

The Interstitial Energy of Immiscible Gas Enhanced Oil Recovery (IGEOR) Gases in Porous Media

Ofasa Abunumah, Priscilla Ogunlode, Edward Gobina*

Department of Engineering, Robert Gordon University, Aberdeen

ABSTRACT

The competitiveness of the energy impact of Immiscible Gas Enhanced Oil Recovery (IGEOR) gases (CH_4 , N_2 , Air and CO_2) in porous media has been determined through an extensive and rigorous experimental approach. Previous studies have stated that the quantity of reservoir oil produced is proportional to the effective energy supplied to the reservoir by the injected fluid. Fluid flow through porous media involves energy interactions or exchanges that can be described by energy continuum or kinetic theory. The energy interactions could be due to geological structures or contact with other pore fluids. Some authors have characterized gas behavior for permeability, velocity, flow rate, and flow regime. However, there is a shortage of studies that explicitly qualifies and quantifies the characterization of energy possession for gases permeating through porous media. Thus, gas interstitial energy has been adopted as an objective function in this research. The optimization requirement for the objective function is to determine which gas possesses the maximum energy impact. An experimental method comprising four gases and five analogous core samples with a varying range of structural parameters (porosities, 3%-24%, pore size, 15-6000 nm) have been employed. The gases were injected into the media at varying pressure (range, 0.2-3.0 atm) and temperature (range, 273 K-673 K) conditions. Results indicate that CH_4 comparatively possesses the most energy thus, making it the most competitive gas in four of the analogous core samples. The normalized interstitial energy possession and potential impact of the gases in IGEOR processes are thus ranked in decreasing order as CH_4 (0.19 J) $>$ Air (0.16 J) $>$ CO_2 (0.14 J) $>$ N_2 (0.13 J). Air is found to be the most competitive in the fifth core sample that has relatively lower porosity (4%) but with the highest pore size (6000 nm). The coefficient of variation (CV) analysis indicates that the energy impact of N_2 (CV=0.66) is the least affected by system heterogeneity and operating variability, such as porosity, pore size, temperature and pressure. This is in contrast to CO_2 (CV=0.81) that is the most affected by heterogeneity. The research offers utility to industries such as reservoir engineering, pharmaceutical, and biotechnology. The knowledge can be directly applied in practice for the selection of gases in fluid porous media processes such as oil recovery, gas separation and fluidized beds.

Keywords: Gas energy; Core; Methane; CO_2 ; Porosity; Gas flow; Porosity; Porous media

INTRODUCTION

In Enhanced Oil Recovery (EOR) technology, common gases such as CH_4 (Methane or hydrocarbon), N_2 (Nitrogen), Air and CO_2 (Carbon Dioxide), are injected into reservoirs pores to displace trapped oil droplets [1-5]. Surguchev [6], Rodríguez and Christopher [7], Surguchev, Koundin, and Yannimaras [8] have extensively investigated Air injection in gas oil displacement processes. Alvarado and Manrique [9] stated that there is an increasing prospect for Air injection and [10,11] further reported significant oil recovery from Air injection. The CO_2 process involves injecting CO_2 gas into the reservoir to enhance oil recovery [9]. The common displacement configurations are miscible and immiscible CO_2 injection [5,12,13]. CO_2 injection is statistically the most injected

IGEOR gas as published in industry journals and reports [13-15].

Fassihi, Yannimaras, and Kumar [16] Babadagli et al. [17], and Teigland and Kleppe [18] deposited different values for gas oil displacement recovery performances. Overall, the oil recovery performances of the different gas IGEOR processes range from 5% to 20% of the volume of oil originally in place (OOIP) [19,20].

Gbadamosi [21] David and Robert [22] and Ahmed and Meehan [23] stated that the performance of hydrocarbon oil displacement is related to the injected pore volume of the fluid and the nature of the energy supplied. Hernández [24] mentioned that the gas energy balance required to displace oil slug in a gas lift process is proportional to the volume of gas injected. Vega and Kovscek [25], Warner and Holstein [26], Yu et al. [27] and Mugeridge et al. [28],

Correspondence to: Edward Gobina, Department of Engineering, Robert Gordon University, Aberdeen; E-mail: e.gobina@rgu.ac.uk

Received: September 16, 2021; **Accepted:** September 30, 2021; **Published:** October 07, 2021

Citation: Abunumah O, Ogunlode P, Gobina E (2021) The Interstitial Energy of Immiscible Gas Enhanced Oil Recovery (Igeor) Gases in Porous Media. J Chem Eng Process Technol 12:9

Copyright: © Abunumah O, et al. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

reveal other common factors held by the oil industry as affecting microscopic and macroscopic gas oil recovery performance of EOR processes. These are (1) initial saturation conditions, (2) fluid viscosity ratios, (3) relative permeability ratios, (4) mobility ratios, (5) formation dip, (6) capillary and gravitational forces, (7) interstitial velocity, (8). Other factors include diffusion, permeability, density difference, and rate of injection, permeability contrast and the cross section of reservoir open to flow. Many studies have thus characterised IGEOR processes based on these quantities and used them to compare the performance of the respective IGEOR gases in displacing trapped oil.

Zhuravl'ov and Lanetc [29] have used numerical simulation to study CH_4 , N_2 and CO_2 for IGEOR. However, they focused their evaluation on the effect of gas compressibility on oil displacement performances. Yin and Ma [10] did an Air injection experiment that suggests that low oxygen Air injection can improve oil recovery in high permeability than low permeability reservoirs. Their results contrast, in principle, those of [28,30,31], which reported that injectant permeability is inversely proportional to the favourable relative mobility (M) condition that enhances oil recovery (i.e. $M < 1$). Other experimental investigators include [32-37]. However, their studies were conducted based on viscosity and molecular weight and limited to a single (usually CH_4 or CO_2) or two gases investigation. These authors have not explicitly considered the characterisation of the energy possession of injected IGEOR gases using experimental methods.

Considering the successful characterisation of gas enhanced oil recovery reservoirs and the performance of injected gases based on the aforementioned engineering quantities, it is expected that energy could also be used to characterise IGEOR processes and hence used to determine the potential competitive performances of the respective IGEOR gases. Consequently, the aim and objectives of this study are focused on the energy characterisation of IGEOR gases for immiscible oil displacement.

The flow of fluids through porous media should typically conform to kinetic theory and laws such as mass, linear momentum, and energy conservation [38]. Gas injected into reservoir pores involves coupling interactions of velocities and masses that can be described by momentum and kinetic energy exchanges [39-42]. When this momentum interacts with *in situ* fluids and pore matrix walls, the quality of the interactions can be further characterised by energy transferability or flux. These interactions can be further reduced to continuum mechanics or kinetic theory of gas as dictated by Knudsen characteristics of the flow [43,44]. Accounting for energy and energy flux has a major utility in understanding and describing the gas oil displacement process. Displacing fluid molecules may possess significant specific energy but a low capacity to diffuse the energy onto the displaced fluid (oil molecules). Therefore, the coupling effect of energy and energy flux potential is essential in evaluating the displacing fluids' competitiveness. As an objective function, the research's optimization goal is to evaluate and identify the gas that offers the most competitive coupling of these quantities.

In this study, the translational kinetic energy, KE, is used as a measure of the energy possession for IGEOR gases. In the rest of this work, kinetic Energy and energy would be used interchangeably. KE is a combinatorial engineering quantity, and it is directly proportional to the component mass, m_i and the square of the velocity, v_i [42-45]. The internal energy possessed by the molecules of a gas is traditionally represented as:

$$KE = \frac{1}{2} \sum_{i=1}^n (m_i v_i^2) \quad (1)$$

Where n is the total number of gas molecules. Other forms of Eq. 1 can be represented in a Kinetic Theory form. For instance, the mean squared speed velocity of the gas is proportional to the thermodynamic temperature, T (in K) and the Boltzmann constant, k_B [40-45] Consequently, the relationship has been derived in Eq. 2:

$$v_{rms} = \left(\frac{3k_B T}{m} \right)^{\frac{1}{2}} = \left(\frac{3RT}{mn} \right)^{\frac{1}{2}} \quad (2)$$

Where R is the gas constant. Replacing the velocity, v, in Eq. 1 with v_{rms} , in Eq. 2 yields KE with respect to pressure and temperature Eq. 4 and Eq. 5 respectively.

$$KE = \frac{3}{2} RT \quad (3)$$

Recall the ideal gas equation (Eq. 4), for a mole of gas with respect to Pressure, P, and volume V, the question is:

$$PV = RT \quad (4)$$

Therefore, in a porous media system the internal energy for a mole of gas can be represented with respect to the injection Pressure and permeated gas volume at steady state in Eq. 5:

$$KE = \frac{3}{2} PV \quad (5)$$

However, the permeate volume reading obtained from the flow meter is a superficial volume, which gives a superficial Kinetic Energy via Eq. 5. To obtain the interstitial KE_{int} an interstitial volume is required and it is obtained by the quotient of superficial volume and core sample porosity (ϕ). Thus equation Eq. 5 becomes:

$$KE_{int} = \frac{3}{2} P \frac{V}{\phi}$$

These equations provide explicit and implicit solutions for the experimental investigation of IGEOR gas energy.

MATERIALS AND METHODS

The gas experimental method used in this study is replicable. The design and materials used have been used previously by investigators such as [1-3,46-51]. The gas and the values of some of their thermophysical properties are presented in Figure 1.

| Thermo physical Property | Molecular Weight, g/mol | Specific Volume, $10^{-2} \text{ cm}^3 \text{ g}^{-1}$ | Apperent Viscosity (Flow Resistance), 10^3 Centipoise @STP | Specific Heat Capacity at Constant Pressure, $\text{J.g}^{-1}\text{K}^{-1}$ | Mean Free Path, Å (@1.01atm and 273K) | Kinetic Diameter, pm (@1.01atm and 273K) |
|--------------------------|-------------------------|--|--|---|---------------------------------------|--|
| CH_4 | 16 | 13.9 | 1.01 | 1.66 | 0.529 | 380 |
| N_2 | 28 | 3.57 | 1.66 | 1.04 | 0.58 | 364 |
| AIR | 29 | 3.45 | 1.73 | 0.99 | 0.60 | 355 |
| CO_2 | 44 | 2.27 | 1.37 | 0.81 | 0.70 | 330 |

Figure 1: Shows the Thermophysical Properties of Igeor Gases Using a Relative Arbitrary Scaling Presentation.

The analogous core samples structural parameters are shown in Table 1 and Figure 2 shows the surface morphology for four of the analogous core samples used. The experimental set up schematic and equipment used are shown in Figure 3

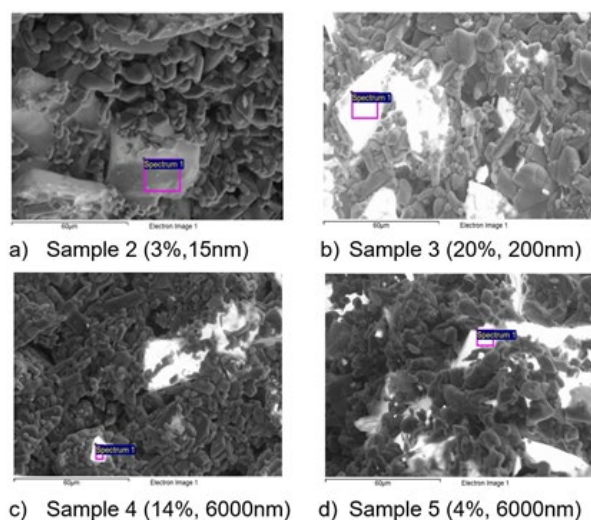


Figure 2: Shows the EDXA morphology characterisation of samples used in the experiment.

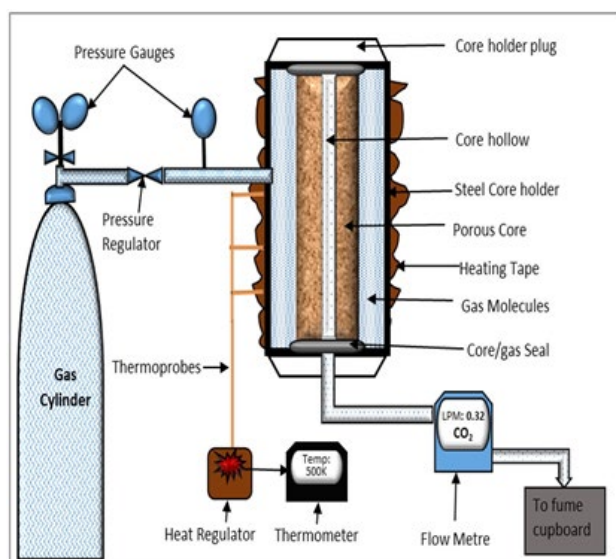






Figure 3: Schematic of the experimental set-up

| S/N | Sample Code | Structural Parameters | | |
|-----|------------------|---|---------------|--------------|
| | | Pore Size | Porosity | Aspect Ratio |
| 1 | Core S13-15 nm |  | $\phi = 13\%$ | 10E+04 |
| 2 | Core S3-15 nm |  | $\phi = 3\%$ | 2E+05 |
| 3 | Core S20-200 nm |  | $\phi = 20\%$ | 8E+05 |
| 4 | Core S14-6000 nm |  | $\phi = 14\%$ | 8E+03 |

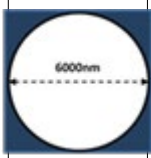
| | | | | |
|---|-----------------|---|--------------|-------|
| 5 | Core S4-6000 nm |  | $\phi = 4\%$ | 2E+02 |
|---|-----------------|---|--------------|-------|

Table 1: Structural parameters of core samples

Experimental procedure and conditions

- Heated and maintain core system at thermal stability (starting temperature: 293 K).
- Injected gas into core system at a set pressure (starting pressure: 0.20 atm)
- Measure outlet flowrate (permeate), temperature and pressure at a steady state.
- Repeat a-c at intervals of 0.40 atm until the maximum pressure (3.0 atm) is reached.
- Repeat a-d for Temperatures 323 K, 373 K, 432 K, 473 K, and 673 K.

Data acquisition and analyses

The data needed for the analyses were acquired in measurements from weight balance, meter rule, vernier calliper, flow meter, thermocouple and thermometer. These data were directly applied to Eq. 6 to obtain the energy of the gases at different operating conditions of pressure, volume and temperature (PVT).

The KE_{int} so obtained was plotted against pressure, system temperature, porosity and pores size. Other correlational analyses include KE_{int} vs gas thermophysical properties.

The combined graph method was used to present the results and analyses. This enables the simultaneous comparison of KE_{int} of the respective gases against multiple experimental variables.

RESULTS AND DISCUSSION

In Figure 4 the energy profiles and the competitiveness of the four IGEOR gases in 5 analogues core samples are shown. The investigation has been described with 5 mother graphs (Figures 4a-4e). Each mother graph contains six sub-graphs demarcated by vertical dotted lines that represent six isotherms in Kelvin (K). The sub-graphs enable the researcher to visually compare the effect of temperature increase on gas energy in the respective core samples. The x-axis of the sub graphs carries the pressure variables ranging from 0.2 atm to 3.0 atm. The subgraphs are 30 in total (5 mother graphs x 6 subgraphs=30). The scale of all 6 graphs is the same, to enable a visual and qualitative comparison of the energy propagation and magnitude of the respective gases.

It can be deduced from Figures 4a-4e that the energy possession of the respective gases in the microscopic interstices of the core sample is positively responsive to an increase in pressure and temperature for all gases and core samples. This result validates the general principle of the Kinetic Theory of gases promoted by previous investigators [40-44], even though those studies were not done on porous media. Figure 4f summarizes the ranking of the gases for each core. CH_4 possesses the most energy for all core samples except in Core S4-S6000 nm (as revealed in Figures 4d and 4f), where there is no significant energy discrimination for CH_4 , Air and CO_2 .

It can be concluded therefore that CH₄ is the most competitive gas.

Suffice to state that the ranking of gas energy competitiveness is correlated to molecular weight when pressure is above 0.2 atm for all core samples (Figures 4a-4d), except for Core S4-6000 nm where there is no energy-molecular weight correlation at all the pressure and temperature range (Figure 4e). Generally, where the correlation existed, increasing the system temperature further increased the R² or correlation strength between molecular weight and gas energy.

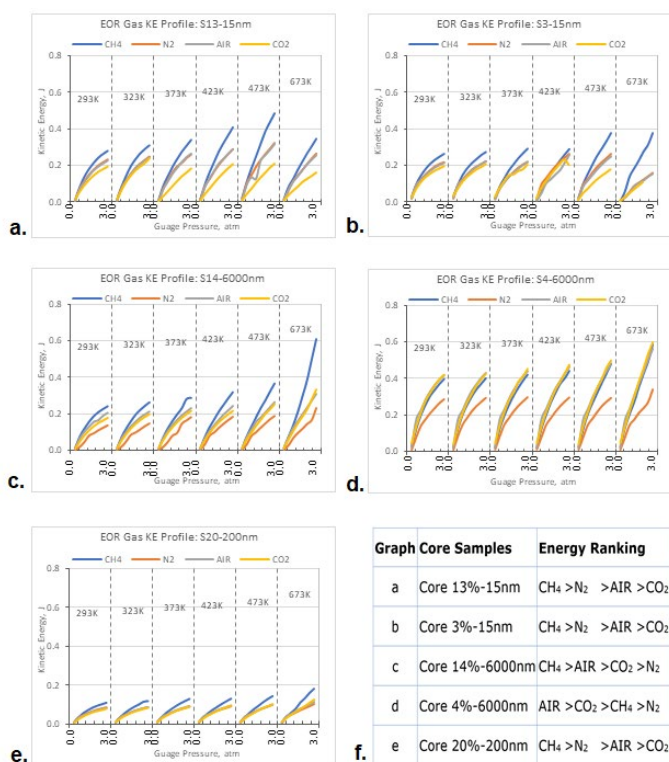


Figure4: Shows the energy profile of gases In analogues core Samples With Porosity/Pore size (a) 13%/15nm, (b) 3%/15nm, (c) 14%/6000nm, (d) 4%/6000nm, (e) 20%/200nm, And (f) showing The ranking of gases.

Comparing the propagation of the gas energy of the respective gases indicates that at low pressure (0.2 atm), the gas energies are hardly discriminated. However, as the pressure increases the energy magnitudes of the respective gases start to quantitatively segregate themselves. The extent of the segregation is significantly proportional to the applied pressure and slightly proportional to the operating temperature. This could be attributed to gas behaviour when departing from the ideal gas expectations due to pressure increase. It is observed also that the pressure required to achieve minimum segregation is dependent on the core sample used and the system (or core sample) operating temperature. For example, in Figure 4a, Core S13-15 nm, it takes about 1.0 atm gauge pressure to register energy segregation at an operating temperature of 293 K and 323 K. However, above 373 K, the pressure required to achieve energy segregation drops to 0.6 atm. This observation can be neatly explained by the law of conservation of energy or the kinetic theory. The reduction in the required pressure can be said to have been compensated by the external heat energy secured or adsorbed from the system or core sample walls as the gases permeate through the matrix. Furthermore, the segregation in Core S14-6000 nm (Figure 4c) is seen to require the least pressure (<0.6 atm) for all temperatures range studied. It is also noticed that the observed segregations are

facilitated by different gases. In Core S13-15 nm (Figure 4a), CO₂ catalyses the segregation. While N₂ catalyses it in Core S14-6000 nm (Figure 4c) and Core S4-6000 nm (Figure 4d). The segregation facilitation could be explained by the transport mechanism as described by Knudsen number and reported in analogical studies on permeance, perm-selectivity, diffusion and gas separation [49-52]. The Knudsen effect is, therefore, implicated in how gas molecules energy interactions are governed in the porous interstices.

Structural parameter

It is observed that the magnitude of energy is generally affected by the core structural parameters. Gases in Core S4-6000 nm comparatively possess the most energy (Figure 4d). While gases in Core S20-200 nm possess the least energy (Figure 4e). This indicates that reservoirs with lower porosity (4%) and larger pore size (6000 nm) would optimise the injected gas energy for displacing trapped oil than higher porosity reservoirs. Perhaps this could explain why tight or low porosity reservoirs mostly applied gas EOR technology (orange marker) compared to other EOR technologies, as revealed in field data analysis of EOR projects (Figure 5).

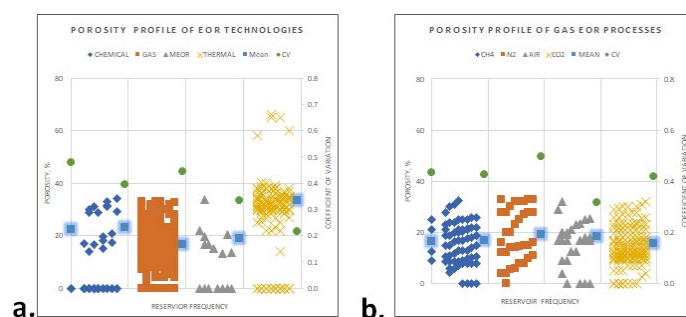


Figure5: Shows porosity clustering for various EOR (a) Technologies and (b) Respective gas EOR processes.

For all gases in Core 13 nm-15 nm (Figure 4a) at 0.2 atm, KE_{int} is correlated (R², 0.5-0.9) to porosity. But the correlation reduces to below R²=0.3 as temperature approach 673 K. KE_{int} correlation with pore size was hardly significant and consistent. Regardless of system operating temperature, the relationship as defined by the slope was generally negative at lower pressure (0.3 atm) but positive at higher pressure (3.0 atm). This relationship profile is found to validate the subject matter of the gaseous thermal conductivity of insulating materials. This experiment has shown that that gaseous thermal conductivity can be minimised in Nano Insulating Material (NIM) by controlling interstitial pressure and nanostructure to achieve a certain Knudsen effect, as earlier opined by authors such as [53].

Gas properties

An attempt was made to study the correlation of gas energy in porous media to gas thermophysical properties listed in Figure 1. It was observed that for Core S13-15 nm, S3-15 nm, S20-200 nm, the energy profile of the gases was significantly correlated to all the investigated properties that were listed in Figure 1, including gas unit cost pice (\$/cm³) of the respective gases. Nevertheless, the R² was below 0.20 at low pressure (0.2 atm) for all temperatures. However, the R² increases with pressure and it is further strengthened by an increase in temperature. This knowledge would find utility in high pressure and high temperature reservoir and industrial processes.

In S20-200 nm, it was observed that the kinetic diameter and mean free path correlation (R²) with gas energy first increases and then starts

decreasing with pressure, which implies a quadratic relationship.

In Core S14-6000 nm, energy correlation values were only significant for Specific Heat Capacity (at Constant Pressure), Absolute Viscosity, and Unit cost of gas.

In Core S4-6000 nm only Kinetic Diameter was significantly correlated, and this was only observed at low pressure (0.2 atm).

Heterogeneity

The energy performance of the gases in a heterogeneous setting was also investigated this is driven by the fact that typical reservoirs experience significant petrophysical heterogeneity and operational variability.

For a heterogeneous system, where the cores are notionally connected in a fashion similar to a layered reservoir, CH₄ was found to possess the highest kinetic energy (KE_{int}=0.19 J), hence it is the most competitive. The competitive ranking for all the gas in a heterogeneous system is thus: CH₄>AIR>CO₂>N₂

The correlation analysis shows that the Gas Molecular Weight, Specific Volume, Specific Heat Capacity (Constant Pressure), Absolute Viscosity and Unit cost of gas are fairly correlated to gas heterogeneous energy (R² 51%-73%).

The coefficient of variation (CV) analysis was carried out on the data to measure gas energy sensitivity to reservoir heterogeneity. The CV is a measure of how varied the distribution of quantity is around studied parameters. Low variability indicates better predictability. Reservoir engineers take pride in their ability to predict the production factors (e.g., energy, mobility and viscosity) and behavior of a reservoir system. Consequently, N₂ is reportedly the least sensitive or responsive to system heterogeneity by virtue of its relatively low CV (0.66), hence the most competitive in the aspect of predictability. The competitive ranking for the gases is thus: N₂>CH₄>AIR>CO₂.

CONCLUSION

It is concluded that the energy of IGEOR gases can be experimentally profiled using core analogues. The segregation of gas energies shows dependency on pressure, temperature and core structural microscopic and macroscopic parameters. CH₄ was the gas that possesses the most interstitial energy and it is well segregated from the other gases as pressure increases, except for the sample with 4% porosity and 6000 nm pore size. The gas energy possession was found to be significantly correlated to different gas properties, including the unit cost of gas. Overall CH₄ is the most competitive gas and N₂ is the least sensitive gas to reservoir heterogeneity. Reservoir and process engineers can directly apply knowledge to practice in selecting gases and screening reservoirs for IGEOR processes. This knowledge can also be applied in selecting gas for process where energy is needed, such as fluidisation to suspend granular or fine particles. It is recommended that an energy loss profile be carried out to determine which gas is prone to lose its intrinsically possessed energy. Such a study would reveal further the energy transferability during fluid interactions in the pore matrix.

REFERENCES

1. Abunumah O, Ogunlode P, Gobina E. Experimental evaluation of the mobility profile of enhanced oil recovery gases. *Adv Chem Engineer and Sci*. 2021; 11(02):154.
2. Ofasa A, Priscilla O, Edward G. Cost description and characterisation of gas enhanced oil recovery processes. In proceedings of the tuba world conference on energy science and technology. 2021;(8):88-89
3. Ofasa A, Priscilla O, Edward G. The effect of pressure and porous media structural parameters coupling on gas apparent viscosity. In proceedings of the tuba world conference on energy science and technology. 2021;(8):86-87
4. Godec M, Kuuskraa V, Van Leeuwen T, Melzer LS, Wildgust N. CO₂ storage in depleted oil fields: The worldwide potential for carbon dioxide enhanced oil recovery. *Energy Procedia*. 2011; (4):2162-2169
5. Dellinger SE, Patton JT, Holbrook ST. CO₂ mobility control. *Society of Petrol Engineers J*. 1984; 24(02):191-196.
6. Surguchev LM. Air injection to improve oil recovery from mature light oil field. *International research institute of stavanger*.2009
7. Rodríguez F, Christopher CA. Overview of air injection potential for pemex. In AAPG international conference.2004
8. Surguchev LM, Koundin A, Yannimaras D. January. Air injection-cost effective IOR method to improve oil recovery from depleted and waterflooded fields. In SPE asia pacific improved oil recovery conference. society of petroleum engineers. 1999
9. Alvarado V, Manrique E.Enhanced oil recovery: An updated review. *Energies*, 2010; 3(9):1529-1575.
10. Jia H, Yin SP, Ma XP. Enhanced oil recovery mechanism of low oxygen air injection in high water cut reservoir. *J Petrol Expl and Prod Tech*, 2018; 8(3): 917-923.
11. Chen ZY, Song H, Zhang XP. Air foam injection for eor in light oil reservoirs with high heterogeneity. *Adv Materials Research* .2012; 524-527
12. Bank GC, Riestenberg DE, Koperna GJ. CO₂-enhanced oil recovery potential of the appalachian basin. in eastern regional meeting. *onepetro*. 2007
13. Guo H, Dong J, Wang Z, Liu H, Ma R, Kong D, et al. EOR survey in china-part 1. In SPE improved oil recovery conference. *onepetro*. 2018
14. Liu ZX, Liang Y, Wang Q, Guo YJ, Gao M, Wang ZB, et al. Status and progress of worldwide EOR field applications. *J Petrol Sci and Engineer*.2020;(193):107449
15. Fassih MR, Yannimaras DV, Kumar VK. Estimation of recovery factor in light-oil air-injection projects. *SPE Reservoir Engineering*. 1997;12(03) :173-178
16. Babadagli T, Al-Bemani A, Boukadi F, Iyoho AW. January. EOR possibilities for development of a mature light-oil reservoir in Oman. In SPE Asia Pacific improved oil recovery conference. Society of Petroleum Engineers. 2001
17. Teigland R, Klepp J. January. EOR survey in the north sea. In SPE/DOE symposium on improved oil recovery. society of petroleum engineers. 2006
18. David FM, Robert MC. Enhanced oil recovery methods. In lyons, w. c. (ed.) standard handbook of petroleum and natural gas engineering: volume 2. texas: gulf professional publishing. 1996
19. Al Adasani A, Bai B. Analysis of EOR projects and updated screening criteria. *J Petrol Scie and Engineer*, 2011;79(1-2):10-24.
20. Gbadamosi AO, Kiwalabye J, Junin R, Augustine A. A review

- of gas enhanced oil recovery schemes used in the North Sea. *J Petrol Explor and Prod Tech.* 2018; 8(4):1373-1387.
21. David FM, Robert MC. Enhanced oil recovery methods. In Lyons, W. C. (ed.) *Standard Handbook of Petroleum and Natural Gas Engineering: Volume 2*. Texas: Gulf Professional Publishing. 1996
 22. Ahmed T, Meehan DN. Chapter 4-performance of oil reservoirs. In T. Ahmed, & D. N. Meehan (Eds.), *Advanced Reservoir Management and Engineering* (second edition) (pp. 433-483). Boston: Gulf Professional Publishing. 2012
 23. Hernández A. Chapter 10-design of intermittent gas lift installations. In A. Hernández (ed.), *Fundamentals of Gas Lift Engineering* (pp. 479-609). Boston: Gulf Professional Publishing. 2016
 24. Vega B, Kovscek AR. Carbon dioxide (CO₂) sequestration in oil and gas reservoirs and use for enhanced oil recovery (EOR). In *Developments and Innovation in Carbon Dioxide (CO₂) Capture and Storage Technology* (pp. 104-126). 2010
 25. Warner HR, Holstein ED. Chapter 12-Immiscible Gas Injection in Oil Reservoirs. In Lake, LW, Fanchi JR, Arnold K, Clegg JD, Holstein ED, Warner HR. *Petroleum Engineering Handbook: Reservoir Engineering and Petrophysics*. Society of Petroleum Engineers. 2007; (1103-1147).
 26. Yu X, Ma YZ, Psaila D, La Pointe P, Gomez E, Li S, et al. Reservoir characterization and modeling: A look back to see the way forward. In Y Z Ma and PR La Pointe, eds., *Uncertainty Analysis and Reservoir Modeling: AAPG Memoir 2011*; 96:289-309.
 27. Muggeridge A, Cockin A, Webb K, Frampton H, Collins I, Moulds T, et al. Recovery rates, enhanced oil recovery and technological limits. *Philosophical Transactions of the Royal Society: A Mathematical, Physical and Engineering Sciences*, 2006; (372): 20120320.
 28. Zhuravljov A, Lanetc Z. Relevance of analytical Buckley-Leverett solution for immiscible oil displacement by various gases. *J Petrol Explor and Prod Tech*, 2019;9(1):617-626.
 29. Buckley SE, Leverett M. Mechanism of fluid displacement in sands. *Transactions of the AIME*, 1942; 146(01):107-116.
 30. Thomas S, Ali S, Scouler JR, Verkoczy B. *Chemical Methods for Heavy Oil Recovery*. Petroleum Society of Canada. 2001.
 31. Gui B, Yang QY, Wu HJ, Zhan X, Lu Y. Study of the effects of low-temperature oxidation on the chemical composition of a light crude oil. *Energy & Fuels*, 2010;24(2):1139-1145.
 32. Khodaei Booran S, Upreti SR, Ein-Mozaffari F. Enhanced oil recovery with air injection: effect of the temperature variation with time. *Energy & Fuels*. 2016; 30(4):3509-3518.
 33. Jia H, Yuan CD, Zhang Y, Peng H, Zhong D, Zhao J, et al. January. Recent progress of high-pressure air injection process (HPAI) in light oil reservoir: laboratory investigation and field application. In *SPE Heavy Oil Conference Canada*. Society of Petroleum Engineers. 2012
 34. Masalmeh SK, Wei L, Blom C. Mobility control for gas injection in heterogeneous carbonate reservoirs: Comparison of foams versus polymers. In *SPE Middle East Oil and Gas Show and Conference*. Society of Petroleum Engineers.
 35. Li K, Horne R. An experimental and analytical study of steam/water capillary pressure. *SPE Reservoir Evaluation & Engineering*. 2001; 4(06):477-482.
 36. Skerget L, Jecl R. 2-boundary element method for transport phenomena in porous medium. In D. B. Ingham, & I. Pop (Eds.). *Transport Phenomena in Porous Media II 2002*; 20-53.
 37. Rapp BE. Chapter 6-thermodynamics. In BE Rapp (Ed.), *Microfluidics: Modelling, mechanics and mathematics*. 2017
 38. Carnot L. *Principes fondamentaux de l'équilibre et du mouvement*; par LNM Carnot. de l'imprimerie de Crapelet. 1803
 39. Ohring M. Chapter 2-vacuum science and technology. In M. Ohring (Ed.), *Materials Science of Thin Films* second edition. San Diego: Academic Press. 2002: 57-93.
 40. Aliu S, Amoo OM, Alao FI, Ajadi SO. 2-mechanisms of heat transfer and boundary layers. In R. O. Fagbenle, O. M. Amoo, S. Aliu & A. Falana (Eds.), *Applications of Heat, Mass and Fluid Boundary Layers*. 2020;23-5
 41. Duan Z, Ma H. Chapter four pressure drop and heat transfer in the entrance region of microchannels. *Advan in Heat Trans.* 2020;52:249-333.
 42. Bastian ER. *Microfluidics: Modelling, Mechanics and Mathematics*. 2017
 43. Britannica. The Editors of Encyclopaedia. Kinetic energy. 2021.
 44. Balmer RT. *Modern Engineering Thermodynamics-Textbook with Tables Booklet* Academic Press. 2011.
 45. Ogunlode P, Abunumah O, Gobina E. A study of gas diffusion characteristics on nano-structured ceramic membranes. *Euro J Engineer and Formal Sci.* 2020;4(1):21-23.
 46. Ogunlode P, Abunumah O, Orakwe I, Shehu H, Muhammad-Sukki F. Comparative evaluation of the effect of pore size and temperature on gas transport in nano-structured ceramic membranes for biogas upgrading. 2019;5(1): 195-205.
 47. Priscilla O, Ofasa A, Firdaus Muhammad-S, Edward Testing membranes for separation of CO₂ from small molecules in landfill gas, In *Proceedings of the TUBA World Conference on Energy Science and Technology*. 2021; 84-85
 48. Kajama M, Shehu H, Okon E, Gobina E. Preparation and characterization of inorganic membranes for hydrocarbon separation from N₂ for environmental applications. *Ener and Environ Res.* 2015; 5(1).
 49. Okon E, Shehu H, Gobina E. Novel application of gas transport properties with ceramic membrane for VOC emission and lactic acid esterification. *Eur J Engineer and Tech.* 2014;2(2)
 50. Okon E, Shehu H, Gobina E. Evaluation of the performance of α -alumina nano-porous ceramic composite membrane for esterification applications in petroleum refinery. *Catalysis Today*. 2018.; (310):146-156.
 51. Kajama MN, Shehu H, Okon E, Orakwe I, Gobina, E. VOC oxidation in excess of oxygen using flow-through catalytic membrane reactor. *Inter J Hydrogen Energy*. 2016. 41(37), 16529-16534.
 52. Baetens R, Jelle BP, Thue JV, Tenpierik MJ, Grynning S. Vacuum insulation panels for building applications: A review and beyond. *Energy and Buildings*, 2010; 42(2):147-172.
 53. Shatat M, Elmer T, Tetlow D, Riffat S. The state of the art: Superinsulation construction materials under the UK's domestic energy building: Aerogel and vacuum insulation technology applications. In *14th International Conference on Sustainable Energy Technologies-SET*. 2015 ;25-27.