EMPIRICAL PREDICTION OF BUBBLE POINT PRESSURE AND SOLUTION GAS OIL RATIO FOR NIGER DELTA

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ABSTRACT: Bubble point correlation was developed and solution GOR solved from it to aid effective reservoir management. The developed correlations buckled on the restriction that PVT correlations use data of certain localities; hence, their application is limited. A total of 189 measured PVT data points from the Niger Delta were used to develop the correlations based on matching acquired PVT parameter with nonlinear function and being resolved using Lower Upper Algorithm to generate nonlinear equation. Out of these measured PVT data points, 159 data points were used to build the model and 30 were used to validate it. Statistical evaluations showed that the newly developed correlation can predict bubble point pressure and solution Gas Oil Ratio of light crude in the Niger delta at accuracy of 99.39%.

Key Words: Empirical Correlation, Prediction, Bubble Point, Solution Gas Oil Ratio

INTRODUCTION

The accurate determination of PVT properties of the reservoir fluid, such as bubble-point pressure, solution GOR is necessary for estimating the quantity of hydrocarbon reserves, reservoir performance studies, production operations and the design of production facilities (Whitson and Brule, 2000). The estimation of these PVT parameters involves some level of uncertainty (Garb, 1988). PVT properties can be obtained from a laboratory experiment using representative reservoir fluid samples. However, they are not always available because the cost of conducting PVT laboratory experiment repeatedly on an oil system is huge and the interpolation severity associated with reading tables and charts is unavoidable.

Bubble-point pressure is usually measured during reservoir depletion or from PVT experiments. It is assumed to be a strong function of bubble-point solution GOR, gas gravity, stock tank oil API gravity, and reservoir temperature.

The empirical prediction of bubble-point pressure from which solution GOR is solved in the absence of PVT analysis, calls to know in advance the values of bubble-point solution GOR. And the difficulty of directly measuring bubble-point solution GOR provided no other choice than to resort to correlations developed by Rollins *et al* (1990), and Valko and McCain (2003) to estimate stock tank GOR. The stock-tank GOR is then added to the readily available separator field GOR to get the bubble point solution GOR when the reservoir pressure is still at or above the bubble point.

The efforts to develop PVT correlations that would better predict the behaviour of black oil buckle on the restriction that PVT correlations use data of certain localities; hence, their application is limited (Danesh, 1998). Specifically, PVT correlations may not predict satisfactory results when applied to hydrocarbon of different compositions from the oil samples on which the correlations were derived. As a result of this regional trend, correlations developed from regional samples that are predominantly paraffinic in nature may not provide acceptable results when applied to other regional crude oil systems that are dominant in naphthenic or aromatic compounds.

Basic Concepts of Bubble-point Pressure and Solution GOR

Accurate estimate of bubble-point pressure and solution GOR for crude oil are essential, particularly for new reservoirs where the computation of fluid initial in place (FIIP) and natural reservoir drive forces are eminent. The accurate knowledge of these parameters can be used to describe the most suitable method to recover oil from the reservoir, and the amounts recoverable under primary, secondary and tertiary recovery methods (Almehaideb, 1997).

The bubble-point pressure and solution GOR are basically functions of pressure temperature and composition. However, in most reservoir applications, the temperature of the reservoir is assumed constant. Secondly, the compositions of the reservoir fluid are not initially available at the discovery of the field. So, the effect of reservoir fluid composition on bubble-point pressure and solution GOR is approximated by the surface oil and gas gravity and the surface GOR. That is, the input to construct bubble-point pressure and solution GOR are:

1. Constant surface properties such as oil gravity, gas gravity and GOR
2. Constant reservoir temperature
3. Amount of impurities such as nitrogen, carbon dioxide and hydrogen sulphide
4. Variable reservoir pressure

Solution GOR is the number of standard cubic feet of gas that dissolves in one stock-tank barrel of crude oil at certain pressure and temperature. At a constant reservoir temperature, the solubility of gas in oil will increase with increasing pressure until the bubble-point pressure is reached. At the bubble-point pressure, all the available gases are dissolved in the oil and the gas solubility attains its maximum value. In practice, the amount of gas that dissolves in reservoir oil is determined by measuring the amount of gas that comes out of stock-tank oil. This is because at stock tank condition, it is reasonably assumed that the reservoir oil will liberate all of its dissolved gas. That is, the same amount of gas the oil contained in the reservoir is given out at the stock tank.

A typical solution GOR functional relationship with pressure for crude oil systems is shown in Figure 2.1. As the pressure is reduced from the initial reservoir pressure, P_i, to the bubble-point pressure, P_b, no gas evolves from the oil and consequently the gas solubility remains constant at its maximum value R_{sb}. Below the bubble-point pressure, the dissolved gas is liberated and the value of R_s decreases with pressure.

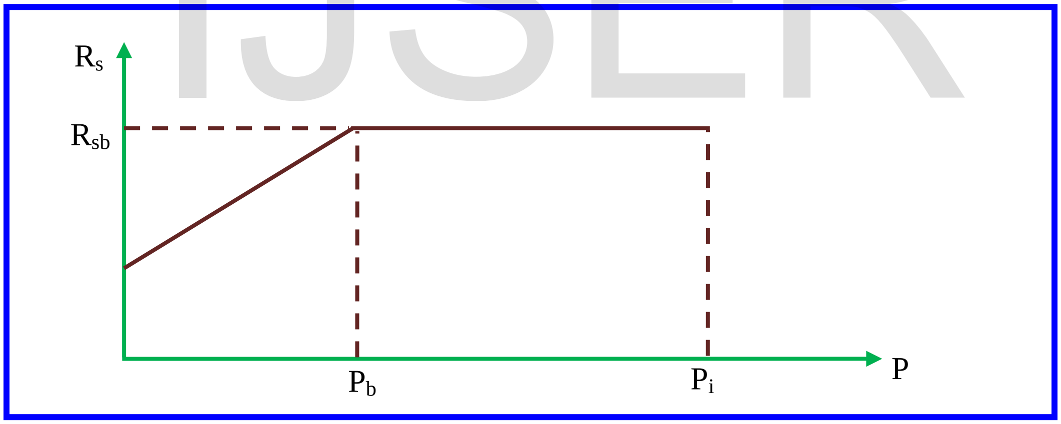

Fig. 1: Typical Solution GOR relationship with Pressure

Solution GOR is a volumetric ratio used to simplify petroleum engineering calculations. Precisely, it is the conversion factor that allows for the introduction of surface volumes into the material balance equations which is an inventory of underground material volumes (Whitson and Brule, 2000).

Correlations for Bubble-Point Pressure

There are many PVT correlations for predicting the bubble-point pressure of oil reservoir (Lasater, 1958; Glaso, 1980; Al-Marhoun, 1988; McCain,1990; Dokla and Osman, 1992; Petrosky and Farshad, 1993; Macary and El-Batanoney, 1993; De Ghetto and Villa, 1994; Frashad *et* al, 1996; Almehaideb, 1997; Hanafy *et al*,1997; Velarde *et al*,1999; Dindoruk and Christman, 2001; Hemmati and Kharrat, 2007; Mazandarani and Asghari, 2007; and Ikiensikimama and Ogboja, 2009). This was prompted by the fact that the PVT correlations are relatively simple and requires inputs which are readily measureable.

Practically, bubble point pressure is usually measured during reservoir depletion or from PVT experiments when samples are acquired. It followed that the bubble point pressure is modeled as a function of bubble point solution GOR, gas specific gravity, API oil gravity and reservoir temperature as indicated in Equation 1.

$$P_b = f\left(R_{sob}, \gamma_g, API, T\right) \quad 1$$

There are several reasons why bubble point pressure correlation has received a lot attention. First, it is the foundation for the derivation of other oil PVT properties. Second, it defines the point of transition of oil from undersaturated to saturated behaviour during depletion (Whitson and Brule, 2000). It has been the convention to solve for solution GOR from bubble point correlation. There are exceptions where the bubble-point Solution GOR is treated as a dependent variable. That is

$$R_{sob} = f_1\left(P_b, \gamma_g, API, T\right) \quad 2$$

Examples of such correlations are the Vasques and Beggs (1980), Elmabrouk and Shirif (2001), and Omar (2001).

Oil reservoir is said to be saturated when the pressure exists at or below the bubble-point pressure, and undersaturated when the pressure exists above the bubble-point pressure (Ahmed, 2007). It therefore connotes that in describing the behaviour of oil reservoir, the correlation must adequately describe the saturated and undersaturated behaviour of the oil mixture. However, from Figure 1, it can be seen undersaturated solution GOR is the solution GOR computed at the bubble-point. That is, above bubble-point, solution GOR is constant and equals bubble-point solution GOR.

There have been concerted efforts to develop bubble-point pressure and solution GOR correlations that would accurately describe the behaviour of black oil. However, these efforts crumple on the restrictions that PVT correlations use data of certain localities; hence, their application is limited (Danesh, 1998).

Table 1: Ranges of data used to Develop Bubble-Point Pressure and Solution GOR

Correlation	**Glaso**	**Standing**	**Lasater**	**Petrosky**	**Marhoun**
BubblePoint, Psia	165-7142	130-7000	48-5780	1574-6523	130-3570
Temperature, ^{o}F	80-280	100-258	82-272	114-288	74-240
GOR, scf/stb	90-2637	20-1425	3-2905	217-1406	26-1602
Oil Gravity, $^o{}_{API}$	22.3-48.1	16.5-63.8	17.9-51.1	16.3-45	19.4-44.6
Gas Gravity	0.65-1.276	0.59-0.95	0.574-1.22	0.578-0.852	0.752-1.367
Sep.Pres., Psia	415	265-465	15-605	NA	NA
Sep. Temp., $^o{}_F$	125	100	36-106	NA	NA

NA – Not Available

Standing Correlations

Standing (1947) developed the first accurate bubble-point correlation, which was based on 105 experimental data points on 22 different California crude oils with an average error of 4.8%. Standing (1981) expressed his 1947 graphical correlation in mathematical form as

$$P_b = 18.2\left(A - 1.4\right) \quad 3$$

where

$$A=\left(\frac{R_{sb}}{\gamma_g}\right)^{0.83}\times 10^{\left(0.00091T-0.0125API\right)} \qquad 4$$

GOR correlations can be calculated by solving the bubble-point pressure correlation for R_s. The solutions are aptly simple and they have been meticulously solved. So solving Equation 3 and b gives the Standing solution GOR

$$R_s=\gamma_g\left[10^x\left(\frac{P}{18.2}+1.4\right)\right]^{1.2048} \qquad 5$$

where

$$x=0.0125API-0.00091T \qquad 5$$

Standing (1947) used flash liberation test to obtain his experimental data and observed oil free of N_2 and H_2S, with CO_2 less than 1 mole percent. Thus, Standing correlations are valid for oil with trace compositions of non-hydrocarbon components (Valerde, 1996).

Lasater Correlation

Lasater (1958) presented a bubble-point correlation based on 158 experimentally measured bubble point pressures of 137 different crude oils from Canada, Western and Mid-Continental USA, and South America. The bubble-point pressure as proposed by Lasater based on the standard physical equation of solution is

$$P_b=P_f\left(\frac{T+459.6}{\gamma_g}\right) \qquad 6$$

The average error of the representation is 3.8% and the maximum error encountered is 14.7% (Lasater, 1958). The Lasater correlation was based on crudes essentially free of non-hydrocarbon components and it is valid for hydrocarbon system not near the critical point. The presence of large amounts of non-hydrocarbons will results in low bubble point prediction.

Whitson and Brule (2000) correlated the bubble-point pressure factor P_f as a function of solution gas mole fraction as shown

$$P_f=\begin{cases}0.83918\times 10^{1.17664y_g}\times {y_g}^{0.57246}; y_g\le 0.6\\ 0.83918\times 10^{1.08y_g}\times {y_g}^{0.31109}; y_g>0.6\end{cases} \qquad 7$$

Similar bubble-point factor correlation was developed by Hanafy and others (1997) as shown in Equation 8,

$$P_f=0.046+2.273y_g+7.522{y_g}^3 \qquad 8$$

The solution gas mole fraction y_g is dependent on solution GOR and properties of stock tank oil and it was defined by

$$y_g = \frac{M_o R_{sb}}{M_o R_{sb} + 132755\gamma_o} \qquad \textbf{9}$$

where oil gravity is given by

$$\gamma_o = \frac{141.5}{131.5 + API} \qquad \textbf{10}$$

Lasater assumed that an effective molecular weight could be assigned to the tank oil. He therefore constructed a graph of effective molecular weight as a function of oil gravity for crude oil system with UOP characterization factor of 11.8, that is, for naphthenic crudes.

However, Whitson and Brule (2000) recommended a mathematical expression based Cragoe's correlation for estimating the effective molecular weight of tank oil.

$$M_o = \frac{6084}{API - 5.9} \qquad \textbf{11}$$

Lasater did not give correlation for solution GOR

Glaso Correlations

Standing (1947) approach was used by Glaso (1980) for 45 oil samples from the North Sea in developing his correlations. He presented bubble-point correlation with average error of 1.28% and a standard deviation of 6.98% thus:

$$P_b = 10^{1.7669 + 1.7447 \log A - 0.30218 (\log A)^2} \qquad 12$$

$$A = \left(\frac{R_{sb}}{\gamma_g}\right)^{0.816} \times \frac{T^{0.172}}{API^{0.989}} \qquad 13$$

Solving the Glaso's bubble-point correlation for solution GOR results to

$$R_s = \gamma_g \left[10^x \left(\frac{API^{0.989}}{T^{0.172}} \right) \right]^{1.2255} \qquad 14$$

$$x = 2.8869 - (14.1811 - 3.3093 \log P)^{0.5} \qquad 15$$

These equations are valid for all types of gas/oil mixtures after correcting for non-hydrocarbons in the surface gases and paraffinicity of the oil (Glaso, 1980).

Vasquez-Beggs Correlation

Vasquez and Beggs (1980) proposed an empirical correlation for estimating solution gas-oil ratio. The correlation was obtained by regression analysis using more than 6000 measured solution GOR, oil FVF and oil viscosity at various pressures. These measurements were made on more than 600 PVT laboratory analyses from different oil field locations around the world. Vasquez and Beggs correlation is unique in that they tried to globalize their formulation. There lies its weakness, since crude oil compositions vary with location. Vasquez and Beggs presented two solution GOR correlations: one for crudes having $API \le 30$ and the other for crudes having $API > 30$ as:

$$R_s = \begin{cases} 0.0362\gamma_{gc} P^{1.0937} \exp\left[25.724\left(\dfrac{API}{T+460}\right)\right]; API \le 30 \\ 0.0178\gamma_{gc} P^{1.187} \exp\left[23.931\left(\dfrac{API}{T+460}\right)\right]; API > 30 \end{cases} \qquad 16$$

Vasquez and Beggs stated that separator conditions affect the gas gravity and consequently adjusted it to a separator pressure of 114.7psia. The normalized gas gravity which corrects for the effect of separator condition, correlated with separator temperature T_{sp} and pressure P_{sp} is

$$\gamma_{gc} = \gamma_g \left[1 + 5.912 \times 10^{-5} API \times T_{sp} \log\left(\frac{P_{sp}}{114.7}\right)\right] \qquad 17$$

If the separator temperature and pressure are not available they are assumed to be 60^{o}F and 14.7psia respectively.

Al-Marhoun Correlations

Al-Marhoun (1988) proposed a correlation based on nonlinear regression of 160 experimental data points from 69 Middle East bottomhole oil samples. Al-Marhoun's correlation covers wide range of non-hydrocarbon gases. The author proposed the following bubble-point equation with an average absolute error of 3.66% and standard deviation of 4.536% when compared with the experimental data used in the correlation.

$$P_b = 0.00538088 R_{sb}^{\ 0.715082} \gamma_g^{\ -1.87784} \gamma_o^{\ 3.1437} (T + 460)^{1.32657} \qquad 18$$

As usual, making solution GOR the subject of Equation 18 gives the Al-Marhoun bubble-point GOR as

$$R_s = \left[185.483208 \gamma_g^{\ 1.87784} \gamma_o^{\ -3.1437} (T + 460)^{-1.32657} P\right]^{1.398441} \qquad 19$$

Based on the concept of Al-Marhoun, Mazandarani and Asghari (2007) developed a set of new PVT correlations, using multiple regression analysis. Their correlations are of the form given by:

$$P_b = 1.09373 \times 10^{-4} R_{sb}^{\ 0.5502} \gamma_g^{\ -1.71956} \gamma_o^{\ 2.5486} (T + 460)^{2.0967} \qquad 20$$

with an average absolute error of 0.066% as against 3.66% computed by Al-Marhoun. Also:

$$R_s = 994.3718 \gamma_g^{\ 2.113367} \gamma_o^{\ -5.48944} (T + 460)^{-1.90488} P^{1.45558} \qquad 21$$

Again, Dokla and Osman (1990) followed the same procedure of Al-Marhoun to develop bubble-point pressure as:

$$P_b = 0.836386 \times 10^4 R_{sb}{}^{0.724047} \gamma_g{}^{-1.01049} \gamma_o{}^{0.107991} (T+460)^{-0.952584} \qquad 22$$

with an average absolute error of 7.61%

Petrosky and Farshad Correlations

Petrosky and Farshad (1993) proposed black oil PVT correlations based on 81 laboratory analyses of crude oil from the Gulf of Mexico. Their correlations are similar to Standing (1947), but introduced three additional fitting parameters to the models functional forms used by Standing to enhance the accuracy of the correlation. This maximum flexibility allows each parameter to have a multiplier and exponent not equal to one (Omar, 2011). Petrosky and Farshad presented a bubble-point correlation with an average absolute error of 3.28% and standard deviation of 2.56% in the following expression.

$$P_b = 112.727 \left(\frac{R_{sb}{}^{0.5774}}{\gamma_g{}^{0.8439} \times 10^x} - 12.34 \right) \qquad 23$$

$$x = 7.916 \times 10^{-4} API^{1.541} - 4.561 \times 10^{-5} T^{1.3911} \qquad 24$$

Petrosky and Farshad (1993) attempted to develop solution GOR correlation using nonlinear regression. However, after ten different models were used in the regression analysis, it dawned on them that the best results were obtained by solving for solution GOR from their bubble-point correlation. They therefore solved their bubble point correlation for solution GOR as in the following expression

$$R_s = \left[\left(\frac{P}{112.727} + 12.34 \right) \times \gamma_g{}^{0.8439} \times 10^x \right]^{1.73184} \qquad 25$$

where x is as defined in Equation 1.13b. They reported an average absolute error of 3.8% and standard deviation of 2.88% for their solution GOR correlation.

METHODOLOGY

The fundamental theory for the development of PVT correlations is hinged on matching PVT report with nonlinear functions of various PVT data. For instance, to develop an empirical prediction for bubble-point pressure, a nonlinear function relating oil and gas gravities, and bubble-point solution GOR is specified at the reservoir temperature.

The nonlinear function assumed by this study is in the form given by

$$P_b = 10^{a_0} API^{a_1} \gamma_g{}^{a_2} R_{sob}{}^{a_3} T^{a_4} \qquad 26$$

Where

P_b = bubble-point pressure, psia
R_{sob} = bubble-point solution GOR, scf/stb
γ_g = gas gravity
API = oil gravity, API

$a_0 - a_5$ = unknown regression constants

This study chose to transform the nonlinear function into a linear logarithmic function given as:

$$\log P_b = a_0 + a_1 \log API + a_2 \log \gamma_g + a_3 \log R_{sob} + a_4 \log T \qquad 27$$

In this form, the issue of initialization is skipped because the nonlinear problem has reduced to a multiple linear optimization problem.

Multiple Linear Least Square Regression

Values of the unknown regression constants were obtain directly from measured PVT data. That is $y = \log p_b$, $x_1 = \log API$, $x_2 = \log \gamma_g$, $x_3 = \log R_{sob}$, and $x_4 = \log T$, then Equation 1.2 becomes

$$y = a_0 + a_1 x_1 + a_2 x_2 + a_3 x_3 + a_4 x_4 + e \qquad 28$$

Here, e is the error or residue due to the approximation of the measured PVT data by a linear function of four variables x_1 to x_4. That is, the residue is the discrepancy between the measured and predicted PVT data. The objective then is to find the values of the unknown regression constants that would minimize Equation 4 such that

$$\sum_{i=1}^{n} e_i = \sum_{i=1}^{n} \left(y_i - a_o - a_1 x_{1i} - a_2 x_{2i} - a_3 x_{3i} - a_4 x_{4i} \right)^2 \qquad 29$$

must be reasonably close to zero. Thus, if Equation 6 is evaluated for the regression constants at its minimum value, the normal equations are given in the matrix form as:

$$\begin{bmatrix} n & \sum x_1 & \sum x_2 & \sum x_3 & \sum x_4 \\ \sum x_1 & \sum x_1{}^2 & \sum x_1 x_2 & \sum x_1 x_3 & \sum x_1 x_4 \\ \sum x_2 & \sum x_1 x_2 & \sum x_2{}^2 & \sum x_3 x_3 & \sum x_2 x_4 \\ \sum x_3 & \sum x_1 x_3 & \sum x_2 x_3 & \sum x_3{}^2 & \sum x_3 x_4 \\ \sum x_4 & \sum x_1 x_4 & \sum x_2 x_4 & \sum x_3 x_4 & \sum x_4{}^2 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix} = \begin{bmatrix} \sum y \\ \sum x_1 y \\ \sum x_2 y \\ \sum x_3 y \\ \sum x_4 y \end{bmatrix} \qquad 30$$

Elements of the normal equations for multiple regressions were assembled for data set using codes.
In order to guide against erroneous result that might be associated with ill-conditioning of the matrix. LU decomposition algorithm or Cholesky's algorithm were observed as the viable options, however, the LU decomposition method being more general and stable was adopted.

Performance Evaluation of the PVT Correlation

The study utilized statistical and graphical error analysis methods to evaluate the performance, as well as the accuracy, of the PVT correlation. The accuracy of the correlation relative to the experimental PVT data is determined by various statistical means. The statistical methods used in this study are average percent relative error, average absolute percent relative error, minimum/maximum absolute percent relative error, standard deviation, and the correlation coefficient. The performance plots employed by the study include cross plot, grouped API plot, and average relative error distribution plot.

PVT Data Validations

The quality of the measured PVT data was examined to ensure it meets the standard to be used in building PVT models was carried out using the following validity checks: opening pressure check, material balance consistency test and the Hoffmann' plot.

RESULTS AND DISCUSSION

A total of 189 measured PVT data points from the Niger Delta were used by the study out of which 159 data points were used to build the model and 30 were used to validate it. The data sets consist of API stock tank oil gravity, gas gravity, bubble-point solution GOR, reservoir, temperature and bubble-point pressure. It is assumed that the crudes do not contain impurities.

All the data were obtained from 39 oil fields covering over 205 oil reservoirs located in the Niger Delta region. Statistical distribution of the PVT database is shown in Table 2

Table 2 Statistical Distribution of PVT Database

Data	Minimum	Maximum	mean	std. Dev.
Oil Gravity [API]	19.4	44.6	32.45	5.652
Gas Gravity [-]	0.752	1.367	0.966	0.169
Rsb [scf/stb]	26	1602	555.9	403.9
Temperature [oF]	74	240	144.8	39.06
bubble-point [psia]	130	3573	1726	1085

The API mean distribution of 32.45 indicates that the Niger crude is light crude since according to De Ghetto *et al* (1994), API oil gravity greater than 31.1 means light crude. McCain (1990) classified black oil as oil with solution GOR less than 1750. So, Table 1 shows that the crude used for this study is balck oil.

The Newly Developed Correlations

The newly developed empirical correlation for bubble-point pressure is a 5 parameter regression model that provides the best curve fit for the acquired PVT database and the model in Equation 26. The newly developed correlations are given as follow:

$$P_b = 10^{1.45274} API^{-0.58612} \gamma_g^{-1.89527} R_{sob}^{0.71363} T^{0.30388} \qquad 30$$

Such that solving for solution GOR gives

$$R_s = 10^{-0.59255} API^{0.82132} \gamma_g^{2.65582} p^{1.40129} T^{-0.42583} \qquad 31$$

The statistical parameters associated with the newly developed bubble-point correlation are given in Table 3

Table 3: Bubble-Point Statistical Parameters

average percent relative error	-0.1151
average absolute percent relative error	3.73636
percent standard deviation of the relative error	0.04883
standard deviation	86.2896
correlation coefficient	0.99388

The correlation coefficient for this equation was 0.9939, indicating that the equation explains 99.39% behaviour of the measured PVT bubble-point correlation. The negative average percent relative error indicates that more of the predicted bubble-point pressures are greater than the measured bubble-point pressure. The average absolute percent relative error is about 3.74% while the percent standard deviation of the relative error is as low as 0.0488%. These are indication that the study's newly developed bubble-point pressure correlation accurately modelled that PVT measured bubble-point pressure as shown by the cross plot in Figure 2.

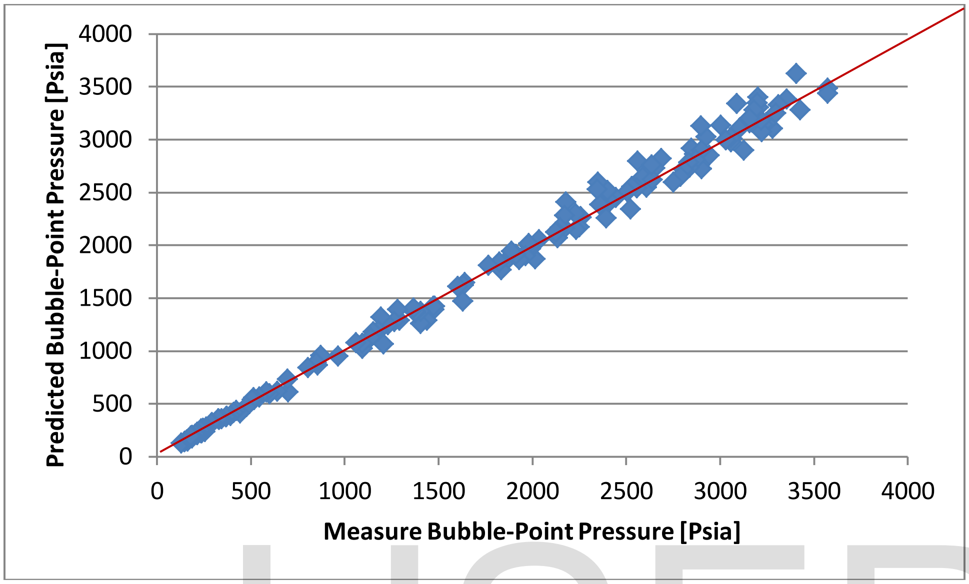

Fig. 2: Bubble-Point Cross Plot

Conclusion

The following conclusions were drawn, founded on the data presented and analyzed by the study.

1. PVT bubble-point and solution GOR correlations for Niger Delta oil mixtures were developed. The development of the models was based on transforming nonlinear equation into a multiple linear equations and imposing a multiple linear optimization scheme on it.
2. All the independent variables used in the development of the new correlation are often measured in the field.
3. Statistical error and graphical analyses indicated that the developed bubble-point correlation and by extension, the solution GOR predicted the measured PVT data by 99.39%.
4. The newly developed correlations did not perform well with heavy crudes.
5. For a database within the range of light crude, it is expected that the statistical parameters should not be significantly different from those reported by this study.

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