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General Equations for the Bubble Point Formation Volume Factor of Crude Oils

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Abstract

General equations for calculating the bubble point formation volume factor of all types of crude oil have been developed.

Unlike present equation used in the oil industry, these new equations do not require the gas gravity of gas that is associated with the crude oil. The new equations are intended to complement the recent general equation (Ohirhian, 2010) for the bubble point formation volume factor of a any type of crude that has a temperature below 220.1 ^{O}F.

The equations were tested with various types of crude oil that have temperatures between 175 and 280 ^{O}F. Absolute error between laboratory measured and calculated bubble point formation volume factor varied between 0 -5.1 %.

The equation by Standing (1977) has absolute errors that ranged from 0 – 28% for the same data used to test the new equations.

Keywords: General Equations, Crude Oil, Volume Factor, Bubble Point.

1.0 Introduction

The formation volume factor of a crude oil (BO) is a coefficient that multiplies a unit volume of the crude oil at standard condition (14.7 psia and 60 ^{O}F) to give the actual volume of the crude oil in an oil reservoir. The formation volume factor is usually measured in the laboratory. Laboratory measurement is expensive and time consuming. Frequently approximating equations are used to calculate the formation volume factor. The most widely used equation is that of Standing [5]. The standing equation was developed for the estimation of the bubble point formation volume factor of California crude oil. It can predict the bible point formation volume factor of California crude oil within an absolute error of 4.5 %. When applied to a foreign crude oil, absolute error can exceed 25 %. Later researchers, for example, Glasso [1] modified the Standing equation, so that it can be used for North Sea Oil. The difficulty of developing general equation(s) led some researchers to develop equations that work best for particular oil producing regions. For example, [2, 3] developed equations that work best for Middle East and Nigeria crudes, respectively.

Recently, [4] developed a single equation that is applicable to various types of crude oils. The [4] is limited to a maximum temperature range of 220 ^{O}F. The [4] equation has a maximum absolute error of 6%. Higher errors are encountered at temperatures that exceed 174 ^{O}F. In this study, new general equations that calculate the bubble point formation volume factor of a crude oil that has a temperature that exceeds 174 ^{O}F are developed. These equations do not require the use of the specific gravity of the associated gas. The equations were developed and tested with the pressure volume temperature (PVT) data of oil companies that operate in Nigeria and the data of [1] for North Sea and miscellaneous crudes. The range of the parameters used is:

API gravity: 22.3 - 48.6
Temperature: 175 – 280 ^{O}F
Gas Oil Ratio: 228 – 2637 SCF / STB.

A Comparison between the measured and calculated values of the bubble point formation volume factor gave an absolute error range of 0 – 5.1 %

The Standing equation has absolute errors that ranged from 0 – 28% for the same data used to test the new equations.

2. Development of the Equations

We empirically found that Oil Reservoirs that exist at temperatures that exceed 174 ^{O}F can be divided into two broad groups, depending on the ratio of solution Gas Oil Ratio (GOR) to temperature (T). The first group (1) consists of:

$$\frac{GOR}{T} \leq 4.155$$

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The second group (2) consists of Oil Reservoirs with:

$$\frac{GOR}{T} > 4.155$$

The first group (1) is further divided into two subgroups 1a and 1b. The parameter used to do the sub division is dented by X in this study and is defined as:

$$X = \text{Exp}\ [\ (RO_1\ /\ SGO\ s)\ \log(GOR\ /\ T)\ ]$$

where,

SGOs = Oil relative density at atmospheric pressure (14.7 psia) and standard temperature (60 ^{O}F)

$RO_1 = SGO\ s\ /\ BO_1$

$BO_1 = 0.968065 + 0.0004203(T\ /\ SGO\ s)$

In this study, the units of GOR and T are SCF and ^{O}F respectively. The first subgroup (1a) is characterised by: $X \leq 1.510$

The second subgroup (1b) is characterised by: $X > 1.510$

The second major group (2) is divided into two subgroups that depend on the value the value of X. The first subgroup is characterised by:

$$X \leq 1.886$$

The first subgroup is further divided into two sub- subgroups, 2a and 2b that depend on a value of a parameter denoted in this study by Y, and defined as:

$$Y = RO_1 \times GOR$$

The first sub-subgroup (2a) is characterised by:

$$Y \leq 738$$

The second sub-subgroup (2b) is characterised by:

$$Y > 738$$

The grouping is easier to visualise in tabular form. The groups, subgroups and sub-subgroups are shown in Table 1. The second subgroup is characterised by:

$$X > 1.886$$

This subgroup is further divided into three-subgroups (2a) to (2c) depending the value of the parameter Y. The values of Y for the various sub-subgroups are shown in Table1.

EQUATION NO.	RANGE OF T (^{O}F)	RANGE OF (GOR/T)	RANGE OF X	RANGE OF Y= ($RO_1\times$ GOR)	EQUATION
1a	175 - 280	≤ 4.155	≤ 1.510	----	$BO_b = BO_1 - 2.791769+0.2030406 \times \ln(API\times T \times GOR)$
1b	175 - 280	≤ 4.155	> 1.510	----	$BO_b = BO_1 - .2715102+0.2441165 \times \ln(X \times RO_1\times GOR)$
2a	175 - 280	> 4.155	≤ 1.886	≤ 738	$BO_b = BO_1 - 4.553860+0.489592 \times \ln(API\times RO_1\times GOR)$
2b	175 - 280	> 4.155	≤ 1.886	>738	$BO_b = BO_1 - 8.0659121 + 0.6952427 \times \ln(T \times GOR)$
2c	175 - 280	> 4.155	> 1.886	≤ 1290	$BO_b = BO_1 - 7.7531510 + 0.7959049 \times \ln(API\times GOR\times RO_1)$
2d	175 - 280	> 4.155	> 1.886	1290 – 1472	$BO_b = BO_1 + 2.3141160+1.1072281 \times \ln(RO_1\ /\ X)$
2e	175 - 280	> 4.155	> 1.886	> 1472	$BO_b = BO_1 - 11.3117945+1.0514493 \times \ln(API \times RO_1\times GOR) + 0.0028883 \times (API\times GOR\ /\ T)$

$BO_1 = 0.968065 + 0.0004203(T\ /\ SGO\ s)$

$RO_1 = SGO\ s\ /\ BO_1$

$X = \text{Exp}\ [\ (RO_1\ /\ SGO\ s)\ \log(GOR\ /\ T)\ ]$

AP I = American Petroleum Institute degree

GOR = Surface oil to gas (SCF / STB)
T = Temperature in degrees Fahrenheit (^{O}F)
SGOs = Oil relative density at atmospheric pressure (14.7 psia) and standard temperature (60 ^{O}F)

The equations developed in this study for estimating the bubble point formation volume factor of crude oil (BO_b) are functions of the formation volume factor of the gas free crude oil (BO_1), American Petroleum Institute Degree (^{O}API), Temperature (T), and surface oil gas ratio (GOR). All equations of this study break down to BO_1, if the surface gas oil ratio (GOR) is zero. This is the first advantage of the equations of this study. A second and better advantage is that they make use of the specific gravity of gas that is associated with the crude oil. Ohirhian [3] has developed an equation for BO_1. The equation is:

$$BO_1 = 0.968065 + 0.0004203(T / SGO\ s) \tag{1}$$

where,

SGO s = Oil relative density at atmospheric pressure (14.7 psia) and standard temperature (60 ^{O}F)

$$SGO_s = \frac{141.5}{{}^oAPI + 131.5} \tag{2}$$

where,

^oAPI = American Petroleum Institute degree

The equations developed for the various subgroups and sub- subgroups are shown in Table 1. All equations were obtained by statistical regression The equations were developed and tested with the pressure volume temperature (PVT) data of oil companies that operate in Nigeria and the data of [1] for North Sea and miscellaneous crudes. The data for Nigerian Crude oil used in this study and the corresponding values of the bubble point formation volume factor produced by the equations are shown in Table 1. For the purpose of comparison, the values of the bubble point formation volume factor produced by [5] single equation are shown in the last column of Table 2. The data for North Sea Crude oil used in this study and the corresponding values of the bubble point formation volume factor produced by the equations of this study and those of Standing are shown in Table 3. The data for Miscellaneous Crude oils used in this study and the corresponding values of the bubble point formation volume factor produced by the equations of this study and those of Standing are shown in Table 4.

The Standing formula is:

$$B_{Ob} = 0.9759 + 12E\text{-}5\ BOBCN^{1.2}$$

where

$$BOBCN = R_S (SG\ g / SG\ o)^{0.5} + 1.25T$$

Table 2: Calculation of Bubble Point Formation Volume Factor, This Work and Standing (1977) (Nigeria Crude Oil)

No	^{O}API	T ^{O}F	SGOs	SGGs	GOR	BO_b Experimental	BO_b This work	BO_b Standing (1977)
1	37.8	220	.836	.880	947	1.514	1.532	1.598
2	39.3	175	.828	.847	806	1.515	1.457	1.473
3	40.3	183	.823	.897	1716	1.988	2.080	2.086
4	43.6	212	.808	.976	1834	2.128	2.115	2.261
5	43.1	178	.810	1.011	616	1.460	1.416	1.403
6	43.8	210	.807	1.038	1124	1.746	1.694	1.776
7	36.9	183.5	.840	.814	1034	1.521	1.517	1.599
8	35.5	176	.847	.632	477	1.289	1.289	1.251
9	40.4	183	.823	.755	1716	2.088	2.080	1.990
10	40.4	186	.823	.650	772	1.421	1.494	1.382
11	45.2	186	.832	.790	690	1.441	1.451	1.407
12	40.6	187	.822	.704	1555	1.973	1.902	1.862
13	40.4	190	.823	.709	356	1.299	1.282	1.218
14	40.9	192	.821	.676	823	1.469	1.483	1.447
15	38.8	194	.831	.750	1659	2.147	2.135	1.955
16	36.5	196	.842	.692	1149	1.654	1.596	1.622
17	32.0	198	.816	.676	933	1.572	1.561	1.510
18	48.6	202	.786	.782	1634	2.128	2.055	1.997

Table 3: Calculation of Bubble Point Formation Volume Factor, This Work and [5] (North Sea Crude Oil)

No	^{O}API	T ^{O}F	SGOs	SGGs	GOR	BO $_{b}$ Experimental	BO $_{b}$ This work	BO $_{b}$ Standing(1977)
1	42.5	260	.813	.799	1409	1.854	1.864	1.893
2	35.1	230	.849	.759	756	1.442	1.484	1.455
3	38.0	245	.835	.935	1924	2.210	2.200	2.303
4	31.7	230	.867	.980	950	1.589	1.565	1.629
5	39.0	250	.830	.761	1623	1.918	1.920	1.986
6	38.8	180	.835	.732	909	1.434	1.446	1.498
7	38.6	180	.832	.756	1280	1.664	1.715	1.719
8	39.2	210	.829	.946	1039	1.596	1.562	1.674
9	38.5	254	.832	.753	2060	2.186	2.258	2.258
10	42.9	245	.811	.793	1450	1.846	1.890	1.904
11	37.3	270	.838	.721	1361	1.784	1.754	1.815
12	37.4	225	.838	1.049	256	1.218	1.249	1.218
13	36.2	280	.844	.760	2036	2.110	2.053	2.262
14	32.5	270	.863	.894	1950	1.784	1.834	2.289
15	33.6	250	.857	.909	2216	2.160	2.178	2.476
16	34.8	254	.851	.889	2637	2.588	2.574	2.771

Table 4: Calculation of Bubble Point Formation Volume Factor, This Work and [5] (Miscellaneous Crude Oils)

No	^{O}API	T ^{O}F	SGOs	SGGs	GOR	BO $_{b}$ Experimental	BO $_{b}$ This work	BO $_{b}$ Standing(1977)
1	44.8	210	.803	.729	770	1.450	1.486	1.453
2	22.3	211	.920	.650	459	1.230	1.231	1.261
3	34.8	210	.851	1.178	267	1.217	1.219	1.223
4	41.7	230	.817	1.158	853	1.515	1.521	1.632
5	40.8	230	.821	1.033	1258	1.755	1.743	1.878
6	41.5	230	.818	1.023	1124	1.680	1.685	1.781
7	27.9	240	.888	1.248	840	1.593	1.525	1.707
8	28.1	200	.885	.975	891	1.380	1.401	1.561
9	28.4	200	.883	.968	887	1.410	1.398	1.557
10	42.4	235	.814	1.000	1718	1.996	2.016	2.205
11	40.3	223	.824	1.053	1850	2.126	2.153	2.322
12	32.6	200	.862	1.276	228	1.162	1.157	1.198
13	40.4	220	.823	.868	780	1.483	1.492	1.498
14	29.9	220	.881	.973	620	1.382	1.422	1.413
15	48.1	248	.758	.985	1344	1.850	1.902	1.951
16	47.7	249	.790	1.034	1452	1.901	1.958	2.056
17	36.6	242	.842	.710	688	1.498	1.450	1.416
18	37.2	253	.839	.863	326	1.326	1.335	1.259

3. 0 Testing of the New Equations

The equations developed in this study are simple. The selection of an appropriate equation is demonstrated by hand working the bubble point formation volume factor of crude oil (BO $_{b}$) of a few reservoirs selected from Tables 2 to 4

Example
Calculate the bubble point formation volume factor (BO $_{b}$) of reservoirs that have the data shown in Table 5.

Table 5: Data for sample calculation of Bubble Point Formation Volume Factor

No	^{O}API	T ^{O}F	GOR (SCF / STB)	SOURCE
1	39.3	175	806	Table 2
2	43.1	178	616	Table 2
3	28.4	200	887	Table 4
4	33.6	250	2216	Table 3
5	47.7	249	1452	Table 4

Solution

1. Specific gravity of oil at standard condition of 14.7 psia and temperature of 60 ^{O}F (SGO s) is:

$$SGO_s = \frac{141.5}{^{o}API + 131.5} = \frac{141.5}{39.3 + 131.5} = 0.828$$

Formation volume factor at 14.7 psia and 175 ^{O}F (BO_1) is:

BO_1 = 0.968065 + 0.0004203(T / SGO s) = 0.968065 + 0.0004203×(175 / 0.828)
= 1.057

RO_1 = SGO s / BO_1 = 0.828 / 1.057 = 0.783

Check for major group

GOR / T = 806 / 175 = 4.406

Since, GOR / T > 4.155, this oil falls into the second major group.

Next, check for the subgroup.

X = Exp [(RO_1 / SGO s) log(GOR / T)] = Exp [(0.783 / 0.828) × log(806 / 175)]
= 1.872

Since, X < 1.886, this oil falls into the first subgroup of the second major group.

Next, check for the sub-subgroup.

Y = RO_1 × SGO = 0.783 × 806 = 631.1

Since, Y < 738, this oil falls into the first sub-subgroup of the first subgroup.. The equation to use is (2a). The equation is:

BO_b = BO_1 – 4.553860+0.489592 × ln(API×RO_1 × GOR)
= 1.057 – 4.553860+0.489592 × ln (39.3× 0.783 × 806) = 1.457

The experimental BO_b is 1.515. Absolute error = 2.64 %.

2. Here, ^{o}API = 43.1. Thus, SGO s = 0.810

Formation volume factor at 14.7 psia and 175 ^{O}F (BO_1) is:

BO_1 = 0.968065 + 0.0004203(T / SGO s) = 0.968065 + 0.0004203×(178 / 0.810)
= 1.060

RO_1 = SGO s / BO_1 = 0.810 / 1.0607 = 0.764

Check for major group

GOR / T = 616 / 178 = 3.46

Since, GOR / T < 4.155, this oil falls into the first major group.

Next, check for the subgroup.

X = Exp [(RO_1 / SGO s) log(GOR / T)] = Exp [(0.764 / 0.810) × log(3.46)]
= 1.662

Since, X > 1.510, this oil falls into the second subgroup of the first major group.

There is no sub-subgroup in the first major group. The equation to use is (1b).

BO_b = BO_1 – 1.2715102+0.2441165 × ln (X ×RO_1× GOR)
= 1.060 – 1.2715102+0.2441165 × ln (1.662×0.764× 616) = 1.415

The experimental BO_b is 1.460. Absolute error = 3.08 %.

3. Here, ^{o}API = 28.4. Thus, SGO s = 0.885

Formation volume factor at 14.7 psia and 175 ^{O}F (BO_1) = 0.968065 + 0.0004203×(200 / 0.885) = 1.063

RO_1 = SGO s / BO_1 = 0.885 / 1.063 = 0.833

Check for major group

GOR / T = 887 / 200 = 4.435

Since, GOR / T > 4.155, this oil falls into the second major group.

Next, check for the subgroup.

$X = \text{Exp}[(RO_1 / SGO\ s) \log(GOR / T)] = \text{Exp}[(0.853 / 0.885) \times \log(4.435)]$
$= 1.838$

Since, $X < 1.886$, this oil falls into the first subgroup of the second major group.
Next, check for the sub-subgroup.

$Y = RO_1 \times SGO = 0.883 \times 887 = 738.9$

Since, $Y > 738$, this oil falls into the second sub-subgroup, of the first subgroup.. The equation to use is (2b). The equation is:

$BO_b = BO_1 - 8.0659121 + 0.6952427 \times \ln(T \times GOR)$
$= 1.063 - 8.0659121 + 0.6952427 \times \ln(200 \times 887) = 1.400$

The experimental BO_b is 1.380. Absolute error = 1.4 %.

4. Here, ^{O}API = 33.6. Thus, SGO s = 0.857
Formation volume factor at 14.7 psia and 175 ^{O}F (BO_1) = $0.968065 + 0.0004203 \times (250 / 0.857) = 1.091$

$RO_1 = SGO\ s / BO_1 = 0.857 / 1.091 = 0.786$

Check for major group

$GOR / T = 2216 / 250 = 8.864$

Since, $GOR / T > 4.155$, this oil falls into the second major group.
Next, check for the subgroup.

$X = \text{Exp}[(RO_1 / SGO\ s) \log(GOR / T)] = \text{Exp}[(0.8786/ 0.857) \times \log(8.864)]$
$= 2.385$

Since, $X > 1.886$, this oil falls into the second subgroup of the second major group.
Next, check for the sub-subgroup.

$Y = RO_1 \times SGO = 0.786 \times 2216 = 1741.8$

Since, $Y > 1472$, this oil falls into the third sub-subgroup, of the second subgroup.. The equation to use is (2e). The equation is:

$BO_b = BO_1 - 11.3117945 + 1.0514493 \times \ln(API \times RO_1 \times GOR) + 0.0028883 \times (API \times GOR / T)$
$= 1.091 - 11.3117945 + 1.0514493 \times \ln(33.6 \times 0.786 \times 2216) + 0.0028883 \times$
$(33.6 \times 2216 / 250) = 1.181$

The experimental BO_b is 2.160. Absolute error = 0.99 %.

5. Here, ^{O}API = 47.7. Thus, SGO s = 0.790
Formation volume factor at 14.7 psia and 175 ^{O}F (BO_1) = $0.968065 + 0.0004203 \times (249 / 0.790)$
$= 1.101$

$RO_1 = SGO\ s / BO_1 = 0.790 / 1.101 = 0.718$

Check for major group

$GOR / T = 1452 / 249 = 5.831$

Since, $GOR / T > 4.155$, this oil falls into the second major group.
Next, check for the subgroup.

$X = \text{Exp}[(RO_1 / SGO\ s) \log(GOR / T)] = \text{Exp}[(0.718/ 0.790) \times \log(5.831)] = 2.006$

Since, $X > 1.886$, this oil falls into the second subgroup of the second major group.
Next, check for the sub-subgroup.

$Y = RO_1 \times SGO = 0.718 \times 1452 = 1042.5$

Since, $Y < 1290$, this oil falls into the first sub-subgroup, of the second subgroup.. The equation to use is (2c). The equation is:

$BO_b = BO_1 - 7.7531510 + 0.7959049 \times \ln(API \times GOR \times RO_1)$
$= 1.101 - 7.7531510 + 0.7959049 \times \ln(47.7, \times 1452 \times 0.718) = 1.955$

The experimental BO_b is 1.901. Absolute error = 2.84 %.

The use of Standing Formula for the estimation of the BO_b of a North Sea crude oil that has:

^{O}API = 32.5
T = 270 ^{O}F
GOR = 1950 SCF / STB
SGGs = 0.895

is as follows.

$SGOs = 141.5 / (131.5 + 32.5) = 0.863$
$BOBCN = GOR\,(SGG\ s / SGO\ s)^{0.5} + 1.25T = 1950 \times (0.895 / 0.863)^{0.5} + 1.25 \times 270$
$= 2323.3$

$BO_b = 0.9759 + 12E\text{-}5\ BOBCN^{1.2} = 0.9759 + 12\times10^{(-5)} \times 2323.3^{(1.2)} = 2.290$

The experimental BO_b is 1.784. Absolute error = 28.4 %.

The performance of the equations of this study on Nigeria crude oil is shown in Table 2.This data came from pressure, volume and temperature (PVT) of oil companies that operate in Nigeria. Also shown in Table 2 are corresponding values from the equation of Standing. The performance of the equations of this study on North Sea crude oil is shown together with the performance of the Standing single equation in Table 3. Table 4 shows the performance of the new equations and the Standing single equation on miscellaneous crude oils. The data shown in tables 3 and 4 came from the article of [1].

Statistical error analysis

The Statistical measures of accuracy used in this study are defined by [6] as:

(a) Percent error (Ei) = $\frac{(X_{est} - X_{\exp})\times100}{X \exp}$ (3)

Where:

X est. = B_{Ob} from this study

X exp = B_{Ob} from PVT report

(b) Average percent error (M.D.) = $\frac{\sum Ei}{N}$ (4)

Where, N = total number of samples

(c) Percent absolute error (AE i) = $|\ Ei\ |$ (5)

(d) Average percent absolute error (A.M.D.) = $\frac{\sum|\ Ei\ |}{N}$ (6)

(e) Standard deviation (SD) = $\sqrt{\frac{(\sum AEi^2)}{N - 1} - \frac{(\sum AEi)^2}{N}}$ (7)

The result of error analysis of the new equations on Nigerian crudes is shown in Table 6. The result of error analysis of the Standing equation on Nigerian crudes is shown in Table 7

Table 6: Error Analysis for Nigeria Crude (This Study)

DATA VALUE	TRUE VALUE	ESTIMIAED VALUE	ERROR	ABSOLUTE ERROR
1	1.514	1.532	-1.189	1.189
2	1.515	1.457	3.828	3.828
3	1.988	2.080	-4.628	4.628
4	2.128	2.115	.611	.611
5	1.460	1.416	3.014	3.014
6	1.746	1.694	2.978	2.978
7	1.521	1.517	.263	.263
8	1.289	1.289	.000	.000
9	2.088	2.080	.383	.383
10	1.421	1.494	-5.137	5.137
11	1.441	1.451	-.694	.694
12	1.973	1.902	3.599	3.599
13	1.299	1.282	1.309	1.309
14	1.469	1.483	-.953	.953
15	2.147	2.135	.559	.559
16	1.654	1.596	3.507	3.507
17	1.572	1.561	.700	.700
18	2.128	2.055	3.430	3.430

AVERAGE PERCENT ERROR = .643

AVERAGE ABSOLUTE PERCENT ERROR = 2.043

STANDARD DEVIATION = 2.283

Table 7: Error Analysis for Nigeria Crude (Standing)

DATA VALUE	TRUE VALUE	ESTIMAIED VALUE	ERROR	ABSOLUTE ERROR
1	1.514	1.598	-5.548	5.548
2	1.515	1.473	2.772	2.772
3	1.988	2.086	-4.930	4.930
4	2.128	2.261	-6.250	6.250
5	1.460	1.403	3.904	3.904
6	1.746	1.776	-1.718	1.718
7	1.521	1.599	-5.128	5.128
8	1.289	1.251	2.948	2.948
9	2.088	1.990	4.693	4.693
10	1.421	1.382	2.745	2.745
11	1.441	1.407	2.359	2.359
12	1.973	1.862	5.626	5.626
13	1.299	1.218	6.236	6.236
14	1.469	1.447	1.498	1.498
15	2.147	1.955	8.943	8.943
16	1.654	1.622	1.935	1.935
17	1.572	1.510	3.944	3.944
18	2.128	1.997	6.156	6.156

AVERAGE PERCENT ERROR = 1.677
AVERAGE ABSOLUTE PERCENT ERROR = 4.296
STANDARD DEVIATION = 4.386

The result of error analysis of the new equations on North Sea crudes is shown in Table 8. The result of error analysis of the Standing equation on Nigerian crudes is shown in Table 9

Table 8: Error Analysis for North Sea Crude (This study)

DATA VALUE	TRUE VALUE	ESTIMAIED VALUE	ERROR	ABSOLUTE ERROR
1	1.854	1.864	-.539	.539
2	1.442	1.484	-2.913	2.913
3	2.210	2.200	.452	.452
4	1.589	1.565	1.510	1.510
5	1.918	1.920	-.104	.104
6	1.434	1.446	-.837	.837
7	1.664	1.715	-3.065	3.065
8	1.596	1.562	2.130	2.130
9	2.186	2.258	-3.294	3.294
10	1.846	1.890	-2.384	2.384
11	1.784	1.754	1.682	1.682
12	1.218	1.249	-2.545	2.545
13	2.110	2.053	2.701	2.701
14	1.784	1.834	-2.803	2.803
15	2.160	2.178	-.833	.833
16	2.588	2.574	.541	.541

AVERAGE PERCENT ERROR = -.644
AVERAGE ABSOLUTE PERCENT ERROR = 1.771
STANDARD DEVIATION = 1.660

Table 9: Error Analysis for North Sea Crude (Standing)

DATA VALUE	TRUE VALUE	ESTIMAIED VALUE	ERROR	ABSOLUTE ERROR
1	1.854	1.893	-2.104	2.104
2	1.442	1.455	-.902	.902
3	2.210	2.303	-4.208	4.208
4	1.589	1.629	-2.517	2.517
5	1.918	1.986	-3.545	3.545
6	1.434	1.498	-4.463	4.463
7	1.664	1.719	-3.305	3.305
8	1.596	1.674	-4.887	4.887
9	2.186	2.258	-3.294	3.294
10	1.846	1.904	-3.142	3.142
11	1.784	1.815	-1.738	1.738
12	1.218	1.218	.000	.000
13	2.110	2.262	-7.204	7.204
14	1.784	2.289	-28.307	28.307
15	2.160	2.476	-14.630	14.630
16	2.588	2.771	-7.071	7.071

AVERAGE PERCENT ERROR = -5.707
AVERAGE ABSOLUTE PERCENT ERROR = 5.707
STANDARD DEVIATION = 8.763

The result of error analysis of the new equations on Miscellaneous crudes is shown in Table 10. The result of error analysis of the Standing equation on Miscellaneous crudes is shown in Table 11

Table 10: Error Analysis for Miscellaneous crudes (This study)

DATA VALUE	TRUE VALUE	ESTIMAIED VALUE	ERROR	ABSOLUTE ERROR
1	1.450	1.486	-2.483	2.483
2	1.230	1.231	-.081	.081
3	1.217	1.219	-.164	.164
4	1.515	1.521	-.396	.396
5	1.755	1.743	.684	.684
6	1.680	1.685	-.298	.298
7	1.593	1.525	4.269	4.269
8	1.380	1.401	-1.522	1.522
9	1.410	1.398	.851	.851
10	1.996	2.016	-1.002	1.002
11	2.126	2.153	-1.270	1.270
12	1.162	1.157	.430	.430
13	1.433	1.492	-4.117	4.117
14	1.382	1.422	-2.894	2.894
15	1.850	1.902	-2.811	2.811
16	1.901	1.958	-2.998	2.998
17	1.496	1.450	3.075	3.075
18	1.326	1.335	-.679	.679

AVERAGE PERCENT ERROR = -.634
AVERAGE ABSOLUTE PERCENT ERROR = 1.668
STANDARD DEVIATION = 1.795

Table 11: Error Analysis for Miscellaneous crudes (Standing)

DATA VALUE	TRUE VALUE	ESTIMAIED VALUE	ERROR	ABSOLUTE ERROR
1	1.450	1.453	-.138	.138
2	1.230	1.261	-2.520	2.520
3	1.217	1.223	-.493	.493
4	1.515	1.632	-7.723	7.723
5	1.755	1.878	-7.009	7.009
6	1.680	1.781	-6.012	6.012
7	1.593	1.707	-7.156	7.156
8	1.380	1.561	-13.116	13.116
9	1.410	1.557	-10.426	10.426
10	1.996	2.205	-10.471	10.471
11	2.126	2.322	-9.219	9.219
12	1.162	1.198	-3.098	3.098
13	1.483	1.498	-1.011	1.011
14	1.382	1.413	-2.243	2.243
15	1.850	1.951	-5.459	5.459
16	1.901	2.056	-8.154	8.154
17	1.496	1.416	5.348	5.348
18	1.326	1.259	5.053	5.053

AVERAGE PERCENT ERROR = -4.658
AVERAGE ABSOLUTE PERCENT ERROR = 5.814
STANDARD DEVIATION = 6.621

The error analysis shows that the new equations can calculate the bubble point Formation Volume Factor of crudes used to develop and test the equations within the following ranges of statistical measures of accuracy.

AVERAGE ABSOLUTE PERCENT ERROR: 0 – 5.14
STANDARD DEVIATION: 1.660 – 2.283

The error analysis shows that the Standing equation can calculate the bubble point Formation Volume Factor of crudes used to develop and test the equations within to following ranges of statistical measures of accuracy.

AVERAGE ABSOLUTE PERCENT ERROR: 0 – 28.31
STANDARD DEVIATION: 4.386 – 8.763

4. Conclusion

Efficient equations for estimating the bubble point formation volume factor of world crude oils have been developed. Absolute error between laboratory measured and calculated bubble point formation volume factor varied between 0 -5.1 %.

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