

Optimization of Kartoatmodjo and Schmidt Oil Formation Volume Factor Correlation with Particle Swarm Optimization Algorithm

By

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Abstract

Knowledge of reservoir fluid properties is very important in reservoir engineering calculations such as reserves estimates, material balance equation, and numerical reservoir stimulation etc. Laboratory measurements are the most dependable methods for pressure-volume-temperature (PVT) analysis of reservoir fluid properties. During reservoir performance evaluation, the measurements of PVT data are not readily available, hence engineers resort to the use of existing empirical correlations to obtain PVT data. Often time, the data obtained from correlations do not agree with the experimental data, thereby yielding a considerable amount of error. To correct that error in this study, Kartoatmodjo and Schmidt correlation for estimating the oil formation volume factor was optimized using the particle swarm optimization (PSO) algorithm to minimize the error in estimating the oil formation volume factor from Kartoatmodjo and Schmidt correlation at various depletion pressure. The optimized correlation is a function of bubble point pressure, API gravity, gas gravity and reservoir temperature. Therefore, to validate the optimized correlation, PVT data from differential liberation test in the laboratory was used as case a study and the result obtained with the optimized correlation matches closely with the experimentally values at various depletion pressure. Also, the Kartoatmodjo and Schmidt optimized correlation was validated with Standing, Kartoatmodjo and Schmidt, Glaso and Petrosky-Fashad correlations. The optimized Kartoatmodjo and Schmidt gave the least average relative error of ± 0.00065 and the highest correlation coefficient of 0.99996 after 154th successive iterations with the PSO algorithm.

Keywords: differential liberation test, gas-oil ratio, oil formation volume factor, PSO, PVT correlations, reservoir fluid sampling, PVT analysis

INTRODUCTION

Pressure-volume-temperature (PVT) data are key input parameters for most reservoir engineering calculations such as material balance, hydrocarbon reserves estimation, reservoir performance prediction, enhanced oil recovery scheme, design and optimization of production systems (Ahmed¹) etc. The material balance equation is a strong function of PVT data. According to Ikiensikimama², the estimation of reserves and the design of the best depletion strategy are only feasible when realistic and reasonably accurate values of the reservoir fluid properties are available. At the earlier stages of a well, it can be difficult or economically impractical to obtain reliable measurements of PVT data. Therefore, in a scenario where the reservoir fluid samples are available, they can be subjected to PVT analysis to determine the key fluid properties. According to Ikiensikimama and Egbe³, PVT analysis are usually performed at reservoir temperature.

PVT data can either be obtained from laboratory analysis or generated from existing correlations developed from different regions. In accordance with the statement made by Bon

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¹ T. H. Ahmed, 2006. *Equation of State and PVT Analysis*. Gulf Publishing, 272-285

² S. S. Ikiensikimama, 2008. The performance of Empirical PVT Correlations for Predicting Reservoir Fluid Properties for Some Niger Delta Crude. Ph. D Dissertation, University of Lagos, Lagos – Nigeria.

³ S. S. Ikiensikimama, and T. Egbe 2006. Improved PVT Screening Methodology. *Technical Transactions on Software Engineering*, 1, 59-67, IPS Applied Technology Series, University of Port Harcourt, Nigeria.

et al.⁴, that for oil reservoirs, the PVT analysis is conducted on samples taken when the reservoir pressure is above the bubble point. Hence, prior to carrying out the laboratory analysis, the reservoir fluid is first sampled either at the subsurface or surface (wellhead/separator) and thereafter conveyed to the laboratory to check for the quality, consistency and possible leakage. Table 1 shows the types of PVT experiments conducted in the laboratory and the respective data obtained.

Table 1: Types of PVT experiment and data derived

Experiment	Data Obtain
Constant composition expansion (black oil and compositional)	Relative volume, Vapor Z factor, Liquid Drop Out
Differential Liberation/Vaporization (black oil only)	Vapour Z factor, Liquid density, Gas-Oil ratio, Relative volume (Formation volume factor), Gas gravity, Liquid viscosity, Vapor viscosity
Constant Volume Depletion (compositional only)	Retrograde liquid drops out, Cumulative fluid produced, Vapor Z factor, Specific gravity of produced fluid plus, Mole weight of produced fluid plus, Final weight of produced fluid plus & Produced vapor composition.
Separator test (black oil and compositional)	Gas-Oil ratio & Stock tank formation volume factor
And others such as Saturation pressure (Dew point) at reservoir temperature, viscosity measurement & compositional analysis.	

Furthermore, carrying the experiments listed in Table 1 are usually expensive and time-consuming, thus, Engineers in the field resorted to using existing correlation to estimate these properties. Several correlations have been developed in literature to estimate PVT properties such as gas-oil ratio and oil formation volume factor. This study focuses on oil formation volume factor only and some of the existing correlations used in the oil and gas industry are:

Standing⁵ correlation for oil formation volume factor (oil FVF) expressed as:

(GO

$$B_o = 0.972 + 0.000147 \left[R_s \left(\frac{\gamma_g}{\gamma_o} \right)^{0.5} + 1.25T \right]^{1.175} \quad (1)$$

Glaso⁶ proposed a correlation for estimating oil formation volume factor as a function of the API gravity, solution gas-oil ratio R), temperature, and gas specific gravity given by:

$$B_o = 1.0 + 10^4 \quad (2)$$

Where

⁴ J. Bon, H. K. Sarma, J. T. Rodrigues, and J. G. Bon, 2007. Reservoir Fluid Sampling Revisited-A Practical Perspective. *SPE Reservoir Evaluation and Engineering*, 10(6), 589-596.

⁵ M. B. Standing, 1947. A Pressure Volume Temperature Correlation for Mixture of California Oils and Gases. *Drill. & Prod. Prac.* API, Dallas. 275-87.

⁶ O. Glaso, 1980. Generalized Pressure-Volume Temperature Correlations. *JPT*, May, pp 785-95.

$$A = -6.58511 + 2.91329 \log \left(R_s \left(\frac{\gamma_g}{\gamma_o} \right)^{0.526} + 0.986T \right) - 0.27683 \left[\log \left(R_s \left(\frac{\gamma_g}{\gamma_o} \right)^{0.526} + 0.986T \right) \right]^2 \quad (3)$$

Al- Marhoun⁷ developed a correlation for estimating oil formation volume factor for Middle East crude oil. These correlations were based on a database of 69 bottom hole fluid samples and expressed as a function of reservoir temperature, solution GOR, gas gravity and oil gravity.

$$B_o = 0.497069 + 0.000826863(T + 459.67) + 0.00182594F + 0.318099 \times 10^{-6}F^2 \quad (4)$$

Where

$$F = R_s^{0.74239} \gamma_g^{0.323294} \gamma_o^{-1.202040} \quad (4a)$$

Petrosky and Farshad⁸ used a nonlinear multiple regression software to develop an oil formation volume factor. The authors constructed a PVT database from 81 laboratory analyses from the Gulf of Mexico crude oil system. Petrosky and Farshad proposed the following expression

$$B_o = 1.0113 + 7.204 \times 10^{-5} \left[R_s^{0.3738} \left(\frac{\gamma_g^{0.2914}}{\gamma_o^{0.6265}} \right) + 0.246T^{0.5371} \right]^{3.0936} \quad (5)$$

Kartoatmodjo and Schmidt⁹ developed a new set of empirical correlation based on a large collection of data developed from all over the world. Their equation is given by

$$B_o = 0.98496 + 0.0001 \times [R_s^{0.755} \gamma_g^{0.25} \gamma_o^{-1.5} + 0.45T]^{1.50} \quad (6)$$

It is imperative to note that most of these correlations yield accurate results when applied at the bubble point pressure. However, for pressures below the bubble point pressure, the computed PVT properties may yield a considerable error, which make the application of these correlations in reservoir studies or material balance equation not accurate because the values obtained from correlations are not equal to the experimental data. Hence in order to minimize error in estimating oil formation volume factor from correlations, an optimization algorithm is required. Few of these algorithms are gradient descend, evolutionary algorithms, particle swarm optimization tool etc. Therefore, the aim of this study is to minimize the error between the experimented results of oil formation volume factor (B_o) and the result from existing correlations. To achieve the aim of this study, Kartoatmodjo and Schmidt oil formation volume factor correlation was modified with PSO.

⁷ M. A. Al-marhoun, 1988. PVT Correlation for Middle East Crude Oils. *JPT*, May 1988, pp. 650–665.

⁸ G. E. Petrosky, and F. Farshad, 1993. Pressure-Volume-Temperature Correlations for Gulf of Mexico Crude Oils, SPE Paper 26644, presented at the 68th Annual Technical Conference of the SPE in Houston, Texas, 3–6 October.

⁹ T. Kartoatmodjo, and Z. Schmidt, 1994. Large data bank improves crude physical property correlations. *Oil and Gas Journal*. pp. 51–51.

METHODOLOGY

The methodological approach of this study is presented in Figure 1.

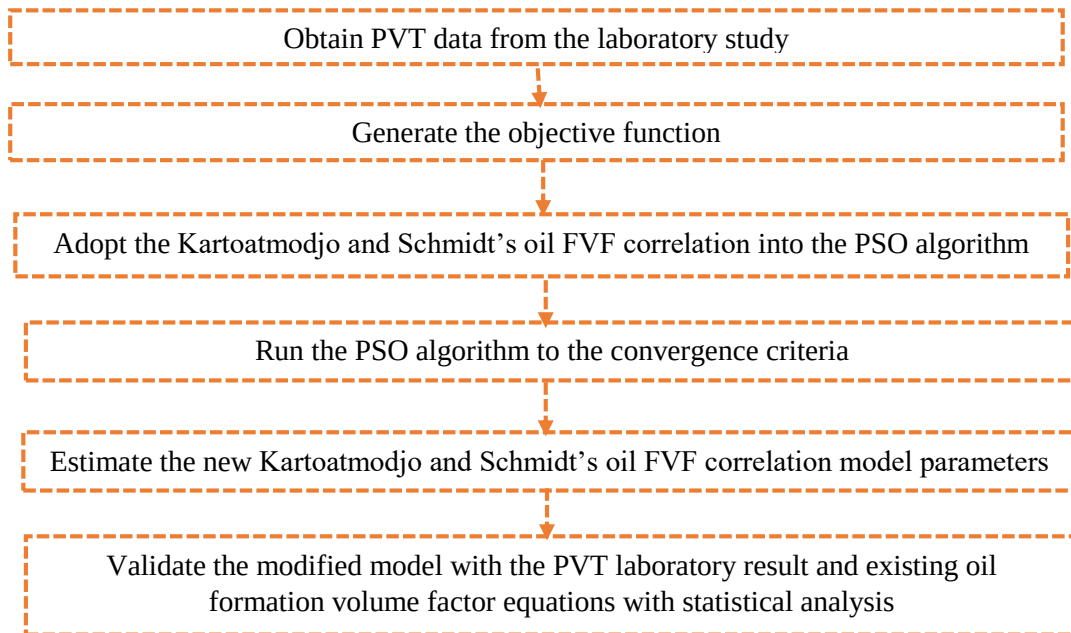


Figure 1: Methodology of study

INPUT DATA

Table 2: Differential liberation test data

SAMPLE No 1- SEPARATOR TEST (T=129°F, P_b =2405psig) R_{sB} (cuft @ 60°F and 14.65psia per STB @ 60°F) 701 B_{oB} (barrels of saturated oil @ P_b and T per STO @ 60°F) 1.356 Stock Tank Gravity (API @ 60°F) γ_g (from separator air = 1) 0.743		37
Pressure(psig)	Formation volume factor (rb/stb)	
2405	1.568	
2200	1.579	
1950	1.476	
1700	1.433	
1450	1.392	
1200	1.353	
950	1.313	
700	1.269	
450	1.219	
200	1.182	

Generation of Objective function

The objective functions developed in this study is based on Kartoatmodjo and Schmidt correlation for oil formation volume factor below the bubble point pressure.

$$B_o = 0.98496 + 0.0001 \times (R_s^{0.755} \gamma_g^{0.25} \gamma_o^{-1.5} + 0.45T)^{1.50} \quad (7)$$

Hence

$$B_{o_{estimated}} = A + B \times (R_s^{0.755} \gamma_g^{0.25} \gamma_o^{-1.5} + 0.45T)^C \quad (8)$$

Hence objective function can be defined as

$$f(x) = \sum |B_{o_{exptal}} - A + B \times (R_s^{0.755} \gamma_g^{0.25} \gamma_o^{-1.5} + 0.45T)^C| = \min \quad (9)$$

Where

$B_{o_{exptal}}$ is the values obtained from laboratory PVT analysis on a nearby field;

A, B, and C is a minimization constant to be determined by PSO optimization tool;

$B_{o_{estimated}}$ is the estimated values obtained from PSO optimization tool;

PSO ALGORITHM STEPS

Step 1: Choose the number of particles

Step 2: Initialize the initial positions of the particles

Step 3: Evaluate the objective function at the initial positions

Step 4: Set the iteration number as $t = i+1$

Step 5: Find the personal best for each particle

Step 6: Find the global best

Step 7: find the velocities of the particles

Step 8: Find the new values of the particles position

Step 9: Find the objective function values of step 6

Step 10: Stopping criterion:

If the terminal rule is satisfied, go to step 4, otherwise stop the iteration and output the results

Therefore, the iterative process of the PSO algorithm is represented in Figure 2.

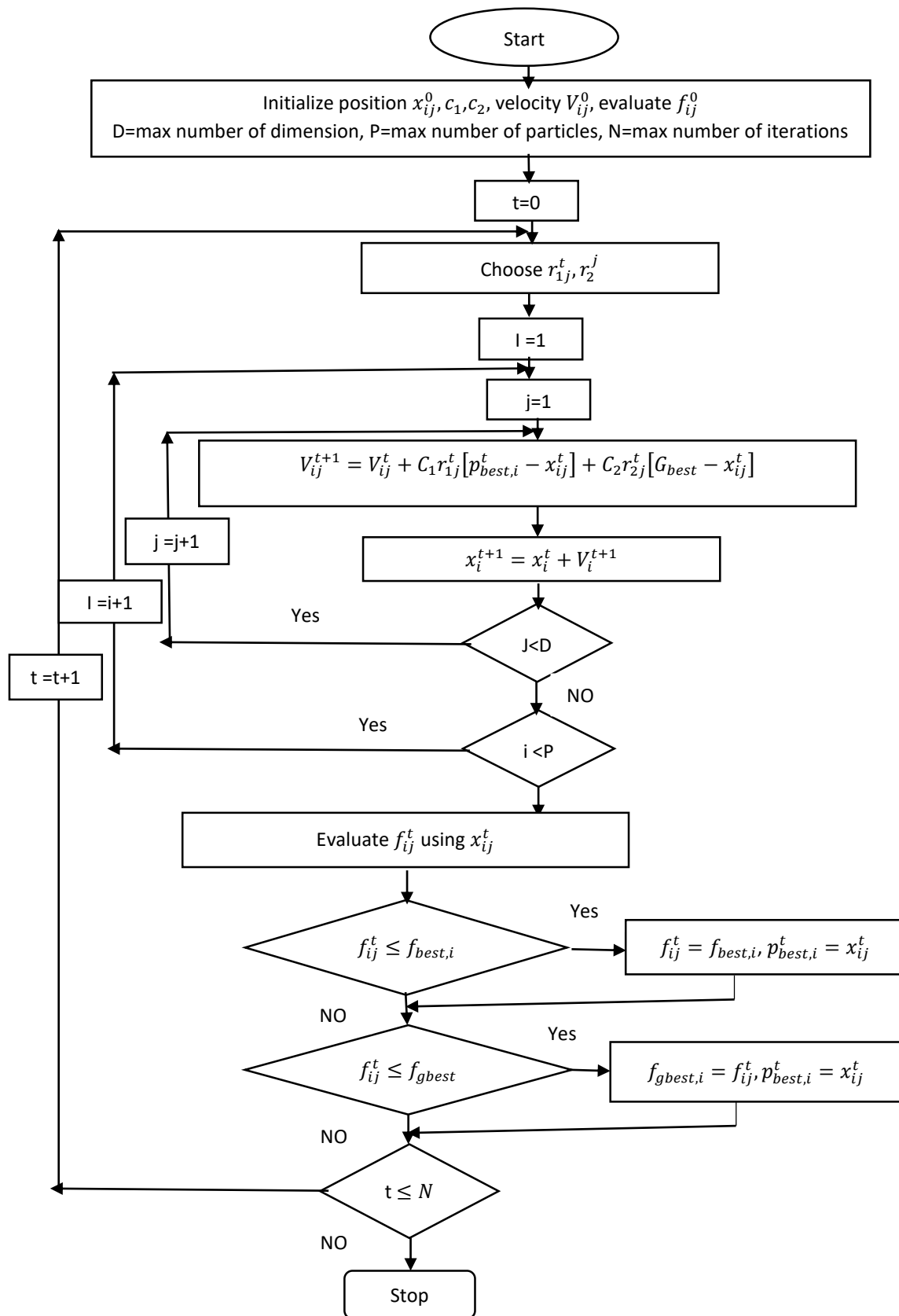


Figure 2: Workflow algorithm for the PSO (Gbest PSO)

RESULTS AND DISCUSSION

The PSO algorithm as shown in Figure 2, is an iterative process that cannot be done manually, thus, it was programmed in Microsoft Excel to get the global best value for the constant A, B, and C respectively as shown in Figures A1 – A3 in appendix A.

Convergence criteria is a phenomenon of PSO in which all particles tend to converge to a single value as shown by Figures A1 – A3 respectively where all three particles maintain a single value at the 154th iterations. The modified Kartoatmodjo and Schmidt's oil FVF correlation parameters are presented in Table 3.

Table 3: Model parameters

Parameter	Oil FVF @ 154 th iterations
A	1.003330294
B	0.000157176
C	1.41992552

Therefore, the modified Kartoatmodjo and Schmidt's oil FVF correlation is given in Equations 10.

$$B_{o_{optimized}} = 1.003330294 + 0.000157176 \times (R_s^{0.755} \gamma_g^{0.25} \gamma_o^{-1.5} + 0.45T)^{1.41992552} \quad (10)$$

The results obtained from the existing oil formation volume factor correlations and the modified Kartoatmodjo and Schmidt's oil FVF correlation with the PSO algorithm for this study are presented in Tables 4. The result clearly shows that the modified correlation performed better the other four correlations for the PVT laboratory data given in this study.

Table 4: Result of gas solubility (scf/stb) from existing correlations

Pressure (bbl/stb)	Experimental	Kartoatmodjo and Schmidt	Petrosky-Fashad	Glaso	Standing	This Study
2405	1.568	1.5967	1.5967	1.5805	1.1835	1.5997
2200	1.519	1.5404	1.5404	1.5171	1.1675	1.5190
1950	1.476	1.4898	1.4898	1.4604	1.1531	1.4762
1700	1.433	1.4395	1.4395	1.4047	1.1388	1.4338
1450	1.392	1.3906	1.3906	1.3512	1.1250	1.3925
1200	1.353	1.3425	1.3425	1.2996	1.1115	1.3520
950	1.313	1.2951	1.2951	1.2502	1.0983	1.3120
700	1.269	1.2431	1.2431	1.1982	1.0841	1.2684
450	1.219	1.1842	1.1842	1.1434	1.0683	1.2190
200	1.182	1.1425	1.1425	1.1081	1.0575	1.1842

RESULT OF CROSS PLOT

To graphically illustrate the success of the existing correlations, a performance or cross plot was performed for the oil FVF correlations as shown in Figures A4 – A7 in Appendix A, which is a plot of the estimated values versus the experimental values. A 45° straight line was drawn on the cross plot on which the estimated value is equal to the experimental value. Fitting the straight line at 45° clearly indicates that, the closer the plotted data points are to this line, the

better the correlation. The result of Petrosky-Fashad, Glaso, Katoantmodjo-Schmidt and Standing correlations show a clear disparity from the experimented values, while the modified Katoantmodjo-Schmidt's correlation gave a better match of the laboratory result at the different depletion pressures.

STATISTICAL ERROR ANALYSIS

From Table 5, the errors calculated by this study's correlation are lower than the other three correlations. The modified correlation is most accurate for pressure below the bubble point pressure, yielding the least average percent relative error of -0.000650% and the highest correlation coefficient of 0.99996, which means that the sum of squares about the regression is minimal i.e. the unexplained variation by regression and thus agree with the theoretical concept that the best correlation should have the least average percent relative error and highest correlation coefficient between zero and one.

Table 5: Statistical Analysis of Correlations

Statistical parameter	This study	Glaso correlation	Petrosky-Farshad correlation	Kartoatmodjo-Schmidt correlation
Average percent relative error	-0.000650	3.2	0.585	1.68
Sum squared residual	0.1480	0.2464	0.2090	0.165
Correlation coefficient	0.99996	0.9573	0.9873	0.9844

CONCLUSION

Based on the results of this evaluations, the following remarks are worth mentioning.

1. An empirical correlation for estimating the oil FVF at the bubble point pressure and below for black oils has been developed.
2. The result obtained with the data from the differential liberation test, shows that the correlation developed in this study performs better than Standing's, Glaso's, Petrosky's and Katoantmodjo-Schmidt's correlations. Hence, engineers can rely on the newly developed correlation to an extent after they have validated it with their field data because it is stated in literature that correlation performs better in the region it was developed.
3. The statistical result indicates a lower value of average relative error and a better coefficient of correlation for this study than for Standing's, Glaso's and Petrosky's correlations at pressures below bubble point.
4. The particle swarm optimization tool achieves a better accuracy by minimizing the objective function generated in this study.

RECOMMENDATION

1. It is recommended that the developed black oil correlations should be optimized using the constant parameters in order to achieve a higher level of accuracy with field data from different geological region before application to a green field.
2. Further study should be done for oil formation volume factor above bubble point pressure.
3. The new correlation developed in this study should be further validated with several field data.
4. It is recommended that existing correlations for formation volume factor be coupled with differential liberation test experiment.
5. It is recommended that further studies considering black oils with significant amount of impurities such as carbon dioxide, hydrogen sulfide and nitrogen should be carried out.
6. Further work is recommended in developing a modification of Particle swarm optimization with faster convergence rate.

Appendix A

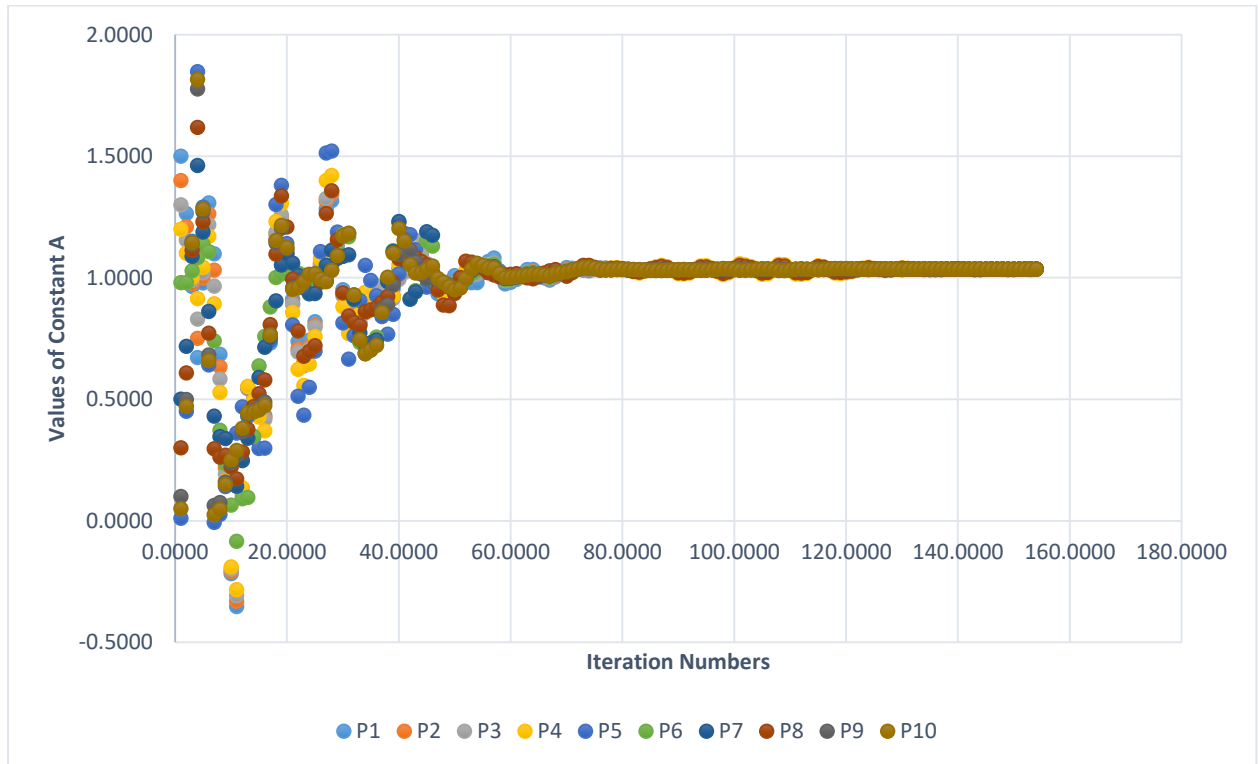


Figure A1: Constant A values from PSO iteration

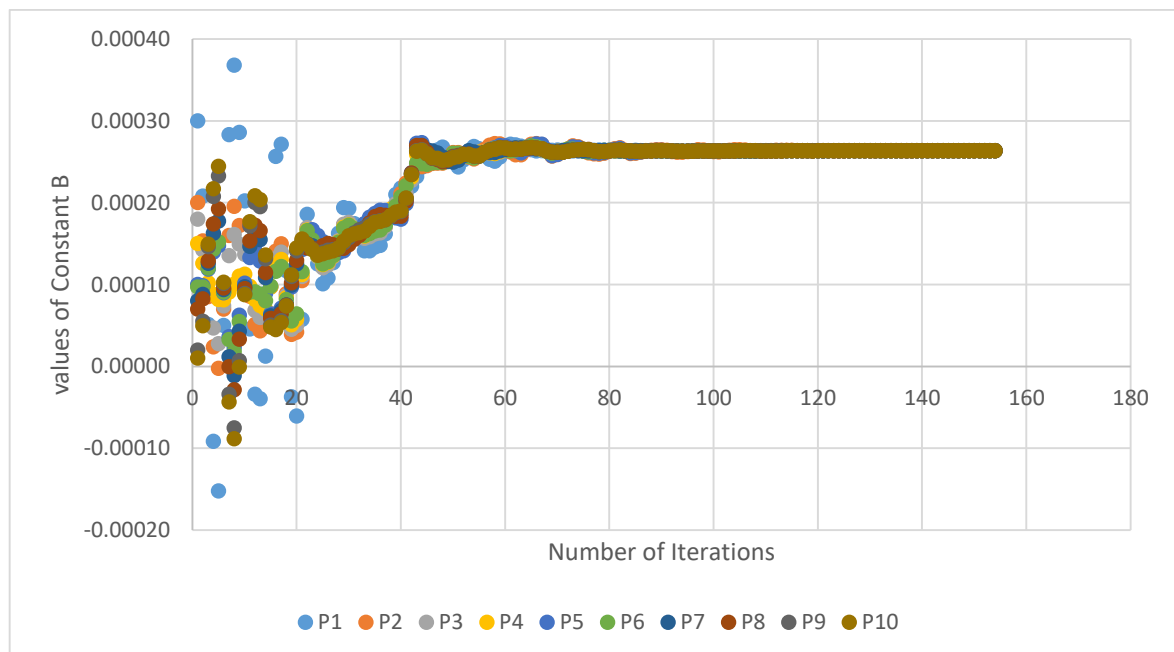


Figure A2: Constant B values from PSO iteration

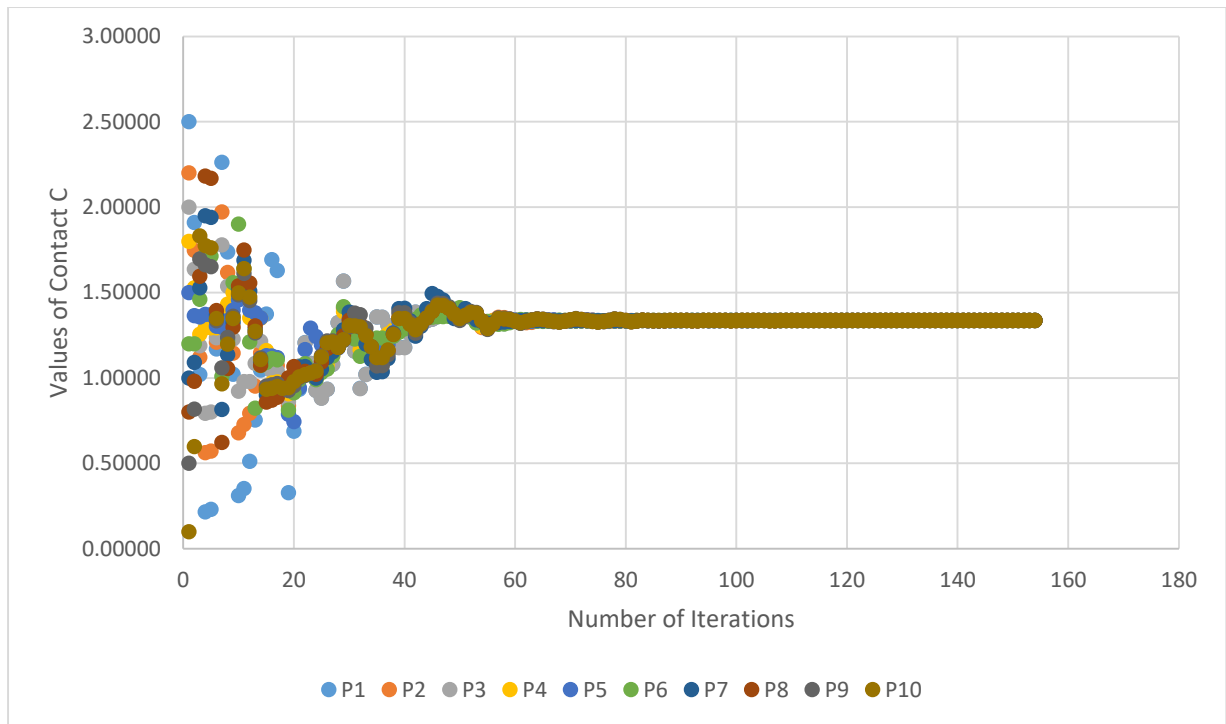


Figure A3: Constant C values from PSO iteration

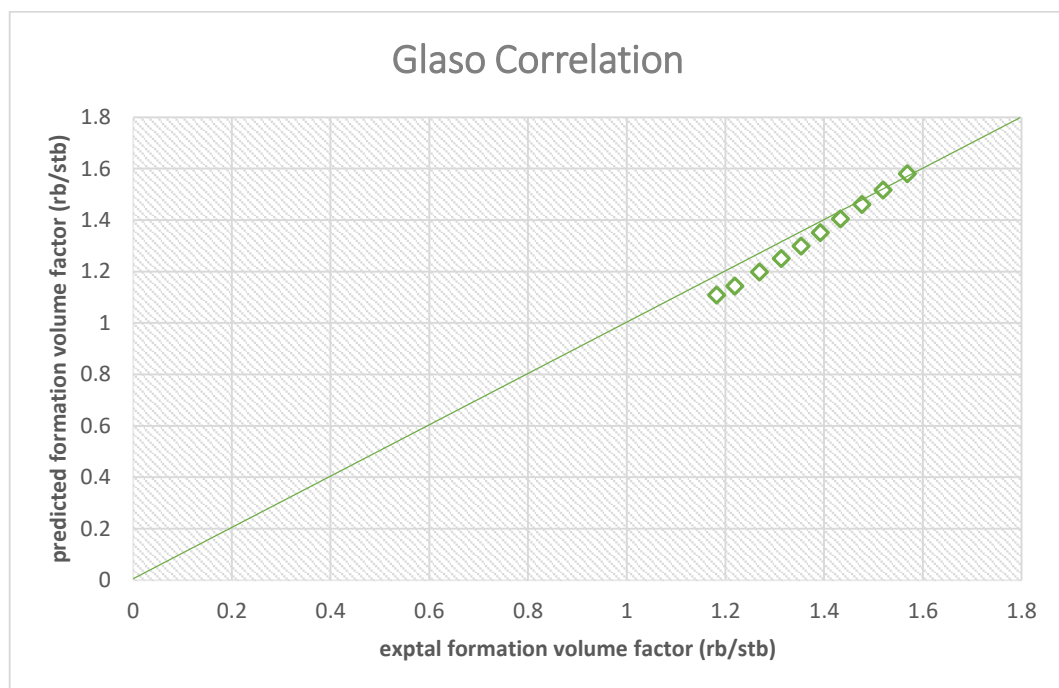


Figure A4: Cross plots for Glaso oil formation volume factor correlation

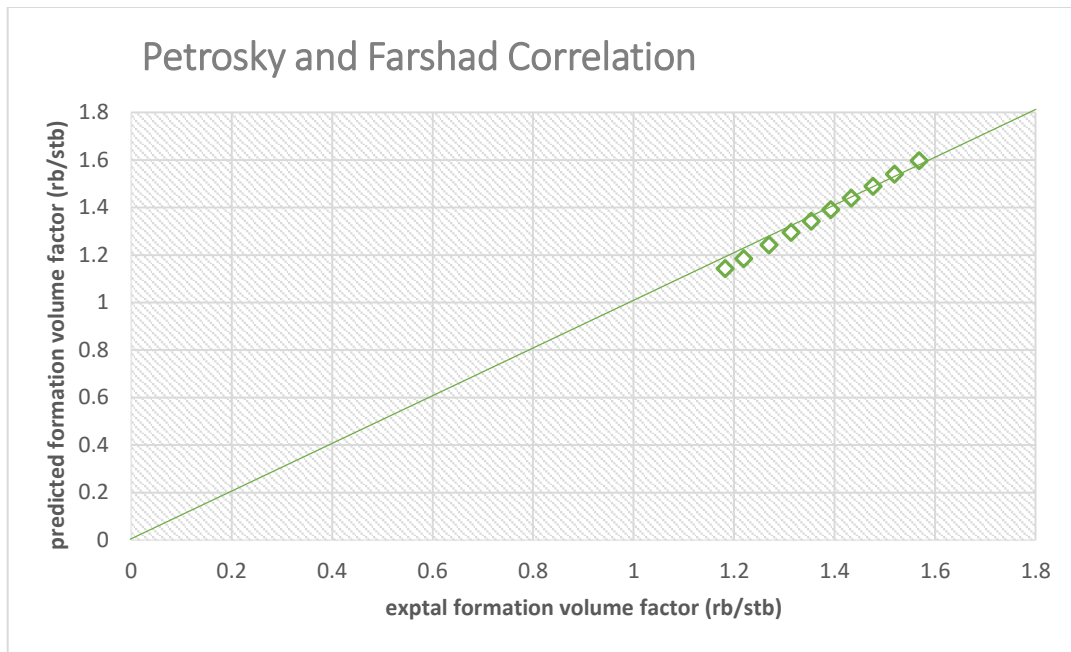


Figure A5: Cross plots of Petrosky and Farshad oil formation volume factor correlation

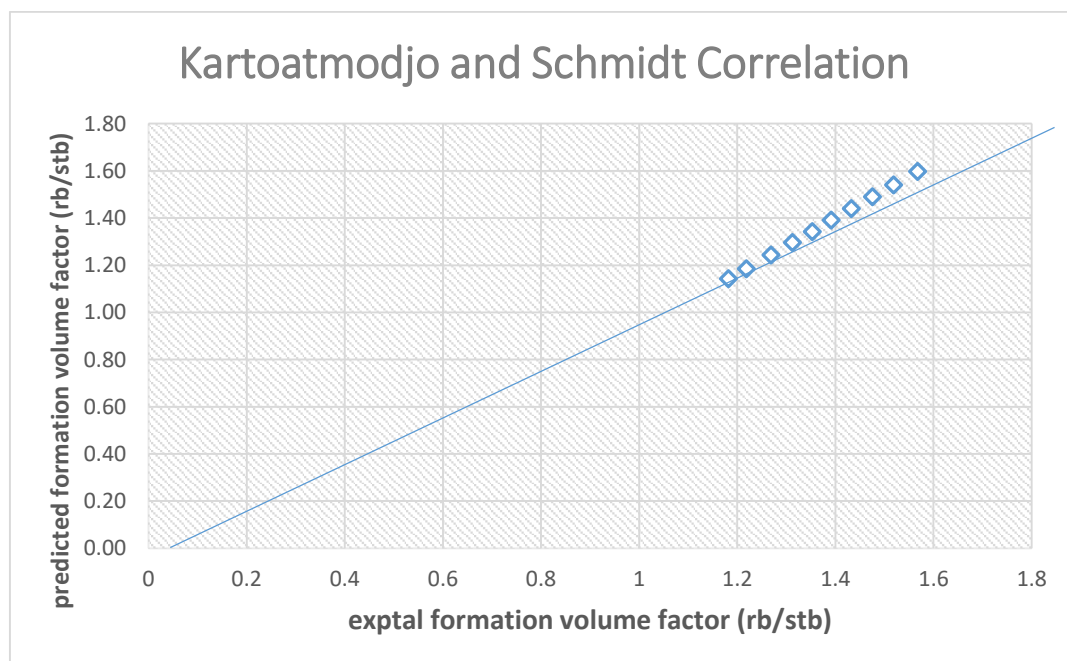


Figure A6: Cross plots of Kartoatmodjo and Schmidt Correlation oil formation volume factor correlation

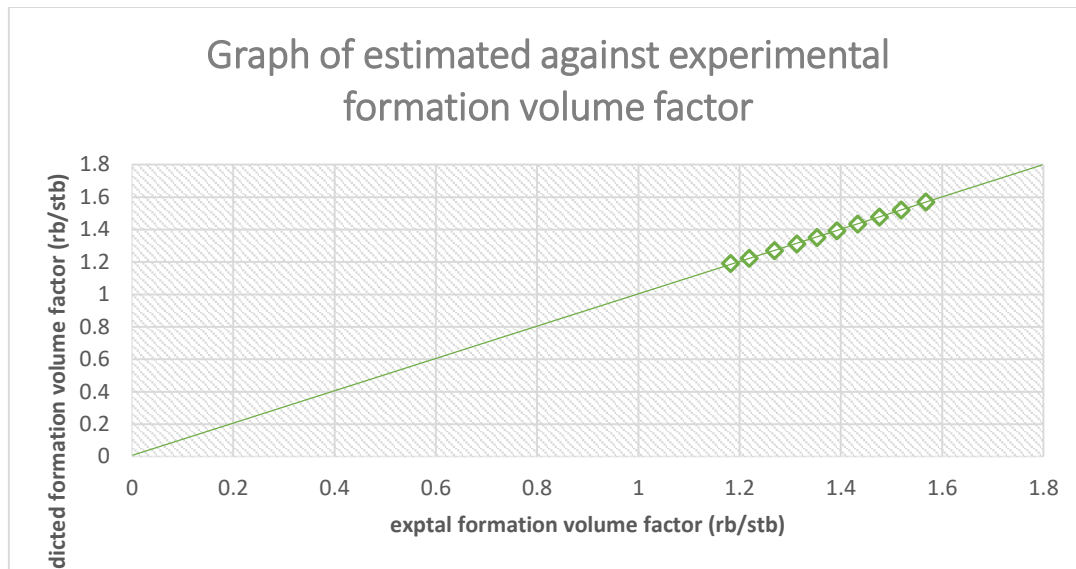


Figure A7: Cross plots for formation volume factor for this study

Error Analysis

The following statistical means are used to determine the accuracy of the correlations

Average percent relative error

$$E_r = \frac{1}{n} \sum_{i=1}^n E_i$$

$$E_i = \left(\frac{x_{exp} - x_{est}}{x_{exp}} \right)_i \times 100$$

Sum squared residual

$$SSR = \sum_{i=1}^n (x_{exp} - x_{est})^2$$

Correlation coefficient

$$r = \sqrt{1 - \left(\sum_{i=1}^n (x_{exp} - x_{est})^2 \right) / \left(\sum_{i=1}^n (x_{exp} - \bar{x})^2 \right)}$$

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n (x_{exp})_i$$