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Evaluation of Solution Gas-Oil Ratio Correlations for Libyan Crude Oil at and Below Bubble Point Pressures

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Abstract

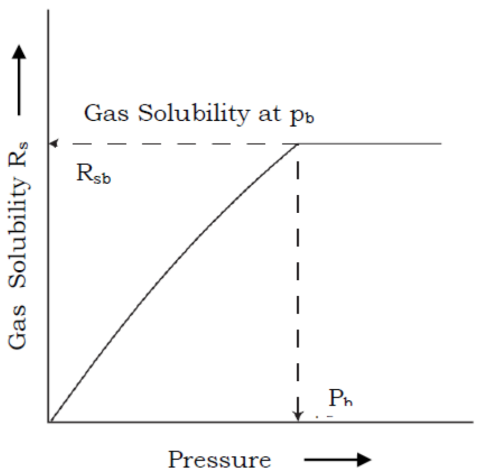
The prediction of reservoir fluids properties, such as bubble point pressure, oil formation volume factor and solution gas-oil ratio, is considered one of most important key factors in reservoir engineering calculations. The best source of oil property data is a laboratory PVT analysis of a reservoir fluid sample. However, in the absence of experimentally measured properties of reservoir fluids, these physical properties must be estimated from correlations. Because crude oils from different regions have different properties, it is recommended to assess the accuracy of the existing correlations. In this paper, correlations by Standing, Lasater, Vasquez and Beggs, Glaso, Al-Marhoun, Petrosky and Farshad, and modified Standing were tested to predict the solution gas-oil ratio (R_s) at and below bubble point pressures for Libyan crude oils. A total of 151 PVT data points representing different Libyan crudes were used in this study. For the conditions considered in this study, Lasater and Standing correlations have been shown to yield the least errors and deviations for the solution gas oil ratio, but such errors are unacceptable and they need further modification to fit adequately Libyan crude oils. Also, the results obtained show that the studied correlations gave less errors if they are applied to the same ranges of data used to develop each correlation. Because all published correlations considered in this study failed to give satisfactory predictions, it is recommended that a correlation for solution gas oil ration should be developed for the Libyan crudes.

Keywords: Solution gas-oil ratio; PVT; bubble point pressure; Libyan crude oil; statistical error analysis.

1. Introduction

Engineers typically require accurate estimates of crude oil properties in order to compute oil reserves, production capacity, and recovery efficiency of a reservoir. Both reservoir engineering and production engineering calculations require estimates of the amount of dissolved gas remaining in solution at oil system pressures below bubble-point pressure. In the absence of experimentally measured solution gas-oil ratio of a crude oil system, it is necessary to determine this property from empirically derived correlations. The solution gas-oil ratio (R_s) The solution gas oil ratio is the amount of gas dissolved in one stock-tank barrel of crude oil (or water) at any pressure and temperature. The solubility of a natural gas in a crude oil is a function of the pressure, the temperature, the API gravity and the gas gravity[1]. For particular gas and crude oil to exist at a constant temperature, the solubility increases with pressure until the saturation pressure is reached. At the bubble-point (saturation) pressure, all the available gases are dissolved in the oil and the gas solubility attains its maximum value. A typical solution gas-oil ratio curve, as a function of pressure for an undersaturated crude oil, is shown in Figure**??** . As the pressure is reduced from the initial reservoir pressure, P_i, to the saturation pressure, P_b, no gas evolves from the oil and consequently the gas solubility stills constant at its maximum value Rsb. Below the saturation pressure, the dissolved gas is liberated and the value of R_s decreases with pressure. For most purposes, the solution GOR at the bubble-point is the value of interest. The solution

Figure 1.1: Typical gas solubility/pressure relationship.



gas oil (or water) ratio is often the most significant component of the *PVT* correlations. It has a very big influence on the oil (or water) formation volume factor (B_o or B_w), the oil (or water) viscosity (μ_o or μ_w), and the oil (or water) compressibility (c_o or c_w). It is also used for calculating the in-situ total reservoir fluid rate.

Many correlations for estimating crude oil *PVT* properties have been published in the past 60 years. The first concerted effort to develop correlations for estimating bubble point pressure, oil formation volume factor and solution gas-oil ratio using field measured data was started by Standing (1947). He proposed a graphical correlation for determining the solution gas-oil- ratio at the bubble point, and the oil and gas gravities[2]. Standing used 105 experimentally determined data points on 22 hydrocarbon mixtures from California crude oil and natural gases. Standing [3] (1981) expressed his proposed graphical correlation in a mathematical form as follow:

$$\mathrm{R_s}=\left(\left(\frac{\mathrm{p}}{18.2}+1.4\right)\mathrm{x}\ \frac{10^{0.0125\ \gamma_{\mathrm{API}}}}{10^{0.00091\ \mathrm{T}}}\right)^{\frac{1}{0.83}} *\gamma_{\mathrm{g}} \qquad (1.1)$$

where
Rs= Solution Gas-Oil Ratio, *scf/STB*
P= Pressure, *psia*
T= Reservoir Temperature, ^oF
γ_{API} = Stock-Tank Oil Gravity, ^oAPI
γg= Solution Gas Specific Gravity (air=1)

In 1958, Lasater [4] presented a bubble-point pressure correlation based on 158 experimentally measured bubble-point pressures using 137 different crude oil systems from reservoirs in Canada, the U.S., and South America. The natural gases associated with these crudes were essentially free of nonhydrocarbons. In 1980, Vasquez and Beggs [5] used laboratory results from more than 600 crude oil systems to develop empirical correlations for several oil properties including the solution gas-oil ratio and the oil formation volume factor (both at the bubble-point). Their database included approximately 6000 data points measured over wide ranges of pressure, temperature, oil gravity, and gas gravity. In 1980, Glaso [6] presented correlations for estimating the bubble-point pressure, as well as the solution gas-oil ratio and the oil formation volume factor at the bubble-point for gas saturated black oils. Glaso analyzed data from 26 different crude oil systems, primarily from the North sea region. In 1988, Al-Marhoun [7] developed correlations for estimating the bubble-point pressure, as well as the solution gas-oil-ratio and the oil formation volume factor for Middle East crude oils at the bubble point pressure. These correlations were developed from a database of 69 bottomhole fluid samples and expressed as functions of reservoir temperature, gas gravity, solution gas-oil-ratio (at P_b). In 1993, Petrosky and Farshad [8] developed empirical *PVT* correlations for Gulf of Mexico crude oils. They took Standing's correlation for solution gas-oil ratio as the basis for developing the new correlation coefficients. Their correlations included the bubble-point pressure, as well as the solution gas-oil-ratio and oil formation volume factor at the bubble-point. Petrosky and Farshad used a total of 90 laboratory analyses and their correlations were developed using nonlinear regression. In (1989), Khazam [9] optimized Standing and Al-Marhoun correlations to fit Libyan crude oils by adjusting the empirical constants of each correlation using regression analysis techniques. He presented correlations for bubble point pressure, solution gas-oil ratio, oil formation volume factor and effective oil molecular weight of stock tank oil. He used 82 different reservoirs in Sirte basin, and total number of 227 data points were obtained. In the literature, there are other several *PVT* correlations (e.g. McCain et al., 1998; Labedi, 1990; Kartoatmodjo and

Schmidt, 1994; Velarde et al., 1999; etc). For more details about these PVT correlations, references are listed at the end of the paper. The primary goal of this paper is to evaluate these correlations. In this study, Standing [3], Lasater [4], Vasquez and Beggs [5], Glaso [6], Al-Marhoun [7], Petrosky & Farshad [8], and Modified Standing correlations [9] were considered to predict the solution gas-oil ratio (R_s) at and below bubble point pressures, and to find if they fit the Libyan crudes or not.

2. Data Description

Experimental PVT data were collected from different Libyan oil reservoirs. 26 laboratory PVT reports and a total number of 151 data points were obtained. The gas specific gravities used in the correlation process are weighted average (separator and stock tank) as seen in Appendix AAppendixA. The APIgravity ($°API$) ranges from 30° to 53°, gas specific gravity from 0.75 to 1.65, initial solution gas-oil ratio from 40 scf/STB to 2546 scf/STB and reservoir temperature from 90 $°F$ to 310 $°F$. These represent the field measured data required for the calculations. The bubble point pressure (P_b) ranges from 160 $psia$ to 4300 $psia$.

3. Evaluation Tools

Statistical error analyses and graphical tools are the criteria adopted for the evaluation in this study. The accuracy of the estimated value of a given fluid property was compared to the measured value using the following statistical parameters (see Appendix AppendixA): Absolute Average Percent Error ($AAPE$), Variance (VAR), Standard deviation (SD), Maximum Absolute Percent Error (Min), Absolute Percent Error (Max). The standard deviation formula used here is as the following form where lower value of SD indicates less degree of scatter:

$$\mathrm{SD}=\sqrt[2]{\frac{\sum_{\mathrm{i}}^{\mathrm{n}}\left(\mathrm{X_{cal}}-\mathrm{X_{mes}}\right)^2}{\mathrm{n-p-1}}} \quad (3.1)$$

where:
X_{mes}= Meaasured Value
X_{cal}= Calculated Value
n= number of observations
p= number of independent variable

Crossplots: All the estimated values are plotted versus the measured values, and thus a crossplot is formed. A 45° straight line is drawn on the crossplot on which estimated values are equal to the experimental values. The closer the plotted data points are to this line, the better the correlation.

4. Results and Discussion

The prediction of the solution gas-oil ratio (R_s) were made using the Standing [3], Lasater [4], Vasquez and Beggs [5], Glaso [6], Al-Marhoun [7], Petrosky & Farshad [8], and Modified Standing correlations [9]. Those correlations were applied on our data set in different data range scenarios to estimate solution gas-oil ratio which are as the following: (1) using only the ranges of data used to develop each correlation, (2) wide range of data, and (3) at bubble-point pressures to estimate solution gas-oil ratio at bubble point (R_{sb}). Therefore, in the first scenario, the points that fall out of range of each correlation are rejected from comparison.

Scenario I: In this scenario, ranges of data used to develop each correlation are used to assess the seven correlations. Therefore, all points that fall out of range of data used to develop each correlation are discarded from evaluation. Table A.1 presents the range of data used to develop each correlation. The results of statistical analysis for each of the seven correlations are shown in Table 4.1. On the basis of the lowest average absolute relative error, variance and standard deviation, the Standing correlation provided the best results followed by Lasater correlation while the Petrosky & Farshad correlation gave poor results to predict solution gas-oil ratio. We note that only 26PVT data points were applied to Standing correlation due to its narrow gas gravity range ($0.59-0.95$) while Lasater correlation was applied to 77PVT data points and Petrosky & Farshad correlation was applied to only 9PVT data points among 151PVT data points (see AppendixA, Table A.1) . Figure B.1 in the AppendixB show crossplots between the experimental and calculated solution gas oil ratio for Standing and Petrosky & Farshad correlations respectively.

Scenario 2: Here, all correlations were tested to predict R_s using a wide ranges of data. Therefore, all points that fall out of range of data used to develop each correlation are not discarded from comparison. Table 4.2 showed that Lasater correlation provided the best results followed by Standing correlation. Lasater [4] introduced the concept of an "effective molecular weight" as means of characterizing the oil composition. We note clearly that Lasater correlation fails for low values of the solution

Table 4.1: Statistical parameters of existing correlations with the ranges of data used to develop each correlation.

Correlations	No. Points	AAPE %	Min	Max	VAR	SD
Standing (1947)	28	20	0	72	5.81E+03	76
Lasater (1958)	77	30	1	107	1.24E+04	111
Al-Marhoun (1988)	49	30	0	80	1.24E+04	112
Modified Standing*(1989)	107	23	0	85	1.45E+04	121
Glaso (1980)	75	22	0	65	1.51E+04	123
Vasquez & Beggs (1980)	105	32	2	120	3.38E+04	184
Petrosky & Farshad (1993)	9	21	2	79	3.44E+05	587

* Modified Standing correlation [9] was developed based on Libyan oil crudes.

Table 4.2: Statistical parameters of studied correlations within and out the ranges of data used to develop each correlation.

Correlations	No. Points	AAPE %	Min	Max	VAR	SD
Lasater (1958)	151	23	0	224	3.62E+04	190
Standing (1947)	151	25	0	229	4.66E+04	216
Glaso (1980)	151	25	0	229	5.33E+04	231
Vasquez & Beggs (1980)	151	31	1	193	5.54E+04	235
Modified Standing (1989)	151	27	0	252	6.00E+04	245
Al-Marhoun (1988)	151	34	0	359	1.03E+05	322
Petrosky & Farshad (1993)	151	63	3	92	3.42E+05	586

Table 4.3: Statistical parameters of studied correlations at bubble point pressures.

Correlations	No. Points	AAPE %	Min	Max	VAR	SD
Lasater (1958)	26	23	1	90	8.18E+04	286
Standing (1947)	26	21	0	59	1.34E+05	367
Vasquez & Beggs (1980)	26	21	2	64	1.42E+05	377
Petrosky & Farshad (1993)	26	68	3	92	1.48E+05	385
Modified Standing (1989)	26	21	2	60	1.65E+05	407
Glaso (1980)	26	21	0	63	1.69E+05	412
Al-Marhoun (1988)	26	31	1	149	3.16E+05	562

gas-oil-ratio. In this scenario, Petrosky & Farshad correlation gave the worst predicted values of solution gas- oil ratio followed by Al-Marhoun correlation. Figure B.2 in the AppendixB show crossplots for Lasater and Petrosky & Farshad correlations respectively.

Scenario 3: Most of the correlations for gas-oil-ratio are simply the bubble-point pressure correlation for that case $P =_{Pb}$, solved for the solution gas-oil-ratio. In this scenario, solution gas-oil-ratio at bubble point pressures (R_{sb}) are estimated only and all points that fall out of range of data used to develop each correlation are not discarded from evaluation. Based on the statistical error analyses, Lasater correlation also provided the better results followed by Standing correlation, while Al-Marhoun correlations performed poorly. Figure B.3 in the AppendixB show crossplots between the estimated and experimental R_s at bubble point pressures for Lasater and Al-Marhoun correlations respectively.

5. Conclusions

The following conclusions are drawn on the basis of the dataset analyzed in this study:

1. Modified Standing correlation does not accurately model the behavior of solution gas-oil-ratio at and below the bubble-point pressures for the studied Libyan crude oils.
2. Although Standing's correlations were developed from Californian crudes and Lasater's correlations from North and South American crudes, they yield the least errors for the solution gas-oil ratio. Also, we note that Lasater correlation fails somewhat for low values of the solution gas oil ratio.
3. Because all published correlations considered in this study failed to give satisfactory predictions, it is recommended that a correlation for solution gas oil ratio be developed for the Libyan crudes.

6. Acknowledgments

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AppendixA. Specific Gravity of the Solution Gas

The weighted average of the specific gravities of the separated gas from each separator is used to describe the specific gravity of the solution gas γ_g [13]. This weighted-average approach is based on the separator gas-oil ratio, or:

$$\gamma_g = \frac{\sum_{i=1}^{n} (R_{SP})_i \, (\gamma_{gSP})_i + R_{ST} \, \gamma_{gST}}{\sum_{i=1}^{n} (R_{SP})_i + R_{ST}} \tag{A.1}$$

where
n = number of separators
R_{sp}= separator gas-oil ratio, scf/STB
γ_{sep}= separator gas gravity (air = 1)
R_{st}= gas-oil ratio from the stock tank, scf/STB
γ_{st}= gas gravity from the stock tank (air = 1)

AppendixA.1. Data Range of Studied Correlations

The ranges of data used to develop each correlation are shown in Table A.1.

AppendixA.2. Modified Standing Correlations

Khazam [9] optimized Standing correlations for bubble-point pressures P_b to fit Libyan crude oils by adjusting the empirical constants of the correlation using regression analysis techniques. The modified Standing correlations for bubble-point pressures has the following form:

$$P_b = 32.1[CNI - 1.05] \tag{A.2}$$

And

$$\mathrm{CNI} = \left(\frac{R_s}{g}\right)^{0.75} \text{ x } 10^{(0.0016\ T\ -\ 0.0166\ API)} \tag{A.3}$$

Equation (A.2) can be solved for the solution gas-oil-ratio.

$$\therefore \quad R_s = \left[\left(\frac{P}{32.1} + 1.05\right) \text{ x } \frac{10^{0.0166\ API}}{10^{0.0016\ T}}\right]^{\frac{1}{0.75}} \text{ x } g \tag{A.4}$$

Where
P_b= bubble-point pressure, $psia$
R_s= Solution gas-oil ratio, scf/STB
T= Reservoir Temperature, ^oF
API= Stock-Tank Oil Gravity, ^oAPI
γ_g= Solution Gas Specific Gravity (air=1)

Table A.1: Data ranges for published PVT correlations

property	Standing (1947)	Lasater (1958)	Vasquez and Beggs (1980)	Glaso (1980)	Al-Marhoun (1988)	Modified Standing* (1989)	Petrosky and Farshad (1993)
Pb, psia	130 - 7000	48 -5680	15-6055	165-7142	130 -3573	206 -3870	1574 -6523
T, oF	100-258	82-272	70-295	80-280	74-240	100-306	114-288
Rsi, scf/STB	20 -	3 -2905	0-2199	90-2637	26 -1602	28 -2503	217 -1406
γAPI, oAPI	1425	17.9 -51.1	15.3 -59.5	22.3-48.1	19.4-44.6	28.7-51.6	16.3-45
γg, air=1	0.59 - 0.95	0.574 - 1.223	0.511-1.351	0.65-1.276	0.752-1.367	0.75-1.68	0.578-0.851

* Modified Standing correlation [9] was developed based on Libyan oil crudes.

AppendixA.3. Error Analysis Equations

The accuracy of the estimated value of a given fluid property was compared to the measured value using the following statistical parameters:

1. Absolute Average Percent Error

$$\text{Percent Error (PE)} = \frac{\mathrm{R_{scal}} - \mathrm{R_{smes}}}{\mathrm{R_{smes}}} \text{ x } 100 \quad (A.5)$$

$$\mathrm{AAPE} = \frac{\sum_i^n |\mathrm{PE_i}|}{\mathrm{n}} \quad (A.6)$$

2. Variance

$$AAPE = \frac{\sum_i^n (R_{s_{mes}} - R_{s_{cal}})^2}{n - p - 1} \quad (A.7)$$

3. Standard Deviation

$$SD = \sqrt{VAR} \quad (A.8)$$

4. Maximum Absolute Percent Error

$$Max \quad = \quad |P_i\ | \quad (A.9)$$

5. Minimum Absolute Percent Error

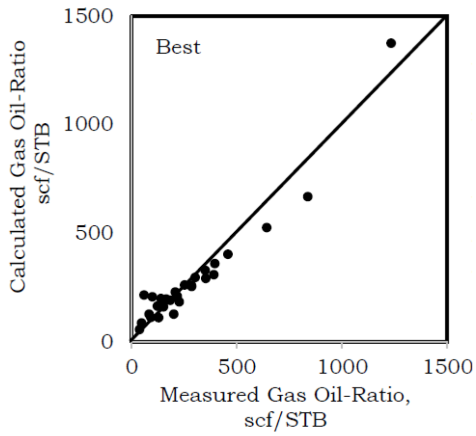
$$Min = min\ |P_i\ | \quad (A.10)$$

where:
$Rs_{mes}$and Rs_{cal} are measured and calculated solution gas oil ratio respectively.

AppendixB. Best and worst correlation Crossplots

Figure B.1: Scenario I: using only the ranges of data used to develop each correlation.

(a) Crossplot for Solution Gas-Oil Ratio (R_s)- Standing (1974) Correlation



(b) Crossplot for Solution Gas-Oil Ratio (R_s) - Petrosky & Farshad (1993) Correlation

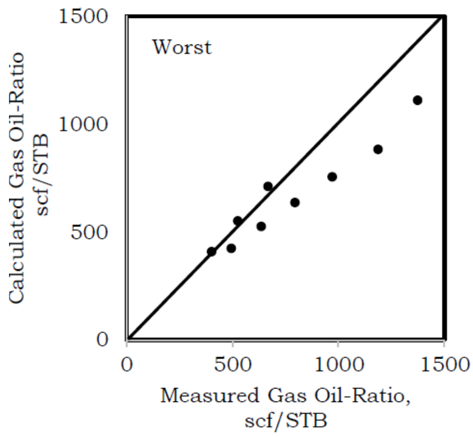
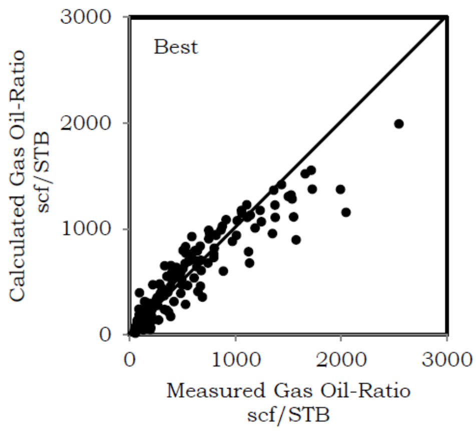


Figure B.2: Scenario 2: wide ranges of data (All 151 PVT data points).

(a) Crossplot for Solution Gas-Oil Ratio (R_s)- Lasater (1958) Correlation



(b) Crossplot for Solution Gas-Oil Ratio (R_s) - Petrosky & Farshad (1993) Correlation

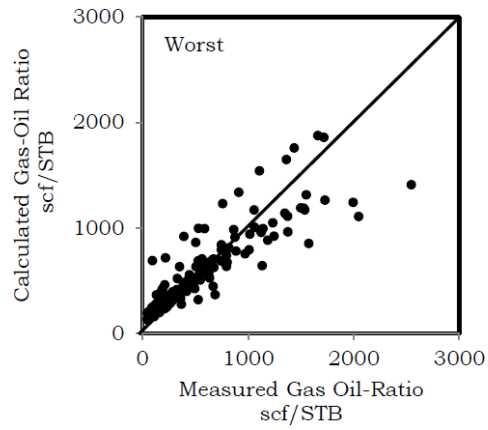
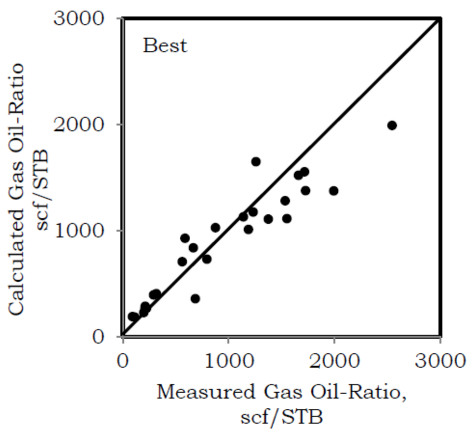


Figure B.3: Scenario 3: solution gas-oil ratio at bubble point pressure (R_{sb}).

(a) Crossplot for Solution Gas-Oil Ratio (R_s)- Lasater (1958) Correlation



(b) Crossplot for Solution Gas-Oil Ratio (R_s)- AL-Marhoun (1988) Correlation