Evaluation and Development of Correlation for Formation Volume Factor and Gas Solubility of Yemeni Oil

تقييم وتطوير معادلات التكوين الحجمي وذوبانية الغاز للنفط اليمني

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ملخص البحث:

إن خصائص سائل المكامن مثل عامل التكوين الحجمي ونسبة الغاز الذائب في النفط لها أهمية كبيرة في حسابات هندسة المكامن مثل معادلة الميزان السلعي، في حين أن لزوجة النفط الخام والكثافة المطلوبة للسيطرة على تدفق النفط من خلال المسامية والأنابيب وتلعب دورا أساسيا في هندسة الإنتاج.

هذه الدراسة تقيم اغلب المعادلات المنشورة سابقا لمعامل التكوين الحجمي ونسبة الغاز الذائب في النفط باستخدام مجموعة من البيانات المكمنية اليمنية.

تقدم الدراسة معادلات جديدة لحساب النفط الخام اليمني لمعامل التكوين الحجمي للنفط ونسبة الغاز الذائب عند

ضغط الفقاعة استنادا إلى مجموعات بيانات يمنية ضخمة باستخدام دالة Tuning.

كما تم استخدام تقنيات برنامج إكسيل مثل دالة Solver للتنبؤ بمعامل التكوين الحجمي للنفط ونسبة الغاز الذائب عند ضغط فقاعة.

لمقارنة أداء ودقة المعادلات الجديدة لخصائص السوائل المكمنية، يتم إجراء تحليل إحصائي للأخطاء.

تشير نتائج التحليل الإحصائي إلى أن معادلات حساب معامل التكوين الحجمي الجديد ونسبة الغاز الذائب في النفط تتفوق على المعادلات المنشورة مسبقا مع أقل متوسط خطأ مطلق وأقل انحراف معياري وأعلى معامل ارتباط.

كلمات مفتاحية: خزان موائع، ميزان سلعي، لزوجة، كثافة، علاقة تجريبية، خواص النفط اليمني، فقاعة، برنامج اكسل.

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ABSTRACT:

Reservoir fluid properties such as oil formation volume factor and solution gas oil ratio are of primary importance in reservoir engineering computations such as material balance calculation, while viscosity of crude oil and density required for controlling the oil's flow through porous media and pipes and play an essential role in production engineering and in well problem analysis.

This study evaluates all available published oil formation volume factor and gas oil ratio empirical correlations against a set of Yemeni PVT data.

The study presents new tuned empirical correlations for Yemeni crude oils for oil formation volume factor and solution gas oil ratio at bubble point pressure based on huge Yemeni data sets.

Excel program techniques such as solver function are also used for predicting oil formation volume factor and solution gas oil ratio at bubble point pressure.

To compare the performance and accuracy of the new reservoir fluid properties correlations, statistical error analysis is performed.

The statistical analysis results indicate that, the new tuned oil formation volume factor and solution gas oil ratio correlations outperforms the most common empirical correlations with least average absolute error, least standard deviation and highest correlation coefficient.

Key words: *Reservoir fluid, material balance, viscosity, density, empirical correlations, Yemeni PVT, bubble point, Excel program.*

1. Introduction:

Reservoir fluid properties such as oil formation volume factor and solution gas oil ratio are very important in reservoir engineering computations. An accurate description of reservoir fluid properties of crude oils is necessary for solving many of reservoir engineering and surface operational problems.

Reservoir fluid properties are very essential physical properties required to control the flow of oil through porous media and pipes. They used comprehensively in most of petroleum engineering applications such as drilling engineering, reservoir engineering and production engineering. Accurate reservoir fluid properties are very important in reservoir engineering computations and a requirement for all types of petroleum calculations such as determination of initial hydrocarbons in place, optimum production schemes, ultimate hydrocarbon recovery, design of fluid handling equipment and enhanced oil recovery methods. As we know, data of these fluid properties are usually determined by laboratory experiments performed on samples of actual reservoir fluids. These samples are collected from the bottom of the wellbore or at the surface. In the absence of

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experimentally measured properties of crude oils, it is necessary for the petroleum engineer to find an accurate, quick and reliable method for predicting the reservoir fluid properties.

Generally, in reservoir fluid properties analyses, there are many laboratory tests that can be made on a reservoir fluid sample such as primary tests, routine laboratory tests and special hydrocarbon reservoir tests. In primary tests, the measurements of the specific gravity and the gas oil ratio can be made measured directly in the field. For routine laboratory tests, there are several laboratory tests that can be conducted to characterize the reservoir fluid properties such as compositional analysis, constant composition expansion, differential liberation, separator tests and constant volume depletion. Actually, the reservoir fluid properties depend on pressure, temperature and chemical compositions. For the development of a correlation, geological condition is considered important because the chemical composition of crude oil differs from region to region. For this reason, it is difficult to obtain the same accurate results through empirical correlations for different oil samples having different physical and chemical characteristics. Engineers should be modified these correlations for their application by recalculating the correlation constants for the region of interest.

This study evaluates the accuracy of the empirically derived PVT correlations relative to PVT data for 245 Yemeni crude oil. The tested correlations are used to estimate the oil formation volume factor and solution volume factor at bubble point. Before measuring the accuracy of different correlations, it should be point out that the effective use of the correlations lies in an understanding of their development and knowledge of their limitations.

2. LITERATURE REVIEW

The history of reservoir fluid properties empirical correlations in the petroleum industry started more than five decades ago. Several reliable empirical correlations for calculating the reservoir fluid properties such as bubble point pressure, oil formation volume factor, solution gas oil ratio, gas formation volume factor and crude oil viscosity have been proposed over the years.

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In recent times, the artificial intelligence has been used extensively to solve petroleum engineering problems and its robust nature and ability to capture non-linearity of systems makes it well suited for modeling PVT properties.

Numerous published empirical correlations and artificial intelligence studies are collected and summarized in this chapter to describe the development history of reservoir fluid properties correlations from 1947 till now.

2.1. Crude Oil PVT Empirical Correlations Review

Since the 1940's engineers have realized the importance of developing empirical correlations for oil formation volume factor and gas oil ratio at bubble point pressure as follows:

In 1947, Standing published several correlations for calculating oil formation volume factor and gas oil ratio at bubble point pressure. Standing correlations were based on laboratory experiments carried out on 105 samples from 22 different crude oils in California. Standing correlations were the first correlation to use these four parameters, it was a very common used after his work in developing correlations. It was and still one of the best correlations and the most widely used in the oil industry [1,2,3,4].

In 1980, Vazquez & Beggs published correlations for oil formation volume factor and gas oil ratio at bubble point pressure based on two oil categories, above 30 API0 gravity and below 30 API0 gravity [5]. The correlations were obtained by regression analysis using 5008 experimentally measured data points from worldwide.

In 1978, Glaso [6] developed correlations for calculating oil formation volume factor and gas oil ratio at bubble point pressure for North Sea hydrocarbon mixtures based on standing assumption. Glaso used up to 45 oil samples, most of them came from the North Sea region, were used in the development of these correlations.

In 1988, Al-Marhoun [7] developed new correlations for estimating oil formation volume factor and gas oil ratio at bubble point pressure for the

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Middle East oils. Al-Marhoun used up to 160 data set from 69 Middle Eastern reservoirs for the correlation development. Al-Marhoun correlations were the first to be developed for Middle East reservoirs.

In November 1988, Abdul-Majeed and Salman [8] published an oil formation volume factor at bubble point pressure correlation based on 420 data sets from unpublished sources. They used Al- Marhoun’s correlation for oil formation volume factor correlation with new calculated coefficients

In 1992, Dokla and Osman [9] published a new set of correlations for estimating oil formation volume factor and gas oil ratio at bubble point pressure for United Arab Emirates crudes. They used 51 data sets to calculate new coefficients for Al-Marhoun’s (1988) Middle East correlations.

In 1993, Petrosky and Farshad [10] proposed new empirical PVT correlations for the estimate of oil formation volume factor and gas oil ratio at bubble point pressure by using 81 laboratory PVT analyses of crude oils exclusively for the Gulf of Mexico.

In 1993, Omar and Todd [11] presented a new correlation of formation volume factors at bubble point pressure based on Standing’s [3,4] assumption oil formation volume factor correlation. They also developed a gas oil ratio correlation at bubble point pressure as a function of the oil formation volume factor in addition to oil gravity, gas gravity, bubble point pressure and reservoir temperature based on 93 data sets from Malaysian oil reservoirs A total of 93 PVT data taken from various Malaysian offshore oil-fields was used in the study. Using both nonlinear and linear regression analyses, new black oil correlations (of bubble point pressure and bubble point oil formation volume factor) were established for Malaysian crudes.

In January 1993, Macary and El-Batanoney [12] presented new correlations for oil formation volume factor and solution gas oil ratio at bubble point pressure. 90 data sets from 30 independent reservoirs in the Gulf of Suez were used to develop the correlations.

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In 1994, Kartoatmodjo and Schmidt [13] used a global data bank to develop new correlations for oil formation volume factor and gas oil ratio at bubble point pressure. Standing correlations were taken as basis for solution gas oil ratio correlations. Vazquez & Beggs5 oil formation volume factor correlation was considered the basis for oil formation volume factor correlation. Data from 740 different crude oil samples gathered from all over the world provided 5392 data sets for the correlation development.

In 1997, Almehaideb [14] published a new set of correlations for UAE crudes. He used 62 data sets from UAE reservoirs which comes from 15 reservoirs, which is used to test the validity of commonly used PVT correlations.

The data then was used to construct a new set of empirical correlations which were also tested against the experimental values, and the results were indicates that the new correlations reduce the error involved in estimating the oil formation volume factor and gas oil ratio at bubble point pressure to within less than half the range of error associated with commonly used correlations when compared to experimented values.

In 1997, Hanafy [15] et al presented new correlations for solution gas oil ratio at bubble point pressure based on 324 data sets collected from different reservoirs in Egypt.

In 1999, El-Sharkawy and Alikhan [16] published oil formation volume factor and gas oil ratio correlations. They modified Beggs and Robinson5 correlations for oil formation volume factor and gas oil ratio with 254 oil samples from the Middle East.

In February 1999, Al-Shammasi [17] produced new correlations for estimating oil formation volume factor and gas oil ratio at bubble point pressure for global oil fields. He used a global data bank of 1243 measurements published in the literature.

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In September 2001, Dindoruk and Christman [18] developed new correlations for gas oil ratio at bubble point pressure for Gulf of Mexico based on 100 data sets obtained from reservoirs in Gulf of Mexico.

In 2007, Hemmati and Kharrat [19] published three nonlinear multiple regression analysis correlations for predicting the gas oil ratio at the bubble point pressure based on the 287 experimentally obtained data points from more than 40 Iranian oil fields.

In 2007, Mazandarani and Asghari [20] presented empirical PVT correlations based on Al-Marhoun's correlations for estimating the gas oil ratio at the bubble point pressure of Iran crude oils. Multiple regression analysis was used in developing these correlations by using an unpublished data set of 55 bottom hole fluid samples collected from different locations in Iran [7].

In March 2009, Khamechi [21,22] et al published three nonlinear multiple regression analysis correlations for predicting the gas oil ratio at the bubble point pressure based on experimentally obtained data points from for the Middle East oils. Table 2.1 shows the range of parameters for different correlations.

(Table2.1) The range of parameters of different correlations

Authors	Samples Origin	No. of Data Points Used	Correlation
Standing (1947)	California	105	o Bo= 1.0240-2.150 (bbl/stb) o T= 100-258 (F°) o Rs= 20-1425(scf/stb) o API=16.5-63.8 o γg =0. 9-0.955 o Pb=130-7000 (psia)
Vazquez & Beggs (1980)	World Wide	5008	o Bo= 1.028-2.226 (bbl/stb) o T= 75-294 (F°) o Rs= 0-2199 (scf/stb) o API= 15.3-59.3 o γg =0.65-1.28 o Pb=15=6055 (psia)

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Glaso (1978)	North Sea	45	o Bo= 1.032-2.588(bbl/stb), o T= 80-280 (F°) o Rs= 90-2637 (scf/stb), o API= 22.3-48.1 o γg =0.65-1.276, o Pb=165-7142 (psia)
Al-Marhoun (1988)	Middle East	160	o Bo= 1.032-1.997 (bbl/stb) o T= 74-240 (F°) o Rs= 26-1602 (scf/stb) o API= 19.4-44.6 o γg=0.75-1. 673 o Pb=130-357 (psia)
Kartoatmodjo & Schmidt (1994)	World Wide	5392	o Bo= 1.007-2.747(bbl/stb) o T= 75-320 (F°) o Rs= 0-2890 (scf/stb) o API= 14.4-59 o γg=0.4824-1.1.668, o Pb=24.7-4746.7(psia)
Dokla & Osman (1992)	U.A. E	51	o Bo=1.216-2.493 (bbl/stb) o T= 190-275 (F°) o Rs= 181-2266 (scf/stb) o API=28.2-40.3 o γg =0.798-1.29 o Pb=590-4640 (psia)
Macary & El-Batanoney (1993)	Gulf of Suez	90	o Bo=1.2-2 (bbl/stb) o T= 130-290 (F°) o Rs= 200-1200 (scf/stb) o API= 25-40 o γg=0.7-1 o Pb=1200-4600 (psia)

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Petrosky & Farshad (1993)	Gulf of Mexico Texas Louisiana	81	o Bo=1.118-1.623 (bbl/stb) o T= 114-288 (F°) o Rs= 217-1406 (scf/stb) o API= 16.3-45.0 o γg=0.58-0.85 o Pb=1574-6528(psia)
Omar &Todd (1993)	Malaysia	93	o Bo=1.085-1.954 (bbl/stb) o T= 125-280 (F°) o Rs= 142-1440 (scf/stb) o API= 26.6-53.2 o γg=0.612-1.32 o Pb= 790-3851 (psia)
Hanafy (1997)	Egypt	324	o Bo= 1.032-4.35 (bbl/stb) o T= 107-327 (F°) o Rs= 7-4272 (scf/stb) o API= 17.8-48.8 o γg=0.623-1.627 o Pb=36-5003 (psia)
Almehaideb (1997)	UAE	62	o Bo= 1.142-3.562 (bbl/stb) o T=190-306 (F°) o API= 30.9-48.6 o Rs= 128-3871 (scf/stb) o γg=0.746-1.116 o Pb= 501-4822 (psia)
Al-Shammasi (1999)	World Wide	1243	o Bo= 1.02-2.916(bbl/stb) o T=74-341.6 (F°), o Rs= 6-32.98.6 (scf/stb), o API=6-63.7 o γg=0.51-3.44 o Pb= 31.70-7127 (psia)
Dindoruk & Christman (2001)	Gulf of Mexico	100	o Bo= 1.0844-2.8984(bbl/stb) o T=117-276(F°) o Rs= 133-3050 (scf/stb) o API=14.7-40 o γg=0.6017-1.03 o p_b=926-12230(psia)

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Hemmati & Kharrat (2007)	Iran	287	o Bo= 1.091-2.54 (bbl/stb), o T=77.5-290 (F°) o Rs=125-2189.25 (scf/stb) o API=18.8-48.34 o γg =0.523-1.415 o Pb=348-5156 (psia)
Abdul-Majeed & Salman (1988)	-	420	o Bo= 1.028-2.042 (bbl/stb), o T=75-290(F°) o Rs=0-1664.25 (scf/stb) o API=9.5-59.5 o γg =0.51-1.35
El-Sharkawy & Alikhan (1999)	Middle East	254	o Bo=1.057-1.770 (bbl/stb), o T=130-250 (°F) o Rs=34-1400 (scf/stb) o API=20-45 o γg = 0.663-1.064 o Pb=317-4375 (psia)
Mazandarani and Asghari (2007)	Iran	55	o Bo= 1.12-1.44 (bbl/stb), o T=77.5-306 (F°) o Rs=284-1620 (scf/stb) o API=18.8-48.34 o γg =0.335-1.872 o Pb=1021-5080 (psia)
Khamechi et al (2009)	Middle East	-	-

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3. METHODOLOGY

To achieve this comprehensive reservoir fluid properties studies, solver equation and the statistical error analysis were used for evaluating and predicting the reservoir fluid properties models.

3.1 Solver function

It's a function in excel program and it has a lot of uses:

- Linear and non-linear equations. In the case of a single equation, the "solver" is more appropriately called a root-finding algorithm.
- Systems of linear equations.
- Non-linear system.
- Systems of polynomial equations, which are a special case of non-linear systems, better solved by specific solvers.
- Linear and non-linear optimization problems.
- Systems of ordinary differential equations.
- Systems of differential algebraic equations.
- Boolean satisfiability problem problems, including SAT solvers.
- Constraint satisfaction problems.
- Shortest path problems.
- Minimum spanning tree problems.
- Search algorithms.

And in our research, we have used this function to reduce the error percentage in the equation (any equation form previous collected equation) so it become more accurate.

3.2 Statistical Error Analysis

The accuracy of the correlation relative to the actual value is determined by using various statistical means. The criteria used in this study were average absolute percent relative error, standard deviation, the correlation coefficient, minimum/maximum absolute percent relative error and graphical error.

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- Average Absolute Percent Relative Error (AAPRE)

It measures the relative absolute deviation from the experimental values, defined by:

$$AAPRE = \frac{1}{n} * \sum_{i}^{n} |Ei| \quad (1)$$

Where:

$$E_i = \left[\frac{X_{exp} - X_{est}}{X_{exp}} \right] * 100 \; i = 1.2.3 \ldots n$$

- Standard Deviation (SD)

The standard deviation is a measure that is used to quantify the amount of variation or dispersion of a set of data values. A low standard deviation indicates that the data points tend to be close to the mean (also called the expected value) of the set, while a high standard deviation indicates that the data points are spread out over a wider range of values.

$$SD = \frac{1}{n-1} * \sum_{i}^{n} E_i^2 \quad (2)$$

- Correlation coefficient R^2

The coefficient of determination is the proportion of the variance in the dependent variable that is predictable from the independent variable(s). And it represents the degree of success in reducing the standard deviation by regression analysis. The correlation coefficient lies between 0 and 1. A value of 1 indicates a perfect correlation whereas a value of 0 implies no correlation at all among the given independent variables.

$$R^2 = \sqrt{1 - \sum_{i=1}^{n} [X_{exp} - X_{est}] / \sum_{i=1}^{n} [X_{exp} - \bar{X}]} \quad (3)$$

Where:

$$\bar{X} = \frac{1}{n} * \sum_{i}^{n} X_{exp}$$

- Graphic error analysis:

Graphic means help in visualizing the accuracy of a correlation. All the estimated values are plotted vs the experimental values, and thus a cross plot is formed. A 45 straight line is drawn on the cross plot on which estimated value is equal to experimental value.

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3.3. PVT CORRELATIONS ASSESSMENT

All collected published oil formation volume factor and gas oil ratio at bubble point pressure empirical correlations have been evaluated based on Yemeni crude oil.

3.3.1 Oil Formation Volume Factor Correlations Assessment

Table 4.3 shows the statistical accuracy for best five oil formation volume factor at bubble point pressure correlations for Yemeni crude oil. The statistical analysis parameters for all oil formation volume factor correlations indicate that Kartoatmodjo and Schmidt (1991) correlation is the best performing correlation model with lowest average absolute relative error followed by Al-Marhoun (1988), Al-Shammasi (1999), Vezquez & Beggs (1980) and standing(1947) correlations. Kartoatmodjo and Schmidt (1991) Correlation has an average absolute error of 1.935%, standard deviation of 2.96% and correlation coefficient of 0.983. The cross plots of estimating values against experimental values for the best five performing oil formation volume factor empirical correlations for Kartoatmodjo and Schmidt, Al-Marhoun, Al-Shmmasi, Vezquez & Beggs and Standing are presented in Figures 3.1 through 3.5 respectively. Figure 3.6 shows average absolute percent relative error for oil formation volume factor correlations.

(Table 3.1) Statistical Error for the best five correlation (Bo)

Correlation	AAPRE	SD	R^2
Kartoatmodjo & Schmidt	1.935201	2.965929	0.983934
Al-Marhoun	2.09165	2.355694	0.982448
Al-Shammasi	2.275966	3.243732	0.981524
Vezquez & Beggs	2.702039	0.670134	0.977577
Standing	2.823103	4.203053	0.976325

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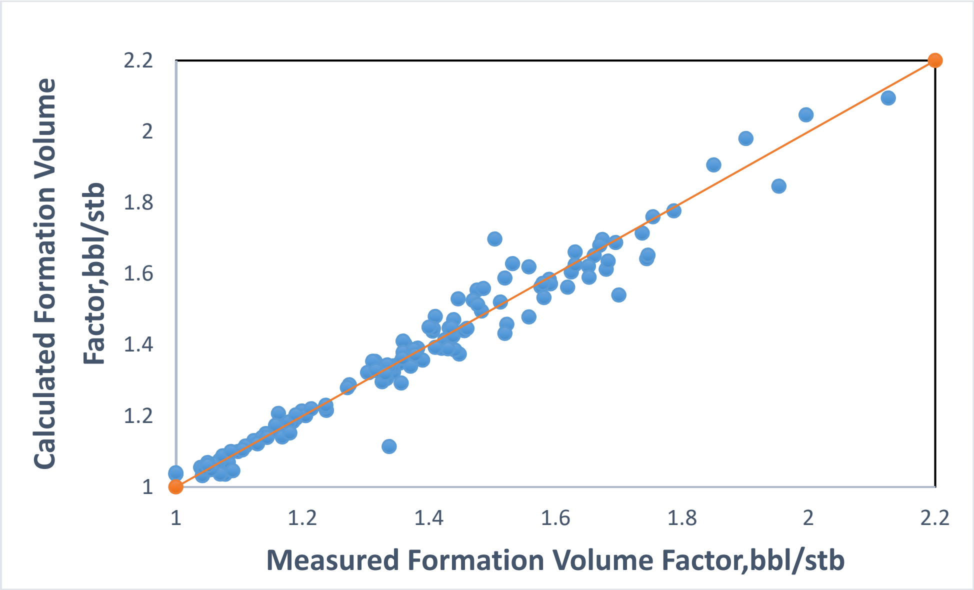
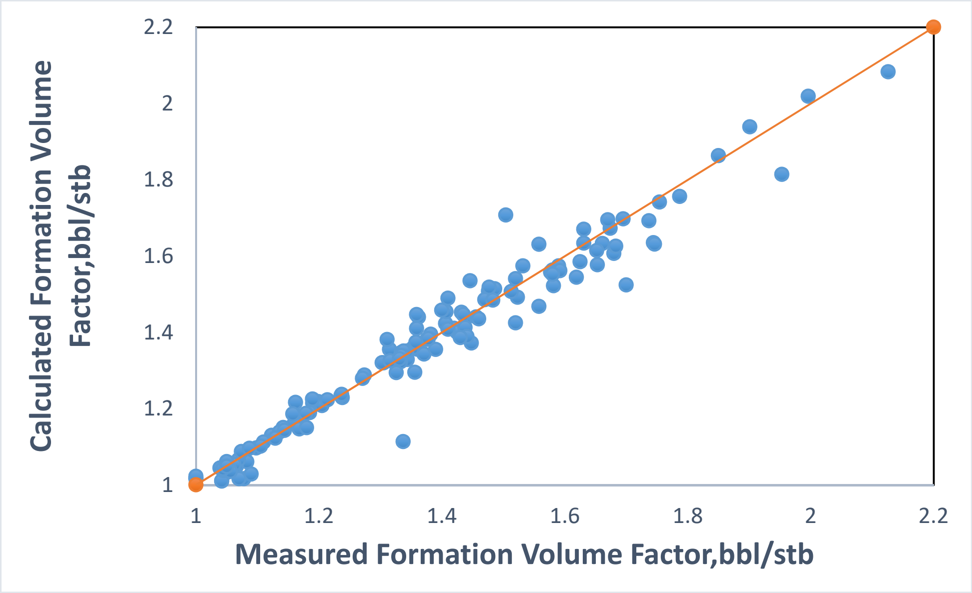


(Figure 3.1)
Cross plot of oil formation volume factor Kartoatmodjo and Schmidit correlation



(Figure 3.2)
Cross plot of oil formation volume factor Al-Marhoun correlation

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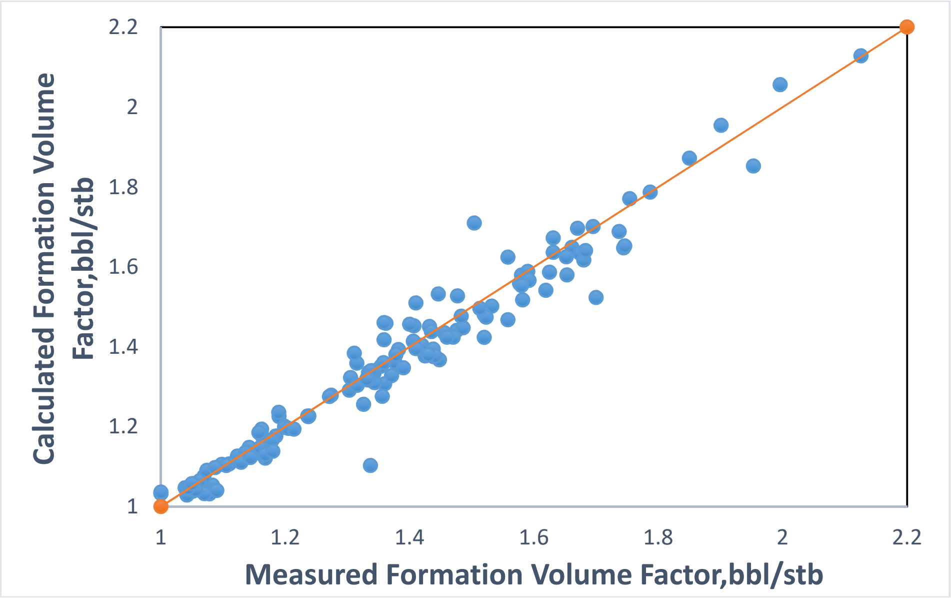
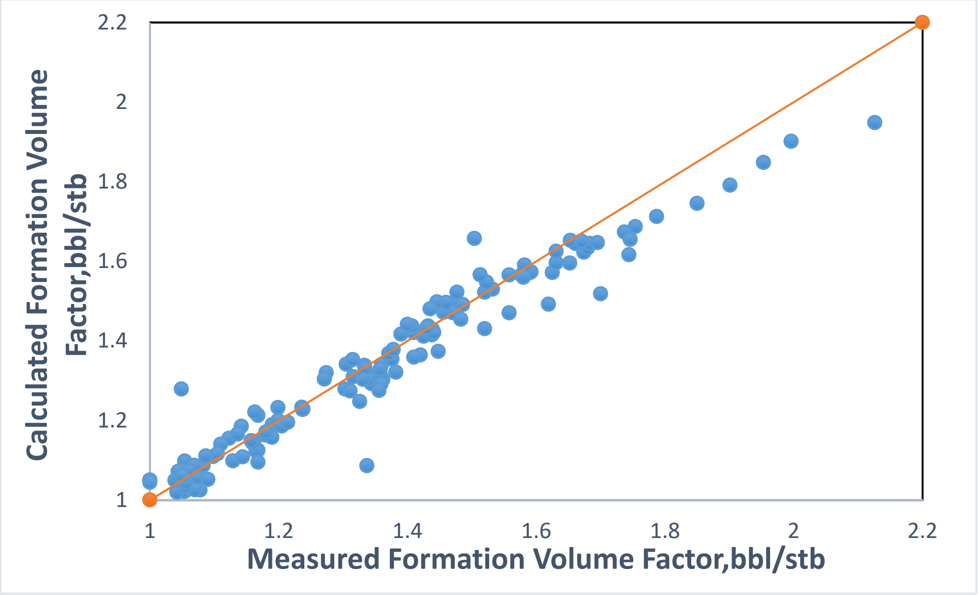


(Figure 3.3)
Cross plot of oil formation volume factor Al-Shammasi correlation



(Figure 3.4)
Cross plot of oil formation volume factor Vezquez & Beggs correlation

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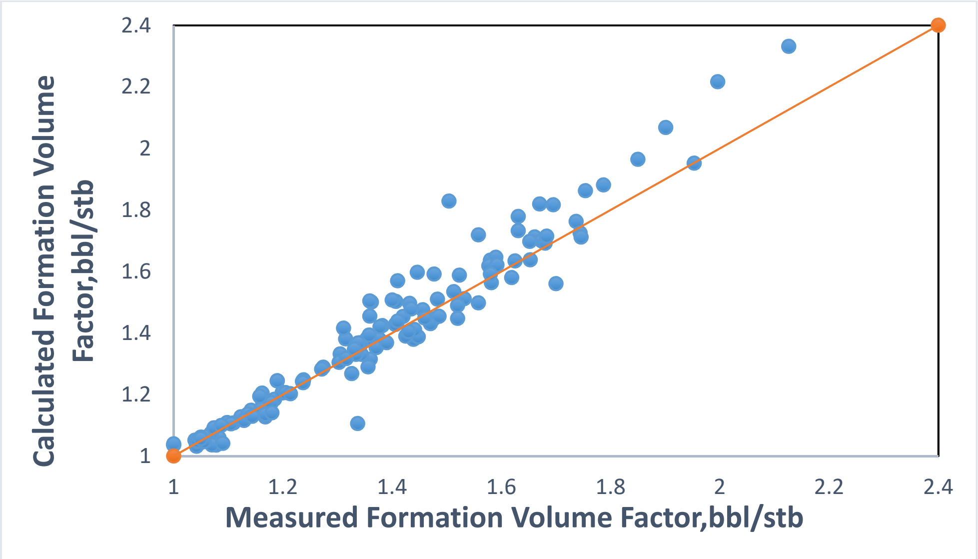
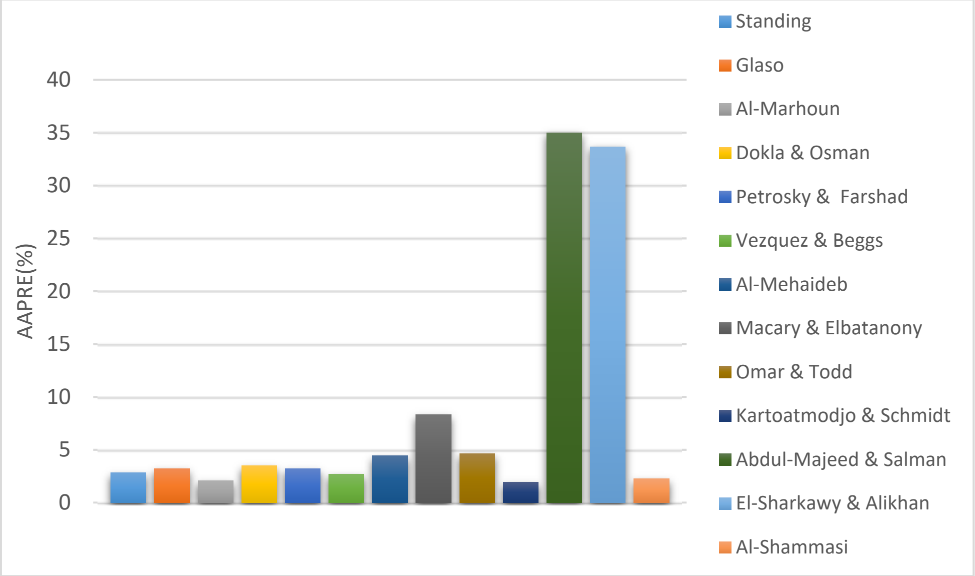


(Figure 3.5)

Cross plot of oil formation volume factor Standing correlation



(Figure 3.6)

average absolute percent relative error for different correlations for (Bo)

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3.3.2 Solution Gas Oil Ratio Correlations Assessment

Both statistical and graphical comparative were used to check the accuracy of solution gas oil ratio at bubble point pressure correlations for Yemeni crude oil. The statistical accuracy for best five solution gas oil ratio correlations for Yemeni crude oil have been summarized in Tables 3.2 As can be seen from this Table, Standing (1947) correlation with lowest average absolute percent relative error followed by Hemmati & Kharrat (2007), Glaso (1978), Mazandarani & Asghari (2007) and Al-Shammasi (1999) correlations.

Standing (1947) correlation has an average absolute error of 8.018%, standard deviation of 9.624% and correlation coefficient of 0.9824, respectively. The cross plots of estimating values against experimental values for the best five performing solution gas oil ratio empirical correlations for Standing, Hemmati & Kharrat, Glaso, Mazandarani & Asghari and Al-Shammasi are presented in Figures (3.7) through (3.11) respectively. Figure (3.12) shows average absolute percent relative error for different solution gas oil ratio correlations.

(Table 3.2) Statistical Error for the best five correlations (Rs)

Correlation	AAPRE	SD	R^2
Standing	8.018052	9.624097	0.98242
Hemmati & Kharrat	9.354213	11.17186	0.985461
Glaso	10.19176	10.74526	0.985461
Mazandarani & Asghari	15.69034	18.64341	0.957564
Al-Shammasi	16.83848	20.9096	0.987748

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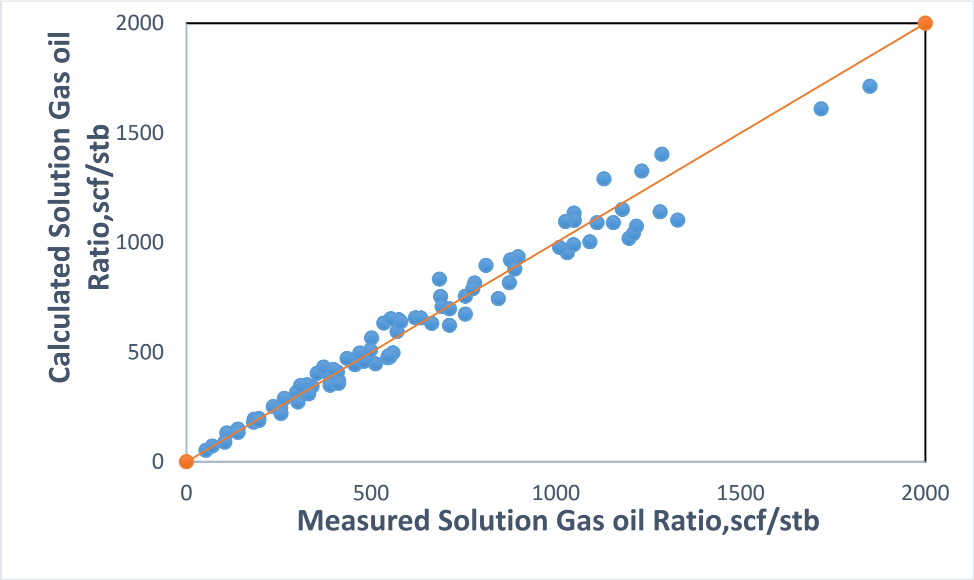
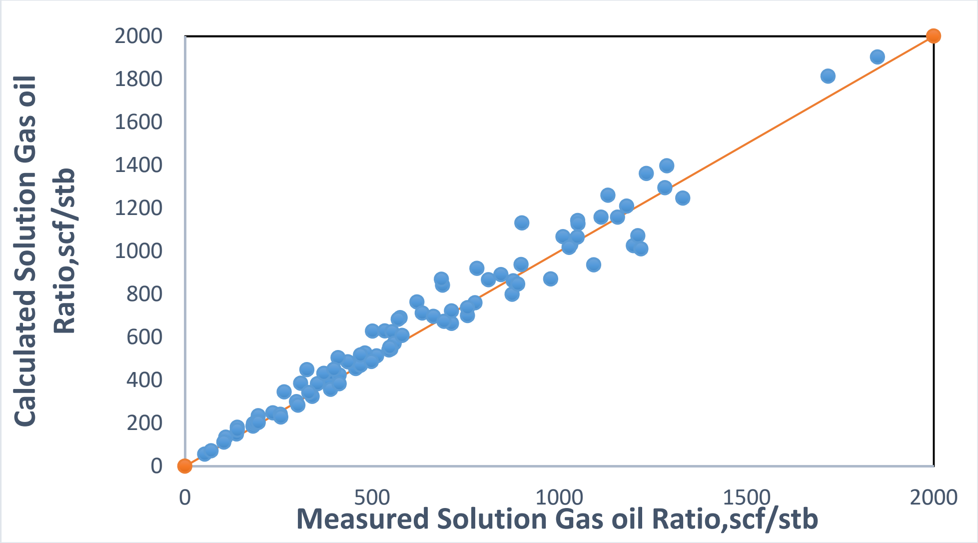


(Figure 3.7)
Cross plot of solution gas oil ratio standing correlation



(Figure 3.8)
Cross plot of solution gas oil ratio Hemmati & kharrat correlation

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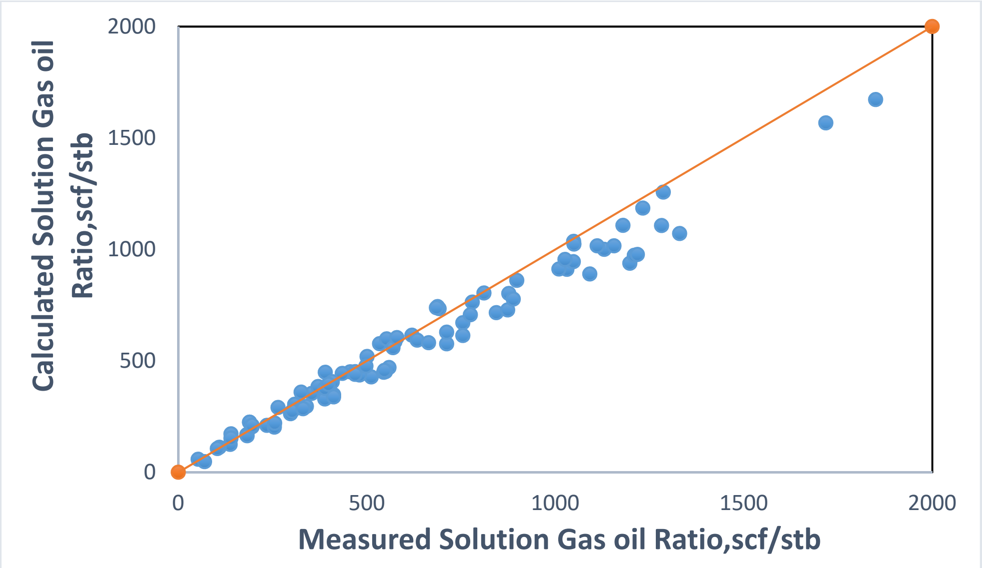
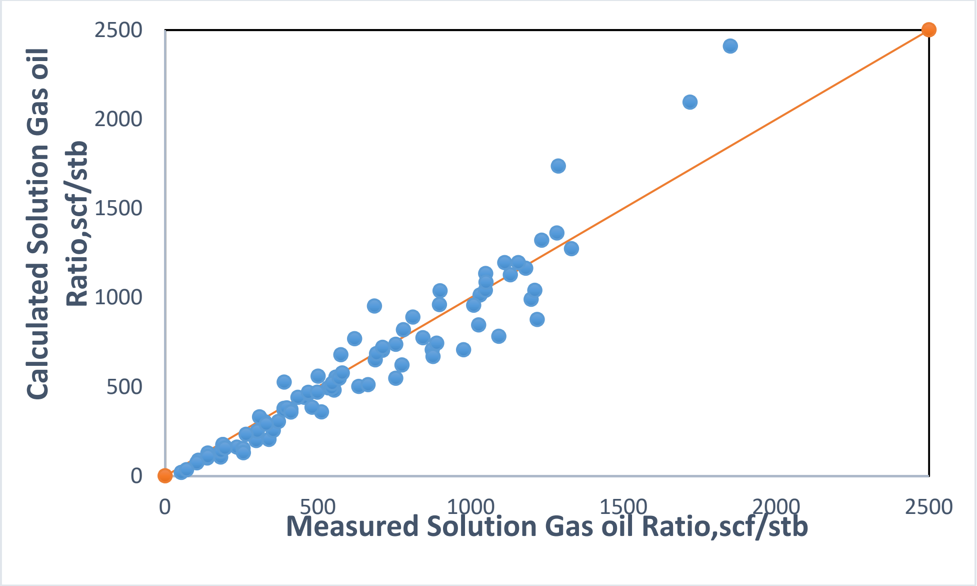


(Figure 3.9)
Cross plot of solution gas oil ratio Glaso correlation



(Figure 3.10)
Cross plot of solution gas oil ratio Mazandarani & Asghari correlation

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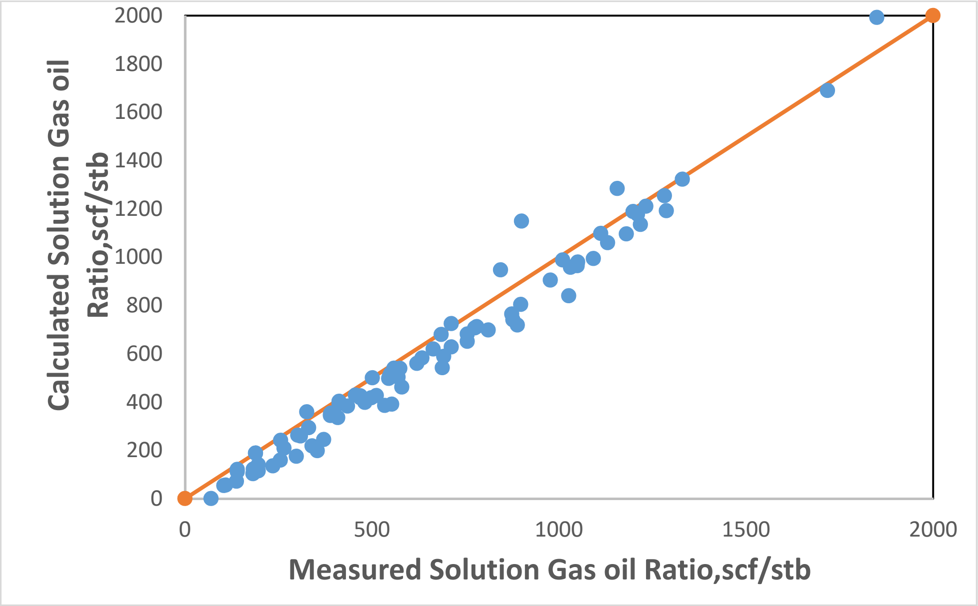
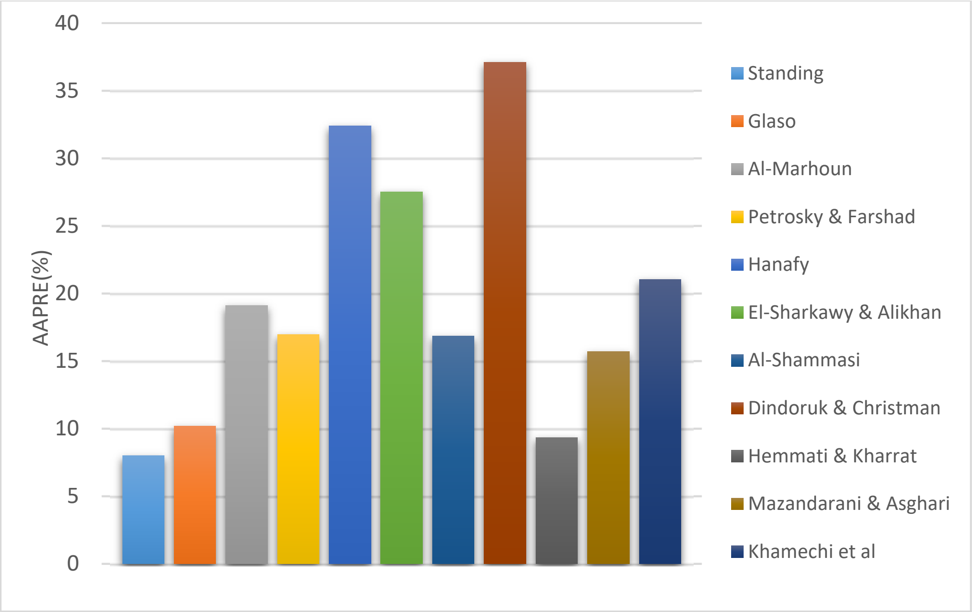


(Figure 3.11)
Cross plot of solution gas oil ratio Al-Shammasi correlation



(Figure 3.12)
average absolute percent relative error for different correlation for (Rs)

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4. RESULTS AND DISCUSSIONS

4.1 DATA ACQUISITION

To achieve this study a lot of data set are used for this work were collected from different Yemeni reservoirs as follows [23]:

156 ➡ Data set were used to calculate the formation volume factor.

89 ➡ Data set were used to calculate the gas oil ratio.

Statistical distributions such as maximum, minimum, mean, range and standard deviation of the input data are shown in Tables 4.2.1 and 4.2.2:

(Table 4.1) Statistical descriptions of the Yemeni data sets for calculating oil formation factor

PROPERTY	UNIT	MAX	MIN	AVG	SD
Pb	Psia	5148	30	1849.197	1373.762
Rs	scf/stb	1850	0.54	539.1317	446.4137
Bo	bbl/stb	2.126	1	1.32917	0.243959
γ_g	-	1.956	0.128	0.919241	0.288072
T	F^O	253	60	169.8474	36.42573
API	API^O	75.97801	13	37.67482	10.10407
γ_o	-	0.979239	0.682	0.839194	0.047182

(Table 4.2) Statistical descriptions of the Yemeni data sets for calculating solution gas oil ratio

PROPERTY	UNIT	MAX	MIN	AVG	SD
Pb	Psia	4186	408	2184.671	1025.081
Rs	scf/stb	1850	53	639.2936	388.2836
Bo	bbl/stb	2.126	1.05	1.372111	0.225226
γ_g	-	1.386	0.511	0.837898	0.164573
T	F^O	253	80	166.9416	43.15244
API	API^O	55.9	13	35.2936	7.056443
γ_o	-	0.978547	0.754536	0.849429	0.037035

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4.2 NEW PVT CORRELATIONS FOR YEMENI CRUDE OIL

After evaluating all available published reservoir fluid properties empirical correlations, we note that error percentage is too high in most of the correlations, tuning is used to reduce or minimize the high error percentage, by change the correlation constants, so we got derivative correlations from the original correlations.

4.2.1 Assessment of New Correlations for Oil Formation Volume Factor

After using tuning in all 13 correlations for oil formation volume factor and statistical analysis error show in Table 4.5 the best five new correlations for oil formation volume factor at bubble point pressure for Yemeni crude oil.

Kartoatmodjo & Schmidt new correlation is the best performing correlation with lowest average absolute percent relative error followed by Omar & Todd, Al-Shammasi, Petrosky & Farshad and Standing new correlations. Kartoatmodjo and Schmidt new correlation has an average absolute error of 1.718%, standard deviation of 2.779% and correlation coefficient of 0.9867. The cross plots of estimating values against experimental values for the best five performing oil formation volume factor empirical new correlations for Kartoatmodjo & Schmidt, Omar &Todd, Al-Shammasi, Petrosky Farshad and Standing are presented in Figures (4.1) through (4.5) respectively. Figure (4.6) shows average absolute percent relative error for different oil formation volume factor new correlations. Table 4.6 shows Old-New correlations statistical error for (Bo).

The tuned correlations are showed in Appendix (A).

(Table 4.3) Statistical Error for the best five new correlation (Bo)

Name	AAPRE	SD	R^2
Kartoatmodjo & Schmidt	1.718056	2.779625	0.986725
Omar & Todd	1.758625	2.888893	0.985833
Al-Shammasi	1.823865	2.849186	0.986592
Petrosky & Farshad	1.83403	2.825538	0.986566
Standing	1.947931	3.021259	0.98453

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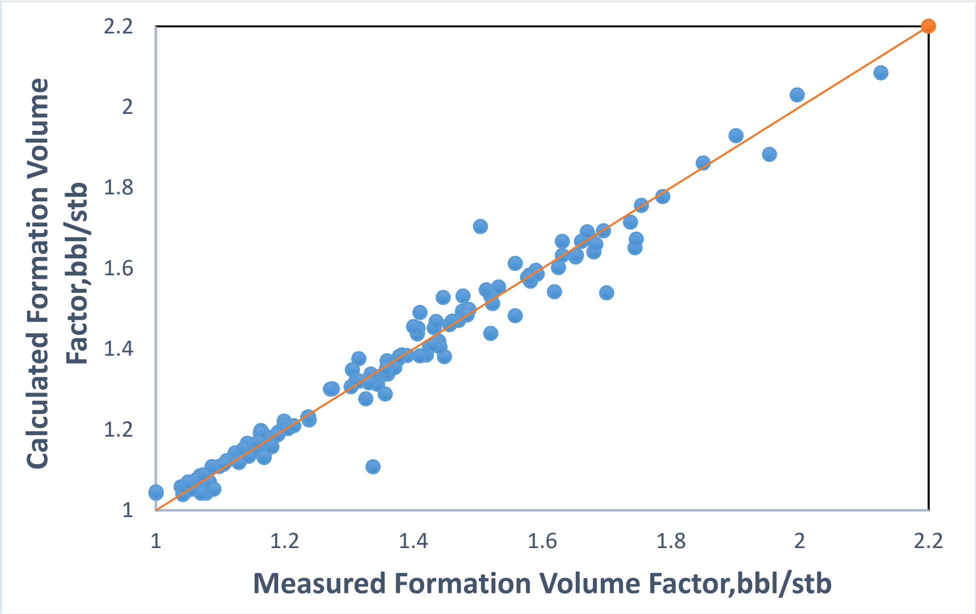
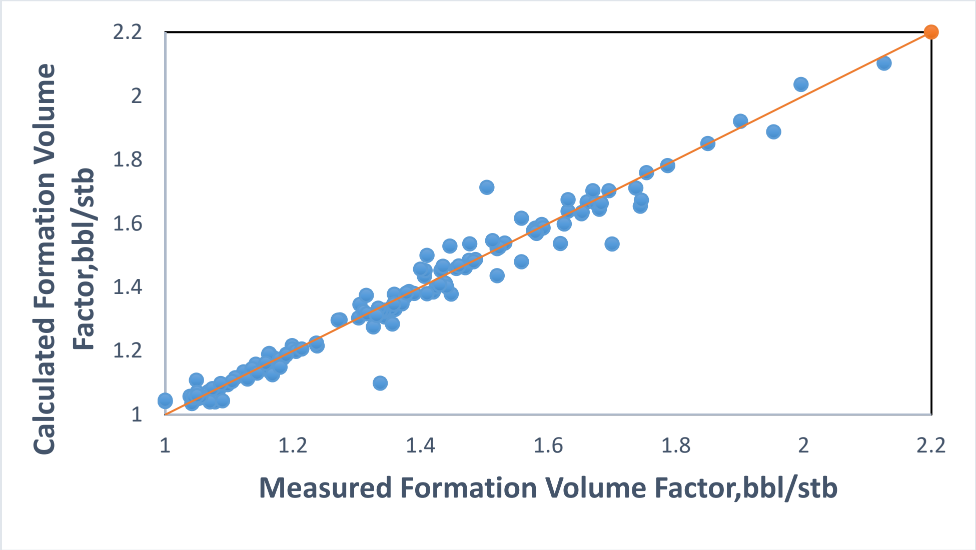


(Figure 4.1) Cross plot of oil formation volume factor Kartoatmodjo and Schmidt new correlation



(Figure 4.2)
Cross plot of oil formation volume factor Omar & Todd new correlation

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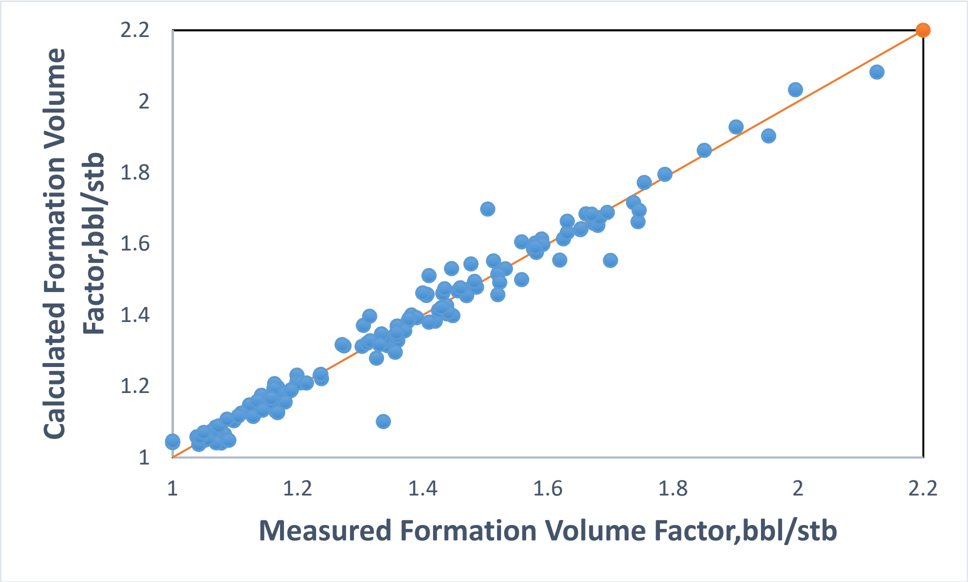
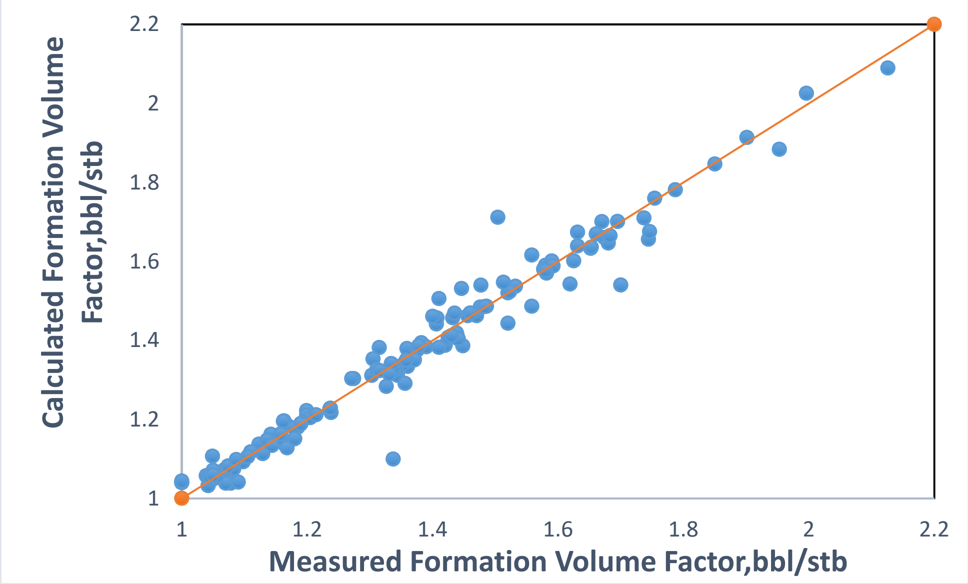


(Figure 4.3)
Cross plot of oil formation volume factor Al-Shammasi new correlation



(Figure 4.4)
Cross plot of oil formation volume factor Petrosky & Farshad new correlation

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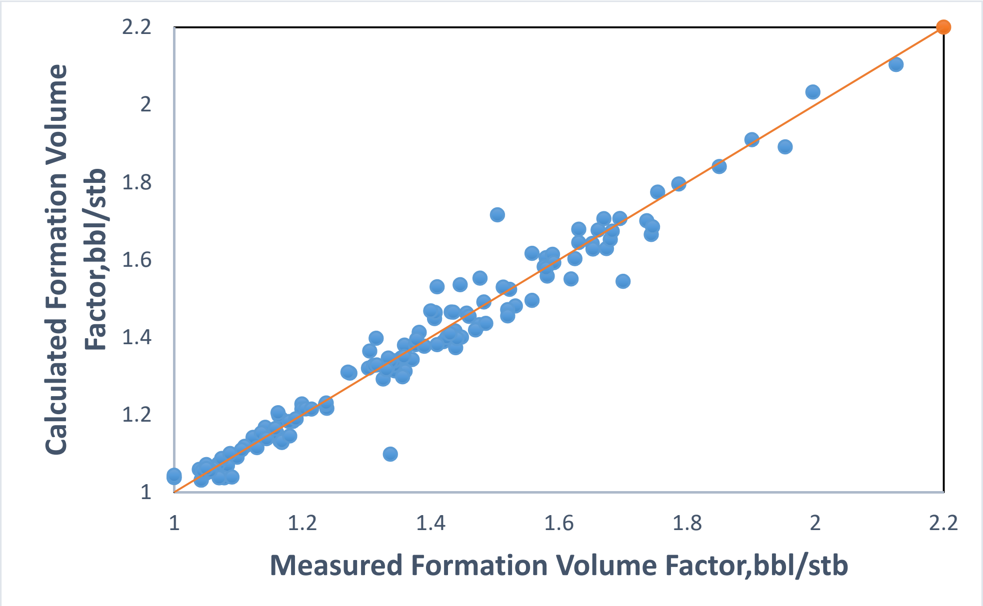
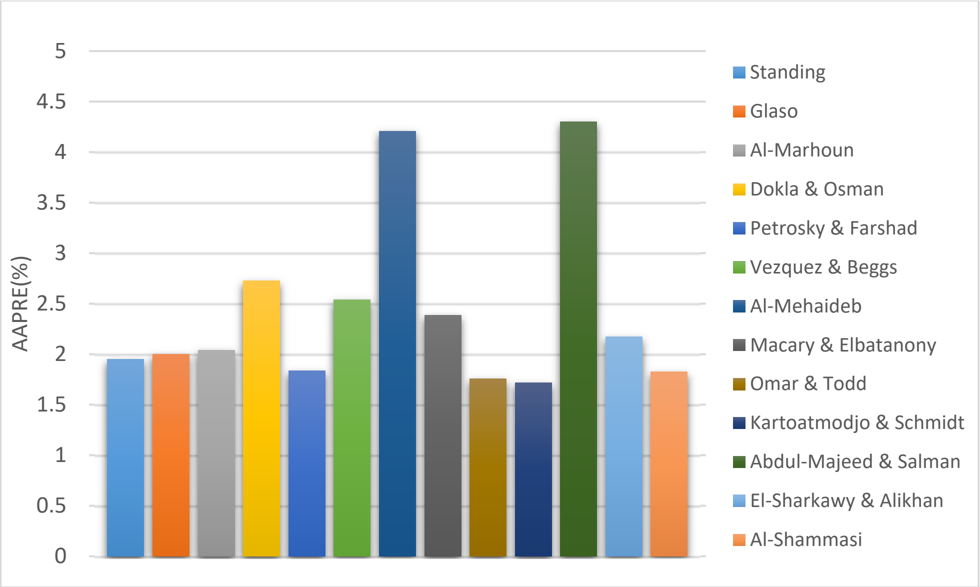


(Figure 4.5)
Cross plot of oil formation volume factor standing new correlation



(Figure 4.6)
average absolute percent relative error for different new correlation for (Bo)

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(Table 4.4) Old-New correlations statistical error for (Bo)

Name	Old correlation			New correlation		
	AAPRE	SD	R^2	AAPRE	SD	R^2
Standing	2.823103	4.203053	0.976325	1.94793058	3.021259252	0.984530347
Glaso	3.232248	4.146016	0.974055	2.0002723	3.13442903	0.983242523
Al-Marhoun	2.09165	2.355694	0.982448	2.04072478	2.320446391	0.98281302
Dokla & Osman	3.491865	4.477947	0.980082	2.72546914	3.683709789	0.980620999
Petrosky & Farshad	3.200044	4.603479	0.970831	1.83402953	2.825537759	0.986566224
Vezquez & Beggs	2.702039	0.670134	0.977577	2.53911333	3.730590582	0.979053989
Al-Mehaideb	4.428311	5.257218	0.971155	4.20708609	4.985772723	0.971155225
Macary & Elbatanony	8.309612	4.080553	0.980798	2.38458477	3.343252382	0.981583653
Omar & Todd	4.644157	3.400157	0.981728	1.75862504	2.888892849	0.985833137
Kartoatmodjo & Schmidt	1.935201	2.965929	0.983934	1.71805617	2.779625244	0.986725285
Abdul-Majeed & Salman	34.99953	9.6477	0.926117	4.29818223	6.383458882	0.933611778
El-Sharkawy & Alikhan	33.66515	29.95671	0.958617577	2.17158134	3.029712993	0.985102777
Al-Shammasi	2.275966	3.243732	0.981524	1.82386518	2.849186475	0.986591895

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4.2.2 Assessment of New Correlations For Solution Gas Oil Ratio

After using tuning in all 11 correlations for solution gas oil ratio and statistical analysis error show in Table 4.7 the best five new correlations for gas oil ratio at bubble point pressure for Yemeni crude oil.

Hemmati & Kharrat new correlation is the best performing correlation with lowest average absolute percent relative error followed by Khamechi et al, Petrosky & Farshad, Mazandarani & Asghari and Al-Marhoun new correlations. Hemmati & kharrat new correlation has an average absolute error of 7.492335%, standard deviation of 9.321% and correlation coefficient of 0.985. The cross plots of estimating values against experimental values for the best five performing solution gas oil ratio empirical new correlations for Hemmati & kharrat, Khamechi et al, Petrosky & Farshad and Al-Marhoun are presented in Figures 4.7 through 4.11 respectively. Figure 4.12 shows average absolute percent relative error for different solution gas oil ratio new correlations.

Table 4.6 shows Old-New correlations statistical error for (Rs)

The tuned correlations are showed in Appendix (B).

(Table 4.5) Statistical Error for the best five new correlations (Rs)

Name	AAPRE	SD	R^2
Hemmati & kharrat	7.492335	9.321042	0.985327
Khamechi et al	7.624863	9.649662	0.986071
Petrosky & Farshad	7.677686	9.577829	0.981838
Mazandarani & Asghari	7.682008	9.038697	0.983421
Al-Marhoun	7.721663	9.103125	0.983248

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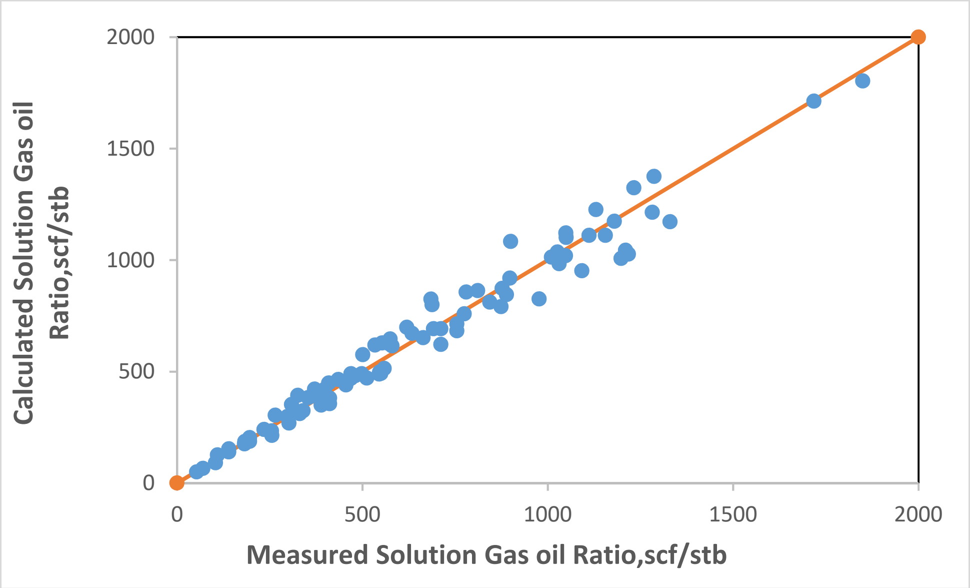
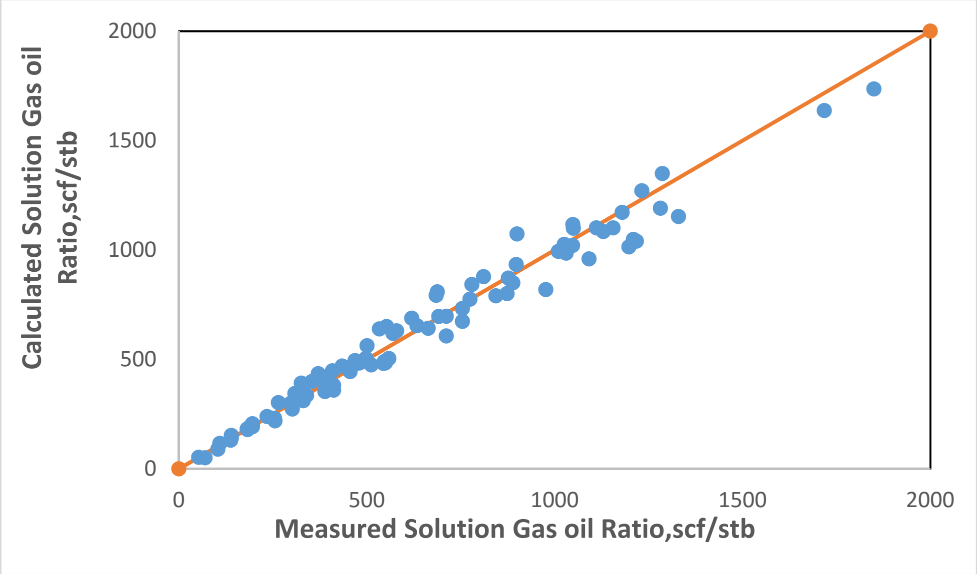


(Figure 4.7)
Cross plot of solution gas oil ratio Hemmati & Kharrat new correlation



(Figure 4.8)
Cross plot of solution gas oil ratio Khamechi et al new correlation

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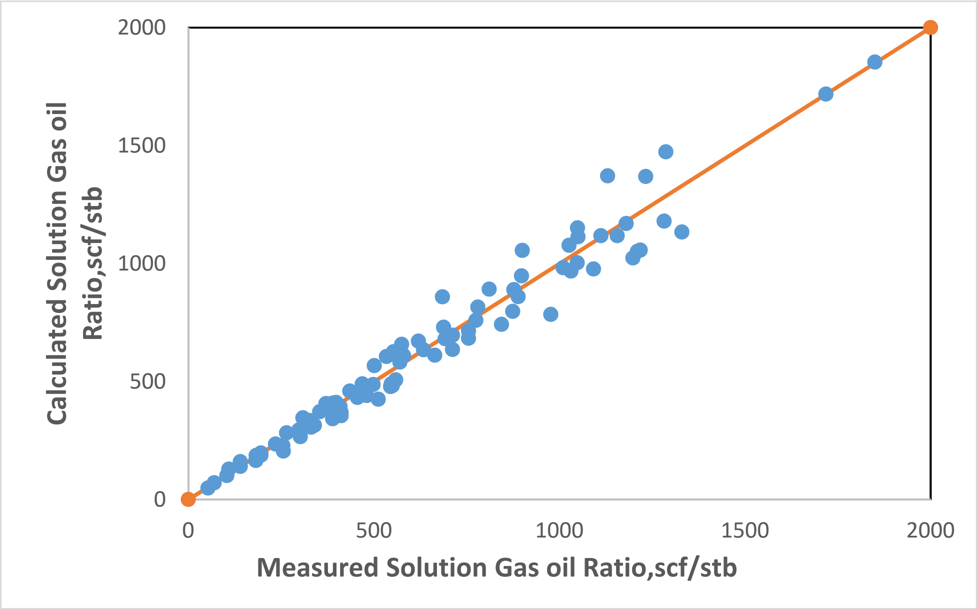
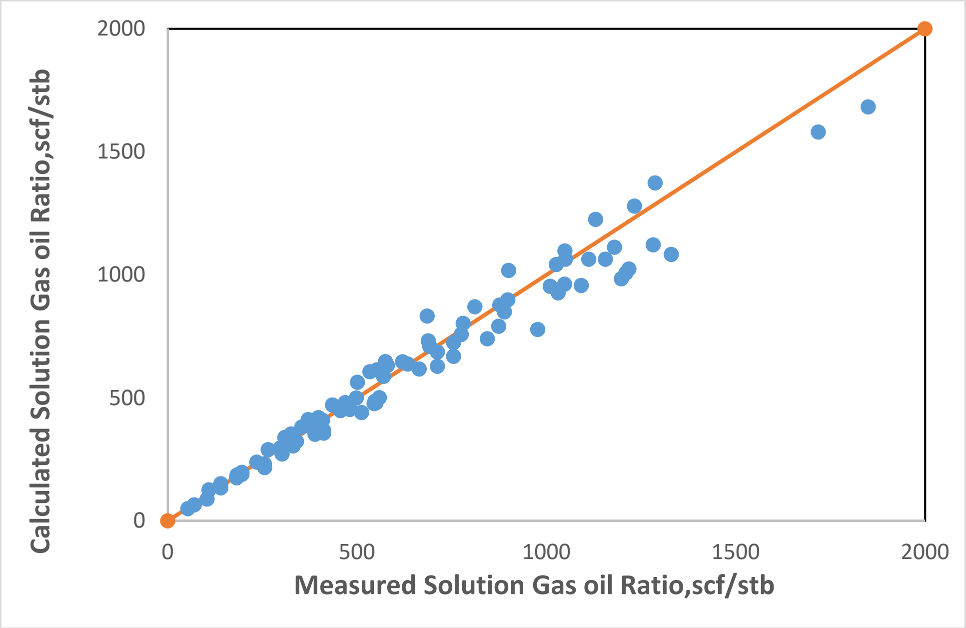


(Figure 4.9)
Cross plot of solution gas oil ratio Petrosky & Farshad new correlation



(Figure 4.10)
Cross plot of solution gas oil ratio Mazandarani & Asghari new correlation

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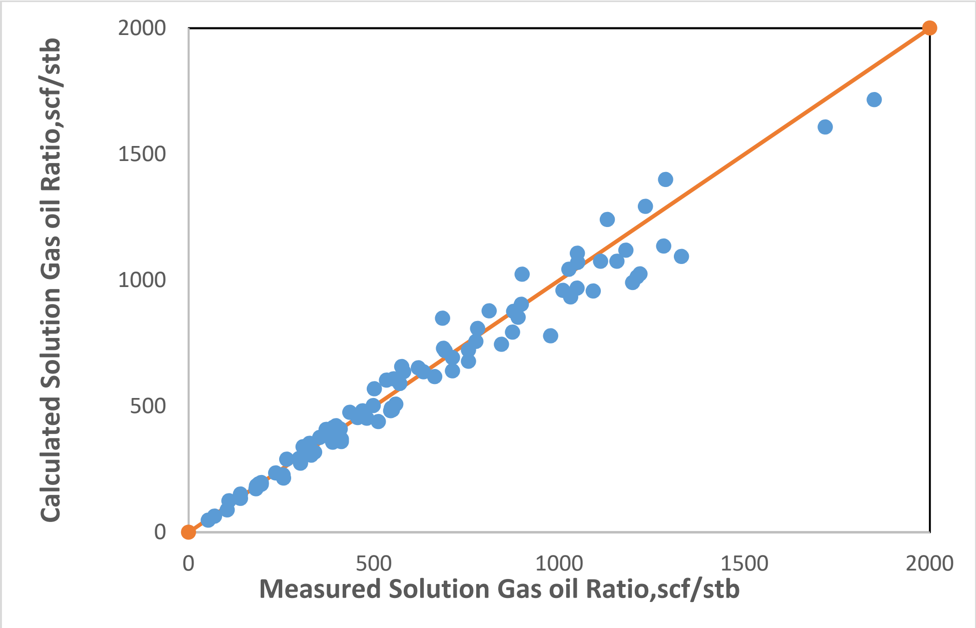
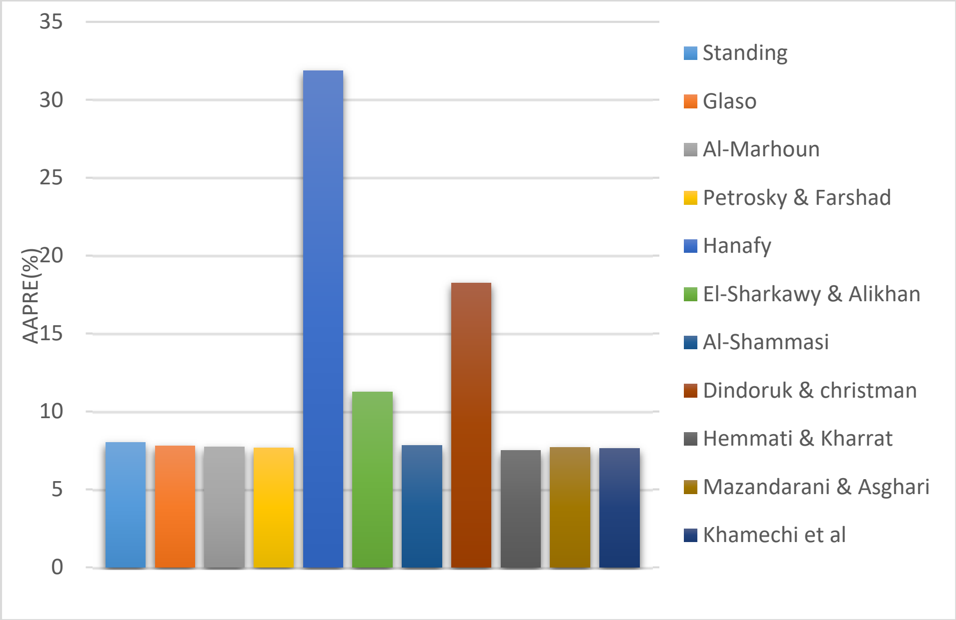


(Figure 4.11)
Cross plot of solution gas oil ratio Al-Marhoun new correlation



(Figure 4.12)
average absolute percent relative error for different new correlation for (Rs)

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(Table 4.6.) Old-new correlation statistical error for (Rs)

Name	Old correlation			New correlation		
	AAPRE	SD	R^2	AAPRE	SD	R^2
Standing	8.018052	5.255	0.98242	7.85	5.2	0.983
Glaso	10.19176	6.71267	0.985461	7.791445	6.195331	0.98561
Al-Marhoun	19.11491	17.5269	0.916716	7.721663	5.113862	0.983248
Petrosky & Farshad	16.96126	15.21603	0.967663	7.677686	5.743119	0.981838
Hanafy	32.38896	41.36577	0.860856	31.858	35.63	0.860856
El-Sharkawy & Alikhan	27.52431	22.99627	0.948041	11.25945	7.0622	0.982974
Al-Shammasi	16.83848	19.644	0.9877	7.924224	8.004527	0.987548
Dindoruk & Christman	37.10219	22.03142	0.87515	10.30802	9.096547	0.980209
Hemmati & Kharrat	9.354213	8.375105	0.982792	7.492335	5.488009	0.985327
Mazandarani & Asghari	15.69034	13.45909	0.957564	7.682008	5.206552	0.983421
Khamechi et al	21.04419	9.084312	0.981898	7.624863	5.879375	0.986071

5. CONCLUSIONS

Based on the analysis of the results obtained in this research study, the following conclusions can be made:

1) Totally 24 published black oil empirical correlations for oil formation volume factor and gas oil ratio at bubble point pressure were collected, summarized and evaluated.
2) For oil formation volume factor correlations, the statistical analysis parameters for all correlations indicate that Kartoatmodjo and Schmidt correlation is the best performing correlation.
3) For solution gas oil ratio correlations, the statistical analysis parameters for all correlations indicate that correlation model Standing is the best performing correlation model for whole data sets used in this work.
4) New correlations have been developed to calculate the oil formation volume factor.
5) New correlations have been developed to calculate the solution gas oil ratio.

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APPENDIX A

New Oil Formation Volume Factor Empirical Correlations

- **New Standing Correlation**

$$\beta_o = 0\cdot929889 + 0\cdot000246\left[R_s\left(\frac{\gamma_g}{\gamma_o}\right)^{0\cdot216702} + 1\cdot885972\,(T-460)\right]^{1\cdot089897}$$

- **New Vazquez & Beggs Correlation**

$$\beta_o = 1\cdot0 + C_1 R_s + (T-520)\left(\frac{API}{\gamma_{gs}}\right)[C_2 + C_3 R_s]$$

	$API \le 30$	$API > 30$
C1	$4.68*10^{-4}$	$4.98*10^{-4}$
C2	$1.75*10^{-5}$	$1.10*10^{-5}$
C3	$-1.81*10^{-8}$	$1.34*10^{-9}$

- **New Glaso Correlation**

$$\beta_o = 1\cdot0 + 10^{A}$$

$$A = -6\cdot781607 + 3\cdot028823\log\beta^*_{ob} - 0\cdot297442\,(\log\beta^*_{ob})^2$$

$$\beta^*_{ob} = R_s\left(\frac{\gamma_g}{\gamma_o}\right)^{0\cdot222131} + 1\cdot490516(T-460)$$

- **New Al-Marhoun Correlation**

$$\beta_o = 0\cdot468574 + 9\cdot29\times10^{-4}\,T + 1\cdot72\times10^{-3}\,F + 3\cdot18\times10^{-6}\,F^2$$

$F = R_s^a\,\gamma_g^b\,\gamma_o^c$

a = 0.742390

b = 0.323294

c = -1.202040

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- **New Dokla and Osman Correlation**

$$\beta_o = 0 \cdot 043194 + 0 \cdot 001567 * T + 0 \cdot 002112 * F - 0 \cdot 647 * 10^{-6} * F^2$$

$$F = R_S{}^{0 \cdot 781409} * \gamma_g{}^{0 \cdot 222876} * \gamma o0.360129$$

- **New Petrosky & Farshad Correlation**

$$\beta_o = 1 \cdot 037823 + 5 \cdot 46 * (10^{-5}) * \left[R_s^{0 \cdot 400763} \left(\frac{\gamma_g^{0 \cdot 051533}}{\gamma_o^{0 \cdot 449631}} \right) + 0 \cdot 194883 * (T - 460)^{0 \cdot 590364} \right]^{2 \cdot 991397}$$

- **New Omar & Todd Correlation**

$$\beta_o = 0 \cdot 957244 + 0 \cdot 000231 \left[R_s(\gamma_g/\gamma_o)^{0 \cdot 306063} + 1 \cdot 699231T \right]^{\times}$$

$$\times = b_1 + b_2(\gamma_{oAPI}/\gamma_g)\, b_3\gamma_g$$

b1 = 1.120591

b2 = 0.349*10-3

b3= 0.91*10-6

- **New Macary & Elbatanoney Correlation**

$$\beta_{ob} = N[0 \cdot 936714 + 0 \cdot 000758\, T]$$

$$N = \exp[0 \cdot 000369R_s + 0 \cdot 000591(\gamma_o/\gamma_g)]$$

- **New Kartoatmodjo and Schmidt Correlation**

$$\beta_o = a1 + a2\left[\frac{R_s{}^{a3}\gamma_g{}^{a4}}{\gamma_o{}^{a5}} + a6T\right]^{a7}$$

a1 = 0.997969	a2 = 0.000108
a3 = 0.81083	a4 = 0.120834
a5 = 0.952401	a6 = 0.481266
a7 = 1.424576	

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- **New Almehaideb Correlation**

$$\beta_o = a_1 + a_2 R_s T / \gamma_o^2$$

a1 = 1.096153

a2 = 1.41*10-6

- **New Abdul-Majeed & Salman Empirical Correlation**

$$\beta_o = 0 \cdot 470207 + 9 \cdot 17 * 10^{-4} * T + 4 \cdot 37 * 10^{-4} * F$$

$$F = R_S{}^{12} * \gamma_g{}^{0 \cdot 270299} * \gamma^{4 \cdot 83484}$$

- **New El-Sharkawy & Alikhan Correlation**

$$\beta_O = 1 + 40 \cdot 428 * 10^{-5} * R_S + 63 \cdot 802 * 10^{-5} * (T - 60) + M$$

$$M = 6 \cdot 31 * 10^{-7} * [R_S * (T - 60) * \frac{\gamma_g}{\gamma_O}]$$

- **New Al-Shammasi Correlation**

$$\beta_O = 1 + 5 \cdot 53 * 10^{-7} * \left(R_S(T - 60)\right) + 0 \cdot 000316791 * \frac{R_S}{\gamma_O} + N$$

$$N = 0 \cdot 000571 * \left(\frac{T - 60}{\gamma_O}\right) + 0 \cdot 0004995 * \frac{R_S * \gamma_g}{\gamma_O}$$

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APPENDIX B

New Solution Gas Oil Ratio Empirical Correlation

- **New Standing Correlation**

$$R_S = \gamma g * [\left(\frac{P}{19 \cdot 48928} + 3 \cdot 718284\right) * 10^A]^{1 \cdot 2048}$$

$$A = 0 \cdot 0125 * API - 0 \cdot 000833 * T$$

- **New Glaso Correlation**

$$R_{S=}\gamma g * [\frac{API^{0 \cdot 955756}}{(T-60)^{0 \cdot 128655}} * A]^{1 \cdot 144234}$$

$$A = 10^X$$

$$X = 3 \cdot 431141 - [9 \cdot 712799 - 2 \cdot 023773 * \log(P)]^{0 \cdot 708011}$$

- **New Al-Marhoun Correlation**

$$R_S = 1195 \cdot 465 * \gamma g^{1 \cdot 104722} * P_b{}^{1 \cdot 174147} * \gamma_o{}^{-5 \cdot 931636} * (T+460)^{-1 \cdot 63068}$$

- **New Petrosky & Farshad Correlation**

$$R_S = [\left(\frac{P_b}{28 \cdot 43765} + 6 \cdot 4\right) * \gamma g^{0 \cdot 883875} * 10^A]^{1 \cdot 355281}$$

$$A = 2 \cdot 25 * 10^{-3} * API^{1 \cdot 364415} - 6 \cdot 40 * 10^{-5} * T^{1 \cdot 427019}$$

- **New Hanafy Correlation**

$$R_S = -49 \cdot 30753 + 0 \cdot 29402 * P_b$$

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- **New El-Sharkawy & Alikhan Correlation**

API ≤ 30

$$R_S = \gamma_g * P_b^{1\cdot094321} * 10^{-1\cdot105148+0\cdot832827*\frac{API}{T}}$$

API ≥ 30

$$R_S = P_b^{1\cdot063093} * \gamma_g^{0\cdot908448} * API^{1\cdot127917} * 10^{-2\cdot46847+0\cdot00012*T}$$

- **New Al-Shammasi Correlation**

$$R_S = [\beta_o - 0 \cdot 976298 - 0 \cdot 000562 * (\frac{T-60}{\gamma_o})/0 \cdot 000428] * \gamma_o$$

- **New Dindoruk & Christman Correlation**

$$R_S = [\frac{P_b}{10 \cdot 72191} + 84 \cdot 6966 * \gamma_g^{1\cdot893016} * 10^A]^{1\cdot030336}$$

$$A = \frac{X}{Y}$$

$$X = 4 \cdot 8699 * 10^{-6} * API^{5\cdot73098} + 0 \cdot 009925 * T^{1\cdot776179}$$

$$Y = (44 \cdot 25002 + \left(2 * \frac{API^{2\cdot70288}}{P_b^{0\cdot631356}}\right))^{1\cdot570038}$$

- **New Hemmati & Kharrat Correlation**

$$R_S = [0 \cdot 198271 * \gamma_g^{0\cdot928728} * \gamma_o^{-4\cdot922048} * T^{-0\cdot233277} * P]^{1\cdot159414}$$

- **New Mazandarani and Asghari Correlation**

$$R_S = 932 \cdot 7977 * \gamma_g^{1\cdot058553} * P^{1\cdot165244} * \gamma_o^{-5\cdot867259} * (T+460)^{-1\cdot582038}$$

- **New Khamechi et al Correlation**

$$R_S = 0 \cdot 007671 * \gamma_g^{0\cdot983715} * P^{1\cdot152492} * API^{1\cdot151965} * T^{-0\cdot294128}$$