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Solution Gas-Oil Ratios Correlation for Sudanese Crude Oil

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Abstract: This paper aims to provide a proposed correlation for Sudanese crude oil in order to estimate solution gas oil- ratio directly without depending on laboratory measurements.There are many correlations that were utilized for a number of international crude oils. However, because the components of crude differ from region to region, it is difficult to use any specified correlation for different regions and that is simply because each region has its own properties. The core hypothesis of this paper is to find that there is a correlation between the solution gas- oil ratios as a function of the physical properties of the critical temperature, critical pressure, normal boiling temperature, bubble point pressure and gas specific gravity. In these the logarithmic regression method on Microsoft Excel Statistics Package programme used to find this correlation. The obtained results should that there are coefficients for correlation pilot. The correlations were tested using laboratory data in order to justify their accuracy and usefulness using statistical tools and graphics. The results obtained well agreed with laboratory results .The results were compared with other values obtained from international correlations which are used to calculate the solution gas oil ratio.The study indicates that this new correlation can predict well the solution gas oil ratio for Sudanese crude oil when compared to any other known correlations.

Keywords*: Sudanese Crude Oil;Gas-oil ratio; Physical properties; Logarithmic regression.*

1. INTRODUCTION

Pressure volume temperature (PVT) properties of reservoir fluid are necessary for various field applications, such as material balance calculations, well test analysis, reserve estimates, inflow performance analysis, recovery and numerical reservoir simulations, flow control of oil through porous media and pipes, determination of initial hydrocarbons in place, optimum production schemes, ultimate hydrocarbon recovery, design of fluid handling equipment and enhanced oil recovery methods. Ideally, these properties should be obtained from laboratory analysis on samples collected from the bottom of the wellbore or at the surface. Laboratory data however are not always available due to economical and or technical reasons. For these reason empirical correlation are used to estimatethe solution gas–oil ratio.Empirical correlations have been developed based on fluid samples from certain specific regions of the world [1],[2]. Because of the varying compositions of crude oils from different regions, prediction of PVT properties from empirical correlations may not provide satisfactory results when they are applied to hydrocarbon behaving differently from the fluid samples on which the correlations were based. This study is carried out to propose correlation of solution gas oil ratio exclusively based on PVT properties of Sudanese crude oils.

Solution Gas-Oil-Ratio R_s is defined as the number of standard cubic feet of gas that will dissolve in one stock-tank barrel of crude oil at certain pressure and temperature, solution gas oil ratio is an important factor in reservoir engineering computations. The solubility of a natural gas in a crude oil is a strong function of the pressure, temperature, API gravity, and gas specific gravity. Correlations are used when the experimental data for PVT properties of a specific field are not available. The solution gas oil ratio in crude oil is a function of pressure, temperature, API gravity and gas specific gravity. The Solution gas oil ratio in crude oil at constant temperature increases by increasing the pressure until the saturation pressure is reached. In this work the solution gas oil is empirically correlated as a function of the oil density at 15.5ºC, gas specific gravity and bubble point pressure. The bubble point pressure and gas specific gravity is readily available from composition analysis and constant-composition expansion respectively. During the last 60 years, several correlations have been developed to estimate solution gas oil ratio. Some of the most widely used correlations are summarised in Table 8.

2. EXPERIMENTAL DATA

The PVT analyses for samples collected from 65 PVT reports of oil reservoirs indifferent locations of Sudan oil fields were used to develop the correlation presented for solution gas / oil ratio in this study. Experimental PVT data were supplied by the Ministry of Petroleum and gas Sudan, for a number of wells representing different reservoirs. The data include composition, bubble point pressure, density at standard conditions (14.65 psia and 60 ^oF), solution gas- oil ratio and gas specific gravity of the reservoir fluid. The number of data points used to obtained solution gas-oil ratio is 46 data point; the data were randomly classified into two sets. A set of 24 data points were used in developing models, and another set of 22 data points were used for testing the models of solution gas-oil ratios. The data specification for proposed correlation is given in **Table 1** and**2**.

Table 1. Data Summary for Developing R_s Models (24 points)

No.	Properties	Max.	Min.	Average
24	Bubble point pressure (psig)	3812	60	910.5
24	Density @60 °F(gm/ml)	0.935	0.823	0.9
24	Oil specific gravity(water= 0.999)	0.936	0.824	0.9
24	Solution gas oil ratio (scf/STB)	770.170	4.000	135.3
24	Gas specific gravity (air = 1)	1.427	0.577	0.8
24	Molecular weight	548.599	189.790	340.8

Table 2. Data Summary for Testing R_s Models (22 points)

No.	Properties	Max	Min	Average
22	Bubble point pressure (psig)	3730.00	129.00	773.7
22	Density @60(gm/ml)	0.93	0.82	0.9
22	Oil specific gravity(water= 0.999)	0.93	0.82	0. 9
22	Solution gas oil ratio (scf/STB)	706.60	10.40	110.4
22	Gas specific gravity (air = 1)	0.99	0.59	0.7
22	Molecular weight	491.71	185.94	309.9

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Table 3. The Value of **RiaziandDaubertConstants**

Parameter	*A*	*b*	*c*	*D*	*F*	*e*
T_b (k)	6.77857	0.401673	1.58262	3.77409	2.98403	-4.2588
P_c(psia)	4.5203×10^4	-0.8063	1.6015	-1.8078×10^{-3}	-0.3084	0
T_c(R)	544.4	0.2998	1.0555	-1.3478×10^{-4}	-0.61641	0

3. THE MODEL

In this study the solution gas oil ratio is empirically correlated as a function of gas specific gravity, bubble point pressure and oil density at 15.5ºC which was used to calculate the critical temperature, critical pressure, bubble point temperature. The gas specific gravity and oil density at 15.5ºC is readily available from composition analysis and the bubble point pressure is determined experimentally from Constant-Composition Expansion (CCE) test.

$$R_s = P\left(T_c, P_c, T_{b,}\gamma_g, M_w, \gamma, P_b\right) \quad (1)$$

The critical temperature, critical pressure, bubble point temperatures as a function of oil specific gravity and molecular weight.

$$T_c, T_b, P_c = P(M_w, \gamma) \quad (2)$$

Hence equations (1) and (2) can be written as

$$R_s = P\left(T_c, T_b, P_c, \gamma_g, P_b\right)(3)$$

The critical temperature, critical pressure and bubble point temperature are calculated byRiazi and Daubert[3] Equation (4).

$$\theta = aexp(bM + c\gamma + dM\gamma)M^f\gamma^e \quad (4)$$

where: θ= T_c ,T_b , P_c

M = Molecular weight

γ = Oil specific gravity

a, b, c, d, f, e = Constants determined by Riazi and Daubert

The molecular weight of mixture can be calculated using equation (5)

$$\gamma_{mix} = \frac{1.008M_{mix}}{4243 + M_{mix}} \quad (5)$$

The oil specific gravity is then calculated by Equation (6)

$$\gamma_\circ = \frac{\rho_\circ}{\rho_w} \quad (6)$$

where:γ_o=specific gravity of the oil

ρ_o= density of the crude oil, kg/m^3

ρ_w= density of the water, kg/m^3

The parameters used to develop and test correlation for solution gas-oil ratio are shown in Table .4.

Table 4.Summary of Calculated Parameters Used to Develop and Test Proposed Correlation

N.o	Pb_{meas}(bar)	ρ @15.5ºC	$\gamma_\circ$	Mw	T_C (k)	T_b (k)	P_c(bar)	γ_g	R_s
1	6.07	0.93	0.93	519.82	960.80	756.76	5.27	1.427	5.2
2	20.90	0.93	0.93	525.05	963.36	758.53	5.19	0.608	28.1
3	18.28	0.93	0.94	548.60	974.52	766.02	4.82	0.577	24.5
4	163.03	0.88	0.88	290.35	808.59	626.31	11.83	0.655	333
5	18.69	0.92	0.92	465.06	932.16	735.66	6.29	0.714	26.3
6	108.34	0.90	0.90	351.39	858.88	673.45	9.35	0.664	179.2
7	6.69	0.93	0.93	534.24	967.78	761.55	5.04	0.878	5.6
8	4.62	0.91	0.91	408.31	898.28	708.14	7.63	0.767	4.6
9	33.10	0.87	0.87	274.79	794.06	612.30	12.60	0.732	62.83
10	61.86	0.89	0.89	310.12	825.96	642.87	10.94	0.649	110.6
11	59.59	0.88	0.88	304.40	821.04	638.21	11.19	0.645	109.3
12	44.14	0.84	0.84	210.55	724.06	543.78	16.62	0.716	78.6
13	219.24	0.82	0.82	189.79	696.92	517.27	18.31	0.823	641
14	53.31	0.88	0.88	289.06	807.41	625.18	11.89	0.673	85.6
15	262.90	0.83	0.83	192.47	700.58	520.83	18.08	1.015	770.17
16	33.10	0.87	0.87	274.79	794.06	612.30	12.60	0.732	62.83
17	53.31	0.88	0.88	289.06	807.41	625.18	11.89	0.673	86.5
18	43.79	0.84	0.84	213.43	727.62	547.27	16.40	0.927	77.7
19	49.66	0.86	0.86	240.92	759.42	578.50	14.52	0.698	98
20	88.76	0.89	0.89	310.12	825.96	642.87	10.94	0.982	163.2
21	4.14	0.92	0.92	422.03	906.91	715.38	7.28	0.775	4.0
22	56.90	0.91	0.91	388.32	885.13	696.84	8.18	0.669	84.5
23	27.59	0.89	0.89	313.65	828.94	645.69	10.79	0.698	52.3
24	69.03	0.89	0.89	313.65	828.94	645.69	10.79	0.974	154
25	30.21	0.85	0.85	231.47	748.91	568.18	15.13	0.686	57.2
26	40.41	0.89	0.89	325.93	839.06	655.19	10.29	0.689	70.9
27	33.45	0.89	0.89	335.71	846.85	662.42	9.92	0.778	63.1
28	35.86	0.89	0.89	326.57	839.58	655.66	10.27	0.782	67.3
29	30.21	0.85	0.85	231.47	748.91	568.18	15.13	0.686	57.2
30	48.48	0.88	0.88	304.63	821.24	638.40	11.18	0.598	79.2
31	48.34	0.88	0.88	298.31	815.72	633.14	11.46	0.592	78.5
32	8.90	0.91	0.91	387.02	884.25	696.08	8.22	0.717	10.4
33	40.90	0.89	0.89	330.43	842.68	658.55	10.12	0.814	83.3
34	16.90	0.92	0.92	472.40	936.21	738.78	6.14	0.619	20.0
35	14.48	0.93	0.93	491.71	946.54	746.54	5.77	0.65	20.0
36	65.24	0.86	0.86	250.64	769.82	588.69	13.93	0.836	144.9
37	64.00	0.90	0.90	354.32	861.06	675.43	9.25	0.651	103.1
38	57.24	0.90	0.90	370.42	872.74	685.94	8.73	0.702	94.8
39	62.21	0.90	0.90	340.11	850.28	665.59	9.76	0.987	144.7
40	15.72	0.82	0.82	185.94	691.58	512.08	18.65	0.807	27.3
41	69.45	0.85	0.85	231.54	748.99	568.26	15.13	0.703	166.6
42	68.97	0.84	0.84	209.95	723.32	543.05	16.67	0.668	134.3
43	59.59	0.88	0.88	304.40	821.04	638.21	11.19	0.645	109.3
44	44.14	0.84	0.84	210.55	724.06	543.78	16.62	0.716	78.6
45	61.86	0.89	0.89	310.12	825.96	642.87	10.94	0.649	110.6
46	257.24	0.88	0.88	305.25	821.78	638.91	11.15	0.649	706.6

In this study a model was adopted using Microsoft Excel (logarithmic regression) to express solution gas- oil ratio. The model is shown in equation 7a and rearrangement in equation 7b.

$$lnR_s = a + bLnT_c + cLnT_b + dLnP_c + fLn\gamma_g + eLnP_b \quad 7a$$

$$lnR_s = a + ln\left(T_c^b T_b^c P_c^d \gamma_g^f P_b^e\right) \quad 7b$$

In order to develop a proposed correlation of solution gas oil ratio, many models were tried as regression equations to obtain a solution gas oil ratio correlation. This correlation was obtained by logarithmic regression analysis using Excel Software. Theindependent variables of proposed correlation were based on thermodynamic properties direct effect on solution gas oil ratio. The natural logarithm of dependent variable was regressed against the natural logarithms of theindependent variables. The regression results with respect to the constant of Equation (7b) shown in **Table 5**.

Table 5. Regression Coefficients for the Proposed Correlation of Solution Gas- Oil Ratio

Constants	***a***	***b***	***c***	***d***	***f***	***e***
Value	11.498502	-2.379291	0.693885	-0.083278	-0.106712	1.182359

Table 6. TheSolution Gas- Oil Ratio Obtained from Proposed Correlation (Develop Data)

R_{smeas} (scf/STB)	T_c (k)	T_b(k)	P_c(bar)	γ_g	P_b(bar)	R_{sest} (scf/STB)	E_i %
5.2	960.80	756.76	5.27	1.427	6.07	5.55	-6.70
28.1	963.36	758.53	5.19	0.608	20.90	26.13	7.01
24.5	974.52	766.02	4.82	0.577	18.28	22.10	9.78
333.0	808.59	626.31	11.83	0.655	163.03	364.78	-9.54
26.3	932.16	735.66	6.29	0.714	18.69	23.45	10.83
179.2	858.88	673.45	9.35	0.664	108.34	208.72	-16.47
5.6	967.78	761.55	5.04	0.878	6.69	6.50	-16.02
4.6	898.28	708.14	7.63	0.767	4.62	4.67	-1.47
62.8	794.06	612.30	12.60	0.732	33.10	55.96	10.94
110.6	825.96	642.87	10.94	0.649	61.86	113.13	-2.29
109.3	821.04	638.21	11.19	0.645	59.59	109.09	0.19
78.6	724.06	543.78	16.62	0.716	44.14	88.34	-12.39
641.0	696.92	517.27	18.31	0.823	219.24	607.66	5.20
85.6	807.41	625.18	11.89	0.673	53.31	97.18	-13.53
770.2	700.58	520.83	18.08	1.015	262.90	731.69	5.00
62.8	794.06	612.30	12.60	0.732	33.10	55.96	10.94
86.5	807.41	625.18	11.89	0.673	53.31	97.18	-12.35
77.7	727.62	547.27	16.40	0.927	43.79	84.62	-8.91
98.0	759.42	578.50	14.52	0.698	49.66	95.96	2.08
163.2	825.96	642.87	10.94	0.982	88.76	165.88	-1.64
4.0	906.91	715.38	7.28	0.775	4.14	4.04	-1.11
84.5	885.13	696.84	8.18	0.669	56.90	93.86	-11.08
52.3	828.94	645.69	10.79	0.698	27.59	43.01	17.81
154.0	828.94	645.69	10.79	0.974	69.03	122.80	20.26
						E_{amax}%	20.26
						E_{amin}%	0.193
						APE%	-0.561
						AAPE%	8.898
						SD	10.7
						R^2%	0.993

4. TESTING CORRELATION

The developed models were tested against experimental values using data sets for testing. The testing results from solution gas – oil ratio prediction are shown in **Table 7**.

5. COMPARISON OF CORRELATIONS

Statistical error analysis was used to evaluate the performance of the correlations. The average per cent relative error, maximum and minimum absolute per cent relative error (APE), average absolute per cent relative error (AAPE), standard deviation (SD) and correlation coefficient(R) were the major statistical parameters used as a comparative criterion for the testing of the evaluated correlations. In this study the proposed correlation gives low values of average per- cent relative error, average absolute percent relative Error and standard deviation of -0.56percent, 8.9per-cent and 10.7respectively. Lower value of AAPE and SD indicates a better accuracy of proposed correlation. The correlation coefficient of the correlation is almost equal to 1.0(0.99), high value (+1) of correlation coefficient indicate a perfect positive relationship between experimental and estimated values obtained from the proposed correlation. The developed models were tested against published correlations using data sets for testing. The correlation gives low values of the average per-cent relative error, average absolute per-cent relative error and standard deviation 4.0 percent, 9.5 percent and 12.0respectively.Lower values of *AAPE* and standard deviation indicates a better accuracy of the correlation. The correlation coefficient of the test correlation is equal to (0.97), high value (+1) of correlation coefficient indicates a perfect positive relationship between experimental and estimated values obtained from the proposed correlation. This shows that a good agreement exists between experimental and calculated bubble point pressure by proposed correlation. The statistical accuracy of solution gas oil ratio is shown in **Table 8** and in **Figs 1**and **2.**

Table 7. The solution gas-oil ratio so btained using equation (5.8b) (Validated data)

P_b(bar)	T_c (k)	T_b (k)	P_c (bar)	R_{smeas} (scf/STB)	γ_g	R_{sest} (scf/STB)	E_i%
231.47	30.21	748.91	568.18	57.20	0.686	54.34	4.99
325.93	40.41	839.06	655.19	70.86	0.689	66.66	5.93
335.71	33.45	846.85	662.42	63.12	0.778	52.02	17.58
326.57	35.86	839.58	655.66	67.28	0.782	57.06	15.20
231.47	30.21	748.91	568.18	57.20	0.686	54.34	4.99
304.63	48.48	821.24	638.40	79.23	0.5981	86.15	8.74
298.31	48.34	815.72	633.14	78.54	0.5915	86.67	10.36
387.02	8.90	884.25	696.08	10.40	0.717	10.40	0.01
330.43	40.90	842.68	658.55	83.30	0.814	66.06	20.70
472.40	16.90	936.21	738.78	19.95	0.619	21.02	5.37
491.71	14.48	946.54	746.54	19.97	0.65	17.19	13.91
250.64	65.24	769.82	588.69	144.90	0.836	127.82	11.79
354.32	64.00	861.06	675.43	103.10	0.651	111.90	8.53
370.42	57.24	872.74	685.94	94.80	0.702	95.69	0.94
340.11	62.21	850.28	665.59	144.70	0.9867	105.11	27.36
185.94	15.72	691.58	512.08	27.30	0.807	27.28	0.09
231.54	69.45	748.99	568.26	166.57	0.7029	145.03	12.93
209.95	68.97	723.32	543.05	134.33	0.6678	151.05	12.45
304.40	59.59	821.04	638.21	109.30	0.645	109.09	0.19
210.55	44.14	724.06	543.78	78.60	0.716	88.34	12.39
310.12	61.86	825.96	642.87	110.60	0.649	113.13	2.29
305.25	257.24	821.78	638.91	706.60	0.649	613.83	13.13
						E_{amax}%	27.36
						E_{amin}%	0.009
						APE%	3.99
						AAPE%	9.54
						SD	12.0
						R^2%	0.971

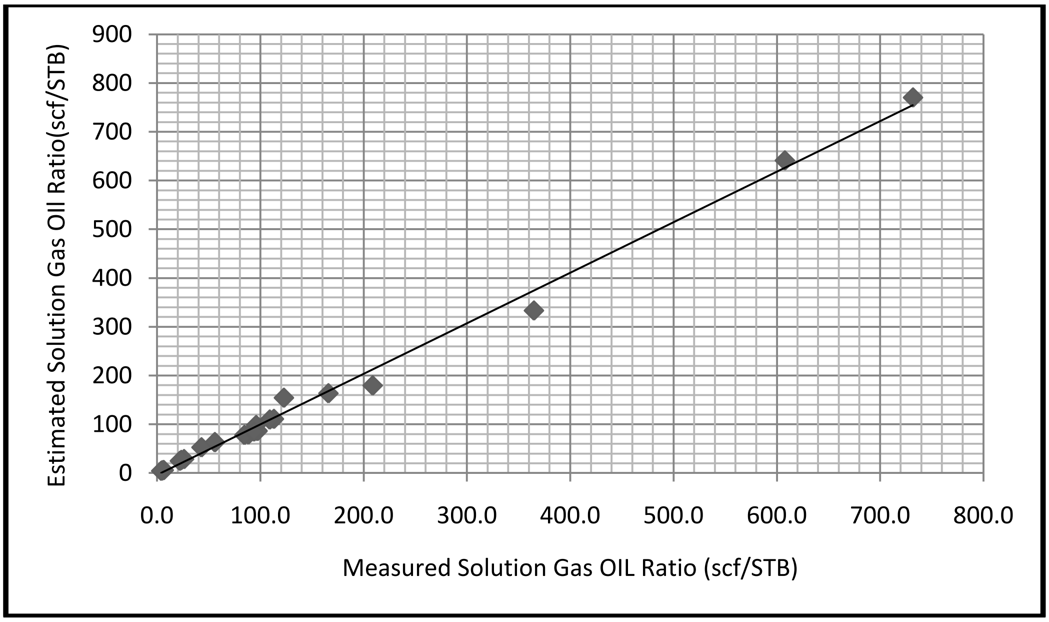

Fig 1. The estimated solution gas oil ratio by proposed correlation on develop dataset versus corresponding laboratory

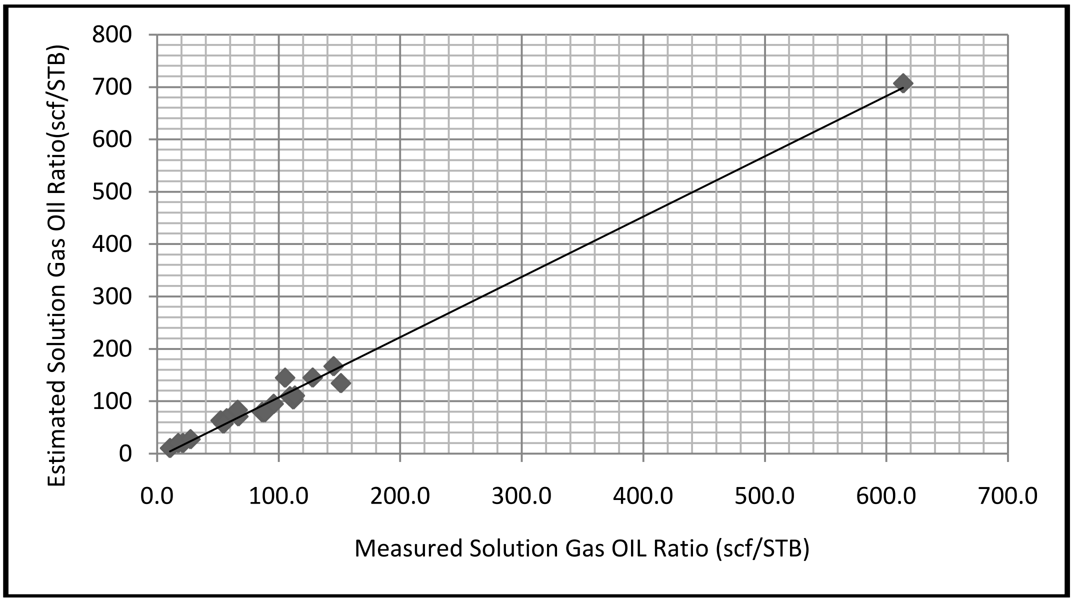

Fig. 2. The estimated solution gas-oil ratios on testing dataset versus corresponding laboratory test

Cross Plot: In these criteria, all the predicted values are plotted versus the experimental values and thus cross plot is formed. A45° straight line is drawn on the cross plot on which the estimated value is equal to the experimental value. The cross plots of estimated values against experimental values for solution gas oil ratio models (proposed correlation) are presented in **Figs 1 and 2.**

6. CONCLUSIONS

In comparison with other known correlations in this study, the average absolute per- cent error *AAPE* and standard deviation gave lowest values. This indicates that the proposed correlation predicts better solution gas oil ratio for Sudanese crude oil compared to other known correlations. Table 8 presents summary of statistical measures for solution gas - oil ratios R_s for common correlation.

Table 8. Summary of Statistical Measures for Solution Gas - Oil ratios R_s for Common Correlation

Authors /Published		Samples Region	AAPE%	APE%	E_{amax}	E_{amin}	SD	R^2
Standing [4]		California	40.79	40.31	255.09	0.02	62.04	0.43
AL –Marhoun [5]		Middle Eastern	44.02	8.63	267.39	8.53	62.7	-0.54
Glaso’s [6]		North Sea	30.92	-11.31	267.91	1.20	57.14	0.87
Vasquez-Beggs [7]	API $\leq 30^o$		31.8	-29.8	218.5	0.8	53.3	0.93
	API $\geq 30^o$	World Wide	56.7	-56.7	123.7	24.8	66.1	0.24
Hanafy*et al.* [8]		Egyptian	130.45	-11.14	858.73	17.62	211.7	0.31
AL –Marhoun [9]		Saudi Arabian	84.19	83.27	95.97	21.05	85.80	-0.36
Petrosky and Farshad [10]		Gulf of Mexico	94.68	-10.28	958.92	7.49	191.3	0.41
Nagi. (Develop)		Sudanese	8.9	-0.6	20.3	0.2	8.9	0.99
Nagi. (Testing)		Sudanese	9.5	4.0	27.4	0.01	12.0	0.97

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APPENDIX

PVT Correlations:

Standing Correlation (California Crude Oil) [4]

Standing [4]expressed the graphical correlation by the following expression:

$$R_s = \gamma_g \left[\left(\frac{P}{18.2} + 1.4\right) 10^x\right]^{1.2048}$$

with

$$x = 0.0125API - 0.00091(T - 460)$$

where:T = temperature, °R

P = system pressure, psia

γ_g = gas specific gravity

AL-Marhoun Correlation (Middle Eastern Crude Oil) [5]

$$R_s = \left[a\gamma_g^b \gamma_\circ^c T^d\right]^e$$

where:R_s= Solution gas oil ratio (scf/STB)

γ_g= gas specific gravity

γ_o= stock-tank oil gravity

T = temperature, °R

a – e= coefficients of the above equation having these values:

$$a = 185.843208 \quad b = 1.877840 \quad c = -3.1437$$
$$d = -132657 \quad e = 1.398441$$

Glaso's Correlation (North Sea Crude Oil) [6]

$$R_s = \gamma_g \left[\left(\frac{API^{0.989}}{(T - 460)^{0.172}}\right) P_b^*\right]^{1.2255}$$
$$P_b^* = 10^x$$

where P_b^* a correlating is number and is defined by the following expression With

$$x = 2.8869 - [14.1811 - 3.3093log(P)]^{0.5}$$

Vasquez and Beggs Correlation (world data) [7]

$$R_s = C_1 \gamma_{gs} P^{C_2} \exp\left[C_3 \left(\frac{API}{T}\right)\right]$$

The values of the coefficients C_1, C_2, and $C_3$are given below:

Coefficient	API ≤ 30	API ≥ 30
C_1	0.0362	0.0178
C_2	1.0937	1.1870
C_3	25.7240	23.931

Hanafy *et al*. [8] Correlation (Egyptian crude Oil

$$R_s = -49.069 + 3.205P_b$$

AL-Marhoun [9] Correlation (Saudi Arabian Oil)

$$R_s = \left(\frac{X}{\gamma_g^{-1.879109} \gamma_\circ^{3.046569} T^{1.302347}}\right)^{\left(\frac{1}{0.722569}\right)}$$

where:

$$X = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

$$a = -2.278475 \times 10^{-9} b = 7.02362 \times 10^{-3} c$$
$$= -64.138910 - P$$

The Petrosky-Farshad [10] Correlation (Gulf of Mexico crude oil)

$$R_s = \left[\left(\frac{P}{112.727} + 12.340\right) \gamma_g^{0.8439} 10^x\right]^{1.73184}$$

With

$$x = 4.561 \times 10^{-5} (T - 460)^{1.391} - 7.916 \times 10^{-4} API^{1.5410}$$

where: P = pressure, psia

T= temperature, °R

γ_g= gas specific gravity

API = Oil API gravity

Nagiet et al. Correlations (Sudanese Crude Oil

$$\ln R_s = 11.498502 + \ln(T_c^{-2.38} T_b^{0.70} P_c^{-0.0838} \gamma_g^{-0.11} P_b^{1.18})$$

where: R_s = Solution gas oil ratios ,scf/STB

P_c = Critical pressure, bar

T_c = Critical temperature, k

T_b = Boiling point temperature, k

P_b =Bubble point pressure,bar

γ_g= Gas specific gravity