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Improved Method for Estimating Bubble point Pressure for Light and Medium Niger Delta Crude Oils [(_^o) API gravity range: 30≤(_^o) API <50]

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Abstract

Knowledge of the bubble point pressure, P_b of a crude oil reservoir is necessary for evaluating fluid phase behaviour and for obtaining insights into reservoir fluid dynamics that enable best strategies for optimum reservoir management. Accurate values of bubble point pressure of crude oil samples are best determined from laboratory PVT measurements, though at great costs of time and man-hours. Empirical correlations, however, provide estimates of P_b at cheaper cost of time and money with acceptable associated errors. A number of correlations have been developed for different regions of the world with only a few targeted at the Niger Delta region, a highly prolific petroleum region in Nigeria. Some correlations in literature have been specifically developed for Niger Delta crude oil systems. These Niger Delta specific - correlations, show limited accuracy when compared to experimentally determined results even while having complex forms of correlating parameters whose coefficients or powers run into several places of decimal. This study, therefore, aims to develop a simple correlation with easy to recall coefficients and powers of coefficients, with improved accuracy in estimating bubble point pressures for light and medium API gravity crudes of the Niger Delta origin, A simple correlation, which relates bubble point pressure to such parameters as specific gravity of gas and oil, oil molecular weight, system temperature and solution Gas-Oil-Ratio R_s was developed using multiple regression, facilitated by "FORTRAN 95" programming. The data set used consisted of 1,289 data points from 48 Niger Delta reservoirs, obtained from literature. Results were compared with estimates from other Niger-Delta based bubble point pressure correlations such as Oloruntoba and Onyekonwu's, Ikpabi and Akinsete's, Francis and Ajienka's and to the Standing's correlation. Statistical analysis using such metrics as Root Mean Squared Error and Average Absolute Relative Error showed that the new correlation shows great improvement over previous models in estimating bubble point pressure of high shrinkage Niger Delta crude oils.

Introduction

The thermodynamic properties of reservoir fluids are of great interest in reservoir engineering and management. The bubble point pressure, denoted as P_b is the pressure at which the first bubble of gas (usually the more volatile molecules in solution) evolves from the liquid oil phase to form a gas phase. However, the gas phase formed remains in equilibrium with the liquid phase, thus, initiating a two-phase equilibrium system consisting of an insignificant amount of gas in equilibrium with a comparatively, infinite amount of liquid. If pressure were to fall below P_b, more gas molecules (volatile molecules) would evolve from and remain in equilibrium with the oil phase, increasing the percentage of gas in equilibrium with liquid, but having the same overall concentration and fugacity. Allowing pressure to fall to (or below) the bubble point pressure during production causes reduction in the crude oil production rate at the surface and a decrease in solution gas oil ratio. These are undesirable effects which can be prevented by either intermittently shutting in the well as pressure falls to values close to the bubble point to allow for pressure build up or by fluid (water or gas) injection through an injection well into the subject reservoir to boost pressure. The bubble point pressure, which is the saturation pressure for crude oil systems, is a function of fluid temperature, pressure, oil and gas gravity, solution Gas-Oil-Ratio, R_s and degree API gravity of the crude. The locus of points joining the pressures at which the first bubble emanates from a crude oil phase at different temperatures, as its pressure falls, during production is called bubble point line. The critical point, which is the condition of temperature and pressure at which the intrinsic properties of the liquid and gas phases are identical, is the meeting point of the bubble point line and the dew point line. The region enclosed by the bubble point line and dew point line is a region where two phases, oil and gas exist at equilibrium with each other. Character lines within this region show the percentages of liquid in equilibrium with gas. In general, the bubble point line separates the two-phase oil and gas region from the single-phase liquid (crude oil) region on a Pressure-Temperature phase diagram, as depicted in figure 1.0 below.

The dew point line separates the two-phase oil and gas envelope from the single-phase gas region which occurs to the right of the critical point, above the dew point line. The maximum temperature of coexistence of the two-phase oil and gas is called cricondentherm, markes as T_{max} in Figure 1. Reservoirs which plot to the right of the critical point before the cricondentherm, are called retrograde condensate reservoirs. This is because, as pressure on such reservoirs fall during production at constant reservoir temperature, the pressure may fall to the dew point, at which case, the first drop of liquid condenses from the gas phase. Condensation from gas as decreasing pressure, is contrary to physical laws which requires that condensation should occur at increasing pressure to enable molecules come close enough together to condense. Therefore, this case, in which condensation occurs at decreasing pressure, an abnormal occurrence, is called, "retrograde condensation" or "abnormal condensation". Crude oil systems are classified broadly into two: volatile oils, which occur to the left of the critical point but in close proximity to it. This class of crude oils contain large volumes of dissolved gas within it at reservoir conditions. On being produced, the dissolved gas escapes at surface or separator conditions as the confining reservoir pressure is no more. The result is that the oil volume suffers great reduction in size, the reason for which this class of reservoirs are also called "high shrinkage crude oils". Further left of the critical point is where the second class of crude oils, "black oils" occur. Due to their great distance from the gas region, this class of oils do not contain significant amount of dissolved gas within it at reservoir conditions. On being produced to the surface where low temperature and low pressure prevails, not much gas is lost from the reservoir oil volume produced to the surface and the resultant volume suffers less shrinkage when compared to volatile oils. Therefore, this category of crude oils (black oil) is often referred to as "low shrinkage crude oil".

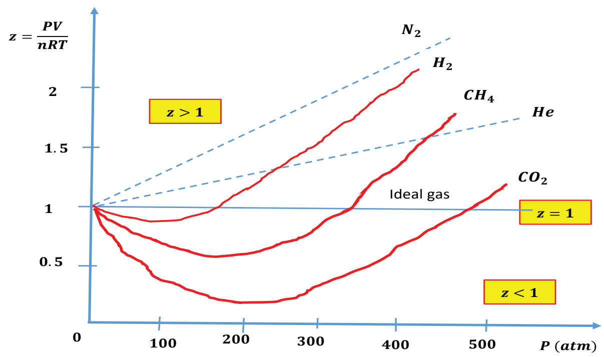

Figure 1: z-factor versus Pressure (atm)

McCain (1994) provided a summary of guidelines for determining fluid type from field data as shown below:

Table 1: Guidelines for determining fluid type from field data

	BLACK OIL	VOLATILE OIL	RETROGRADE GAS	WET GAS	DRY GAS
Initial producing gas/oil ratio (scf/stb)	$< 1{,}750$	1,750 to 3,200	$> 3{,}200$	$> 15{,}000$	1000,000
Initial stock tank liquid gravity (^oAPI)	< 45	> 40	> 40	$Up\ to$ 70	No Liquid
Color of stock tank liquid	Dark	Colored	Lightly colored	Water white	No Liquid

Nigeria's Niger Delta province is one of the major hydrocarbon provinces in the world and is the second largest producer of petroleum in Africa (after Angola). Crude oils are categorized on the basis of the type of hydrocarbon compound that is most prevalent in their composition: Paraffinic, Naphthenic or Aromatic. The Niger Delta crude oils are characteristically low in Sulphur content consisting majorly of the Paraffinic hydrocarbon category.

Crude oil from the Niger Delta basin occur in a wide variety of degree API gravity which for this study, has been classified broadly into two as follows:

(i) Light crudes (with API gravity greater than 30), called Volatile oil (or High shrinkage crude oil) and

(ii) the comparatively heavy crude oils (having API gravity within the ranges of 20-30$^o API$), called black oil or low shrinkage crude oils.

This study focuses on the first category, being light crudes or high shrinkage crude oils of Niger Delta origin.

Review of literature on Bubble Point Pressure Correlations for Niger Delta Crude oils:

Several authors have developed bubble point correlations for different oil provinces of the world. For example, the Dindoruk and Christman (2004) correlations of the Gulf of Mexico has the form shown below:

$$P_b = 1.869979257 \left(\frac{R_s{}^{1.221486524}}{\gamma_g{}^{1.370508349}} 10^A + 0.011688308 \right)$$

(2.1)

Where, $= \frac{1.42828 \, x \, 10^{-10} T^{2.844591797} - 6.74898 \, x \, 10^{-04} API^{1.225226436}}{\left(0.033383304 + \frac{2R_s{}^{-0.272945957}}{\gamma_g{}^{-0.084226069}}\right)^2}$

T = reservoir temperature, (_^o) F

API = Stock tank oil gravity, $^p API$

γ_g = gas gravity

Standing's Correlation (1947)

Based on 105 experimentally measured bubble point pressures on 22 hydrocarbon systems from California oil fields, Standing proposed a correlation with a reported average error of 4.8%. The correlation which has as parameters, gas solubility, gas gravity, oil API gravity and the system temperature has the form:

$$P_b = 18.2 \left[\left(\frac{R_s}{\gamma_g} \right)^{0.83} * (10)^A - 1.4 \right]$$

(2 . 2)

Where,

$A = 0.00091(T\,(^oR) - 460) - 0.0125 * (API)$

P_b = bubble point pressure, psia

R_s= gas solubility, scf/stb

T = system temperature, ^oR

It is advisable to note that Standing's correlation should be used with caution if non-hydrocarbon components are known to be present in the system. Standing's correlation was based on data from laboratory experiment carried out on 106 samples from 22 different crude oil reservoirs in California oil fields based in USA. The samples had temperature range of $100 - 258^oF$, API range of $16.5 - 63.8$ and gas gravity range of $0.59 - 0.95$. The resulting correlation was reported to have an average absolute error of 4.8%.

Oloruntoba and Onyekonwu (2016):

Oloruntoba and Onyekonwu proposed a bubble point correlation based on data from Niger Delta fields which had an average absolute deviation of 3.7% as reported by the authors. The correlation has the form:

$$P_b = 10^{1.45274} * API^{-0.58612} * \gamma_g{}^{-1.89527} * R_s{}^{0.71363} * T^{0.30388}$$

(2.3)

Where the system temperature, T is in (_^o) R

This correlation was developed with data which covered degree API range of $19.4 - 44.6$, gas gravity range of $0.752 - 1.367$ and temperature range of $74 - 240^oF$. The authors reported that their correlation was able to predict bubble point pressure of Niger Delta crudes with an average absolute error of 3.74%.

Francis J and Ajienka J (2019):

These authors developed a bubble point pressure correlation based on data from deep offshore fields of the Niger Delta. Non-linear multiple regression analysis was utilized to develop the correlation which was stipulated to be applicable to crude oils with degree API gravity within the range of 38 to 56. The authors reported an average absolute percent error of 4.8% with use of the correlation. The correlation has the form below:

$$P_b = 67.3506 * ({R_s}^{0.070147} * {\gamma_g}^{1.066621} * {\gamma_o}^{2.313833} * T^{0.682024}) \quad (2.4)$$

Where, R_s = Gas oil ratio. Sm^3/m^3.
P_b = Bubble point Pressure, psia
T = System Temperature, (_^o) F

Ikpabi P and Akinsete O (2022):

The authors used a total of 314 PVT data points from the Niger Delta region obtained from literature to develop a correlation for predicting bubble point pressure for 22.3≤°API≥45 crude oils using a white-box machine learning approach to regress the multiple correlation parameters and the final correlation has the form:

$$P_b = 10^{3.03928815} * \left[\frac{R_s}{\gamma_g}\right]^{0.25715277} * API^{-0.24433212} * \left(\frac{1}{T}\right)^{0.32761462} \quad (2.5)$$

Model Development

The methodology adopted was iterative refinement, with each successive iteration step ensuring improvement on the previous step by minimizing error at current step of iteration. Data sets collected from conventional PVT reports and published literature provided experimentally derived values of bubble point pressure from different oil fields in the Niger Delta, for different fluid properties to be used for model performance evaluation. Each data set contains measured bubble point pressure (P_b), total solution gas oil ratio (R_s), average gas gravity, (γ_g) crude oil density, ((_^o) API), reservoir pressure, (P) and reservoir temperature in degree Fahrenheit, (T, ((_^o) F)). A total of 1,289 data sets from 48 reservoirs from the Niger Delta, collected from literature were used in this study. The data ranges for the parameters used is as contained in Table 2.0. The total data collected were sorted and model development for light and medium ^oAPI gravity oils (30≤(_^o) API <50) adopted the general form of Standing's (1947) model:

$$P_b = f[R_s, \gamma_g, (\_^o) API, T] \quad (3.0)$$

Which expresses bubble point pressure of crude oil systems as a function of solution gas oil ratio, R_s, gas gravity, γ_g, oil gravity (API), and temperature, T.

Table 2: Range of Data used for study

PVT Parameter	Minimum	Maximum	Mean
$BHP(psi)$	4520.375	5358.965	6109.43
$R_{si}\ (scf/stb)$	1137.629	5540.787	15909.06
$T(\,^oF)$	40	320	
	38.13	49.6183	55.85
Molecular weight C_{7+}	106	235	
Specific gravity C_{7+}	0.7330	0.8681	
Oil gravity (γ_o)	0.71	0.809	0.95
Gas gravity (γ_g)	0.5804026	1.98943	1.864004
^oAPI	20.0	50.0	35.0

The various crude oil samples considered had composition of hydrocarbon and non-hydrocarbon components in the ranges shown in Table 3.

Table 3: Range of Composition Constituents (Mole fraction)

Composition,mole fraction	Minimum	Maximum
Methane	0.0349	0.9668
Ethane	0.0037	0.1513
Propane	0.0011	0.1090
Butanes	0.0000	0.3750
Pentanes	0.0000	0.0710
Hexanes	0.0000	0.0871
Heptane Plus	0.0000	0.0136
Nitrogen	0.0000	0.4322
Carbon dioxide	0.0000	0.9192
Hydrogen sulphide	0.0000	0.2986

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The data were sorted and those corresponding to the oil gravity ranges of interested separated. The data were then shared into three categories in the ratio: $2:1:1$, for training, validation and testing, respectively. Several forms of Equation (3.0) depicting bubble point pressure as the dependent parameter and reservoir temperature, average gas gravity, oil gravity in (_^o) API and solution gas oil ratio, as independent parameters were programmed in FORTRAN 95. At each run, predicted bubble point pressures at given set of independent parameters were checked against observed values and errors calculated. The powers (indices) of the correlating parameters were constantly being adjusted to ensure minimization of the bias between estimated and measured bubble point pressure values at subsequent run of the program.

The final correlation which gave the least Average Absolute Relative Error (AARE) and least Root Mean Square Error (RMSE has the form shown below:

$$P_b = 10^a * [(T ** b) * (R_s ** c) * (API ** d) * (\gamma_g ** e)] \quad (3.1)$$

Where, the powers of the correlating coefficients are as follows: a=2.22, b=0.33, c = 0.33, d= -0.3 and e=-0.6. Therefore, the final expression is:

$$P_b = 10^{2.22} * [(T ** 0.33) * (R_s ** 0.33) * (API ** -0.3) * (\gamma_g ** -0.6)] \quad (3.2)$$

T is in degree Fahrenheit ((_^o) F).

Model Validation

The new model developed was validated by comparative evaluation with other correlations developed with Niger Delta crude oil samples, and with the Standin's model, being the fundamental structure, which was modified by this study. Error metrics such as Average Absolute Relative Error (AARE), Mean Square Error (RMSE), Minimum Absolute Percent Error and Maximum Absolute Percent Error were used to evaluate the performance of the developed correlation. Formulae for computing these metrics are included as APPENDIX.

Results and Discussion of Results

The results for bubble point pressure estimations using the various correlations reviewed in this literature for selected data points which capture the range of degree API of interest are presented in Tables 4.0 below:

Table 4: Comparative performance of Bubble point Pressure correlations for Light and Medium (_^o) API gravity range (30≤(_^o) API <50) for Niger Delta Crude Oils.

S/N	$(\frac{scf}{stb})$	(γ_o)	(γ_g)	API	T $((\_\^o)F)$	Exponential P_b (psi)	Estimated Bubble Point Pressure				
							P_b (psi) F&Aj	P_b (psi) Standing	P_b (psi) I&A	P_b (psi) O&O	P_b (psi) New
1	329	0.87	0.60	31.14	134	**2,273**	1200	1820	1914	2758	2740
2	328	0.87	0.60	31.14	137	**2,521**	1218	1827	1899	2771	2757
3	386	0.87	0.59	31.14	137	**3,173**	1210	2125	1988	3213	2939
4	723	0.83	0.65	33.03	215	**3,554**	1710	3700	1938	4637	3889
5	355	0.85	0.59	34.97	142	**3,198**	1168	1790	1869	2859	2794
6	1,292	0.85	0.85	34.97	197	**3,486**	2360	4371	2131	3974	3829
7	1,307	0.85	0.85	34.97	198	**3,219**	2370	4423	2134	4013	3850
8	378	0.84	0.65	36.95	144	**3,284**	1278	1649	1820	2420	2659
9	377	0.84	0.65	36.95	154	**3,285**	1337	1681	1779	2465	2717
10	256	0.84	0.65	36.95	149	**2,050**	1273	1199	1628	1851	2365
11	735	0.84	0.65	36.95	220	**3,222**	1787	3384	1879	4424	3809
12	283	0.83	0.65	38.98	155	**2,155**	1281	1245	1628	1951	2437
13	1,546	0.83	0.65	38.98	204	**5,125**	1740	5739	2302	7123	4673
14	401	0.83	0.65	38.98	159	**3,415**	1335	1686	1766	2521	2757
15	1,485	0.83	0.65	38.98	210	**4,711**	1769	5620	2257	6982	4656
16	1,702	0.83	0.65	38.98	221	**4,521**	1850	6445	2299	7817	4953
17	444	0.82	0.59	41.06	149	**3,008**	1874	1836	1128	3098	2912
18	579	0.82	0.62	41.06	163	**3,220**	1288	2268	1924	3502	3179
19	914	0.81	0.67	43.19	178	**3,603**	1491	3023	2035	4176	3577
20	540	0.81	0.65	43.19	163	**3,516**	1311	1932	1844	2958	2974
21	1,611	0.81	0.65	43.19	186	**3,551**	1548	5063	2339	6716	4456
22	478	0.8	0.65	45.38	163	**3,642**	1263	1635	1765	2634	2815
23	321	0.8	0.65	45.38	163	**2,072**	1228	1168	1594	1982	2468
24	276	0.79	0.65	47.61	162	**1,960**	1188	1092	1578	1924	2310
25	746	0.79	0.65	47.61	208	**3,399**	1494	2451	1806	3789	3483
26	1,287	0.78	0.65	49.91	190	**4,201**	1417	3485	2116	5291	3990
27	385	0.78	0.67	49.91	144	**2,873**	1113	1116	1686	1941	2401
28	535	0.78	0.64	49.91	153	**3,504**	1131	1562	1820	2727	2806
29	701	0.78	0.65	49.91	165	**3,742**	1233	1986	1896	3286	3116

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Estimates of performance of the new model when compared with older models using such error metrics as Average Absolute Relative Error, Root Mean Square Error, Maximum and Minimum relative errors are shown in table 5.0 below:

Table 5: Measures of Error from P_b estimation for the various models evaluated

Correlation/ ERROR	Standing's	Francis & Ajienka's	Ikpabi & Akinsete's	Oloruntoba & Onyekonwu's	This Study's
Average Relative Error (%)	22.421	54.00	40.57	-7.91	-0.10
Average Absolute Relative Error (AARE), (%)	22.42	54.00	40.57	7.91	0.10
Minimum Absolute Relative Error (%)	-42.56	26.37	15.79	-89.13	-25.49
Maximum Absolute Relative Error (%)	61.16	67.72	62.50	27.68	22.71
Root Mean Square Error (RMSE), (%)	1247.13	1954.28	1531.30	1189.08	470.67

Bar charts showing Average Absolute Relative Error (AARE) for the model from this study in comparison with those of Oloruntoba and Onyekonwu's, Ikpabi and Akinsete's, Francis and Ajienka's and Standing's correlations are included as Figures 2.0 below. Figure 2.0 shows that the correlation from this study gave the least AARE value of 0.1 for the range of degree API gravity tested. The correlation of Oloruntoba and Onyekonwu gave the next best result with a value of 7.91. Standing's correlation, which was not developed using Niger Delta crude oil samples data, performed well, coming in at the third place with AARE of 22.4. Ikpabi and Akinsete's correlation had an AARE value of 40.57. The worst performing correlation, judging by AARE for the range of degree API tested for Niger Delta crude oils was the correlation of Francis and Ajienka with AARE of 54.0%.

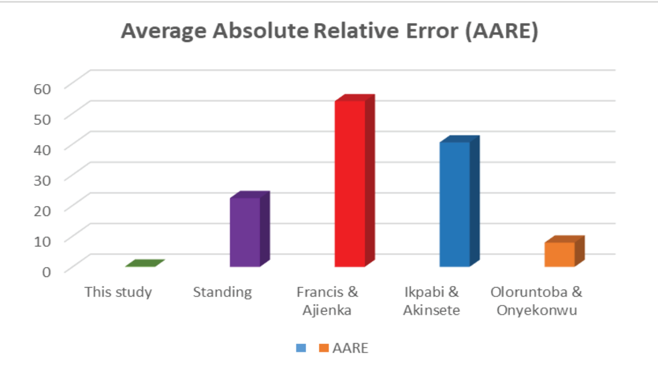

Figure 2: Bar charts of Average Absolute Relative Errors (%) for various Correlations

The Root Mean Square Error was also tested and plotted as figure 3.0. The correlation developed by this study also showed superior performance with the least RMSE value of 470.67. The RMSE values in increasing order, after that from this study were 1189.08 (Oloruntoba & Onyekonwu (2016)), 1954.28 (Standing (1947)), 1531.30 (Ikpabi & Akinsete (2022)) and 1954.28 (Francis & Ajienka (2019)).

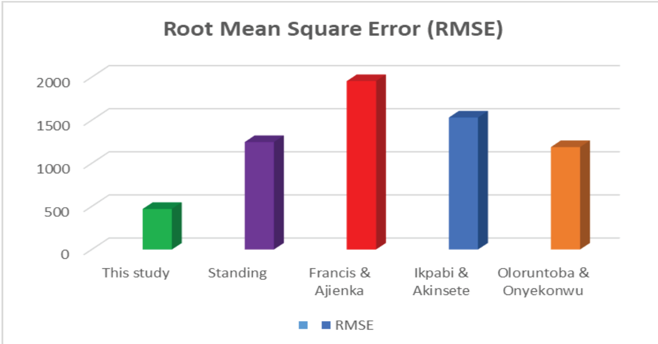

Figure 3: Plot of Root Mean Square Error (RMSE) for the correlations tested

Conclusion

A bubble point pressure correlation has been developed for Niger Delta light and medium crudes with (_^o)API gravity range of (30≤(_^o) API <50). This correlation can be used in estimating bubble point pressure of reservoirs without the rigour associated with experimental determination in laboratories and with greater confidence of its accuracy, over older correlations, over the same API range. The model is a non- linear multivariate model which can predict bubble point pressure of light and medium crude oils with less than 1% average absolute relative error. The new correlation also gave the lowest Root Mean Square Error (RMSE), when compared to the empirical correlations developed by earlier researchers of note in the industry.

Conflicts of interest: None

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APPENDIX

The formulae for the error measures are as follows:

Average Percent Relative Error

$E_r = \frac{1}{n}\sum_{i=1}^{n} E_i$, Where, $E_i = \frac{(y_i - \widehat{y_i})}{y_i}\, x\, 100$,

y_i=value determined experimentally & (y_i)^ is value estimated,i=1,2,3,.,.,.,n

Average Absolute Relative Error (AARE): measures the relative absolute deviation of the estimated values from the experimental values and is computed as follows:

$E_r = \frac{1}{n}\sum_{i=1}^{n}|E_i|$

1. The minimum and maximum absolute percent relative error, which define the ranges of error for each correlation, are respectively given by: $E_{min} = \min|E_i|, \quad i = 1,2,3,.,.,.,n.$ While the $E_{max} = \max|E_i|, i = 1,2,3,.,.,.,n$

2. Root Mean Square Error (RMSE): The formula for RMSE is : $RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\hat{y}_i - y_i)^2}$ where, $\widehat{y_i}$ represents the predicted value for the ith data point, y_i represents the actual (experimentally observed) value for the ith data point and n is the number of observations.

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