ABUNUMAH, O., OGUNLUDE, P. and GOBINA, E. 2021. Gas injection power requirements in gas enhanced oil recovery (EOR). Presented at 2021 International congress on scientific advances (ICONSAD'21), 22-25 December 2021, [virtual conference].

Gas injection power requirements in gas enhanced oil recovery (EOR).

ABUNUMAH, O., OGUNLUDE, P. and GOBINA, E.

2021

ROBERT GORDON UNIVERSITY ABERDEEN

GAS INJECTION POWER REQUIREMENTS IN GAS ENHANCED OIL RECOVERY (EOR)

By

Dr Ofasa Abunumah, Priscilla Ogunlude, Prof Edward Gobina

Centre for Process Integration and Membrane Technology
School of Engineering
The Robert Gordon University, Aberdeen, UK

December, 2021.

Table of Content

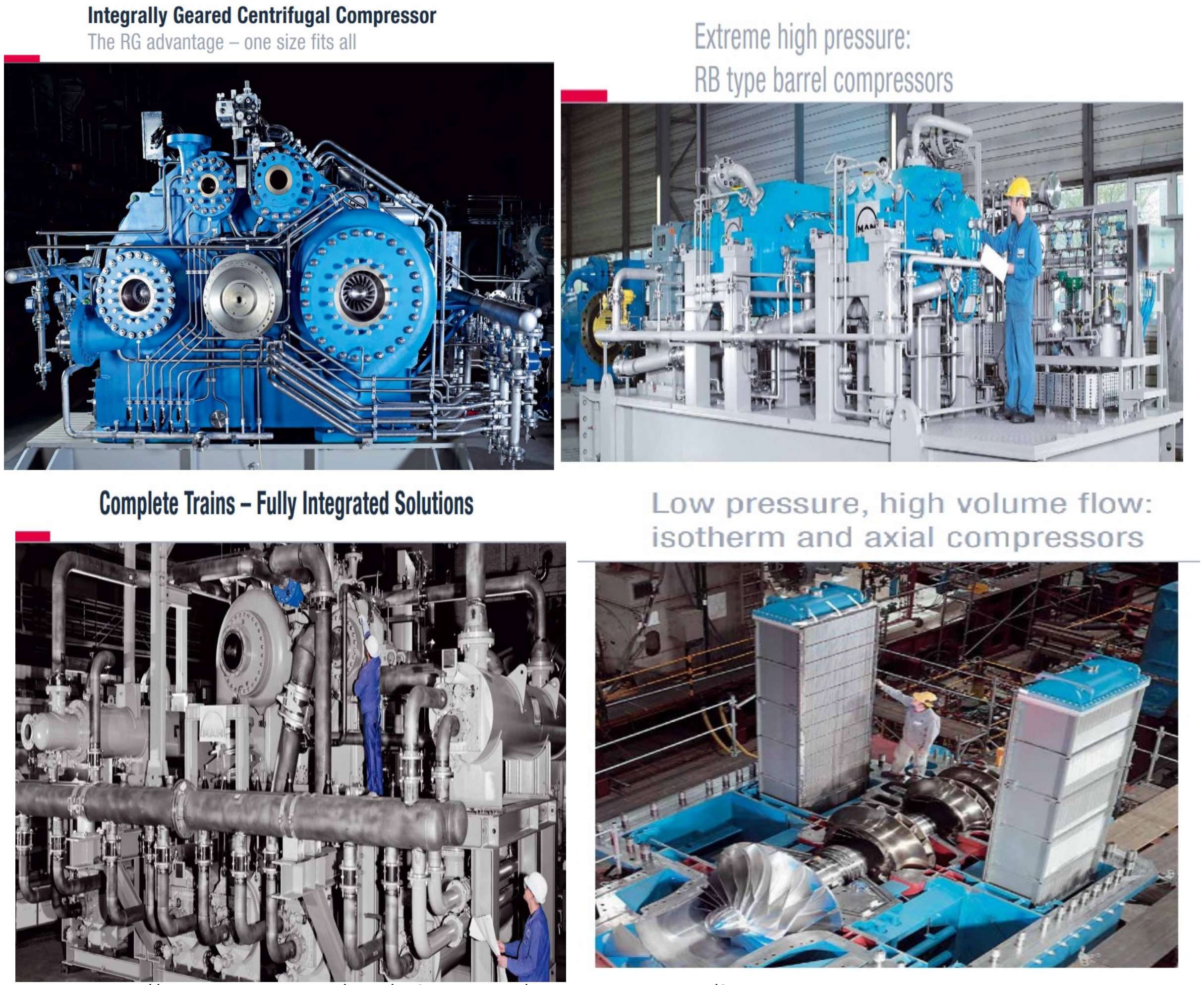
Overview

Globally, **70% of oil droplets are trapped** in layers of reservoir pores. **10-40%** of the trapped oils can be displaced by gases (**CH_4, N_2, Air, CO_2**) in an immiscible gas enhanced oil recovery (IGEOR) process.

These gases distinctive characteristics might couple with the reservoirs geological settings differently, such that the **compressor ratings** (power and size) required to achieve a certain compression and displacement would differ from gas to gas and from one reservoir layer to another.

The aim of the study is to identify the gas and geological settings that enable **compressor ratings optimisation** in gas EOR processes.

Overview

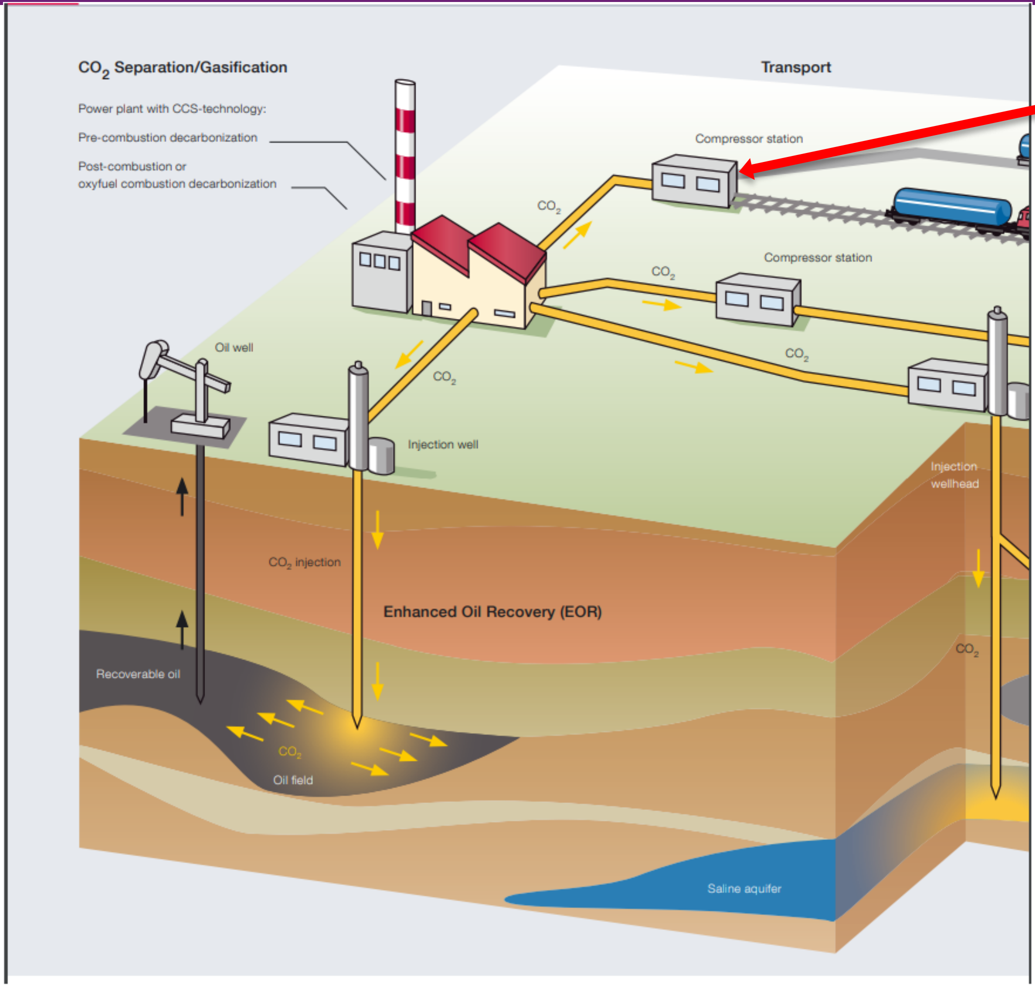


Source: https://mandieselturbo.com/docs/default-source/shopwaredocuments/forward-thinkinge37da7a0c5b64851b3175821c9acdc8a.pdf?sfvrsn=6

Figure 1 Showing different types, ratings and sizes of compressors ranging from 4 to 10 stages, with speed and pressure requirements ranging from 8,000-48,000rpm and 20-180bar. Powered by electric motor.

According to what is known of fluid dynamics and porous media parameters, it is expected that the coupling of these two would inform the required compressor specification for effective injection and gas-oil displacement in EOR projects

Overview



Source: https://mandieselturbo.com/docs/default-source/shopwaredocuments/forward-thinkinge37da7a0c5b64851b3175821c9acdc8a.pdf?sfvrsn=6

Figure 2 The layout for CO_2 gas injection show the compressor station is a major unit in EOR projects, hence a significant economic and technical centre, such that it affects:

1. Power cost
2. Well density
3. Injection direction
4. Gas cost
5. Recovery efficiency

Methodology

Stages	Objective	Method
	# Theories, principles and practices that describe fluid dynamics . # Identify **quantities** (Structural and Fluid)**, functions** and **indicators** relevant for the acquisition and evaluation of CRs in EOR processes.	Literature Review
PHASE 1	# **Characterise** gas EOR reservoirs by identified quantities, functions and indicators. # Determine degree of functional and parametric relationships.	Data Mining
PHASE 2	# Design gas experiments to measure CRs indicators. # **Characterise** EOR gases by measured indicators and determine their **Competitiveness**.	Gas Experiments

Fluid Dynamics

Law & Theory

Darcy's Law	Fick's Law	Bernoulli's Law	Ideal Gas Law	Hagen-Poiseuille's Law	Knudsen

↓

Practice & Application

Enhanced Oil/Gas Recovery	Gas Separation	Catalytic Reaction	Water treatment	Insulation	Carbon Caption and Storage

Quantities, Functions and Indicators

A: Fluid Quantities

1. Pressure = P
2. Temperature $= T$
3. Volume = V
4. Gas Constant $= R$
5. Compressibility Factor $= z$
6. Number of Moles $= n$
7. Molecular Weight = MW
8. Density = ρ
9. Subscript o = oil
10. Subscript g = gas
11. Parachor = Pch
12. Contact angle = θ
13. Core Outer Radius = r_{outer}
14. Core Inner Radius = r_{inner}
15. Pay Zone or Core Height = h

B: Structural Parameters (Geological and Geometrical)

1. Parameter, Par
2. Pore Size, r_p = Supplied by manufacturer
3. Porosity, $\phi = 1 - \left(\frac{Specific\ Particle\ Density}{Specific\ Bulk\ Density}\right)$
4. Tortuosity, $\tau = (1 - 0.41 ln\phi)$
5. Gas Entering Surface Area, $A = 2\pi r_{outer}\ h$
6. Radial Thickness, $r_{thickness} = r_{outer} - r_{inner}$
7. Aspect Ratio, AR $= \frac{r_p}{r_{thickness}}$
8. Parameter Gradient, $\lambda_{Par} = \left(\frac{Par_{exit} - Par_{entering}}{\sum Par_{extents}}\right)$
9. Reservoir Quality Index, RQI $= 0.0314\sqrt{\frac{K}{\phi}}$
10. Number of Pores, $N_p = \phi h \frac{(r_{outer} + r_{inner})}{(r_{pore})^2}$
11. Pores Density, $P_p = \frac{N_p}{A} = \phi h \frac{(r_{outer} + r_{inner})}{2\pi r_{outer}\ h (r_p)^2}$

C: Parametric Functions (Fluid and Engineering)

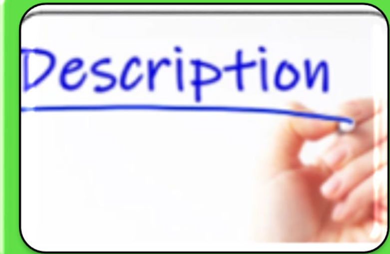
1. The Ideal Gas Law, PV $= nRT$
2. Reservoir (rev) and Standard (std) States Analogy, $\left(\frac{PV}{zT}\right)_{res} = \left(\frac{PV}{T}\right)_{std}$
3. Darcy Radial Gas Flow, $Q_{std} = 858 \frac{K}{\mu} \frac{h}{T} \frac{(P_1{}^2 - P_2{}^2)}{\ln\frac{r_1}{r_2}}$
4. Interstitial Flow Throughput, $IFT = \frac{Q_{std}}{\phi} = 858 \frac{1}{\phi} \frac{K}{\mu} \frac{h}{T} \frac{(P_1{}^2 - P_2{}^2)}{\ln(\frac{r_{outer}}{r_{inner}})}$
5. Interstitial Pore Holding Capacity, $IPHC = \frac{Darcy\ Flowrate}{Number\ of\ Pores} = \frac{Q_{std}}{N_p} = \frac{Q_{std}\ (r_{pore})^2}{\phi h (r_{outer} + r_{inner})}$
6. Capillary Pressure, $P_c = P_o - P_i = \frac{2\sigma cos\theta}{r_p} = P_d$
7. Surface Tension $\sigma = \left(Pch_o \left[\frac{\rho_o}{MW_o}\right] - Pch_g \left[\frac{\rho_g}{MW_g}\right]\right)^4$

ROBERT GORDON UNIVERSITY ABERDEEN

Evaluation Method

Evaluation

- Compressor ratings (Power and Size) are functions of the injection pressure, energy and momentum required for gas-oil displacement to occur in an EOR process and reservoir.
- Capillary Pressure (CP) and Displacement Pressure (DP) can effectively be adopted as the Indicators of injection pressure in laboratory scale.



Indicators & Description

- Capillary Pressure (CP): Minimum pressure required to overcome fluid flow resistance in a porous or reservoir media.
- Displacement Pressure (DP): Minimum pressure required to displace fluid (gas) through a porous media.
- CP and DP are technically equal and are influenced by similar properties such as pore size.

Data Acquisition

- Capillary pressure is obtained from global EOR field data using parametric function.
- Displacement pressure is experimentally determined from the intercept of the backward extrapolation of the graph of Injection Pressure vs Flow Rate.

Method Summary

Objective Function:

Compressor Ratings

↓

Adopted Indicators:

Capillary Pressure (CP) and Displacement Pressure (DP)

↓

Optimisation Extrema Requirements:

Minima CP and DP	EOR Competitiveness- Lowest CP	Gas Competitiveness- Lowest DP

Phase 1: Data Mining Results

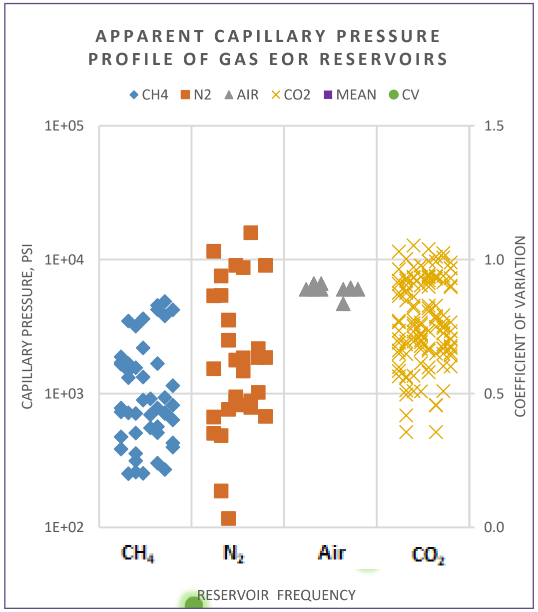


Figure 3 Scatter plots of the CP profiles of the respective gas EOR processes implemented in 450 reservoir projects.

From **Figure 3** the following can be deduced:

- Gas EOR reservoirs can be characterised by capillary pressure.
- The mean values of the respective gas CPs indicate that reservoir implementing CH_4 EOR process requires the least pressure, hence the least CRs.
- While Air requires the most CRs.
- The most clustered capillary pressure is Air. The coefficient of variation (CV) suggest that Air is the most sensitive to compressor rating selection.
- N_2 has the highest CV, hence the least sensitive to compressor rating selection.
- **Consequently, the competitive Ranking for CRs in the field data: CH_4 > N_2 > CO_2 > Air.**

The data mining outcome thus gave the impetus for the experimental design.

Phase 2: Media Structural Parameters

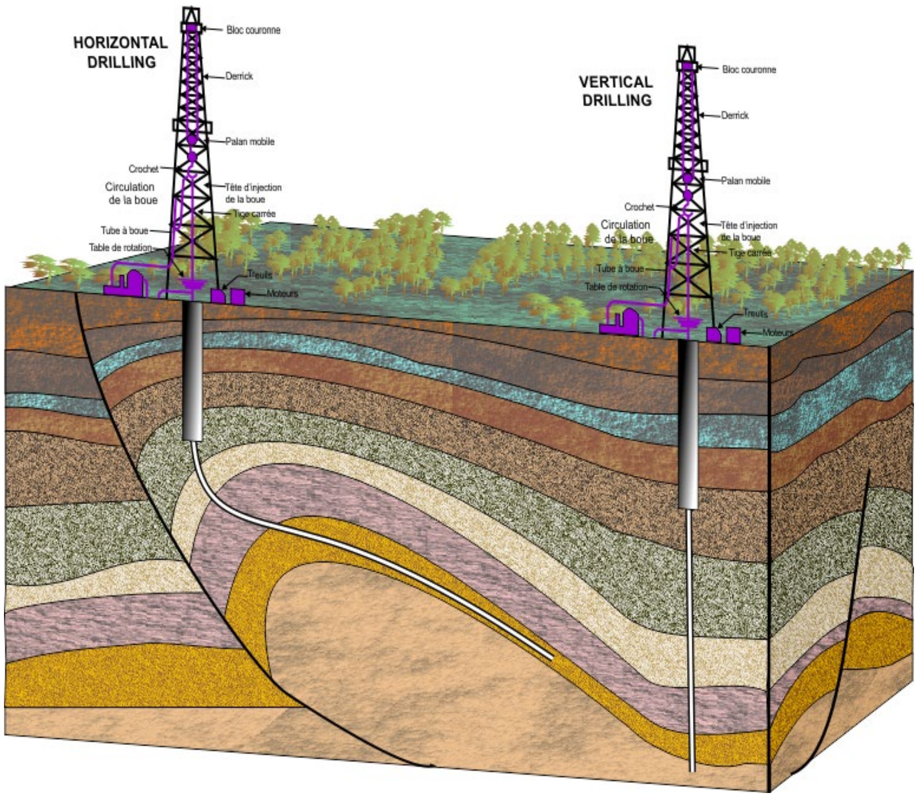
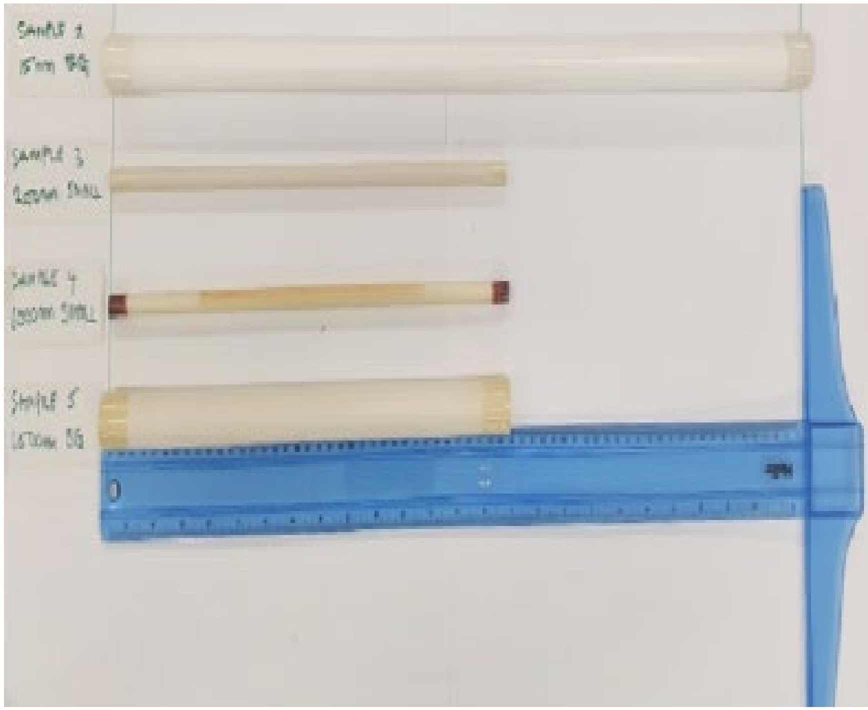


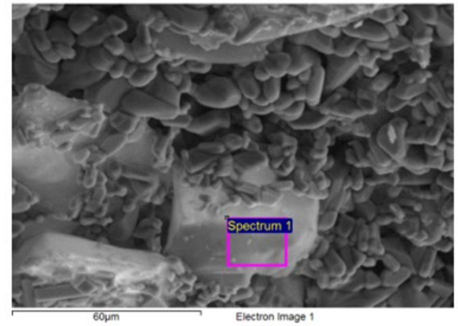
Figure 4 Showing reservoir geological layers with different structural parameters that leads to structural rhythms and gradients that may affect CP and DP.

Table 1 Showing 5 porous samples used in the experiment and their structural characteristics representing of 5 geological layers.

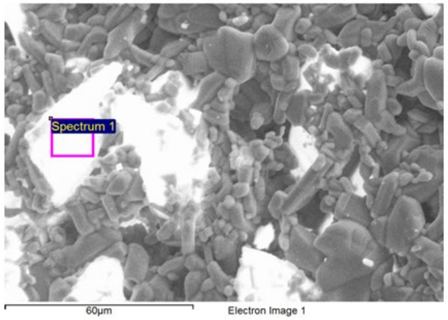
Porous Sample	Structural Parameters			
	Geometry		Porosity	Aspect Ratio
	Pore Size	Radial Thickness		
.1	15nm	0.14cm	φ= 13%	10E+04
.2	15nm	0.25cm	φ= 3%	2E+05
.3	200nm	0.16cm	φ= 20%	8E+03
.4	6000nm	0.14cm	φ= 14%	2E+02
.5	6000nm	0.24cm	φ= 4%	4E+02

Phase 2: Media Structural Parameters

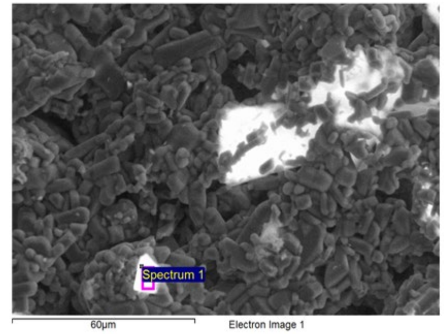




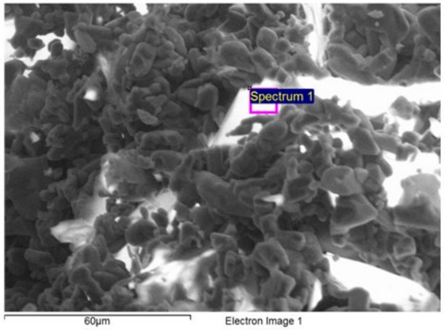
Sample Core 3-15nm



Sample Core 20-200nm



Sample Core 14-6000nm



Sample Core 4-6000nm

Figure 5 Showing 4 of the porous core samples (Sample 2, 3, 4 and 5), their relative dimensions and their EDXA morphologies.

Phase 2: Connections & Configurations

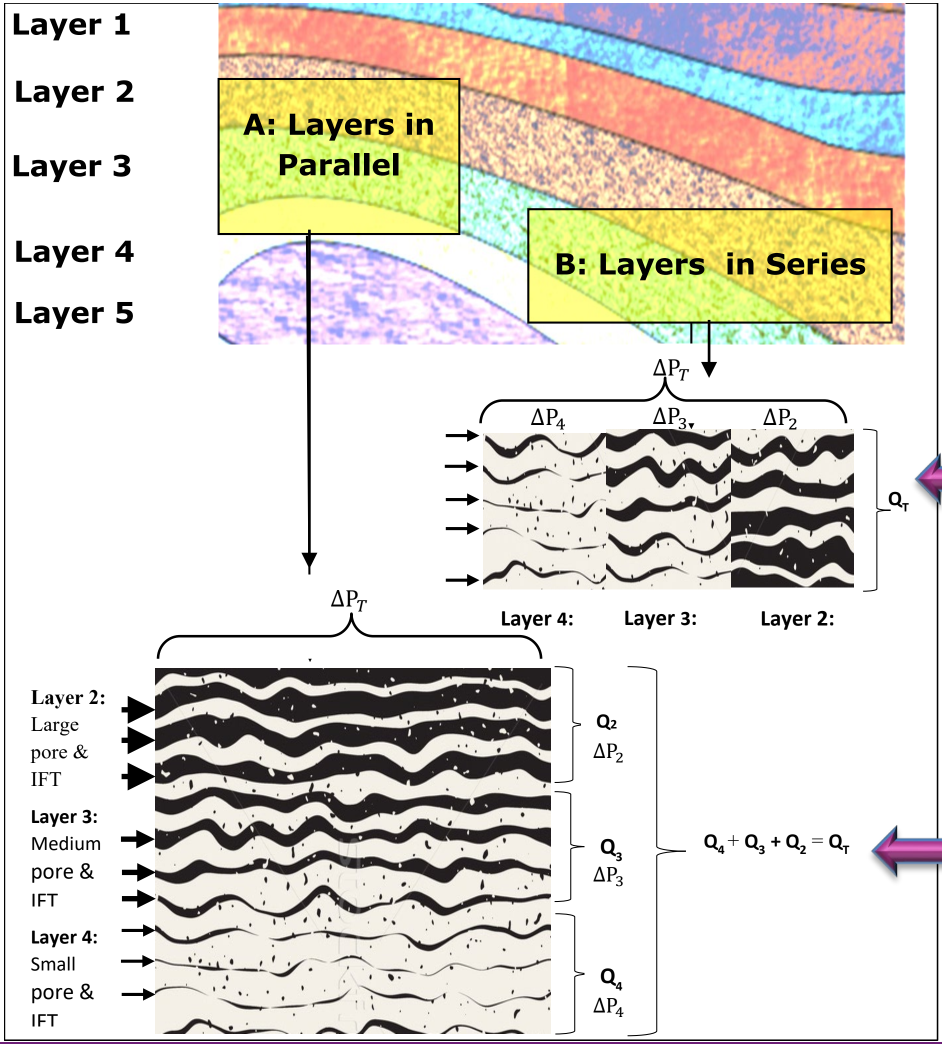


Figure 6 Showing 5 reservoir layers with geological sections (yellow highlights) that are representative of parallel (A) and series (B) flow connections and structural configurations with distinct pressure profiles. The pressure profile influences the compressor ratings.

Fluid dynamics principles suggest that:

the total pressure drop, ΔP_T across all flow units (layer 4, 3, 2) connected in series is the summation of pressure drop across the individual flow units (i.e., layer 4, 3, 2).

So, $\Delta P_T = \sum_i^3 \Delta P_i = \Delta P_4 + \Delta P_3 + \Delta P_2$

Fluid dynamics principles suggest that:

the total pressure drop, ΔP_T across all flow units (layer 2, 3, 4) connected in parallel is equal to the pressure drop across the individual flow units (i.e., layer 2, 3, 4).

So, $\Delta P_T = \Delta P_2 = \Delta P_3 = \Delta P_4$

ROBERT GORDON UNIVERSITY ABERDEEN

Phase 2: Gas Experiments

- **Procedure:**

Gas is injected into porous media setup at constant pressure and core temperature. Permeation rate records are taken at steady state and 1atm.

- **Operating Condition:**

Temperature range 293-673K

Pressure range 20-300KPa

- **Experimental Data:**

1,097 runs.

8,777 data points.

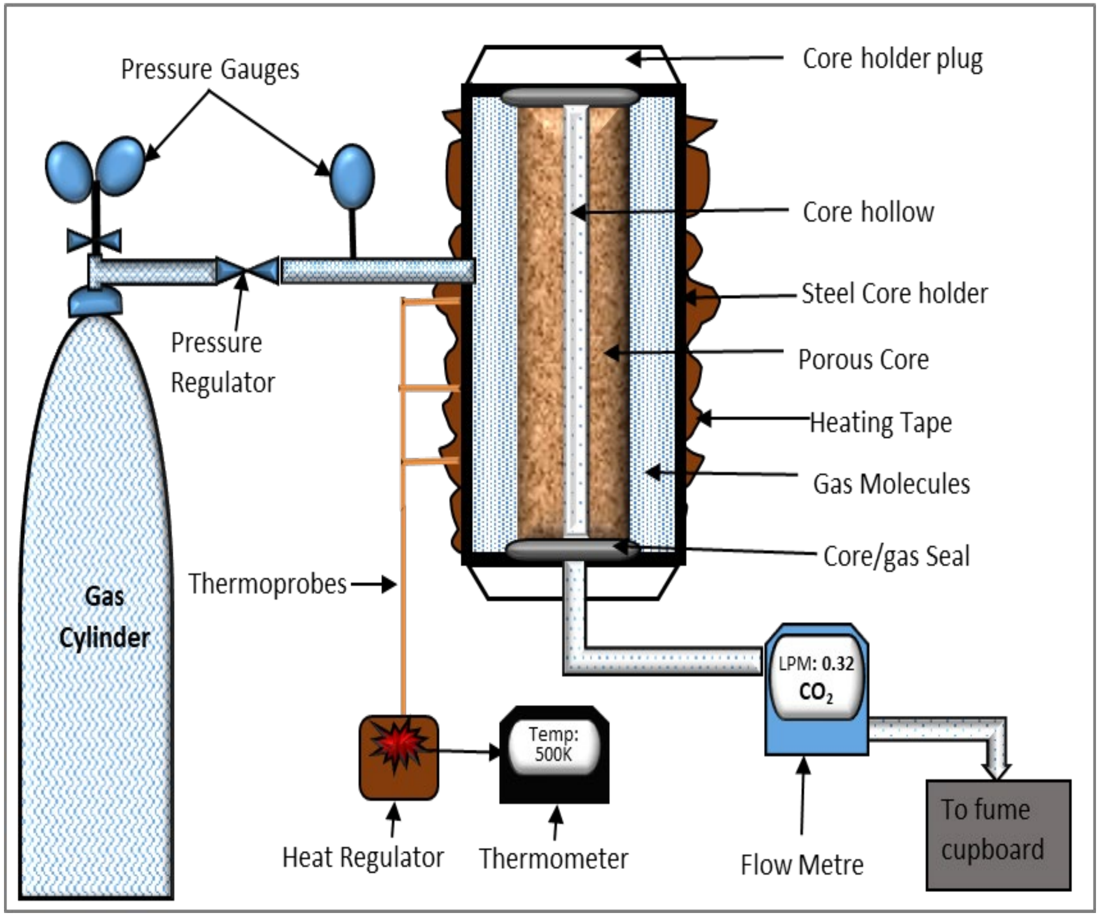


Figure 7 schematic of experimental set up.

ROBERT GORDON UNIVERSITY ABERDEEN

Phase 2: Experimental Results

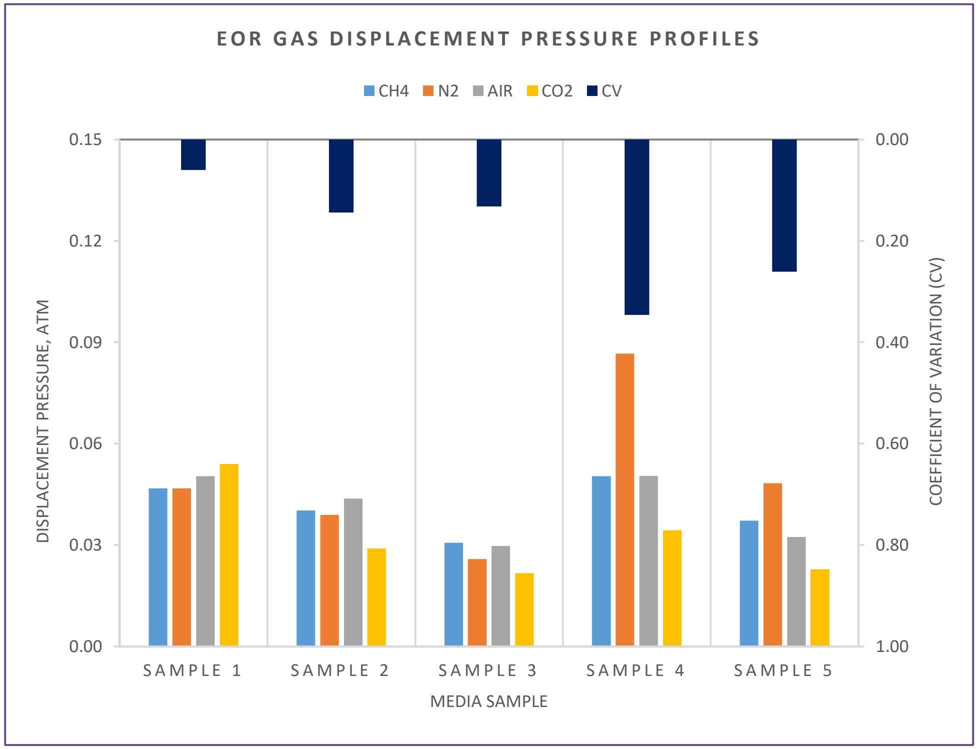


Figure 8 Showing the DP profiles in samples 1,2,3,4 and 5 and the degree of DP discrimination by each sample.

- The bar chart in **Figure 8** indicates that CO_2 consistently required the least DP in Sample 2,3,4, and 5. Hence satisfying the extremum criteria of minimum CRs.
- Sample 1 has the least coefficient of variation (CV). Furthermore, CH_4 and N_2 have the least DPs. The outcome in Sample 1 could be due to transport mechanism, such as the Knudsen characterisation, thereby allowing the fluid flows to be influenced by the respective gas molecular weights.
- The CV is relatively high for Sample 4 (6000nm) and 5 (6000nm). The high CV values suggest that Sample 4 and 5 have the most significant DP discrimination for the gases. Therefore implying that pore size is a critical factor that influence the respective gas CRs.

Phase 2: Experimental Results

a

Gas	Pore Dimension	Porosity	Tortuosity	Displacement Pressure	Analogous Core Sample
CH_4	6000nm	14	3.42	0.050	Suitable layer for Injection Well
	15nm	13	3.38	0.047	
	15nm	3	3.20	0.040	
	6000nm	4	3.84	0.037	
	200nm	20	3.49	0.031	Suitable layer for Production Well
Parameter Gradient	-0.0006	0.0646	0.0600	-0.0197	

b

Gas	Pore Dimension	Porosity	Tortuosity	Displacement Pressure	Analogous Core Sample
N_2	6000nm	14	3.42	0.087	Suitable layer for Injection Well
	6000nm	4	3.84	0.048	
	15nm	13	3.38	0.047	
	15nm	3	3.20	0.039	
	200nm	20	3.49	0.026	Suitable layer for Production Well
Parameter Gradient	-0.0006	0.0646	0.0600	-0.0608	

c

Gas	Pore Dimension	Porosity	Tortuosity	Displacement Pressure	Analogous Core Sample
Air	6000nm	14	3.42	0.0504	Suitable layer for Injection Well
	15nm	13	3.38	0.0503	
	15nm	3	3.20	0.044	
	6000nm	4	3.84	0.032	
	200nm	20	3.49	0.030	Suitable layer for Production Well
Parameter Gradient	-0.0006	0.0646	0.0600	-0.0207	

d

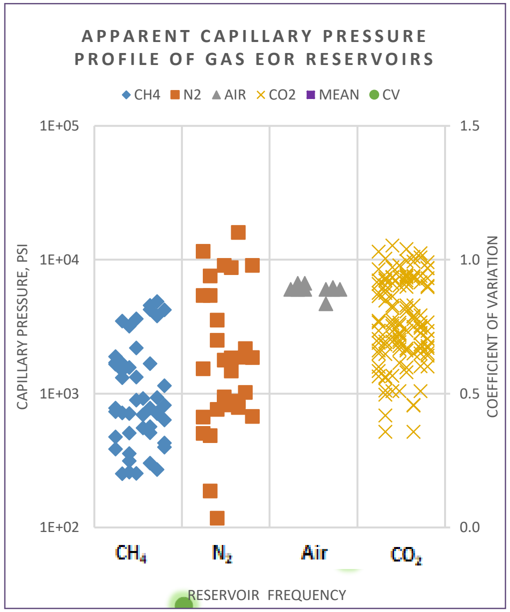
Gas	Pore Dimension	Porosity	Tortuosity	Displacement Pressure	Analogous Core Sample
CO_2	15nm	13	3.38	0.054	Suitable layer for Injection Well
	6000nm	14	3.42	0.034	
	15nm	3	3.20	0.029	
	6000nm	4	3.84	0.023	
	200nm	20	3.49	0.022	Suitable layer for Production Well
Parameter Gradient	0.00002	0.1079	0.0700	-0.0323	

Figure 9 Showing the structural approaches (rhythms and gradients) that optimise CRs for (a) CH_4, (b) N_2, (c) Air, (d) CO_2.

It is observed in **Figure 9** that the respective gases optimise DP via different compound structural routes or rhythms.

- The structural gradients and well topologies for N_2 and CH_4 are similar, but the rhythms are different. CH_4 and Air share the same structural approach (rhythm, gradient and topology).
- CO_2 has a unique structural approach.
- For all gases, the layer with 20% porosity is the most suitable for placing the production well.

Coupling of Phase 1 & 2 Results



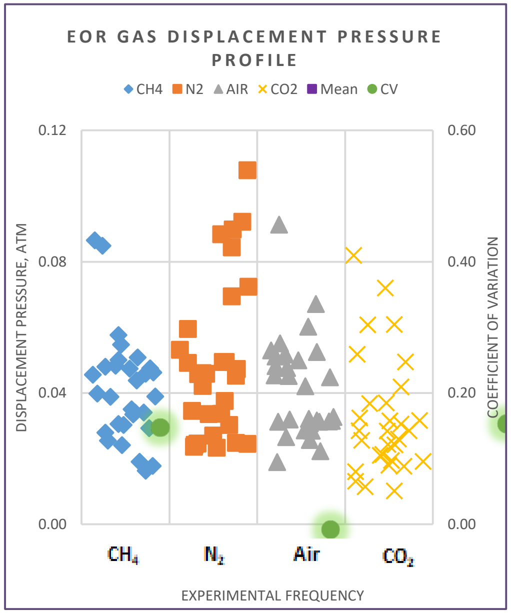


Figure 10 Show the displacement pressure profile for (a) gas EOR processes by data mining and (b) EOR gases by experimental method.

The scatter plots in **Figure 10** offer a qualitative and quantitative comparison of field and experimental data in a heterogeneous reservoirs settings.

- The mean values of the gas DP suggest N_2 requires a relatively high CRs, while CO_2 requires the least ratings. Therefore, CO_2 is the most competitive gas for heterogeneous system.
- In the two graphs, the CV analyses shows Air injection power rating is the most affected by structural variability or reservoir heterogeneity.

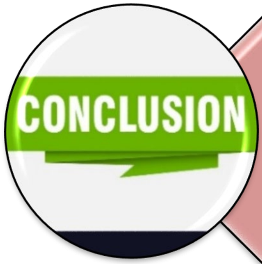
Consequently, experimentally determined competitive Ranking for CRs:

CO_2 >Air > CH_4 > N_2

Data Mining determined competitive Ranking for CRs:

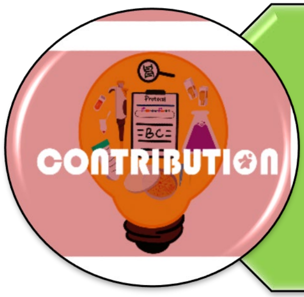
CH_4 > N_2 >CO_2 >Air

Conclusion/Contribution/Recommendation



The competitive ranking for compressor power and sizing requirements is experimentally determined as:

CO_2 >Air > CH_4 > N_2



Knowledge: Study can be directly applied in selecting gas and screening reservoirs for GEOR processes to minimise power cost.

Practice: Facilitates engineers' selection of gas based on process objectives, reservoir structural heterogeneity & rhythm.

Two-phase study of oil and gas is encouraged.

Thank you

for

Listening