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Experimental Approach of Minimum Miscibility Pressure for CO_2 Miscible Flooding: Application to Egyptian Oil Fields

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***Abstract*— At the present time, carbon dioxide (CO_2) miscible flooding has become an important method in Enhanced Oil Recovery (EOR) for recovering residual oil, and in addition it may help in protection of the environment as carbon dioxide (CO_2) is widely viewed as an important agent in global warming. This paper presents a study of the effect of carbon dioxide (CO_2) injection on miscible flooding performance for Egyptian oil fields and focuses on designing and constructing a new miscibility lab with low cost by setup a favorable system for carbon dioxide (CO_2) injection to predict the minimum miscibility pressure (MMP) which was required for carbon dioxide (CO_2) flooding projects where every reservoir oil sample has its own unique minimum miscibility pressure (MMP). Experimental data from different crude oil reservoirs carried out by slim tube test that is the most common and standard technique of determining minimum miscibility pressure (MMP) in the industry, but this method is expensive, there for we designed this kind of a favorable system (slim tube test) for carbon dioxide (CO_2) injection. The Possibility of carbon dioxide (CO_2) miscible flooding application to 45.5 % of Egyptian oil fields would be very beneficial for Egypt's reservoirs and subsequently the national economy.**

Index Terms: **Enhanced oil recovery; PVT; (EOR) screening criteria; Miscible flooding injection; Minimum miscibility pressure (MMP);, Slim tube test.**

I. INTRODUCTION

A huge amount of carbon dioxide (CO_2) is discharged to the air which causes greenhouse effect and results in global warming, which leads to melting of glacier, frozen soil and rising of sea level. So all researcher focus on how to decrease the amount of carbon dioxide (CO_2), those were discharged to the air and use it for energy development [1]. In conventional oil recovery projects, the decline of primary and secondary stage of oil production to an uneconomic level led to the development of various schemes to improve the efficiency of oil recovery before the reservoir abandonment.

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The term of "Enhanced Oil Recovery" (EOR) is defined as the oil that was recovered by any method beyond the primary and secondary stage [2]. Enhanced oil recovery processes are divided into three categories: gas miscible flooding, thermal flooding and chemical flooding [3]. Figure (1) shows oil production from different (EOR) projects with an increasing in the world oil percentage. [4-7].

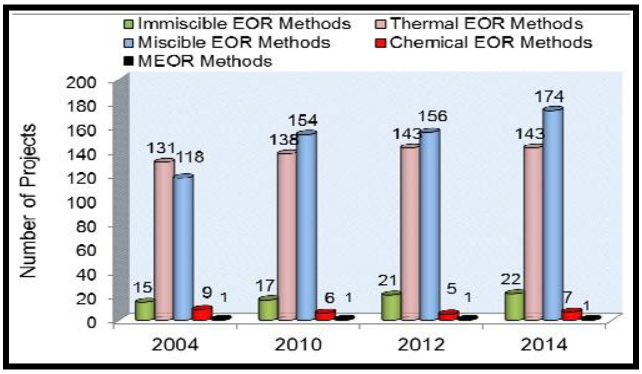


Figure (1): World wade different (EOR) Projects.

A. *Selection of an (EOR) Method*

Not all reservoirs are amenable to enhanced oil recovery (EOR), because the presence of geologic, environmental, chemical, petro-physical, environmental and fluid properties (density & viscosity which are dependent on temperature), must be considered for each individual case of enhanced oil recovery. So the effective screening practices must be employed to identify the suitable method for enhanced oil recovery (EOR). Table (1) shows a simplified method for selection the enhanced oil recovery (EOR) method not only for our case but also for other cases [8].

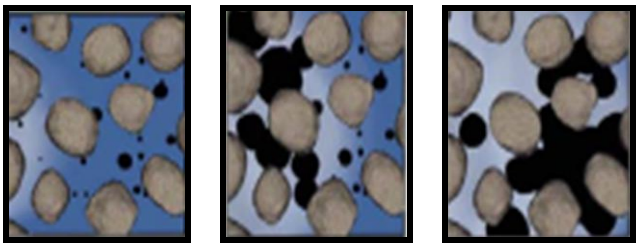
Table (1): EOR Screening criteria.

		Oil properties				Reservoir characteristics				
		Gravity API	Viscosity (CP)	Composition	Oil saturation	Formation Type	Net Thickness (ft)	Average permeability (md)	Depth (ft)	Temp (^{o}F)
Gas injection Methods	Water flood	> 25	<30	N.C.	>10% mobile oil	Sandstone or carbonate	N.C.	N.C.	N.C.	N.C.
	Hydrocarbon	>35	<10	High % of C_2-C_7	>30% PV	Sandstone or carbonate	Thin uniess dipping	N.C.	>2000(LPG) >5000(H.P. gas)	N.C.
	Nitrogen & Flue Gas	>24 >35 for N_2	<10	High % of C_1-C_7	>30% PV	Sandstone or carbonate	Thin uniess dipping	N.C.	>4500	N.C.
	Carbon Dioxido	>26	<15	High % of C_5-C_{12}	>30% PV	Sandstone or carbonate	Thin uniess dipping	N.C.	>2000	N.C.
	Surfactant / polymer	>25	<30	Light intermediate desired	>30% PV	Sandstone preferred	>10	>20	>8000	<175
Chemical Flooding	polymer	>25	<150	N.C.	>10% PV	Sandstone Preferred Carbonato possible	N.C.	>10 (normally)	<9000	<200
	Alkaline	13-35	<200	Some organic acids	Above water flood residual	Sandston preferred	N.C.	>20	<9000	<200
Themal	Combustion	<40(10-25 normally)	<1000	Some asphaltic components	>40-50% PV	Sand or sandstone with high porosity	>10	>10	>500	<150 preferred
	Steam flooding	<25	>20	N.C.	>40-50% PV	Sand or sandstone with high porosity	>20	>200	300-5000	N.C.

N.C. – Not Critical

B. *Carbon Dioxide Flooding*

The application of miscible gas flooding as an enhanced oil recovery technique has increased rapidly, especiallycarbon dioxide (CO_2) miscible flooding injection that is proven enhanced oil recovery technique to recover (15-20%) of the oil in the place and it can be applied to 45.5 % of Egyptian oil reservoirs. A large amount of carbon dioxide (CO_2) gas is usually associated with oil in the reservoir, which can be separated and re-injected into reservoir again for miscible flooding [9]. Carbon dioxide (CO_2) enhanced oil recovery (EOR) process is determined by the property of miscibility where carbon dioxide (CO_2) has the property of mixing with oil to swell it, make it more lighter, detach it from the rock surfaces to flow more freely within the reservoir to producer wells as shown in Figures (2) [10].



Injected (CO_2) encounters trapped oil | (CO_2) and oil mix | Oil expands and move towards producing well

Figure (2): The following photographs illustrate (CO_2) miscible process for oil reservoir.

C. Minimum Miscibility Pressure (MMP)

Minimum miscibility pressure (MMP) is needed to achieve the dynamic miscibility between oil and hydrocarbon gas, where it is an important parameter for screening and selecting reservoirs for miscible gas injection projects and it is defined as the lowest pressure at which (90-92%) of oil recovery reached at (1.2 PV) of carbon dioxide (CO_2) injected. The injected gas and oil in the place become a multi-contact miscible at a fixed temperature [11]. Figure (3) shows compositional phase diagram for a definite temperature and pressure which is called ternary diagram. In thermodynamic criteria for defining the minimum miscibility pressure (MMP) by using ternary diagrams, the minimum miscibility pressure (MMP) is the pressure at which the limiting tie line passes through the point representing the oil composition [12].

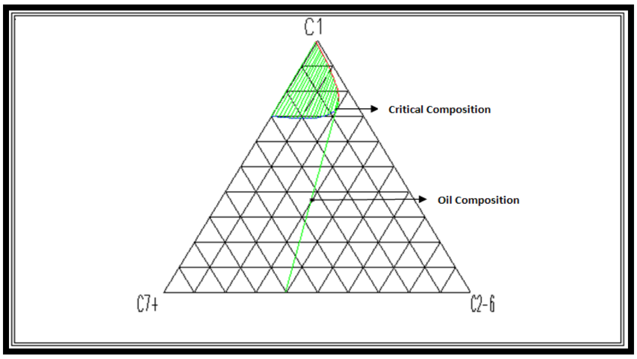


Figure (3): Ternary phase diagram for a hydrocarbon system: the limiting tie line passes through the oil composition at minimum miscibility pressure (MMP).

D. Minimum Miscibility Pressure (MMP)

Factors influencing on the Minimum Miscibility Pressure (MMP), Reservoir temperature and chemical compositions of the oil are affected on minimum miscibility pressure (MMP) as the following:

1) Minimum miscibility pressure (MMP) is inversely related to the total amount of (C_5 to C_{30}) present in the reservoir oil.
2) Higher reservoir temperature results in higher minimum miscibility pressure (MMP).
3) Minimum miscibility pressure (MMP) does not require the presence of (C_2 to C_4).
4) The presence of methane (C_1) in the reservoir doesn't change the minimum miscibility pressure (MMP) appreciably.
5) Minimum miscibility pressure (MMP) increases as the oil becomes heavier, so heavy oil reservoirs with API less than 22 degrees are not suitable to carbon dioxide (CO_2) miscible flooding [13].

There are several methods for determining minimum miscibility pressure (MMP) of miscible gas flooding that include slim tube test, rising bubble test, vapor-liquid equilibrium studies and mixing cell methods. Vapor-liquid equilibrium (VLE) studies are not convenient and applicable in that because it requires an enormous amount of calculation [14]. Mixing cells and rising bubble methods are not so common in oil and gas industry. A slim-tube experiment remains the most reliable experimental method of estimating minimum miscibility pressure (MMP) in the oil and gas industry, because they can replicate the actual interaction of oil and gas in a one-dimensional porous medium [13].But this method is expensive, there for we designed and constructing this kind of a favorable system (slim tube test) for (CO_2) injection with low cost as compared if we purchased it.

II. EXPERIMENTAL

In the current study, carbon dioxide (CO_2) injection was evaluated by some a series of laboratory tests involve PVT tests studies and slim tube tests that is designing and constructing a favorable system (slim tube test). These procedures are performed with ten different bottom hole oil samples were obtained from different Egyptian oil reservoirs.

A. PVT Study of Reservoir Fluid

The laboratory tests involve sample validation, primary tests and constant mass depletion tests.

- Sample Validation Test

Validation test is carried out by measuring opening pressures of bottom hole sample at reservoir temperature to ensure against leakage. If the measuring opening pressure is not valid (i.e. more than 2% of the operating pressure), re-sampling was done [15].

- Primary Test

After validation, there are primary test that involve atmospheric flashing of bottom hole sample by free mercury PVT cell from reservoir conditions Pres and T_{res} to standard conditions of P=14.73 psia and T=60°F to obtain stock tank oil and flashed gas, as shown in Figure (4). The properties of gas and oil are determined which include API gravity of the stock-tank oil was measured using density meter, flashed gas-oil ratio (GOR) was calculated by using volume

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of stock tank oil and flashed gas, the viscosity was measured by Rolling-Ball viscometer and composition of gas and oil were measured using chromatography analyzer then the reservoir fluid composition was calculated [15&16].

- Constant Mass Depletion (CMD)

The test objective of constant mass depletion (CMD) is to determine bubble-point pressure. By charging the fluid sample (oil and gas) into a visual PVT cell and adjust temperature to reservoir temperature and at a pressure greater than the reservoir pressure. The cell is agitated regularly to ensure that the contents homogenous. Figure (5) shows schismatic procedure for measuring constant mass expansion test. The pressure was reduced in steps at constant temperature by releasing the piston from the cell and the change in the total hydrocarbon volume was measured for each pressure increment. The saturation pressure (bubble-point pressure) and the corresponding volume were recorded [17&18].

Figure (4): Free mercury PVT cell.

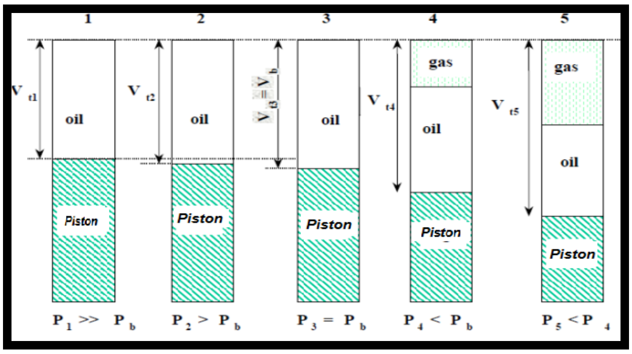

Figure (5): Constant mass depletion test.

A. Reservoir Fluid Miscibility Study

After constant mass depletion test, slim tube test is conducted to estimate minimum miscibility pressure (MMP), but firstly we evaluate porosity and permeability measurement for slim tube.

- Porosity Measurement

One of the parameters that show the fluids volume in the reservoir at any time is porosity [18], where it is determined in this work by measuring initially mass of dry sand, then it was saturated with distilled water and the mass was measured again. The difference between two measured mass was equivalent to the mass of water which was saturating the sand pack. The porosity can be determined using Eq (1) as shown in Table (2)[19].

$$\phi = \frac{V_{fluid}}{V_{total}} \quad \text{..........(1)}$$

- Permeability Measurement

It is resistance measuring to flow, where the sand pack permeability was measured with brine solution after porosity measurement and can be calculated by Darcy's law using Eq (2) as shown in Table (2)[18].

$$\frac{q\mu}{A} = k\,\frac{\Delta P}{L} \quad \text{..........(2)}$$

- New Model description

A slim-tube is a long narrow stainless steel tube packed with glass beads or sand from 160 to 200 mesh (sand packing is used in this study). The length of the tube is between 3 and 120 ft (Actual used in this design 14 meter) [19&20], and the diameter varies from 0.12 to 0.63 in, with 0.25 in as a typical diameter (Actual used in this design 0.63 for outside diameter and 0.45 for internal diameter) [20]. Because of this large length-to-diameter ratio, the slim-tube experiment comes close to a one dimensional displacement, thus isolating the effect of phase behavior on displacement efficiency. The slim-tube displacement velocity is typically between 4 to 8 cm3/ hr (Actual used in this design 4 cm3/ hr) [14]. The schematic of the slim tube setup is shown in Figure (6). In slim-tube experiments; gas is injected into a slim-tube that is saturated with oil. The injection temperature and pressure are kept constant by a back-pressure regulator to prevent pressure from one side of the diaphragm of the back pressure regulator from becoming significantly higher than the pressure on the other side and damage the diaphragm, it was necessary to pressurize the system slowly. Effluent is continuously flashed to atmospheric conditions, where the separator gas is connected to a flow meter and the separator liquid is collected in a graduated cylinder as shown in Figure (6). Residual oil in the slim tube was removed by at least 2 PV of methylene chloride to clean the slim tube before the next experiment [13].

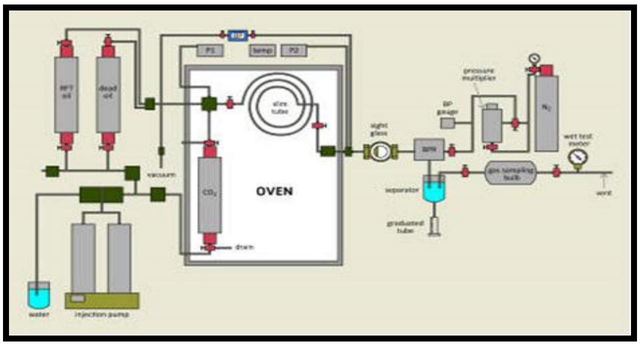

Figure (6):Schematic of slim tube setup

The entire experiment was then repeated several times at different pressures above saturation pressure (bubble-point pressure), so slim tube test is conducted after constant mass depletion test, where saturation pressure (bubble-point pressure) of the reservoir oil was measured. In each experiment, oil recovery and pore-volume of injected gas are recorded. The recovery data are then used to estimate minimum miscibility pressure (MMP) after typically injecting 1.2 pore volume of gas. The most common criterion is the break-over pressure in a plot of recovery versus pressure, when recovery is recorded after typically injecting 1.2 pore volume of gas [21]. Other minimum miscibility pressure (MMP) criteria are 80% recovery at gas breakthrough [22] and 90%–95% of ultimate recovery [22-26]. The actual image of vital components of the slim-tube apparatus in new miscibility lab are shown in Figures (7 through 11).

Figure (7):An actual image of slim tube experimental setup (New miscibility lab)

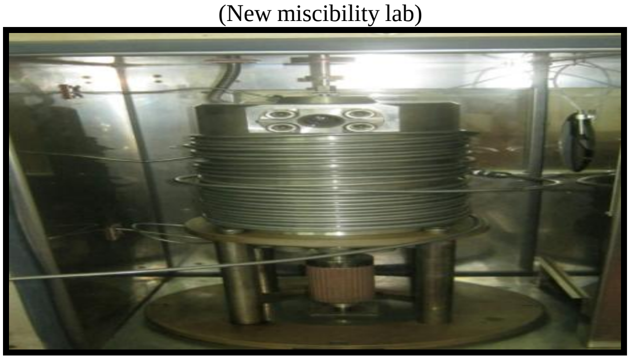

Figure (8):Slim tube central unit

Figure (9):Proportional displacement pump

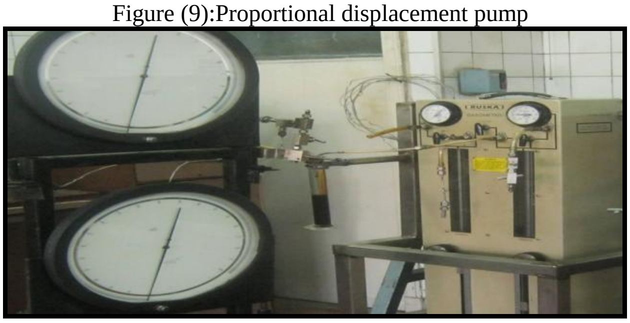

Figure (10):Oil and gas gathering and measuring

Figure (11):Back pressure regulator

III. Results and Discussion

High pressure slim tube displacement tests were performed for ten different live crude oil samples. The purpose of this slim tube experiment is to determine the minimum miscibility pressure (MMP) to optimize the volumes of carbon dioxide (CO_2) that was required to produce the residual oil [24]. First step in this study, is conducted the rock and fluid properties, in order to get the most suitable oil reservoirs indifferent region in Egypt for carbon dioxide (CO_2) miscible flooding according to screening criteria.

A. Oil Physical Properties

Mostly data of physical properties of oil reservoirs come from experimental measurements by PVT analysis of reservoir fluid, where saturation pressure (bubble-point pressure) were resulted from constant mass depletion test (CMD) and gas solubility (gas/oil ratio), oil gravity and dead oil viscosity at standard condition (P=14.73 psia and T=60°F) were resulted from primary test. Another data like rock properties that are discussed in term of permeability and porosity, and also data come from field in term of reservoir pressure and reservoir temperature. All this data were statistically treated and the results are given in Table (2). It shows the basic characteristics of the collected Egyptian crude oil samples, which comprise the values of arithmetic mean, maximum, minimum and standard deviation and the results are plotted in Figure (12), which ensure clarifies variation in data selection due to the differences in source.

Table (2): Statistical data ranges of the most suitable depleted reservoirs for carbon dioxide (CO_2) injection.

Property	Maximum value	Minimum value	Arithmetic mean
Res. T, °F	246.0	160.3	192.6
Res. P, psi	4200.0	2325.1	3336.2
GOR, SCF/STB	619.5	10.0	163.5
Vis at ST, cp	15.9	5.4	11.3
BP, psi	1400.6	74.1	464.8
Permeability, md	589.0	210.0	359.9
Porosity, PV	29.0	23.0	26.1
°API	40.5	26.4	34.1

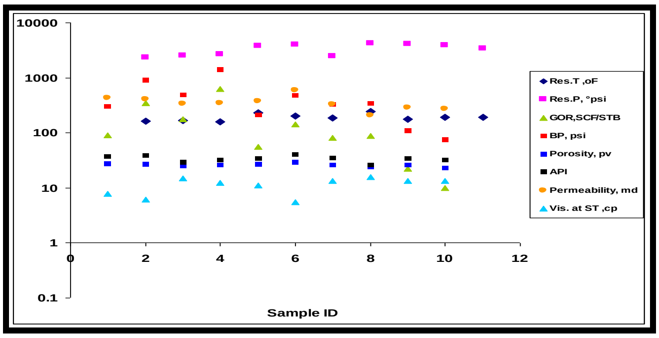

Figure (12):Schematic of slim tube setup

B. Oil Physical Properties

Compositional analysis of reservoir fluid to pentane plus (C_5^+) was calculated by using the measured compositions of the stock tank oil (flashed oil) and flashed gas in conjunction with gas solubility (gas/oil ratio) ,oil density at stander condition (P=14.73 psia and T=60°F) and molecular weight of stock tank oil. The minimum miscibility pressure (MMP) for any reservoir oil is based on the analysis of the reservoir fluid composition as shown in Figure (13), which clarifies the variation in composition analysis for these studies [25].

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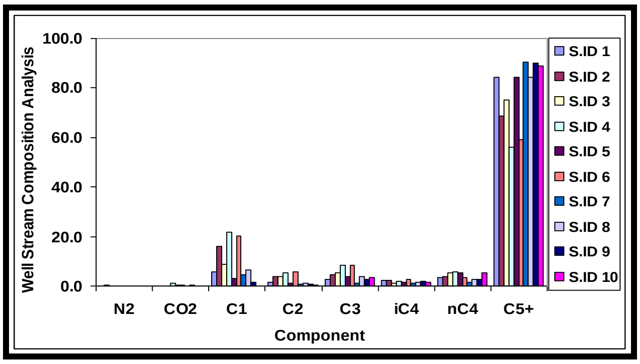

Figure (13): Variation of reservoir fluid composition analysis for ten Egyptian live crude oils

Second step in this study, is conducting the effect of pressure on carbon dioxide (CO_2)miscible flooding, where each oil sample is tested with ten pressures gradually starting from pressure above saturation pressure (bubble-point pressure). Percentage of oil recovery against tested pressure is plotted at (1.2 PV) of carbon dioxide (CO_2) injection to determine the minimum miscibility pressure (MMP) of the system at reservoir temperature as shown in Figures (14 through 23), where the percentage of oil recovery and pore volume (PV) of carbon dioxide (CO_2) injected were calculated as shown in Eqs. (3&4).

Oil Recovery, %= (Weight of Oil Produced) / (Pore Volume*Oil Density)*100% ....(3)

(PV) of CO_2 injected = (Time* CO_2 Flow Rate) / (Pore Volume) ....(4)

Minimum miscibility pressure (MMP) is obtained by drawing a line through (90-92%) of the oil recovery and the corresponding pressure is known as minimum miscibility pressure (MMP) (The intersection of a line though the highest slope and a line through the nearly horizontal slope), where miscibility development between carbon dioxide (CO_2) and oil is a function of both temperature and pressure, but the most concern is pressure [18]. When minimum miscibility pressure (MMP) is reached as shown in Figures (14 through 23), the displacement becomes very efficient [22&23]. By carbon dioxide (CO_2) displacement of crude oil in slim tube test, the miscibility of carbon dioxide (CO_2) injection gas and the reservoir fluid increases, where higher injection pressure will give a greater oil recovery (the ability of carbon dioxide (CO_2) to extract components from crude oil decreases as the pressure decrease)[24]. Above the minimum miscibility pressure (MMP), the increase in the oil recovery will not be as a great with an equivalent increase in injection pressure as it below the minimum miscibility pressure (MMP), thus a break over in the oil recovery-pressure relation is observed at the minimum miscibility pressure (MMP)[27]. The term of near miscible is understood as the transition from immiscible region (partially dissolve) to miscible region (completely dissolve). Near miscible refers to displacements at pressures slightly below minimum miscibility pressure (MMP), where the recovery efficiency is improved over immiscible displacements. The pressure range of near miscible region was selected from 0.8 (MMP) to 0.1 (MMP) [28]. In this study, the near miscible region for ten live crude oil samples is presented in Figures (14 through 23). The oil recovery results of slim tube displacements at reservoir temperature were plotted against (1.2 PV) of carbon dioxide (CO_2) Injected as shown in Figures (24 through 33).

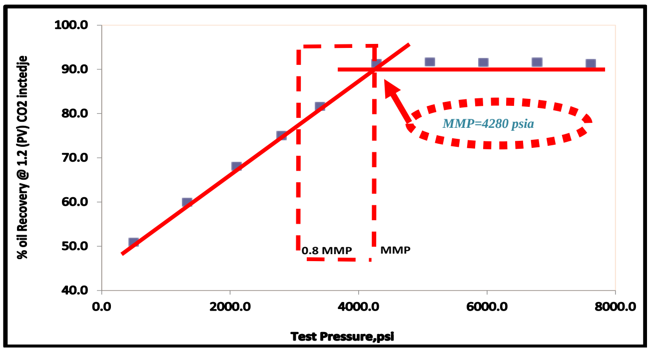

Figure (14): Minimum miscibility pressure for sample NO.(1)

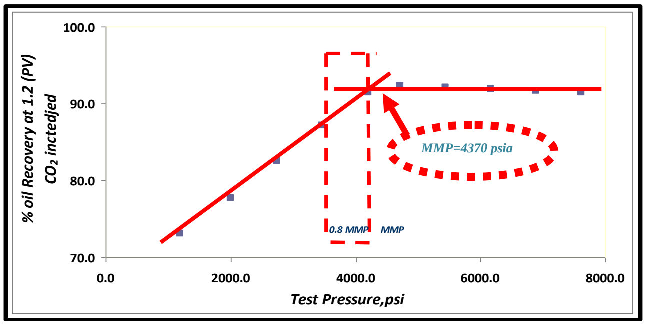

Figure (15): Minimum miscibility pressure for sample NO.(2)

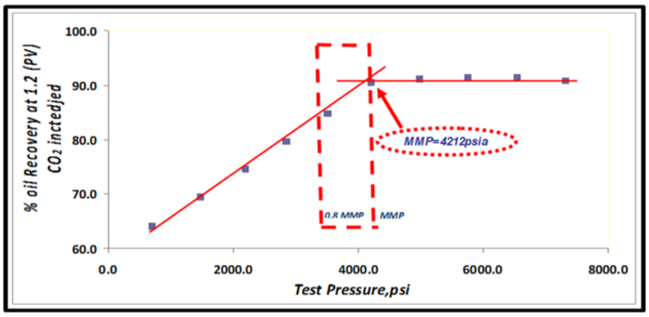

Figure (16): Minimum miscibility pressure for sample NO.(3)

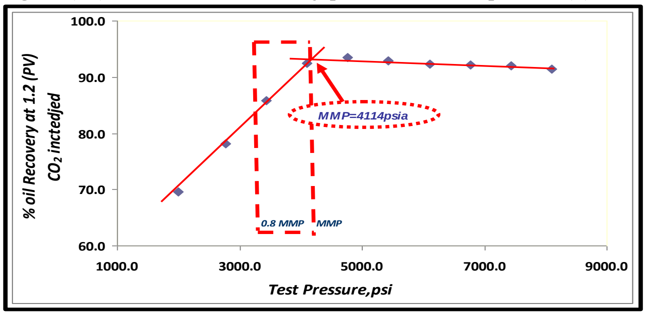

Figure (17): Minimum miscibility pressure for sample NO.(4)

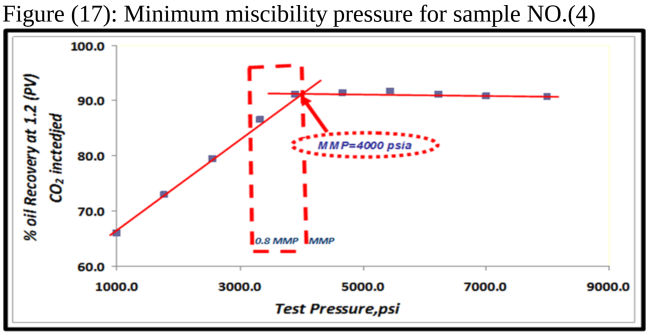

Figure (18): Minimum miscibility pressure for sample NO.(5)

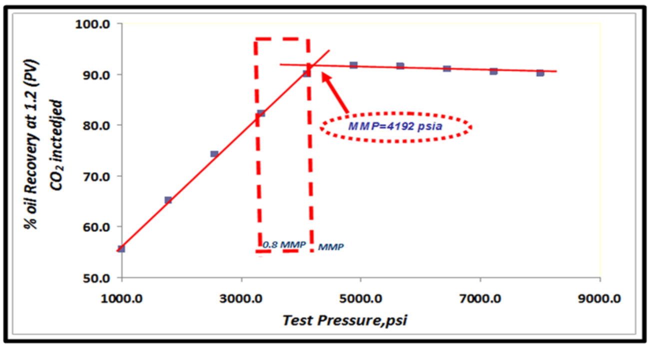

Figure (19): Minimum miscibility pressure for sample NO.(6)

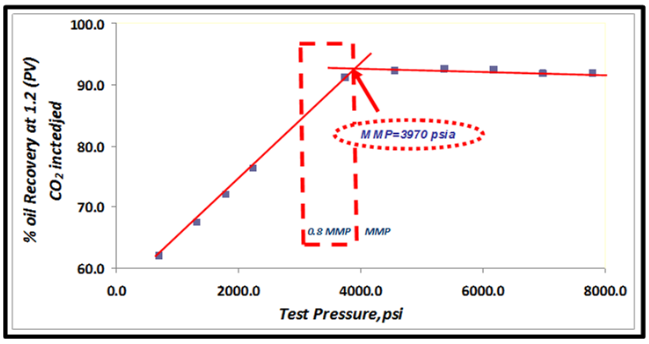

Figure (20): Minimum miscibility pressure for sample NO.(7)

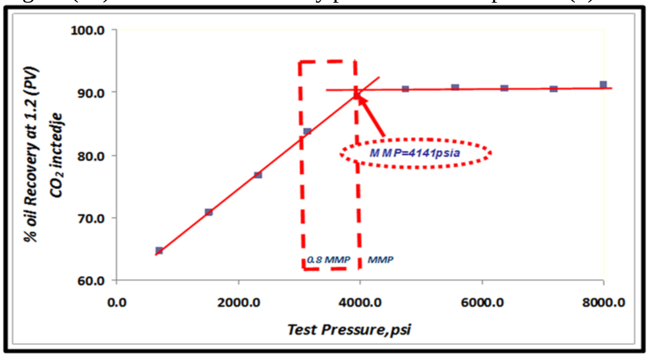

Figure (21): Minimum miscibility pressure for sample NO.(8)

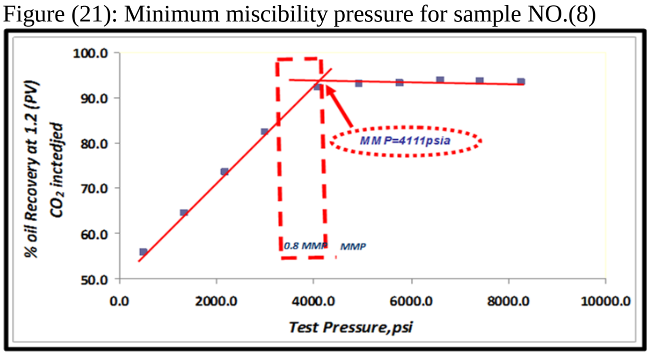

Figure (22): Minimum miscibility pressure for sample NO.(9)

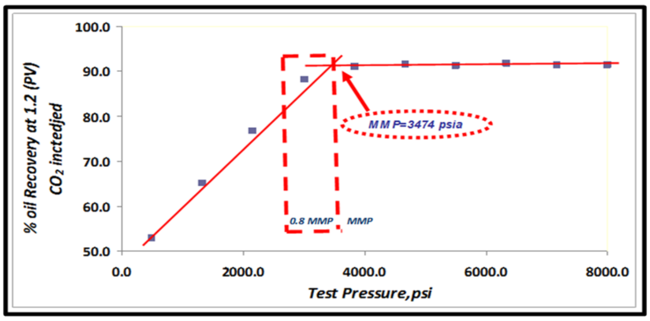

Figure (23): Minimum miscibility pressure for sample NO.(10)

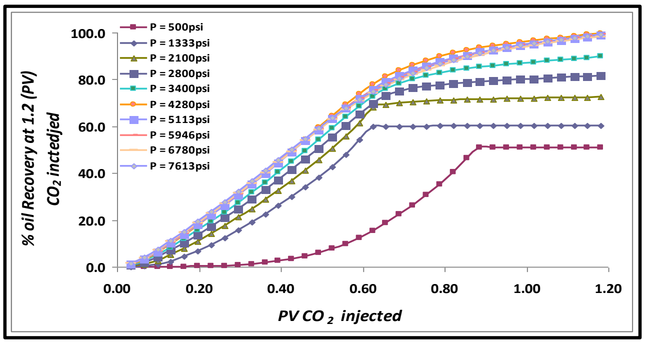

Figure (24): Results of displacement test for sample NO. (1)

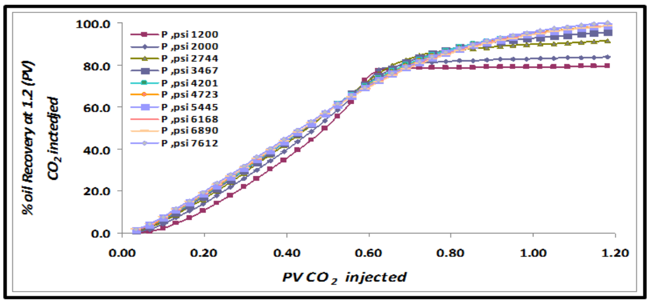

Figure (25): Results of displacement test for sample NO. (2)

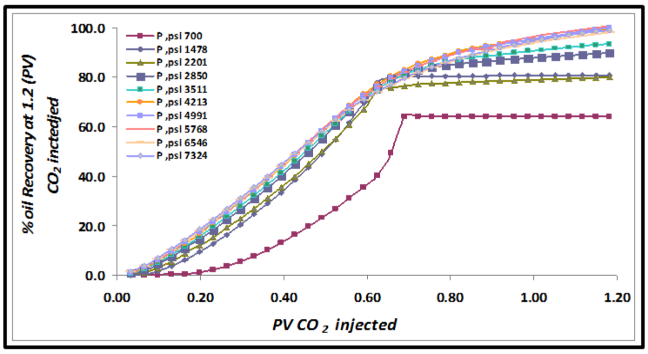

Figure (26): Results of displacement test for sample NO. (3)

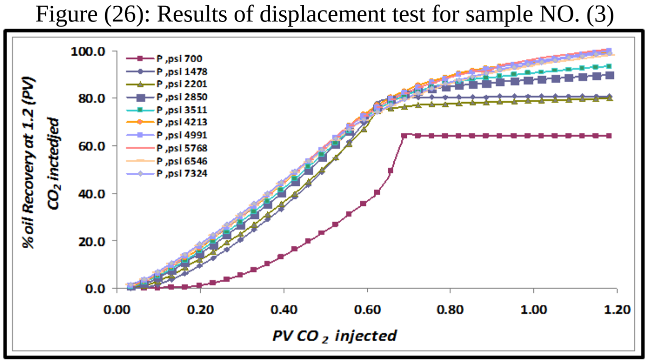

Figure (27): Results of displacement test for sample NO. (4)

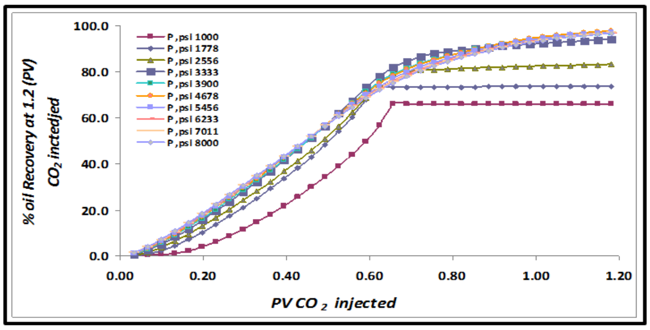

Figure (29): Results of displacement test for sample NO. (5)

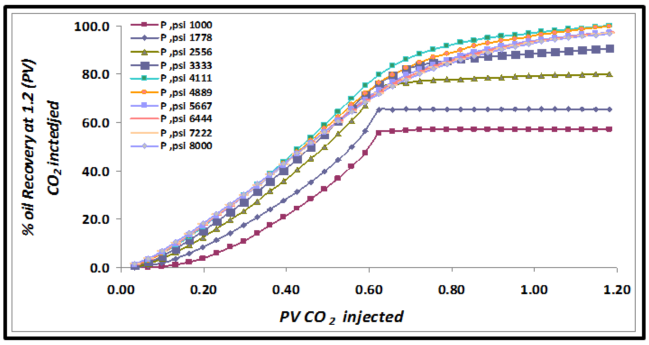

Figure (30): Results of displacement test for sample NO. (7)

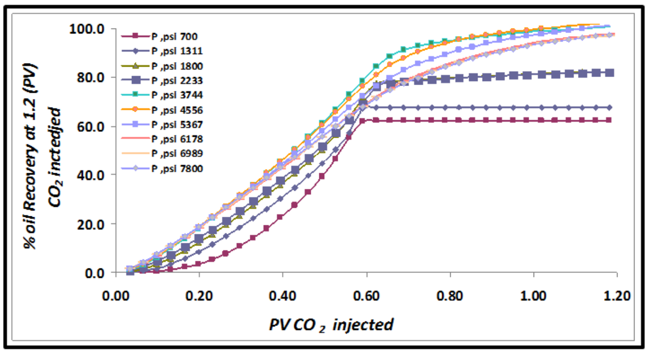

Figure (31): Results of displacement test for sample NO. (8)

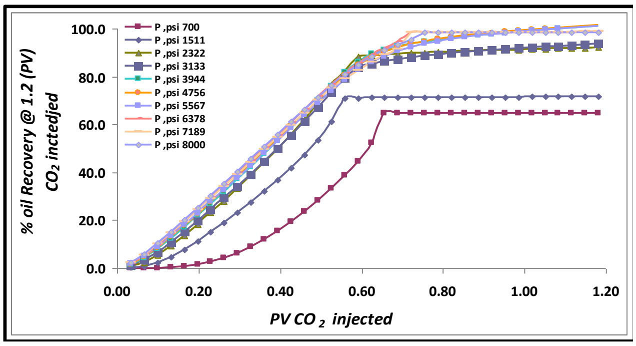

Figure (32): Results of displacement test for sample NO. (9)

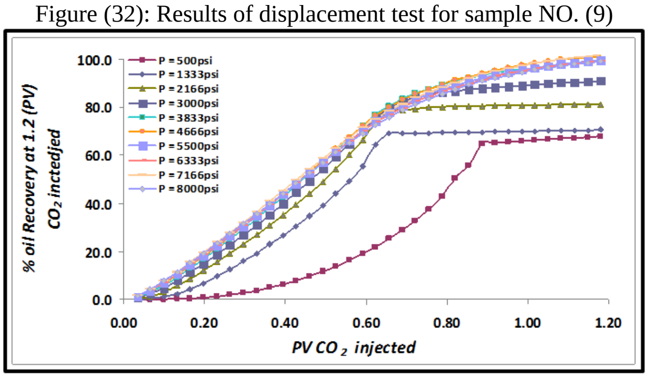

Figure (22): Minimum miscibility pressure for sample NO.(9)

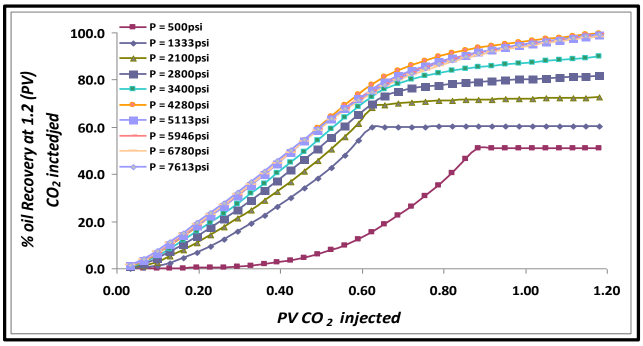

Figure (33): Results of displacement test for sample NO. (10)

Figure (34) shows (MMP) versus current reservoir pressure for ten live crude oil samples, where in many (CO_2) miscible flooding, the reservoir pressure is maintained well above the (MMP) to avoid a pressure drop below the (MMP) in the parts of the reservoir, thus causing poor recovery. Therefore, the expense of maintaining the reservoir pressure well above the (MMP) is accepted as shown in sample ID (5&7) [29]. This case when reservoir pressure more than (MMP) pressure in range (300-500 psi), but if more than this range, it is need to increase miscibility pressure and this is more costly. If in case reservoir pressure less than (MMP) within also the range, so it is very close to reservoir pressure and it is accepted as shown in sample ID (4&8&9&10). But the lowering of reservoir pressure below the (MMP) more than this range will significantly affect the displacement efficiency. Because In fact, less reservoir pressure will be needed to increase to pressure near to (MMP) by more injection of (CO_2) and this is more costly as shown in sample ID (1&2&3&6).

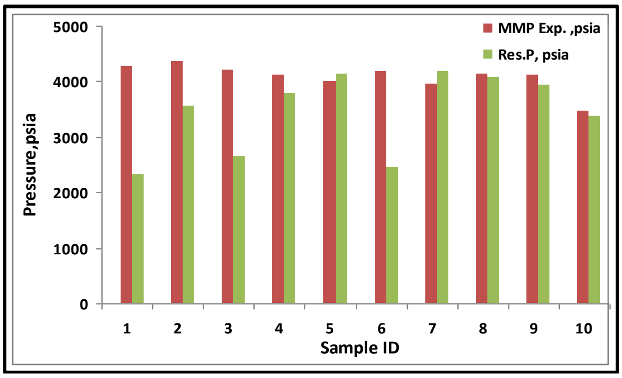

Figure (34): Variation between minimum miscibility pressure and current reservoir pressure

IV. Conclusions

The Possibility of (CO_2) miscible Flooding application to Egyptian Oil Fields would be very beneficial for Egypt's reservoirs and subsequently the national economy.

Designing and constructing a new miscibility lab (slim tube test) with low cost.

Every reservoir oil sample has its own unique (MMP) as each oil sample has its own distinctive oil composition. Thus it is critical to rapidly determine the (MMP) for each reservoir oil sample when screening for (CO_2) flooding projects.

V. Nomenclature

A	The cross-sectional area of the sand pack
API	American Petroleum Institute, degree.
Bb	Bubble point, psi
CMD	Constant Mass Depletion
CO_2	Carbon dioxide
EOR	Enhanced Oil Recovery
GOR	Gas oil ratio, SCF/STB
K	Permeability
L	length of the sand pack
MMP	Minimum Miscibility Pressure
^oF	Fahrenheit degree
p	Reservoir pressure, psia.
psi	Pound/square inch
psia	Pound/square inch absolute

PV	Pour volume
PVT	Pressure, Volume, Temperature
q	The flow rate
Res	Reservoir
S.ID	Sample ID
SCF/STB	Stander cubic feet per stock tank barrel.
T	Reservoir Temperature, ^oF
μ	Viscosity of fluid
φ	Porosity

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