Comparison of Different Enhanced Oil Recovery Techniques for Better Oil Productivity

Saleem Qadir Tunio
Universiti Teknologi Petronas
Malaysia

Abdul Haque Tunio
Mehran University of Enginering & Technology
Jamshoro, Pakistan

Naveed Ahmed Ghirano
Mehran University of Enginering & Technology
Jamshoro, Pakistan

Ziad Mohamed El Adawy
Universiti Teknologi Petronas
Malaysia

Abstract

Most of the studies and reviews show that the amount of oil that can be extracted with primary drive mechanisms is about 20 – 30% and by secondary recovery can reach up to 40% but using modern enhanced oil recovery (EOR) techniques, recovery can reach up to 60 – 65%. These techniques of enhanced oil recovery (EOR) are essentially designed to recover oil commonly described as residual oil. The oil that cannot be extracted by primary recovery as well as secondary recovery techniques, this amount of recovery depends on the amount of oil produced from the primary recovery [1]. According to the Department of Energy U.S.A, the amount of oil produced worldwide is only one third of the total oil available. So by using the EOR techniques we will be able to produce more oil as the demand increase while we have a shortage in the supply. The project is research and experiment based on the advancement in enhanced oil recovery techniques, it aims reviewing the current used techniques and what are the advancements in these techniquesthat results in better production of oil. Experimenting (two of these techniques; direct carbon dioxide injection and WAG injection) and then comparing the laboratory results for the recovery through a series of laboratory experiments on core flooding and lastly the discussion on the obtained results.

Keywords: Oil productivity, Enhanced Oil Recovery (EOR), CO_2, WAG

Background

According to the Department of Energy U.S.A, the amount of oil produced worldwide is only one third of the total oil available. So, by using the EOR techniques we will be able to produce more oil as the demand increase while we have a shortage in the supply. Over the last 3 decades a lot of research is taking place in the field of enhanced oil recovery and since then EOR methods have been developing. These techniques are applied on mature and depleted reservoirs and showed improved efficiency compared with primary and secondary recovery (water-flooding).Enhanced oil recovery is the process of increasing the oil recovery after the primary recovery (the recovery done by the main drive mechanisms) and the secondary recovery which is done by water flooding. The enhanced oil recovery process can be achieved by many techniques like; (gas injection, chemical injection, ultrasonic stimulation, microbial injection or thermal recovery).

This research aims to review all the enhanced oil recovery techniques and the experimental part helps in concluding the recovery percentage of Carbon dioxide and WAG injection on medium light oil.

Problem statement

It is a known fact that the term "easy oil" refers to the oil that can be extracted easily in inhabitant areas is now vanishing and the amount of oil produced by the primary recovery from these areas accounts only 20 to 30 % of the total amount available. [2] Petroleum companies are looking for oil in a very remote areas; like deep waters, areas where the temperature is below zero and to develop fields in areas like these is very costly, instead we can still produce the remaining amount of oil in the existing fields by applying new technologies to increase the recovery factor through introducing the enhanced oil recovery techniques.

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By applying the enhanced oil recovery techniques millions of barrels of oil can be extracted from existing fields, as it increases the recovery up to 60 % of the oil in the reservoir, billions of dollars are invested in enhanced oil recovery researches to get the maximum amount of recovery with the lowest possiblecost from the existing fields before moving to the remote areas.

Literature review

"In the year 1998, U.S produced a total of about 707,000 barrels of oil per day (BOPD) using enhanced oil recovery EOR methods, which is about 12% of total national crude oil production.

Thermal EOR (mostly steam, hot water drive and huff-and-puff operations) accounts for about 393,000 BOPD which is about 7% of the states production. Oil recovered using carbon dioxide (CO_2) EOR is about 196,000 BOPD is about 3% of U.S. production. Amount of oil recovered by hydrocarbon miscible EOR (mostly natural gas injection) accounts for about 86,000 BOPD or about 1.5 % of U.S. production and nitrogen miscible/immiscible EOR accounts for about 32,000 BOPD or about 0.5% of U.S. production. These methods account for well over 99% of all U.S. EOR production with considerably less than 1% coming from chemical EOR and microbial EOR which is still in the research stage." [2]

Nowadays, enhanced oil recovery techniques account for about one-third of Alberta's conventional recoverable oil reserves. As in the fullness of time exploration prospects suffer from depletion, the ability to obtain more from what has already been found gained greater importance as a source of additional oil supply. [3]

"EOR is gaining attention as it is considered to provide us with the future fuel. The wide survey available every couple of years by the Oil & Gas Journal (Moriti) shows that the production using EOR techniques in Canada and U.S.A. is about 25% and 10% respectively of the total oil production and is growing"[4]

The prices of oil are getting higher and concerns about future oil supply are leading to a renewed emphasis on Enhanced Oil Recovery. EORtechniques which can significantly increase the recovery factor from reservoirs through injection of some fluids in the reservoir to sweep the remaining oil. Some of these EOR techniques are currently being used in producing substantial incremental oil. Other techniques have not yet made a commercial impact like the microbial technique. [5]

EOR techniques fall under two categories in general, (increasing the volumetric sweep efficiency and improving displacement efficiency).Poor sweep efficiency can be a result of reservoir heterogeneity or poor mobility, mobility can be controlled through controlling the mobility of the injected fluid which can be done by polymer flooding or else we can control the mobility of the hydrocarbons which is the desired fluid and this can be done using thermal methods. For the displacement efficiency, the capillary force has a great impact on it, as it holds the oil in the reservoir matrix so in order to decrease this action chemical surfactants, caustic alkaline flooding, miscible gases, nitrogen flooding and microbial process are used but it depends on many aspects and answers of some questions before choosing the right technique, For miscible processes: What is the anticipated phase behavior between reservoir fluid and injected fluid? What is the mobility of the anticipated phase(s)? Will the process be first contact miscible or developed miscibility?

For immiscible gas injection processes: What is the remaining oil saturation after water flooding? What is residual to immiscible gas? How will fault blocks or low permeability layers be drained?

For chemical processes: What is the design of the chemical slug to develop the ultra-low interfacial tension necessary for a successful displacement? To what extent will the chemical interact with the clays in the reservoir rock through adsorption? What is the salinity of the reservoir water and how will that salinity impact the activity of the chemical slug during the process? Howcan be the mobility control of oil and chemical bank is accomplished?

For polymer processes: What is the polymer concentration necessary to provide mobility control? What portion of the polymer slug will be adsorbed on the clays in the reservoir rock?

For thermal processes: What are the anticipated thermal losses in the wellbore, to cap and base rock, to water in the formation? Can the thermal front be controlled in the reservoir? Can the reservoir pressure be controlled in the range necessary for efficient heating of the reservoir fluid? For microbial processes: Can microbes be identified that can be sustained in the reservoir, utilize in-situ nutrients and/or oxidants, generate surfactants and polymers which will accomplish the goals of the project?

How will the microbes and/or their products be stably transported through the reservoir? For any EOR process: Can the process selected be used in the selected reservoir, given the reservoir rock and fluid environment in place? Can this process be implemented in such a way that it will result in an economically attractive project?

Answering the above questions is not enough to choose the right technique because other aspects are included in these projects like the geological, laboratory analysis, economical analysis and project design. [5]

Among the other techniques used for enhanced oil recovery is "the solvent and improved gas drive method" this method can be divided into three methods, such as;

i) Solvent flooding.
ii) Enriched gas drive.
iii) High pressure gas drive.

Some of the aspects responsible for increasing the recovery factor using carbon dioxide are:
a) Promotes swelling.
b) Reduces viscosity.
c) Decreases oil density.
d) Vaporizes and thus extracts portions of oil.

Following are the properties that enhance the recovery:
a) Carbon dioxide is highly soluble in water.
b) It exerts an acidic effect on the oil.
c) Carbon dioxide is transported.

In addition to the above mentioned:
i) Eliminates swabbing.
ii) Provides rapid cleanup of silt.
iii) Prevents and removes emulsion blocks.
iv) Increases the permeability of the carbonate formations.
v) Prevents the swelling of clay and the precipitation of iron and aluminum hydroxides.

Carbon dioxide is used in EOR techniques due to the combination of solution gas drive, swelling of the oil, reduction of its viscosity and the miscible effects resulting from the extraction of hydrocarbon from the oil.

Carbon dioxide is highly soluble in hydrocarbons and this solubility causes the oil to swell, but for reservoirs containing methane a smaller amount of the carbon dioxide dissolves in the crude oil causing a less oil swelling.When reservoir oil is saturated with carbon dioxide at elevated pressures that will result in a substantial decrease in oil viscosity in the reservoir, the water in the formation is also affected by carbon dioxide, some expansion occurs for the water as well causing the density to decrease, so it means after injecting carbon dioxide both the densities of oil and water decreases moving their values near to each other which reduces the effect of gravity segregation.

Combination of CO_2 and water can be used as water alternating gas (WAG) shown in figure 1. In this technique, more favorable mobility ratios can be established and this technique is used later in this project. [6]

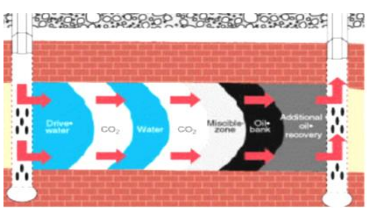

Fig. 1:WAG (Water Alternating Gas) involves alternating the injection of water & CO_2. [7]
Here, the most important EOR techniques used nowadays are discussed which are given below:

Gas Injection

Gas injection is the most popular technique used worldwide, in United States alone around 50% of the EOR production involves gas injection techniques and it has proven success in most of the oil reservoir types. [9]

Goals of the gas injection are: [8]
1- Restore reservoir pressure.
2- Increase oil production.
3- Lower the operating cost.

Types of Gases used in the injection: [8]
1- Carbon dioxide (the most popular).
2- Nitrogen / Air.
3- Natural gas.

Types of gas injection: [8]
I- Gas injection into a gas cap:
In order for this to happen there must be a gas cap initially or a gas cap that has been formed during the primary recovery in which separation between oil and gas occurs forming a gas cap. In this method of injection the gas is injected in the gas cap above the oil zone which helps in maintaining the reservoir pressure and forcing the oil to move towards the producing wells.

II- Gas injection in an oil zone:
Since there is no gas cap so the injected gas will be injected radially into the oil phase which will sweep the oil from the injector in the direction of the producer.

The degree of success of a gas injection project depends on:
i- The mechanism of which gas displaces the oil (displacement efficiency).
ii- The contact between the injected fluid and the reservoir volume (sweep efficiency).

Gas injection can be miscible or immiscible displacement process. This is determined by the temperature and pressure conditions of the injection. It can also be combined with water as water alternating gas (WAG)

Carbon dioxide injection

For oil to be displaced by the CO_2 injection it relies on some mechanisms related to the gas behavior of the CO_2 and the crude mixture and most importantly of these techniques is the reservoir temperature and the reservoir pressure we have 4 phases but only phase one (below the miscibility pressure) to be discussed as shown in figure 2. [10]

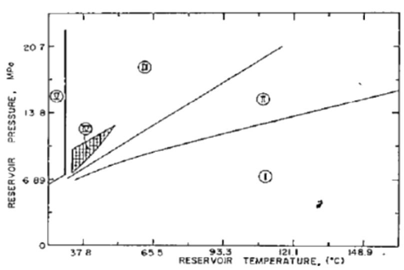

Fig. 2: The effect of reservoir temperature and pressure on carbon dioxide injection recovery mechanism. [10]

Recovery mechanisms

Following factors help in increasing oil recoveryin the immiscible CO_2 injection [10]
A) Swelling of oil.
B) Oil viscosity reduction.
C) Blow down recovery.
D) Increased injectivity.

A. Swelling of oil:
Carbon dioxide is soluble in hydrocarbons but it depends on the saturation pressure, composition of the crude and the reservoir temperature. The dissolution of CO_2 in the crude will increase the volume of oil that can reach up to 40% hence decreasing the value of the residual oil thus increasing the recovery.

B. Oil viscosity reduction:
The reduction in the crude oil viscosity occurs when the carbon dioxide gas saturates the crude, so crudes saturated with carbon dioxide is easily swept than the crudes which are not saturated by the carbon dioxide gas, this is for miscible injection.

C. Blow down recovery:
This mechanism is somehow complex as the pressure decrease with the production (flooding termination). Carbon dioxide gas will come out of the solution while sweeping the oil to the wellbore.

D. Increased injectivity (increased permeability):
When carbon dioxide and water react they form acidic content which react with carbonate portions in the reservoir which dissolves some of the formation's matrix, hence increasing the permeability of the rocks but these acids may also react with the asphaltene causing it to precipitate thus plugging the pore spaces causing a major reduction in the permeability, so a thorough study must be performed.

WAG (Water Alternating Gas)

Almost all the projects involving gas injection employ the WAG method, it is reported that US has the largest share of WAG application followed by Canada and it can be applied to different types of reservoir like sandstone and chalk. Mostly CO_2 gas is used in the WAG processes 47% followed by the hydrocarbon 42%. [11]

WAG is a combination of water flooding and gas flooding; first field application was in 1959 by Exxon Mobil in Alberta, in order to increase recovery miscible gas is injected after water flooding, it works through the dissolution of the injected gas in the residual oil increasing the amount of oil that can be recovered. [11]

Immiscible Water Alternating Gas (IWAG)

Oil recovery efficiency of IWAG can be higher than that of water flood because of one or more of the following mechanisms [12]:

- Improved volumetric sweep by water following gas. Presence of free gas in the porous medium causes water relative permeability in three-phase zones to be lower than in pores occupied by only water and oil which favors water diversion to previously unswept areas.
- Oil viscosity reduction resulting from gas dissolution makes the mobility ratio of water-oil displacement more favorable in the case of (initially) under saturated oil.
- Oil swelling by dissolved gas causes residual oil to contain less stock tank oil and thus increases recovery even in the absence of any additional residual oil saturation (Sor) reduction mechanism.
- Interfacial tension (IFT) reduction (gas-oil IFT being lower than water-oil IFT) in principle allows gas to displace oil through small pore throats not accessible by water alone under the prevailing pressure gradient.
- Residual oil saturation reduction due to three-phase and hysteresis effects. In water-wet rock, trapping of gas during imbibitions cycles can cause oil mobilization at low saturations and an effective reduction in the three-phase residual oil saturation.

Thermal techniques

Thermal techniques are mostly used for heavy oil reservoirs, heat is introduced to the oil reservoir through steam and heat applied is to lower the viscosity of highly viscous fluids allowing the oil to flow easier and to be produced easily. Dolberry Oil estimates that steam accounts for 52% of the market methods utilized for EOR. In comparison with gas injection, carbon dioxide is at 31% and nitrogen is at 17%. Steam provides additional pressure that produces greater oil production as the additional heat assists in losing the crude oil in the "pay zone" surrounding the well.

Following are the types of thermal recovery [6];

a) Hot fluid injection
Here, hot fluids are injected in the reservoir like hot water and steam in its saturated or superheated form which should decrease the viscosity of the heavy oil and increase the recovery.

b) In-situ combustion
It is done by injecting air or oxygen bearing gas in the reservoir and burning a portion of the crude in the formation which will increase the amount of residual oil produced. It is recommended for reservoirs with high oil saturation, high porosity, good permeability and oil of moderate viscosity.

c) Cyclic steam
Cyclic steam injection is a single well process and involves the injection of steams for 2 to 6 weeks into a producing well after a short soak period of 3 to 6 days, the well produces at a higher rate for several months to a year also called the huff and puff method (Figure 3).

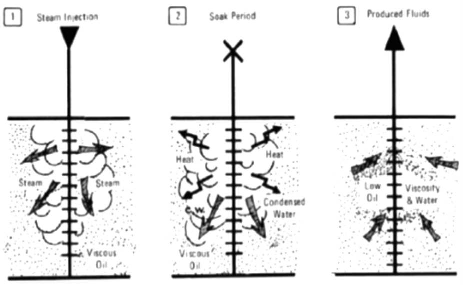

Fig. 3: The cyclic steam method

Microbial Enhanced Oil Recovery (MEOR)

It is a new technology going on in oil and gas industries to increase oil recovery. It is done through doing some alteration in the function and structure in the oil reservoir.

Some of the advantages of this technique are:

i. Increase in oil production.
ii. Doesn't require a lot of modification in the facilities.
iii. Environment friendly.
iv. It is considered cheap as compared to other techniques.

Research Methodology

In order to reach the goals of this research, research and study has been carried out while reviewing society of petroleum engineers (SPE) technical papers, reference books, internet and lastly the laboratory experiments in the center of excellence EOR of Universiti Teknologi PETRONAS (UTP).

Equipments used in the experiment

Following equipments are used to carry out this research;

1. Porperm (Porosity - permeability testing device).
2. RPS 800 (Relative Permeability System).

The Experiment

For poroperm

The POROPERM instrument is a permeameter and porosimeter used to determine properties of plug sized core samples at 400 psi confining pressure. In addition to the direct properties measurement, the instrument offers reporting and calculation facilities thanks to its user-friendly windows operated software. Measurements:

i. Pore volume Vp (cc).
ii. Sample Porosity (%).
iii. Sample bulk volume Vb (cc).
iv. Grain volume Vg (cc).
v. Grain density(g/cc).
vi. Gas permeability Kg (mD).
vii. Liquid permeability K (mD).
viii. Slip factor “b” (psi).
ix. Inertial resistivity (ft-1).
x. Turbulent factor (μm).

The measurement is based on the unsteady state method (pressure falloff) whereas the pore volume is determined using the Boyle's law technique.

Here are the specifications of poroperm equipment as stated in table.1 [13]

Table.1:Describing the specifications of the Poroperm device.

Item	Type / model / specification
Confining Pressure:	400 psi
Pore Pressure	250 psi
Core diameter	1" or 1.5"
Core length:	1" to 3"
Permeability Range	0.1 to 5000 mD
Porosity Range	0.01 to 60%
Power	110 / 240 VAC, 50 or 60 Hz
Air	125 psi (dry)
Gas supply	400 psi nitrogen or helium

RPS 800

The TEMCO RPS-800-10000 HTHP Relative Permeability Test System is designed for Permeability and Relative Permeability flow testing of core samples, at in-situ conditions of pressure and temperature. Tests that can be performed with the system include initial oil saturation, secondary water flooding, tertiary water flooding, permeability, and relative permeability. Brine, oil, or other fluids can be injected into and through the core sample. Refer to flow/plumbing diagram D-1558-2/PLUMB. The core holder supplied as part of this system can also be installed into X-ray core scanner for measurement of the in-situ. Test conditions can be up to 10000 psig flowing pressure, and up 10,000 psig overburden (confining) pressure, at 177°C (350°F). The pressure at the inlet/outlet of the core sample and the overburden (confining) pressure are all measured using individual pressure transducers. Likewise, the differential pressure across the core is measured with a differential-pressure transmitter. Fluids produced through the core sample are collected in a beaker after the back pressure regulator or the fluids are injected into a two phase separator for production measurement at pressure and temperature.

The system is also designed for the measurement of gas or liquid permeability. A single phase of gas can be injected through core sample. Two fluids can be injected simultaneously to measure relative permeability. [14]

Fig. 4: The Poroperm device

The Poroperm device (figure 4) described above is used to test the cores and get the following data;

Data

The laboratory Experiment
In this laboratory experiment, two cores were used; one for the direct CO2 injection and the other one for WAG injection, both of the cores are barite sandstone (Table. 2).

Table.2: Core data

Core-1

Weight	188.032 g
Diameter	37.85 mm
Height	77.12 mm
Permeability	125.3 mD
Pore volume	14.394 cc
Porosity	16.588 %

Core-2

Weight	188.834 g
Diameter	37.87 mm
Height	77.75 mm
Permeability	35.579 mD
Pore volume	15.171 cc
Porosity	17.323 %

Core-3

Weight	178.113 g
Diameter	37.95 mm
Height	75.32 mm
Permeability	201.842 mD
Pore volume	17.344 cc
Porosity	20.363 %

Results and discussions

The results for core-1, 2 & 3 recorded from the Poroperm device are shown in table.2but core-2 had to be replaced by core-3 since this experiment is a comparison between 2 EOR techniques, so the value of permeability should be close. In this case the difference between the permeability of core-1 and core-2 is huge and it will definitely affect the results.The core was replaced by core-3 which has a closer value of permeability to core-1 which resulted in a more comprehensive result.

THE RPS EXPIRMENT

Core-1 (CO_2 injection) failure

The core was plugged in the RPS machine; all the valves have been tested and checked on, charge the cylinders with the fluids going to be injected; water, oil and carbon dioxide gas, the parameters of the injection (Table.3) has been set, inlet pressure 800 psi, over burden pressure 1200 psi, water (brine) has been injected at 800 psi and 2 ml/min, until the core has been fully flooded with water then the valves controlling the oil flow have been opened and oil started to flow through the core replacing some of the water filled pores with oil.So, we calculate the amount of water extracted and that'sthe way we can know how much oil in place is in the core, the amount of brine recovered 5.03 ml should be deducted from it (the tubing size from the core till the beaker) then starts the CO2 injection.

Table.3: Injection Parameters

Inlet pressure	800 psi
Overburden pressure	1200 psi
Injection rate	2 ml/min

Calculations
Recovered brine 12.8 ml
Amount of oil in place = 12.8-5.03 = 7.77 ml

Water Injection (secondary recovery)
Amount of oil recovered = 7.4 - 5.03 = 2.37
Recovery percent by water injection (secondary recovery) = 2.37/7.77
= 30.5 % of oil has been recovered using the water injection technique
The remaining oil after the water injection = 7.77-2.37
= 5.04 ml

CO_2 injection
Amount of oil recovered = 1.3 ml
During the experiment the carbon dioxide gas cooled of so it plugged the tubings, which resulted in a fictitious results, the experiment was repeated again to get the right results.

CORE-3 (CO_2 INJECTION) SUCCESS
The same procedures for the first run were repeated again, but with different core parameters, as expected the results will be slightly different but still in the same range.
Amount of water recovered= 14.8 ml
The amount of oil in place= 14.8- 5.03
= 9.77 ml
Total PV= 17.344

Water Injection (secondary recovery)
Amount of oil recovered by water inj. = 4.28 ml
Percentage recovered = 4.28/9.77
= 43 % of oil has been recovered using the water injection technique
The remaining oil after the secondary recovery = 9.77-4.28
= 5.49 ml

CO_2 injection
This time heaters are used to avoid cooling of the gas and plugging the tubings gives the results mentioned below;
Amount of oil recovered = 3.4 ml
The percentage recovered = 3.4/5.49
= 61.9 % of oil has been recovered using CO2 injection technique

CORE-1 (WAG) SUCCESS

The core was flooded with water and CO_2 gas alternatively after the water flooding. The experiment was run at 9 ml/min injection rate and pressure ranging between 800-900 psi, the WAG process was done at a ratio of 1:1, with a slug volume of 0.6 PV, 6 cycles was done due to the time constraint (Table.4).

Table.4: Injection parameters, ratio & slug size

Inlet pressure	800 – 900 Psi
Overburden pressure	1200 Psi
Injection Rate	9 ml/min
Injection Ratio	1:1
Slug size	0.6 PV

Water replaced due to oil injection = 13– 5.03 = 7.97 ml is also the amount of oil in place.

Water injection (secondary recovery)
During the brine injection, early water break through was experienced, which yielded a high water cut, and resulted in a low recovery considerably

Amount of oil recovered = 6.8 – 5.03= 1.77

Recovery percentage = 1.77 / 7.97 = 22.2 % of oil has been recovered due to the water injection, it is considered low as compared to the first core but this maybe due to the uncleanness of the core from the first failed run due to the time constraint in the lab time.

Water alternating gas injection (WAG)

Amount of oil in place before WAG injection = 7.97 – 1.77

= 6.2 ml

Amount of oil recovered by WAG injection = 3.3 ml

Recovery percentage = 3.3 / 6.2 = 53.2 % of oil has been recovered using the WAG technique

Discussions (Comparing the results)

The two techniques used in this research are now widely used in the oil and gas field. The experiment was to test both the techniques and compare on the basis of oil recovery.

Water injected was introduced to the experiment to imitate the real case but it is not for discussion. The direct carbon dioxide injection showed better performance in oil recovery around 62 % of the oil originally in place which is very high while the WAG injection recovered around 54 % of the oil originally in place (Figure.5). The results are shown in table.5.

Table.5: Recovery percentage from different core samples

Exp	Core 1	Core 3
Recovery by Water injection	22.3 %	43 %
Recovery by Direct CO2 injection	-	61.9 %
Recovery by WAG injection	53.2 %	

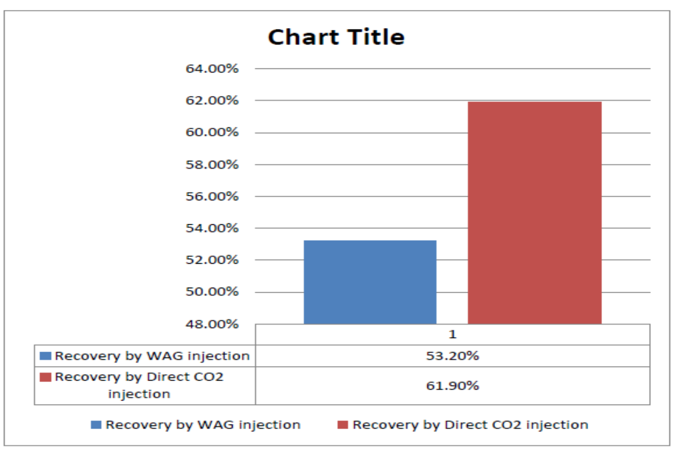

Fig. 5: Recovery profile by WAG and direct CO_2 injection alone.

Conclusions

Enhanced oil recovery techniques researches are very crucial these days because it will help us produce the unrecovered oil to help the humanity advancement. EOR techniques can produce from 50 – 60 % of the oil in place to provide us with fuel in the next decades. The Recovery of direct carbon dioxide injection is higher than the recovery from WAG injection.

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