MODEL FOR PREDICTING DENSITY AND VISCOSITY OF CO_2 FOR ENHANCED GAS RECOVERY AND CARBON SEQUESTRATION IN DEPLETED GAS RESERVOIR. A CASE STUDY OF NIGER-DELTA FORMATION

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Abstract

In response to United Nations Paris Agreement of 2050 Carbon Neutrality Goal and in compliance with Kyoto Protocol on Clean Development Mechanism (CDM), all hands must be on deck to achieve these goals, including Niger-Delta region of Nigeria. No mathematical correlation in place for predicting density and viscosity of supercritical carbon-dioxide (CO_2), necessary for Enhanced Gas Recovery - Carbon Sequestration (EGR-CS) operation in Niger-Delta Formation (NDF). Three categories of mathematical correlations were developed by Split Regression Analytical method (SRA) and validated using Equation of State Models (EOS-M) for predicting density and viscosity of pure carbon-dioxide under supercritical conditions as expected in (EGR-CS) operation. The models ranges from reservoir depths of 1000-1500m, 1600-5000m and beyond 5000m for both density and viscosity, which are ideal for carbon sequestration and covers depths of most gas reservoirs in Niger-Delta. The new "NDF-Model" matched with Peng Robinson and Soave-Redlich-Kwong Equation of States (EOS) at the tested reservoir conditions, with low Absolute Average Deviation (AAD). Application of these models on four depleted gas reservoirs (Res.1, Res.2, Res.3 & Res.4) in Niger-Delta Formation (NDF) shows encouraging Relative Density Difference (RDD) and Relative Viscosity Difference (RVD). CO_2 densities at those depths ranges from 0.5 - 0.6 g/cm^3, 0.6 - 0.7g/cm^3 and 0.7 -0.8g/cm^3 respectively while the viscosities ranges from 0.05 - 0.06cP, 0.06 - 0.07cP and 0.07 - 0.08cP respectively, which promises smoother displacement of natural gas by CO_2 during Enhanced Gas Recovery.

Key Words: Model, Density, Viscosity, Enhanced Gas Recovery, CO_2 sequestration, Equation of state.

1.0 INTRODUCTION

Oil exploration activity has gained prominence in Niger-Delta, Nigeria for over 60 years. This has enabled the accumulation of thousands of informative reservoir data including temperature and pressure from well logs and other source. Long time production over these years has led to depletion and abandonment of most reservoirs in Niger-Delta and on that context, many are today termed marginal fields. CO_2 sequestration is a sure tool for reducing the concentration of emitted CO_2 in the environment. The technology in a depleted gas reservoir is a win-win venture because the revenue accruing from produced gas could contribute to defray the cost of CO_2 sequestration project (Mohammed, N et al., 2020; Abba M. et al., 2019; Leeuwenburgh, O. et al., 2014).

Before embarking on any capital-intensive project such as CCS – EGR projects, it is necessary to evaluate the potential benefits or setbacks from the project using the reservoir property data to conduct preliminary simulation or experimental test. Enhanced Gas Recovery and Sequestration projects needs adequate knowledge and estimates of formation pressures and temperatures to determine the expected in-situ fluid density and viscosity which would enable proper design for injection. The efficiency of gas-gas displacement dynamics are not only affected by injection rate, rock and fluids properties but also by the density and viscosity of the fluids (Hamza A et,al, 2021).

In petroleum engineering, enhancement recovery from gas or oil reservoirs requires accurate PVT data gathered at the reservoir conditions (Ghanbari, M et al, 2017). Also, experimental data are not only expensive but time consuming and, in some case, the validity of the reported experimental results are doubtful (Polishuk, I, & Segura, H. 2001), hence the need for simulation and mathematical models.

Geological storage for CO_2 is mainly in saline aquifers, but its injection into depleted oil or gas reservoirs are advantageous due to its ability to produce the residual oil or gas that was not producible during the primary production stage and for the presence of basic infrastructures already in place for

injection, therefore making it easier to develop, operate and maintain. (Gou,Y et al.,2014, Ayotunde A.T 2013, Anene, C. Z., & Odumodu, C. F 2021).
Additionally, Depleted Gas Reservoirs (DGR) have the potential to, securely, sequester CO_2 with a storage capacity between 390 and 750 Giga-tons based on the replacement ratio (Hamza, A et al., 2021; Hoteit, M., & Soltanian, M. 2019; Ladbrook B et al., 2009). Regan, M. L. M. (2011); Vega, B., & Kovscek, A. R. (2010) , concluded that residual gas saturation vary from 15% to 50%, depending on the type of reservoir, indicating substantial amount of natural gas remaining in the reservoir after depletion.

1.1 Carbon-Dioxide Property Prediction

To appropriately design and favorably operate a Carbon Capture & Sequestration - Enhanced Gas Recovery (CCS-EGR) projects, the accurate representation of carbon-dioxide properties, mainly density and viscosity is a must (Ouyang, L. B. (2011). These are the two critical properties required for well injectivity for CCS projects as well as stable displacement and sweep efficiency for EGR projects. Carbon-dioxide density and viscosity can be calculated using black oil PVT Model, Equation of States (EOS) Model or Empirical Mathematical Model (EMM) (Perez, A et al., 2017; Ghanbari, M et al., 2017; Ouyang, L. B. 2011).

Black oil PVT model is a simplified fluid model used for surface gas and oil. This model cannot be applied to pure carbon-dioxide but for oil and gas where CO_2 component is less than three percent (3%) and where the CO_2 component can reach 10-20% as in the case of sour gas (Ouyang, L. B. (2011). Equation of state (EOS) is a function that relates pressure (P), volume (V), temperature (T) as well as molar amount (n) of some substance properties.

EOS are important tools in PVT calculations designed for predicting phase equilibria, thermo-physical properties, and volumetric behavior of fluid system, both in subcritical and supercritical domain, which gives foundation for other calculations like reservoir simulation, fluid mapping, surface processing etc. (Ghanbari, M et al, 2017). Models by Peng-Robinson (PR-EOS) (Robinson, D. B., & Peng, D. Y. 1978) and that of Soave-Redlich-Kwong (SRK-EOS) (Soave, G. 1972) are the two common and primary Equation of State (EOS) for two-phase modeling in different areas of petroleum and chemical engineering.

There have been few correlations proposed for predicting CO_2 phase behavior under supercritical condition in the subsurface but non-has been specifically formulated, designed, and developed for use in Niger-Delta formation based on their pressure and temperature gradients.

1.2 Geothermal and Pressure Gradient of Niger-Delta Formation

Geothermal gradient is a measure of the rate of change of temperature with depth (Emujakporue G.O & Ekine A.S 2014; Godec. M. 2013). The geothermal gradients of subsurface formations are computed using a linear relationship as shown in equation (1)

$$\mathbf{T = G*D+ T_o} \quad \text{..... (1)}$$

Where: T = Wellbore temperature (^oC); G = Geothermal Gradient ($^oC/Km$)
D = Depth of reference (KM); T_o = Mean Surface Temperature (^oC)
Formation pressure is the pressure acting on the fluids (gas, oil, water) in the pore spaces of the rock (Rabia, H. (2002). It is affected by the density of the in-situ fluid and the weight of the overlying rock materials, with respect to the depth of reference. Mathematically,

$$Fp = 0.052\ x\ \rho(f,r)xD \quad \text{..... (2)}$$

Fp= Formation pressure (Psi); ; D = True vertical depth (ft)
$\rho(f,r)$ = formation fluid/rock matrix density

Accumulated reservoir data in Niger-Delta over the years led to the development of the following mathematical correlation. (Lawal K.A 2011; Lawal, K. A., & Adenuga, A. O. (2010)

$P_r = 0.434D + 14.7$……..(3)

$T_r = 0.0105D + 71.4$……...(4)

Where, Pr = Reservoir pressure (Psia); Tr = Reservoir temperature (°F);

D = Reservoir depth (ft). *Note: The above correlations in equation (3 & 4), was adopted in this research.*

2.0 MATERIALS AND METHOD

This study is divided into two parts: First is focussed on model development for CO_2 density and viscosity and second part is the application of the predicted results from the models for EGR-CCS project in Niger-Delta formation. Niger-Delta Formation data and PVTsim software are the basic tool employed in this research.

2.1 Model development

The study adopts extensive literature review and analytical framework to validate the Niger-Delta formulation gradients as reported in equation (3 & 4) of the work.

2.1.1 Validation of the Adopted Niger-Delta Formation Gradient using Absolute Average Deviation (AAD) Approach.

Below is sensitivity analyses of reservoir gradients formulated few years after the model was developed.

$$\text{Pressure Gradient (Psi/ft)} = \frac{Pressure\ (Psi)}{Depth\ (ft)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

:. Pressure (Psi) = Gradient X Depth

1. Nwozor, K. K., & Onuorah, L. O. (2014). Average pressure gradient of Niger-Delta formation as 0.429 psi/ft
2. Ogbamikhumi, A., Akanzua-Adamczyk, A. H., & Ahiwe, L. (2017). Average pressure gradient of Niger-Delta formation as 0.433 psi/ft
3. Emudianughe, J. E., & Ogagarue, D. O. (2018). Average pressure gradient of Niger-Delta formation as 0.445 psi/ft
4. Udo, K. I., Akpan, M. J., & Agbasi, O. E. (2015). Average pressure gradient of Niger-Delta formation as 0.445 psi/ft

$$\text{AAD (\%)} = \frac{100}{n}\ x\ \sum_{i=1}^{n} \frac{|Xi^A - Xi^B|}{Xi^A} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Xi^A=Niger-Delta Formation gradient adopted for this work

Xi^B= Reported Formation gradientsfor Niger-Delta

Table 1: Comparative Analysis of the adopted Pressure Gradient Correlation with other Gradient Correlations.

	MODEL (Equation.3)	Nwozor, K. K., & Onuorah, L. O. (2014)		Ogbamikhumi. A et al, (2017)		Emudianughe, J. & Ogagarue, D. O. (2018)		Udo et al,2015		Remark MFFP: Model Fit For Purpose MNFFP: Not Fit For Purpose
Depth (m)	Pressure @ Model (Psi)	Pressure (Psi)	AAD (%)	Pressure (Psi)	AAD (%)	Pressure (Psi)	AAD (%)	Pressure (Psi)	AAD (%)	MFFP
800	1,153.8	1,125.98	2.41	1,136.48	1.50	1,167.97	1.23	1,141.72	1.05	MFFP
1000	1,438.58	1,407.46	2.16	1,420.59	1.25	1,459.96	1.49	1,427.15	0.79	MFFP
1200	1,723.36	1,688.96	1.99	1,704.70	1.08	1,751.95	1.66	1,712.58	0.63	MFFP
1400	2,008.14	1,970.45	1.88	1,988.82	0.96	2,043.94	1.78	1998.01	0.51	MFFP

In the same vein the AAD's for the adopted Thermal Gradient (Equation 4) are less than 3% for those reported by Akpabio Idara & Joe Ejedawe (2013); Emujakporue G.O & Ekine A.S (2014); Anene, C. Z., & Odumodu, C. F (2021); Onuoha, K. M., & Ekine, A. S. (1999).

2.2 Model Development Approach

Carbon-dioxide properties, specifically density and viscosity were generated from PVT simulation (PVTsim) using Niger-Delta pressure and temperature gradients data generated from equations (3 & 4) of this work at reservoir depths ideal for sequestration and EGR. Below is a flow diagram on how the model was developed.

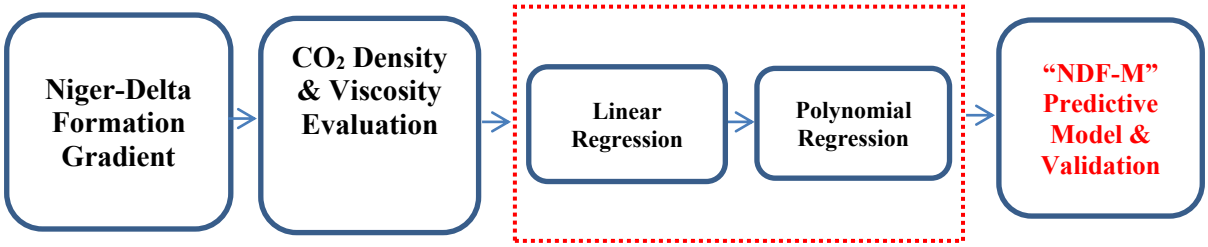


Figure 1: Model Development Algorithm

The developed correlations and the associated constants were adjusted to meet two significant criteria as defined below:

2.2.1 Criteria One: Least Square Curve:

$$Sum = \sum_{1=1}^{n}\left[\rho(NDF)_{PiTi} - \rho(EOS)_{piTi}\right]^2 = Minimum \quad \ldots\ldots (7)$$

$$Sum = \sum_{1=1}^{n}\left[\mu(NDF)_{PiTi} - \mu(EOS)_{piTi}\right]^2 = Minimum \quad \ldots\ldots (8)$$

2.2.2 Criteria Two: Absolute deviation from standard:

$$Sum = \sum_{i=1}^{n}\left[\frac{\rho(NDF)_{P_iT_i} - \rho(EOS)_{P_iT_i}}{\rho(EOS)_{P_iT_i}}\right] = Minimum \quad \ldots\ldots (9)$$

$$Sum = \sum_{i=1}^{n}\left[\frac{\mu(NDF)_{P_iT_i} - \mu(EOS)_{P,T_i}}{\mu(EOS)_{P_iT_i}}\right] = Minimum \quad \ldots\ldots (10)$$

Where:

$(NDF)_{Pi,Ti}$= Niger-Delta Formation Model as a function of Pressure and Temperature

$(EOS)_{Pi,Ti}$ = Equation of State Model as function of Pressure and Temperature

μ=Viscosity (cP); ρ= Density (g/cm^3)

2.2.3 The Generalised Equation

The general equation for model formulation is as shown in equation (11)

$$\check{R}_{(P,T)} = \boldsymbol{\delta}_0 + \boldsymbol{\delta}_1 P + \boldsymbol{\delta}_2 T + \boldsymbol{\delta}_3 P^2 + \boldsymbol{\delta}_4 T^2 + \boldsymbol{\delta}_5 P.T \quad \ldots\ldots (11)$$

Where: $\check{R}$= Estimator of the mean response of density and viscosity at test condition.

$\boldsymbol{\delta}_0, \boldsymbol{\delta}_1, \boldsymbol{\delta}_2, \boldsymbol{\delta}_3, \boldsymbol{\delta}_4, \boldsymbol{\delta}_5 = \boldsymbol{\delta}_j$= Estimator of the Model constants

P,T = Reservoir Pressure and Temperature respectively.

2.2.4 Split Regression Approach (SRA)

Split 1: From generalised equation (11)

$$\check{R}_{(P,T)} = \boldsymbol{\delta}_0 + \boldsymbol{\delta}_1 P + \boldsymbol{\delta}_2 T \quad \ldots\ldots (12)$$

The normal equations for equation (13)

$$\sum_{i=1}^{n}(\check{R}) = \delta_0 N + \delta_1 \sum_{i=1}^{n} P + \delta_2 \sum_{i=1}^{n} T$$

$$\sum_{i=1}^{n}(\check{R}.P) = \delta_0 \sum_{i=1}^{n} P + \delta_1 \sum_{i=1}^{n}(P^2) + \delta_2 \sum_{i=1}^{n}(P.T)$$

$$\sum_{i=1}^{n}(\check{R}.T) = \delta_0 \sum_{i=1}^{n}(T) + \delta_1 \sum_{i=1}^{n}(P.T) + \delta_2 \sum_{i=1}^{n}(T^2)$$

Split 2: From generalised equation (11)

$\check{R}_{(P,T)} = \boldsymbol{\delta}_0 + \boldsymbol{\delta}_1 P^2 + \boldsymbol{\delta}_2 T^2 + \boldsymbol{\delta}_3 P.T$ ..... (13)

The normal equations for equation (13)

$$\sum_{i=1}^{n}(\check{R}) = \delta_0 N + \delta_1 \sum_{i=1}^{n}(P^2) + \delta_2 \sum_{i=1}^{n}(T^2) + \delta_3 \sum_{i=1}^{n}(P.T)$$

$$\sum_{i=1}^{n}(\check{R}.P^2) = \delta_0 \sum_{i=1}^{n}(P^2) + \delta_1 \sum_{i=1}^{n}(P^4) + \delta_2 \sum_{i=1}^{n}(P^2T^2) + \delta_3 \sum_{i=1}^{n}(P^3.T)$$

$$\sum_{i=1}^{n}(\check{R}.T^2) = \delta_0 \sum_{i=1}^{n}(T^2) + \delta_1 \sum_{i=1}^{n}(P^2\,T^2) + \delta_2 \sum_{i=1}^{n} T^4 + \delta_3 \sum_{i=1}^{n}(P.T^3)$$

$$\sum_{i=1}^{n}(\check{R}.P.T) = \delta_0 \sum_{i=1}^{n}(P.T) + \delta_1 \sum_{i=1}^{n}(P^3.T) + \delta_2 \sum_{i=1}^{n}(P.T^3) + \delta_3 \sum_{i=1}^{n}(T^2 P^2)$$

The split functions below at varying validity

$$\left\{\begin{array}{l} \sum_{i=1}^{n}(\check{R}) = \delta_0 N + \delta_1 \sum_{i=1}^{n} P + \delta_2 \sum_{i=1}^{n} T \\ \sum_{i=1}^{n}(\check{R}.P) = \delta_0 \sum_{i=1}^{n} P + \delta_1 \sum_{i=1}^{n}(P^2) + \delta_2 \sum_{i=1}^{n}(P.T) \\ \sum_{i=1}^{n}(\check{R}.T) = \delta_0 \sum_{i=1}^{n}(T) + \delta_1 \sum_{i=1}^{n}(P.T) + \delta_2 \sum_{i=1}^{n}(T^2) \end{array}\right\} \quad \left\{\begin{array}{l} \sum_{i=1}^{n}(\check{R}) = \delta_0 N + \delta_1 \sum_{i=1}^{n}(P^2) + \delta_2 \sum_{i=1}^{n}(T^2) + \delta_3 \sum_{i=1}^{n}(P.T) \\ \sum_{i=1}^{n}(\check{R}.P^2) = \delta_0 \sum_{i=1}^{n}(P^2) + \delta_1 \sum_{i=1}^{n}(P^4) + \delta_2 \sum_{i=1}^{n}(P^2T^2) + \delta_3 \sum_{i=1}^{n}(P^3.T) \\ \sum_{i=1}^{n}(\check{R}.T^2) = \delta_0 \sum_{i=1}^{n}(T^2) + \delta_1 \sum_{i=1}^{n}(P^2T^2) + \delta_2 \sum_{i=1}^{n} T^4 + \delta_3 \sum_{i=1}^{n}(P.T^3) \\ \sum_{i=1}^{n}(\check{R}.P.T) = \delta_0 \sum_{i=1}^{n}(P.T) + \delta_1 \sum_{i=1}^{n}(P^3.T) + \delta_2 \sum_{i=1}^{n}(P.T^3) + \delta_3 \sum_{i=1}^{n}(T^2P^2) \end{array}\right\}$$

Linear Equations
Validity: Reservoir depth (1000-5000m)

Quadratic equations
Validity: Reservoir depth: (>5000m)

2.3 Viability of EGR-CCS Project in Niger-Delta Gas Reservoirs

The second part is the viability of EGR-CCS project in Depleted Gas reservoirs in Niger-Delta.The efficiency of displacing in-situ CH4 (Natural Gas in place) by CO_2 (Injected Gas) during Enhanced Gas Recovery (EGR) operation is affected by the operating conditions i.e (reservoir pressure, temperature and injection rate),the fluids properties i.e (reservoir petrophysical property, connate water saturation, pore geometry and fractures) (Hamza A et al., 2021).

Table 2: Data for four Depleted Gas Reservoirs (DGR) in Niger-Delta

Depth/Condition	**DEPLETED GAS RESERVOIRS**			
	Res.1	**Res.2**	**Res.3**	**Res.4**
Sampling Depth (ft)	8501	9755	5525	11237
Pressure (Psi)	3561	2291	2412	4906
Temperature (oC)	88.00	79.44	54.44	88.33
Swc	N/A	N/A	N/A	N/A
Sgr	0.135	0.153	0.141	0.092
Element/	Composition			
C1	79.48	82.72	82.05	72.53
C2	7.62	7.25	7.42	8.58
C3	7.06	4.47	4.55	5.42
n-C4	3.39	1.34	1.4	3.39
n-C5	0.7	0.38	0.43	0.7
C6	0.21	0.42	0.47	0.21
C7+	0.2	0.66	0.73	0.2
N2	0.17	0.78	0.9	0.17
CO2	1.17	0.5	0.45	1.17

Samples from four depleted gas reservoirs (Table 2) from Niger-Delta region were evaluated to examine the applicability of these concepts with regards to stable displacement and efficient storage processes using the predicted CO_2 density and viscosity as yardsticks.

3.0 RESULTS AND DISCUSSION

3.1 CO_2 Density Correlation for Niger-Delta Formation (NDF) at Varying depths

1. $\mathbf{CO_2(\rho)=0.104061+0.000053P+0.0084T}$……..(14)

   Validity Depth (1000-1500m)

2. $\mathbf{CO_2(\rho)=11.263097+0.006631P-0.491576T}$…….(15)

   Validity Depth (1600-5000m)

3. $\mathbf{CO_2(\rho)=500.53x10^{-3}+7.4312x10^{-3}(T^2)–1.64x10^{-8}(P^2)+7.6437x10^{-8}(PT)}$…….(16)

   Validity Depth (>5000m)

   Where: T= Temperature (°C), P= Pressure (Psi), ρ= Density (g/cm^3), μ=Viscosity (cP**).**

Graphical Comparison between the new model (NDF) and PR&SRK EOS

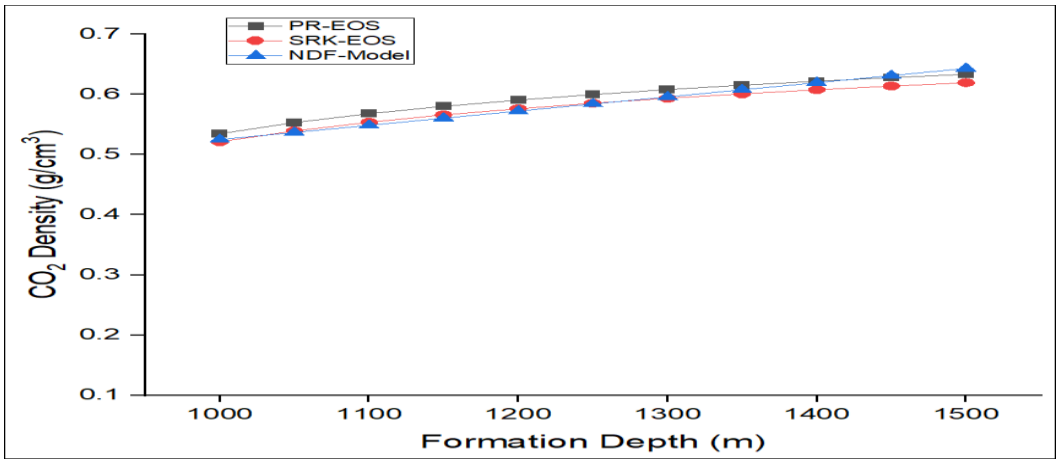


Figure 2: Density Model comparison with PR-EOS & SRK-EOS at depth of 1000-1500m

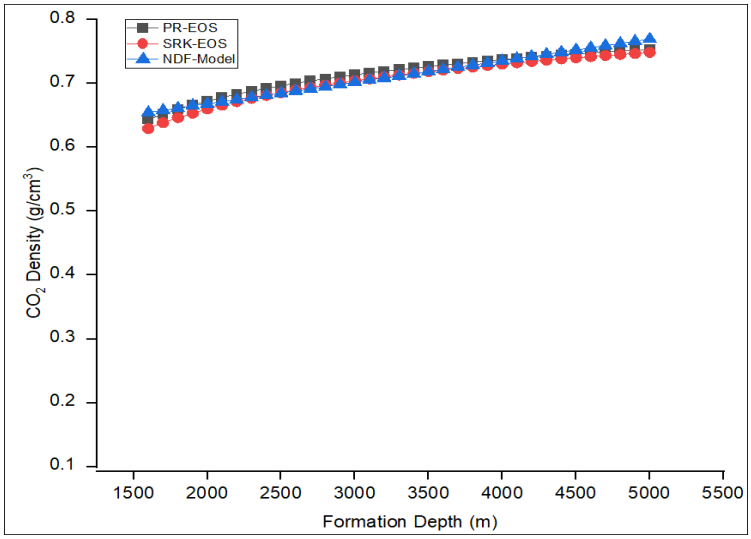


Figure 3: Density Model comparison with PR-EOS & SRK-EOS at depth of 1600-5000m

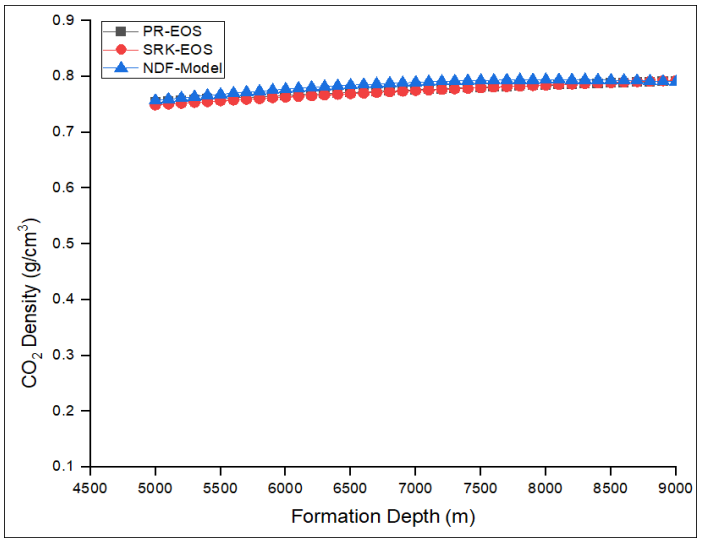


Figure 4: Density Model comparison with PR-EOS & SRK-EOS at depth >5000m

3.2 CO_2 Viscosity Correlation for Niger-Delta Formation (NDF) at Varying depths

1. **$CO_2(\mu)$= 0.00001971P-0.00068063T+0.059601**…… (17)

   Validity Depth (1000-1500m)

2. **$CO_2(\mu)$=0.0033503T-0.00004285P-0.0085675**……... (18)

   Validity Depth (1600-5000m)

3. **$CO_2(\mu)=6.262\times10^{-6}(T^2)-1.3727\times10^{-9}(P^2)+7.0729\times10^{-9}(PT)+56.29\times10^{-3}$**…… (19)

   Validity Depth (>5000m)

   Where: T= Temperature (^oC), P= Pressure (Psi), ρ= Density (g/cm^3), μ=Viscosity (cP**).**

Graphical Comparison between the new model (NDF) and PR&SRK EOS

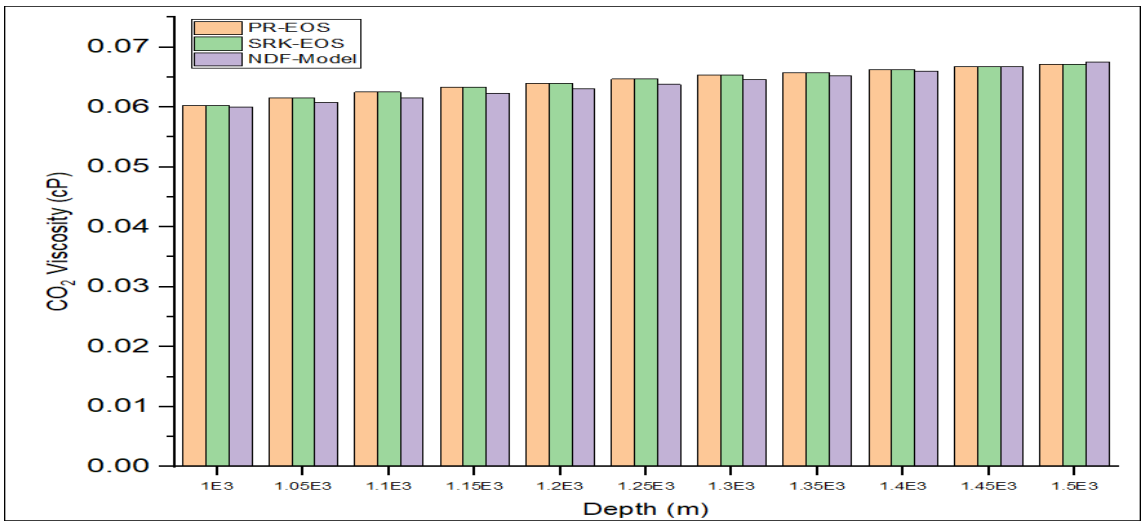


Figure 5: Viscosity Model comparison with PR-EOS & SRK-EOS at depth of 1000-1500m

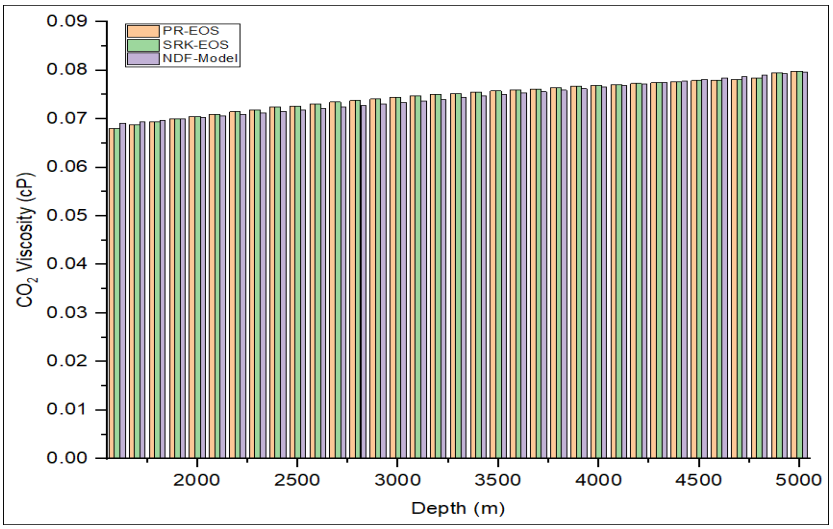


Figure 6: Viscosity Model comparison with PR-EOS & SRK-EOS at depth of 1600-5000m

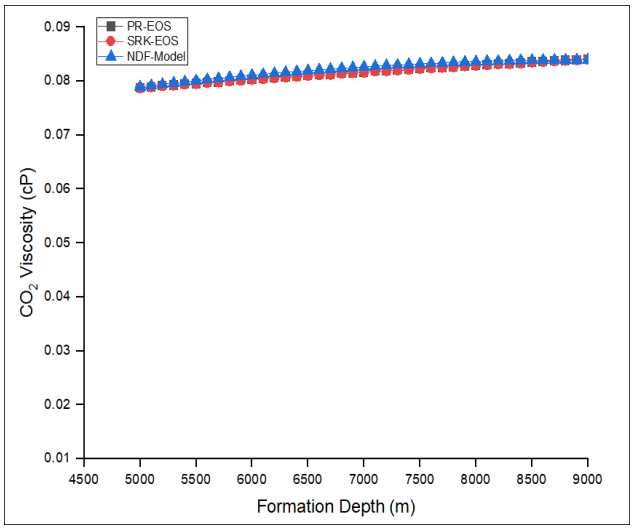


Figure 7: Viscosity Model comparison with PR-EOS & SRK-EOS at depth >5000m

3.3 Determination of Absolute Average Deviation (AAD)

Average Absolute Deviation (%AAD) as evaluated for the newly developed "NDF-Model" vis-à-vis "PR-EOS" and "SRK-EOS" are shown in tables (3, 4 & 5)

Table 3: Category 1: Reservoir depths between (1000-1500m)

Depth (m)	CO_2 Density, ρ (g/cm^3)			AAD (%) for ρ		CO_2 Viscosity, μ (cP)			AAD (%) for μ	
	PR-EOS	SRK-EOS	NDF Model	PR-EOS	SRK-EOS	PR-EOS	SRK-EOS	NDF Model	PR-EOS	APD SRK
1000	0.5347	0.5213	0.5249	**-1.86**	**0.69**	0.0603	0.0603	0.0600	**-0.45**	**-0.45**
1050	0.5531	0.5392	0.5367	**-3.05**	**-0.46**	0.0615	0.0615	0.0608	**-1.18**	**-1.18**
1100	0.5679	0.5537	0.5486	**-3.53**	**-0.94**	0.0625	0.0625	0.0615	**-1.57**	**-1.57**
1150	0.5801	0.5658	0.5604	**-3.52**	**-0.97**	0.0633	0.0633	0.0623	**-1.63**	**-1.63**
1200	0.5905	0.5761	0.5722	**-3.20**	**-0.68**	0.0640	0.0640	0.0630	**-1.52**	**-1.52**
1250	0.5997	0.5853	0.5840	**-2.69**	**-0.22**	0.0647	0.0647	0.0638	**-1.43**	**-1.43**
1300	0.6079	0.5935	0.5958	**-2.03**	**0.39**	0.0653	0.0653	0.0645	**-1.17**	**-1.17**
1350	0.6152	0.6009	0.6076	**-1.25**	**1.11**	0.0658	0.0658	0.0653	**-0.77**	**-0.77**
1400	0.6218	0.6076	0.6194	**-0.38**	**1.91**	0.0663	0.0663	0.0660	**-0.38**	**-0.38**
1450	0.6278	0.6137	0.6312	**0.54**	**2.78**	0.0668	0.0668	0.0668	**0.00**	**0.00**
1500	0.6333	0.6193	0.6431	**1.52**	**3.69**	0.0672	0.0672	0.0676	**0.52**	**0.52**

Table 4: Category 2: Reservoir depths between (1600-5000m)

Depth (m)	CO_2 Density, ρ (g/cm^3)			AAD (%) for ρ		CO_2 Viscosity, μ (cP)			AAD (%) for μ	
	PR-EOS	SRK-EOS	NDF Model	PR-EOS	SRK-EOS	PR-EOS	SRK-EOS	NDF Model	PR-EOS	APD SRK
1600	0.6433	0.6295	0.6545	**1.72**	**3.82**	0.0680	0.0680	0.0691	**1.60**	**1.60**
1800	0.6595	0.6464	0.6613	**0.27**	**2.25**	0.0694	0.0694	0.0697	**0.47**	**0.47**
2000	0.6725	0.6600	0.6680	**-0.67**	**1.20**	0.0705	0.0705	0.0703	**-0.21**	**-0.21**
2200	0.6833	0.6714	0.6748	**-1.26**	**0.51**	0.0715	0.0715	0.0710	**-0.75**	**-0.75**
2400	0.6925	0.6812	0.6816	**-1.60**	**0.05**	0.0724	0.0724	0.0716	**-1.13**	**-1.13**

2600	0.7004	0.6897	0.6883	**-1.75**	**-0.20**	0.0731	0.0731	0.0722	**-1.23**	**-1.23**
2800	0.7074	0.6973	0.6951	**-1.77**	**-0.32**	0.0738	0.0738	0.0728	**-1.33**	**-1.33**
3000	0.7137	0.7041	0.7019	**-1.69**	**-0.32**	0.0744	0.0744	0.0735	**-1.29**	**-1.29**
3200	0.7193	0.7102	0.7086	**-1.51**	**-0.22**	0.0750	0.0750	0.0741	**-1.25**	**-1.25**
3400	0.7244	0.7159	0.7154	**-1.26**	**-0.07**	0.0755	0.0755	0.0747	**-1.07**	**-1.07**
3600	0.7291	0.7210	0.7221	**-0.96**	**0.16**	0.0760	0.0760	0.0753	**-0.90**	**-0.90**
3800	0.7334	0.7258	0.7289	**-0.62**	**0.43**	0.0765	0.0765	0.0759	**-0.74**	**-0.74**
4000	0.7374	0.7302	0.7357	**-0.24**	**0.74**	0.0769	0.0769	0.0766	**-0.44**	**-0.44**
4200	0.7411	0.7344	0.7424	**0.18**	**1.08**	0.0773	0.0773	0.0772	**-0.15**	**-0.15**
4400	0.7445	0.7383	0.7492	**0.63**	**1.45**	0.0777	0.0777	0.0778	**0.13**	**0.13**
4600	0.7477	0.7419	0.7559	**1.09**	**1.86**	0.0780	0.0780	0.0784	**0.54**	**0.54**
4800	0.7508	0.7454	0.7627	**1.56**	**2.27**	0.0784	0.0784	0.0790	**0.82**	**0.82**
5000	0.7537	0.7487	0.7695	**2.05**	**2.70**	0.0787	0.0787	0.0797	**1.21**	**1.21**

Table 5: Category 3: Reservoir depths between (>5000m)

	CO_2 Density, ρ (g/cm^3)			**AAD (%) for ρ**		**CO_2 Viscosity, μ (cP)**			**AAD (%) for μ**	
Depth (m)	**PR-EOS**	**SRK-EOS**	**NDF Model**	**PR-EOS**	**SRK-EOS**	**PR-EOS**	**SRK-EOS**	**NDF Model**	**PR-EOS**	**APD SRK**
5000	0.7537	0.7487	0.7568	**0.41**	**1.07**	0.0787	0.0787	0.0789	**0.29**	**0.29**
5100	0.7551	0.7503	0.7592	**0.54**	**1.18**	0.0789	0.0789	0.0792	**0.35**	**0.35**
5200	0.7564	0.7518	0.7615	**0.67**	**1.28**	0.0791	0.0791	0.0794	**0.39**	**0.39**
5300	0.7577	0.7533	0.7638	**0.79**	**1.37**	0.0792	0.0792	0.0796	**0.55**	**0.55**
5400	0.7590	0.7547	0.7659	**0.90**	**1.46**	0.0794	0.0794	0.0799	**0.58**	**0.58**
5500	0.7602	0.7562	0.7680	**1.01**	**1.54**	0.0795	0.0795	0.0801	**0.72**	**0.72**
5600	0.7615	0.7576	0.7700	**1.10**	**1.61**	0.0797	0.0797	0.0803	**0.74**	**0.74**
5700	0.7626	0.7589	0.7719	**1.20**	**1.68**	0.0798	0.0798	0.0805	**0.87**	**0.87**
5800	0.7638	0.7603	0.7737	**1.28**	**1.74**	0.0800	0.0800	0.0807	**0.86**	**0.86**
5900	0.7649	0.7616	0.7755	**1.36**	**1.79**	0.0801	0.0801	0.0809	**0.98**	**0.98**
6000	0.7661	0.7629	0.7772	**1.42**	**1.83**	0.0803	0.0803	0.0811	**0.96**	**0.96**
6100	0.7672	0.7642	0.7788	**1.48**	**1.87**	0.0804	0.0804	0.0813	**1.06**	**1.06**
6200	0.7682	0.7654	0.7803	**1.55**	**1.91**	0.0806	0.0806	0.0814	**1.03**	**1.03**
6300	0.7693	0.7666	0.7817	**1.59**	**1.93**	0.0807	0.0807	0.0816	**1.11**	**1.11**
6400	0.7703	0.7678	0.7831	**1.63**	**1.95**	0.0808	0.0808	0.0818	**1.19**	**1.19**
6500	0.7713	0.7690	0.7843	**1.66**	**1.96**	0.0810	0.0810	0.0819	**1.14**	**1.14**
6600	0.7723	0.7701	0.7855	**1.69**	**1.97**	0.0811	0.0811	0.0821	**1.20**	**1.20**
6700	0.7732	0.7712	0.7867	**1.71**	**1.97**	0.0812	0.0812	0.0822	**1.25**	**1.25**
6800	0.7742	0.7723	0.7877	**1.71**	**1.96**	0.0814	0.0814	0.0824	**1.18**	**1.18**
6900	0.7751	0.7734	0.7887	**1.72**	**1.94**	0.0815	0.0815	0.0825	**1.22**	**1.22**
7000	0.7760	0.7745	0.7895	**1.72**	**1.91**	0.0816	0.0816	0.0826	**1.25**	**1.25**
7100	0.7769	0.7755	0.7903	**1.70**	**1.88**	0.0818	0.0818	0.0828	**1.16**	**1.16**
7200	0.7778	0.7766	0.7911	**1.68**	**1.83**	0.0819	0.0819	0.0829	**1.18**	**1.18**
7300	0.7787	0.7776	0.7917	**1.64**	**1.78**	0.0820	0.0820	0.0830	**1.19**	**1.19**
7400	0.7795	0.7786	0.7923	**1.61**	**1.73**	0.0821	0.0821	0.0831	**1.19**	**1.19**
7500	0.7804	0.7796	0.7928	**1.56**	**1.66**	0.0823	0.0823	0.0832	**1.07**	**1.07**
7600	0.7812	0.7806	0.7932	**1.51**	**1.58**	0.0824	0.0824	0.0833	**1.06**	**1.06**
7700	0.7820	0.7815	0.7935	**1.45**	**1.51**	0.0825	0.0825	0.0834	**1.04**	**1.04**

7800	0.7828	0.7825	0.7937	**1.38**	**1.42**	0.0826	0.0826	0.0835	**1.02**	**1.02**
7900	0.7836	0.7834	0.7939	**1.30**	**1.32**	0.0828	0.0828	0.0835	**0.87**	**0.87**
8000	0.7844	0.7843	0.7940	**1.21**	**1.22**	0.0829	0.0829	0.0836	**0.83**	**0.83**
8100	0.7851	0.7852	0.7940	**1.12**	**1.11**	0.0830	0.0830	0.0837	**0.79**	**0.79**
8200	0.7859	0.7861	0.7939	**1.01**	**0.99**	0.0831	0.0831	0.0837	**0.74**	**0.74**
8300	0.7866	0.7870	0.7938	**0.90**	**0.85**	0.0832	0.0832	0.0838	**0.68**	**0.68**
8400	0.7873	0.7879	0.7936	**0.79**	**0.71**	0.0833	0.0833	0.0838	**0.61**	**0.61**
8500	0.7881	0.7887	0.7932	**0.65**	**0.57**	0.0835	0.0835	0.0839	**0.42**	**0.42**

Table 6: Relative density and viscosity comparison of CO_2 and Natural Gas at varying reservoirs

Reservoir I.D & Depth		**Reservoir condition**		**CO_2 Property**		**Gas Property**		**Relative Difference ρCo2>ρN.G; μCo2>μN.G**	
	Depth (ft)	Tempt. (^oC)	Pres. (Psi)	Density (g/cm^3)	Viscosity (cP)	Density (g/cm^3)	Viscosity (cP)	RDD (%)	RVD (%)
Res.1	8501	88.00	3561	0.6689	0.0784	0.1989	0.0250	70.26	68.11
Res.2	9755	79.44	2291	0.6471	0.0798	0.1280	0.0185	80.22	76.82
Res.3	5525	54.44	2412	0.6605	0.0698	0.1569	0.0200	76.25	71.35
Res.4	11237	88.33	4906	0.6959	0.0737	0.2416	0.0302	65.28	59.02

Where**:** Relative Density difference (RDD); Relative Viscosity difference (RVD)

3.4 NDF Model Development Discussion

In this work, the adopted correlation for pressure and temperature gradients of Niger-Delta formation (NDF) was validated using reported gradients in literature by Absolute Average Deviation (AAD) method as shown in table (1).

Stepwise reservoir depth was used to compute the pressures and temperatures of NDF using the adopted Niger-Delta formation gradients equations (3 & 4) respectively. The generated densities and viscosities at those reservoir depths as evaluated by PVTsim software were used to develop three Novel Models (NM) using Regression Split Approach (RSA). This was after the data were rigorously trained and tested at those conditions to meet criteria (1) and (2) of this report. The developed models were transversed from Linear - Second degree - Interactive (LSI) terms of (P;T),(P^2;T^2) and (P*T) respectively. This was necessitated due to the non-linearity relationships between density, viscosity (dependent variables) and pressure, temperature (independent variables) at some depths in the formation.

The insi-tu density (ρ) and viscosity (μ) relationship with the independent variables appears to have presents of interactions and curvilinear relationships, hence the need for two algorithms (Linear-quadratic split models) at varying depths.
Additionally, for significant improvement in the fit, three types of models were generated independently at different reservoir depths for the correlations.

3.4.1 NDF Model Validation

Peng Robinson (PR-EOS) and Soave-Redlich-Kwong (SRK-EOS) are the most successful equation of states which have been modified repeatedly to improve their accuracy in different ranges of pressure and temperatures, alongside their extrapolative ability to condition reservoir parameters outside their correlation ranges. These PVT models (PR-SRK-EOS) have attracted a lot of attentions for predicting the properties of pure and mixed components both in subcritical and supercritical states, hence considered for validating the newly developed NDF Mathematical Model.

Sensitivity analysis was used to examine the responses of the newly developed correlation (NDF-Model) vis-à-vis that of Peng Robinson (PR-EOS) and Soave-Redlich-Kwong (SRK-EOS) under defined boundaries. The predicted results from the models were assessed and validated by comparing percentage Absolute Average Deviation (ADD%) between NDF model and PR-SRK-EOS using the relationship below:

$$\text{AAD (\%)} = \frac{100}{n}\ x\ \sum_{i=1}^{n} \frac{|Xi^{NDF} - Xi^{EOS}|}{Xi^{NDF}} \quad \text{..... (20)}$$

Where; X = Evaluated CO_2 property (Density and Viscosity)

EOS= Equation of state (PR-EOS and SRK-EOS); N = Number of data.

3.5 Application of EGR-CCS in Niger-Delta Formation

Table (6) revealed that CO_2 at those simulated depths possess higher density and viscosity than in-situ natural gas at same reservoir conditions. The calculated Relative Density difference (RDD) of "CO_2 & Natural Gas" ranges from 65.28 - 80.22% and Relative Viscosity difference (RVD) ranges from 59.02 - 76.82% for the four gas reservoirs under study.

Therefore, under optimum injection rate, using CO_2 as the displacement fluid would encourage infinitesimal gas mixing and stable displacement due to expected low mobility ratio between the displacing and the displaced fluid. The results are in agreement with (Al-Hasami,et al 2005; Hamza A et al, 2021; Hoteit, M., & Soltanian, M. 2019; Oldenburg, C. M., & Benson, S. M. 2002; Clemens, T., & Wit, K. 2002).

4.0 CONCLUSION

Niger-Delta formation screening and ranking for CO_2 sequestration are rated "Very Good" and "Excellent" in all assessed scenarios for CCS as reported by researchers like "Umar B.A et al, (2020)" and "Davis et al, (2022)". However, field deployment of EGR-CCS project in Niger-Delta is dependent on reliable experimental assessment or reservoir simulation.

Over the last decade, geological sequestrations of CO_2 have been an area of active research to mitigate greenhouse gas emission in our environment. Understanding phase behaviors of CO_2 at varying subsurface associated PVT conditions are essential for knowing the flow dynamics as a displacing fluid for enhanced recovery and sequestration. On that basis, comprehensive reservoir characterization data of formations to be injected are required for numerical simulations and laboratory investigation. Density and viscosity are the two critical parameters for pure CO_2 in supercritical conditions needed for EGR-CS projects in depleted gas reservoirs.

In this work, three categories of mathematical models within reservoir depths of 1000-1500m, 1600-5000m and beyond 5000m were developed for CO_2 density (ρCO_2) and viscosity (μCO_2) necessary for EGR-CCS projects in Niger-Delta formation. CO_2 densities at those depths ranges from 0.5-0.6 g/cm^3, 0.6-0.7g/cm^3 and 0.7-0.8g/cm^3 respectively while the viscosities ranges from 0.05-0.06cP, 0.06-0.07cP and 0.07-0.08cP respectively.

The new correlation was validated using Peng Robinson and Soave-Redlich-Kwong Equation of States Model (EOS-M) by Absolute Average Deviation (AAD) method as shown in tables 3, 4 & 5 of this work. The model was consequently applied to four depleted gas reservoirs (Res.1, Res.2, Res.3 and Res.4) in Niger-Delta for recovery potential. It revealed promising relative density and viscosity differences as shown in table 6. These indicates smooth displacement potentials and promising less dispersion coefficient of CO_2 on the displaced natural gas under optimum injection rate.

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