American Journal of Engineering Research (AJER)
E-ISSN: 2320-0847 p-ISSN: 2320-0936
Volume-8, Issue-2, pp-149-157
www.ajer.org
Research Paper Open Access

Predictive Tool for Gas Compressibility Factor at High Pressure High Temperature

Ijeoma I. Azubuike[1], Sunday S. Ikiensikimama[2] andOyinkepreye D. Orodu[3]
[1]*World Bank African Center of Excellence for Oil Field Chemicals Research Institute of Petroleum Studies, University of Port-Harcourt, Petroleum Engineering, Nigeria.*
[2] *University of Port-Harcourt, Department of Petroleum Engineering, Nigeria.*
[3]*Covenants University, Department of Petroleum, Otta, Nigeria.*
Corresponding author: Ijeoma I. Azubuike

ABSTRACT : *Prediction of gas z-factor is required for fundamental petroleum engineering calculations that allow one to monitor the management of gas fields. This work focuses on the development of predictive tool for gas compressibility factor for high pressure high temperature gas reservoirs. Majority of the exiting correlations give large errors at high gas reservoir pressure. The 153 measured data of natural gas sample from Niger Delta region was regressed using Mat Lab. Statistical analysis and cross plots were used in the correlation comparison. The new correlation outperformed other evaluated models with a mean absolute error (MAE) of 0.9262, coefficient of correlation (R) of 0.996 and Rank of 0.8919. The model matched closely to the measured data with a good performance plot. The developed correlation is a function of gas density, reduced temperature, and reduced pressure and is valid for reduced temperature of 1.7 - 3.0 and reduced pressure of 10 - 20.*

KEYWORDS *-Correlation, High pressure, High temperature, Gas Compressibility factor, Natural Gas.*

Date of Submission: 03-02-2019 Date of acceptance: 19-02-2019

I. INTRODUCTION

Natural gas as a global energy source has been gaining broader usage in recent years [1]. Natural gas utilization has become an interesting topic because of significant growth of energy demand globally.Thus, natural gas is a promising energy alternative due to its availability and having similar property to petroleum [1]. As the exploration of this resource continues, it is highly essential to understand the condition and physical properties of the reservoir because they constitute a vital part of the data required for the comprehensive knowledge and understanding of reservoirs system. These reservoir data also aid in accurate calculation of gas recovery and optimum production systems design. The estimation of reserves and the design of these equipment are obtainable when reservoir fluid (oil, condensate or gas) properties are available [2].

Gas compressibility factor is a useful thermodynamic property of a reservoir fluid that modifies the ideal gas law to account for behavior of real gases. The industry standard is to measure this property in the laboratory using reservoir samples. The procedures of acquiring experimental data are 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 [2].

Prior to 1960s, natural gas reservoirs targeted for search and development were less than 15,000 ft, pressure less than 10,000 psia and temperature less than 300^{o}F ([3], [4], [5]). Majority of these natural gas resources show normal pore pressure and temperature gradients. The growing demand for natural gas is driving the petroleum industry to look for new resources in previously unexplored and deeper areas, where High-Pressure and High- Temperature (HPHT) reservoirs may be encountered [4].

High Pressure High Temperature (HPHT) gas reservoirs are defined as reservoirs having pressure greater than 10,000 psia and temperature over 300^{o}F [4]. Recently, some researchers ([4]. [6] [5], [7]) has reported that at higher pressures and temperature, majority of the popular gas compressibility factor models such as ([8], [9], [10]) gave more than 100% error.

Several well-known correlations are used in the petroleum industry to determine the values of gas z-factor. Some of these available mathematical equations in literature are ([8], [9], [11], [5], [7], [12], [13]). [3] shows the experimental capacities of gas deviation factor for HPHT conditions prevailing in reservoir. They measured gas density and z-factor for numerous dry gas sample at pressures to 20,000psia and temperatures of 300^{o}F and 400^{o}F. Laboratory data was used for evaluation with other existing correlation like [9] and [11] and mathematical model for generating pseudocritical properties. [11] with [14] outperformed [11] for the entire data studied. The correlations studied overestimated the z- factor for HPHT conditions.

[15] evaluated some selected gas deviation factor correlation using Niger-Delta data. The data comprise of 513 values acquired from gas reservoirs in Niger-Delta of Nigeria. Data employed for the analysis lies within the following range of reduced temperature and pressure of $0.5796 \leq T_r \leq 1.758$ and $0.410 \leq Pr \leq 8.985$ respectively. [10] has the best performance with rank of 2.82, an absolute percentage error (E_a) of 3.234 and the finest performance plot. They recommended [10] where experimental PVT data is limited.

[16] developed a mathematical model using viral equation of state. The formulated model is valid within the range of $1.01 \leq T_r \leq 3$ and $0.01 \leq P_r \leq 15$. The developed model was divided based on pressure region into two sections resulting to two sets of coefficients for $0.01 \leq P_r \leq 3$ and $3 \leq P_r \leq 15$. The authors reported that the developed model performed better than other correlation evaluated within the data range used.

[5] developed a newer and simpler correlation using 300 data points (via linear regression function) that can predict gas z - factor at any region. The approach returned an error less than 3% associated to laboratory data. [7] also developed a model via Fourier series expansion using over 6000 data points prepared by careful laboratory measurements of natural gas mixtures and the result was found to match accuracy, without over fitting. [12] generated an equation for computing z – factor using least square support vector machine (LSSVM). 2200 data comprising of sour and sweet gas samples mixture was utilized in building the model. The maximum pressure of 11,000 pisa and temperature of 441.80 ^{o}K was used to obtain the new z – factor correlation. The calculated z – factor values from the new established model did better than other correlations studied with absolute relative error of 0.19% and correlation of 0.999.

[13] developed a z-factor chart using [10] z -factor equation. 359 validated data of Niger Delta region were used in building the z-factor chart. The authors validated their new chart with [8] and observed that their chart performed well as long as the pseudo-reduced properties are within the specified range of reduced properties. The z-factor chart performed best at pseudo reduced properties ranges between $1.40 < T_r < 1.90$ and $0.198 < P_r < 10.8$. [17] developed a new z- factor correlation for the Niger Delta gas reservoirs. The correlation was developed using Microsoft Excel Analysis Tool and SPSS statistical software using 300 data points from the PVT analyses of 14 fluid samples from Niger Delta. The developed correlation was compared to the best performing correlations with some of the statistical parameters like percent mean relative error, percent mean absolute relative error, standard deviation and correlation coefficient. The developed correlation was found to outperform other existing correlations. The model is valid for pseudo reduced properties ranges between $1.10 < T_r < 1.65$ and $0.68 < P_r < 8.2$.

Recently, [18] did an evaluation work for gas compressibility factor for high pressure high temperature reservoir conditions. Experiments were conducted to measure gas density and z-factor for two samples of gas mixture at high pressure of 6000psig to 14000psig and temperatures 270^{o}F and 370^{o}F. It was found from their evaluation work that majority of the existing z-factor correlations cannot be used to predict z-factor at high pressure and high temperature region. Based on the result of the measured data, some of the selected correlations performed well within certain pressure range and show a high deviation at high pressure region. The authors concluded by recommending the development of new predictive tool for gas z- factor at high pressure and temperature for a good reservoir performance.

Presently, [8] is still the correlation used widely by the petroleum industry to determine the natural gas compressibility factor. Unfortunately, the range of pressure and temperature conditions represented by the data used to generate the standing and Katz correlation are not typical of those conditions encountered in deep natural gas reservoirs. Improvements to the [8] correlation as well as extensions to higher pressures and temperatures have been made using mathematical models or equations of state (EOS), unfortunately, the [11] EOSs was matched to the same data base used to generate the [8] correlations. The [9] model was not only matched to the [8] data, but was also tested against a limited set of additional data from twelve natural gas reservoirs that do not represent extreme pressure and temperature conditions. Also, these models were not compared to actual measured data to validate the new proposed correlations to estimate gas compressibility factor.

Modeling the performance of these unconventional reservoirs requires the understanding of gas reservoir behavior at elevated pressure and temperature. Therefore, this paper presents the development of a predictive tool for gas compressibility factor for higher pressures high temperatures reservoir conditions.

II. METHODOLOGY

The research was done entirely at Laser Engineering and Resources Consultant Limited located at Port Harcourt City in Rivers State. The equipment and procedures were considered to account for both high-pressure and high-temperature (HPHT) conditions and the corrosive environments caused by non-hydrocarbon contaminants such as Carbon dioxide (CO_2), and Hydrogen Sulfide (H_2S). The gas compressibility laboratory measurement procedures can be found in [18].

2.1.1 Data Description and Analysis

During the laboratory measurement of gas compressibility factor, 153 data points were obtained. Table 1 shows the minimum, maximum and mean values of the reservoir temperature, pressure, density, reduced temperature, reduced pressure and experimental z-factor values for the experimental z- factor measured at 270°F and 370°F for the pressures of 6000 to 13200]]Pisa. This data was used to develop and evaluate some of the selected existing gas z- factor correlations.

Parameter	**Minimum**	**Maximum**	**Mean**
Reservoir Temperature (°R)	730.0	830	780
Reservoir Pressure (Psia)	6014.7	13214.7	10130.25
Specific gravity	0.6536	0.8228	0.7549
Reduced Temperature	1.712	2.019	1.848
Reduced Pressure	9.7	20.11	15.227
C_1	90.05	90.44	90.245
C_2	4.06	4.07	4.065
C_3	1.29	1.29	1.29
$i\text{-}C_4$	0.29	0.29	0.29
$n\text{-}C_4$	0.31	0.41	0.36
$i\text{-}C_5$	0.09	0.51	0.3
$n\text{-}C_6$	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

TABLE 1. Data Range for the Study of HPHT Z-factor

2 .2 Correlation 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 on the gas z-factor. The formulation of problem involves identifying the dependable and independent parameters. Gas compressibility factor 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 [19]. The general relationship for z-factor with its dependent variable is given in equation 1;

$$Z\ Factor = f(P_r, T_r \gamma_g) + \varepsilon \qquad (1)$$

where: Gas z-factor is response or independent variable, P_r, T_r, 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. 1. shows the flow chart used in building the correlation.

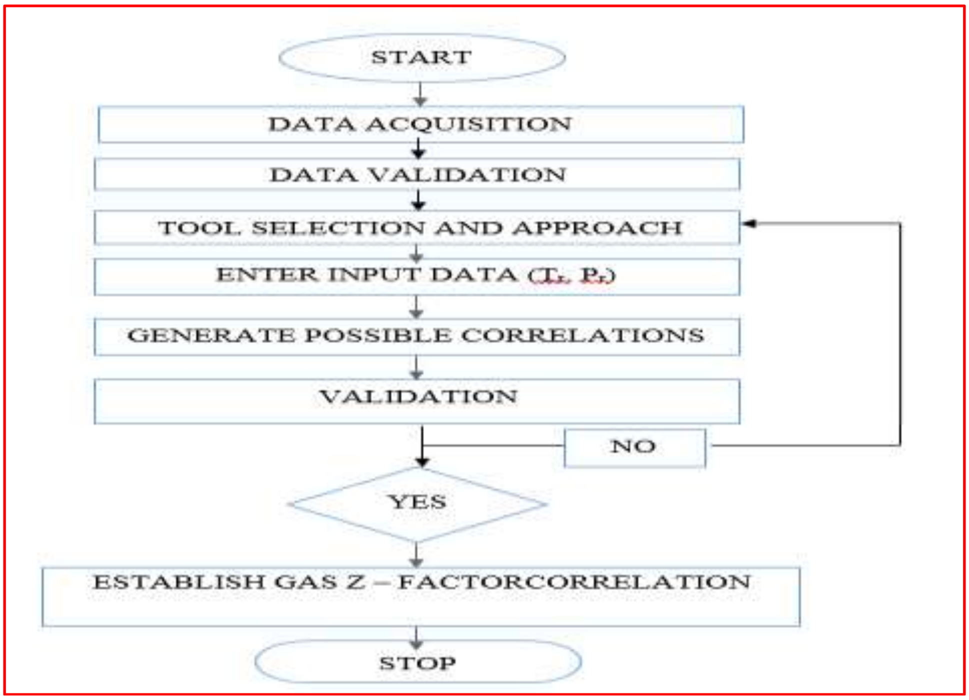

Fig. 1 method of generating predictive tool for this study

2.3 Correlation Comparison

2.3.1 Ranking Method

In order not to depend on just one statistical parameter when choosing the most accurate correlation, ranking method is applied and is a one-point estimator that brings the statistical parameters together. This approach integrate the following statistical parameters like average relative error, average absolute error, relative standard deviation error, absolute standard deviation error and correlation coefficient. The method is known Multiple Statistical Optimization Model (MULSOM) applying the Rank as a single point selection criterion. The relationship among other statistical parameters can be obtained as a constraint optimization problem with the objective function given in equation 2;

$$Min\ Z_i = \sum_{j=1}^{m} S_{i,j} q_{i,j} \qquad (2)$$

Subject to

$$\sum_{i=1}^{n} S_{i,j} = 1, \tag{3}$$

with

$$0 \le S_{i,j} \le 1, \tag{4}$$

Where, $S_{i,j}$is the strength of the statistical parameter j of correlation i and $q_{i,j}$the statistical parameter j corresponding to correlation i.j = MRE, MAE ...... R_1, where $R_1 = 1 - R$, Z_i gives the rank or weightiness of the accepted model and i is the number of model for each fluid property.

The following values were assigned to the statistical parameter used: Mean Relative Error (MRE) = 0.1, Mean Absolute Error (MAE) = 0.4, Correlation Coefficient (R) = 0.2, Standard Deviation Relative Error (SRE) = 0.15, Standard Deviation Absolute Error (SAE) = 0.15 [19].

2.3.1 Graphical Analysis (Use of Cross Plot)

To further determine the equation's suitability and correctness, cross plots are used. It is a graph of calculated versus experimental values to 45° reference line. A perfect correlation would plot as a straight line with a slope of 45°. The visual examination of these cross plots would give a basis for compromise where necessary; especially where statistical results might be misleading.

III. RESULTS AND DISCUSSION

High pressure and high temperature gas deviation factor model (HPHTM) was developed using 153 laboratory measured data. The correlation was acquired by fitting the data through non-linear regression function and the following correlation was obtained (equations 5-7);

$$z = 0.74375 + ab - 0.00743\, T_r P_r \tag{5}$$

$$a = 0.15614\, P_r - 0.78748\, T_r + 0.3366\, T_r^2 \tag{6}$$

$$b = \frac{\gamma_g}{T_r} \tag{7}$$

Predicting gas z - factor can be achieved by combing equations 5 to 7. The developed correlation depends on, gas density, reduced temperature, and reduced pressure. The applicability of this model is valid for reduced temperature of 1.7 - 3.0 and reduced pressure of 10 - 20.

Statistical accuracy and ranking for the different correlations studied are giving in Figure 2. High pressure high temperature (HPHT) model performed better than other correlations studied with a rank of 0.8919, mean absolute relative error of 0.9262 and correlation coefficient of 0.996; followed by [11]), with the rank of 3.103, MAE of 4.898 and correlation coefficient of 0.924. The excellent performance of HPHT Model is expected since the equation was specifically developed for high pressure and temperature gas reservoir conditions.[10] ranked third with a numerical value of 3.486, MAE of 5.367 and correlation coefficient of 0.91.

The good performance of [11]among the correlations studied agreed with the report given by [3] and [5]however, the computational procedure used for their assessment involves iteration. The performance of [5] and [9]correlations were not very impressive compared to the other in terms of statistical measures (Table 2). This trend is expected since these correlations were developed using low to moderate pressure and temperature data and therefore, cannot be used in predicting gas compressibility factor at HPHT reservoir conditions.

TABLE 2: Statistical Accuracy of Gas Compressibility Factor using HPHT Data

Correlations	%MRE	%MAE	%SRE	%SAE	R	Rank
Hall and Yarborough (1973)	-79.722	79.722	19.264	19.264	0.8030	29.856
Mahmoud (2013)	-30.860	31.010	19.880	19.650	0.9100	15.429
Beggs and Brill (1973)	-3.8090	5.3670	5.8250	4.4305	0.9100	3.4862
Dranchuk et al (1974)	-2.1390	4.8980	5.1499	2.6679	0.9248	3.1029
This Study	-0.1535	0.9262	1.3109	0.94	0.9959	0.8919

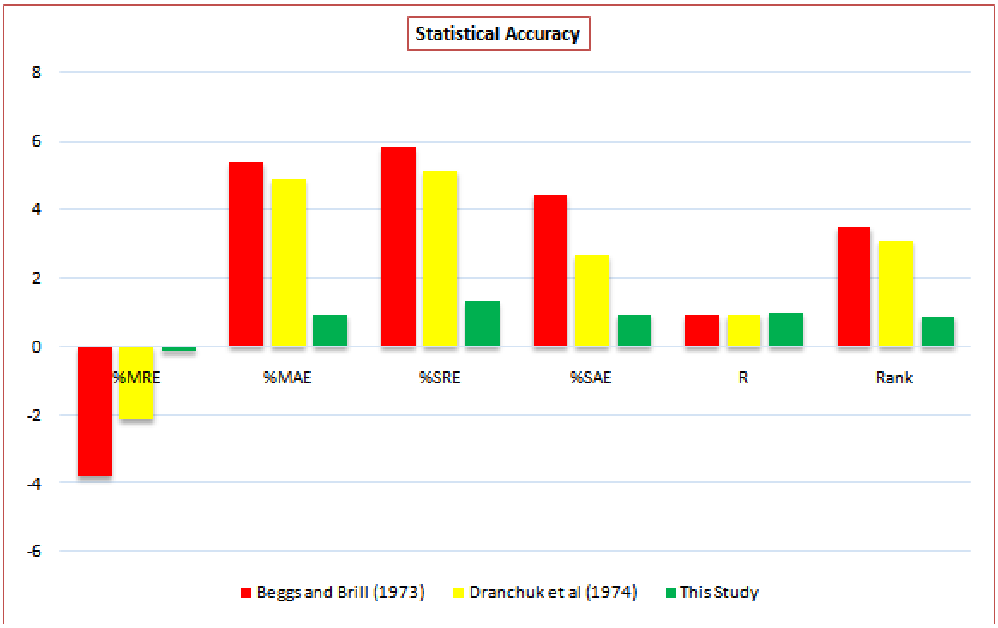

Fig. 2 statistical accuracy for different correlations studied

Figs. 3 to 7 illustrate cross plots of the calculated versus experimental gas z - factor using high pressure high temperature data for all the correlations studied ([10],[11],[9],[5]) and in addition to the correlations developed in this study.

Comparing to other cross plots,Fig. 3 indicated the close-fitting of calculated and experimental measured and values about the 45^{o} line with very good clusters, showing the excellent agreement between the laboratory and the calculated data values. Fig.3 shows the HPHT model with excellent cross performance plot, and this gives an indication of the capability of this model in predicting gas deviation factor for extreme reservoir temperature and pressure conditions.

The cross plots for [5]and [9](Figs. 5 and 6) show over prediction of the laboratory data of the gas compressibility factor for extreme conditions.

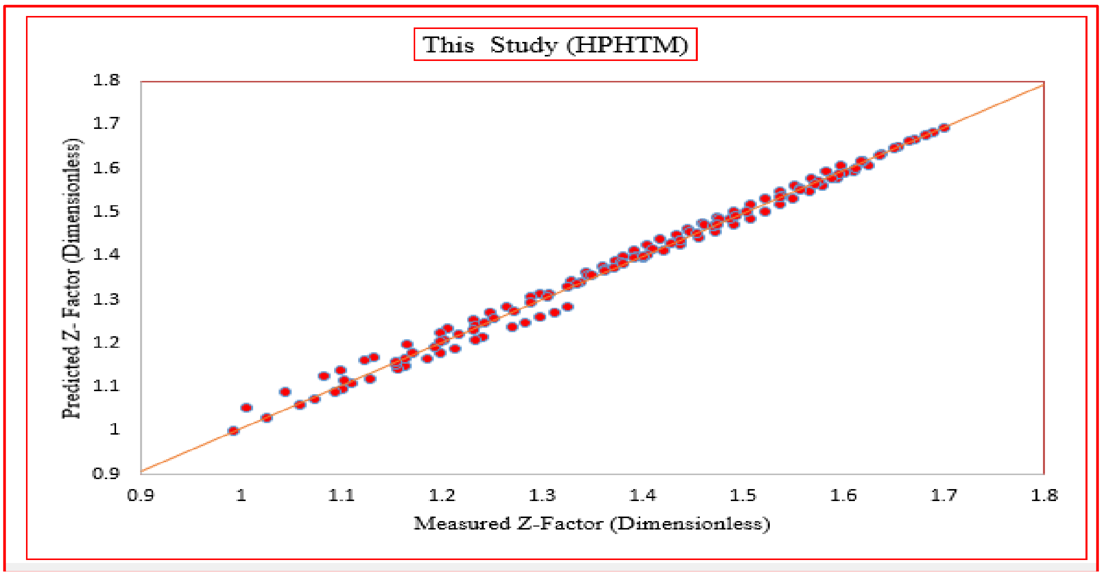

Fig. 3 plot of predicted against measured compressibility factor for this study

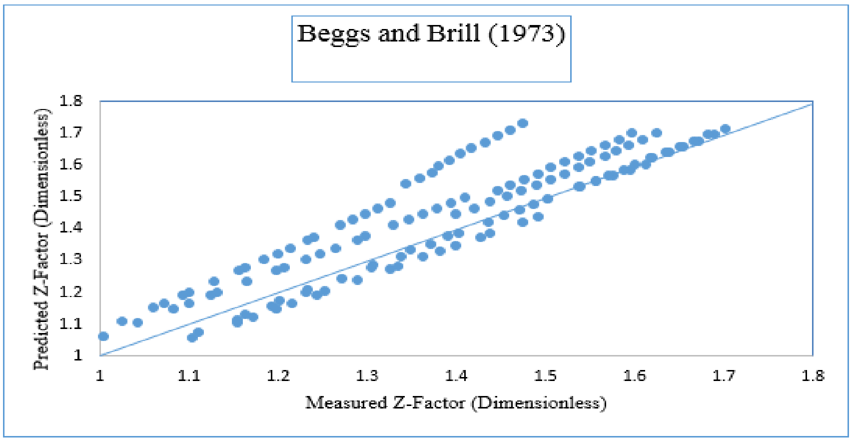

Fig. 4 plot of predicted against measured compressibility factor for Beggsand Brill (1973)

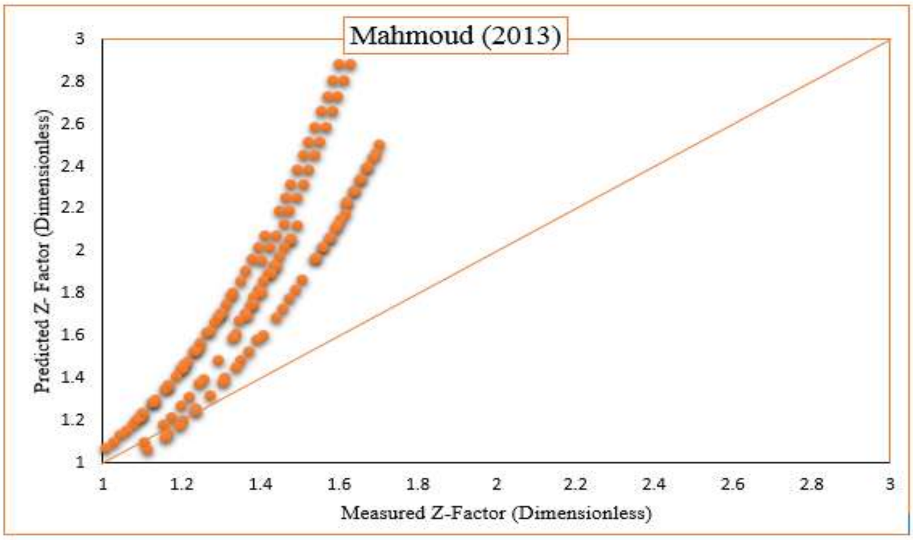

Fig. 5 plot of predicted against measured compressibility factor for Mahmoud (2013)

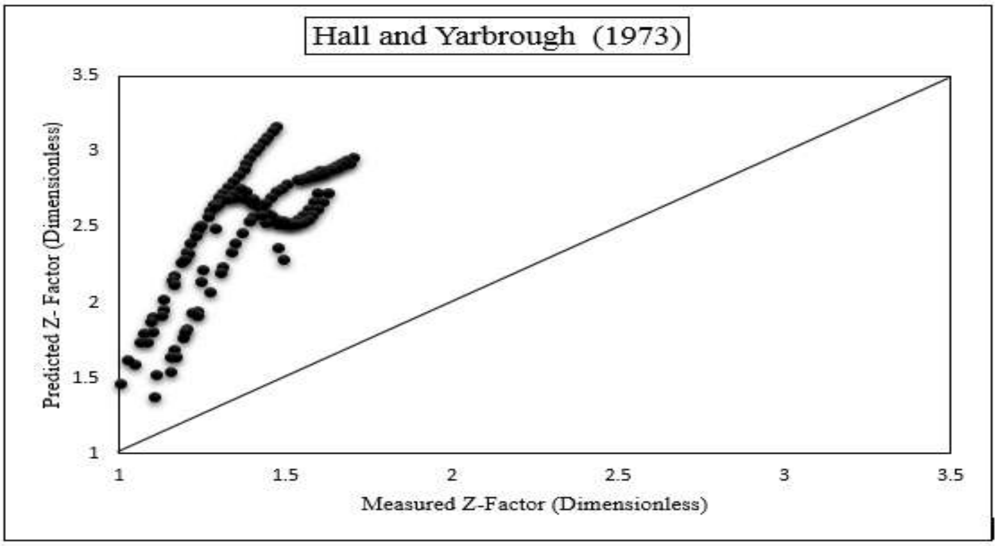

Fig. 6 plot of predicted against measured compressibility factor for Hall and Yarbrough (1973)

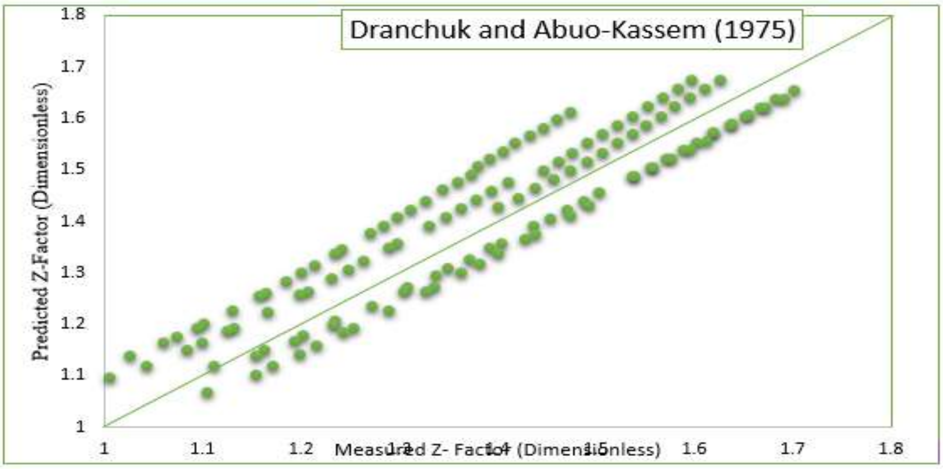

Fig. 7 plot of predicted against measured compressibility factor for Dranchuk and Abuo-kassem (1975)]

IV. CASE STUDY FOR GAS Z - FACTOR

The predictive capacity of the developed correlation was compared to measured data from [3]which was not included in the building of the model. The z – factor was calculated for the two different gas samples (Table 3). The compressibility factor was calculated using reservoir pressure of 13,200psia and temperature of 760^{o}R. The gas samples are having the critical pressure of 668.5psia and temperature of 352.73^{o}R for Sample- 1 and 749psia and 392 ^{o}R for Sample- 2 when calculated using data from Table 3. Fig. 8 shows the accurateness of the predictive tool with the two best behaved models in predicting z – factor at high pressure high temperature gas system. HPHT model exhibited a good result as compared to other correlations evaluated with the MAE of 1.06682 for the first sample- 1 and 1.03673 for sample- 2.

[3] and[12] reported that [11]can closely estimate gas z-factor at high pressure high temperature but the method requires an iterative procedures which may even offer different answer subject to the initial guess. Therefore, HPHT model generated in this work is recommended, which can compute gas z- factor with minimal error at extreme reservoir conditions.

TABLE 3. Gas Composition for the Samples used in calculating Z- factor (Rushing et al. 2008)

Composition	Critical Pressure, Psia	Critical Temperature, ^{o}R	Sample-1	Sample- 2
CH_4	667.8	343.33	0.96	0.768
C_2H_6	707.8	549.20	0.03	0.024
C_3H_8	616.3	666.06	0.01	0.008
CO_2	1071	547.6	0.00	0.200

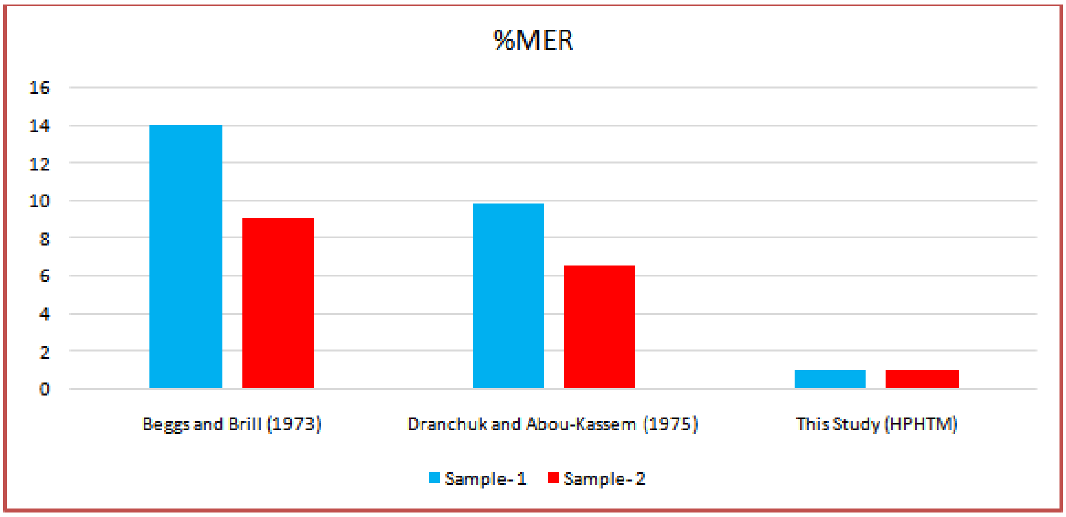

Fig. 8 accuracy of the proposed correlation for case study samples-1 and -2

V. CONCLUSION

The gas deviation factor is an extremely important parameter in gas engineering. It is useful to determine the gas density, gas viscosity, gas compressibility and other reservoir fluid properties. New predictive tool was generated for computing gas compressibility factor at 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 extreme 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. HPHT model generated in this work is recommended for the computation of gas z – factor at extreme reservoir conditions with a very minor error.

VI. 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.

REFERENCE

[1]. O. M Anyiador,S. S. Ikiensikimama, and I. I Azubuike, Evaluation of Viscosity Correlation for Niger Delta Gas Reservoir, International Journal of Science and Engineering Investigations, Vol 4, Issue 46, ISSN: 2251-8843.2015.

[2]. T. Ahmed, reservoir engineering hand book(Copyright, Elsevier Inc. Gulf Publishing, 30 Corporate Drive. Suite 400. Burlington, MA 01803, USA,2006)

[3]. J. A. Rushing, K. E. Newshan, S. A. Van Fraassen, Mehta, andG. R Moore. Natural Gas Z-Factors at HP/HT Conditions: Comparing Laboratory Measurements with Industry-Standard Correlations for a Dry Gas. SPE-114518.2008.

[4]. K. Ling, E. C.Davani, Teodoriu, J. McCain and G. Falcone G. Measurement of Gas Viscosity at High Pressures and High Temperatures.International Petroleum Technology Conference held in Doha, Qatar, IPTC 13528,2009.

[5]. M. A. Mahmoud, Development of a new correlation of Gas Compressibility Factor for High Pressure Gas Reservoirs, SPE paper 164587 presented at the North Africa Technical Conference and Exhibition held in Cairo, Egypt.(2013):

[6]. E. Davani, K. Ling, C.Teodoriu, J. McCain and G. Falcone. Inaccurate Gas Viscosity at HP/HT Conditions and its Effects on Unconventional Gas Reserves Estimation, SPE 122827.2009.

[7]. A. K LateefExplicit Half Range Fourier Series Expansion For Z factor, SPE Paper 167579 presented at Nigeria Annual International Conference and Exhibition held in Lagos, Nigeria, 2014

[8]. M. B Standing. andD. L. Katz. (): Density of Natural Gases, Trans. AIME, Vol. 146, 1942. pp 140-149.

[9]. K. R Hall, and L. J. Yarborough. “A new equation-of-State for Z-factor Calculations” Oil and Gas Journal, 1973pp 82-92

[10]. H. Beggs, andJ. Brill. Two-phase flow in Pipes, Tusla, OK; The University of Tusla.1973

[11]. Dranchuk, P. M. and Abu-Kassem, J. H. (1975): “Calculation of Z-factors for Natural Gases Using Equation-of-State”, Journal of Canadian Petroleum Technology, pp 34-36

[12]. Fayazi, A., Arabioo, M. and Mohammadi, A. H. (2014): “Efficient Estimation of Natural Gas Compressibility Factor Using a Rigorous Method” Journal of Natural Gas Science and Engineering, vol. 16, pp. 8-17.

[13]. Elechi V. U. Ikiensikimama S. S. and Azubuike, I. I. “A Correlation for estimating Gas Compressibility Factor in the Niger Delta”, Festschrift for J. A. Ajienka, pp. 137-148. 2015.

[14]. Sutton, R. P. (2005): “Fundamental PVT Calculations for associated and Gas/Condensate Natural Gas System,” Paper SPE 97099 presented at the 2005 SPE Annual Technical Conference and Exhibition held in Dallas, Texas, USA.

[15]. Olajide, O. F. and Ikiensikimama, S. S. (2010): “Evaluation of Compressibility Factor Correlations for Niger Delta Gas Reservoirs”. Paper SPE 136967, presented at the 34th Annual SPE International Conference and Exhibition.

[16]. Sanjari, E., Nemati, L. and Peymani, M. (2012): “An Accurate Empircal Correlation for Predicting Natural Gas Viscosity”, J. Nat. Gas, Chem, Vol. 20, Pp. 654-658.

[17]. Mounagor, C. M. and Ikiensikimama, S. S. (2016): “Compressibility Factor Correlation for the Niger Delta Gas”. SPE-184287.

[18]. Azubuike, I. I., Ikiensikimama, S. S. and Orodu, O. D. Natural Gas Compressibility Factor Measurement and evaluation for high pressure high temperature gas reservoirs international journal of scientific & engineering research, volume 7, issue 7. july-2016issn 2229-5518

[19]. Ikensikimama, S. S. (2009): “Reservoir Fluid Property Correlations” Advances in Petroleum Engineering, Chi Ikoku Petroleum Engineering Series, IPS Publications, Port Harcourt.

Ijeoma I. Azubuike" Predictive Tool for Gas Compressibility Factor at High Pressure High Temperature" American Journal of Engineering Research (AJER), vol.8, no.02, 2019, pp.149-157