[Regular Paper]

Derivation of PVT Correlations for the Gulf of Suez Crude Oils

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Proper evaluation of physical properties of hydrocarbon mixtures is a prerequisite for the design of various stages of oil field operations. In many cases these properties are required at a time when the only information available consists of oil and gas gravities and reservoir pressure and temperature.

The purpose of this study is to utilize 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 β_o of Gulf of Suez crude oil systems, °API of which ranges from 25 up to 40. Our tool in this work is some of regression analyses techniques.

The correlations are based on 90 experimentally measured data which represent about 30 independent reservoirs. These data are expressed in terms of the usually measured field parameters-flash separation gas-oil ratio, tank oil gravity, surface gas gravity (at separator conditions) and reservoir temperature.

Derived correlations are valid within the ranges used for the above mentioned variables (GOR, T , γ_g). The gases are relatively free from non-hydrocarbons. Statistical accuracy tests show that the application of derived correlations for Egyptian reservoirs gives more accuracy than the known correlations (Standing and Glaso). The use of the derived relationships requires no graphs nor charts, and their applicability is convenient to use with the computer or calculator.

1. Introduction

The calculation of reserves in an oil reservoir or the determination of its performance requires a knowledge of the fluid's physical properties at elevated pressure and temperature. Of primary importance are bubble point (saturation) pressure, solution gas/oil ratio (GOR), and oil formation volume factor (β_o). Ideally, these properties are determined from laboratory studies which are designed to duplicate the conditions of interest. Experimental data quite often are unavailable; however, because adequate samples can not be obtained or because the producing horizons do not warrant the expense of in-depth reservoir fluid study. In these cases, Pressure-Volume-Temperature (PVT) properties must be determined by analogy or through the use of empirically derived correlations¹⁾.

During the last four decades several correlations have been proposed for determining PVT properties. Data of crude oil systems from various oil-producing localities were used in the development of these correlations. These crude oils exhibit regional trends^{2)~4)}.

Other trials have been run in order to generalize the derived correlations over a wide range of crude oil systems (overall world applications)^{5), 6)}.

Because of the differences in composition, correlations developed from regional samples, that are predominantly of one chemical base, may not provide satisfactory results when applied to crude oils from other regions.

Another limiting factor is the lack of mathematical expressions for ease of handling of computations.

A complete understanding of the development of these correlations and a knowledge of their limitations (application range) are the key to an effective use and better results.

In Egypt, most of the national oil production belongs to the Gulf of Suez. Oils of this region can be classified as conventional black oils. No attempt was run to derive PVT correlations for the prediction of PVT parameters of Egyptian oil systems, but only a study was conducted^{7), 8)} to evaluate the applicability of the most commonly used correlations to Egyptian oil fields.

2. Gulf of Suez PVT Data

Data representing different crude oil systems

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Table 1 Ranges of Gulf of Suez Oils Characteristics

Parameters	Measuring units	Range
Saturation pressure	psi	1,200—4,600
Temperature	°F	130—290
Oil FVF	RB/STB	1.2—2.0
Solution GOR	scf/STB	200—1,200
Oil gravity	°API	25—40
Gas gravity	air=1	0.7—1.0
Separator pressure	psi	60—240
Separator temperature	°F	60—200

were gathered from PVT samples taken along the Gulf of Suez. This information consists of 90 data points for both gas saturated and under-saturated oils. About one fifth of these points are recombined samples. The majority of data comes from oils of moderate to high volatility. The gases are relatively free from impurities. However, CO₂ in a few analyses exceeds 7% while N₂ is found to be nil.

The data were obtained from conventional PVT reports that derive the various fluid properties through a differential liberation process.

Using the statistical criteria of anomaly determination⁹⁾ missing points were detected and excluded.

Finally, we defined the ranges of the field conditions and parameters within which the bulk of producing fields in which the Gulf of Suez falls in. Table 1 shows the ranges of values covered by these data.

3. Correlation Development

It was found that all of the desired fluid properties—bubble point pressure P_b , solution gas/oil ratio GOR, and oil formation volume factor β_o could be correlated as functions of reservoir temperature T , gas and oil gravities γ_g , °API, and separator gas/oil ratio GOR. These field parameters are the only tools which we use up to derive PVT correlations. So the basic assumption used in this development is Ref. 10).

$$BPP = f(R_s, \gamma_g, \text{°API}, T) \quad (1)$$

To detect the weighting of the above mentioned factors in the prediction of bubble point pressure and, consequently, the sequence of data treatment by regression analysis some techniques of sensitivity analysis¹¹⁾ were used. Sensitivity analysis study proves th GOR to be the most correlatable factor with the bubble point pressure (Fig. 1-a).

One of the regression analysis techniques, known as Brandon's method, was used to develop new PVT correlations^{12,13)}. This method is illustrated in Appendix A.

Fig. 1-a Saturation Pressure–GOR (scatter diagram)

Fig. 1-b Saturation Pressure–Temperature (scatter diagram)

Fig. 1-c Saturation Pressure–API Gravity (scatter diagram)

Fig. 1-d Saturation Pressure–Gas Gravity (scatter diagram)

The following equations were obtained:

$$BPP = 204.257K[(R_s)^{0.51} - 4.7927] \quad (2)$$

where

$$K = \exp(0.00077T - 0.0097^\circ\text{API} - 0.4003\gamma_g) \quad (3)$$

By separating variables we get an expression for R_s to be

$$R_s = [0.0049(P/K) + 4.7927]^{1.9606} \quad (4)$$

where $P \leq P_b$ (5)

$$\beta_{ob} = N[1.0031 + 0.0008T] \quad (6)$$

where

$$N = \exp[0.0004R_s + 0.0006(\gamma_o/\gamma_g)] \quad (7)$$

It is important to notice that the general form and the constants of the derived correlations differ from that of the other commonly used correlations but the trend of the affecting variables is the same, *i.e.*, the positive and negative effect (relationship) are approved.

Oil field units used in all derived equations are P_b the bubble point pressure in psia, R_s the producing gas/oil ratio in scf/STB, γ_g the gas specific gravity of the surface gas (air=1), T the reservoir temperature °F, and °API the stock tank oil gravity.

4. Discussion

The volume of data vector, of course, has affected the resulted error (see **Appendix B**). In this work it was interesting to investigate whether our data bank satisfies the study requirements or a shortage of data will result in an unreliable output. A histogram was constructed to display the error ranges *vs.* their frequencies. **Table 2** and **Fig. 2** show this relationship to be a normally distributed curve. This type of normally distributed curves is termed a skewed curve, left skewed distribution, where the number of readings decreases to zero more rapidly on one side of the “hump” of the curve than on the other side. Skewness is often the result of the operation of some strong factors. This confirms our conclusion that GOR is the most powerful affecting variable. Any how, as these errors obey the law of normal distribution, so they introduce accidental or random errors. These errors come out of a multitude of factors

Table 2 Frequency Distribution of Errors Resulted from the Estimation of Saturation Pressure Using New Derived Correlation

No. of intervals	Errors range	Occurrences	Frequency [%]
1	$E^{ab} \leq 2.5$	13	14.4
2	$2.5 < E \leq 5.0$	18	20.0
3	$5.0 < E \leq 7.5$	19	21.1
4	$7.5 < E \leq 10.0$	17	18.9
5	$10.0 < E \leq 12.5$	14	15.6
6	$E < 12.5$	9	10.0

a) Absolute value of errors.

Fig. 2 Error Frequency Distribution

whose individual effects are so small. So, they cannot be identified and accounted for on an individual base¹⁰. As a rule, no field experiment is free of a chance factor, *i.e.*, variation in the obtainable data is to some extent due to the unknown accidental causes, or errors.

Random errors of the same magnitude can be eliminated if they are equally liable to be positive or negative. With a large number of observations, random errors differing in sign are canceled out and thus minimize the error of the generalized data and derived means, so, that is why we introduce in this study both concepts: average and absolute average errors. **Figure 2** shows more tendency of the occurrence of random errors of small magnitude.

This means that the length of the data vector has no negative effect on the error distribution and we can conclude that our data bank is quite sufficient and free of heterogeneities.

Table 3 summarises the calculated average and absolute average errors resulted from the application of newly derived correlations and both Standing and Glaso correlations. For comprehensive purposes the table also shows the results of Ref. 7). Here it is worth to mention that the volume of data used in the present study is about 10 times of that used in case of Saleh study^{7),8)}.

The interpretation of **Table 3** may result in the following consideration: when calculating P_b

Table 3 Comparison between Results of Current Study and Results of Ref. 7)

	BPP		R_{sb}		β_{ob}	
	$\bar{E}$	$ \bar{E} $	$\bar{E}$	$ \bar{E} $	$\bar{E}$	$ \bar{E} $
M & B ^{a)}	00.52	7.04	19.87	19.90	-0.66	02.92
Standing ⁷⁾	-30.17	30.17	41.72	44.74	00.81	05.55
Standing (P)	-30.32	30.48	24.69	24.69	26.85	26.85
Glaso ⁷⁾	-03.61	07.34	30.10	46.48	03.59	07.56
Glaso (P)	-07.50	11.98	29.99	29.99	28.99	28.99

a) Macary and Batanoney.

(P) Results of present study considering a data vector of 90 readings.

using Standing's correlation the error is the same in both cases of 9 points and 90 points which leads us to suspect the validity (the applicability) of Standing's correlation to Egyptian oils of the Gulf of Suez. Standing correlation is expected to be unsatisfactory correlation for these oils as it has a great influence in cases of low °API oils.

Also the equality of the magnitude of both average and absolute average errors with different signs means that the prediction of the parameter according to this correlation is always higher than the actual value, which means that the applicability of this correlation for given oils is susceptible.

Based on the results of **Table 3** we can conclude that the newly derived correlations yield much better matching in PVT properties of the Egyptian crudes than the commonly used correlations.

Table 3 also shows the prediction of R_s to be not so accurate in comparison with the other two parameters. This is due to that the R_s equation is yielded by separating variables of the derived equation of BPP (it is worth to mention that all R_s correlations are derived in such a manner); hence, the error of BPP prediction is translated to R_s not only as it is but in a powered form (as shown in Eq. (4)). This also explains why only the error of R_s prediction is always positive, as all errors of the determination of BPP and the constant K are approximately squared.

Statistically, the significance of any mathematical model is evaluated by the statistic R^2 which equals the ratio between the variance of the estimated values with respect to the real expectation

$$\sum_{i=1}^N (\hat{Y}_i - \bar{Y})^2$$

and the variance of the actual measurements from their expectation (average)

$$\sum (Y_i - \bar{Y})^2$$

So that:

$$R^2 = \sum (\hat{Y}_i - \bar{Y})^2 / \sum (Y_i - \bar{Y})^2 \quad (8)$$

Table 4 R^2 Values

Correlations	Parameters		
	BPP	R_{sb}	β_{ob}
M & B	0.845	0.997	0.94
Standing	0.691	0.983	0.28
Glaso	0.670	0.935	0.46

Other words:

$$R^2 = \hat{\sigma}^2 / \sigma^2 \quad (9)$$

$$\text{where } 0 < R^2 < 1 \quad (10)$$

The greater the value of R^2 , the more efficient the model is. R^2 was calculated, in the process of the three parameters prediction, using three models: Standing, Glaso and new one. Results are shown in **Table 4**. Again the values of R^2 approve the efficiency of our models for Egyptian oils.

The efficiency here means to what extent does the variance of the predicted values match that of actual ones. Both variances are from the representative of sample which is the average. The nature of error evaluation varies from that of variance estimation, that is why there is a difference between the error of R_s prediction (less accuracy) and its R^2 (the biggest value). The asymmetry of R_s prediction results (all predicted values are greater than the actual values) is the source for such contrast.

Generally, to have a fair evaluation of Standing correlations applicability the authors recommend, as a point for further investigation, to apply Standing's correlations using the data of the last stage separation.

To make sure of the validity of newly derived correlations another population of samples (PVT analyses) was gathered. The points of these samples were not switched in the process of correlations derivation. The P_b , β_{ob} and R_{sb} of this population were calculated using the newly derived correlations and the commonly used ones (Standing, Glaso). **Table 5** displays the comparison results. The calculated average and absolute average errors prove the superiority of our

Table 5 Results of Confirmation Process

	BPP		R_{sb}		β_{ob}	
	$\bar{E}$	$ \bar{E} $	$\bar{E}$	$ \bar{E} $	$\bar{E}$	$ \bar{E} $
M & B	-00.83	4.62	19.84	19.84	-0.22	02.69
Standing	2.08	15.42	19.91	19.91	24.36	24.36
Glaso	-06.24	15.59	19.88	19.88	26.92	26.92

new correlations.

It is worth to mention that all the errors resulted from the confirmation process (Table 5) fall in the already specified error range.

5. Conclusions

1) Pressure-volume-temperature correlations for Gulf of Suez oils have been developed, based on similar work by Standing. Eqs. (2), (4), and (6) form the basis for calculating the bubble-point (saturation) pressure, solution gas/oil ratio, and oil FVF at saturation pressure. Input parameters for these three equations are, from flash data, the produced gas/oil ratio, surface gas gravity, stocktank oil gravity, and reservoir temperature. The use of this prediction methods requires no graphs nor charts, and the methods are convenient to use with computers or calculators.

2) Average deviations and variances of predicted values from experimentally determined ones, in case of an estimation based on M&B (Macary and Batanoney) correlations, are lower than that estimation based on commonly used correlations (Standing and Glaso).

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Appendix A

Development of Multiple Regression Equation by Brandon's Method

In this method, the estimate regression equation is given in the form:

$$Y = af_1(X_1)f_2(X_2)...f_j(X_j)...f_k(X_k) \quad (A-1)$$

where $f_j(X_j)$ is any function of X_j .

The arrangement of the factors $X_1, X_2, ..., X_k$ in Eq. (A-1) has a direct bearing on the accuracy in the reduction of observations: the greater effect that X_j has on Y , the smaller the j -index should be. The

form of the function f_j is chosen on the basis of graphical construction. To begin with, a correlation field (scatter diagram) and an empirical regression line $Y-X_1$, are plotted on the basis of samples of quantities $Y_1, X_1, X_2, ..., X_k$. Thus, one finds that $Y_{X_1}=f_1(X_1)$ and, using the least squares procedure, estimates the coefficients of this regression equation. Now a new sample is built up

$$Y_1 = Y/f_1(X_1) \quad (A-2)$$

This quantity is no longer dependent on X_1 , and solely determined by the parameters $X_2, X_3, ..., X_k$. Therefore, one may write

$$Y_1 = af_2(X_2)f_3(X_3)...f_k(X_k) \quad (A-3)$$

Using new samples of Y_1 and X_2 , another correlation field and another empirical regression line depicting the dependence of Y_1 on X_2 are constructed such that

$$Y_{X_2} = f_2(X_2) \quad (A-4)$$

The coefficients are again estimated, and a sample of the new quantity is built up.

$$Y_2 = Y_1/f_2(X_2) = Y/f_1(X_1)f_2(X_2) \quad (A-5)$$

This quantity is independent of two factors, X_1 and X_2 , and can be found from the following regression equation:

$$Y_2 = af_3(X_3)...f_k(X_k) \quad (A-6)$$

This procedure is iterated until the sample of Y_k is obtained. This quantity is independent of all factors, $X_1, ..., X_k$, and is defined by the coefficient of the original equation

$$Y_k = a = \sum_{i=1}^N Y_{ki}/N \quad (A-7)$$

where n : the sample size.

Appendix B

Statistical Accuracy Terms

$$Ei = \frac{X_{\text{act}} - X_{\text{pred}}}{X_{\text{act}}} \times 100$$

$$\bar{E} = \sum Ei / N$$

$$|\bar{E}| = \sum |Ei| / N$$

$$\hat{\sigma}^2 = \sum (\hat{Y}_i - \bar{Y})^2 / N - 1$$

$$\sigma^2 = \sum (Y_i - \bar{Y})^2 / N - 1$$

Si Matric Conversion Factors

°API	: 141.5/(131.5+°API)	[g/cc]
°F	: (°F-32)/1.8	[°C]
psi	×6.894757	[kPa]

Nomenclatures

°API	: stock-tank oil gravity (at separator conditions)	
BPP	: bubble point pressure	[psi]
CO ₂	: carbon dioxide	
Ei	: error	[%]
E	: average error	[%]
\bar{E}	: average absolute error	[%]
exp	: exponential	
f	: function	
GOR	: gas oil ratio	[scf/STB]
N ₂	: nitrogen	
n	: number of points	
P _b	: saturation pressure	[psi]
R _s	: flash separation gas/oil ratio (measured at separator conditions)	[scf/STB]
R ²	: coefficient of determination	
T	: reservoir temperature	[°F]
X	: parameter value	
Y _i , \hat{Y}_i	: actual and estimated values of parameter respectively	
\bar{Y}	: expectation of a sample (average or mean value)	
\beta_o	: oil FVF at P _b	[RB/STB]
\gamma_g	: gas gravity (air=1), measured at separator conditions	
\gamma_o	: oil gravity, gm/cc, measured at separator conditions	

$\sigma, \hat{\sigma}$: standard deviation of actual and estimated values
respectively

<Subscripts>

act	: actual
b	: bubble-point
g	: gas
i	: point number, i=1, 2,...,N
o	: oil
pred	: predicted
s	: solution

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要 旨

スエズ湾原油の PVT 相関

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約 30 の油井から得られた API が 25～40 度のスエズ湾原油 90 試料について、回帰分析により飽和圧力、ガス溶解度、油容積係数を予測するための PVT 関係式が導かれた。この関係式は一般的な測定パラメーターであるガス油比、油比重、ガ

ス比重、油井温度を用いて表現され、エジプト原油に関してこれまで知られている Standing および Glaso の関係式よりも正確であった。また、グラフやチャートを必要としないので、コンピューターなどの活用が期待される。

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Keywords

New PVT correlation, Egyptian oil, Standing correlation, Glaso correlation, Statistical accuracy test