SPE 105983

A Correlation to Predict the Viscosity of Light Crude Oils

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This paper was prepared for presentation at the 31st Annual SPE International Technical Conference and Exhibition in Abuja, Nigeria, July 31- August 2, 2006.

Abstract

Direct viscosity measurements are often expensive or unavailable. Therefore, empirical correlations are often used for predicting the viscosity of crude oils. However, several published correlations are either too simplistic or too complex for routine operational use. Many of the common correlations in use were developed using data from other regions of the world.

Empirical correlations for predicting the viscosity of light crude oils in the Niger Delta have been presented in this paper.

Data from over 400 oil reservoirs from the Niger Delta were collected. The samples were representative of the two crude oil viscosity regimes: above and below the bubble point. After normal quality checks, non-linear multiple regression with linear partial correlation coefficient techniques were used to establish simple correlations between viscosity, pressure, temperature, oil specific gravity and solution gas oil ratio.

Statistical error analysis of the developed correlation showed average absolute relative percentage error of 4.00% and 3.25% and R^2 of 0.99 and 0.97 for oil viscosity above and below the bubble point respectively. These results constitute considerable improvements over existing correlations.

Introduction

Viscosity is an important property of reservoir fluids. It is important during the design of pipelines, production equipment, pump ratings, in oil well testing calculations and reservoir simulation.

Reservoir oil viscosity is usually measured experimentally in the laboratory using subsurface or surface (recombined) samples. However, obtaining representative fluid samples could be difficult and carrying out PVT analysis at reservoir conditions could be expensive. Surface oil viscosity can also be easily measured from wellhead samples. However, there is always the challenge of accurate conversion to subsurface values. Sometimes, experimental data are not available, and a quick estimate may be urgently needed. Hence, empirical correlations are often found very useful. These correlations usually relate viscosity to other fluid properties such as density, dissolved gas content, pressure, temperature, etc. The relationship between these factors could vary from simple expressions to rather complex formulations.

The earliest work on viscosity estimation dates back to Reynolds in 1866, contrary to a common belief that Philip started it all in 1912[1]. Reynolds suggested that liquid viscosity can be related to temperature by the expression:

$$\mu = Ae^{B/T} \qquad (1)$$

Since then, hundreds of formulations have been furnished in the literature.

The most commonly used "black oil" correlations in the oil industry today include those by Beal[2], Standing[3], Chew and Connally[4], Little and Kennedy[5], Glaso[6] and several others.

An earlier work by Amoo and Isehunwa[7] specifically on Niger Delta crudes, used only oil specific gravity as the main correlating parameter for estimating viscosity. This limited its accuracy to viscosity estimates above the bubble point. The attempt by Afuape[8] to improve on Amoo and Isehunwa's work was not very successful. The experimental work of Abdulkareem and Koro[14] was mainly on dead crudes and products, which cannot be applied to reservoir conditions. This present study develops three different correlations for oil viscosity above, below and at the bubble point in order to achieve improved accuracy on the prediction of reservoir oil viscosity.

Theoretical Framework

From the works of Beal, Standing, Vazquez and Beggs[9] and other researchers, the idea of a geometric progression has become widely accepted for validating the relationship between viscosity and pressure[8].

Above the bubble point,
We assume Khan's et al.[10] method, such that:

$$\mu_a = \mu_{ob}\left(\frac{P}{P_b}\right)^n \quad (2)$$

or,

$$\mu_a = f(\mu_{ob}, P, P_b) \quad (3)$$

The exact relationship can be obtained using the principles of partial correlation to obtain:

$$\mu_a = \mu_{ob}\left(\frac{P}{P_b}\right)^c e^{a(P-P_b)} \quad (4)$$

Above the bubble point, we assume c = 0.
Therefore,

$$\mu_a = \mu_{ob} e^{a(P-P_b)} \quad (5)$$

or,

Linearizing,

$$\ln\mu = \ln\mu_{ob} + a*(P - P_b) \quad (6)$$

The constant 'a' can be readily obtained.

Below the bubble point,
We assume:

$$\mu_a = f(\mu_{ob}, P, P_b) \quad (7)$$

Using the principles of partial correlation, we obtain the expression:

$$\mu_a = \mu_{ob} e^B \quad (8)$$

where

$$B = a + b\left(\frac{P}{P_b}\right) + c(P - P_b) \quad (9)$$

or

$$\ln\mu_a = \ln\mu_{ob} + B \quad (10)$$

Thus the constants a, b or c can be readily obtained.

At the bubble point,
The previous power expression did not give very accurate results. Therefore, we assume:

$$\mu_{ob} = K * \gamma_o^a * R_s^b * T^c \quad (11)$$

or,

$$\mu_a = f(\gamma_o, R_s, T) \quad (12)$$

Linearising,

$$\ln\mu_{ob} = i + a*\ln\gamma_o + b*\ln R_s + c*\ln T \quad (13)$$

The constants i, a, b and c can be readily obtained using linear multiple regression analysis.

Statistical Error Analysis

Statistical and graphical error analyses have been used to assess the performance of the correlations developed in this work.

Average Absolute Percentage Relative Error, E_r
This is a measure of the deviation of estimated values from the experimental data. It indicates the relative absolute deviation in percentage, from the observed values; the lower value the better the correlation. It is expressed as:

$$E_r = \frac{1}{N}\left(\sum_{i=1}^{N}\left|\frac{y_{obs} - y_{est}}{y_{obs}}\right|_i\right) \times 100 \qquad (14)$$

Coefficient of Determination, R^2

The coefficient of determination is a simple statistical parameter that tells how the model fits the data, and thereby represents a measure of the utility of the model. In general, the closer the value of R^2 is to 1, the better the model fits the data. It is expressed as:

$$R^2 = 1 - \frac{SSE}{SS_{yy}} \qquad (15)$$

where

$$SSE = \sum_{i-1}^{n}(y_i - \hat{y}_{est})^2, \quad SS_{yy} = \sum_{i-1}^{n}(y_i - \hat{y}_{obs})^2 \qquad (16)$$

Results and Discussion

Table 1 gives the summary of the ranges of data used in this study.

Viscosity Correlation above Bubble point

The correlation above bubble point obtained is:

$$\mu_a = \mu_{ob} e^{1.02\times10^{-4}(P-P_b)} \qquad (17)$$

Viscosity Correlation below Bubble point

The correlation below bubble point obtained is given as:

$$\mu_a = \mu_{ob}^{0.888} e^{B} \qquad (18)$$

where

$$B = 0.808 + 0.86\left(\frac{P}{P_b}\right) + 2.35*10^{-5}(P - P_b) \qquad (19)$$

Viscosity Correlation at Bubble point

The correlation developed in this work is:

$$\mu_{ob} = e^{B} R_s^{-0.38} T^{-4.34} \qquad (20)$$

where

$$B = 27.07 - 17.51\gamma_o + 8.56e^{\gamma_o^2} \qquad (21)$$

Table 1 shows that oil viscosity ranged from 0.08 – 40 cp above the bubble point, 0.02 – 35 cp below the bubble point and 0.03 – 9.1 cp for crudes at the bubble point.

Table 2 to Table 7 give the results of the statistical error analysis.

Table 2, 3 and 4 show sample data and the estimated viscosity values for this study compared to other published correlations above bubble point, below bubble point and at bubble point respectively.

Table 5 shows the statistical error analysis for crude oil viscosity above bubble point. The average absolute relative error obtained by this study is 4.00 compared to 4.13 for Khan et. al and 4.75 for Beggs and Robinson while the R^2 obtained is 0.993 compared to 0.992 and 0.983 for Khan et. al and Beggs and Robinson respectively.

Statistical error analysis for crude oil viscosity below bubble point is shown in Table 6. An average absolute relative error of 3.25 was obtained by this study compared to 4.87 for Khan et. al with an R^2 value of 0.97 compared to 0.93 for Khan et. al.

Table 7 displays the statistical error analysis for crude oil viscosity at bubble point. The average absolute relative error obtained by this study is 29.82 compared to 30.12 for Beggs and Robinson and 60.47 for Chew and Connally while the R^2 obtained is 0.80 compared to 0.77 and 0.75 for Beggs and Robinson, and Chew and Connally respectively.

The crossplots shown in Figs. 1, 2 and 3 for crude oil viscosity above, below and at bubble point respectively validate the accuracy of the developed correlations.

Conclusions

Improved correlations for predicting viscosity of Niger Delta crude oils has been developed for three pressure regimes: at bubble point, above bubble point and at bubble point.

The correlations employ simple relationships and do not require the knowledge of dead oil viscosity to obtain bubble point viscosity. The results obtained were more accurate for the Niger Delta oils because other correlations used data from other regions of the world.

However, the correlations should prove to be applicable for predicting viscosity of other crude types having properties within the range of data used in this study.

Acknowledgments

This paper was supported through research grant from the Shell Petroleum Development Company to the Shell Chair in Petroleum Engineering, University of Ibadan.

References

1. Eakin, B. E., and Ellington, R. T., "Predicting the viscosity of pure light hydrocarbons", Trans. AIME, 1963, Vol. 228, 210.
2. Beal, C., "The Viscosity of Air, Water, Natural Gas, Crude Oil and its Associated Gas at oil-field temperature and pressure", Trans., AIME, 1946.
3. Standing, M. B., "Volumetric and Phase Behaviour of Oil Field Hydrocarbon Systems" Society of Petroleum Engineers of AIME, Dallas, TX, 1981.
4. Chew, J. and Connally, C., "A Viscosity correlation for Gas-saturated crude oils", Trans., AIME, 1959.
5. Little, J. E., and Kennedy, H., "A correlation of the viscosity of hydrocarbon systems with Pressure, Temperature and Composition" Trans., AIME 1968.
6. Glaso, O., "Generalised Pressure-Volume-Temperature Correlations", JPT, May 1980.
7. Amoo, O. A., and Isehunwa, S. O. "A Correlation for Predicting the Viscosity of Nigerian Crude Oils" SPENC 9011 presented at the 14th Annual Conference of the SPE, Nigerian Council, held in Warri, Nigeria, August 22-24, 1990.
8. Afuape, O. G., "Improved prediction of the Viscosity of Nigerian Crudes", Unpublished B.Sc. Project, Department of Petroleum Engineering, University of Ibadan, 1998.
9. Vasquez, M., and Beggs, H. D., "Correlations for fluid Physical Property Prediction", JPT, 1980.
10. Dindoruk, B., and Christman, P. G., "PVT Properties and Viscosity Correlations for Gulf of Mexico Oils", paper 71633-MS presented at SPE Annual Technical Conference and Exhibition, 30 September-3 October, New Orleans, Louisiana, 2001
11. Khan, S. A., Al-Marhoun, S. O., and Abu-Khamsin, U., "Viscosity Correlations for Saudi Arabian Crude Oils" Presentation at the Fifth SPE Middle East Oil Show held in Manama, Bahran, March 7-10, 1987
12. Dexheimer, D., Jackson, C. M., and Barrufet, M. A., "A Modification of Pedersen's Model for Saturated Crude Oil Viscosities Using Standard Black Oil PVT Data" SPE Computer Applications, 1995.
13. Bennison, T., "Prediction of Heavy Oil Viscosity" Presented at the IBC Heavy Oil Field Development Conference, London, 2-4 December 1998
14. Abdulkareem, A. S., and Kovo, S. A., "Simulation of Viscosity of Different Nigerian Crude Oils" Leonardo Journal of Sciences, Issue 8, June-January 2006, p. 7-12.
15. Lucic, B., Bašic, I., Nadramija, D., Milicevic, A., Trinajstic, N., Suzuki, T., Petrukhin, R., Karelson, M., and Katritzky, A. R., "Correlation of liquid viscosity with molecular structure for organic compounds using different variable selection methods", *J. Chem. Inf. Comput. Sci.* 2000, *40*, 403.
16. Oil and Gas Automation Solutions No 14, 4, 2005 'Online Correlation Calculator Predicts Fluid Properties' www.unicous.com
17. Yucel, H. G., "The Empirical and Semi-Theoretical Methods for Predicting Viscosity of Binary n-Alkane Mixtures" *Fuel*, 2006, 85(874).

Abbreviations

°API	-	Oil gravity, °API
N	-	Number of observations
P	-	Pressure, psia
P_b	-	Bubble Point Pressure, P_b
T	-	Temperature, °R
y_{est}	-	Estimated Value
y_{obs}	-	Observed (Experimental) Value
$\hat{y}_{est}$	-	Mean of Estimated Value
$\hat{y}_{obs}$	-	Mean of Observed Value
γ_o	-	141.5/(°API + 131.5) = Oil Relative Density at 14.7 psia and 60°F
μ_a	-	Oil Viscosity above Bubble Point, cp
μ_b	-	Oil Viscosity below Bubble Point, cp
μ_{ob}	-	Bubble Point Oil Viscosity, cp
BEGGS	-	Vasquez and Beggs
KHAN	-	Khan
VC&C	-	Chew and Connally

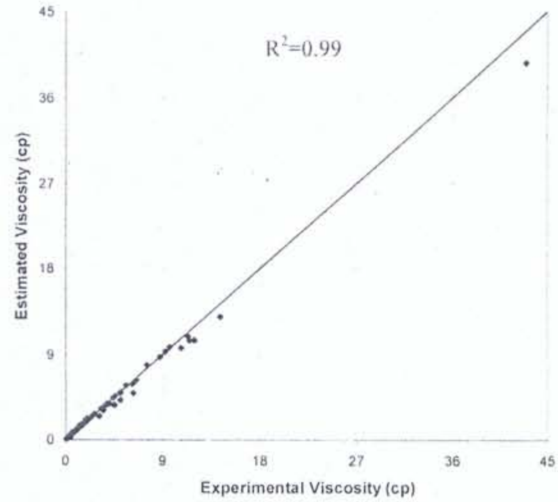

Fig. 1 Crossplot for oil viscosity above bubble point (this study)

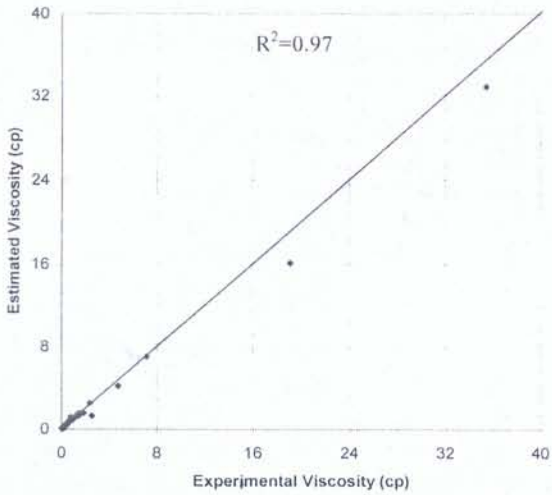

Fig. 2 Crossplot for oil viscosity below bubble point (this study)

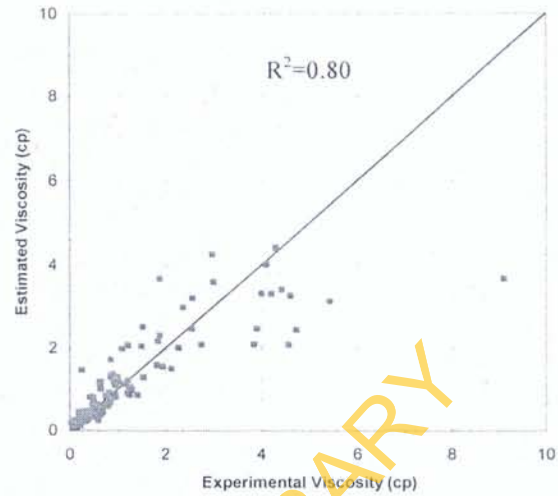

Fig. 3 Crossplot for oil viscosity at bubble point (this study)

Table 1: The ranges of the data used in this study

PVT Property	Range
Bubble Point Oil Viscosity	0.03 – 9.1 cp
Oil Viscosity above Bubble Point	0.08 – 43.00 cp
Oil Viscosity below Bubble Point	0.0241 – 35.52 cp
Bubble Point Pressure	300.3 – 6593 psia
Solution Gas Oil Ratio	42.9 – 19149 scf/STB
Relative Oil Density	0.8 – 0.94
Temperature	124 – 289 °F
Pressure	299 – 9407 psia

Table 2: Comparison of Predicted Oil Viscosities above Bubble Point

P_s, psi	P_b, psi	μ_{ob}, cp	T, °F	Exp. μ, cp	Est. μ, cp	Rel. Dev.	KHAN	Rel. Dev.	BEGGS	Rel. Dev.
2122	2080	2.6	160	2.62	2.611162	0.0034	2.610504	0.0036	2.609947	0.003837
2148	1859	4.93	147.9	5.11	5.07749	0.0064	5.068693	0.0081	5.069674	0.007892
2157.7	644.7	1.95	155	2	2.275399	0.1377	2.254836	0.1274	2.465604	0.2328
2207.225	1941.418	1.07	141.8	1.09	1.099407	0.0086	1.097655	0.0070	1.097622	0.00699
2302.7	2057.7	1.02	158	1.04	1.045811	0.0056	1.044275	0.0041	1.04404	0.00388
2312.7	2003.7	1.84	170	1.86	1.898917	0.0209	1.895399	0.0190	1.895707	0.0192
2327	1937	1.88	148	1.9	1.956294	0.0296	1.951721	0.0272	1.953556	0.02819
2339.7	2283.7	0.525	185	0.527	0.528007	0.0019	0.52783	0.0016	0.527682	0.00129
2403.4	803.7	1.27	160	1.31	1.49509	0.1413	1.480808	0.1304	1.60887	0.22815
2448.001	2029.477	0.8	159.8	0.85	0.834891	0.0178	0.832797	0.0202	0.833657	0.019227
2467.092	2392.667	1.01	165.38	1.02	1.017696	0.0023	1.017242	0.0027	1.016875	0.003064
2474	375	10.5	140	14.36	13.00681	0.0942	12.84403	0.1056	15.9636	0.11167
2568.4	2412	3.27	140	3.31	3.322584	0.0038	3.319468	0.0029	3.317634	0.00231
2572.7	2484.7	0.54	185	0.548	0.544869	0.0057	0.544581	0.0062	0.54435	0.00666
2574.7	2434.7	0.46	186	0.467	0.466616	0.0008	0.466224	0.0017	0.465972	0.002201
2670	2557	0.65	166	0.66	0.657535	0.0037	0.65709	0.0044	0.656748	0.004927
2696.7	2649	1.16	154	1.17	1.165658	0.0037	1.165324	0.0040	1.165002	0.004272
2727.7	1971	1.24	1.24	1.34	1.339498	0.0004	1.33343	0.0049	1.342185	0.00163

Table 3: Comparison of Predicted Oil Viscosities below Bubble Point

P_s, psi	P_b, psi	μ_{ob}, cp	T, °F	Exp. μ, cp	Est. μ, cp	Rel. Dev.	KHAN	Rel. Dev.
514.7	739	6.16	144	7.2	7.037361	0.022589	6.193571	0.139782
554.7	1840	0.96	171	1.871	1.593205	0.148474	1.119218	0.401808
814.7	1989	1.84	170	2.43	2.5389	0.04481	2.177944	0.103727
814.7	2484.7	0.54	185	0.82	0.936454	0.14202	0.701315	0.144738
1014.7	1623	1.22	170	1.43	1.563008	0.09301	1.329988	0.069938
1014.7	2825	0.44	172	0.61	0.761449	0.24828	0.599443	0.017306
1071	3900	0.41	168	0.76	0.816076	0.07378	0.694001	0.086841
1114.7	1434.7	1.215	158	1.494	1.465199	0.019278	1.270502	0.149597
1214.7	2420	0.46	186	0.63	0.698972	0.10948	0.564564	0.103867
1250	2039	1.02	158	1.28	1.31024	0.02363	1.160149	0.093634
1294	1971	1.24	144	1.49	1.517203	0.01826	1.384652	0.070703
1433.263	2029.477	0.8	159.8	1.06	1.001709	0.054992	0.884453	0.16561
1500	3499	0.22	164	0.35	0.392471	0.12135	0.322079	0.079775
1514.7	2204.7	0.7	186	0.89	0.892686	0.00302	0.789206	0.113251
1514.7	2830	0.51	180	0.58	0.739683	0.27532	0.649191	0.1193
1525	4557	0.66	240	0.82	1.175469	0.4335	1.20832	0.47356
1614.7	2214.7	0.667	176	0.716	0.833426	0.164	0.741411	0.03549
1614.7	2484.7	0.54	185	0.64	0.720213	0.12533	0.631898	0.012659

Table 4: Comparison of Predicted Bubble Point Crude Oil Viscosities

P_b, psi	T, °F	R_s, scf/stb	γ_o	Exp. μ, cp	Est. μ, cp	Rel. Dev.	BEGGS	Rel. Dev.	VC&C	Rel. Dev.
4415	225	267	0.806	0.2	0.328628	0.643138	0.385352	0.926759	0.445578	1.227889
3963	216	1232	0.807	0.22	0.196409	0.107231	0.225324	0.024198	0.220531	0.002412
4662	234	3100	0.807	0.23	0.123408	0.463442	0.14654	0.362869	0.157852	0.313685
2694.7	176	1371	0.808	0.22	0.230639	0.048361	0.234406	0.065484	0.236637	0.075624
1968	188	995	0.809	0.19	0.241082	0.268853	0.264743	0.393383	0.280626	0.476978
2655	180	1237	0.809	0.31	0.236127	0.238301	0.244809	0.210294	0.25048	0.191999
3499	164	1696	0.81	0.22	0.240735	0.094249	0.220328	0.001491	0.2247	0.021365
3513.7	164	1696	0.81	0.22	0.240735	0.094249	0.220328	0.001491	0.2247	0.021365
1353.7	184	463	0.81	0.47	0.331887	0.293857	0.37044	0.21183	0.458448	0.024578
1312.7	180	437	0.8123	0.535	0.387713	0.275304	0.39085	0.269439	0.494573	0.075565
1312.7	180	437	0.8123	0.535	0.087349	0.836732	0.108677	0.796866	0.154371	0.711457
2775.479	179.6	1301	0.816	0.28	0.266052	0.049814	0.249251	0.109819	0.258564	0.076557
1979	180	632	0.819	0.42	0.350957	0.164389	0.35273	0.160167	0.434725	0.035059
4076	195	1523	0.82	0.22	0.233212	0.060057	0.228989	0.040859	0.232238	0.055627
3784.7	233	2168	0.8207	0.18	0.159821	0.112104	0.182497	0.013871	0.183344	0.01858
2882	191	1246	0.821	0.23	0.261897	0.138684	0.255166	0.109419	0.267043	0.161055
3944.7	218	2021	0.8215	0.169	0.183655	0.086716	0.193755	0.146482	0.195504	0.156829
2736	183	1119	0.822	0.3	0.292745	0.024183	0.275104	0.082986	0.29798	0.006734

Table 5: Statistical Analysis for Crude Oil Viscosity above Bubble Point

	Beggs & Robinson	Khan et. al	This Study (Est. μ)
Average Abs. Relative Error, E_r	4.75	4.13	4.00
Coefficient of Determination, R^2	0.9833	0.9926	0.9932

Table 6: Statistical Analysis for Crude Oil Viscosity below Bubble Point

	KHAN et. al	This Study
Average Abs. Relative Error, E_r	4.87	3.25
Coefficient of Determination, R^2	0.9328	0.9669

Table 7: Statistical Analysis for Bubble Point Crude Oil Viscosity

	Chew & Connally	Beggs & Robinson	This Study (Est. μ)
Average Abs. Relative Error, E_r	60.47	30.12	29.82
Coefficient of Determination, R^2	0.753	0.77	0.80