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Comparison of Dead Oil Viscosity and Gas Solubility Empirical Correlations

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Abstract— Reservoir fluid properties are very important physical properties that control the flow of oil through porous media and pipes. They used comprehensively in most of petroleum engineering applications such as drilling engineering, reservoir engineering, and production engineering. Perfectly, these properties should be obtained from actual laboratory measurements on samples collected from the bottom of the wellbore or at the surface. Quite often, however, these measurements are either not available, or very costly to obtain. For these reasons, it is necessary for the petroleum engineer to find an accurate, quick and reliable method for predicting the reservoir fluid properties. Therefore, the concept of numerical correlation equations has been proposed to the petroleum industry to alleviate all difficulties in reservoir fluid properties determination.

For this study, more than 50 published black oil empirical correlations for dead oil viscosity and gas oil ratio were collected and summarized from 1946 till now in chronological order. The comparison results are presented graphically and also summarized in tables that can be used to guide reservoir fluid properties correlations users in selecting the most appropriate black oil empirical correlations.

Keywords— Reservoir fluid properties; empirical correlations; dead oil viscosity; gas solubility

I. INTRODUCTION

Reservoir fluid properties such as oil bubble point pressure, oil formation volume factor, solution gas-oil ratio, gas formation volume factor, and oil viscosities are very important in reservoir engineering computations. Accurate reservoir fluid properties are very important in reservoir engineering computations and a requirement for all types of petroleum calculations such as determination of initial hydrocarbons in place, optimum production schemes, ultimate hydrocarbon recovery, design of fluid handling equipment and enhanced oil recovery methods.

Actually, the reservoir fluid properties depend on pressure, temperature, and chemical compositions. For the development of a correlation, geological condition is considered important because the chemical composition of crude oil differs from region to region. For this reason, it is difficult to obtain the same accurate results through empirical correlations for different oil samples having different physical and chemical characteristics. Engineers should be modified these correlations for their application by recalculating the correlation constants for the region of interest.

The purpose of this work is to study the performance of dead oil viscosity and gas oil ratio models available in the literature, based on huge data sets collected from different published literature papers and PVT reports from different oil fields in the Saudi Arabia and Yemen.

II. LITERATURE REVIEW

The history of reservoir fluid properties empirical correlations in the petroleum industry started more than five decades ago. Several reliable empirical correlations for calculating the reservoir fluid properties such as crude oil viscosity, oil formation volume factor, oil bubble point pressure, solution gas-oil ratio, gas formation volume factor and isothermal compressibility have been proposed over the years.

Since the 1940's engineers have realized the importance of developing empirical correlation for dead oil viscosity and gas oil ratio. Studies carried out in this field resulted in the development of new correlations. Several studies of this kind were published by Beal (1942)[1], Standing (1947)[2] and Beggs and Robinson (1975)[3].

For several years, these correlations were the only source available for estimating dead oil viscosity and gas oil ratio when experimental data were unavailable. In the last thirty years there has been an increasing interest in developing new correlations for crude oils obtained from the various regions in the world. Glaso (1980)[4],Vazquez and Beggs (1980)[5], Ng and Egbogah (1983)[7], Kaye (1985)[8], Al-Khafaji et al (1987)[9], Al-Marhoun (1988)[10], Rollins et al (1990)[11], Kartoatmodjo and Schmidt (1991)[12], Labedi (1992)[13], Petrosky and Farshad (1993)[14], De Ghetto et al (1994)[15], Petrosky and Farshad (1995)[16], Farshad et al (1996)[17], Hanafy et al (1997)[18], Elsharkawy and Alikhan (1997)[19], Velarde et al (1997)[20], Bennison (1998)[21], Al-Shammasi (1999)[22], Elsharkawy and Alikhan (1999)[23], Bergman (2000)[24], Whitson and Brule (2000)[24], Elsharkawy and Gharbi (2001)[25], Dindoruk and Christman (2001)[26],Naseri et al (2005)[27], Hossain et al (2005)[28], Hemmati and Kharrat (2007)[29], Mazandarani and Asghari (2007)[30], Ikiensikimama and Ogboja (2009)[31], Khamechi et al (2009)[32], Oyedeko and Ulaeto (2011)[33], Hassan (2011)[34], Naseri et al (2012)[35] and Ulaeto and Oyedeko (2014)[36] carried out some of the recent studies.

A summary of dead oil viscosity and gas oil ratio published empirical correlations are provided in appendix B and appendix C.

III. RESEARCH METHODOLOGY

To achieve this work, MATLAB statistical error analysis and MATLAB cross plot error analysis were used to compare the performance and accuracy of dead oil viscosity and gas oil ratio models. The statistical parameters used for comparison are: average absolute percent relative error, standard deviation and correlation coefficient.

IV. DATA ACQUISITION AND ANALYSIS

A huge data sets used for this work were collected from different published literature papers and conventional PVT reports that derive the various fluid properties through differential liberation process from different oil fields in the Saudi Arabia and Yemen.

Each data set contains bubble point pressure, formation volume factor, total solution gas oil ratio, oil gravity, crude oil density, average gas gravity, dead oil viscosity, reservoir temperature, boiling point temperature and reservoir pressure. Statistical distributions such as maximum, minimum, mean, range, mid-range and standard deviation of the input data are shown in Tables1.

As can be seen from Table 1 bubble-point pressure of the data ranged between 110.416 psia to 8647 psia. For formation volume factor, the data ranged between 1.028 bbl/stb to 2.588 bbl/stb. Corresponding solution gas oil ratio ranged from 4.951 scf/stb to 2637 scf/stb. Similar to solution gas oil ratio, oil gravity, crude oil density and average gas gravity varied between 15.3 to 63.7 API, 25.022 to 62.37 lb/ft^3 and 0.511 to 1.731, respectively. For dead oil viscosity, the data ranged between 0.056 cp to 1139.8 cp. The reservoir temperature and boiling point temperature ranged between 58 ^{0}F to 294 ^{0}F, 590.8 ^{0}F to 1557.2 ^{0}F respectively. Corresponding reservoir pressure ranged from 165 psia to 2637 psia.

The data sets have been divided into the following three different API gravity classes: heavy oils for ^{0}API< 22, medium oils for 22≤ ^{0}API< 31 and light oils for ^{0}API≥31.

Table 1 Statistical descriptions of data sets

Property	Min	Max	Mean	Range	Mid-Ran.	Std
P_b	110.416	8647	1809.3	8636.6	4328.7	1151.2
β_o	1.028	2.588	1.330	1.56	1.808	0.230
R_s	4.951	2637	534	2632	1321	389.4
API	15.3	63.7	35.31	48.4	39.5	7.5
ρ_o	25.022	62.37	48.58	37.3476	43.6962	5.8
γ_g	0.511	1.731	0.896	1.22	1.121	0.167
μ_o	0.056	1139.88	18.1	1139.8	570	56.4
T_f	58	294	172	236	176	49.1
T_b	590.8	1557.2	1076.8	966.4	1074	223.7
P	165	7411.54	2911.7	7246.54	3788.27	1631.7

V. RESULTS AND DISCUSSION

To compare the performance and accuracy of dead oil viscosity and gas oil ratio correlations statistical and graphical error analysis were performed.

5.1 Dead Oil Viscosity Correlations Assessment

Most of dead oil viscosity empirical correlations are functions of oil gravity (API) and reservoir temperature (T). 29 methods for calculating dead oil viscosity have been evaluated using a large database consisting of data from oil PVT reports and literature sources.

The best three correlations for each class and for the whole range of API gravity for dead oil viscosity have been summarized in Tables 2.

As can be seen from Tables 2, Glaso (1980) correlation outperforms the most common published empirical correlations followed by Bergman (2000) and Kartoatmodjo and Schmidt (991) correlations for whole data sets. Glaso (1980) correlation has an average absolute error of 24.04%, standard deviation of 34.83% and correlation coefficient of 0.856.

Dead oil viscosity correlations statistical analysis for heavy oils indicate that Beal-l (1947) correlation model is the best performing correlation model with least average absolute error of 41.06%, least standard deviation of 50.73% and the highest correlation coefficient of 0.811 followed by Bennison correlation (1998) and Elsharkawy and Alikhan (1999) correlations.

The statistical analysis for dead oil viscosity correlations for medium oils indicate De Ghetto et al-3-(1994) correlation outperforms the dead oil viscosity published empirical correlations with least average absolute error of 52.26%, least standard deviation of 54.32% and the highest correlation coefficient of 0.780 followed by Naseri et al-1 (2005) and Naseri et al-2 (2012) correlations.

For light oils, the statistical analysis for dead oil viscosity correlations indicate that Naseri et al-2 (2012) correlation model is the best performing correlation model with least average absolute error of 37.37%, least standard deviation of 41.14% and the highest correlation coefficient of 0.832 followed by Naseri et al-1 (2005) and Kaye-2 (1985) correlations.

The statistical accuracy of for all correlations dead oil viscosity are summarized in Table A1 in Appendix A.

The crossplots of estimated values against experimental values for the best three performing dead oil viscosity correlations of Glaso, Bergman and Kartoatmodjo and Schmidt are presented in Figures 1 through 3.

Table 2 Dead oil viscosity correlations assessment summary

Dead oil viscosity correlations assessment summary for whole data sets					
Correlation	Year	No. of data	AARE	Std	R^2
Glaso	1980	3000	24.04	34.83	0.856
Bergman	2000	3000	24.42	39.86	0.854
Kartoatmodjo and Schmidt	1991	3000	24.60	45.21	0.844
Dead oil viscosity correlations assessment summary for heavy oils ^{0}API< 22					
Beal-l	1946	115	41.06	50.73	0.811
Bennison	1998	115	41.76	54.83	0.809
Elsharkawy and Alikhan	1999	115	43.18	58.81	0.806
Dead oil viscosity correlations assessment summary for medium oils 22≤ ^{0}API< 31					
De Ghetto et al-3	1994	627	52.26	54.32	0.780
Naseri et al-1	2005	627	54.33	55.20	0.720
Naseri et al-2	2012	627	54.89	66.37	0.726
Dead oil viscosity correlations assessment summary for light oils ^{0}API≥31					
Naseri et al-2	2012	2243	37.37	41.14	0.832
Naseri et al-1	2005	2243	40.29	47.77	0.825
Kaye-2	1985	2243	40.34	55.93	0.823

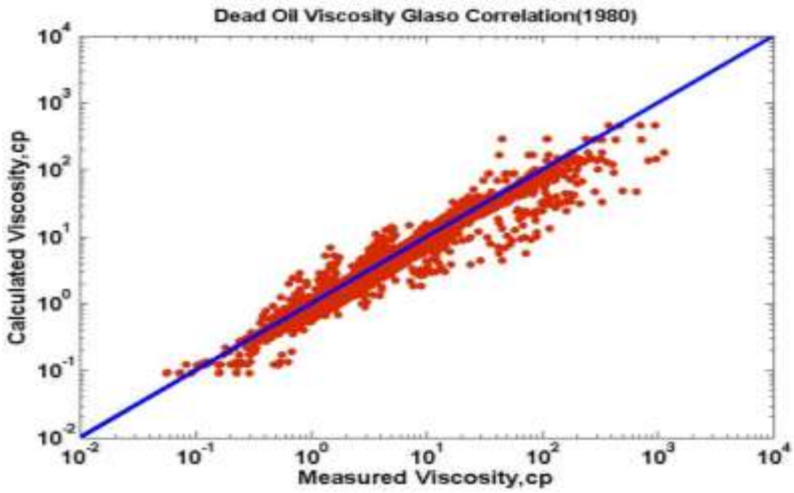

Figure 1 Accuracy of Glaso correlation

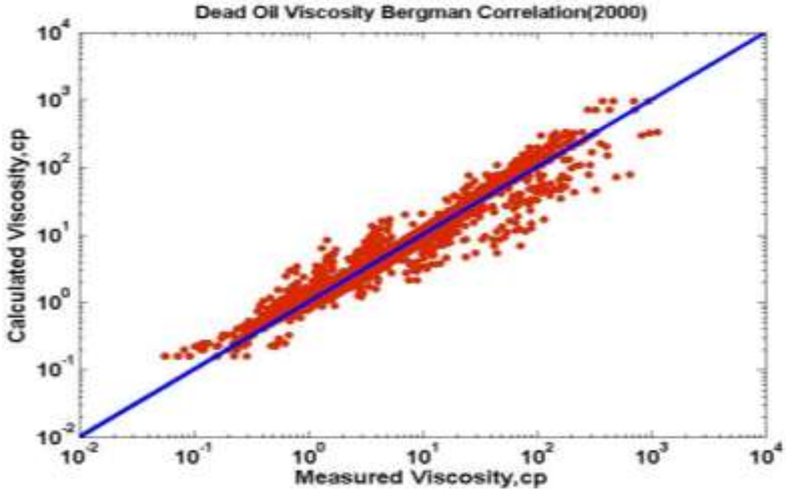

Figure 2 Accuracy of Bergman correlation

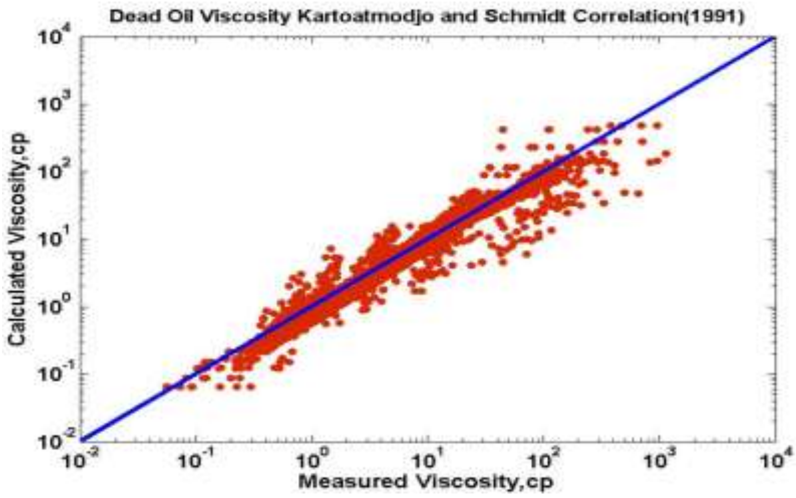

Figure 3 Accuracy of Kartoatmodjo and Schmidt correlation

5.2 Solution Gas-Oil Correlations Assessment

A total of 22 solution gas-oil ratio empirical correlations have been evaluated using a large database consisting of data from oil PVT reports and literature sources. Both statistical and graphical comparative were used to check the accuracy of solution gas-oil ratio correlations.
The best three correlations for each class and for the whole range of API gravity for solution gas-oil ratio have been summarized in Tables3.
As can be observed from this table, for the whole range of API gravity, the statistical analysis show Vazquez and Beggs-1 (1980) correlation has the least average absolute error, least standard deviation and the highest correlation coefficient followed by Kartoatmodjo and Schmidt-1 (1991) and Standing (1947) correlations. Vazquez and Beggs-1 (1980) correlation has an average absolute error of 20.36%, standard deviation of 34.91% and correlation coefficient of 0.922.
Solution gas-oil ratio correlations statistical analysis for heavy oils indicate that Vazquez and Beggs-1 (1980) correlation model is the best performing correlation model with least average absolute error of 20.85%, least standard deviation of 20.52% and the highest correlation coefficient of 0.778 followed by Kartoatmodjo and Schmidt-1 (1991) and Farshad et al-1 (1996) correlations.
For medium oils, the statistical analysis for all correlations indicate that Kartoatmodjo and Schmidt-1 (1991) correlation model is the best performing correlation model with least average absolute error

of 21.67%, least standard deviation of 30.67% and the highest correlation coefficient of 0.839 followed by Vazquez and Beggs-1 (1980) and Vazquez and Beggs-2 (1980) correlations.

The statistical analysis for solution gas-oil ratio correlations for light oils indicate Vazquez and Beggs-1 (1980) correlation outperforms the solution gas-oil ratio published empirical correlations with least average absolute error of 20.04 %, least standard deviation of 35.05 % and the highest correlation coefficient of 0.904 followed by Kartoatmodjo and Schmidt(1991) and Standing (1947) correlations.

The statistical accuracy of for all solution gas-oil ratio correlations are summarized in Tables A2 in Appendix A.

The crossplots of estimated values against experimental values for the best three performing solution gas-oil ratio correlations of Vazquez and Beggs-1, Kartoatmodjo and Schmidt-1 and Standing are presented in Figures 4 through 6.

Table 3 Solution gas-oil ratio correlations assessment summary

Solution gas-oil ratio correlations assessment summary for whole data sets					
Correlation	Year	No. of data	AARE	Std	R2
Vazquez and Beggs- 1	1980	3000	20.36	34.91	0.922
Kartoatmodjo and Schmidt- 1	1991	3000	20.58	38.72	0.920
Standing	1947	3000	21.25	38.86	0.917
Solution gas-oil ratio correlations assessment summary for heavy oils ^{0}API< 22					
Vazquez and Beggs- 1	1980	115	20.85	20.52	0.778
Kartoatmodjo and Schmidt- 1	1991	115	21.06	27.36	0.764
Farshad et al-1	1996	115	21.53	27.44	0.755
Solution gas-oil ratio correlations assessment summary for medium oils 22≤ ^{0}API< 31					
Kartoatmodjo and Schmidt- 1	1991	627	21.67	30.67	0.839
Vazquez and Beggs- 1	1980	627	22.39	35.12	0.836
Vazquez and Beggs-2	1980	627	22.93	36.24	0.838
Solution gas-oil ratio correlations assessment summary for light oils ^{0}API≥31					
Vazquez and Beggs- 1	1980	2243	20.04	35.05	0.904
Kartoatmodjo and Schmidt- 1	1991	2243	20.28	36.39	0.902
Standing	1947	2243	20.59	39.14	0.900

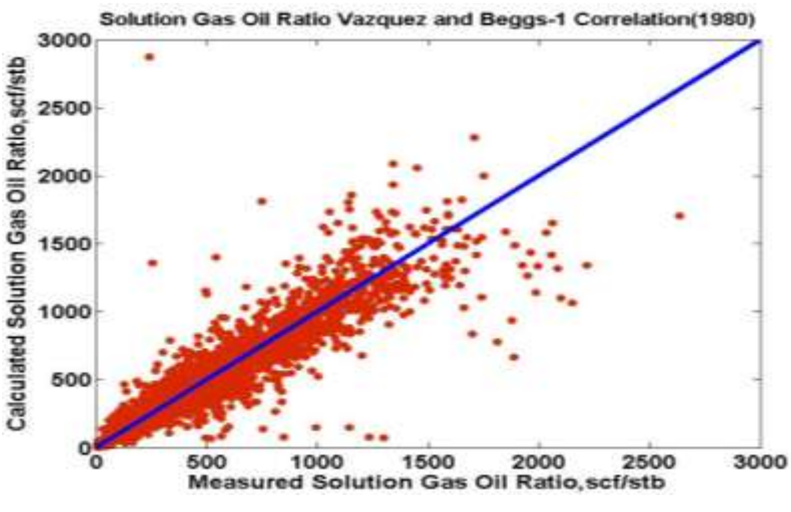

Figure 4 Accuracy of Vazquez and Beggs -1 correlation

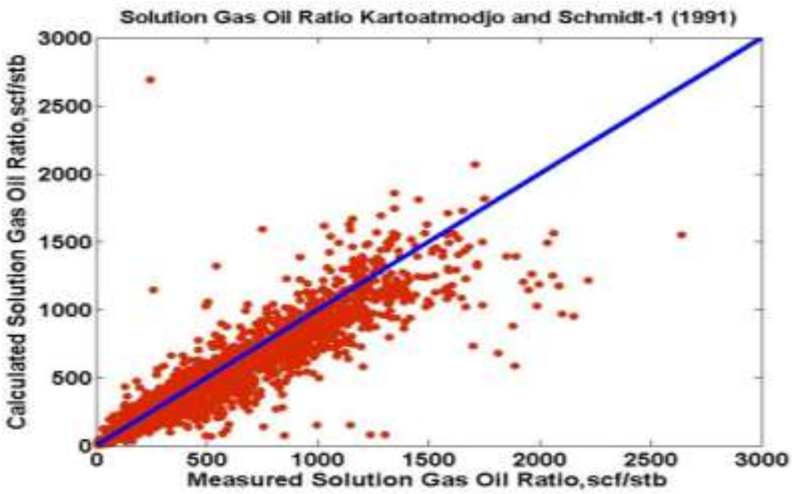

Figure 5 Accuracy of Kartoatmodjo and Schmidt-1 correlation

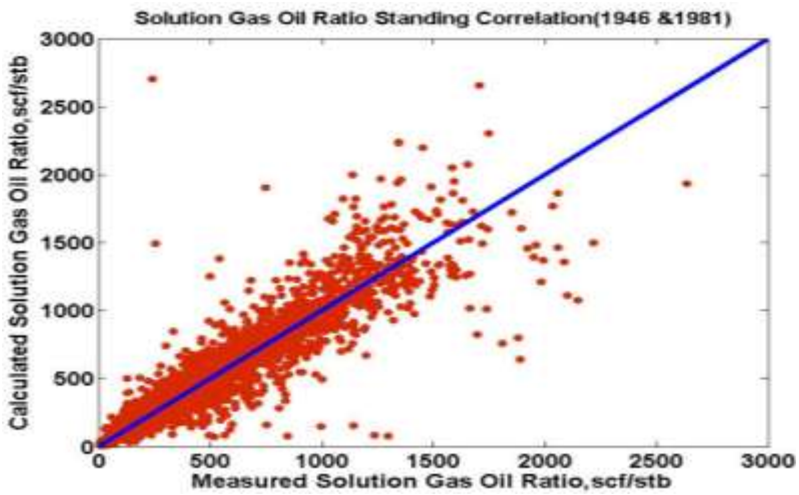

Figure 6 Accuracy of Standing correlation

VI. CONCLUSIONS

Based on the analysis of the results obtained in this research study, the following conclusions can be made:-

1- Totally, 51 published black oil empirical correlations for dead oil viscosity and gas oil ratio were collected, summarized and evaluated.

2- For dead oil viscosity correlations, for whole data sets, Glaso (1980) correlation outperforms the most common published empirical correlations followed by Bergman (2000) and Kartoatmodjo and Schmidt (991) correlations.

3- Dead oil viscosity correlations statistical analysis for heavy oils indicate that Beal-l (1947) correlation model is the best performing correlation model with least average absolute error, least standard deviation and the highest correlation coefficient followed by Bennison Correlation (1998) and Elsharkawy and Alikhan (1999) correlations.

4- The statistical analysis for dead oil viscosity correlations for medium oils show that De Ghetto et al-3- (1994) correlation outperforms the published empirical correlations with least average absolute error followed by Naseri et al-1 (2005) and Naseri et al-2 (2012) correlations.

5- For light oils, the statistical analysis for dead oil viscosity correlations indicate that Naseri et al-2 (2012) correlation model is the best performing correlation model followed by Naseri et al-1 (2005) and Kaye-2 (1985) correlations.

6- For solution gas-oil ratio correlations, for whole data sets, the statistical analysis show Vazquez and Beggs-1 (1980) correlation has the least average absolute error, least standard deviation and the highest correlation coefficient followed by Kartoatmodjo and Schmidt-1 (1991) and Standing (1947) correlations.

7- Solution gas-oil ratio correlations statistical analysis for heavy oils indicate that Vazquez and Beggs-1 (1980) correlation model is the best performing correlation model followed by Kartoatmodjo and Schmidt-1 (1991) and Farshad et al-1 (1996) correlations.

8- For medium oils. the statistical analysis for all correlations indicate that Kartoatmodjo and Schmidt-1 (1991) correlation model is the best performing correlation model with least average absolute error, least standard deviation and the highest correlation coefficient followed by Vazquez and Beggs-1 (1980) and Vazquez and Beggs-2 (1980) correlations.

9- The statistical analysis for solution gas-oil ratio correlations for light oils indicate Vazquez and Beggs-1 (1980) correlation outperforms the solution gas-oil ratio published empirical correlations followed by Kartoatmodjo and Schmidt-1(1991) and Standing (1947) correlations.

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Nomenclature

μ_{do} = Dead oil viscosity, cp
K_w = Watson characterization factor
γ_o = Oil specific gravity
P_b = Bubble- point pressure, psia
β_o = Formation volume factor at the bubble- point pressure, RB/STB
R_s = Solution gas oil ratio, SCF/STB
API = Oil density
ρ_o = Crude oil density,lb/ft^3
γ_g = Gas specific gravity (air=1.0)
T = Reservoir temperature, degrees Fahrenheit
P = Reservoir pressure,psia
γ_{g100} = Gas gravity (air = 1) that would result from separator conditions of 100 psig
γ_{gsep} = Gas gravity obtained at separator conditions.
P_{sep} = Actual separator pressure, psia
T_{sep} = Actual separator temperature, ^{0}F
R_{sf} = Separator solution gas oil ratio, SCF/STB.
γ_{gcorr} = Gas Specific gravity at separator pressure of 114.7 psia.
Min = Minimum
Max = Maximum
AARE = Average absolute percent relative error
Std = Standard deviation error
R^2 = Correlation coefficient

Appendix A

Table A1 Statistical error analysis for dead oil viscosity correlations for whole data

No.	Correlation	Year	No. of data	AARE	Std	R^2
1	Beal-l	1946	3000	25.41	48.16	0.792
2	Beal-2	1946	3000	32.59	46.97	0.798
3	Beggs and Robinson	1975	3000	48.44	63.99	0.732
4	Glaso	1980	3000	24.04	34.83	0.856
5	Ng and Egbogah	1983	3000	29.11	40.53	0.786
6	Kaye-1	1985	3000	133.27	105.06	0.798
7	Kaye-2	1985	3000	45.14	72.83	0.754
8	Al-Khafaji et al	1987	3000	27.64	47.07	0.674
9	Kartoatmodjo and Schmidt	1991	3000	24.60	45.21	0.844
10	Labedi-1	1992	3000	57.23	102.22	0.517
11	Labedi-2	1992	3000	41.34	57.97	0.733
12	De Ghetto et al-1	1994	3000	627.35	346.60	0.727
13	De Ghetto et al-2	1994	3000	104.70	88.13	0.755
14	De Ghetto et al-3	1994	3000	53.49	75.38	0.644
15	De Ghetto et al-4	1994	3000	42.20	48.40	0.687
16	De Ghetto et al-5	1994	3000	30.58	36.94	0.782
17	Petrosky and Farshad	1995	3000	29.23	38.19	0.686
18	Bennison	1998	3000	63.69	45.34	0.794
19	Elsharkawy and Alikhan	1999	3000	27.02	42.75	0.800
20	Bergman	2000	3000	24.42	39.86	0.854
21	Whitson and Brule	2000	3000	27.23	37.19	0.676
22	Elsharkawy and Gharbi	2001	3000	33.26	49.82	0.744
23	Naseri et al-1	2005	3000	40.58	27.70	0.744
24	Hossain et al	2005	3000	68.86	52.90	0.796
25	Ikiensikimama	2009	3000	54.01	22.70	0.771
26	Oyedeko and Ulaeto	2011	3000	35.89	38.72	0.687
27	Naseri et al-2	2012	3000	32.05	30.56	0.606
28	Ulaeto and Oyedeko-1	2014	3000	76.98	125.01	0.507
29	Ulaeto and Oyedeko-2	2014	3000	57.62	139.28	0.273

Table A2 Statistical error analysis for solution gas oil ratio correlations for whole data

No.	Correlation	Year	No. of data	AARE	Std	R^2
1	Standing	1947	3000	21.25	38.86	0.917
2	Glaso	1980	3000	24.13	39.73	0.899
3	Vazquez and Beggs-1	1980	3000	20.36	34.91	0.922
4	Vazquez and Beggs-2	1980	3000	22.40	33.21	0.910
5	Al-Marhoun	1988	3000	30.07	48.90	0.835
6	Rollins et al	1990	3000	30.32	45.86	0.835

7	Kartoatmodjo and Schmidt-1	1991	3000	20.58	38.72	0.920
8	Kartoatmodjo and Schmidt-2	1991	3000	25.38	47.27	0.912
9	Petrosky and Farshad	1993	3000	60.85	205.82	0.892
10	De Ghetto et al	1994	3000	36.23	51.74	0.907
11	Farshad et al-1	1996	3000	25.57	41.82	0.896
12	Farshad et al-2	1996	3000	38.25	103.29	0.873
13	Hanafy et al	1997	3000	42.12	74.41	0.829
14	Elsharkawy and Alikhan-1	1997	3000	27.68	39.83	0.866
15	Elsharkawy and Alikhan-2	1997	3000	46.31	56.00	0.877
16	Al-Shammasi	1999	3000	35.12	83.72	0.912
17	Velarde et al	1999	3000	38.36	30.19	0.881
18	Dindoruk and Christman	2001	3000	35.87	69.77	0.824
19	Hemmati and Kharrat	2007	3000	26.11	41.81	0.910
20	Mazandarani and Asghari	2007	3000	26.83	44.22	0.876
21	Khamehchi et al	2009	3000	24.70	30.27	0.913
22	Hassan	2011	3000	35.34	51.22	0.901

Appendix B

Dead oil viscosity empirical correlations summary

Beal-1 Correlation (1942)[1&6]

$$\mu_{do} = (0.32 + \frac{1.8 * 10^7}{API^{4.58}})(\frac{360}{T+200})^A$$

$$A = exp(2.30285 * (0.43 + \frac{8.33}{API})$$

Beal-2 Correlation (1942)[1&6]

$$\mu_{do} = 10^X$$

$$X = A + B + C$$

$$A = 10.5439 - 0.44521 * API + 0.66470 * 10^{-2} * API^2 - 0.335972 * 10^{-4} * API^3$$

$$B = -0.470516 * 10^{-1} * T + 0.831557 * 10^{-4} * T^2 - 0.789049 * 10^{-4} * T^7$$

$$C = 0.1352 * 10^{-2} * T * API - 0.1145 * 10^{-4} * API^2 * T - 0.955 * 10^{-6} * T^2 * API$$

Beggs and Robinson Correlation (September, 1975)[3]

$$\mu_{do} = 10^{10^C} - 1$$

$$C = (3.0324 - 0.2023 * API) * T^{-1.163}$$

Glaso Correlation (May, 1980)[4]

$$\mu_{do} = (\frac{3.141 * 10^{10}}{T^{3.444}}) * log\ API^A$$

$$A = 10.313 * log(T) - 36.447$$

Ng and Egbogah Correlation (May, 1983)[7]

$\mu_{do} = 10^{10^X} - 1$

$X = 1.8653 - (2.5086 * 10^{-2} * API) - [0.56444 log(T)]$

Kaye Correlation (August, 1985)[8]
API≤12

$\mu_{do} = 10^D - 1$

$D = T^{-0.65} * 10^{2.203 - 0.025 * API}$

API≥12

$\mu_{do} = 10^D - 1$

$D = T^{-0.65} * 10^{2.305 - 0.03354 * API}$

Al-Khafaji et al Correlation (December, 1987)[9]

$\mu_{do} = \frac{10^A}{B}$

$A = 4.9563 - 0.0088 * T$, $B = (API + \frac{T}{30} - 14.29)^{2.709}$

Kartoatmodjo and Schmidt Correlation (June, 1991)[12]

$\mu_{do} = 16 * 10^8 * T^{-2.8177} * [log(API)]^A$

$A = 5.7526 * log(T) - 26.9718$

Labedi-1 Correlation (October, 1992)[13]

$\mu_{do} = 10^{9.224} * API^{-4.7013} * T^{-0.6739}$

Labedi-2 Correlation (October, 1992)[13]

$\mu_{do} = 10^{9.37} * API^{-2.92} * T^{-2.0356}$

De Ghetto et al Correlation (October, 1994)[15]
Extra heavy oil (API≤10 API)

$log * log(\mu_{do} + 1) = 1.90296 - 0.01269 * API - 0.6148 * log(T)$

Heavy oil viscosity (10<API≤22.3 API)

$log * log(\mu_{do} + 1) = 2.06492 - 0.0179 * API - 0.70226 * log(T)$

Medium oil viscosity (22.3<API≤31.1 API)

$\mu_{do} = 220.15 * 10^9 * T^{-3.556} * [log(API)]^A$

$A = 12.5428 * log(T) - 45.2874$

Light oil viscosity (API >31.1 API)

$log * log(\mu_{do} + 1) = 1.67083 - 0.017628 * API - 0.61304 * log(T)$

Agip's sample

$log * log(\mu_{do} + 1) = 1.8513 - 0.0255 * API - 0.56238 * log(T)$

Petrosky and Farshad Correlation (September, 1995)[16]

$$\mu_{do} = 2.3511 * 10^7 * T^{-2.10255} * [\log(API)]^X$$

$$X = 4.59388 * log(T) - 22.82792$$

Bennison Correlation (December, 1998)[21]

$$\mu_{do} = 10^A * T^B$$

$$A = 0.10231 * API^2 - 3.9464 * API + 46.5037$$
$$B = -0.04542 * API^2 + 1.70405 * API + 46.19.18$$

$$\mu_{do} = 10^C * T^D$$

$$C = -0.8021 * API + 23.8765$$
$$D = 0.31458 * API - 9.21592)$$

Elsharkawy and Alikhan Correlation (June, 1999)[23]

$$log * \log(\mu_{do} + 1) = 2.16924 - 0.02525 * API - 0.68875 * \log(T)$$

Bergman Correlation (2000)[24]

$$\mu_{do} = e^{e^X} - 1$$

$$X = 22.33 - 0.194 * API + 0.00033 * API^2 + (-3.2 + 0.0185 * API) * ln(T + 310)$$

Whitson and Brule Correlation (2000)[24]

$$log \frac{\mu_{do}}{\rho_o} = \frac{1}{A} - 2.17$$

$$A = X_3 * [K_w - (\frac{8.24}{\gamma_o} + 1.639 * X_2 - 1.059)]$$

$$X_1 = 1 + 8.69 * log[\frac{T + 459.67}{559.67}]$$

$$X_2 = 1 + 0.544 * log[\frac{T + 459.67}{559.67}]$$

$$X_3 = -0.1285 * [\frac{(2.87 * X_1 - 1) * \gamma_o}{(2.87 * X_1 - \gamma_o)}]$$

$$\rho_o = \frac{\gamma_o}{1 + 0.000321 * (T - 60) * 10^{0.00462 * API}}$$

Elsharkawy and Gharbi Correlation (February, 2001)[25]

$$\mu_{do} = 10.7580 - 3.9145 * \log(API) - 1.9364 * log(T)$$

Naseri et al Correlation (June, 2005)[27]

$$\mu_{do} = 10^B$$

$$B = 11.2699 - 4.2699 * log(API) - 2.052 * log(T)$$

Hossain et al Correlation (November, 2005)[28]

$$\mu_{do} = 10^A * T^B A$$

$A = -0.71523 * API + 22.13766$
$B = 0.269024 * API + 8.268047$

Ikiensikimama and Ogboja Correlation (2009)[31]

$$\mu_{do} = 10^{10^{D}} - 1$$

$$D = 2.0930 - 0.0350 * log(API) - 0.6063 * log(T)$$

Oyedeko and Ulaeto Correlation (2011)[33]

$$\mu_{do} = 10^{7.173} * API^{-2.9986} * T^{-1.1226}$$

Naseri et al Correlation (2012)[35]

$$\mu_{do} = 10^{10^{B}} - 1.12$$

$$B = 7.9684 - 2.7942 * \log(API) - 1.6044 * \log(T) + A$$

$$A = -\frac{47.3757}{T} - \frac{165.1894}{API^2}$$

Ulaeto and Oyedeko Correlation (2014)[36]

$$\mu_{do} = X_1 * (1 + X_2 * \ln(API) + X_3 * \ln(T))$$

For general crude oil

$$X_1 = \frac{47209999.96}{API^{3.185} * T^{0.176}}$$

$$X_2 = 0.045454082 * (\ln(API) - 6.644518272)$$

$$X_3 = 0.014721569 * (\ln(T) - 11.67542323)$$

For typical Niger Delta crude oil

$$X_1 = \frac{52270000 * T^{0.7327}}{API^{4.655}}$$

$$X_2 = 0.049288568 * (\ln(API) - 6.369426752)$$

$$X_3 = 0.015379637 * (\ln(T) - 11.40250855)$$

Appendix C

Solution gas oil ratio empirical correlations summary

Standing Correlation (1947&1981)[2,6]

$$R_s = \gamma_g * [(\frac{P}{18.2} + 1.4) * 10^{A}]^{1.2048}$$

$$A = 0.0125 * API - 0.00091 * T$$

Glaso Correlation (May, 1980)[4]

$$R_s = \gamma_g * [\frac{API^{0.989}}{(T - 60)^{0.172}} * A]^{1.2253}$$

$A = 10^X \quad , X = 2.8869 - [14.1811 - 3.3093 * \log(P)]^{0.5}$

Vazquez and Beggs Correlation (June, 1980)[5]
API≤30

$$R_s = 0.0362 * \gamma_{gs} * P^{1.0937} * \exp[25.724 * (^{API}/_{T} + 460)]$$

API≥30

$$R_s = 0.0178 * \gamma_{gs} * P^{1.1870} * \exp[23.931 * (^{API}/_{T} + 460)]$$

$$\gamma_{g100} = \gamma_{gp} * [1 + 5.915 * 10^{-5} * API * T_{sep} * \log(\frac{P_{sep}}{114.7})]$$

Al-Marhoun Correlation (May, 1988)[10]
$$R_s = 1.4903 * 10^3 * \gamma_g{}^{2.6260} * P_b{}^{1.3984} * \gamma_o^{-4.3963} * (T + 460)^{-1.8600}$$

Rollins et al Correlation (January, 1990)[11]
$$logR_s = 0.4896 - 4.9161 * log\gamma_{osep} + 3.469 * log\gamma_{sep} + C$$

$$C = 1.50 * logP_{sep} - 0.9213 * logT_{sep}$$

Kartoatmodjo and Schmidt Correlation (June, 1991)[12]
$API \leq 30$

$$R_s = 0.05958 * \gamma_{g100}{}^{0.7972} * P_b{}^{1.0937} * 10^A$$

$$A = 13.140 * API/(T + 460)$$

$API \geq 30$

$$R_s = 0.03150 * \gamma_{g100}{}^{0.5587} * P_b{}^{1.0937} * 10^A$$

$$A = 11.289 * API/(T + 460)$$

$$\gamma_{g100} = \gamma_{gsep} * [1 + 0.1595 * API^{0.4078} * T_{sep}{}^{-0.2466} * T_{sep} * \log(\frac{P_{sep}}{114.7})]$$

Petrosky and Farshad Correlation (October, 1993)[14]
$$R_s = [\left(\frac{P_b}{112.727} + 12.340\right) * \gamma_g{}^{0.8439} * 10^A]^{1.73184}$$

$$A = 7.916 * 10^{-4} * API^{1.5410} - 4.561 * 10^{-5} * T^{1.3911}$$

De Ghetto et al Correlation (October, 1994)[15]
Extra-Heavy oils

$$R_s = \gamma_g * [\left(\frac{P_b}{10.7025}\right) * 10^A]^{1.1128}$$

$$A = 0.01694 * API - 0.00156 * T$$

Heavy oils

$$R_s = \left(\frac{P_b^{\,1.2057}\gamma_{gcorr}}{56.434}\right) * 10^{\left[\frac{10.9267*API}{T+460}\right]}$$

$$\gamma_{gcorr} = \gamma_g * P_{sep} * [1 + 0.5912 * API * T_{sep} * \log\left(\frac{P_{sep}}{114.7}\right) * 10^{-4}]$$

Medium-oils

$$R_s = 0.1008 * \gamma_{gcorr}^{\,0.2556} * P_b^{\,0.9868} * 10^{\left[\frac{7.4576*API}{T+460}\right]}$$

$$\gamma_{gcorr} = \gamma_g * P_{sep} * [1 + 0.1595 * API^{0.4078} * T_{sep}^{\,-0.2466} * \log(\frac{P_{sep}}{114.7})]$$

Light oils

$$R_s = 0.01347 * \gamma_{gcorr}^{\,0.3873} * P_b^{\,1.1715} * 10^{\left[\frac{12.753*API}{T+460}\right]}$$

$$\gamma_{gcorr} = \gamma_g * P_{sep} * [1 + 0.1595 * API^{0.4078} * T_{sep}^{\,-0.2466} * \log(\frac{P_{sep}}{114.7})]$$

Agip's sample

$$R_s = \left(\frac{P_b^{\,1.1535}\gamma_{gcorr}}{37.966}\right) * 10^{\left[\frac{9.441*API}{T+460}\right]}$$

$$\gamma_{gcorr} = \gamma_g * P_{sep} * [1 + 0.5912 * API * T_{sep} * \log\left(\frac{P_{sep}}{114.7}\right) * 10^{-4}]$$

<u>Farshad et al Correlation </u>(April, 1996)[17]
One stage Separation

$$R_s = \frac{0.01456 * \gamma_{gc} * P_b^{\,1.2073} * 10^A}{1 - 24.663 * \frac{\gamma_o}{T_{sep}}}$$

$$A = 0.1714 * API - 0000446 * T$$

$$\gamma_{gc} = \gamma_{sep} + 15.5727 * \frac{\gamma_o}{T_{sep}} * \log(\frac{P_{sep}}{114.7})$$

Two stage Separation

$$R_s = 0.01936 * \gamma_{gc}^{\,0.73495} * P_b^{\,1.1574} * 10^A$$

$$A = 0.000337 * API - 01771 * T$$

<u>Hanafy et al Correlation </u>(February, 1997)[18]
$R_s = -49.069 + 0.312 * P_b$

<u>Elsharkawy and Alikhan Correlation </u>(May, 1997) [19]
$API \leq 30$

$$R_s = \gamma_g * P_b^{1.18026} * 10^{-1.2179+0.4636*\frac{API}{T}}$$

$API \geq 30$

$$R_s = P_b^{0.94776} * \gamma_g^{0.04439} * API^{1.1394} * 10^{-2.188+0.0008392*T}$$

Velarde et al Correlation (June ,1997)[20]

$$R_s = [((\frac{P_b}{1091.47})^{0.18675} + 0.740152)/A]^{1.22752}$$

$$A = \gamma_{gs}^{-0.161488} * 10^X$$

$$X = [0.013098 * T^{0.282372}] - B$$

$$B = [8.2 * 10^{-6} * API^{2.176124}]$$

Al-Shammasi Correlation (February, 1999) [22]

$$R_s = [(\beta_o - 1 - 0.000650 * (\frac{T-60}{\gamma_o})/0.000412] * \gamma_o$$

Dindoruk and Christman Correlation (September, 2001)[26]

$$R_s = [\frac{P_b}{3.35975} + 28.1013 * \gamma_g^{1.5790} * 10^A]^{0.92813}$$

$$A = \frac{X}{Y}$$

$$X = 4.8699 * 10^{-6} * API^{5.73098} + 9.925 * 10^{-3} * T^{1.776179}$$

$$Y = (44.25002 + (2 * \frac{API^{2.70288}}{P_b^{0.744335}}))^2$$

Hemmati and Kharrat Correlation (March, 2007) [29]

$$R_s = [0.1769 * \gamma_g^{1.0674} * \gamma_o^{-5.0956} * T^{-0.1294} * P]^{1.0857}$$

Mazandarani and Asghari Correlation (September, 2007) [30]

$$R_s = 994.3718 * \gamma_g^{2.113367} * P^{1.45558} * \gamma_o^{-5.48944} * (T + 460)^{-1.90488}$$

Khamechi et al Correlation (March,2009) [32]

$$R_s = 0.0103 * \gamma_g^{0.719} * P^{1.014} * API^{1.182} * T^{-0.223}$$

Hassan Correlation (2011)[34]

$$R_s = 0.0006 * P_b^{0.856} * \gamma_g^{0.351} * T^{1.829} * API^{1.462} * R_s^{-2.116} * P^A$$

$$A = 3.867 * P_b^{-0.306} * \gamma_g^{-0.0831} * T^{-0.306} * API^{-0.288} * R_s^{0.525}$$

