Nigerian Journal of Engineering Science Research (NIJESR),
Vol. 3, Issue 1, pp.01-16

ISSN: 2636-7114
Journal homepage: www.nijesr.iuokada.edu.ng

The Mechanism and Characteristics of Carbon (IV) Oxide Enhanced Oil Recovery Technique: A Review and Technical Approach

[1]Akene, A., [2]Ikpoza, E., and [3]Ogie, N.A.

[1]Department of Mechanical Engineering, Federal University of Petroleum Resources, Effurun, Delta State, Nigeria
akene.alexander@fupre.edu.ng
[2]Department of Production Engineering, University of Benin, Benin City, Nigeria
emmanuel.ikpoza@uniben.edu
[3]Department of Mechanical Engineering, Petroleum Training Institute, Effurun, Delta State, Nigeria
ogie_na@pti.edu.ng

**Corresponding author: Alexander Akene (akene.alexander@fupre.edu.ng)*

Manuscript History
Received: 06/01/2020
Revised: 05/03/2020
Accepted: 18/03/2020
Published: 20/04/2020

Abstract: *Carbon (IV) oxide (CO_2) is mainly used in gas enhanced oil recovery because it is relatively cheap with good swelling properties and it is readily available both in natural and artificial sources. In this research work, the mechanism and characteristics of CO_2 Enhanced Oil Recovery Technique (EOR) technique with emphasis on its processes, including its advantages and disadvantages, operational and reservoir problems and limitations were successfully reviewed. An analytical approach was used to determine which technique is best suitable for a particular reservoir as well as the potential of such process. A SWOT (strength, weakness, opportunity and threat) analysis was carried-out on the two most applied EOR process (continuous CO_2 injection and WAG). The outcome of the research work reveal that CO_2 EOR technique produces high GOR due to conformity and fractures of high permeability layers present in the reservoir, thus leading to higher recovery efficiency. Also, the success of CO_2 EOR projects is largely dependent on the availability because CO_2 flooding processes require large volume of CO_2 on a continuous basis throughout the field's life. More so, CO_2 EOR process is dependent on temperature, fluid composition, relative permeability, reservoir pressure, reservoir geometry, gravity and oil saturation in the pores of the formation rock. It was also observed that continues CO_2 injection process accounts for high recovery efficiency at the early stage of injection but with lesser recovery period due to poor sweep efficiency, while water alternating gas (WAG) process account for increase displacement and sweep efficiency. Hence, it is widely employed in most CO_2 fields. Also, Continuous CO2 injection encourages early production and recovers more oil but is limited to large CO_2 and reservoir problems however, water alternating gas (WAG) recovers less oil from the reservoir at the initial stage of operation but with a much better long term recovery process owing to improved sweep and increased displacement efficiency of the process. Besides its opportunities, the major operating problems associated with these techniques are CO_2 break through, gravity segregation, viscosity fingering and corrosion. However, both techniques are potentially viable EOR technique for recovering more oil from mature and depleted oil reservoirs as they can extend the recovery life of a field for further and future production.*

Key words: Mechanism and Characteristics of Carbon (IV) Oxide, Enhanced Oil Recovery Technique, Analytical Approach, Continuous Carbon (IV) Oxide Injection, Water Alternating Gas Process

INTRODUCTION

The Carbon (IV) oxide (CO_2) is one of the most abundant gases present in the atmosphere. It is obtained from natural or anthropogenic activities. Its application in mature and depleting oil reservoirs have long gained attention since the 1950's with much field-testing and laboratory research indicating that CO_2 is capable of recovering much of the oils left behind by conventional recovery mechanisms. Besides, Understanding the properties of CO_2 gives an idea of how CO_2 probably behaves and flows in the reservoir at different temperature and pressure conditions. However, it is very importantly to understand how CO_2 interacts with the reservoir fluid and rock during CO_2 flooding process (Abdulrazag *et al.*, 2002; UDE, 2005; Abiodun and Shameem, 2009). CO_2 gas is one of the major gases used in gas EOR recovery. This is because it is relatively cheap with good swelling properties and it is readily available both in natural and artificial sources. The goal of CO_2 EOR project is to maximise profit by minimising the total amount of CO_2 injected per barrel of oil recovered. CO_2 EOR technique is not a recent technology as its practice is well understood within the oil and gas industry especially in the United State of America with over 30 years of EOR experience (Aurel, 1992; Carl and Michael, 2004; Bank and Koperna, 2007). It involves the injection of carbon (IV) oxide into mature or depleted oil reservoirs for more oil recovery. It can be achieved through two processes, miscible or immiscible displacement. Miscible displacement process is most efficient and most used enhanced oil recovery technique. Experience gained worldwide from CO_2 flooding indicates that CO_2 EOR technique is capable of recovering up to 7% - 15% additional original oil initially in place (Buckley and Liu, 1996; Brummeri, 1999; Blaine and Ashok, 2004). Over one hundred and twenty five (125) CO_2 EOR projects are currently in operation, but less than 10% of them use CO_2 captured from anthropogenic sources. Most use CO_2 from natural sources (David, 2009).

Conventional primary and secondary oil production techniques used for recovery in oil and gas reservoirs typically produces only about 15% to 40% of original oil in place (OOIP) leaving about two thirds behind. With much of the ''easy to produce'' oil already recovered worldwide, and the rate of depletion of oil fields coupled with the cost of finding and producing new oil fields, the oil and gas industry was force to develop and employ different enhanced oil recovery (EOR) methods to recover a greater proportion of residual oil from the reservoir. An EOR technique improves the efficiency of oil recovery, extends field's life and increases profitability of the field when compared with conventional method of oil production (Fayers, 1981; Grigg and Sigan, 1998; Hao, 2004). Gas, chemical and thermal recovery are the three major EOR techniques use employed in oil recovery in the oil and gas industry (Grigg and Sigan, 1998). However, much of these EOR projects are onshore based, this is due to the technical and economic complexity (e.g. platform spacing, well spacing, logistics, etc.) of offshore EOR projects (McGinnis and Shatto, 1993; UDE, 2005).

RESEARCH METHODOLOGY

A. Mechanism of Carbon (IV) Oxide Miscible Displacement

Two fluids are said to be miscible if they combine in all proportions without any interface forming. CO_2 is readily soluble in oil as shown in Fig. 1 and forms single-phase fluid without any interface as it mixes with reservoir oil. Solubility, diffusion and dispersion are the three mass transfer mechanisms through which CO_2 mixes with the oil. However, of these three, solubility accounts for the greatest part of the mixing. Furthermore, CO_2 miscibility is controlled by the composition of CO_2, composition of the oil, pressure and temperature. Carbon (IV) oxide miscibility process involves vaporisation of the lighter oil fraction and extraction of the heavier carbon chain (i.e., C_5 to C_{30}) range of hydrocarbon from the reservoir oil into the injected CO_2 phase and also condensing back into the reservoir oil phase.

This potentially leads to improved oil recovery through decrease in the oil density and viscosity, increase in the oil volume (oil swelling), and lowering of the trapping forces in the reservoir. Dynamic remobilisation of the residual oil in the reservoir's pore space is the primary objective of CO_2 miscible displacement (Ivan and Rafael, 2007).

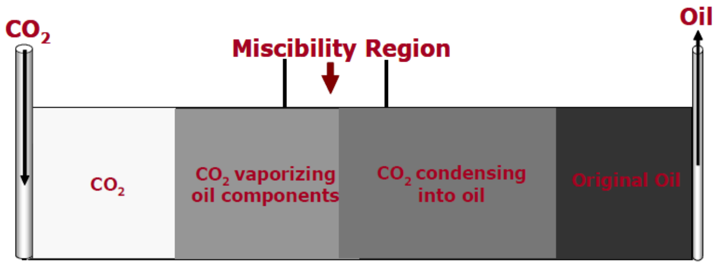

Fig.1 One Dimensional CO_2 Flooding Schematics **(**Jarrel *et al.,* 2002)

B. Multiple Phase Generation during Carbon (IV) Oxide Flooding

Studies conducted with CO_2 in single contact PVT revealed that multiple phases (e.g., vapour, CO_2-rich liquid, asphaltenes, hydrocarbon-rich liquid) were observed as CO_2 mixes with some reservoir oils (Jackson, 1985; Holm, 1986). Generally, miscibility between CO_2 and reservoir oil develops through mass transfer of the components. According to Richard and Robert (Richard and Robert, 1983), the displacement of oils by CO_2 at the same conditions does not generally result in multiple phases. Thus, the temperature and pressure regions at which multiple phases occur for reservoir oil displacements needs to be determined. In Shell Oil Co.'s North Cross Devonian continuous CO_2 flooding, it was observed that reduced injection was partially due to formation of multiple flooding within the transition zone, which could have a relative permeability effect on the mobility of the fluids (CO_2/oil) transition zone, and could increase CO_2 sweep efficiency. However, not all reservoir oil displacements create multiple phase behaviour with CO_2 at similar pressure and temperature conditions (Nute, 1983).

C. Factors that make CO_2 an EOR Displacing Agent

The high solubility of CO_2 in oil is one of the major advantages it has over other solvent used for EOR processes. Thereby resulting to the following EOR contribution factors, namely; miscibility effects, oil swelling and reduced oil density, reduced oil viscosity, acid effect on shaley and carbonate rocks (Nute, 1983).

i. Miscibility Effects

Given the right temperature and pressure conditions, CO_2 will mix with the reservoir oil and form a single homogeneous phase fluid without the existence of an interface. It does this by vaporization of the intermediate (C_2 to C_6) components present in the hydrocarbon thus, allowing the displacement front to become miscible at lower temperatures, as well as at high temperatures above the critical (89°F). More so, CO_2 can achieve miscibility at attainable pressure in a wide range of reservoirs. The miscibility effect generated as CO_2 mixes with the oil, reduces the residual oil saturation to zero in the swept region due to elimination of the interfacial tension (IFT = 0) that exist between the fluids. Hence, an increase in the oil volume and a decrease in its viscosity are observed, which subsequently leads to a higher oil recovery (McGinnis and Shatto, 1993; Nute, 1983).

ii. Oil Swelling

CO_2 is highly soluble in oil and studies show that it is about 2 to 10 times more soluble in oil than in water. The high solubility of CO_2 at high pressure enhances the expansion of the volume of oil generated as it swells thus making it less viscous. As the oil swells, it forces the trapped oils out of the pores of the rock in the reservoir thereby causing then to become more mobile.

However, the amount of swelling is dependent on the mole fraction of CO_2 in the oil, crude oil composition, temperature and pressure. Hao (1986), investigated the swelling of oil due to CO_2 flooding in some fields. They stated that at approximately 60 mol.% of most oil fields tested showed great amount of swelling that ranges between 1.2 to 1.6, indicating that CO_2 considerably swells the oil thus contributing to the oil recovery rate (Holm, 1986).

iii. *Viscosity Reduction of Crude Oil*

The injection of CO_2 into the reservoir significantly reduces the viscosity of the oil as CO_2 becomes soluble in it. However, its reduction depends on the viscosity of the non-carbonate oil, temperature and pressure conditions available in the reservoir. CO_2 acts more like a thinning agent. Generally, the higher the initial reservoir oil viscosity the more noticeable the reduced viscosity will be. Additionally, its reduction is more noticeable with heavier and medium oils.

iv. Acid Effect on Carbonate and Shaley Rocks

Carbon (IV) oxide forms carbonic acid as it dissolves in water, and subsequently dissolve the magnesium and calcium carbonates in the reservoir. This, increases the permeability of the carbonate rock, increases fluid flow, and in general improves well injectivity. The action of CO_2 to shaley rocks prevents it from swelling, reduces the pH and in general prevents the blockage of porous medium formation, which subsequently enhances oil mobility in the reservoir (Richard and Robert, 1983). Rogers and Briggs stated that particle migration/invasion, precipitation and dissolution might occur during CO_2 WAG.

D. Carbon (IV) Oxide Injectivity

Injectivity according to Goodyear (2003), refers to the relationship between flow rate and pressure gradient deep inside the formation and in the wellhead region. Injectivity abnormality is a major parameter to be considered in the successful implementation of any CO_2 injection project. A substantial reduction in the injectivity, which could lead to a further reduction in pressure, can potentially lead to lower oil recovery efficiency of the entire process. According to Howard and Micheal (2003), some project investigated showed some degree of losses in water injectivity after CO_2 injection, and about 20% loss of water injectivity could occur during WAG process. However, it can be mitigated by increasing the injection pressure, decreasing the WAG ratio, and adding more injection wells. The injection of CO_2 in oil reservoirs in the U.S have experience some form of decreasing or increasing injectivity issues during CO_2 injection or WAG implementation. The fact remains that with the injection of the first slug of CO_2, some reservoir may loss injectivity, while orders may display an increase in injectivity.

E. Injectivity Reduction

Injectivity reduction is a serious issue in CO_2 flooding projects as it leads to injection pressure loss especially in WAG processes. In West Texas, as well as in the Brent formation frequent injectivity reduction had occurred after CO_2 injection. More so, injectivity loss have been reported in (Wasson, Levelland, slaughter field) the San Andres formation (Jackson, 1985). In the Levelland field, a loss of about 50% water injection and a 10% CO_2 miscible gas was reported as against the pre-water gas injection. While at Slaughter field Unit, the reservoir suffered a 40% loss of CO_2 injection and a 57% water injection loss. A study conducted by Schneider and Owens (1976)to evaluate the injectivity in oil-water carbonate reservoirs revealed that the reservoir's water rates which was average to be about 350 b/d before the rich-gas water injection had significantly dropped to about 100b/d. After the injection of CO_2, a lower mobility was observed in the composition observation well, suggesting that the reduced injectivity occurred deep in the reservoir rather than a near-wellbore condition. The factors affecting injectivity includes: entrapment, relative permeability, wettability, and heterogeneity.

F. Mechanism of Carbon (IV) Oxide EOR Schemes Applied in most Oil Field

Three main types of CO_2 injection process have been field-tested and successfully implemented in different oil reservoir to recovery the residual saturation oil left in the pore spaces of the rock formation, and these are continuous CO_2 injection, cyclic CO_2 stimulation or CO_2 Huff' n' Puff, and water alternating Gas (WAG) flooding process.

i. Continuous Carbon (IV) Oxide Injection Process

Continuous CO_2 injection process is a proven recovery process that can be applied in various oil reservoirs to recover substantial amount of oil from the reservoir. It is similar to water flooding in the sense that large volume of a particular fluid is injected continuously into the reservoir to mobilise and sweep the stranded oils up the well. However, CO_2 flooding is distinguished from water flooding technique by the miscibility property of CO_2 with the reservoir oil. Additionally, it recovers more oil beyond the recovery point of water-flooding technique. Continuous CO_2 injection process involves the continuous injection of large volume of CO_2 into the reservoir. The soluble, miscible and extractive property of CO_2 plays a major role in the recovery efficiency of this process. At lower pressure, CO_2 attains miscibility with the oil, extracts heavier hydrocarbon into the CO_2 phase thereby mobilising the residual oil due to swelling and reduction in viscosity of the oil, and reduction in IFT that exist between the oil and CO_2. With the injection of only CO_2 into the reservoir, macroscopic bypass of the trapped oil can occur due to greater mobility of CO_2 as compared to the oil hence, gravity segregation and viscosity fingering develops. The physical displacement of the produced oil in the reservoir according to Stern (1991) is by extraction mechanism in the CO_2 flooding. The advantages of continuous CO_2 injection are as follow;

i. High recovery factor in sweep areas
ii. Attainment of miscibility at relatively low pressures
iii. Extractive mechanism

The disadvantages of continuous CO_2 injection include;

i. Viscous fingering occurrence due to poor mobility ratio
ii. Large volume of CO_2 is required
iii. Reduction in miscibility due to impure CO_2
iv. Reduction in permeability due to asphaltene deposition

ii. Cyclic CO_2 Stimulation (Carbon (IV) Oxide Huff'n'Puff) Process

Studies reveal that cyclic CO_2 stimulation process is economically viable in most reservoirs, and has been successfully applied to diverse oil reservoirs to recover more oil since 1984. More so, data from oil produced with this process indicates that optimum slug size is dependent on reservoir conditions and that oil recovered is proportional to the mass of injected CO_2. CO_2 Huff'n'Puff method relies more on the extractive property of CO_2 in the crude oil. Thus, the incremental oil produced during cyclic CO_2 stimulation is due to hydrocarbon vaporisation, interfacial tension reduction, viscosity reduction, oil swelling and altered relative permeability of water by a gas. CO_2 Huff'n'Puff process involves the injection of the required volume of CO_2 into the reservoir, shut-in of the well (soak period), and then bringing the well back to production. During the injection stage, miscibility is not achieved since the CO_2 used in the process contains impurities such as nitrogen to delay miscibility. CO_2 bypasses the oil and remain immiscible as it sinks deep into the reservoir. Mass transfer between CO_2 and the oil also occurs by the end of the injection stage. After the well is shut-in, CO_2 dissolves into the oil and the reservoir formation. Increased production is achieved as the oil swells, viscosity and capillary forces are reduced. The process is repeated for optimum number of cycle.

The advantages of cyclic CO_2 stimulation include;

i. CO_2 is highly utilised
ii. Relatively low investment cost with quick payout
iii. Operates with both extraction and physical displacement mechanism
iv. Can operate in areas of communication difficulty between the wellbores
v. Does not require high purity CO_2

The disadvantages of cyclic CO2 stimulation include;

i. Recovery is low as compared to WAG or continuous injection processes
ii. Operates in a relatively narrow range to optimise miscibility

iii. *Water Alternating Gas (WAG) Flooding Process*

It is a combination of water flooding and gas injection technique. A schematic of WAG process is shown in Fig. 2. In this process, slugs of water and gas are injected intermittently into the reservoir. During this stage, the mobility ratio of the injected fluid (CO_2) relative to the oil, is reduced and controlled due to the slug of water injected, thus improving the mobility ratio. If the velocity of the gas and water injected are equal in the reservoir, then optimum conditions of oil displacement can be achieved. The gas injected improves mobility of the oil as it swells and reduces its viscosity, while the injected water stabilises the front, controls displacement mobility and improves sweep efficiency. Additionally, the amount of water injected extends the time required for CO_2 injection, and at a ratio of 1:1, assuming no effect on injectivity the injection time doubles, thus an increase in gas peak production rate and CO_2 breakthrough time may occur. WAG process is a technique that combines an improved microscopic displacement and macroscopic sweep efficiency of the oil by significantly increasing the breakthrough time, which subsequently leads to an increase in the overall recovery process. Industrial survey indicates that WAG process is the most employed CO_2 EOR method in oil reservoirs especially in the U.S and Canada (UDE, 2005).

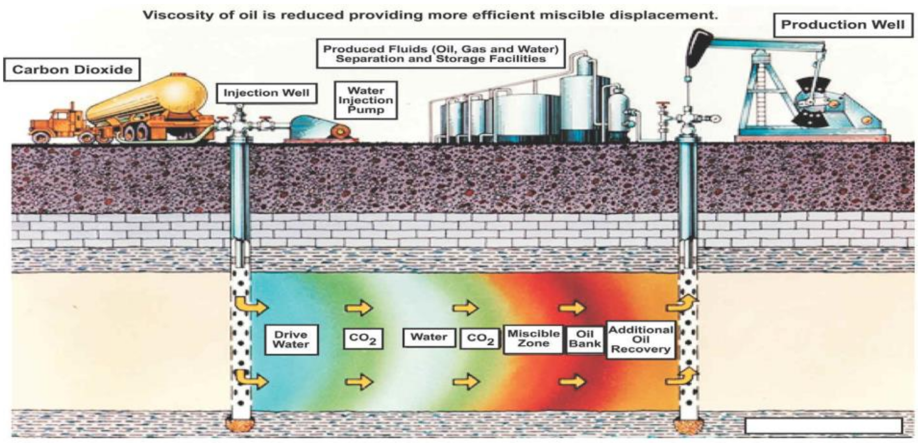

Fig.2 WAG flooding process (UDE, 2005)

The advantages of WAG process include;

i. Less CO_2 is required compared to continuous injection process
ii. Reduces gravity segregation and viscous fingering as it alleviates mobility problems associated with continuous CO_2 injection

The disadvantages of WAG process include;

i. Oil recoveries are lower when compared to continuous injection process but higher than cyclic CO2 stimulation
ii. Not viable where there poor water injectivity

iii. Water separation and water lifting issues
iv. Asphaltene deposition

G. Operational and Reservoir Problems of Carbon (IV) Oxide Injection Processes
Carbon (IV) oxide injection processes from field experience pose some operational problems. Among which are scale deposition, corrosion, and precipitation of heavy ends from the hydrocarbon. Scale deposition can be reduce by the use of scale inhibitor both on surface facilities and down hole, while the corrosion problem can be minimize and controlled by proper drying of CO_2. More so, before injection, appropriate alloy steel, and separate injection lines introduced for the water and CO_2 flow. During and after the injection process of continuous CO_2 injection or WAG processes, reservoir problems such as CO_2 early breakthrough, injectivity reduction, unstable front, scale formation, corrosion, asphaltene and hydrate formation can be expected. The ability to manage the various problems that may arise throughout the production life of the field will ultimately result in a more economical and efficient recovery process.

H. Limitations of Carbon (IV) Oxide Injection Process
The implementation of CO_2 EOR processes in oil reservoir for incremental oil recovery is limited by the following factors;
• CO_2 source of supply is considered a major limitation to this process, as without it availability and accessibility the process cannot be feasible.
• It requires a large processing facility to handle its application. More so, additional facilities are needed to separate CO_2 from the produced hydrocarbon, and this can have significant impact on the economic viability of the process.
• Gravity segregation and viscosity fingering due to difference in density between CO_2 and the oil can result in poor vertical sweep efficiency.
• Cost of CO_2, cost of processing and transportation it, is another limiting factor to the development of CO_2 EOR process especially in a case where the field is located far away from the CO_2 source.
• Tax or CO_2 credits can also prevent operators from producing some fields.
• Pressure drop in the reservoir during and after the CO_2 injection process, which can cause reduction in mobility, can limit this technique.
• Scale and hydrate formation at low pressures can cause problems to the recovery efficiency of the process.

RESULTS AND DISCUSSION

The mechanism and characteristics of CO_2 EOR technique with emphasis on its processes (continuous CO_2, cyclic stimulation or CO_2 huff 'n' puff, and WAG), including their advantages and disadvantages, operational and reservoir problems, and limitations have been reviewed and discussed in this research work. However, a more analytical approach is been done to determine which technique bests suit an EOR reservoir and the potential of such process as well. A SWOT (strength, weakness, opportunity and threat) analysis was carried-out on the two most applied EOR process (continuous CO_2injection and WAG) as shown in Table 1 and Table 2 to determine the most suitable method.

Table 1. **SWOT analysis of continuous Carbon (IV) Oxideinjection process**

Strength	*Weakness*
• It is a well-understood and established technique for recovering more oil from the reservoir. • It can be applied to a variety of reservoir, which includes sandstone, dolomite, carbonate, etc. • CO_2 is readily available in natural and anthropogenic sources. • Use in depleted and mature onshore fields of light to medium crude oil (>25° to 48° API gravity), and in reservoir depths greater than 2300ft. • Availability of screening criteria from other successfully applied fields makes the evaluation in other candidate fields much easier to predict. • An increase of between 5% to 15% OOIP is recoverable with this process.	• Very large volume of CO_2 is required for its effective implementation. • A minimum miscibility pressure must be attained between CO_2 and the reservoir oil for the recovery to be efficient. • It is recovery efficiency is very poor with heavy crude oil. • Requires additional facilities at the surface for extraction of CO_2 from the crude oil produced, thus reducing its economic viability. • Viscosity fingering and gravity segregation due to high mobility of CO_2 can lead to poor recovery efficiency. • Asphaltene, scale and hydrate formation can effectively reduce its recovery efficiency.
Opportunity	*Threat*
• Substantial recovery of residual oil left in the reservoir after conventional recovery techniques have been exhausted. • Industrial capturing of CO_2 can favour CO_2 EOR future sustainability. • Reduction of gas flaring and greenhouse gases (GHG) from the atmosphere. • Job creation.	• Mobility ratio of gas to oil in the reservoir due to density differences, hence gravity segregation occurs. • The use of an alternative form such as WAG technique for better sweep efficiency. • Bypass of residual oil in pore spaces due to inefficient sweep. • Technological advancement

Table 2. **SWOT analysis of WAG process**

Strength	*Weakness*
• Optimises CO_2 utilisation and recovery efficiency, since the water injected extends the time at which CO_2 is injected, thereby increasing CO_2 breakthrough time. • Applied in a wide range of reservoirs (sandstone, carbonate, dolomite, etc) and crude oil (>16° to 48°API gravity oil). • Cheap and readily available fluids (CO_2 and Water). • Better mobility control due to injected water • Applied in mature and depleted oil reservoirs of light, medium and heavy crude oil. • The technique is well understood and established in the oil industry for enhanced oil recovery process. • Increased displacement efficiency of oil and improved sweep efficiency to the	• Lower recovery efficiency of 5% to 12% of OOIP • Corrosion due to formation of carbonic acid by CO_2 in water can affect processing facilities thus, influencing the economic viability of the project. • Scale and hydrate formation both downhole and surface facilities. • Higher operating cost due to additional facilities for separation and reinjection CO_2 and water from produced crude. • More demanding and challenging process due to the involvement of two different fluids

producing well.

Opportunity	*Threat*
• Reduces greenhouse gases effect from the atmosphere • Well accepted and ever growing technology for incremental oil recovery in the oil and gas industry. • Sustainable technology due to availability of CO_2 from anthropogenic sources.	• Cost of technology investment due to the injections of two different fluids. • New technology (gel polymer, surfactant foam, etc.) • Cost of CO_2 and crude oil price

Laboratory research and field-testing since 1950 indicates that continuous CO_2 injection process is a very promising technique. Subsequently, with the first practical application since 1972 till date, the oil industry have gained a lot of field experience and technical expertise in this regard thus, making the process more successfully and economically applied in oil reservoirs for incremental oil recovery. The successful and economic application of this technique in diverse reservoirs (carbonate, sandstone, dolomite, etc.) of light to medium crude oil gives it a greater advantage over other processes. It can potentially recover stranded oils left in depleting and mature oil reservoirs by conventional recovery techniques, thus generating more revenue from the field. However, the following can be deduced from the CO_2 analysis conducted;

i. The natural and anthropogenic source of available CO_2 for this technique increases the potential and economic viability of this technique for future EOR application.
ii. Continuous CO_2 injection process is found to have the highest recovery efficiency of OOIP of between 5% to 12% when compared to other technique used for oil recovery.
iii. The use of very large volume of CO_2, and the cost of transporting CO_2 to the required field is one of its major drawback that can effectively increase the operating cost of the project.
iv. Viscosity fingering and gravity segregation due to high mobility and density of CO_2 compared to the oil is a major threat to this process
v. More so, CO_2 requires a certain minimum miscibility pressure for it to attain miscibility with the oil in other for the recovery process to be efficient.

Moreover, for the WAG Injection technical analysis, the following can be deduced;

i. This technique is well understood and practiced in the oil and gas industry that uses two fluids, CO_2 and water to increase displacement and sweep efficiency of trapped oils in the reservoir.
ii. Its greatest advantages WAG injection is its ability to reduce viscosity fingering and gravity segregation that develops during continuous CO_2 injection process thus, improving the efficiency of the overall process.
iii. Optimum utilisation of CO_2 slug injected is achieved with this process thus resulting in reduced cumulative volume of CO_2 for the overall process, thereby, making WAG injection more economically feasible.
iv. Both fluids needed for this process are readily available, thus the future potential for its application in mature and depleting reservoirs are high for recovering more oil from the reservoir upon exhaustion of conventional techniques.
v. WAG technique is a more demanding process since it involves the injection of two fluids. The fluids are injected one at a time through the same well or through different wells, thus making the process more expensive. Additionally, separation facilities need to be in place in other to extract the water and CO_2 produced along with the crude oil for reinjection purposes, thus increasing its capital expenditures.

vi. Corrosion, scale and hydrate formation are considered to be some of the major issues with this process since water in involve and this can lead to a more expensive management approach and technique in reducing their effect thus reducing its economic viability in field implementation.

In deciding the viability of CO_2 EOR technique in depleting oil field operations, the technical and economical assessment of the entire project operation needs to be critically evaluated and ascertained. Continuous CO_2 injection encourages early production and recovers more oil but is limited to large CO_2 and reservoir problems however, WAG recovers less oil from the reservoir at the initial stage of operation but with a much better long term recovery process owing to improved sweep and increased displacement efficiency of the process. Both techniques are potentially viable EOR technique for recovering more oil from mature and depleted oil reservoirs as they can extend the recovery life of a field for further and future production.

Table 3. Primary Recovery Data

Oil Price ($/bbl)		50.00	Inflation (%)	4.00	Effective Tax rate (%)		40.00	Discount rate (%)		15.00	CAPEX Allowance		0.25		
Year	Prod.	Infl.	Revenue		CAPEX		Capital	OPEX		Taxable	Tax ($m)	Cash flow		cumulative	
	Mbbls	Factor	BYC ($m)	MOD ($m)	BYC ($m)	MOD ($m)	Allowance	BYC ($m)	MOD ($m)	Income ($m)		MOD	Real	C.RCF	D. RCF
1	0	1.04	0.00	0.00	5,300,000.00	5,512,000.00		0.00	0.00	0.00	0.00	-5,512,000.00	-5,300,000.00	-5,300,000.00	-4608696
2	0	1.08	0.00	0.00	2,250,000.00	2,433,600.00		0.00	0.00	0.00	0.00	-2,433,600.00	-2,250,000.00	-7,550,000.00	-1701323
3	70680	1.12	3,534,000.00	3,975,269.38			1,986,400.00	562,380.00	632,601.02	1,356,268.36	542,507.34	2,800,161.02	2,489,332.95	-5,060,667.05	1636777
4	111600	1.17	5,580,000.00	6,527,810.76			1,986,400.00	705,600.00	825,452.20	3,715,958.56	1,486,383.43	4,215,975.14	3,603,833.22	-1,456,833.84	2060503
5	167400	1.22	8,370,000.00	10,183,384.79			1,986,400.00	900,900.00	1,096,082.60	7,100,902.19	2,840,360.88	6,246,941.32	5,134,530.40	3,677,696.57	2552769
6	178560	1.27	8,928,000.00	11,296,768.20			1,986,400.00	939,960.00	1,189,349.26	8,121,018.93	3,248,407.57	6,859,011.36	5,420,776.31	9,098,472.88	2343551
7	186000	1.32	9,300,000.00	12,238,165.55				966,000.00	1,271,190.10	10,966,975.45	4,386,790.18	6,580,185.27	5,000,400.00	14,098,872.88	1879836
8	159960	1.37	7,998,000.00	10,945,815.27				874,860.00	1,197,306.32	9,748,508.95	3,899,403.58	5,849,105.37	4,273,884.00	18,372,756.88	1397140
9	96720	1.42	4,836,000.00	6,883,135.92				796,888.00	1,134,220.10	5,748,915.82	2,299,566.33	3,449,349.49	2,423,467.20	20,796,224.08	688901
10	66960	1.48	3,348,000.00	4,955,857.87				768,984.00	1,138,284.17	3,817,573.69	1,527,029.48	2,290,544.22	1,547,409.60	22,343,633.68	382496
11	37200	1.54	1,860,000.00	2,863,384.54				704,534.00	1,084,597.72	1,778,786.82	711,514.73	1,067,272.09	693,279.60	23,036,913.28	149016
12	29016	1.60	1,450,800.00	2,322,777.54				685,445.00	1,097,419.53	1,225,358.01	490,143.21	735,214.81	459,213.00	23,496,126.28	85830.2
13	20088	1.67	1,004,400.00	1,672,399.83				617,985.00	1,028,990.45	643,409.38	257,363.75	386,045.63	231,849.00	23,727,975.28	37681.9
14	14880	1.73	744,000.00	1,288,367.28				508,993.00	881,411.19	406,956.09	162,782.43	244,173.65	141,004.20	23,868,979.48	19927.9
15	12648	1.80	632,400.00	1,138,916.67				423,449.00	762,607.73	376,308.95	150,523.58	225,785.37	125,370.60	23,994,350.08	15407.4
													23,994,350.08		

An economic evaluation of a field was done using primary and tertiary data obtained from it to ascertain the viability and potential of CO_2 EOR technique implementation in depleting oil reservoirs. The data obtained from both recovery processes (primary and CO_2 EOR) as shown in Table 3-Table 5 and Fig 3 – Fig. 6, were used to generate the Net Present Value (NPV) during the primary recovery life of the field and as at the time of CO_2 EOR implementation. With primary means of recovery, oil production from the 13^{th} to 15^{th} year has dropped so low such that the cost of operating the field almost equals the revenue generated. However, with the implementation of CO_2 EOR technique, the daily production rate increased and higher revenue was generated.

Table 4. CO_2 EOR Data

Oil Price ($/bbl)		50.00	Inflation (%)	4.00	Effective Tax rate (%)		40.00	Discount rate (%)		15.00	CAPEX Allowance		0.25		
Year	Prod.	Infl.	Revenue		CAPEX		Capital	OPEX		Taxable	Tax ($m)	Cash flow		cumulative	
	Mbbls	Factor	BYC ($m)	MOD ($m)	BYC ($m)	MOD ($m)	Allowance	BYC ($m)	MOD ($m)	Income ($m)		MOD	Real	C.RCF	D. RCF
1	0	1.04	0.00	0.00	2,530,000.00	2,631,200.00		0.00	0.00	0.00	0.00	-2,631,200.00	-2,530,000.00	-2,530,000.00	-2200000
2	0	1.08	0.00	0.00	868,100.00	938,936.96		0.00	0.00	0.00	0.00	-938,936.96	-868,100.00	-3,398,100.00	-656408
3	32224	1.12	1,611,200.00	1,812,380.88			892,534.24	784,764.00	882,752.77	37,093.86	14,837.55	914,790.56	813,245.48	-2,584,854.52	534722.1
4	38688	1.17	1,934,400.00	2,262,974.40			892,534.24	806,908.00	943,968.23	426,471.93	170,588.77	1,148,417.40	981,672.00	-1,603,182.52	561274.2
5	44640	1.22	2,232,000.00	2,715,569.28			892,534.24	827,740.00	1,007,072.27	815,962.76	326,385.11	1,382,111.90	1,135,995.23	-467,187.29	564790.4
6	50220	1.27	2,511,000.00	3,177,216.06			892,534.24	847,270.00	1,072,066.84	1,212,614.97	485,045.99	1,620,103.22	1,280,391.11	813,203.82	553548.4
7	63240	1.32	3,162,000.00	4,160,976.29				892,840.00	1,174,916.53	2,986,059.76	1,194,423.90	1,791,635.85	1,361,496.00	2,174,699.82	511836.8
8	72540	1.37	3,627,000.00	4,963,799.95				925,390.00	1,266,460.11	3,697,339.83	1,478,935.93	2,218,403.90	1,620,966.00	3,795,665.82	529896.7
9	78864	1.42	3,943,200.00	5,612,403.14				947,524.00	1,348,622.10	4,263,781.04	1,705,512.41	2,558,268.62	1,797,405.60	5,593,071.42	510934.9
10	84816	1.48	4,240,800.00	6,277,419.96				968,356.00	1,433,403.43	4,844,016.53	1,937,606.61	2,906,409.92	1,963,466.40	7,556,537.82	485338.9
11	79986	1.54	3,999,300.00	6,156,738.61				951,451.00	1,464,715.10	4,692,023.51	1,876,809.40	2,815,214.10	1,828,709.40	9,385,247.22	393068.7
12	66968	1.60	3,348,400.00	5,360,896.28				905,888.00	1,450,355.87	3,910,540.41	1,564,216.16	2,346,324.24	1,465,507.20	10,850,754.42	273913.8
13	62496	1.67	3,124,800.00	5,203,021.70				890,236.00	1,482,308.38	3,720,713.32	1,488,285.33	2,232,427.99	1,340,738.40	12,191,492.82	217907.5
14	52824	1.73	2,641,200.00	4,573,703.83				856,384.00	1,482,980.00	3,090,723.83	1,236,289.53	1,854,434.30	1,070,889.60	13,262,382.42	151347.4
15	44640	1.80	2,232,000.00	4,019,705.90				827,740.00	1,490,712.98	2,528,992.93	1,011,597.17	1,517,395.76	842,556.00	14,104,938.42	103545.5
													14,104,938.42		

The implementation of CO_2 EOR technique to the oil field have increased the production life of the field by another 15 years thus, indicating that CO_2 EOR process extends the abandonment period of the field thereby allowing more oil to be recovered. Although CO_2 EOR does not yield profit as high as primary mechanism, it is evident from the field that a total of US$14 million was further realised by its implementation, which would not have been if it had been decommissioned 15 years ago. More so, the cost of decommissioning the field is over U.S$5.2 million, and this would have been done during the period when production have stopped thereby, reducing the cumulative net value of the field at the primary recovery stage. However, with the implementation of CO_2 EOR technique, a cumulative net present value of U.S$14 million was further realised from the field. This goes to show that the process is equally profitable, and the cost of decommissioning of the oil field can be financially handled.

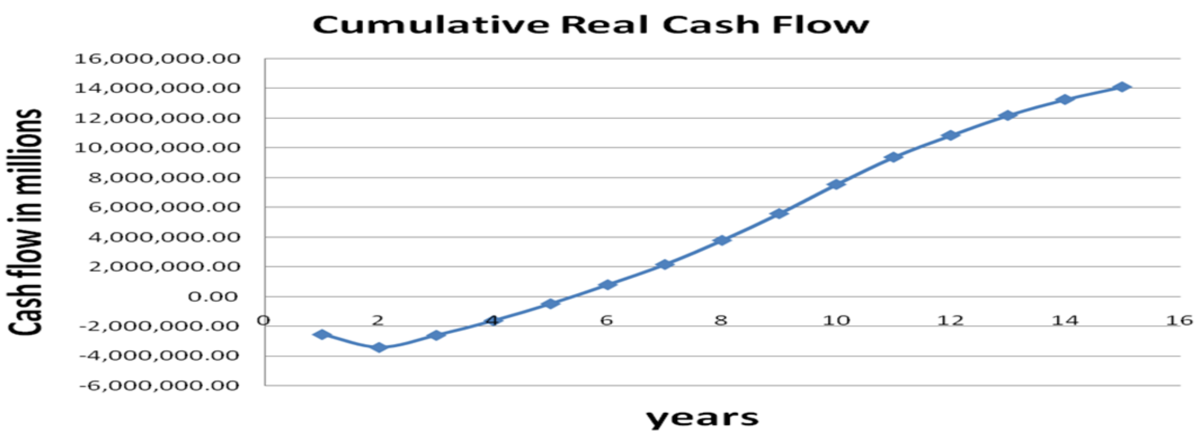

Fig.3 CO_2 Cumulative Net Cash Flow

It is evident also from Fig.3 that the oil production rates with CO_2 EOR techniques are not as high as primary means but the payback period of the process is close to the 5th year thus, indicating a relatively short payback time, allowing investors better rate of returns. Overall, it is evident from the economic evaluation conducted that CO_2 EOR technique has a relatively short payback period, generate more revenue from oil that would have been left on ground by primary mechanism and has good future potential as it extends the fields life for future development.

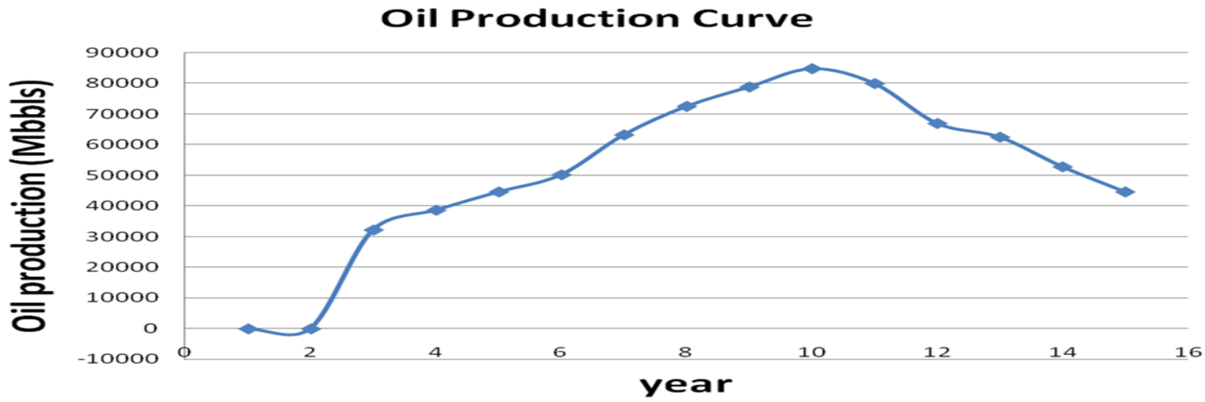

Fig. 4 CO_2 Oil production curve

Fig. 5 Primary recovery Cumulative Net Cash Flow

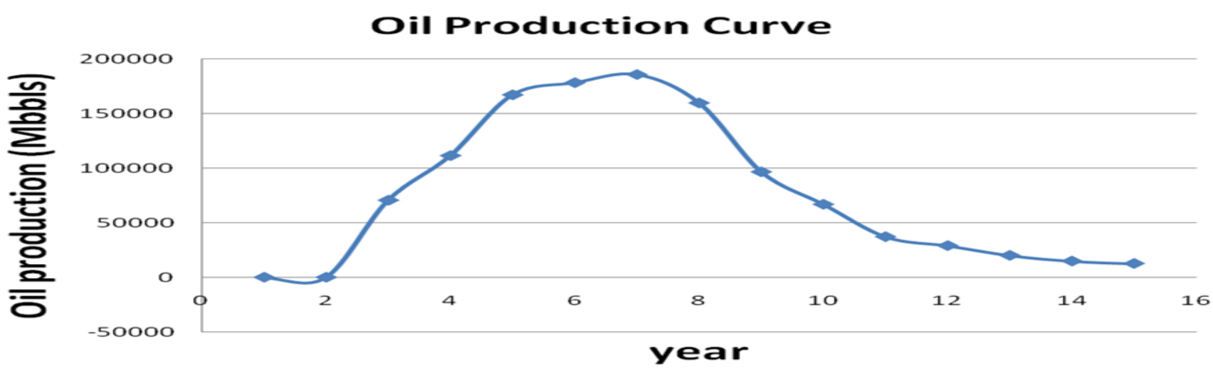

Fig. 6 Primary recovery Oil production curve

Table 5a. CO_2 Net Present Value (NPV)

CO_2 EOR	
CAPEX	Value (U.S$)
Recycling and vapour compressors	1,773,000
Plant	113,600
Distribution line	87,000
Header	67,000
Production equipment	555,000
Upgrade of production facility	190,500
Workover of existing well	605,000
Total	3,389,100
OPEX	
Surface maintenance (repair/services)	95,100
Subsurface maintenance and normal daily expenses	213,300
CO2 injection and recycling cost	318,000
Production well services	158,364
Total	784,764

Table 5b. CO_2 Net Present Value (NPV)

Primary recovery	
CAPEX	Value (U.S$)
Drilling and completion	3,500,000
Production facilities	4,000,000
Total	7,500,000
OPEX	
Surface maintenance (repair/services)	65,100
Subsurface maintenance and normal daily expenses	113,300
Production facilities services	158,364
Operating cost	3.5/bbl
Total	562,380

Furthermore, a number of CO_2 operational problem have been identified from information gathered from some CO_2 EOR operation companies. These include

i. Early CO_2 Breakthrough

Early CO_2 breakthrough is seen as a major problem in many CO_2 flooding fields. It occurs mainly in high-stratified reservoirs with high permeability channels thus, leading to low recovery efficiency of the flooding process. It is can be mitigated by injection of water after CO_2 injection to provide a better front to increase, moving to a different pattern or by continuous recycling of the injected CO_2. Additionally, it is better corrected by sealing off with surfactant or polymer gel.

ii. Gravity Segregation and Viscosity Fingering

These are due to high mobility ratio of CO_2 to oil. The use of WAG flooding process has been employed in many fields to reduce this problem. However, it can be controlled better by the addition of surfactant to water and addition of an aqueous CO_2 foaming agent or surfactant to increase the viscosity of CO_2, thereby stabilizing the displacement process for better mobility and improved sweep efficiency.

iii. Injectivity Losses

Injectivity losses as high as 50% have been recorded in some fields, especially in the water phase. This may be due to high injection pressures, resulting in fractures, and dissolution of CO_2 in water, oil and rocks. Injection losses are better mitigated by running injection profiles, injection tracer logs and tracer materials (radioactive materials) to determine the flow pattern of the injectant.

iv. Corrosion

Corrosion is one of the major problems observed in CO_2 EOR flooding field especially in WAG process. An acidic solution is formed when CO_2 dissolves in water. This create major problems both down hole and subsurface facilities. This can be reduced by injection of dry CO_2 into oil reservoirs in case of continuous CO_2 injection and provision of separate injection lines for CO_2 and water in WAG process. More so, the use of corrosion inhibitors, better stainless steel material, coating, plastic coated tubing, and better corrosion management practice.

v. High Injection Pressure

High injection pressure of CO_2 that exceeds the fracturing pressure of the reservoir can cause facture the formation. This can lead to great reduction of the injectant (CO_2 or/and water), reduction in injection pressure, plugging issues, and reduced permeability. However, this can be mitigated by better understanding of the reservoir characteristics, water log and recovery history.

vi. Biofouling

Biofouling alters the geochemistry of the system and occurs due to the injection or reinjection of impure CO_2 or water into the reservoir. It causes reduction injectivity and reservoir pressure drop. It can be controlled by use of water and CO_2 that are free of impurities, and installation of better CO_2 and water treatment facilities.

CONCLUSION

It can be deduced from the research work that;

i. CO_2 EOR technique can be applied to both mature and depleting reservoirs of diverse reservoir, and can recovery between 5% to 15% of OOIP. CO_2 EOR process is dependent on temperature, fluid composition, relative permeability, reservoir pressure, reservoir geometry, gravity and oil saturation in the pores of the formation rock.
ii. Continues CO_2 and WAG processes are the main scheme employed in CO_2 EOR processes. Continues CO_2 injection process accounts for high recovery efficiency at the early stage of injection but with lesser recovery period due to poor sweep efficiency. While WAG process account for increase displacement and sweep efficiency. Hence, it is widely employed in most CO_2 fields.
iii. CO_2 EOR technique produces high GOR due to conformity and fractures of high permeability layers present in the reservoir, thus leading to poor recovery efficiency.
iv. The major operating problems associated with this technique are CO_2 break through, gravity segregation, viscosity fingering and corrosion.
v. CO_2 implementation can potently prolong the production life of field as evident in the economic analysis carried-out using both conventional and tertiary recovery mechanism, thus recovering more oil from the field and increasing the profitability of the field.
vi. CO_2 screening criteria availability provides guideline for CO2 field application. However, there are no one know technique that can satisfactory be used for oil recovery in different reservoirs.

vii. A good understanding of the reservoir characteristics and geology, as well as the water log and recovery history of the candidate field is a key parameter for successful implementation and recovery efficiency of the flooding process.

viii. The high soluble nature of CO_2 in oil gives it a greater advantage as against order gases or fluid used in the oil industry for oil recovery. Thus, reducing the viscosity and IFT of the oil, as it swells and extract the heavier hydrocarbon from the crude.

ix. Based on the numerous advantages of CO_2 flooding process, the rate of depleting reservoirs, availability of CO_2 both in natural and anthropometric sources, coupled with the amount of hydrocarbon left in the reservoir by conventional techniques, CO_2 flooding process is seen as a sustainable and economical technique for recovering more oil from the reservoir for today and future needs.

RECOMMENDATION

Having successfully carried out the research work, the following recommendations were made;

i. Further study needs to be done on reducing the volume of CO_2 utilised per barrel of oil produced.

ii. Further Laboratory research and field-testing needs to be done one ways of increasing the density and viscosity of CO_2 for better sweep efficiency especially in CO_2 continuous injection scheme.

iii. More economical technique of capturing and injection of CO_2fro anthropogenic sources needs to be developed for provisions in wells with further proximity to naturally sourced CO_2.

CONFLICT OF INTEREST

This research work was carried out by us and there is no conflict of interested associated with it.

REFERENCES

Abdulrazag, Y. Z., and Jerbi, K. K., (2000). Economic Evaluation of Enhanced Oil Recovery.Society of Petroleum Engineers Inc. Presentation at the SPE International Oil and Gas Conference and Exhibition. Beijing, China.

Abiodun, M.A., and Shameem, S., (2009). Permian Basin: Historical Review of CO_2 EOR Process, Current Challenges and Improved Optimization Possibilities. Presented at the international symposium of the Society of core analysts.Noordwijk, Nertherland

Aurel, C., (1992). Applied Enhanced Oil Recovery. Prentice Hall Inc, Englewood Cliff, New Jersey, U.S.A

Bank, G.C., and Koperna, G.J., (2007). CO2 Enhanced Oil Recovery Potential of the Appalachian Basin. Society of Petroleum Engineers. Lexington, Kentucky, U.S.A.

Blaine, H., and Ashok, S., (2004). Enhanced Oil Recovery Water Usage: Presentation on advisory committee on water use practice and policy.Alberta Research council. Available from: http://www.waterforlife.gov.ab.ca/docs/enhanced_oil_recovery_march_2004.pdf (Accessed 18 August 2019)

Brummeri, A. C., (1999_. Economic Evaluation of a CO2 EOR Flood AT THE rock Creek Field, Roane County, West Virgina.Society of Petroleum Engineers. Oklahoma. U.S.A

Buckley, J.S., and Liu, Y, (1996). Some Mechanisms of Crude Oil/Brine/Solid Interactions. Presented at the 1996 Symposium on Reservoir Wettability and Its Effect on Oil Recovery, Montpellier, France

Carl, W, H., and Michael A, L., (2004). Mechanisms and incentives to promote the use and storage of co2 in the North Sea. In European Energy Law Report I, pp. 355–380.Intersentia, CO2-Norway AS.

David, H., (2009). Comparisons of Conventional CO_2WAG Injection Techniques used in the Permian Basin.Presented at the 15thAnnual CO_2Flooding Conference. Midland, Texas

Fayers, F. J., (1981). Enhanced Oil Recovery.Elsevier scientific publishing company B.V. Amsterdam, The Netherland, pp: 237– 351

Goodyear, S. J., 2003. Subsurface Issues for CO_2 Flooding of UKCS Reservoirs. Institution of Chemical Engineers. Shell International Exploration and Production B.V., Aberdeen, UK

Grigg and Sigan, (1998). Understanding and Exploiting Four-Phase Flow in Low-Temperature CO_2 floods. SPE 39790, Presented at the SPE Permian Basin Oil & Gas Recovery Conference, Midland, Texas.

Hao, Y., (2004). Laboratory Investigation of CO2 Flooding.Society of Petroleum Engineers Inc. International Technical Conference and Exhibition. Abuja, Nigeria.

Holm, L. W., (1986). Miscibilty and Miscible Displacement. Society of Petroleum Engineers. *Journal of Petroleum Technology*

Howard, H. and Micheal K., (2003). The Economics of CO2 Storage.Massachusetts Institute of Technology, Laboratory for Energy and the Environment. Cambridge

Ivan, S., and Rafael, S., (2007). Global Oil Reserves – Recovery Factors Leave Vast Target for EOR Technologies. Oil & Gas Journal. Oklahoma. U.S.A

Jackson, D.D., (1985). Optimum WAG Ratio vs. Rock Wettability in CO2 Flooding," SPE 4303. Presented at the 1985 Annual Technical Conference and Exhibition, Las Vegas, NV

McGinnis, R. A., and Shatto, A. G., (1993). $C0_2$ EOR Economics for Small-to-Medium-Size Fields.Society of Petroleum Engineers, Inc. presentation at the 68th Annual Technical Conference and Exhibition of the Society of Petroleum Engineers. Houston, Texas.

Nute, A. J., (1983). Design and Evaluation of a Gravity-Stable, Miscible CO_2-Solvent Flood, Bay St. ElianeLield.SPE 11506.Presented at the Middle East Technical Conference. Manama, Bahrain.

Odd, M. M., (2003). CO_2 as Injection Gas for Enhanced Oil Recovery and Estimation of the Potential on the Norwegian Continental Shelf.Norwegian University of Science and TechnologyDepartment of Petroleum Engineering and Applied Geophysics. Trondheim, Norway.

Richard, L. H., and Robert, S. M., (1983). Multiple Phase Generation during CO_2 Flooding. SPE OF AIME, Society of Petroleum Engineering Journals. Tusla, Oklahoma.

Schnieder, F.N., and Owens, W.W., (1976). Relative Permeability Studies of Gas-Water Flow Following Solvent Injection in Carbonate Rocks. Society of Petroleum Engineering Journals

Stern, D. (1991_. Mechanism of Miscible Oil Recovery: Effects of Pore-Level Fluid Distribution. SPE 22652, Presented at the 1991 SPE Annual fall meeting. Dallas, U.S.A.

U.S. Department of Energy (2005). Oil Exploration and Production Program: Enhanced Oil Recovery. National Energy Technology Laboratory.Strategic Center for Natural Gas and Oil. U.S.A