American Journal of Engineering Research (AJER)
E-ISSN: 2320-0847 p-ISSN: 2320-0936
Volume-8, Issue-3, pp-177-187
www.ajer.org
Research Paper Open Access

Predictive Tool for High Pressure High Temperature Gas Viscosity

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ABSTRACT : *Viscosity of natural gas is an important parameter of theoretical and practical significance in the domain of natural gas recovery, transmission and processing. Small errors in gas viscosity affect the inflow performance relationship (IPR) curves and eventually changes the reserves estimate negatively for high pressure high temperature(HPHT) gas reservoirs.Majority of the exiting correlations give large errors at high gas reservoir pressure. The study centers on development of comprehensive model to predict natural gas viscosity at high pressure high temperature conditions.Microsoft Excel Solver was employed in building the model using 154 data set from Niger Delta region of Nigeria. Both quantitative and qualitative assessments were employed to evaluate the accuracy of the model to the existing empirical correlations. The new developed gas viscosity correlation gave good prediction when compared to other gas viscosity models with Mean Average Error of 3.4443, coefficient of correlation of 0.9556 and Rank of 2.004 which is acceptable for accurate engineering calculations. The statistical analysis and cross plots demonstrated the superiority of the proposed tool to other existing methods.*

KEYWORDS *-Correlation, high pressure, high temperature, Natural Gas, Viscosity*

Date of Submission: 23-02-2019 Date of acceptance: 13-03-2019

I. INTRODUCTION

Knowledge of pressure-volume-temperature (PVT) relationships and other physical and chemical properties of gases are essential for fluid characterization, gas reservoir performance calculations, and for the design of production systems in gas reservoir engineering. Of the most important gas reservoir property is gas viscosity which is our interest in this research paper.

Viscosity is a measure of a fluid's internal resistance to flow. The industry standard is to measure this property in the laboratory using reservoir samples. This experimental data is sometimes very expensive, and time consuming, hence methods such as correlations and equation of state are used to predict this property at reservoir pressure and temperature conditions [1].

Gas viscosity has been studied thoroughly by many authors such as [2], [3], [4], [5], [6], [7], [8], [9] at low – intermediate pressures and temperatures, yet there is still lack of detailed knowledge of gas viscosity for high pressures and high temperature (HPHT) in the oil and gas production. [2] 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 [10] 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. [2] 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. The computational procedure of applying the proposed correlations is summarized in the following steps:

Step 1:Calculate the pseudo-critical pressure, pseudo-critical temperature, and apparent molecular weight from the specific gravity or the composition of the natural gas. Corrections to these pseudocritical properties for the presence of the nonhydrocarbon gases (CO_2, N_2, and H_2S) should be made if they are present in concentrations greater than 5 mole percent.

Step 2: Obtain the viscosity of the natural gas at one atmosphere and the temperature of interest from Fig. 1. This viscosity, as denoted by μ_1, must be corrected for the presence of nonhydrocarbon components by using the inserts of Fig. 1. The nonhydrocarbon fractions tend to increase the viscosity of the gas phase. The effect of nonhydrocarbon components on the viscosity of the natural gas can be expressed mathematically by the following relationships:

$$\mu_1 = (\mu_1)_{uncorrected} + (\Delta\mu)_{CO_2} + (\Delta\mu)_{H_2S} \tag{1}$$

where:

μ_1 = "corrected" gas viscosity at one atmospheric pressure and reservoir temperature, cp
$(\Delta\mu)N_2$ = viscosity corrections due to the presence of N_2
$(\Delta\mu)CO_2$ = viscosity corrections due to the presence of CO_2
$(\Delta\mu)H_2S$ = viscosity corrections due to the presence of H_2S
(μ_1) uncorrected = uncorrected gas viscosity, cp

Step 3:Calculate the pseudo-reduced pressure and temperature.

Step 4: From the pseudo-reduced temperature and pressure, obtain the viscosity ratio (μ_g/μ_1) from Fig. 2. The term μ_g represents the viscosity of the gas at the required conditions.

Step 5:The gas viscosity, μ_g, at the pressure and temperature of interest is calculated by multiplying the viscosity at one atmosphere and system temperature, μ_1, by the viscosity ratio.

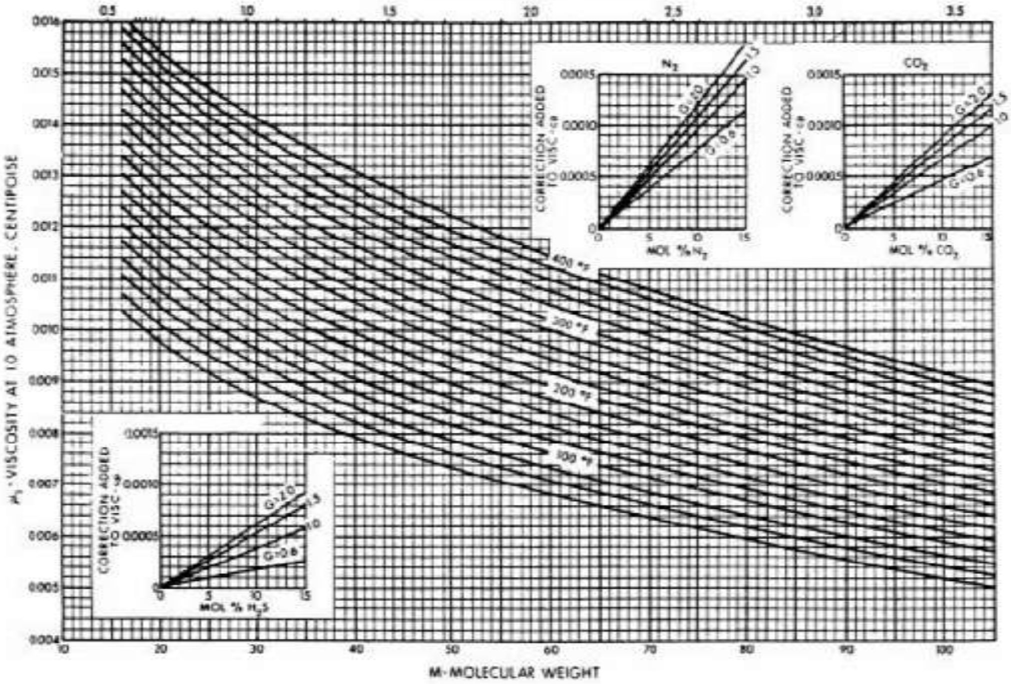

Fig. 1. Carr's Atmospheric Gas Viscosity Relationship. (copyright SPE-AIME)

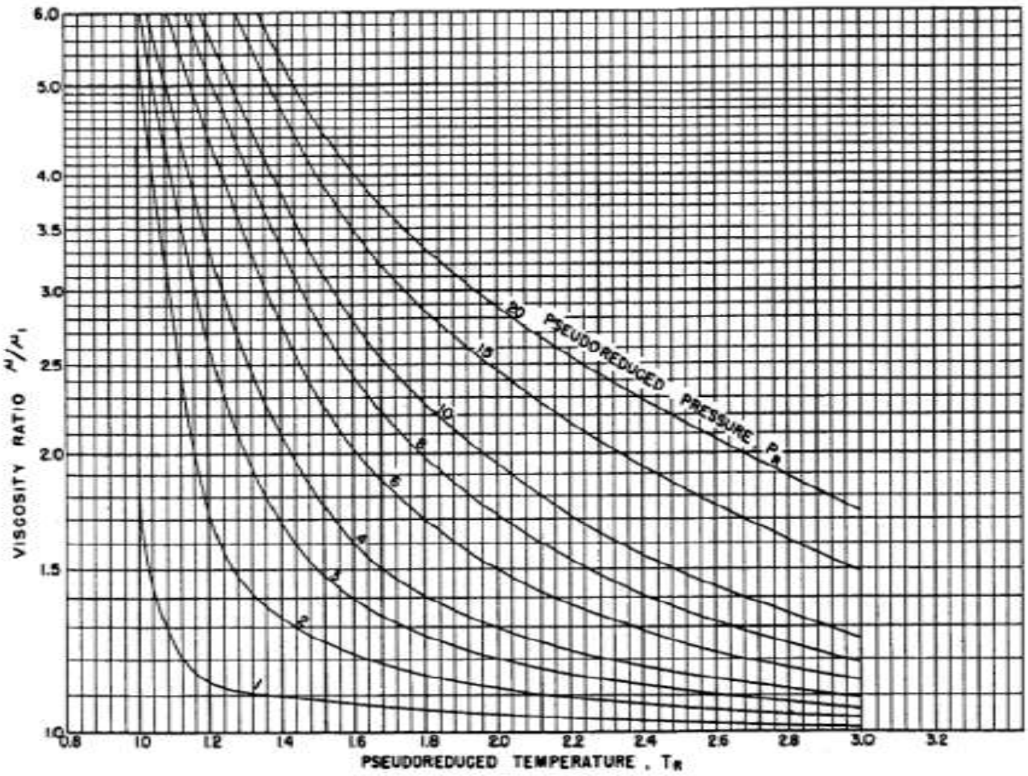

Fig. 2. Carr's Viscosity Ratio Correlation (SPEAIME)

[5] developed a models applying [2] data and acquired the following expressions which hold for the complete collection of [2] correlation.

$$\ln\left[T_{Pr}\left(\frac{\mu_g}{\mu_1}\right)\right] = a_0 + a_1 p_{Pr} + a_2 p_{Pr}^2 + a_3 p_{Pr}^3 + T_{Pr}(a_4 + a_5 p_{Pr} + a_6(p_{Pr}^2 + a_7 p_{Pr}^3)$$

$$+ T_{Pr}^2(a_8 + a_9 p_{Pr} + a_{10} p_{Pr}^2 + a_{11} p_{Pr}^3) + T_{Pr}^3(a_{12} + a_{13} p_{Pr} + a_{14} p_{Pr}^2 + a_{15} p_{Pr}^3) \quad (2)$$

$$\ln\left[\left(\frac{\mu_g}{\mu_1}\right)\right] = X \quad (3)$$

$$\frac{\mu_g}{\mu_1} = e^{(X)} \quad (4)$$

$$\mu_{g1} = \mu_1 * e^{(X)} \quad (5)$$

where:

$$(X) = \left(a_0 + a_1 p_{Pr} + a_2 p_{Pr}^2 + a_3 p_{Pr}^3 + T_{Pr}(a_4 + a_5 p_{Pr} + a_6(p_{Pr}^2 + a_7 p_{Pr}^3)\right.$$

$$\left.+ T_{Pr}^2(a_8 + a_9 p_{Pr} + a_{10} p_{Pr}^2 + a_{11} p_{Pr}^3) + T_{Pr}^3(a_{12} + a_{13} p_{Pr} + a_{14} p_{Pr}^2 + a_{15} p_{Pr}^3)\right)$$

T_r = Gas mixture pseudo-reduced temperature, °R
P_r = Gas mixture pseudo-reduced pressure, psia
$a_0 \ldots a_{17}$ = Equations constants are given below:

a_0 = -2.46211820, a_1 = 2.970547414, a_2 = -2.86264054 (10^{-1}), a_3 = 8.05420522 (10^{-3}), a_4 = 2.80860949, a_5 = -3.49803305, a_6 = 3.60373020 (10^{-1}), a_7 = -1.044324 (10^{-2}), a_8 = −7.93385648 (10^{-1}), a_9 = 1.39643306, a_{10} = -

1.49144925 (10^{-1}), a_{11} = 4.41015512 (10^{-3}),a_{12} = 8.39387178 (10^{-2}), a_{13} = -1.86408848 (10^{-1}), a_{14} = 2.03367881 (10^{-2}), a_{15} = -6.09579263 (10^{-4})

[6] 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. The developed correlation is given by

$$\mu_g = 10^{-4} K \exp\left[X \left(\frac{\rho_g}{62.4} \right)^Y \right] \quad (6)$$

$$k = \frac{(a_1 + a_2 M) T^c}{a_3 + a_4 M + T} \quad (7)$$

$$X(T) = a_5 + \frac{a_6}{T} + a_7 M_w \quad (8)$$

$$Y(T) = a_8 + a_9 X \quad (9)$$

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. [11] 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, [11] modified [6] 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 [6]. [11] modified the [6] correlation and the equation is presented as follows.

$$\mu_g = K \exp\left(X \rho_g^y \right) \quad (10)$$

$$K = \frac{0.0001(5.0512 - 0.2888 M) T^{1.832}}{-443.8 + 12.9 M + T} \quad (11)$$

where:

$$X = -6.1166 + [\frac{3084.9437}{T}] + 0.3938 M \quad (12)$$

$$Y = 0.5893 - 0.1563 X \quad (13)$$

[8] 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. The final equation for generating gas viscosity at high pressure was given as

$$\mu_g = \frac{0.0109388 - 0.0088234 X - 0.0075720 X^2}{1.0 - 1.3633077 X + 0.0461989 X^2} \quad (14)$$

where:

$$\mu_g = \text{Viscosity of gas at elevated pressure,(Cp)}$$

$$X = Rg / (100 Bg)$$

and

$$Rg = \frac{0.001031 PT}{P - 0.061T} \quad (15)$$

$$Bg = \frac{0.0283 zT}{P} \quad (16)$$

P = Pressure, (psia)

T = Temperature, (^oR)

[12] measured gas viscosity at high pressures and high temperatures (HPHT) using falling body viscometer. The experiments showed that [6] 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.[13] 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. [9] 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 [5] 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 [5] 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.

[14] 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, [15] 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 [8] 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 [5] 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. [3]and [11] 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 t0 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 at high pressure high temperature conditions. High Pressure High Temperature (HPHT) gas reservoirs are defined as reservoirs having pressure greater than 10,000 psia and temperature over 300^{o}F [12].

II. METHODOLOGY

2.1 Data Description

The 154 data points gotten from PVT reports were used in this research after the laboratory measurement of gas viscosity using natural gas samples from Niger Delta. Table 1 shows the minimum, maximum and mean values of the reservoir temperature, reservoir pressure, gas gravity, reduced temperature, reduced pressure and experimental gas viscosity values for the measured gas viscosity at 270^{o}F and 370^{o}F for the pressure of 6000 – 14000 Psia.

TABLE 1. Data Range for the Study of HPHT Gas Viscosity

Parameter	Minimum	Maximum	Mean
Reservoir Temperature (^oR)	730.0	830.0	780.0
Reservoir Pressure (Psia)	6014.7	14014.7	10323.51
Specific gravity	0.6056	1.1457	0.7356
Reduced Temperature	1.8732	2.12	2.00
Reduced Pressure	1.777	20.9122	15.4540
Experimental gas viscosity	0.0214	0.0388	0.0289
C_1	90.05	90.44	90.245
C_2	4.06	4.07	4.065
C_3	1.29	1.29	1.29
i-C_4	0.29	0.29	0.29
n-C_4	0.31	0.41	0.36
i-C_5	0.09	0.51	0.3
n-C_6	0.08	0.10	0.09
C_7^+	0.14	0.25	0.195
N_2	0.13	0.14	0.135
CO_2	3.00	3.21	3.105

2.2Correlation Development

2.2.1 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, pseudo-reduced temperature, pseudo-reduced pressure, gas gravity and gas density. 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 17.

$$GasVis\cos ity = f(P, T\gamma_g) + \varepsilon \qquad (17)$$

where: Gas viscosity is response or independent variable, P, T and γ_g are set of the influent or dependent variables and ε 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. Fig. 3 shows the flow chart used in building the correlation.

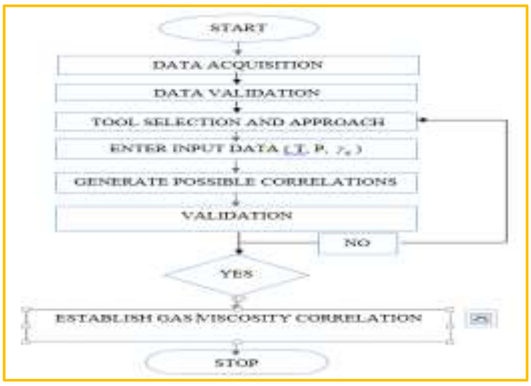

Fig. 3. Method of Generating Predictive tool for this Study

2.3Correlation 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 [17]. 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;

$$\mathbf{Min}\ Z_i = \sum_{j=1}^{m} S_{i,j} q_{i,j} \tag{18}$$

Subject to

$$\sum_{i=1}^{n} S_{i,j} \tag{19}$$

with

$$0 \leq S_{ij} \leq 1 \tag{20}$$

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-R) and Z_i is the rank, (or weight) of the desired correlation. The optimization model outlined in equations 18 to 20 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 20 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 18 to 20) 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.

III. RESULTS AND DISCUSSION

High pressure high temperature gas viscosity correlation was developed for predicting gas viscosity basically at extreme reservoir conditions i.e. at pressures above 10,000 psia and temperature above 300^{o}F. The newly developed equation for predicting gas viscosity at high pressure and high temperature conditions is given by equations 21 and 22. The developed correlation depends on, gas density (lb/ft^3), temperature (^{o}R), and pressure (Psia) and it is applicable to reduced temperature of 1.8 to 3.0 and reduced pressure of 10 to 20. The performance of the model was compared with the measured data and prediction from other empirical correlations such as [6], [8], [5], [3] and [11]. These predictive tools were carefully selected, having been developed specifically for the prediction of gas viscosity and some of which were recommended for the estimation of gas viscosity at HPHT condition in absence of HPHT equation.

$$\mu_g = 0.30887 - K\gamma_g \tag{21}$$

Where:

$$K = 0.416374 + 3.8*10^{-5}T - 2.0*10^{-6}P \tag{22}$$

The results of the assessment as presented in Fig. 4 gives the statistical accuracies for all the gas viscosity models examined. From the Fig. 4, HPHT model ranked best with MAE of 3.443 and correlation coefficient (R) of 0.955, while [6] has MAE of 48.2848 and correlation coefficient of 0.733 for the entire data set studied. [3]and [11] correlations gave a very high error margin which cannot be quantify and were not picked in the plot.

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Majority of the existing correlation evaluated using HPHT measured data showed a very large discrepancy, but the deviation associated with [5] correlation gave a better result as to compare with other evaluated equations with correlation coefficient of 0.84 and MAE of 16.27. Knowing that prediction of gas properties depends on its properties, HPHT model which is an equation developed in this research work has proved its reliability in forecasting gas viscosity therefore, this model is recommended to predict gas viscosity precisely at extreme conditions globally.

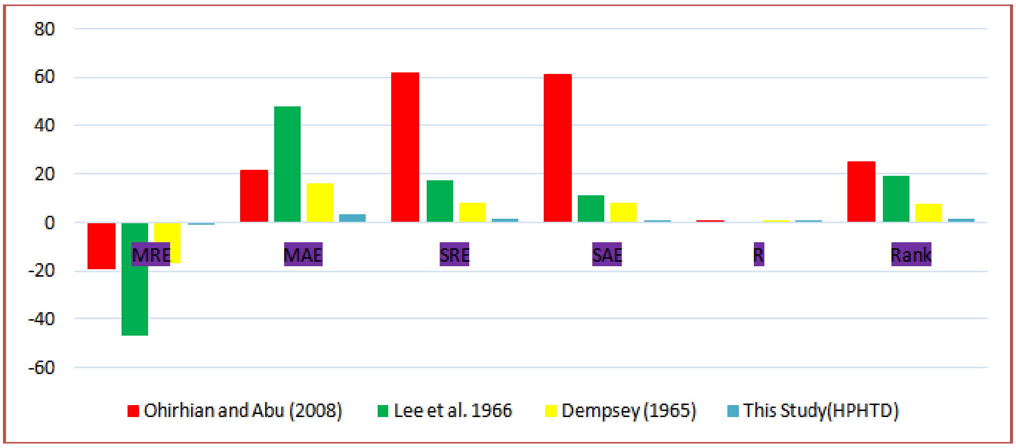

Fig. 4. Statistical Accuracy for Different Correlations Studied

Figs. 5 to 8 are the cross plots of measured and predicted gas viscosity using high pressure high temperature measured data. Fig. 8 gave the best performance plot when compared to Figs. 5 to 7. It can be observed that Figs. 5 to 7 overestimated the gas viscosity measured data at high pressure high temperature condition, showing that these correlations cannot comfortably be used in predicting this parameter at HPHT condition. The result shows the ability of the newly developed correlation in estimating gas viscosity for high pressure high temperature conditions.

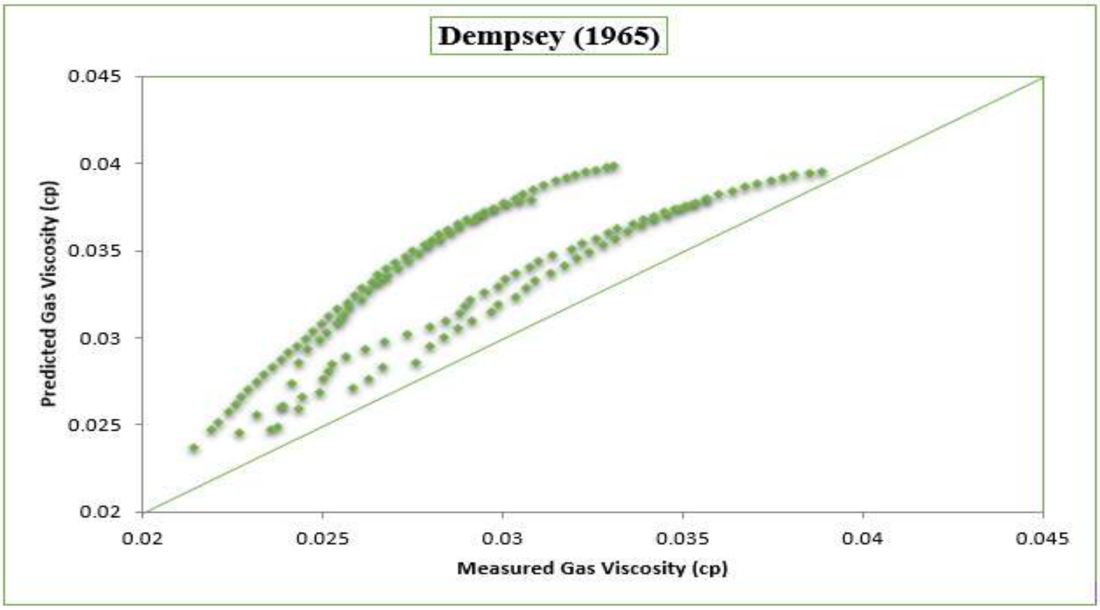

Fig. 5. Plot of predicted against measured gas viscosity for Dempsey (1973)

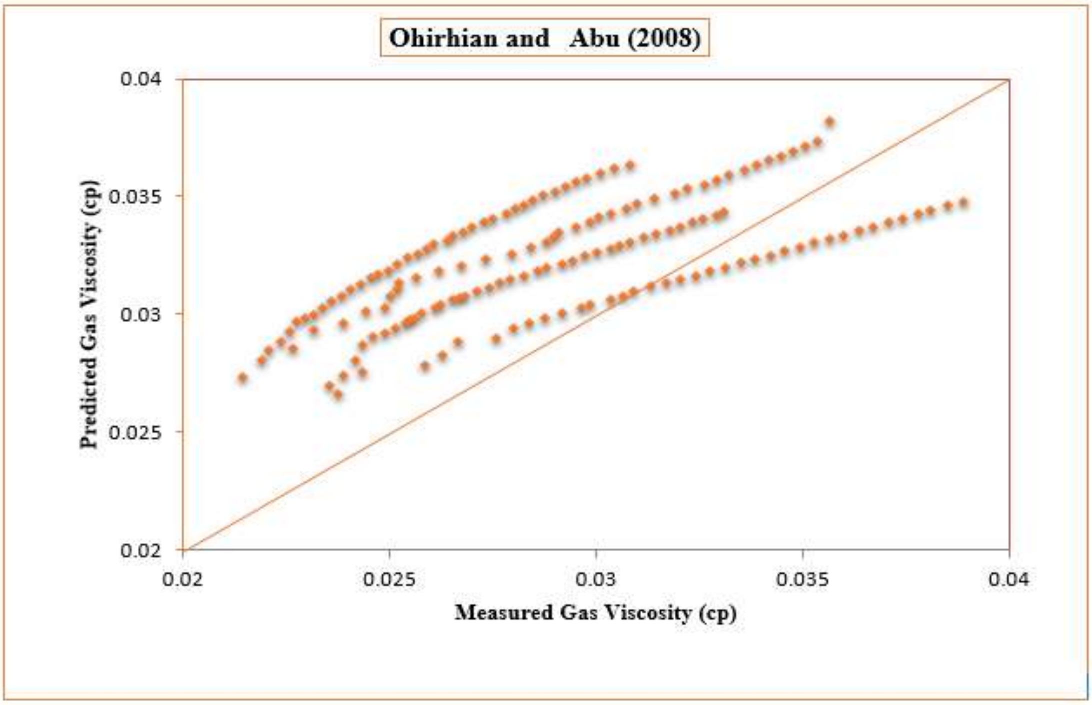

Fig. 6. Plot of predicted against measured gas viscosity for Ohirhian and Abu (2008)

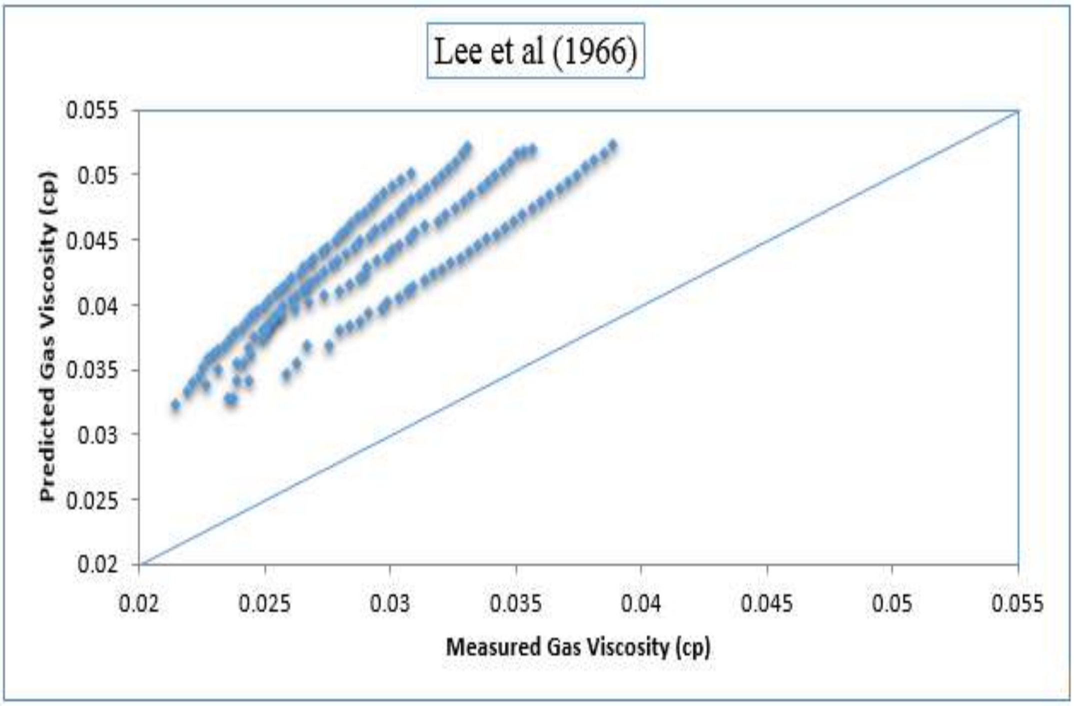

Fig. 7. Plot of predicted against measured gas viscosity for Lee et al (1966)

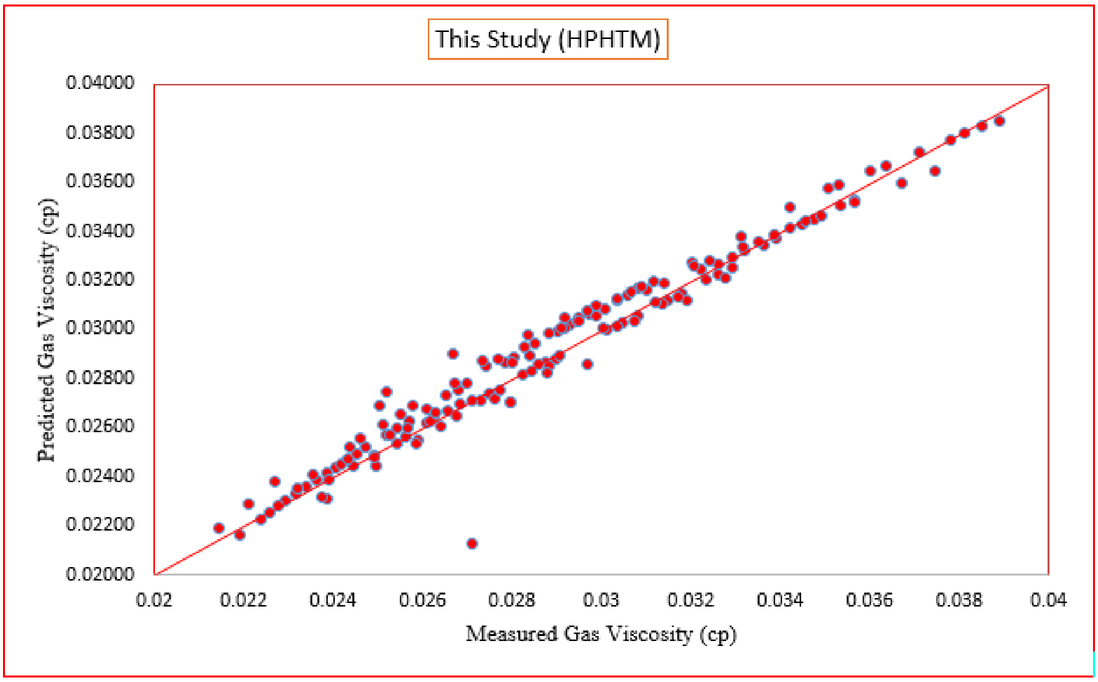

Fig. 8. Plot of Predicted against Measured Gas Viscosity for this study

IV. CONCLUSION

The study reports new mathematical equation to predict natural gas viscosity at high pressure and high temperature for a natural gas mixture from Niger Delta region of Nigeria. At these tremendous pressures and temperatures conditions, the exiting correlations give large error margin.The gas viscosity model developed in this work outperformed the other correlations by the statistical parameters used. It also shows the best rank of 2.004 and better performance plot as compared to the existing empirical correlations for those higher conditions where the data was used.

V. ACKNOWLEDGEMENTS

The authors would like to thank the sponsors of World Bank African Center of Excellence for Oil Field Chemicals Research for supporting this project and Laser Engineering and Consultant Resource Port Harcourt, Nigeria where the experiment was conducted.

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