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Review of Bubble Point Pressure and Oil Formation Volume Factor Correlations for Libyan Crude Oils

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Abstract

Accurate determination of the crude oil PVT properties is essential for solving many reservoir engineering, production engineering, and surface production and operational problems. This paper attempts to evaluate several well-known empirical PVT correlations for Libyan crude oils and to define the most suitable correlations to estimate bubble point pressure and formation volume factor. Sixty-three individual crude oil samples representing 478 PVT data points from different Libyan oil fields were used in this study. Although no correlation provides a perfect answer all over the range, a few of them can be considered as giving a reasonably good bubble point pressure and oil formation volume factor estimation for our database. The PVT correlations can be placed in the following order with respect to their accuracy: (1) for bubble point pressure, Khazam (1995), Standing (1947) and Valkó and McCain (2003); (2) for FVF at bubble point pressure, Khazam, Shalk and Alkhaboli (2016), Vasquez and Beggs (1980), Farshad, Leblanc and Garber (1996) and Khazam (1995); 3) for FVF below bubble point pressure, Khazam (1995), Khazam, Shalk and Alkhaboli (2016) and Glaso (1980). The effective use of these correlations lies in the understanding of their development and the knowledge of their limitations.

Keywords: *PVT analysis, Bubble Point Pressure, Oil Formation Volume Factor, black oil.*

1. Introduction

The PVT (Pressure Volume Temperature) properties are keys for reservoir management. They are used by reservoir engineers for estimating reserves in place, fluid flow through the porous media, production schemes, and enhanced oil recovery planning. They are also used by production engineers to design the surface process facilities, and manage an efficient production.

Al these physical properties are normally measured and calculated accurately in a PVT laboratory. During the prospecting phase, these properties are generally not available and are estimated from correlations. These correlations have been designed from data acquired in various geographical areas during well testing operations. The input data is limited to the measurements currently available during a well testing operation, and the output data is taken from PVT studies run on samples taken during the same tests. Due to the limited amount of data available to a specific author, each correlation is a statistical relation, which cannot likely be applied safely to other fluid compositions. During the last 60 years, there were a lot of published correlations that are sometimes used as a universal way for estimating PVT properties. The emphasis of this paper is to evaluate several well-known empirical PVT correlations for Libyan oil crudes and to determine a suitable set of correlations for estimating the PVT properties and having them presented graphically and in a summary table. In this study, the only bubble-point pressure (P_b) and formation volume factor (B_o) correlations were investigated.

2. Literature Review Of The Black Oil Correlations

Many correlations for estimating crude oil PVT properties have been published in the past 60 years. In 1947, the first concerted effort to develop correlations for estimating bubble point pressure, oil formation volume factor and solution gas-oil ratio using field measured data was started by Standing [1]. Standing used 105 experimentally determined data points on 22 hydrocarbon mixtures from California crude oil and natural gases. In 1958, Lasater [2] presented a bubble-point pressure correlation based on 158 experimentally measured bubble-point pressures using 137 different crude oil systems from reservoirs in Canada, the U.S., and South America. In 1962, Arps [3] proposed a simple relationship for approximating the oil formation volume factor of light crude oil systems. The proposed relationship provides a quick estimation of the B_o and can only be used when the properties of gas and oil are not known. In 1980, Vasquez and Beggs [4] used laboratory results from more than 600 crude oil systems to develop empirical correlations for several oil properties including the solution gas-oil ratio and the oil formation volume factor. Their database included approximately 6000 data points measured over wide ranges of pressure, temperature, oil gravity, and gas gravity. In 1980, Glaso [5] presented correlations for estimating the bubble-point pressure, as well as the solution gas-oil ratio and the oil formation volume factor at the bubble-point for gas saturated black oils. Glaso analyzed data from 26 different crude oil systems, primarily from the North Sea region. In 1981, Standing [6] expressed his proposed graphical correlation in a mathematical form to estimate bubble point pressure, oil formation volume factor and solution gas-oil ratio. In 1988, Al-Marhoun [7] developed correlations for estimating the bubble-point pressure, as well as the solution gas-oil-ratio and the oil formation volume factor for Middle East crude oils at the bubble point pressure. These correlations were developed from a database of 69 bottomhole fluid samples and expressed as functions of reservoir temperature, gas gravity, solution gas-oil-ratio (at P_b). In 1990, Labedi [8] collected more than 100 oil samples from three African countries, namely Libya (97 samples), Nigeria (27 samples), and Angola (4 samples) were used for developing his correlations. He presented correlations for estimating bubble point pressure, oil FVF, oil density, and oil compressibility. His correlations are mainly function of measurable field data such as first-stage separator pressure and temperature, producing gas/oil ratio, stock-tank oil gravity, reservoir pressure, and reservoir temperature. In 1992, Al-Marhoun [9] presented paper for a correlation of formation volume factors, for saturated and under-saturated oils, as a function of solution gas-oil ratio, oil and gas relative density, and reservoir pressure and temperature. He analyzed approximately 700 bottom hole samples from around the world, mostly from Middle East and North America. At bubble-point pressure, the correlation was computed using 4012 experimentally measured oil formation volume factors. In 1992, Casey and Cronquist [10] computed gas/oil ratio and formation volume factors from PVT analysis, based on 78 US Gulf Coast area oil reservoirs. In 1992, Dokla and Osman [11] presented correlations for the estimation oil formation volume factor, on a database around 51 PVT samples, all the data points used in this study are exclusively obtained from U.A.E. In 1992, Macary and El-Batanony [12] utilized a sufficient base of laboratory-measured PVT data to derive specific empirical correlations for the prediction of the saturation pressure P_b, gas in solution R_s and formation volume factor B_o of Gulf of Suez crude oil systems. Their correlations were based on 90 experimentally measured data which represent about 30 independent reservoirs. In 1993, Petrosky and Farshad [13] developed empirical PVT correlations for Gulf of Mexico crude oils. They took Standing's correlation for solution gas-oil ratio as the basis for developing the new correlation coefficients. Their correlations included the bubble-point pressure, as well as the solution gas-oil-ratio and oil formation volume factor at the bubble-point. Petrosky and Farshad used a total of 90 laboratory analyses and their correlations were developed using nonlinear regression. In 1994, Kartoatmodjo and Schmidt [14] developed a new set of empirical correlations based on a large data collection from reservoirs all over the world. The authors used two independent databases. The first data bank A included 740 different crude oil samples, mainly from Indonesia, North America, the Middle East and Latin America, including thousands of measurements per physical property, and the second data bank B contained a set of 998 samples to validate the correlations. In 1995, Khazam [15] developed empirical PVT correlations for Libyan crude oils. His correlations included the P_b, R_s, and B_o. He used 82 different reservoirs in Sirte basin, and his correlations were developed using nonlinear regression based on the optimization of Standing and Al-Marhoun forms of correlations by changing of their empirical constants for better predictions of Libyan crude properties. In 1996, Farshad *et al*. [16] presented correlations for the estimation of bubble-point pressure, solution gas/oil ratio and oil formation volume factor on a database composed of 98 PVT laboratory analysis for Colombian crude oils. In 1997, Elsharkawy and Alikhan [17] computed PVT correlations for predicting solution gas/oil ratio, oil formation volume factor, and undersaturated oil compressibility. They considered 175 analyses from Kuwaiti crude oils. In 1997, Velarde, Blasingame and McCain [18] proposed correlations to predict black oil properties especially at pressure below bubble-point pressure. They used a database of 2097 laboratory measurements, of origin not detailed in the paper. In 1997, Almehaideb [19] computed PVT correlations for formation volume factor at bubble-point pressure especially for UAE crude oils, considering PVT analyses on 15 reservoirs. In 1999, Al-Shammasi [20] compared the different correlations published to date using a global data bank of 1243 measurements published in the literature. He developed a new correlation to explore the relationship between variables and measurements through graphical means and linear regression for bubble-point pressure, to improve the performance compared to earlier published data. Al-Shammasi also computed a correlation for oil formation volume factor, with four parameters, as a function of the reservoir temperature, solution gas/oil ratio, oil and gas gravity, or three parameters, not dependent on the gas gravity. In 2003, Valkó and McCain [21] presented correlations for the estimation bubble point pressure; a large set of service company fluid property data has been assembled. The data set is truly worldwide with samples from all major producing areas of the world. In 2016, Khazam, Shalk and

Alkhaboli [22] presented correlations for the estimation of bubble-point pressure, solution gas/oil ratio and oil formation volume factor on a database around 300 PVT sample data points. All the data points used in their study are exclusively obtained from Libya, mostly for reservoirs from Sirte, Ghadames, Murzuq and offshore basins.

3. Bubble Point Pressure

The bubble point pressure (saturation pressure P_b) is the highest pressure at which the first gas bubble appears. This important property can be determined in PVT lab, or using on-site equipment, but early need of this figure lead to the development of correlations. From experience the saturation pressure correlations are often predicting values that can be far from the experimental ones [23]. Generally, authors are publishing a set of correlations that include B_o, P_b, and sometimes viscosity and oil gravity, therefore the bubble point pressure correlations come mainly from the papers where the B_o was taken. These correlations are essentially based on the assumption that the bubble-point pressure is a strong function of gas solubility R_s, gas gravity γ_g, oil gravity API, and temperature T, or:

$$P_b = f\,(R_s, \gamma_g, API, T) \qquad (1)$$

Several different methods of predicting the bubble-point pressure are listed in Table 1.

Table 1. Studied correlations for estimating the bubble-point pressure.

Authors	Published Year	Sample Origin	Reference
Standing	1947	California	1
Lasater	1958	Canada USA	2
Vasquez and Beggs	1980	Worldwide	4
Glaso	1980	North sea	5
Al-Mahroun	1988	Middle-East	7
Macary and El-Batanony	1992	Gulf of Suez	12
Petrosky and Farshad	1993	Gulf of Mexico	7

Kartoatmodjo and Schmidt	1994	Worldwide	13
Khazam	1995	Libya	15
Farshad, Leblanc and Garber	1996	Columbia	16
Velarde, Blasingame and McCain	1997	Worldwide	18
Al-Shammasi	1999	Worldwide	20
Valkó and McCain	2003	Worldwide	21
Khazam, Shalk and Alkhaboli	2016	Libya	22

4. Oil Formation Volume Factor

The oil formation volume factor (B_o or FVF) is defined as the ratio of the volume of the oil phase at the prevailing reservoir conditions to the volume of dead oil at standard conditions [23].

$$B_o = \frac{V_o}{(V_o)_{sc}}\ , \text{bbl/STB} \qquad (2)$$

Where; V_o = volume of oil under reservoir pressure p and temperature T, bbl

$(V_o)_{sc}$ = volume of oil is measured under standard conditions, STB

During a lab PVT study, the dead oil at standard conditions can be determined from two experiment types: the differential liberation and the flash separation. The differential liberation study is used by reservoir engineers for calculations where both gas and oil phases are moving differentially in the rock, as the separation tests are used for process purposes [23].

In order to have experimental data that follows the real process in the field a composite differential liberation study is sometimes requested. It consists of a differential liberation process where a part of the oil phase is flashed through a single stage separation test at each pressure step. This type of study requires more time and sample, and is often replaced by a simple calculation to compute the differential data to separation flash one. Most of the published empirical B_o correlations utilize the following generalized relationship:

$$B_o = f\ (R_s, \gamma_g, \gamma_o, T) \qquad (3)$$

It is important to address here that Labedi [8] correlations are mainly function of measurable field data such as first-stage separator pressure and temperature, producing gas/oil ratio, stock-tank oil gravity, reservoir pressure, and reservoir temperature. Presently, this is the only existing correlation in the literature, which can be applied directly to obtain B_{ob} in the absence of PVT analysis. Several different methods of predicting the oil formation volume factor are presented in Table 2.

Table 2. Studied oil formation volume factor correlations

Authors	Published Year	Sample Origin	Reference
Standing	1947	California	1
Arps	1962	NA	3
Vasquez and Beggs	1980	Worldwide	4
Glaso	1980	North sea	5
Al-Mahroun 1	1982	Middle-East	7
Labedi	1990	Libya, Nigeria and Angola	8
Al-Marhoun 2	1992	Worldwide	9
Casey and Cronquist	1992	US Gulf Coast Area	10
Dokla and Osman	1992	U.A.E	11
Petrosky and Farshad	1993	Gulf of Mexico	7
Kartoatmodjo & Schmidt	1994	Worldwide	13
Khazam	1995	Libya	15
Farshad, Leblanc and Garber	1996	Columbia	16
Elsharkawy and Alikhan	1997	Kuwait	17
Almehaideb	1997	U.A.E	19
Al-Shammasi	1999	Worldwide	20
Khazam, Shalk and Alkhaboli	2016	Libya	22

5. Data Description

Experimental PVT data were collected from different Libyan oil reservoirs. 62 laboratory PVT reports and a total number of 487 data points were obtained. The data in these reports were derived from differential vaporization and separator tests. The ranges of data used in this study are shown in Table 3.

Table 3. Range of data which used in this study.

Property	Unit	Max	Min
Bubbel point pressure (P_b)	psia	123	6101
Temperature (T)	˚F	132	300
Solution GOR at P_b (R_{sb})	scf/STB	28	2156
Stock-Tank Oil Gravity (γ_{API})	˚API	24.7	46.8
Specific Gas Gravity (γ_g)	Air =1	0.701	1.462
Dead oil viscosity (μ_{od})	cp	0.774	5.036
Saturated oil viscosity (μ_{ob})	cp	0.2	3.811
UnderSaturated oil viscosity (μ_o)	cp	0.123	6.584
Oil formation volume factor (B_o)	bbl/STB	1.035	2.220

6. Evaluation Tools

This work exhibits the behavior of each correlation when applied to fluids that were not used to define them. Statistical error analyses and graphical tools are the criteria adopted for the evaluation in this study. The accuracy of the estimated value of a given fluid property was compared to the measured value using the following statistical parameters:

Average Absolute Relative Error (AARE)
$$\frac{1}{n}\sum_{i=1}^{n}\left|\frac{X_{cal}-X_{mes}}{X_{mes}}\right| x\ 100 \quad (4)$$

Minimum Error
$$\min_{i=1}^{n}\left[\left|\frac{X_{cal}-X_{mes}}{X_{mes}}\right|\right] \quad (5)$$

Maximum Error $\max_{i=1}^{n}\left[\left|\frac{X_{cal}-X_{mes}}{X_{mes}}\right|\right]$ (6)

Standard Deviation $\sqrt{\frac{\sum_{i=1}^{n}(PE_i-APE_i)^2}{n-1}}$ (7)

where:

X_{mes} = Meaasured Value
X_{cal} = Calculated Value
n = number of points
PE = Percent Error $(\frac{X_{cal}-X_{mes}}{X_{mes}}x100)$
APE = Average Percent Error $(\frac{1}{n}\sum_{i=1}^{n} PE_i \; x\, 100)$

Crossplots: All the estimated values are plotted versus the measured values, and thus a crossplot is formed. A 45° straight line is drawn on the crossplot on which estimated values are equal to the experimental values. The closer the plotted data points are to this line, the better the correlation.

7. Results and Discussion

7.1 Estimation of Bubble point pressure P_b

A number of correlations might give reasonable estimations as shown in Table 4, but in some they would predict unrealistic figures (see maximum relative error), therefore this type of prediction should always be used carefully as it cannot replace a bubble point pressure experimental determination. Therefore, the correlations that show the lest disadvantages are:

- Khazam (1995)
- Standing (1947)
- Valkó and McCain (2003)

On the other side following correlations should be avoided:

- Khazam, Shalk and Alkhaboli (2016)
- Lasater (1958)
- Macary and El-Batanony (1992)

- Petrosky and Farshad (1993)

Appendix A show crossplots between the estimated and experimental bubble point pressures for all studied correlations. It can be seen from the crossplots that Valkó and McCain (2003) correlation yielded reasonably accurate all over the range comparing to Khazam and Standing correlations to predict bubble point pressure for Libyan crude oils. Also, it can be noted that the Khazam, Shalk and Alkhaboli (2016) gave reasonable P_b estimations (AARE = 15.77%) but it failed somewhat to predict P_b at low solution gas oil ratio as indicated by the maximum relative error of 121%.

Table 4. Statistical parameters of existing correlations for Bubble point pressure.

Correlations	Number of Points	Average Absolute Relative Error (%)	Minimum Error (%)	Maximum Error (%)	Standard Deviation
Khazam	62	13.69	0.11	36.86	15.95
Standing	62	17.29	0.22	46.70	16.20
Valkó and McCain	62	16.03	0.12	36.79	16.37
Farshad, Leblanc and Garber	62	21.06	0.01	84.44	16.82
Velarde, Blasingame and McCain	62	20.70	0.47	53.04	17.38
Al-Shammasi	62	17.86	0.52	38.30	17.67
Kartoatmodjo and Schmidt	62	15.50	0.23	40.69	17.94
Glaso	62	16.75	0.19	76.34	18.87
Vasquez and Beggs	62	16.85	0.21	59.26	19.63
Al-Marhoun	62	23.08	0.04	54.92	22.68
Khazam, Shalk and Alkhaboli	62	15.77	0.24	120.86	24.12
Lasater	62	18.79	0.27	83.13	24.70
Macary and El-Batanony	62	25.00	0.16	119.44	36.00
Petrosky and Farshad	62	76.74	0.51	935.44	165.28

7.2 Estimation of Formation Volume Factor at Bubble Point Pressure B_{ob}

Formation Volume Factor at bubble point pressures are estimated only at bubble point pressure (B_{ob}) and all points that fall out of range of data used to develop each correlation are not discarded from evaluation. Most of these correlations yield reasonably accurate results when applied at the bubble point pressure as seen in Table 5.

Amongst the tested correlations, the best results were obtained with the following:

- Khazam, Shalk and Alkhaboli (2016)
- Arps (1962)
- Vasquez and Beggs (1980)
- Farshad, Leblanc and Garber (1996)
- Khazam (1995)

On the other side, the following correlations exhibit major deviations:

- Elsharkawy and Alikhan (1997)
- Casey and Cronquist (1992)
- Dokla and Osman (1992)
- Labedi (1990)

Appendix B show crossplots between the estimated and experimental FVF at bubble point pressures (B_{ob}) for all studied correlations.

Table 5. Statistical parameters of studied correlations at bubble point pressures (B_{ob}).

Correlations	Number of Points	Average Absolute Relative Error (%)	Minimum Error (%)	Maximum Error (%)	Standard Deviation (SD)
Khazam, Shalk and Alkhaboli	62	1.71	0.03	8.86	2.31
Arps	62	3.39	0.26	9.84	2.45
Vasquez and Beggs	62	3.21	0.33	9.10	2.53
Farshad, Leblanc and Garber	62	2.09	0.03	8.46	2.77
Khazam	62	2.03	0.01	8.48	2.78
Al-Marhoun 88	62	2.40	0.02	9.72	2.98
Al-Shammasi	62	2.62	0.04	9.50	3.14
Kartoatmodjo and Schmidt	62	2.90	0.01	10.02	3.25
Casey and Cronquist	62	4.82	0.32	12.29	3.66
Almehaideb	62	2.99	0.06	12.68	3.67
Standing	62	2.83	0.01	9.56	3.71
Glaso	62	3.11	0.10	8.20	3.85
Petrosky and Farshad	62	3.48	0.16	13.46	3.85
Elsharkawy and Alikhan	62	4.13	0.20	12.29	4.08
Dokla and Osman	62	4.96	0.02	13.53	4.81
Labedi	62	3.10	0.06	13.73	5.98

7.3 Estimation of Oil Formation Volume Factor below Bubble Point Pressure (B_o)

All correlations were tested to predict B_o below bubble point pressure using a wide range of data. Therefore, all points that fall out of range of data used to develop each correlation are not discarded from comparison. Although no correlation gives a perfect answer all over the range, a few of them can be considered as giving a reasonably good B_o estimation for our database as seen in Table 6.

Therefore, the best results were obtained with the following:

1) Khazam (1995)
2) Khazam, Shalk and Alkhaboli (2016)
3) Arps (1962)
4) Glaso (1980)

Some correlations exhibit significant deviations such as:

1) Standing (1947)
2) Dokla and Osman (1992)
3) Casey and Cronquist (1992)

Appendix C show crossplots between the estimated and experimental FVF (B_o) for all studied correlations.

Table 6. Statistical parameters of studied B_o correlations within and out the ranges of data used to develop each correlation.

Correlations	Number of Points	Average Absolute Relative Error (%)	Minimum Error (%)	Maximum Error (%)	Standard Deviation (SD)
Arps	487	3.98	0.00	12.43	3.39
Khazam	487	2.54	0.00	19.84	3.74
Khazam, Shalk and Alkhaboli	487	2.61	0.03	23.44	3.85
Glaso	487	3.79	0.03	15.18	3.94

Farshad, Leblanc and Garber	487	2.73	0.00	18.14	4.04
Al-Shammasi	487	2.92	0.01	20.85	4.11
Al-Marhoun 1988	487	3.30	0.01	24.36	4.17
Al-Marhoun 1992	487	2.96	0.01	20.54	4.19
Vasquez and Beggs	487	3.60	0.05	17.83	4.30
Almehaideb	487	3.50	0.01	20.53	4.46
Kartoatmodjo and Schmidt	487	3.51	0.02	23.65	4.50
Petrosky and Farshad	487	3.38	0.00	14.22	4.53
Elsharkawy and Alikhan	487	4.17	0.04	4.71	4.71
Standing	487	2.98	0.01	19.63	5.47
Dokla and Osman	487	5.77	0.02	31.85	5.81
Casey and Cronquist	487	6.87	0.04	66.38	9.46

8. Discussion

It is important to address here that Arps correlation is very simple and use less input parameters than the others, without significant loss in accuracy. However, it can only be used when the necessary PVT data for other equations are not available. This survey only demonstrates the difficulty of extrapolating these correlations that have all been designed statistically on a limited number of data coming generally from limited reservoir fluid compositions (same areas and producing zones). Each author did a good work, and generally advised not to use the correlation as a universal one. But this consideration is ignored when the correlation is given in another document, and certainly when used in a software. This was the main interest of this study to avoid using correlations that diverge during extrapolation. Selecting appropriate form for the equations with more physics than mathematics will do this. Therefore, the results obtained by using best correlations will improve the use of material balance calculations as well as estimates of production capacity and the recovery efficiency of a reservoir, and any other potential applications where black oil PVT properties below the bubble-point might be required.

The effective use of these correlations lies in the understanding of their development and the knowledge of their limitations. Also, it depends on the region from which the crudes are obtained.

9. Conclusions

The following conclusions are drawn on the basis of the dataset analyzed in this study:

- Several correlations might give reasonable estimations, but in some they would predict unrealistic figures.
- Khazam (1995) is recommended to predict bubble point pressure for Libyan oils
- Khazam, Shalk and Alkhaboli (2016) is recommended to estimate formation volume factor for Libyan oils
- Though fluid properties can be estimated from the empirical correlations, the accuracy of each correlation depends on the region from which the crudes are obtained and the knowledge of their limitations.

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