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# A New Forecast Model for Natural Gas Viscosity

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***Abstract***— *Gas viscosity for natural gas system can be determined from Carr et al charts using the pseudo critical gas pressure and temperatures. These charts give accurate values for gas viscosity. Reservoir simulation softwares need accurate correlations to estimate the values of gas viscosity, one of the popularly used correlation is Dempsey correlation. This correlation gives large errors at high gas reservoir pressure. Old correlations give good estimation of gas viscosity at low gas reservoir pressures below 6000psia, at high pressures the error starts to appear. In this study, a new accurate gas viscosity correlation has been developed which accommodate higher region. The equation was developed by regressing 483 data points of measured natural gas viscosity using Matlab. The developed correlation shows a superiority as to compare with other evaluated correlations and is a function of gas gravity, pseudo reduced pressure and temperature of the gas. The new correlation is applicable to gas viscosity at any pressure range.*

***Keywords***— *Correlation, high pressure, high temperature, Natural Gas, Viscosity.*

## I. Introduction

Viscosity measures the internal resistance to fluid flow. It increases with pressure and temperature, and the magnitude is less significant to that of oil or water; and therefore, the mobility of gases are higher inside the reservoir as to compare to oil or water. Measuring of viscosity in the laboratory is very difficult and costly, hence predictive models are employed with a little error. Like all intensive properties, natural gas viscosity is completely designated by these

$$\mu_g = f(P,T,y) \tag{1}$$

Where μg = gas phase viscosity. Equation (1) specifies the extremely dependent of viscosity on pressure, temperature, and composition.

Several well-known correlations are used in the petroleum industry to determine the values of gas viscosity. Some of these available mathematical equations in literature are [1], [2], [3], [4], [5], [6] [7], [8] which performed well at low – intermediate pressures and temperatures, but few works has been done in the area of gas viscosity for high pressures and high temperature (HPHT) in the oil and gas production [9], [10], [11], [12], [13] . [1] graphical correlations has been the most popular charts in the petroleum industry, because their chart set is perhaps the most complete, including the atmospheric pressure chart, the viscosity ratio charts and correcting charts for non-hydrocarbons. They used experimental technique of [14] to create the correlation, as a function of pseudo-reduced pressure, pseudo-reduced temperature and viscosity ratio. It was reported to have an average of 0.38 absolute error. [1] correlation is recommended to be used for gases with specific gravity between 0.55 and 1.22 and a temperature range between 100 and 300$^o$F.

[4] Developed a models applying [1] data and acquired the following expressions which hold for the complete collection of [1] correlation. [5] in 1966 built a semi mathematical model used in computing gas viscosity. The forecasting model was generated using these independent variables which include reservoir temperature, gas density, and gas molecular weight. This correlation was generated for pressure ranges between 100 and 8000 psia and temperature ranges between 100 and 340$^o$F. The model can determine viscosity at SDA of 2.7% with 8.99% maximum deviation. Gases having higher specific gravities does not perform well using this correlation and also for sour gases.

[9] Measured the viscosity of natural gas using Cambridge SPL440 viscometer using metane sample for pressure at 5,000 to 30,000psia and temperatures from 100 to 400$^o$F. From the measurements, Viswanathan modified the [5] model and comparison was made using data from NIST. The results showed a good performance with the NIST data as to compare to the main [5] correlation. Viswanathan modified the [5] correlation and the equation is presented as follows.

[7] Modeled a viscosity relation for gas in surface and reservoir condition. He developed the correlation using experimental values from gas samples from Nigeria. The authors compared equation formulated with experimental PVT viscosity and then tested the general performance by using it to solve two problems form which solutions by the complex charts were available.

[10] Measured gas viscosity at high pressures and high temperatures (HPHT) using falling body viscometer. The experiments showed that [5] correlation predicted the gas viscosity at low-moderate pressure and temperature, but gave a high error at the elevated conditions. The authors then concluded that an equation for gas viscosity should be developed for higher pressure and temperature region.

[11] Evaluated some existing viscosity correlation and reported that gas viscosity equations are not reliable at HPHT condition. This can negatively impact the inflow performance relationship (IPR) curves and gave a wrong estimation of reserves at extreme conditions and hence drastically influence production forecasting.

[8] Evaluated natural gas viscosity using 319 data from the Niger Delta. The evaluation was based on percentage mean relative error, percentage absolute error, relative error standard deviation, absolute error and the coefficient of correlation. From the statistical measures result, the authors reported that [4] correlation ranked best with the numerical value of 0.705

and also with good plot for the data range studied. Charts of Viscosity against Pseudo Reduced Pressure and Temperature and Viscosity Ratio versus Pseudo Reduced Pressure and Temperature were also built depending on [6] model for Niger Delta region. The developed chart is acceptable for data range of $1.4 < T_r < 1.90$ and $0.2 < P_r < 10.80$.

[15] Presented a report on natural gas viscosity measurement at high pressure and high temperature for a sour natural gas mixture. The measurement was done using capillary tube viscometer at pressures ranging from 10.3 to 138MPa and temperatures up to 444 K. The authors also developed a comprehensive model to predict natural gas viscosity in a wide range of pressures, temperatures and compositions. They concluded that their new developed correlation performed better than other existing equations with the absolute error of 2.4%.

Recently, [12] presented a paper on laboratory measurement of gas viscosity at High Pressure and High Temperature (HPHT) using natural gas samples from Niger-Delta region. The capillary electromagnetic viscometer was used to measure gas viscosity for pressures of 6,000 psia to 14,000 psia; at temperatures of 270 $^{o}$F and 370 $^{o}$F. The authors also did a comparative study of some commonly used gas viscosity models in oil and gas industry. Among all the equations studied [7] performed better than other evaluated correlations with the mean relative error of -5.22 and absolute error of 8.752 for the temperature of 270$^{o}$F while [4] came out the best for the temperature of 370$^{o}$F with mean relative error of -16.88 and 16.88 for absolute mean error. [2] and [9] were also among the correlation studied by the authors but their error margin is very high for the data set used. Cross plots showed the poor performance of the evaluated correlations using the measured data at HPHT conditions. The authors concluded that gas viscosity correlations in literature are not very reliable at HPHT conditions.

[16] Presented a model for predicting gas viscosity for carbon iv oxide bearing gas samples. The new equation is developed with 1539 experimental data measured at 250 to 450K and 0.10 to 140MPa. The authors reported that their model performed better than other eight equations valuated with the maximum relative deviation of 0.98%.

From the literature, conclusion can be drowned that the correlations of gas viscosity available in open access are not having a sufficiently wide collection of applicability for extraordinary pressure and temperature, and so their accuracy may not be reliable in predicting natural gas viscosity at higher regions. Monitoring the behavior of these exceptional reservoirs needs a proper knowledge of gas reservoir characteristic at extreme condition. Therefore, this paper focuses on modeling gas viscosity for low-moderate- high pressure high temperature conditions.

## II. METHODOLGY

### A. *PVT Data Validation*

Before any experimental PVT data are used for design or study purposes, it is necessary to ensure that there are no errors or major inconsistencies that would render any subsequent work useless. Data validation was done using the Campbell diagram (Buckley plot) and the Mass Balance plot.

### B. *Buckley Plot (Campbell Diagram)*

[17] Described a technique for hydrocarbon gas and liquid phase equilibrium.

Linear relationship exist between log of the discrete components of K-values and their corresponding temperatures squared. As a component becomes less paraffinic in nature, the greater will be the deviation from linearity. Thus, it is common for the component heavier than $C_5$ to show such deviations. For the components, any substantial deviance from the linear relationship indicates possible non-equilibrium separation; therefore, suspect the analysis, or numerical errors in data reporting. Since is a log scale, any deviation of log K higher than 0.1 is significant.

### C. *Mass Balance Diagram*

The mass balance diagram is based on the following general equation describing the individual component material balances around a flash separation stage:

$$F.Z_i = L.X_i + V.Y_i \tag{2}$$

Where F, L and V are the molar flow rates of feed, flashed liquid/vapor separately and $Z_i$, $X_i$, and $Y_i$ are the mole fractions of the component i in the feed, flashed liquid/vapor separately. For one feed mole, equation 2 becomes

$$\frac{Y_i}{Z_i} = -\frac{L.X_i}{V.Z_i} + \frac{1}{V} \tag{3}$$

This is a linear equation and thus a plot of $Y_i/Z_i$ versus $X_i/Z_i$ should result in a straight line of gradient –L/V

The well fluid compositions reported in PVT reports are normally obtained from mathematical recombination of the test separator gas and liquid compositions in a mole ratio corresponding to the measured separator GOR, i.e. the well fluid is calculated by a component mass balance. In such cases, deviations on the mass balance diagram normally indicate arithmetic error in the data recombination. Fluid composition of the recombined fluid is also usually measured. This functions as an additional check on the mathematical recombination [18].

The methods above were used to check for the validity of the PVT reports using the flashed data of each well. The valid data was sorted and used to compute the gas viscosity.

## III. DATA ACQUISITION AND ANALYSIS

Two sets of gas viscosity data were used in the development of the new gas viscosity model:

i. The PVT analyses of 198 reservoir fluid samples comprising of low - moderate pressure and temperature values

ii. 285 high pressure high temperature (HPHT) data gotten from laboratory measurement..

Table 1 shows the minimum and maximum values of 483 data set gotten after merging the low to moderate data to high pressure high temperature data. Both data set was acquired from the Niger-Delta part of Nigeria.



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TABLE 1. Data Range used for this Study

| Parameters | Min. | Max. | Mean |
|---|---|---|---|
| Reservoir Temperature ($^oR$) | 611 | 830.0 | 687.65 |
| Reservoir Pressure (Psia) | 130 | 14014.7 | 5006.87 |
| Specific gravity | 0.6056 | 1.1457 | 0.7685 |
| Experimental Gas Viscosity | 0.0122 | 0.0388 | 0.022 |
| $C_1$ | 86.31 | 90.44 | 86.307 |
| $C_2$ | 4.06 | 6.51 | 5.734 |
| $C_3$ | 1.29 | 2.8 | 2.224 |
| i-$C_4$ | 0.29 | 0.84 | 0.677 |
| n-$C_4$ | 0.31 | 0.85 | 0.701 |
| i-$C_5$ | 0.09 | 0.45 | 0.346 |
| n-$C_6$ | 0.1 | 0.42 | 0.358 |
| $C_7^+$ | 0.14 | 2.24 | 1.31 |
| $N_2$ | 0.13 | 0.14 | 0.0386 |
| $CO_2$ | 1.68 | 3.21 | 2.09 |

### *A. Correlation Development*

Description of Microsoft Excel solver: The in-built MS Excel Solver is a linear and non-linear equation solver applied for curve fitting (data fitting) for a system of equations, for both constraint and unconstrained adjustment problems. It is partly add-in functions that is employed in the Excel worksheet.

Microsoft Excel Solver operates on Generalized Reduced Gradient (GRG2) non-linear optimization code built by Leon Lasdon, University of Texas at Austin, and Allan Warren, Cleveland State University.

*The stages involved are as follows:*

Step 1: Problem Formulation / Problem Statement

The regression analysis began with the formulation of problem by detection of the influential variables of gas viscosity. The formulation of problem involves identifying the dependable and independent parameters. Gas viscosity is a function of reservoir pressure, reservoir temperature and gas composition. Defining the problem is the major and possibly the paramount step in regression analysis. The general relationship for gas viscosity with its dependent variable is given in equation 4.

$$GasViscosity = f(P, T\gamma_g) + \varepsilon \quad (4)$$

where: Gas viscosity is response or independent variable, P, T and $\gamma_g$ are set of the influent or dependent variables and $\varepsilon$ is the assumed random error indicating the differences in the approximation.

Step 2: Suggestion of Mathematical Equations

Many mathematical equations were suggested by the software so as to establish the right relationship between response variable and predictor variables.

Step 3: Filtration Process This stage involves using many statistical criteria (Mean relative error, Mean absolute error etc) to select the optimum form of the correlation. Finally, after statistical analysis, mathematical and graphical checking was also done to produce the suitable correlation.

### *B. Correlation Comparison*

To compare the performance and accuracy of the new model to other empirical correlations, two forms of analyses were performed which are quantitative and qualitative screening. For quantitative screening method, statistical error analysis was used. The statistical parameters used for the assessment were percent mean relative error (MRE), percent mean absolute error (MAE), percent standard deviation relative (SDR), percent standard deviation absolute (SDA) and correlation coefficient (R).

For correlation comparison, a new approach of combining all the statistical parameters mentioned above (MRE, MAE, SDR, SDA and R) into a single comparable parameter called Rank was used [18]. The use of multiple combinations of statistical parameters in selecting the best correlation can be modeled as a constraint optimization problem with the function formulated as;

$$\text{Min } Z_i = \sum_{j=1}^{m} S_{i,j} q_{i,j} \quad (5)$$

Subject to

$$\sum_{i=1}^{n} S_{i,j} \quad (6)$$

with

$$0 \leq S_{ij} \leq 1 \quad (7)$$

Where $S_{i,j}$ is the strength of the statistical parameter j of correlation i and $q_{ij}$, the statistical parameter j corresponding to correlation i. j = MRE, MAE, …. $R^1$, where $R^1 = (1\text{-}R)$ and $Z_i$ is the rank, (or weight) of the desired correlation. The optimization model outlined in equations 5 to 7 was adopted in a sensitivity analysis to obtain acceptable parameter strengths. The final acceptable parameter strengths so obtained for the quantitative screening are 0.4 for MAE, 0.2 for R, 0.15 for SDA, 0.15 for SDR, and 0.1 for MRE. Finally, equation 7 was used for the ranking. The correlation with the lowest rank was selected as the best correlation for that fluid property. It is necessary to mention that minimum values were expected to be best for all other statistical parameters adopted in this study except R, where a maximum value of 1 was expected. Since the optimization model (Equations 5 to 7) is of the minimizing sense a minimum value corresponding to R must be used. This minimum value was obtained in the form (1-R). This means the correlation that has the highest correlation coefficient (R) would have the minimum value in the form (1-R). In this form the parameter strength was also implemented to 1-R as a multiplier. Ranking of correlations was therefore made after the correlations had been evaluated against the available database.

For qualitative screening, performance plots were used. The performance plot is a graph of the predicted versus measured properties with a $45^o$ reference line to readily ascertain the correlation's fitness and accuracy. A perfect correlation would plot as a straight line with a slope of $45^o$.

## IV. RESULTS AND DISCUSSION

A novel correlation to estimate gas viscosity has been developed in this study using 483 data sets. Equations 8 through 11 are the gas viscosity models developed using Low - moderate - high pressure and temperature data points. The new model is a function of gas gravity, temperature, reduced pressure and reduced temperature.

$$\mu_g = \left(\frac{a_1}{10^4}\right) + \left(\frac{a_2}{10^4}\right)\gamma_g - \left(\frac{a_3}{10^7}\right)T \quad (8)$$



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where:

$$a_1 = 140.9 + 17.78T_r + 9.5726P_r + 4.1025P_rT_r \quad (9)$$

$$a_2 = 70.549 + 8.9042T_r + 4.7946P_r + 2.058P_rT_r \quad (10)$$

$$a_3 = 129.06 + 16.289T_r + 8.771P_r + 3.759P_rT_r \quad (11)$$

The developed empirical equation were assessed alongside laboratory data and published correlations to check their performance and degree of accuracy in approximating gas viscosity for the various gas reservoirs pressure temperature conditions. The published correlations evaluated are: [5], [4], [7], [2] and [9]. The statistical parameters such as percent relative error (MRE), percent absolute error (MAE), standard deviation relative error (SRE), standard deviation absolute error (SAE), correlation coefficient (R) and Rank were used to validate the new developed and some of the existing correlations. The results of the assessment as presented in Fig1. gives the statistical accuracies for all the gas viscosity models examined. From the Fig. 1, this study which is the model developed in this work ranked best with the numerical value of 4.3065, MAE of 6.1300 and correlation coefficient (R) of 0.8150, while [4] has MAE of 8.3741 and correlation coefficient of 0.6900 and rank of 6.1522 for the entire data set studied. [2] and [9] correlations gave a very high error margin which cannot be quantify and were not picked in the plot.

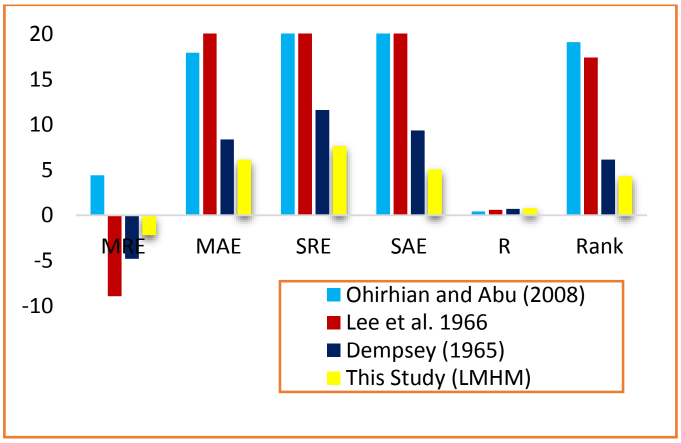


Fig. 1. Statistical Accuracy for Different Correlations using different gas viscosity correlations

Figs. 2 to 5 are performance plots of calculated and measured gas viscosity data. Comparing Fig. 4 to all other cross plots, it gave the closest cloud of points about the 45$^o$ line with very good clusters both at small to high region, indicating the good relationship for the laboratory and the predicted values.

[4] Equation (Fig. 3) gave a good prediction at lower to moderate region than [5] (Fig. 2) and [7] (Fig. 5) showing its capability to estimate gas viscosity from low to moderate pressure and temperature conditions. From Figs. 2, 3 and 5 it can be found that those correlations did not match measured data specifically at higher conditions, indicating the limitation of those equations basically in predicting gas viscosity at higher reservoir conditions. Therefore, the new developed correlation (Fig. 4) can estimate gas viscosity ranging from low - moderate - higher pressure temperature reservoir conditions.

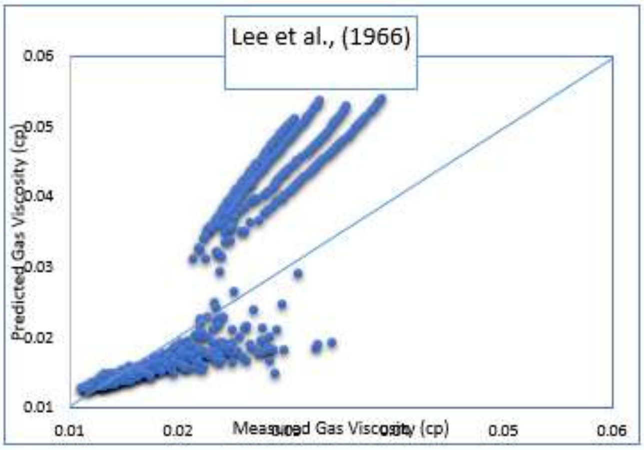


Fig. 2. Plot of predicted against measured gas viscosity for Lee *et al*., (1966)

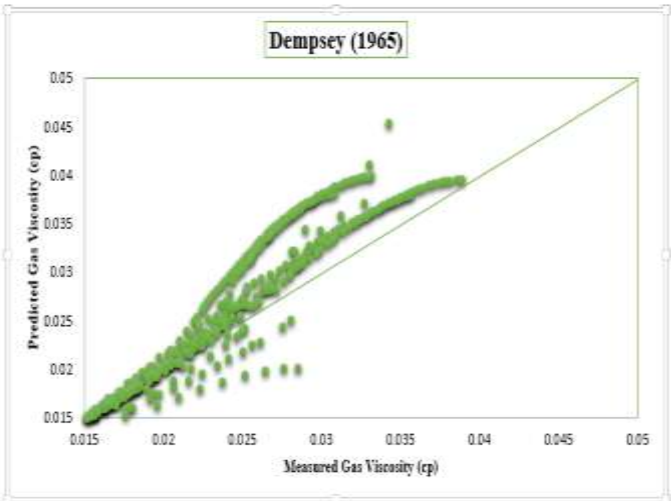


Fig. 3. Plot of predicted against measured gas viscosity for Dempsey (1965)

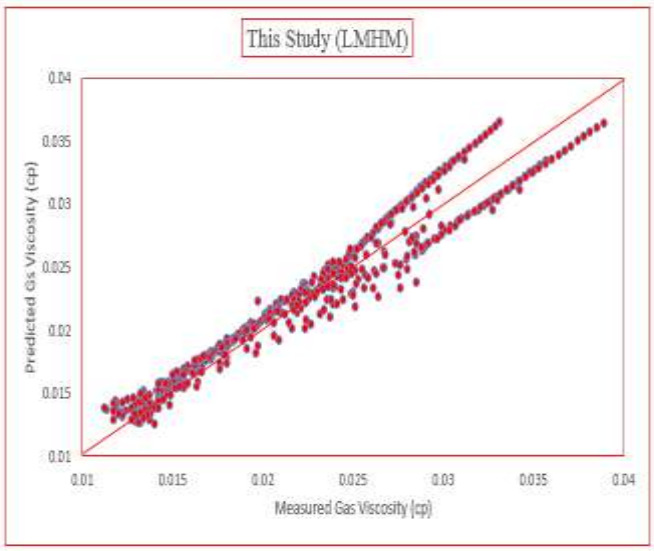


Fig. 4. Plot of Predicted against Measured gas viscosity for this Study



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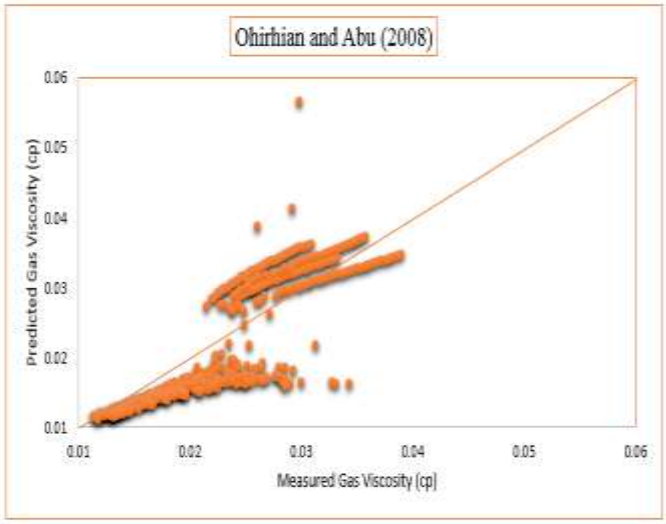


Fig. 5. Plot of predicted against measured gas viscosity for Ohirhian and Abu (2008)

## V. CONCLUSION

The gas viscosity is an extremely important parameter in gas engineering. It is useful to determine the gas density, gas compressibility and other reservoir fluid properties. New predictive tool was generated for computing gas viscosity for low- moderate -high pressure high temperature conditions. The correlations of gas z- factor accessible in the literature are not having a sufficiently wide collection of applicability for the accommodation of higher conditions, and so their accuracy may not be reliable in predicting this parameter. The new model outperformed the other correlations by the statistical parameters used. It also shows the best rank of 2.449 and better performance plot as compared to the existing empirical correlations. The model generated in this work is recommended for the computation of gas z – factor at extreme reservoir conditions with a very minor error.


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