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Estimation of Solution Gas Oil Ratio

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Abstract

Many methods for estimating solution gas-oil ratio (GOR) exist in the literature. These methods can be classified into two categories. The first includes empirical correlations with different formulas. The other category includes models that derived from intelligent techniques. In this work, a simple on-line questionnaire is designed and distributed to 132 petroleum/chemical engineers (24 persons in the University, 26 persons in the headquarter of the oil ministry and 82 are working in the field near oil wells) to define what they practically prefer for estimating GOR. Analysis of the results shows that 119 of them (90%) prefer using simple empirical correlation with reasonable accuracy. To achieve this desire, all the existing empirical GOR correlations are compared based on simplicity criteria. The results reveal that the correlation developed by Baniasadi *et al.* is the simplest one since it has a simple structure with only one tuning parameter. To check the accuracy of this correlation, its performance is evaluated against three different measured PVT databases. The evaluation indicates a tendency to underpredict the measured data. An improved revision is suggested in this study which results in better prediction.

Keywords: Solution GOR; PVT; Empirical; Intelligent Models.

1. Introduction

Estimation of PVT properties is one of the main concerns in handling different oilfield operations such as calculation of two-phase flow, pressure losses, the design of reservoir performance and design of production facilities. Some of these properties are solution GOR, oil gas surface tension, oil viscosity and oil FVF [1].

Many methods for predicting solution GOR are presented in the literature. These methods can be divided into two main categories. The first category consists of empirical correlations [2-22]. This category also includes some works that started with the equation of state and gene expression programming and ended with empirical equations [23-24]. The other category includes models derived from intelligent techniques [25-35]. The intelligent techniques used in the derivation of these models are: neural network (NN); artificial neural network (ANN); adaptive neuro-fuzzy inference systems (ANFIS); Support Vector Machine (SVM); Least Square SVM (LSSVM) and coupled simulated annealing (CSA).

The present work deals with the correlations of solution GOR and represents an attempt to achieve the desire of petroleum and chemical engineers to recommend a simple empirical solution GOR equation with acceptable accuracy.

2. Selection of solution GOR method

Most of the existing GOR evaluation studies are based on criteria of accuracy using statistical parameters [36-37]. None of these studies take into consideration the ease of implementation, especially for persons who are working in the field near the oil wells, where some techniques required for implementation are often not available. In this study a simple on-line questionnaire is distributed to 132 persons (petroleum/chemical engineers) working in different places as shown below:

- 24 engineers working in the PVT laboratories of universities.
- 26 engineers working in the headquarter of oil ministry (Division of studies).
- 82 engineers working in the oil fields.

The questionnaire consisted of three parts: a brief description of all 22 methods mentioned in the introduction; a question of "Which solution GOR method do you prefer?" with two option answers (category one and category two); the third part defines the criteria for selection with two option answers [ease of implementation (simplicity, availability of prerequisite tools) and accuracy]. On-line access is made available for one week. Ninety percent of the participants (119 persons) prefer using methods of category one, based on ease of implementation criteria. In the text box of feedback, these 119 persons report that in many cases, they used a simple calculator for estimating PVT properties. Therefore the ease of implementation is selected as primary criteria. In addition, they mention that the accuracy is also important with a second priority. Their final request is that the researchers can offer simple empirical correlations with a reasonable accuracy for solution GOR and other PVT properties.

3. Comparison of empirical solution GOR correlations

Table 1 shows all the 22 empirical solution GOR correlations. As can be seen, most of these correlations have complex structures and required multiple coefficients. For example Dindoruk and Christma [16] correlation requires eleven coefficients. Other correlations consist of multiple equations based on selected ranges of API Gravity. The only correlation that required one coefficient is that of Baniasadi *et al.*[24]. This correlation is considered as the simplest one in this study. This correlation was developed using genetic programming conducted to 1038 measured data points covered wide ranges of fluid physical properties.

4. Analysis of Baniasadi *et al.* correlation

Baniasadi *et al.* [24] correlation has the following simple form:

$$R_s = 0.0026191\ API\ P_b\ (2\ \gamma_g + 1) \tag{1}$$

where R_s is solution GOR; P_b is bubble point pressure and γ_g is gas specific gravity.

The performance of Eq. (1) and some other empirical equations against variation of API, γ_g, and P_b are shown in Figures 1 through 3, respectively. For API gravity (Figure. 1), all equations show approximately the same trend with very small differences for $API \leq 40$, above 40 values the difference is increased slightly. Effect of gas specific gravity on Rs is shown in Figure 2. Again, all equations reveal the same trend, except Al-Marhoun [6] equation, which shows the sharp effect and clearly over-predicts R_s for γ_g greater than one as compared with other equations. The reason for this observation is the high value of tuning coefficient associated with gas specific gravity, therefore recently Al-Marhoun [19] proposed lower coefficient value when modifying his correlation. Table 1 indicates that Al-Marhoun [6] correlation used the highest tuning coefficient associated with γ_g as compared to all other empirical correlations. Figure 3 presents the effect of pressure. As can be seen, Eq. (1) shows a tendency to under-predict R_s as compared to others, in particular for high-pressure values. This observation agrees with the positive value of average percent error reported by Baniasadi *et al.* [24] in their work (i.e. predicated R_s values are almost less than measured values). Another issue regarding Eq.(1), is the requirement of P_b for estimating R_s, which is either obtained using individual empirical equations or by experimental measurements.

5. Revision of Baniasadi *et al.* correlation

For further simplicity by avoiding the requirement of obtaining bubble point pressure (P_b) for estimating Rs, the P_b has been replaced with P in the present study. Eq. (1) has been rewritten as shown below:

$$R_s = C\ \ API\ \ P^A\ (2\ \gamma_g + 1) \tag{2}$$

where *C* is a constant and *A* is a power added to the revised equation to overcome the under-prediction of R_s with increasing pressure, which is expected to be greater than one.

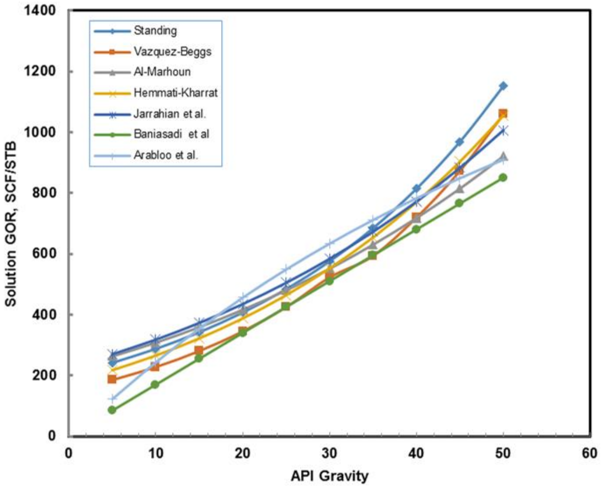

Figure 1. Effect of API gravity on solution GOR

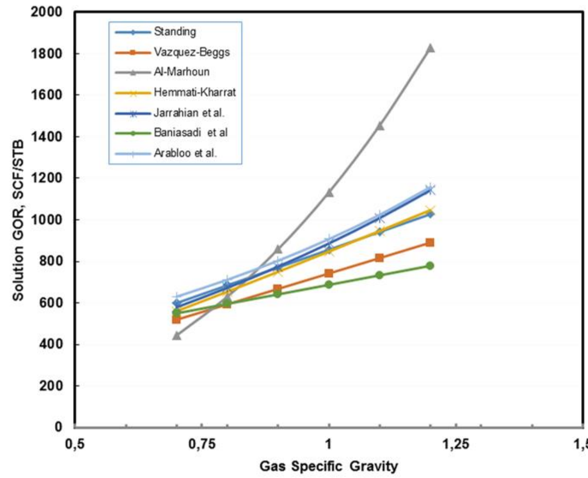

Figure 2. Effect of gas specific gravity on solution GOR

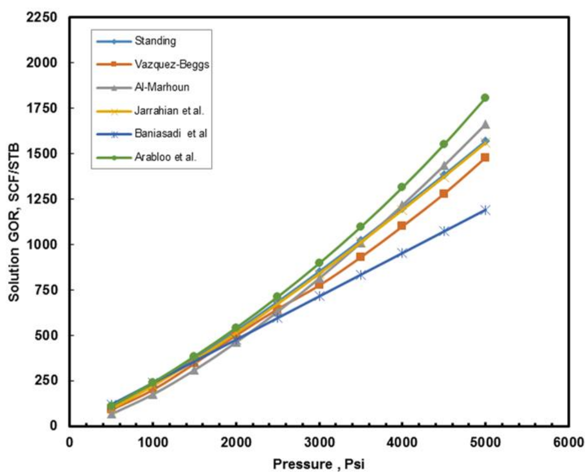

Figure 3. Effect of pressure on solution GOR

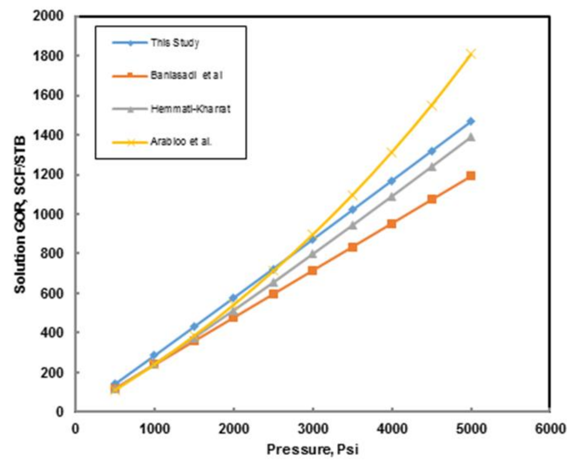

Fig. 4. Effect of pressure on solution GOR using revised and some existing correlations

None linear regression is used in this study to determine the two constants (*A* and *C*), based on new experimentally measured PVT data (100 data points). A brief description of the measured data is given in Table 2. As shown wide ranges of oil, properties are covered by the measured data set. A complete list of this dataset is given in Table 3. The final form of the revised equation is:

$$R_s = 0.002721\ API\ P^{1.015}\ (2\ \gamma_g + 1) \tag{3}$$

The effect of pressure on R_s, using Eq. (1), Eq. (3) and some other existing equations is presented in Figure 4. As can be seen, the revised equation shows the same trend of the existing correlations and gives greater R_s values as compared to the original one. This, of course, will decrease the under-prediction of R_s with increasing of pressure.

Table 1. The existing solution GOR empirical correlations

No.	Date	Correlation	Author
1	1947	$R_S = a_1\,\gamma_g\,P_b{}^{a_2}\exp[a_3\,API - a_4\,T]$ $a_1 = 0.0307343;\ a_2 = 1.2048;\ a_3 = 0.034677;\ a_4 = 0.0025245$	*Standing* **[2]**
2	1980	$R_S = (W\,API^{a_1}\,T^{a_2})^{a_3}\gamma_g$; $W = a_4 + a_5 P_b + a_6\,P_b{}^2$ $a_1 = 0.989; a_2 = -0.172; a_3 = 1.225; a_4 = 3.8315;\ a_5 = 0.0028;\ a_6 = 5.1E - 7$	*Glaso* **[4]**
3	1980	$R_S = a_1\,\gamma_g\,P^{a_2}\,exp\left[\frac{a_3\,API}{Tr}\right]$ $For\ API\ \leq 30;\ a_1 = 0.0362; a_2 = 1.0937; a_3 = 25.724$ $For\ API\ > 30;\ a_1 = 0.0178; a_2 = 1.187; a_3 = 23.931$	*Vazquez and Beggs* **[5]**
4	1988	$R_S = a_1\gamma_g{}^{a_2}\,P_b{}^{a_3}\,\gamma_o{}^{a_4}\,Tr^{a_5}$ $a_1 = 1490.3;\ a_2 = 2.262;\ a_3 = 1.3984;\ a_4 = -4.3963;\ a_5 = -1.86;\ Tr = (T + 460)$	*Al-Marhoun* **[6]**
5	1992	$R_S = [a_1\,P_b\,\gamma_g{}^{a_2}\,Tr^{a_3}\,\gamma_o{}^{a_4}]^{a_5}$ $a_1 = 1.196E - 4; a_2 = 1.01049; a_3 = 0.9526; a_4 = -0.108; a_5 = 1.38113$	*Dokla and Osman* **[7]**
6	1993	$R_S = \left[a_1\,\frac{P_b}{K} + a_2\right]^{a_3}$; $K = exp(a_4\,T - a_5 API - a_6\gamma_g)$ $a_1 = 0.0049; a_2 = 4.7927; a_3 = 1.9606; a_4 = 7.7E - 4; a_5 = 0.0097;\ a_6 = 0.4003$	*Macary and El-Batanoney* **[8]**
7	1993	$R_S = \left[(a_1\,P_b - a_2)\,\frac{\gamma_g}{R}\right]^{a_3}$; $R = 10^{(a_4 T - a_5 API)}$ $a_1 = 0.0546; a_2 = 2.2; a_3 = 1.205; a_4 = 9.1E - 4; a_5 = 0.0125$	*Hasan et al.* **[9]**
8	1997	$For\ API > 30;\ R_S = P^{a_1}\gamma_g{}^{a_2}\,API^{a_3}\,M;\ M = 10^{(a_4 T - a_5)}$ $a_1 = 0.94776; a_2 = 0.04439; a_3 = 1.1394; a_4 = 8.392E - 4;\ a_5 = 2.188$ $For\ API \leq 30;\ R_S = P^{a_1}\,\gamma_g\,M; M = 10^{\left(a_2\frac{API}{T} - a_3\right)}$ $a_1 = 1.18026; a_2 = 0.4636; a_3 = 1.2179$	*Elsharkawy and Alikhan* **[10]**
9	1998	$R_S = \left[10^K\,\gamma_g{}^{a_1}\,\left(a_2 + \frac{P_b}{a_3}\right)\right]^{a_4}$; $K = a_5 API^{a_6} - a_7 T^{a_8}$ $a_1 = 0.8439; a_2 = 12.34; a_3 = 112.727; a_4 = 1.73184$ $a_5 = 7.916E - 4; a_6 = 1.541; a_7 = 4.561E - 5; a_8 = 1.3911$	*Petrosky and Farshad* **[11]**
10	1996	$R_S = a_1\,\gamma_g\,P_b{}^{a_2}\,\frac{10^{F_1}}{F_2}$; $F_1 = a_3\,API - a_4 T;\ F_2 = 1 - a_5\,\frac{\gamma_o}{T}$ $a_1 = 0.01456; a_2 = 1.2073; a_3 = 0.017174; a_4 = 4.467E - 5;\ a_5 = 24.663$	*Frashad et al.* **[12]**
11	1998	$R_S = a_1 P_b{}^{a_2}\gamma_g{}^{a_3} API^{a_4} T^{a_5}$ $a_1 = 0.001167; a_2 = 1.7319; a_3 = 2.5417; a_4 = 1.785;\ a_5 = -1.1502$	*Kairy et al* **[13]**
	1999	$R_S = \gamma_g[a_1 P_b\,\gamma_o{}^{a_2} Tr^{a_3}]^{a_4}$ $a_1 = 805.887;\ a_2 = -5;\ a_3 = -1.5;\ a_4 = 1.1765$; Tr=(T+460)	*Levitan and Murtha* **[14]**
13	2001	$R_S = [S\ \ P_b\,\gamma_o{}^{-a_1}\,\gamma_g{}^{-a_2}\,Tr^{-a_3}]^{a_4}$; $S = \exp(a_5\,\gamma_g\,\gamma_o)$ $a_1 = 5.527215;\ a_2 = 0.783716;\ a_3 = 0.783716;\ a_4 = 1.276;\ a_5 = 1.841408$	*Al-Shammasi* **[15]**
14	2001	$R_S = [(a_1\,P_b + a_2)\,\gamma_g{}^{a_3}\,10^W]^{a_4}$ $W = \left[\frac{a_5\,API^{a_6} + a_7 T^{a_8}}{(a_9 + \ 2\,API^{a_{10}}\,P_b{}^{a_{11}})^2}\right]$; $a_1 = 0.2976; a_2 = 28.10133$ $a_3 = 1.5791;\ a_4 = 0.92813;\ a_5 = 4.87E - 6;\ a_6 = 5.731$ $a_7 = 0.009925;\ a_8 = 1.7762;\ a_9 = 44.25;\ a_{10} = 2.7029;\ a_{11} = 0.74434$	*Dindoruk- and Christman* **[16]**
15	2007	$R_S = [a_1\,\gamma_g{}^{a_2}\,\gamma_o{}^{-a_3}\,T^{-a_4}\,P_b]^{a_5}$ $a_1 = 0.1769;\ a_2 = 1.0674;\ a_3 = 5.0956;\ a_4 = 0.1394;\ a_5 = 1.0857$	*Hemmati and Kharrat* **[17]**
16	2007	$R_S = \ a_1\,\gamma_g{}^{a_2}\,P_b{}^{a_3}\,\gamma_o{}^{-a_4}\,Tr^{-a_5}$	*Mazandarani and Asghari*

No.	Date	Correlation	Author
		$a_1 = 994.3718;\ a_2 = 2.113367;\ a_3 = 1.4556;\ a_4 = 5.48944;\ a_5 = 1.90488$	[18]
17	2004	$R_S = a_1 \gamma_g^{a_2} P_b^{a_3} \gamma_o^{a_4} Tr^{a_5}$ $a_1 = 5534.1;\ a_2 = 1.46538;\ a_3 = 1.166;\ a_4 = -6.0447;\ a_5 = -1.851; Tr = (T + 460)$	*Modified Al-Marhoun* [19]
18	2004	$R_S = a_1\, \gamma_g\, P_b^{a_2} \exp[a_3\, API - a_4\, T]$ $a_1 = 0.064778;\ a_2 = 1.0934;\ a_3 = 0.040159;\ a_4 = 0.002787$	*Modified Standing* [19]
19	2012	For API ≤ 45 $\quad R_S = \left[(a_1\, P_b + a_2)\, 10^{(a_3\, API - a_4\, T)}\right]^{a_5}$ $a_1 = 0.059155;\ a_2 = 1.40573;\ a_3 = 0.0128746;\ a_4 = 9.13115E-4$ For API > 45 $\quad R_S = \left[\frac{a_1\, P_b\, \gamma_g^{a_2}}{10^{(a_3\, T - a_4\, API)}}\right]^{a_5}$; $a_1 = 0.03117; a_2 = 1.2854$ $a_3 = 1.4111E-4; a_4 = 0.0152714; a_5 = 1.23153$	*Ikiensikimama and Ajienka* [20]
20	2015	$R_S = \frac{5000\, R_{SN}}{(1 - R_{SN})};\ R_{SN} = [a_1\, A_N\, P_b\, G_N^{-a_2}\, T_N^{-a_3}]^{a_4}$ $G_N = \frac{1}{\gamma_g + 5};\ A_N = \frac{API}{API + 50};\ T_N = \frac{T}{T + 500}$ $a_1 = 6.102089E-9; a_2 = 5.651436; a_3 = 0.095371; a_4 = 1.091273$	*Arabloo et al* [21]
21	2015	$R_S = \left[\frac{a_1 P_b\, \gamma_g^{a_2}}{\gamma_o^{a_3}\, G_g\, Tr^{a_4}}\right]^{a_5}$; $G_g = exp\left(\frac{a_6\, \gamma_g}{\gamma_o}\right)$ $a_1 = 33.382; a_2 = 0.448067; a_3 = 3.32023; a_4 = 1.074756$ $a_5 = 1.21255;\ a_6 = -0.542446$	*Jarrahian et al* [22]

Table 2. Brief description of measured PVT data used for developing the revised equation

Parameter	Min.	Max.
Pressure (psi)	238.07	5181.31
Temperature (°F)	80.6	285.08
Tank Oil Gravity (°API)	0.52	1.015
Gas Specific Gravity (air=1)	9.5	49.4
Solution GOR (SCF/STB)	16.28	1311.82

6. Evaluation

The revised equation and all the 22 empirical correlations are tested against the present experimental PVT data described in Table 2. The following statistical parameters are used in the evaluation:

- Average Percent Error, *APE*:

$$APE = \frac{100}{N}\sum_{i=1}^{N}\frac{X_{measured} - X_{predicted}}{X_{measured}} \quad (4)$$

- Average Absolute Percent Error, *AAPE*:

$$AAPE = \frac{100}{N}\sum_{i=1}^{N}\left|\frac{X_{measured} - X_{predicted}}{X_{measured}}\right| \quad (5)$$

- Correlation Coefficient, R^2:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(X_{meaured} - X_{predicted})^2}{\sum_{i=1}^{N}(X_{measured} - X_{mean})^2} \quad (6)$$

- Root Mean Square Error , *RMSE*:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(X_{measured} - X_{predicted})^2} \quad (7)$$

Table 3. Complete list of measured PVT data used for developing the revised equation.

No.	Pressure, psi	Temperature, F	API Gravity	Gas gravity	RS, SCF/STB
1	541.1399	125.06	14.2	0.77	57.03824
2	1378.238	100.04	14.9	0.74	159.999
3	400.1243	120.02	14	0.75	42.105
4	550.1347	122	14.5	0.65	46.98918
5	2418.301	170.06	24	0.75	508.6284
6	2133.513	170.06	24	0.75	401.9624
7	1778.45	170.06	24	0.75	376.138
8	1422.342	170.06	24	0.75	225.9635
9	2527.631	200.12	27	0.54	389.4993
10	2658.665	188.06	29	0.54	430.257
11	3775.938	165.02	28	0.58	647.0696
12	1884.473	159.98	25	0.58	296.9806
13	1130.982	170.06	33.7	0.7	243.7037
14	782.201	170.06	33.7	0.7	164.0972
15	497.9068	170.06	33.7	0.7	103.0169
16	284.57	170.06	30.7	0.7	61.02418
17	3395.849	242.6	35.7	0.681	890.3804
18	2438.611	128.012	39.4	0.822	878.0296
19	1867.44	143.96	38.2	0.792	474.9444
20	1410.359	129.92	39.4	0.829	385.2888
21	1409.357	179.96	49.1	0.673	377.2608
22	3686.918	253.4	49	0.753	1239.571
23	1622.404	140	40.3	0.713	409.0361
24	3435.876	138.92	42.6	0.798	1183.263
25	425.1067	110.012	13.2	0.72	38.00678
26	350.0871	100.04	13.7	0.68	27.7893
27	310.0746	100.04	13.9	0.68	25.8244
28	300.0788	95	14.2	0.71	33.01032
29	285.0777	85.01	14.4	0.7	27.5086
30	500.1265	100.04	14.6	0.72	51.25582
31	668.17	96.97999	14.4	0.89	75.5083
32	238.0726	207.014	15	0.85	30.37174
33	1250.309	111.2	15	0.88	146.9184
34	950.2591	270.014	14.4	0.8	91.84504
35	698.1721	198.014	15	1.015	86.76437
36	512.1244	123.008	14.7	0.72	50.97512
37	600.1503	120.2	14.8	0.74	62.76452
38	300.0788	102.2	10.3	0.65	22.00688
39	285.0777	95	9.5	0.63	16.2806
40	310.0776	100.04	11	0.7	27.00334
41	515.1275	112.01	12	0.72	60.0698
42	600.1503	135.014	13	0.73	60.0698
43	414.1099	111.2	13.8	0.71	44.99621
44	525.1813	122	14	0.72	62.98908
45	318.0829	114.08	14.3	0.69	21.6139
46	702.1762	128.012	13.2	0.74	81.9644
47	666.1969	116.06	12	0.73	62.53996
48	611.1545	110.012	11.8	0.77	55.35404
49	555.1399	105.98	12	0.68	56.9821
50	510.1266	118.04	9.5	0.71	39.99975
51	405.1005	96.08	10.8	0.75	46.98918
52	435.2332	105.08	10.9	0.75	46.98918
53	522.2798	113	10	0.72	52.99616
54	513.1399	116.06	11	0.7	33.1226
55	622.1513	100.04	10.7	0.65	58.77858
56	633.1627	100.04	10	0.64	52.7716

No.	Pressure, psi	Temperature, F	API Gravity	Gas gravity	RS, SCF/STB
57	710.1555	100.04	11	0.64	62.14698
58	1501.38	134.06	36.9	0.809	407.015
59	2935.735	227.012	44.2	0.811	947.8116
60	2415.544	148.01	25	0.55	359.9697
61	2775.692	278.006	48.4	0.787	943.152
62	1937.513	159.98	26	0.564	313.2612
63	450.1472	120.2	26	0.52	71.07324
64	491.4218	132.08	30	0.66	96.5608
65	4991.254	185	28.1	0.58	893.9172
66	2158.539	105.98	38.6	0.775	645.61
67	2650.686	220.01	46.1	0.752	823.0124
68	2271.569	175.01	41.5	0.832	711.8553
69	1200.301	145.004	28	0.62	209.1215
70	1712.425	222.8	37.3	0.758	392.98
71	2127.565	244.4	40.5	0.808	550.7334
72	3487.871	162.014	39	0.839	1182.982
73	2884.725	159.98	46.1	0.75	965.608
74	1690.446	140	40.3	0.703	468.2076
75	1387.349	180.014	46.5	0.763	456.1038
76	2886.757	150.08	38.4	0.713	782.0302
77	455.1088	125.6	26.8	0.68	115.087
78	1000.311	80.6	29	0.72	227.9845
79	940.2487	80.6	29	0.72	224.953
80	2620.684	180.014	29	0.61	439.5762
81	1317.306	135.014	25.1	0.72	221.753
82	2984.684	210.2	27.8	0.63	666.6625
83	1880.497	138.2	28.2	0.67	419.9272
84	2300.57	170.06	29.1	0.73	580.7122
85	5181.306	177.98	36.1	0.661	1311.823
86	3020.808	204.08	40.5	0.716	887.0119
87	2473.619	190.04	41.6	0.813	756.2058
88	1852.497	110.012	41.4	0.812	617.54
89	2000.477	212	41.4	0.81	673.68
90	1524.332	151.7	40.3	0.819	471.576
91	2103.627	156.2	40.6	0.795	617.54
92	2534.653	264.2	49.4	0.724	916.7662
93	894.2591	105.98	37.6	0.833	257.1212
94	2996.725	132.98	46.7	0.75	1094.73
95	2765.747	131	44.4	0.762	962.2395
96	2521.596	265.01	43	0.8	848.8368
97	844.2072	204.98	25.6	0.72	155.5078
98	3074.777	140	25.4	0.75	600.698
99	572.1865	165.2	26.3	0.76	112.8414
100	2124.518	285.08	26.3	0.73	421.05

The statistical results are summarized in Table 4. As indicated, the revised equation (besides its simplicity) gives the best performance based on the value of *AAPE*, R^2 and *RMSE*. Arabloo *et al.* [21] correlation is determined as the second best one. The correlations of Glaso [4], Vazquez-Beggs [5], Al-Marhoun [6], Hasan *et al.* [9], Kairy *et al.* [13], Levitan-Murtha [14], Mazandarani–Asghari [18], and Baniasadi *et al.* [24] are tended to under-predict measured data, whereas the correlations of Elsharkawy-Alikhan [10], Petrosky-Farshad [11], Dindoruk-Christman [16], show a tendency to predict measured Rs values over. The modified Al-Marhoun [19] correlation gives better results than the original [6] one. No improvement is obtained when comparing Standing [2] correlation with the modified one [19]. As can be seen in Table 4, the revision made in this study results in an improvement of 30% over Baniasadi *et al*. [24] correlation.

Table 4. Statistical evaluation of empirical solution GOR correlations for measured data used for developing the revised equation

Correlation	*APE*	*AAPE*	R^2	*RMSE*
Standing[2]	5.17912	12.838	0.967291	63.0903
Glaso[4]	11.32628	24.32508	0.8912077	115.069
Vazquez-Beggs[5]	14.10149	15.7581	0.954245	74.61895
Al-Marhoun[6]	33.31635	34.70558	0.84605	136.8772
Dokla-Osman [7]	0.173198	22.05082	0.9238804	96.25142
Macary-ElBatanoney[8]	-3.086735	27.36566	0.8872571	117.1396
Hasan *et al.*[9]	17.9851	19.4445	0.9534331	75.28321
Elsharkawy-Alikhan[10]	-37.54764	41.02809	0.6433356	208.3478
Petrosky-Farshad [11]	-23.51855	43.48007	0.9188034	99.40949
Frashad *et al.*[12]	9.66001	16.2354	0.9524991	76.02961
Kairy *et al.*[13]	35.04746	54.34214	0.482917	250.8645
Levitan-Murtha[14]	11.53503	15.03186	0.9599586	69.80939
Al-Shammasi[15]	7.351121	14.61087	0.9637171	66.45234
Dindoruk-Christman[16]	-9.086775	41.71082	0.8811901	120.2501
Hemmati-Kharrat[17]	4.197917	11.91203	0.975088	55.06338
Mazandarani-Asghari[18]	32.99119	33.9753	0.9071871	106.2829
Modified Al-Marhoun[19]	12.5736	17.0748	0.94451	82.1771
Modified Standing[19]	-1.86921	14.4278	0.94431	82.3811
Ikiensikimama-Ajienka[20]	1.770827	13.19303	0.9486159	79.08126
Arabloo *et al.*[21]	0.153493	10.22230	0.979001	50.111
Jarrahian *et al.*[22]	4.642792	11.79443	0.9781836	51.5289
Baniasadi *et al.*[24]	11.44833	13.17579	0.9611001	68.80708
This Study	-2.238885	**10.01868**	**0.9832234**	**45.18673**

For further evaluation, all the empirical correlations are tested against two additional databases not used in the revision process. Table 5 displays the statistical results for the 15 data points presented by Zamani *et al.* [25]. The results reveal that based on *AAPE*, Al-Shammasi [27] correlation gives the best performance followed by the suggested revised equation, whereas based on values of R^2 and *RMSE*, Arabloo *et al*. [21] correlation shows the best performance followed by both the revised equation and Mazandarani-Asghari [18] correlation. However, Table 1 indicates that Arabloo *et al.* [21], Al-Shammasi [27] and Mazandarani-Asghari [18] correlations had a complex structure and required multiple tuning parameters as compared to the revised equation. The second database used for evaluation consists of 120 measured PVT data from unpublished* sources. The statistical results of all correlations are shown in Table 6. The values of *AAPE* indicate that the best performance is given by Hemmati-Kharrat [17] correlation followed by the revised equation. Based on R^2 and *RMSE*, the best performance is given by modified Standing [19] correlation followed by modified Al-Marhoun [19] and then by the revised equation. Based on simplicity, Table 1 indicates that Hemmati-Kharrat [17], modified Standing [19] and modified Al-Marhoun [19] correlations require five tuning constants whereas the revised equation requires only two constants. Comparison the performance of the revised equation with the original one of Baniasadi *et al.* [24] shows an improvement exceeds 60%.

For completeness, Eq. (3) along with those listed in Table 1 and the statistical results are forwarded to the 132 participating engineers. The feedback indicates 100% agreement with the analysis and results of the present work. Other indicators from their feedback are the importance of: (1) publishing the complete set of measured data and (2) documenting all the empirical correlations, which will be an excellent contribution to future research in development and evaluation.

Table 5. Statistical evaluation of empirical solution GOR correlations using Zamani *et al.* measured data

Correlation	*APE*	*AAPE*	*R^2*	*RMSE*
Standing[2]	3.85663	8.00294	0.728031	136.5552
Glaso[4]	28.35018	28.35018	0.1512228	241.2374
Vazquez-Beggs[5]	16.19441	16.19441	0.59389	186.2905
Al-Marhoun[6]	-8.09961	11.24091	0.888311	87.51023
Dokla-Osman [7]	-28.22058	31.53982	0.2842595	296.7387
Macary-ElBatanoney[8]	8.923435	10.57353	0.8431308	103.7091
Hasan *et al.*[9]	9.666306	9.857312	0.6421876	156.6302
Elsharkawy-Alikhan[10]	-15.01539	17.10919	0.786592	120.9637
Petrosky-Farshad [11]	13.23558	13.23558	0.5645519	172.7889
Frashad *et al.*[12]	6.92751	8.362669	0.840341	104.6530
Kairy *et al.*[13]	-27.25072	29.60984	0.1207997	389.0872
Levitan-Murtha[14]	11.19403	11.45286	0.5524782	175.168
Al-Shammasi[15]	5.568124	**5.929737**	0.8286732	108.3828
Dindoruk-Christman[16]	14.77543	14.77543	0.6671861	151.0597
Hemmati-Kharrat[17]	5.790189	7.899983	0.8013043	116.7191
Mazandarani-Asghari[18]	-3.123164	7.762594	0.9058308	94.35302
Modified Al-Marhoun[19]	4.37311	10.05351	0.6915241	145.4142
Modified Standing[19]	5.27441	11.20725	0.600101	165.5853
Ikiensikimama-Ajienka[20]	5.290437	8.16771	0.6924479	145.2135
Arabloo *et al.*[21]	-7.496915	8.523624	**0.944888**	**61.47109**
Jarrahian *et al.*[22]	-0.1121374	7.037467	0.838750	105.1469
Baniasadi *et al.*[24]	19.05	19.0511	0.44272	195.471
This Study	1.525	7.01010	0.90422	93.5801

Table 6. Statistical evaluation of empirical solution GOR correlations using 120 unpublished measured PVT data

Correlation	*APE*	*AAPE*	*R^2*	*RMSE*
Standing[2]	6.10421	11.9755	0.92963	108.4471
Glaso[4]	14.3703	25.4696	0.65781	238.2492
Vazquez-Beggs[5]	-17.2906	25.1890	0.58923	261.0281
Al-Marhoun[6]	0.88258	12.7629	0.81388	175.7058
Dokla-Osman [7]	3.0962	19.4711	0.75181	202.8791
Macary-ElBatanoney[8]	19.8511	22.3143	0.68331	229.2093
Hasan *et al.*[9]	12.7515	13.4812	0.90621	124.7284
Elsharkawy-Alikhan[10]	-6.13691	18.0407	0.8055	179.6473
Petrosky-Farshad [11]	-0.68371	22.3885	0.8406	162.5913
Frashad *et al.*[12]	8.42076	11.5309	0.9386	100.909
Kairy *et al.*[13]	-31.3689	50.0122	0.2681	585.4768
Levitan-Murtha[14]	11.4764	12.7781	0.8926	133.4924
Al-Shammasi[15]	8.95621	14.1276	0.89511	131.8958
Dindoruk-Christman[16]	13.8068	18.0361	0.7539	202.0086
Hemmati-Kharrat[17]	5.85961	**8.29472**	0.9178	116.7279
Mazandarani-Asghari[18]	4.62551	14.7095	0.8953	131.7723
Modified Al-Marhoun[19]	3.50286	9.34784	0.9404	98.43771
Modified Standing[19]	1.69115	10.1191	**0.9459**	**94.6871**
Ikiensikimama-Ajienka[20]	5.71622	10.5713	0.9278	109.4528
Arabloo *et al.*[21]	-1.7400	12.2107	0.8853	137.1491
Jarrahian *et al.*[22]	4.0051	10.6531	0.9207	114.6599
Baniasadi *et al.*[24]	17.9493	18.1074	0.7072	220/3937
This Study	4.5414	9.1251	0.9388	99.2211

* *A complete list of these data can be obtained from the Journal on call.*

7. Conclusion

The on-line questionnaire is designed and distributed to 132 engineers (most of them are working in the field near the oil wells) to determine what they prefer to estimate solution GOR. Analysis of this questionnaire indicates their desire to use the empirical equation with a simple structure and acceptable accuracy. Among all the existing empirical correlations, *Baniasadi et al.* [24] are considered as the simplest one since it has only one tuning parameters whereas all the other correlations require at least five parameters. Testing the accuracy of this correlation against three different databases shows high values of *AAPE* and *RMSE*, the low value of R^2 and a tendency to under-predict the measured R_S values. An improved revision to this correlation is suggested in this study, which results in better prediction as compared to the original one and to the existing correlations.

Nomenclature

AAPE	*Absolute average percent error*	*RMSE*	*Root mean square error*
APE	*Average percent error*	R_S	*Solution gas-oil ratio, SCF/STB*
API	*Stock-tank oil gravity ,°API*	$X_{measured}$	*Measured solution gas-oil ratio, SCF/STB*
FVF	*Formation volume factor*	$X_{predicted}$	*Predicted solution gas-oil ratio, SCF/STB*
GOR	*Gas oil ratio, SCF/STB*	*T*	*Temperature, °F*
N	*number of data*	*Tr*	*Temperature, °R (T+460)*
P_b	*Bubble point pressure. Psi*	γ_g	*Gas specific gravity (air=1)*
PVT	*Pressure-volume-temperature*	γ_o	*Oil specific gravity (water=1)*
R^2	*Correlation coefficient*		

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