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An Empirical Correlation for Estimation of Formation Volume Factor of Gas Condensate Reservoirs at Separator Conditions

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Abstract

Gas condensate reservoirs represent half of hydrocarbon sources in different geological strata, so prediction of their physical properties are of great importance on the scale of petroleum industry. These hydrocarbons are not stable even at stock tank conditions as oil shrinkage continued due to vaporization of light components, consequently estimation of oil formation volume factor at separator conditions represents a critical property for these reservoirs. Experimental PVT analysis including flash liberation at separator conditions are carried out on gas condensate samples covering a great range of PVT properties. An empirical correlation is developed to estimate oil formation volume factor (B_o) at separator pressure and temperature using statistical regression analysis. Assessment and validation of the developed correlation were carried out by statistical and graphical error analysis in comparison to published correlations.

Keywords: Gas condensate reservoirs; Oil formation volume factor (FVF); Statistical regression analysis; Flash liberation and empirical correlation

Introduction

Gas condensate reservoirs in which reservoir temperature lies between critical temperature (T_c) and cricondentherm temperature (T_{ct}). When reservoir pressure declines below the dew point pressure, the gas begins to condense isothermally until reach to separator conditions. Typical phase diagram of gas condensate is shown in Figure 1. By declining of pressure isothermally starting from point 1, condensation begins at point 2, and reach maximum at point 3 then begin to decrease [1]. Point (G) represents separator condition that lies in two-phase region, in which well stream separated into separator gas and separator oil. These reservoirs characterized by high percentage of light components so vaporization process continued even at stock tank conditions, consequently estimation of oil formation volume factor (FVF) at separator conditions is a very critical physical property for gas condensate reservoirs in order to adjust separator performance. For gas condensate reservoirs, phase behavior changes not only in the formation but also in the wellbore during the whole production life. Recently, the phase behavior in the wellbore ignored in most of deliverability equations, and the volume factor was used to represent the relationship between flow rate in the bottom-hole and in the wellhead [2].

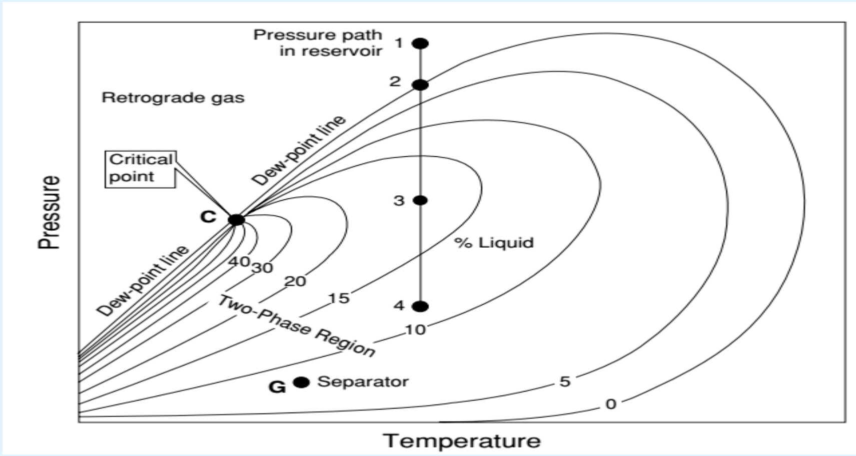

Figure 1: Phase behavior of gas condensate reservoirs [3].

Fluid properties of gas condensate either detected in the lab or estimated from empirical relations [4]. Oil formation volume factor (FVF) at separator conditions measured through flashing of separator oil from separator condition to standard conditions. This factor is valuable for predicting the future of the reservoir, adjustment of separator performance and optimizing separator gas-oil ratio [5,6]. B_o defined as the volume of separator oil at separator conditions (P,T) to volume of oil at standard conditions [7]. Flash liberation study carried out experimentally to determine volume of oil at separator conditions and standard conditions (14.7 psia & 60 °F). Generally, oil FVF expressed mathematically as Equation (1);

$$B_o = \frac{(V_o)_{P,T}}{(V_o)_{sc}} \quad \text{(Equation 1)}$$

where B_o= oil formation volume factor, bbl/STB, $(V_o)_{P,T}$= volume of oil under separator pressure p andtemperature T, and $(V_o)_{sc}$= volume of oil is at standard conditions [8]. Petroleum engineers may resort to empirical correlation in case of; non representative samples, PVT analyses are not available when needed [9], quality check lab analysis, estimating the potential reserves to be found in an exploration prospects, and evaluating the original oil in place and reserve for a newly discovered area [9-11]. Empirical correlations usually developed for regional geographical provinces with given chemical composition of reservoir fluid and data range [7,11]. Thus, generalized accurate PVT relations are rare. Most empirical PVT relations were developed by multiple linear or non-linear regression techniques, others used graphical techniques [11,12]. To the best of our knowledge based on screening of the published correlation concerning with prediction of oil FVF at separator conditions for gas condensate reservoirs, we found that they are too few. On the other hand,several empirical correlations for prediction of oil FVF for black and volatile oils have been proposed and demonstrated in the literature, based on linear regression, nonlinear multiple regression, and graphical techniques [5]. These correlations based mainly on the hypothesis that the oil FVF is a strong function of the solution gas-oil ratio (Rs), the reservoir temperature(T), the gas specific gravity (γ_g), and the oil specific gravity (γ_o) [4]. These correlations are reported in literature Abdul-Majeed, Salman NH [13], Al-Marhoun [14], Al-Marhoun [15], Almehaideb R [16], Bolondarzadeh, et al. [17], Dindoruk and Christman PG [18], Dokla and Osman [19], El-Banbi, et al. [20], Frashad, et al. [21], Glaso [22], Hemmati and Kharrat [9], Kartoatmodjo and Schmidt [23], Macary and El-Batanoney [24], Mehran, et al. [25], Omar and Todd [26], Petrosky and Farshad [27], Standing [28], Sulaimon, et al. [29], Vazquez and Beggs [30]. Few authors modify correlating parameters of black oil to predict gas condensate PVT properties. El-Banbi [20] used modified black oil approach (MBO) for modelling gas condensate properties [20]. The authors modify correlating parameter of standing correlation (1947) to calculate Bo of gas condensate [20]. Ba-Jaalah [31] modify Al-Marhoun and Petrosky correlation parameters by regression analysis to calculate Bo of gas condensate reservoirs [31]. Detailed description of these correlations including number and origin of data set, correlating parameters ranges, relative errors percentage and mathematical expressions found in literature Edreder [8], Fattah and Lashin [4], Karimnezhad [32], Mahdiani and Kooti [6], Moradi [33], Salehinia [34]. By applying the published black oil correlations for prediction of gas condensate oil FVF at separator conditions, a great relative error and high standard deviation is reported. This led the authors in this study to build up a novel relation predicting oil FVF for gas condensate reservoirs. Moreover, accuracy of developed correlations determined through statistical error analysis (E_r, E_a, E_{max}, E_{min}, S, E_{rms}, and r) and correlation validated by other data set not used in correlation built up.

Experimental PVT Analysis

Complete PVT analysis of about (63) gas condensate samples covering different production regions in Egypt was studied in our PVT-lab as follow ;A) Validity check of samples was carried out at sampling pressure to assure that the sample is representative of reservoir fluid [35]. B) Flash liberation test summarized as follow [3].

1. Separator oil sample was shacked very well and adjusted at separator pressure and temperature.
2. A definite volume of separator oil sample $(V_o)_{sep}$ flashed from separator condition to standard condition.
3. Volume of dissolved gas reported and compositional analysis of separator, dissolved gases and stock tank oil (STO) determined by gas chromatography.
4. Measure density and weight of STO, so volume of oil at standard conditions $(V_o)_{sc}$ can be determined.
5. physical parameters like B_o, dissolved gas-oil ratio (GOR), gas gravity and oil gravity can be determined from the following relations (Equations 2-6);

$$B_o, bbl/STB = \frac{(V_o)_{sep}}{(V_o)_{sc}} \quad \text{(Equation 2)}$$

$$(GOR)_{diss}, scf/STB = \frac{(V_g)_{diss}}{(V_o)_{sc}} \quad \text{(Equation 3)}$$

$$\gamma_{diss} = \frac{\sum (Y_i.M_i)_{diss}}{M_a} \quad \text{(Equation 4)}$$

$$\gamma_{sep} = \frac{\sum (Y_i.M_i)_{sep}}{M_a} \quad \text{(Equation 5)}$$

$$\gamma_o = \frac{\rho_o}{\rho_w} \quad \text{(Equation 6)}$$

Correlation Built Up and Computation Method

Generally, regression analysis used to build up empirical correlations [4,36]. Regression analysis correlate a set of independent variables to predict one dependent variable. If only one independent variable is involved then it is called simple regression analysis while, multiple regression analysis involve more than one independent variable [11]. A general multiple regression model, which relates a dependent variable y to k predictor independent variables, x_1, x_2, ...,x_k, is given by Equation 7:

$$y = \alpha + \beta_1 x_1 + \beta_2 x_2 + \ldots\ldots\ldots + \beta_k x_k$$
(Equation7)

Where α and β's are coefficients to be determined by the regression analysis and expressed in matrix form as follow [11].

$$\begin{bmatrix} 1 & x_{11} & x_{12} & .. & x_{1n} \\ 1 & x_{21} & x_{22} & .. & x_{2n} \\ 1 & x_{31} & x_{32} & .. & x_{3n} \\ 1 & .. & .. & .. & .. \\ 1 & .. & .. & .. & .. \\ 1 & .. & .. & .. & .. \\ 1 & x_{nk1} & x_{nk2} & .. & x_{nkn} \end{bmatrix} \begin{bmatrix} \alpha \\ \beta_1 \\ \beta_2 \\ .. \\ .. \\ .. \\ \beta_n \end{bmatrix} = \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ .. \\ .. \\ .. \\ y_{nk} \end{bmatrix} \quad \text{(Equation8)}$$

Least-squares regression technique is applied upon the nonlinear weighted values to minimize the sum-of squared residuals between measured and simulated quantities. The data fitted by a method of successive approximations [4,37]. The linearity or nonlinearity of the data pattern checked using scatter gram plotting. In this study, real experimental PVT data of (63) gas condensate samples covering most of gas condensate reservoirs in Egypt, have been analyzed and used. Physical properties and data range reported in Table 1. Multiple least-square regression analysis used to develop the proposed correlation as a function of separator pressure & temperature, mole fraction of $(C_1)_{sep}$, dissolved gas-oil ratio, mole fraction of $(C_1)_{diss}$, dissolved gas gravity, separator gas gravity and oil specific gravity. (P_{sep}, T_{sep},

$(Y_{C1})_{sep}$, $(GOR)_{diss}$, $(Y_{C1})_{diss}$, $(\gamma_g)_{diss}$, $(\gamma_g)_{sep}$ and γ_o) respectively.

B_o= f [P_{sep}, T_{sep}, $(Y_{C1})_{sep}$, $(GOR)_{diss}$, $(Y_{C1})_{diss}$,$(\gamma_g)_{diss}$, $(\gamma_g)_{sep}$ and γ_o] (Equation9)

$$B_o = Exp[x_0 + x_1 \ln P_{sep} + x_2 \ln T_{sep} + x_3 \ln\left(Y_{C1}\right)_{sep} + x_4 \ln\left(GOR\right)_{diss} + x_5 \ln\left(Y_{C1}\right)_{diss} + x_6 \ln(\gamma_g)_{diss} + x_7 \ln(\gamma_g)_{sep} + x_8 \ln \gamma_o] \quad \text{(Equation10)}$$

Where,

x_0= 0.142 x_1= -0.183 x_2= 0.066 x_3= 0.012 x_4= 0.216
x_5= 0.254 x_6= 0.02 x_7= 0.219 x_8= 0.085

Parameters	Maximum	Minimum	Average
B_o, bbl/STB	1.8416	1.0061	1.1775
(Reservoir pressure, P_{res}) psig	6500.0000	896.0000	2794.1984
(Reservoir temperature, T_{res}) °F	275.0000	113.0000	185.8540
Separator gas gravity$(\gamma_g)_{sep}$	0.8140	0.5748	0.6620
Oil gravity (γ_o)	0.8501	0.7192	0.7688
(Separator pressure, P_{sep}) psig	1246.0000	34.0000	563.4492
(Separator temperature, T_{sep}) °F	127.0000	15.7000	81.3429
°API gravity	65.2518	34.9448	52.7389
(Separator gas oil ratio, $(GOR)_{sep}$scf/STB	916527.5459	5300	74132.83199
mole fraction of $(C_1)_{sep,}$ $(Y_{C1})_{sep}$	0.971857628	0.6873	0.877386792
(Dissolved gas oil ratio, $(GOR)_{sep}$scf/STB	1178.5	5.6	305.1291508
mole fraction of $(C_1)_{diss,}$ $(Y_{C1})_{diss}$	0.823632791	0.23371	0.546075448
Dissolved gas gravity$(\gamma_g)_{diss}$	1.422	0.7253	1.049352018

Table 1: Range of data for gas condensate samples

Results and Discussions

The accuracy and reliability of the developed correlation checked by using both statistical and graphical error means [11].

Statistical Error Analysis

Accuracy and validity of the developed model was evaluated using the following statistical means; Average percent relative error (E_r), Average absolute percent relative error (E_a), Maximum absolute percent relative error (E_{max}), Minimum absolute percent relative error (E_{min}), Root mean square error (E_{rms}) and Standard deviation (S) [5,27,29,38-40]. Mathematical expression of each parameter reported in literature [7]. Statistical errors of the published correlations and developed one in this study are reported in Table 2. It is observed that the developed correlation has lower relative errors, lower root mean square error and standard deviation as compared to the published one, so it has more reliability to measured values. As a result, it is expected that this correlation is more accurate than any of the published ones relevant to Egyptian oil crudes.

Correlations	E_r	E_a	E_{max}	E_{min}	E_{rms}	S	R^2	r
Standing (1947)	4.645	7.659	34.062	0.056	0.144	0.108	0.335	0.579
Vazquez and Begg (1980)	3.868	7.220	33.294	0.088	0.140	0.104	0.376	0.613
Glaso (1980)	5.301	8.063	32.673	0.150	0.150	0.112	0.276	0.525
Al-Marhoun (1988)	4.655	7.622	34.508	0.069	0.136	0.104	0.406	0.637
Abdul-Majeed and Salman(1988)	-32.234	32.234	84.152	7.823	0.381	0.346	0.125	0.354
Dokla and Osman (1992)	17.268	17.328	43.292	0.250	0.265	0.196	0.205	0.453

Al-Marhoun (1992)	4.504	7.490	30.177	0.069	0.145	0.106	0.326	0.571
Macary and Batanoney (1992)	-2.037	7.519	43.359	0.466	0.126	0.106	0.488	0.699
Omar and Todd (1993)	10.892	11.336	39.494	0.426	0.213	0.150	0.221	0.470
Petrosky and Farshad (1993)	3.795	7.265	29.758	0.028	0.142	0.104	0.351	0.592
Kartoamodjo and Schmidt (1994)	3.283	6.742	34.224	0.009	0.131	0.099	0.446	0.668
Farshad et al. (1996)	-37.876	37.941	75.188	2.038	0.441	0.405	0.104	0.322
Almehaideb (1997)	-1.202	9.399	28.349	0.872	0.146	0.112	0.318	0.564
El-Banbi (2006)	3.236	6.931	35.256	0.001	0.136	0.103	0.409	0.640
Sulaimon (2014)	0.279	6.725	39.004	0.167	0.127	0.100	0.484	0.696
Dindoruk&Christman (2001)	-0.591	6.440	61.358	0.020	0.134	0.117	0.427	0.653
Bolondarzadeh et al. (2006)	3.344	7.028	32.112	0.041	0.134	0.100	0.422	0.650
Merhen et al. (2006)	3.764	7.595	30.429	0.088	0.145	0.106	0.330	0.574
Hemmati&Kharrat (2007)	3.918	7.575	30.592	0.090	0.145	0.106	0.326	0.571
Khaled (2015) Modified Al-Marhoun	6.290	29.861	323.187	2.985	0.561	0.511	0.290	0.539
Khaled (2015) Modified Petrosky	-16.579	48.056	307.822	0.217	0.799	0.702	0.220	0.469
This study	**-0.842**	**5.477**	**25.727**	**0.116**	**0.094**	**0.071**	**0.717**	**0.847**

Table 2: Statistical accuracy of the published and developed correlations

Graphical Error Analysis

Graphical error analysis such as cross plot techniques was used in this study, in which the predicted results are plotted against the measured one. Trend line is drawn through predicted data, where, the closer the plotted data to this line, the higher is the accuracy and prediction capability of the correlation [7]. Graphical plots of the published and developed correlations reported in Figures 2 & 3 respectively.

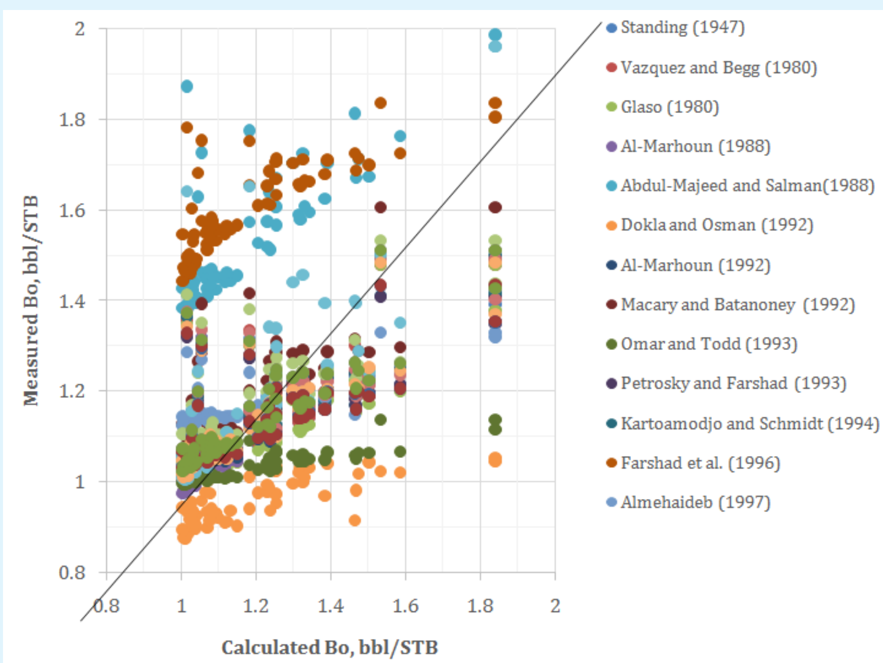

Figure 2: Cross plot of the Published correlations versus Experimental data.

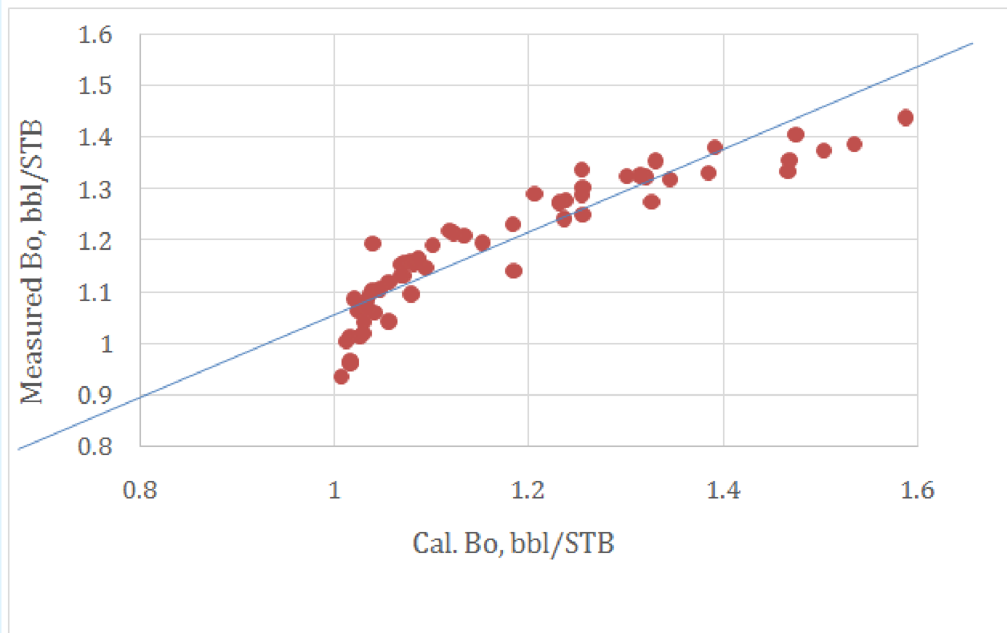

Figure 3: Cross plot of measured and calculated data for the developed correlation.

The coefficient of determination (R^2) indicates the strength of association between two variables, experimental data and predicted one. The closer the R^2 to one, the closer the predicted values to the experimental data [7]. The cross plot figures indicate that the developed correlation has higher coefficient of determination (R^2= 0.8357& r=0.9141) than the published relations, so it is expected that it has high accuracy.

Validation of Correlation

Validity and applicability of the newlydeveloped empirical correlations carried out through graphical and statistical error analysis using (50) data sets that were not used in the correlation development. Figure 4 shows cross plot of measured data and predicted one. We can observe that coefficient of determination (R^2= 0.9898) which indicate high accuracy of this correlation related to validation samples. At this point, it should be mentioned the proposed correlationsare only applicable to Egyptian oils and their applicability to otherregions should be checked [11]. In addition, the statistical analyses show low relative error percentage and high coefficient of determination.

E_r=1.7942 E_a=2.1646 E_{max}=12.4180 E_{min}=0.0894
Erms=0.0509 S=0.0337 R^2=0.9169

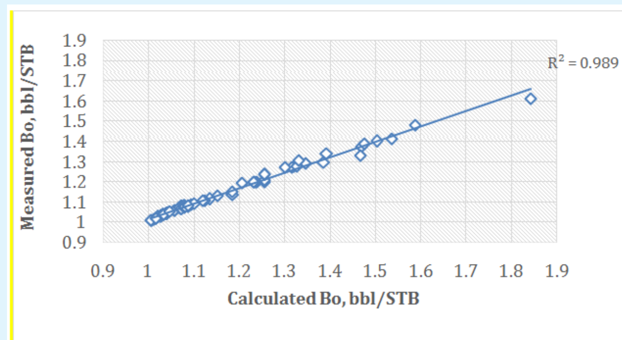

Figure 4: Cross plot of new correlation validation.

Conclusion

A novel correlation based on (63) data set covering different Egyptian oil production regions was developed to estimate oil formation volume factor at separator conditions for gas condensate reservoirs, where the following results can be concluded;

A. The new relation introduce new correlating properties greatly affected by separator conditions like separator and dissolved gas gravity, mole fraction of methane in separator and dissolved gases, so it is expected to improve the developed correlation accuracy.

B. Experimental PVT analysis carried out to determine all parameters in the presented model.

C. Comparative evaluation of the developed correlation and the well-known published correlations from the literature carried out using statistical and graphical error analyses.

D. The obtained results indicate that, the developed correlation are more relevant and accurate to the Egyptian crude oils than the published ones as it shows high correlation coefficient(r= 0.914) and lower relative errors (E_a= 5.477 , E_r= -0.842).

E. Model validation carried out on (60) oil samples through graphical and statistical error analysis where coefficient of determination reach to (R^2= 0.9898) which indicate high reliability of the proposed correlation.

Nomenclature

Oil FVF	Oil formation volume factor
PVT	Pressure-Volume- Temperature
Bob, bbl/STB	Bubble point oil formation volume factor
Rs, scf/STB	Solution gas-oil ratio
T, °F	Reservoir temperature
γg	Gas specific gravity
γo	Oil specific gravity
Er	Average percent relative error
Ea	Average absolute percent relative error
Emax	Maximum absolute percent relative error
Emin	Minimum absolute percent relative error
S	Standard deviation
Erms	Root mean square error
r	Correlation coefficient
GOR, scf/STB	Gas -oil ratio
API	American Petroleum Institute
STO	Stock tank oil
Pres, psig	Reservoir pressure
Tres, °F	Reservoir temperature
ρob, g/cc	Density of oil at bubble point
Pb, psig	Bubble point pressure
Psep, psig	Separator pressure
Tsep, °F	Separator temperature
R2	Coefficient of determination

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