud	2013	59.679	0.2877	11.847	20.845	_
Papay	1968	94.108	0.3613	20.498	27.486	_
Gopal	1977	122.42	0.4121	31.425	36.035	_
Bahadori et al.	2007	887.58	1.1095	92.697	93.534	_
Niger Delta	2013	1200.2	1.2902	95.138	111.72	_
Al-Anazi and Al-Quraishi	2010	$4.1*10^{8}$	$7.5*10^{2}$	$4.7*10^{3}$	$5.8*10^{4}$	_
Burnett	1979	_	_	_	_	_

Table C-10 statistical parameters values for explict emperical correlations when using Al-Sharkawy et al and riazi & Daubert method for ppe and tpe.

Explicit empirical correlation	Year	RSS	RMSE	AARE %	SD	R^2
New proposed correlation	2018	0.6304	0.0296	1.8722	2.4925	0.9503
Beggs and Brill	1973	0.6288	0.0297	1.8606	2.4755	0.9478
Heidaryan-Moghadasi-Rahimi	2010	0.6650	0.0304	1.9318	2.6098	0.9476
Shell Oil Company	2004	0.7201	0.0316	2.0525	2.7839	0.9432
Heidaryan-Salarabadi-Moghadasi	2010	1.0101	0.0374	2.6876	3.3460	0.9204
Sanjari and Nemati Lay	2012	1.1652	0.0402	2.4637	3.3116	0.9082
Shokir et al.	2012	10.656	0.1216	7.3520	9.7294	0.1602
Azizi et al.	2010	54.980	0.2761	22.856	23.275	_
M.A. Mahmoud	2013	63.246	0.2962	12.156	21.466	_
Papay	1968	99.702	0.3719	21.039	28.280	_
Gopal	1977	122.59	0.4123	31.443	36.063	_
Bahadori et al.	2007	901.29	1.1181	93.351	94.221	_
Niger Delta	2013	1214.6	1.2979	95.871	112.37	_
Al-Anazi and Al-Quraishi	2010	$1.8*10^{8}$	$5.0*10^{2}$	$3.7*10^{3}$	$3.9*10^{4}$	_
Burnett	1979	_	_	_	_	_

Table C-11 statistical parameters values for explict emperical correlations when using Al-Sharkawy et al, riazi & Daubert and Daubert and kesler& Lee method for ppe and tpe.

Explicit empirical correlation	Year	RSS	RMSE	AARE %	SD	R^2
New proposed correlation	2018	0.5574	0.0278	1.7070	2.3424	0.9561
Heidaryan-Moghadasi-Rahimi	2010	0.6371	0.0297	1.8164	2.5462	0.9498
Shell Oil Company	2004	0.6706	0.0305	1.9142	2.6746	0.9471
Beggs and Brill	1973	0.6804	0.0309	1.9635	2.5528	0.9435
Heidaryan-Salarabadi-Moghadasi	2010	0.9180	0.0357	2.5144	3.1932	0.9277
Sanjari and Nemati Lay	2012	1.1521	0.0400	2.5300	3.3065	0.9092
Shokir et al.	2012	10.120	0.1185	7.1543	9.4762	0.2025
Azizi et al.	2010	56.018	0.2787	23.065	23.478	_
M.A. Mahmoud	2013	56.894	0.2809	11.604	20.354	_
Papay	1968	90.599	0.3545	20.177	26.985	_
Gopal	1977	122.87	0.4128	31.499	36.096	_
Bahadori et al.	2007	881.12	1.1055	92.407	93.221	_
Niger Delta	2013	1200.5	1.2904	95.150	111.73	_
Al-Anazi and Al-Quraishi	2010	$4.4*10^{12}$	$7.9*10^4$	$2.3*10^5$	$6.2*10^6$	_
Burnett	1979	_	_	_	_	_

Table C-12 statistical parameters values for explict emperical correlations when using Al-Sharkawy mixing parameters for ppe and tpe.

Explicit empirical correlation	Year	RSS	RMSE	AARE %	SD	R^2
New proposed correlation	2018	0.5755	0.0283	1.7661	2.3830	0.9546
Heidaryan-Moghadasi-Rahimi	2010	0.6484	0.0300	1.9136	2.5754	0.9489
Shell Oil Company	2004	0.6811	0.0307	1.9788	2.6514	0.9463
Beggs and Brill	1973	0.6818	0.0309	1.9555	2.5463	0.9434
Heidaryan-Salarabadi-Moghadasi	2010	0.9459	0.0362	2.5746	3.2502	0.9255
Sanjari and Nemati Lay	2012	1.0904	0.0389	2.4833	3.2314	0.9141
Shokir et al.	2012	10.416	0.1202	7.4037	9.6283	0.1791
Azizi et al.	2010	55.349	0.2771	22.962	23.360	_
M.A. Mahmoud	2013	56.757	0.2806	11.975	20.491	_
Papay	1968	91.438	0.3561	21.187	27.353	_
Gopal	1977	108.17	0.3873	29.444	33.905	_
Bahadori et al.	2007	889.49	1.1107	92.934	93.729	_
Niger Delta	2013	1046.2	1.2046	88.331	104.29	_
Al-Anazi and Al-Quraishi	2010	$4.3*10^{14}$	$7.7*10^5$	$2.3*10^6$	$6.3*10^7$	_
Burnett	1979	_	_	_	_	_

Table C-13 statistical parameters values for explict emperical correlations when using Sutton(1985), Standing, Wichert& Aziz and Casey method for ppe and tpe.

Explicit empirical correlation	Year	RSS	RMSE	AARE %	SD	R^2
New proposed correlation	2018	0.5346	0.0272	1.7200	2.2819	0.9579
Shell Oil Company	2004	0.6280	0.0295	1.8617	2.5175	0.9505
Heidaryan-Moghadasi-Rahimi	2010	0.6591	0.0302	1.8920	2.5707	0.9481
Beggs and Brill	1973	0.7836	0.0331	2.1572	2.7101	0.9350
Heidaryan-Salarabadi-Moghadasi	2010	0.8663	0.0347	2.3905	3.1048	0.9317
Sanjari and Nemati Lay	2012	1.1245	0.0395	2.6121	3.2902	0.9114
Shokir et al.	2012	9.6475	0.1157	7.1114	9.2906	0.2397
M.A. Mahmoud	2013	51.473	0.2672	11.528	19.523	_
Azizi et al.	2010	56.764	0.2806	23.245	23.643	_
Papay	1968	84.708	0.3428	20.277	26.295	_
Gopal	1977	108.95	0.3887	29.498	34.005	_
Bahadori et al.	2007	864.65	1.0951	91.695	92.446	_
Niger Delta	2013	1025.4	1.1925	87.019	103.19	_
Al-Anazi and Al-Quraishi	2010	$1.5*10^9$	$1.4*10^3$	$8.9*10^3$	$1.1*10^5$	_
Burnett	1979	_	_	_	_	_

Table C-14 statistical parameters values for explict emperical correlations when using Sutton(1985), Standing, Modified Wichert& Aziz and Casey method for ppe and tpe.

Explicit empirical correlation	Year	RSS	RMSE	AARE %	SD	R^2
New proposed correlation	2018	0.5449	0.0275	1.7516	2.2936	0.9571
Shell Oil Company	2004	0.6302	0.0296	1.8609	2.5048	0.9503
Heidaryan-Moghadasi-Rahimi	2010	0.6687	0.0305	1.9089	2.5743	0.9473
Beggs and Brill	1973	0.8002	0.0335	2.1772	2.7347	0.9336
Heidaryan-Salarabadi-Moghadasi	2010	0.8591	0.0345	2.3789	3.0765	0.9323
Sanjari and Nemati Lay	2012	1.1369	0.0397	2.6056	3.2913	0.9104
Shokir et al.	2012	9.3929	0.1141	7.0584	9.1841	0.2598
M.A. Mahmoud	2013	51.473	0.2672	11.538	19.520	_
Azizi et al.	2010	56.905	0.2809	23.276	23.674	_
Papay	1968	84.323	0.3420	20.214	26.236	_
Gopal	1977	108.14	0.3873	29.396	33.876	_
Bahadori et al.	2007	861.87	1.0933	91.528	92.290	_
Niger Delta	2013	1011.7	1.1846	86.512	102.50	_
Al-Anazi and Al-Quraishi	2010	$8.0*10^7$	$3.3*10^2$	$2.3*10^3$	$2.6*10^4$	_
Burnett	1979	_	_	_	_	_

Table C-15 statistical parameters values for explict emperical correlations when using piper et al. mixing rules for ppe and tpe.

Explicit empirical correlation	Year	RSS	RMSE	AARE %	SD	R^2
New proposed correlation	2018	0.4897	0.0261	1.7048	2.1754	0.9614
Shell Oil Company	2004	0.5237	0.0270	1.7305	2.2674	0.9587
Heidaryan-Moghadasi-Rahimi	2010	0.6270	0.0295	1.8935	2.5181	0.9506
Beggs and Brill	1973	0.7555	0.0326	2.1500	2.6717	0.9373
Heidaryan-Salarabadi-Moghadasi	2010	0.8049	0.0334	2.3067	3.0170	0.9366
Sanjari and Nemati Lay	2012	1.1904	0.0406	2.6123	3.3559	0.9062
Shokir et al.	2012	9.8669	0.1170	7.2581	9.4105	0.2224
Azizi et al.	2010	56.433	0.2798	23.200	23.617	_
M.A. Mahmoud	2013	59.221	0.2866	12.321	20.979	_
Papay	1968	89.906	0.3531	20.952	27.101	_
Gopal	1977	98.560	0.3697	27.926	32.417	_
Bahadori et al.	2007	857.44	1.0905	91.303	92.039	_
Niger Delta	2013	886.97	1.1091	80.461	95.989	_
Al-Anazi and Al-Quraishi	2010	$1.0*10^{11}$	$1.2*10^4$	$5.2*10^4$	$9.3*10^5$	_
Burnett	1979	_	_	_	_	_

Table C-16 statistical parameters values for explict emperical correlations when using Al-Sharkawy- El Kamel emprical correlations for ppe and tpe.

Explicit empirical correlation	Year	RSS	RMSE	AARE %	SD	R^2
Heidaryan-Salarabadi-Moghadasi	2010	1.1004	0.0391	2.6006	3.2640	0.9133
New proposed correlation	2018	1.6940	0.0485	3.3294	4.0378	0.8665
Shell Oil Company	2004	1.7669	0.0495	3.4333	4.0495	0.8607
Heidaryan-Moghadasi-Rahimi	2010	1.8167	0.0502	3.5252	4.1279	0.8568
Sanjari and Nemati Lay	2012	2.5885	0.0599	4.2765	4.8969	0.7960
Beggs and Brill	1973	2.8051	0.0628	4.5465	5.2090	0.7663
Shokir et al.	2012	6.6353	0.0959	6.1721	7.8839	0.4771
M.A. Mahmoud	2013	46.433	0.2538	11.172	18.546	_
Azizi et al.	2010	62.932	0.2954	24.483	24.948	_
Papay	1968	65.555	0.3015	17.260	22.941	_
Gopal	1977	75.580	0.3238	24.658	28.421	_
Niger Delta	2007	510.53	0.8415	61.992	72.763	_
Bahadori et al.	2013	734.92	1.0096	84.482	85.245	_
Al-Anazi and Al-Quraishi	2010	$9.5*10^5$	36.308	313.43	2729.8	_
Burnett	1979	_	_	_	_	_

Table C-17 statistical parameters values for explict emperical correlations when using Sutton(1985), Standing, Wichert& Aziz and Casey method for ppe and tpe.

Explicit empirical correlation	Year	RSS	RMSE	AARE %	SD	R^2
New proposed correlation	2018	0.5360	0.0273	1.7406	2.2824	0.9578
Shell Oil Company	2004	0.5937	0.0287	1.7793	2.4241	0.9532
Heidaryan-Moghadasi-Rahimi	2010	0.6312	0.0296	1.8721	2.5007	0.9503
Beggs and Brill	1973	0.7573	0.0326	2.1316	2.6772	0.9371
Heidaryan-Salarabadi-Moghadasi	2010	0.8367	0.0341	2.3412	3.0333	0.9341
Sanjari and Nemati Lay	2012	1.1728	0.0403	2.5396	3.2726	0.9076
Shokir et al.	2012	10.561	0.1210	7.5369	9.7284	0.1677
Azizi et al.	2010	55.427	0.2773	22.996	23.410	_
M.A. Mahmoud	2013	61.828	0.2928	12.727	21.443	_
Papay	1968	93.131	0.3594	21.392	27.607	_
Gopal	1977	97.851	0.3684	27.510	32.244	_
Bahadori et al.	2007	871.10	1.0992	91.983	92.761	_
Niger Delta	2013	909.73	1.1233	80.822	97.251	_
Al-Anazi and Al-Quraishi	2010	$2.0*10^{11}$	$1.7*10^4$	$5.4*10^4$	$1.3*10^6$	_
Burnett	1979	_	_	_	_	_

Table C-18 statistical parameters values for explict emperical correlations when using Sutton(1985), Standing, Modified Wichert& Aziz and Casey method for ppe and tpe.

Explicit empirical correlation	Year	RSS	RMSE	AARE %	SD	R^2
New proposed correlation	2018	0.5474	0.0276	1.7756	2.2980	0.9569
Shell Oil Company	2004	0.5984	0.0288	1.7849	2.4188	0.9528
Heidaryan-Moghadasi-Rahimi	2010	0.6415	0.0298	1.9014	2.5073	0.9494
Beggs and Brill	1973	0.7763	0.0330	2.1564	2.7078	0.9356
Heidaryan-Salarabadi-Moghadasi	2010	0.8303	0.0339	2.3301	3.0070	0.9346
Sanjari and Nemati Lay	2012	1.1887	0.0406	2.5347	3.2786	0.9063
Shokir et al.	2012	10.317	0.1196	7.4785	9.6302	0.1870
Azizi et al.	2010	55.560	0.2776	23.024	23.440	_
M.A. Mahmoud	2013	61.794	0.2928	12.735	21.435	_
Papay	1968	92.703	0.3586	21.323	27.546	_
Gopal	1977	97.096	0.3670	27.414	32.117	_
Bahadori et al.	2007	868.35	1.0974	91.818	92.606	_
Niger Delta	2013	897.24	1.1155	80.379	96.580	_
Al-Anazi and Al-Quraishi	2010	$9.3*10^9$	$3.6*10^3$	$1.3*10^4$	$2.8*10^5$	_
Burnett	1979	_	_	_	_	_

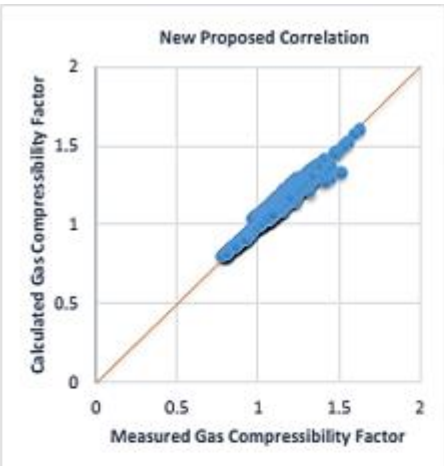

Figure C-1 Accuracy of the new proposed explicit

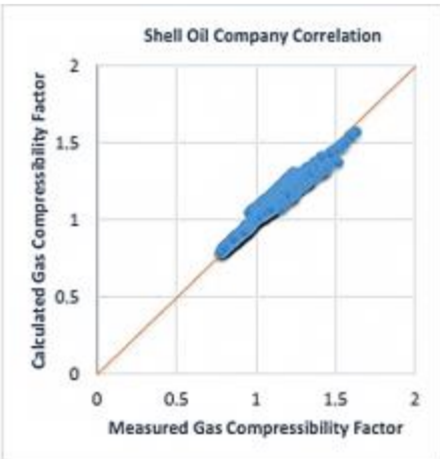

Figure C-2 Accuracy of Shell Oil Company correlation

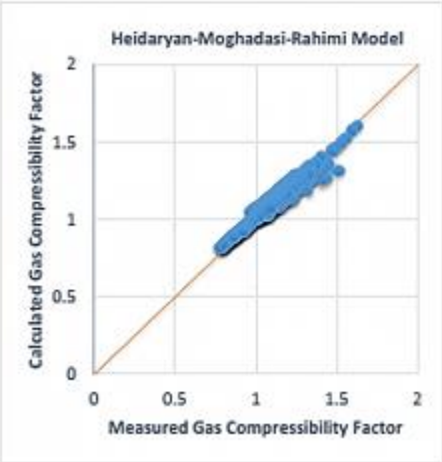

Figure C-3 Accuracy of Heidaryan-Moghadasi-Rahimi model

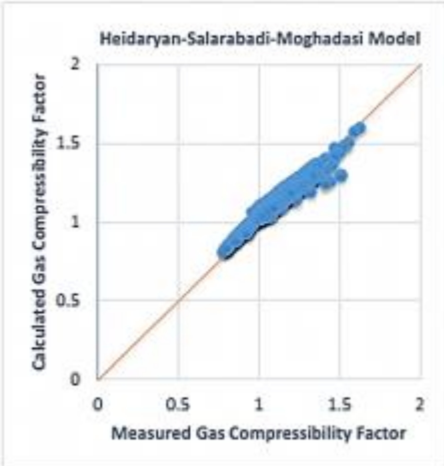

Figure C-5 Accuracy of Heidaryan-Salarabadi-Moghadasi model

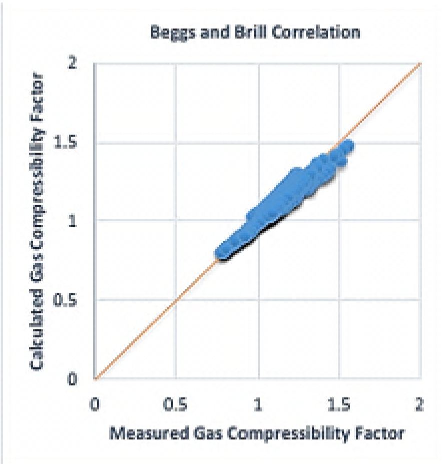

Figure C-4 Accuracy of Brill and Beggs correlation

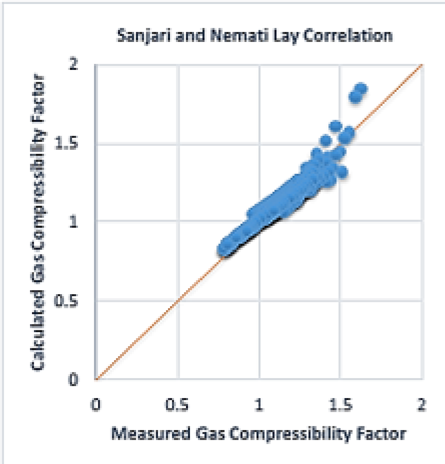

Figure C-6 Accuracy of Sanjari and Nemati Lay correlation