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Assessment of Parameters for a Successful Screening for Miscible Carbon dioxide Enhanced Oil Recovery

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Abstract: Miscible gas injection is the widely applied enhanced oil recovery method. Among the gases which fines application in gas injection, CO_2 gas is leading in worldwide application. The availability, cost efficient and miscible ability of CO_2 even at lower pressure as compare to other gases has given it the edge. Enhanced oil recovery has become necessary for oil and gas industry in order to meet the global demand in energy of the fossil source and to remain in business. This is because primary and secondary recovery techniques can only recover about 35 to 45% of OOIP. Total of 1078 reservoir fields all located in United State of America were screened and evaluated as potential candidates for miscible CO_2 enhanced oil recovery. Oil properties such as oil viscosity and oil API gravity were considered for the screening exercise. Whereas reservoir properties such as oil saturation, and reservoir depth were also used to screened the reservoir field data. Taber *et al*., 1997 recommended screening criteria were used and a new range for parameters used in the screening were suggested for better productivity based on the output of the screening carried out. The minimum miscibility pressure (MMP) which represents the minimum pressure at which the final recovery reaches 90-95% with 1.2PV CO_2 injection, is estimated for the reservoir fields and it gives a range of 942 psi to 3156 psi. The plot of MMP with temperature shows that MMP increases with increasing temperature and vice versa.

***Keywords**: CO_2, Enhanced Oil Recovery, Screening Criteria, MMP.*

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I. INTRODUCTION

Enhanced Oil Recovery becomes necessary after primary and secondary recovery mechanisms failed to improve the recovery of oil to meet the global demand on fossil oil. About two-third of OOIP remained in the reservoir after the traditional recovery methods were exhausted (Shaw and Martin 2002). Primary mechanism can recover only about 20 to 40% of the oil in reserve, while EOR has proving to recover about 30 to 60%. Oil and gas reservoirs are depleting in nature and not all the oil in reservoirs are produce by the influence of primary recovery mechanisms. Enhanced oil recovery helps in increasing the productivity and extends the life span of reservoirs. Over the years, there exist EOR mechanisms such as: thermal injection (used of heat to reduce the viscosity of oil by thinning it), Chemical injection (used of polymers or surfactants to improve oil flow and reduce surface tension), Gas injection (used of gases such as Nitrogen, flue gas, air injection, and CO_2, to reduce the oil viscosity thereby improving the ease of oil flow) and Microbial EOR (used of microorganisms such as Bacteria). EOR has become the practicable solution for petroleum industries in order to meet up with the global demand on crude oil and to stay in business. Studies have shown that CO_2 flooding can improve oil recovery by 15-25% OOI (Shuli *et al*., 2011).

➢ *CO_2 Flooding*

CO_2 flooding is very vital EOR method as over the years CO_2 flooding has account for over 180,000 stb/day recovered from miscible CO_2 injection (Ghedan, 2009). The CO_2 flooding is used to recover oil from the reservoir after

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waterflooding. CO_2 becomes soluble in oil when the interfacial tension between the CO_2 and the residual oil is broken. When CO_2 dissolves in oil, it swells the oil and reduces the viscosity of the oil, thereby influencing the displacement of the oil. To achieve effective CO_2 injection, a simulation is run to model the reservoir characteristics so as to achieve the target task. CO_2 at low pressure is immiscible or partially miscible depending on the condition (Ennin and Grigg, 2016). When CO_2 is injected into reservoir, it causes the oil to swell at the same time reducing the viscosity of the oil. CO_2 flooding works best when used with WAG. CO_2 injection goes well in reservoirs with higher pressure. CO_2 injection which is a form of gasflooding method can become miscible or remain immiscible with the reservoir oil depending on the condition of the injection. The injected CO_2 continues on a cyclic process from the injection well to being soak and produced alongside the oil. The soak stage can last for days or weeks, here the oil swells and the viscosity of the oil is reduced. Afterward the oil is being produced alongside with CO_2. The production is achieved by taking the advantage of increase pressure from the injected CO_2 and change in the properties of the oil which is cause as a result of the injected gas. Figure 1 shows the described process.

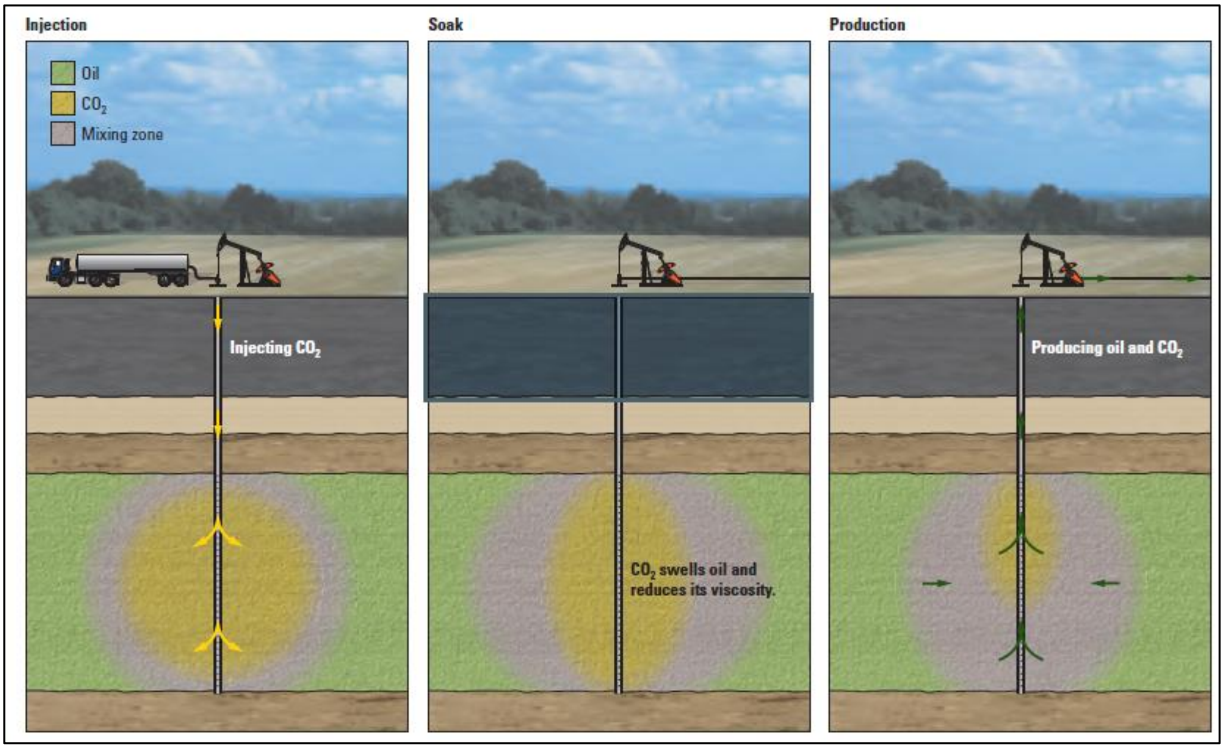

Fig 1 Cyclic Miscible CO_2 Injection Process.
Source: Al-Mjeni *et al.*, (2011)

➢ *Screening for EOR*

EOR process involves a lot of capital which requires a serious screening to determine which method will be best for a certain reservoir keeping in mind the economics involve and the available resources. It is important to study the oil and reservoir properties in order to provide a basic ground for decision making.

- *The Primary Objective of EOR Screening Process According to Sheng, 2013 is to:*

✓ Rank the potential candidate reservoirs for gas flooding,
✓ Identify potential injection fluids,
✓ Identify analogue fields,
✓ Make more preliminary production rate estimate and scoping economic calculations, and
✓ Identify which reservoirs should be examined in a later more detailed.

- *To Achieve the Primary Objectives, the Reservoirs are Screened Based on:*

✓ Reservoir geology,
✓ Minimum miscibility pressure (MMP), and
✓ Oil gravity

II. METHOD

Oil properties which influence oil recovery such as oil API gravity, oil viscosity, and oil composition needs to be screen. Same applies to the reservoir properties such as the oil saturation, formation type, net thickness, average permeability, depth, and temperature need to be screen.

The screening carried out in this project is based on data of miscible CO_2 EOR projects obtained from institute of Drilling Technology and Fluid Mining, TU Bergakademie Freiberg, Germany. The data were subjected to screening base on the screening criteria highlighted in table 1 for CO_2 flooding. Oil properties such as oil viscosity, oil API were

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considered and reservoir properties such as oil saturation, and reservoir depth were also considered. Total number of 1078 (USA fields) and 49 (fields in other parts of the world) reservoir fields were considered in this research. The data runs from 1986 to 2014 in interval of two years (table 2). The behaviour of these parameters with respect to total production were evaluated in order to ascertain the accompanied changes.

Screening for CO_2 flooding is shown in table 1, the recommended screening guide can be seen for both the oil and reservoir properties. CO_2 injection which involves the injection of large quantities of CO_2 into the reservoir. The injected CO_2 can be miscible or immiscible depending on the conditions at which the injection is carried out. Nevertheless, miscible flooding fines more application because more recovery is achieved under miscible condition. Miscible flooding goes well when the oil API is greater than 22 and depth greater than 2500 ft. At depth between 2500ft to 1800ft, immiscible flooding can take place whereas at below 1800ft the reservoir fails. It is important to screen the reservoir so as to have a profitable EOR process. Other parameters considered in this screening is the oil viscosity (<10), and oil saturation (>20).

Table 1 Screening Criteria for Carbon Dioxide Flooding

CARBON DIOXIDE FLOODING				
Properties	Literature Recommendation			Current Project Values
Oil- API Gravity	>22			22 to 48
Oil Viscosity (cp)	<10			0.35 to 46
Composition	High percentage of intermediate hydrocarbons (especially C_5 -C_{12})			
Oil Saturation (%PV)	>20			3 to 89
Formation Type	Sandstone or carbonates and relatively thin unless dipping			Conglomerate, Dolomite, Dolomite/Limestone, Shale, Sandstone, Tripolitic Chert, Limestone/Dolomite, Shale/Limestone-Dolomite, Dolomite/Tripolitic Chert
Net thickness(ft)	width range			
Average permeability (md)	Not critical if sufficient rates can be maintained			2 to 41,675
Depth (ft)	>2500 for mscible while immiscible >1800			1150 to 15600
Temperature (degF)	Not critical			82 to 260
	for CO_2 miscible flooding	Oil Gravity	Depth (ft) must be greater than:	
		>40	2500	
		32-39.9	2800	
		28-31.9	3300	
		22-27.9	4000	
		<22	Fails miscible, screen for immiscible	
	For immiscible CO_2 flooding	13-21.9	1800	
		<13	All oil reservoirs fail at depth below 1800	

Table 2 Total Number of Fields Considered.

Year	Number of Fields	
	USA	**Other parts of the world**
1986	40	-
1988	48	3
1990	51	5
1992	51	6
1994	53	6
1996	59	5
1998	65	-
2000	60	5
2002	65	2
2004	69	2
2006	79	-
2008	98	7
2010	107	6
2012	110	-
2014	123	2
Total	**1078**	**49**

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The minimum miscibility pressure is estimated using Yellig and Metcalfe 1978 correlation which makes use of temperature as the only dependent parameter.

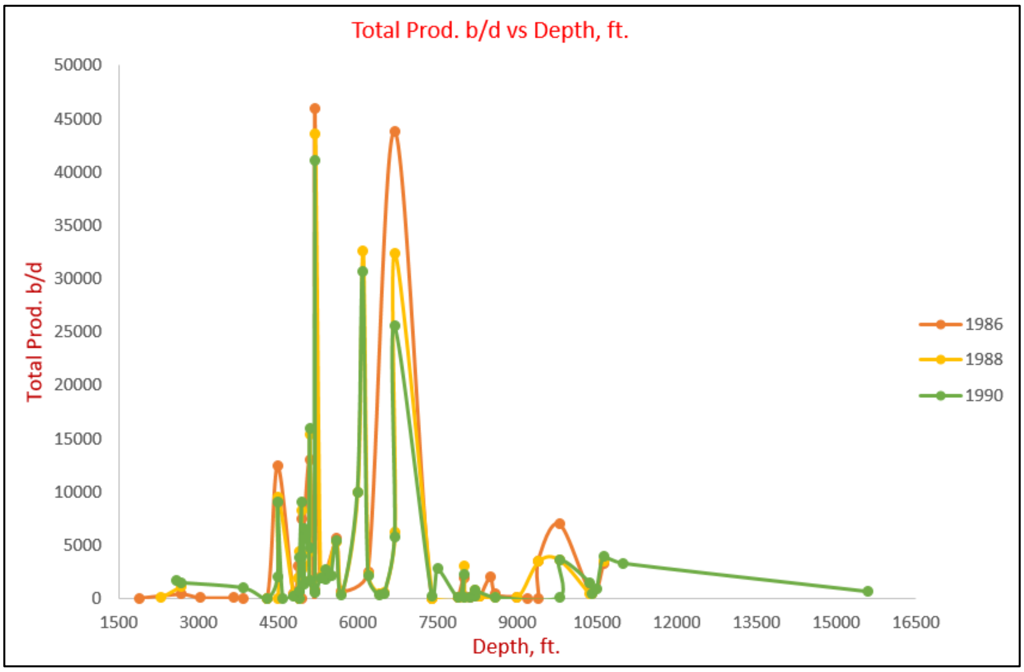
$$MMP = 1833.7217 + 2.25180055T + 0.01800674T^2 - 103949.93/T$$

This correlation is chosen because it is less complicated without need for other reservoir data

III. RESULT AND DISCUSSIONS

➢ *Screening by Formation Depth*

The depth of the reservoir plays a vital role in screening for EOR. Miscibility is a key factor that depends on pressure of injection and the depth of the reservoir determines to a large extent the pressure require for miscibility. The reservoir fields were subjected to screening for miscible CO_2 EOR. The recommended depth is greater than 2500 ft (table 1) for effective miscibility. The range of reservoir depth for the data of this project is 1150 to 15600 ft. From figure 2(e) it can be seen that at that low depth of 1150 ft the total production recorded was zero. At depth below the recommended, the total production is low, whereas at above 2500 ft to about 7000 ft the production has increased. Worthy of note is that for both figures 2(a-e), at depth above 7000ft, the production is low. It is therefore recommended at this point that depth 4000 to 7000 ft is a very good range for effective miscibility as it gives the highest production rate of 46000b/d at 1986 and 30800b/d at 2014.



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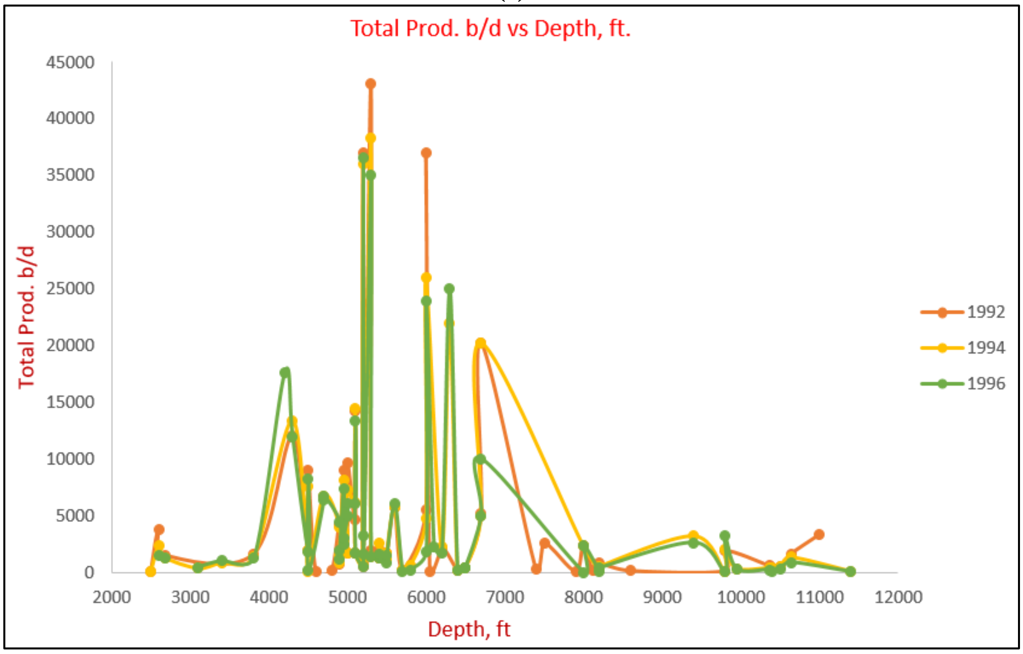

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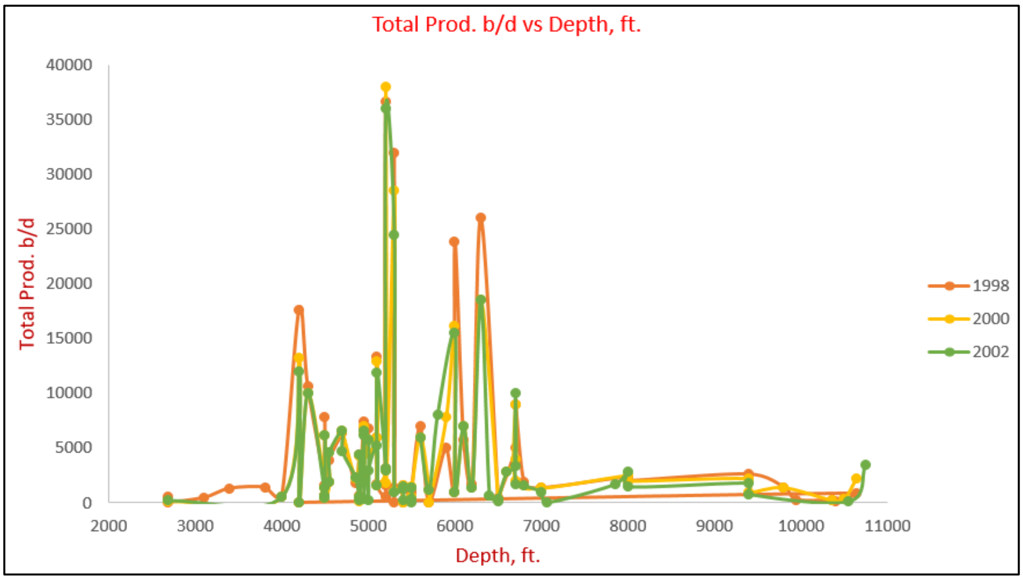

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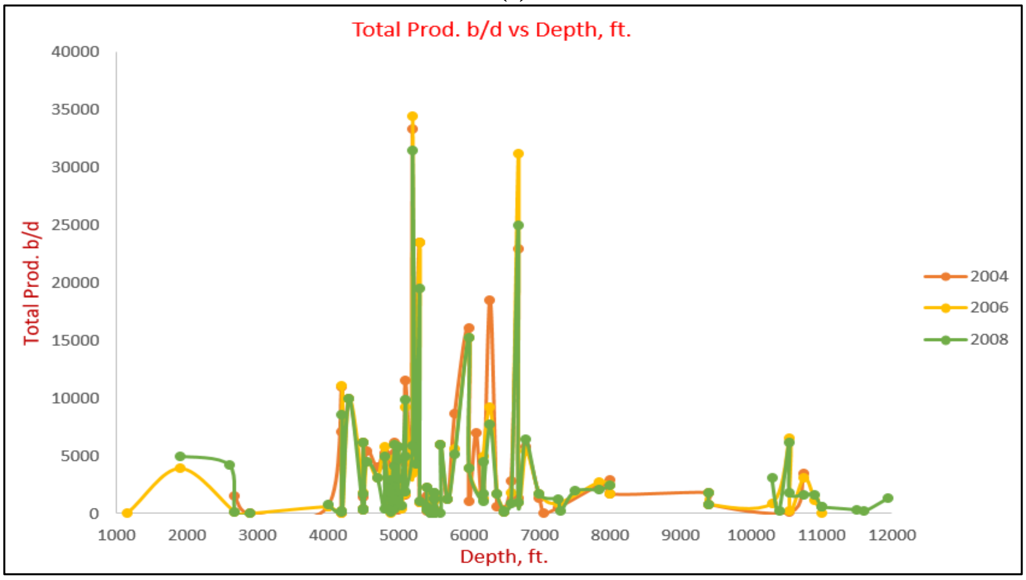

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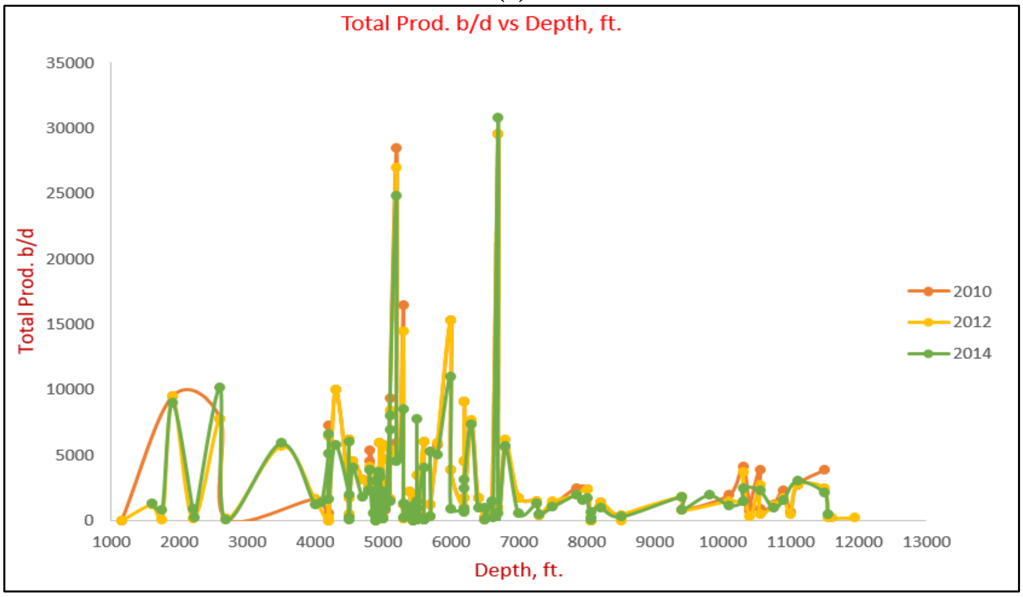

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Fig 2 Total Production b/d vs Depth Ft.

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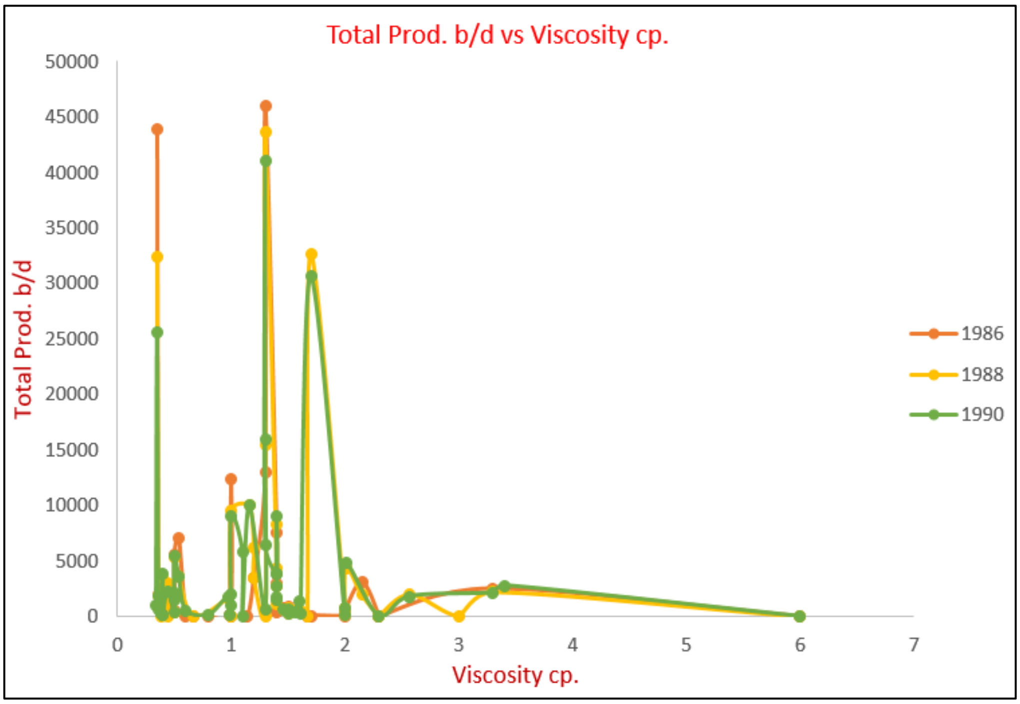
➢ *Screening in Terms of Oil Viscosity*

Viscosity of oil defines the degree at which oil is viscous which in turn affects the rate of oil flow from the reservoir to the surface. Oil with high viscosity requires mechanism which will reduce the viscosity in order to enable an efficient EOR. CO_2 EOR which helps in improving recovery efficiency, the injected CO_2 becomes miscible and reduces the viscosity of the oil in the reservoir for easy recovery supported by the MMP. Screening value recommendation for oil viscosity is given to be less than 10cp. The range of oil viscosity data for the project is 0.35 to 46cp. From figure 3(a-e), it can be seen that at higher oil viscosity value the total production is very low, the maximum value of total production was obtained for both cases at oil viscosity less than 2cp. This implies that for a successful and productive miscible CO_2 EOR, the oil viscosity should be less than 2cp at reservoir conditions and reservoir fields with greater viscosity above 3cp for this data should be screen for other methods other than miscible CO_2 EOR. The reservoir fields with oil viscosity less than 2cp should be taking forward for laboratory studies. The highest production at 1986 is 46000 b/d while at 2014 is 30800 b/d as stated earlier.



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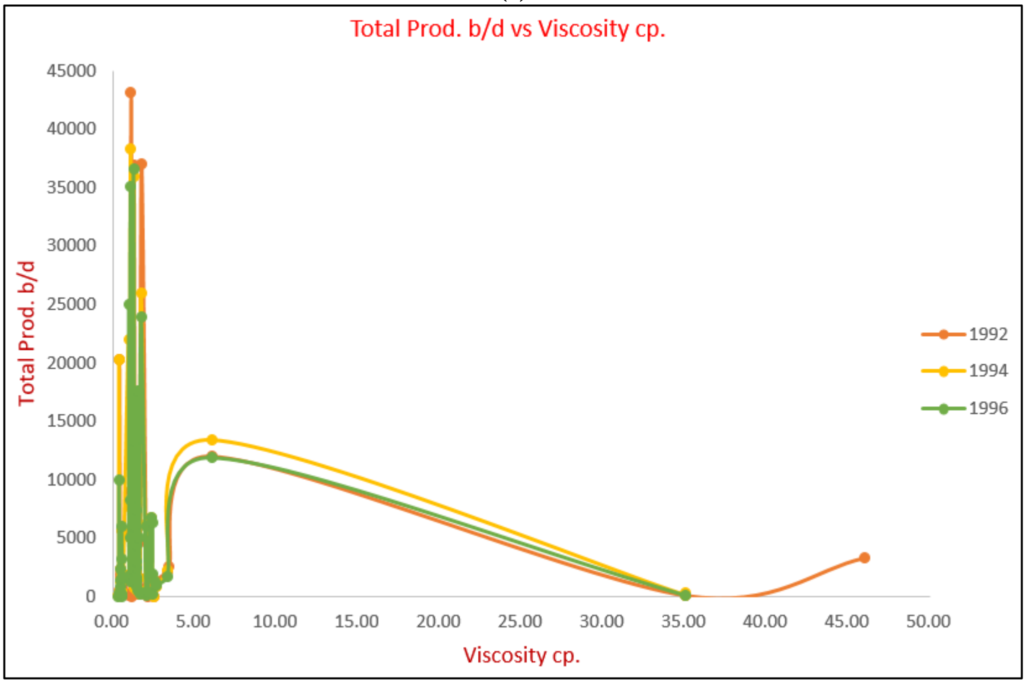

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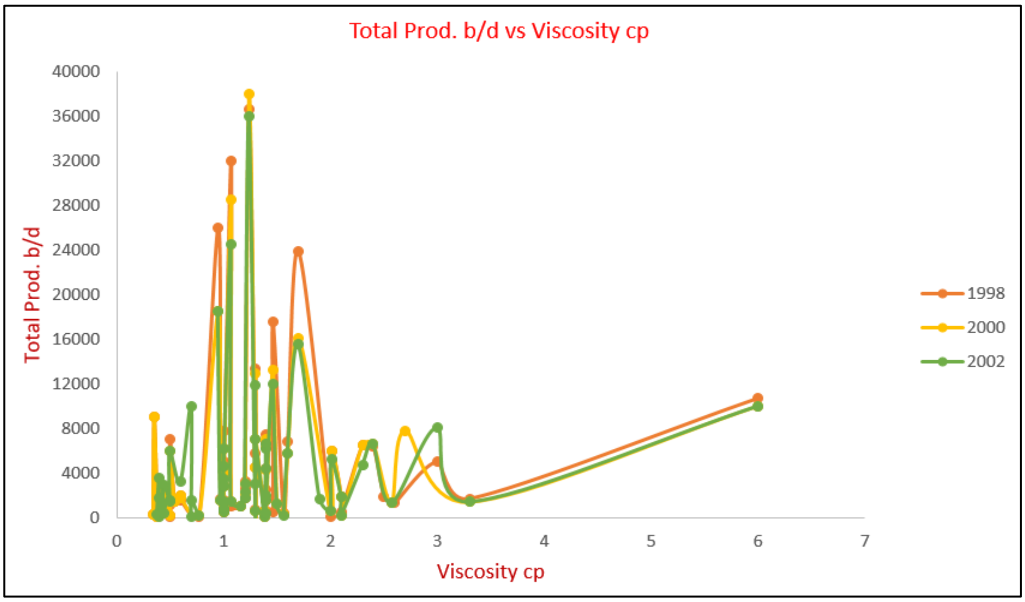

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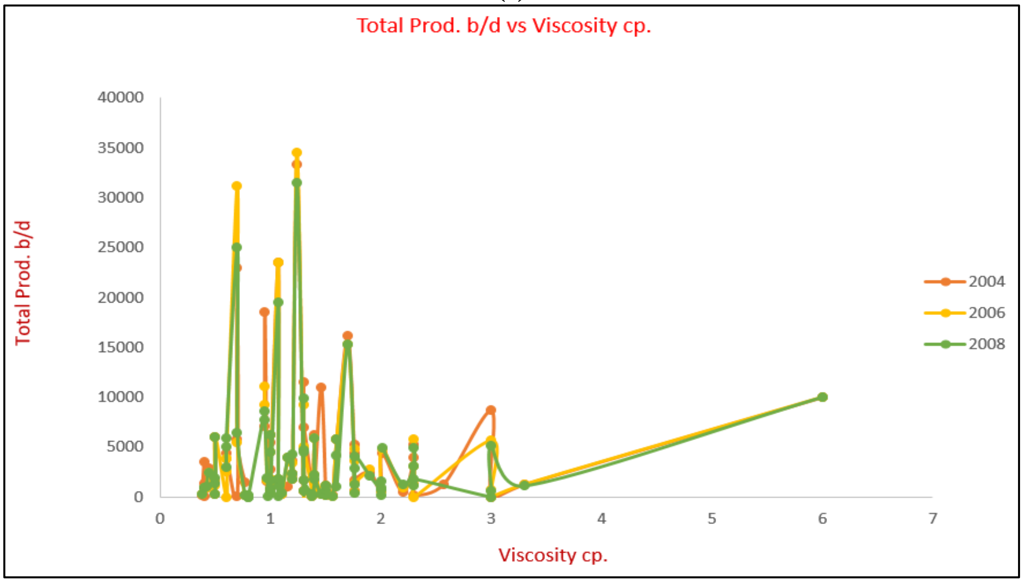

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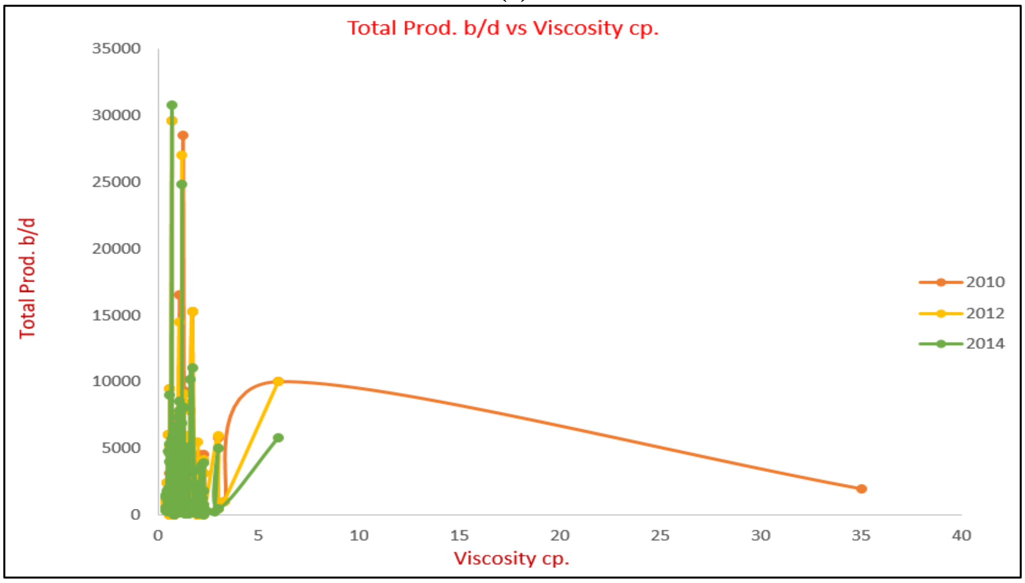

(e)

Fig 3 Screening Base on Oil Viscosity

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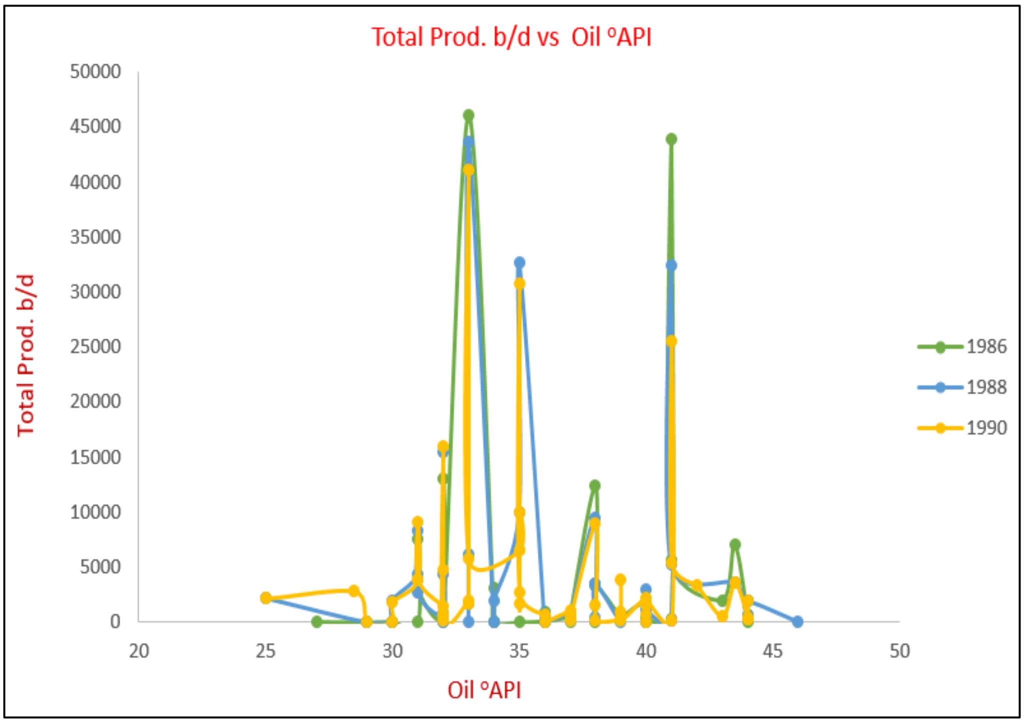
➢ *Screening Base on Oil API Gravity*

Oil API gravity is inversely proportional to specific density of oil. Higher oil API corresponds to lower specific density and vice versa. Crude oil is being classified base on oil API as either light, medium or heavy. Crude oil with API from 10 to 22 are classified as heavy oil, 22 to 31 are medium whereas greater than 31 API are light oil. The recommended screening value for oil API is greater than 22. This implies that CO_2 flooding goes well with medium to light oil reservoirs. The range of values for this project is 22 to 48 API. The highest total production of 46000 b/d at 1986 and 30800 b/b at 2014 are captured within the range of 22 to 45 oil API (figure 4 a-e). Beyond 45 API the production is very low. It is therefore recommended here that the reservoirs with oil API gravity greater than 45 should not be move forward for laboratory studies.



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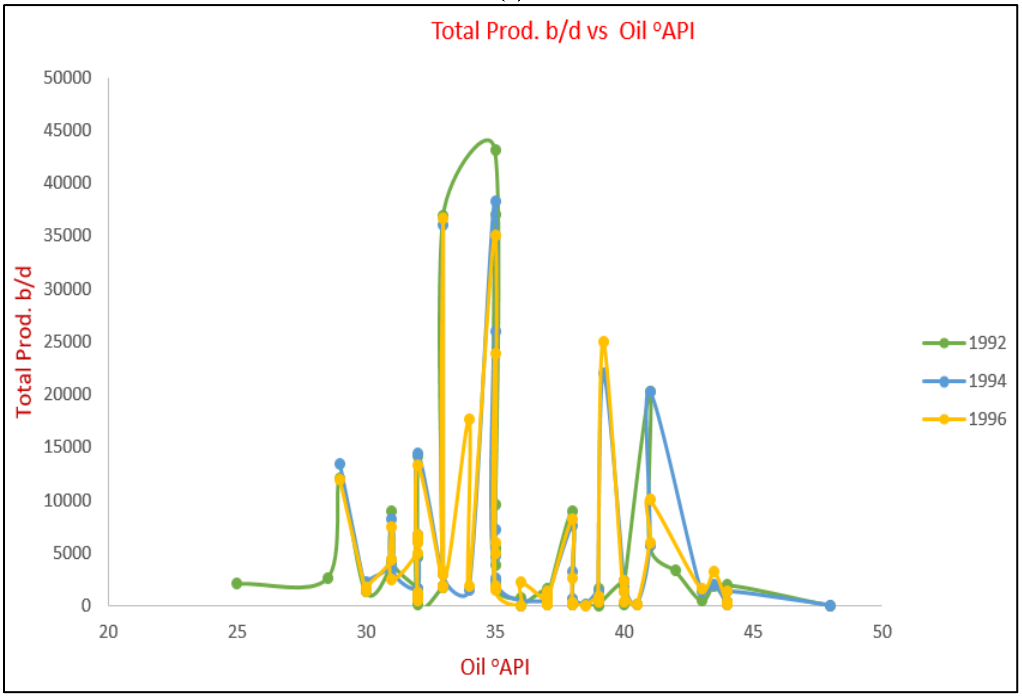

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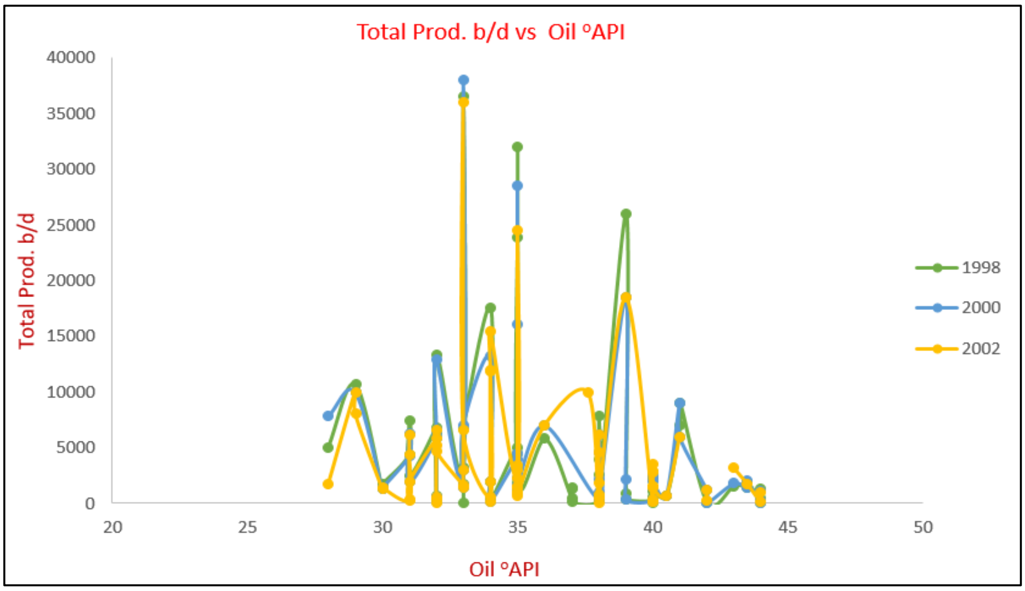

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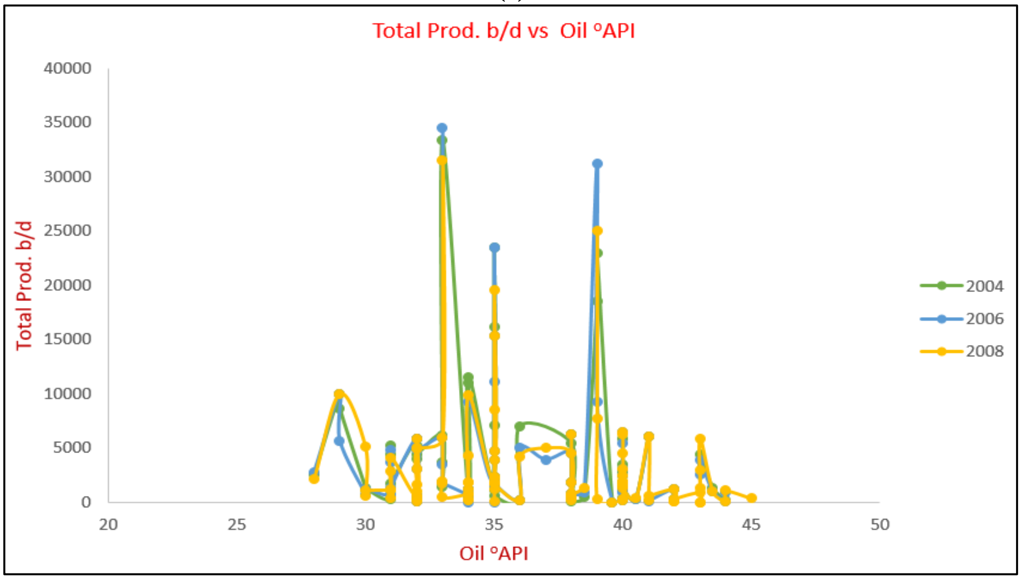

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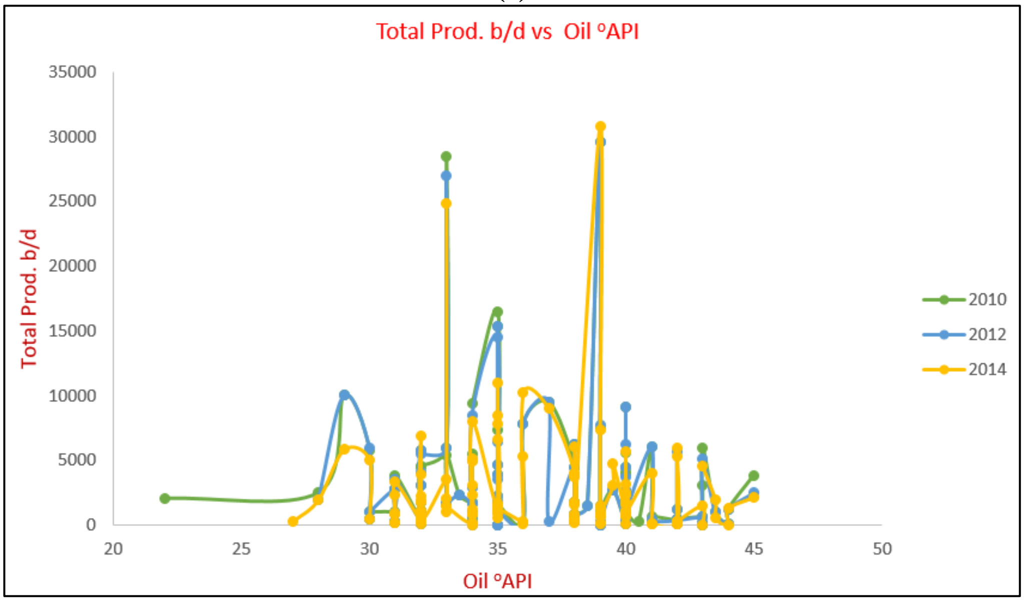

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Fig 4 Screening Base on Oil API

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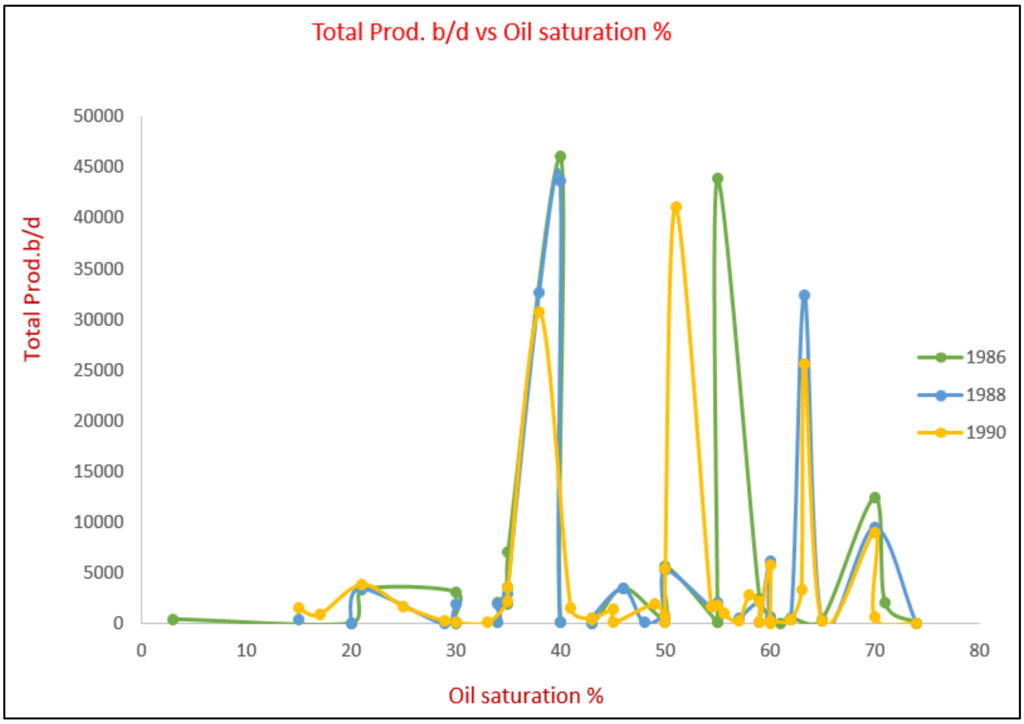
➢ *Screening Base on Oil Saturation*

Oil saturation represents the fraction of pore space occupied by oil in the reservoir. Most oil reservoirs are not completely made up of oil; it also contains connate water. This implies that oil saturation is rarely 100% which may range between 10 to 90% in the oil/water transition zone. The screening guide presented in table 1, recommends oil saturation of greater than 20% PV. The range of oil saturation value under consideration is between 3 to 89% PV. The result of evaluation of the reservoir fields under consideration shows that maximum production is witness between 30 to 89% PV (figure 5a-e). Sequence to the information obtained from the evaluation, it is recommended that reservoir fields with oil saturation between 30 to 89% PV should be move forward for laboratory studies.



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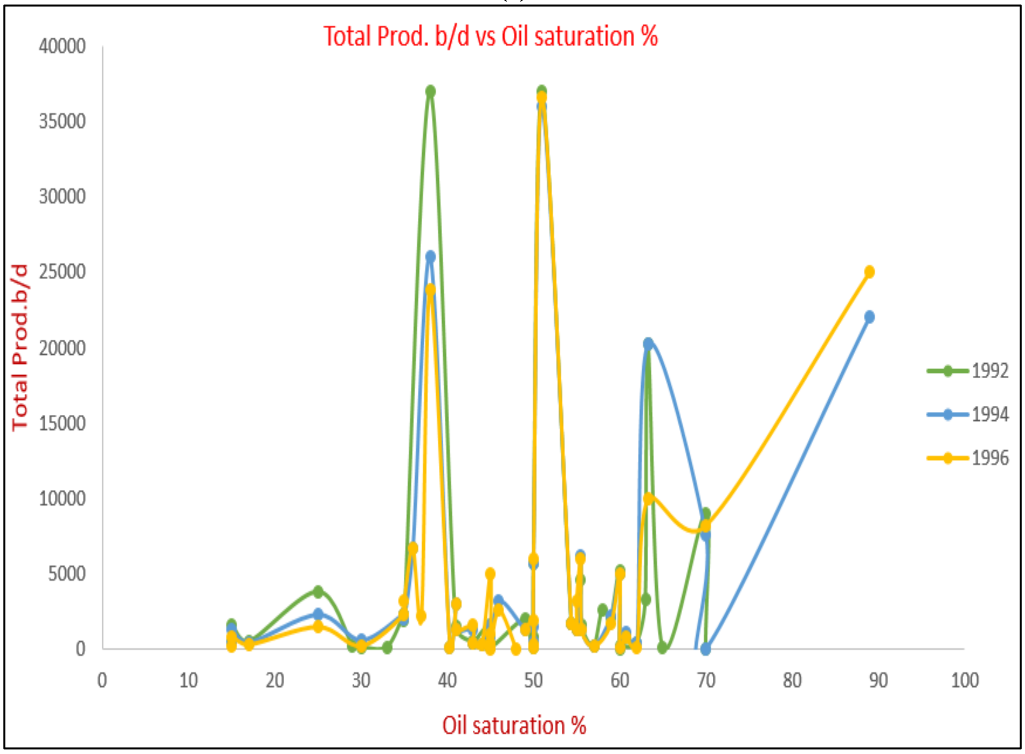

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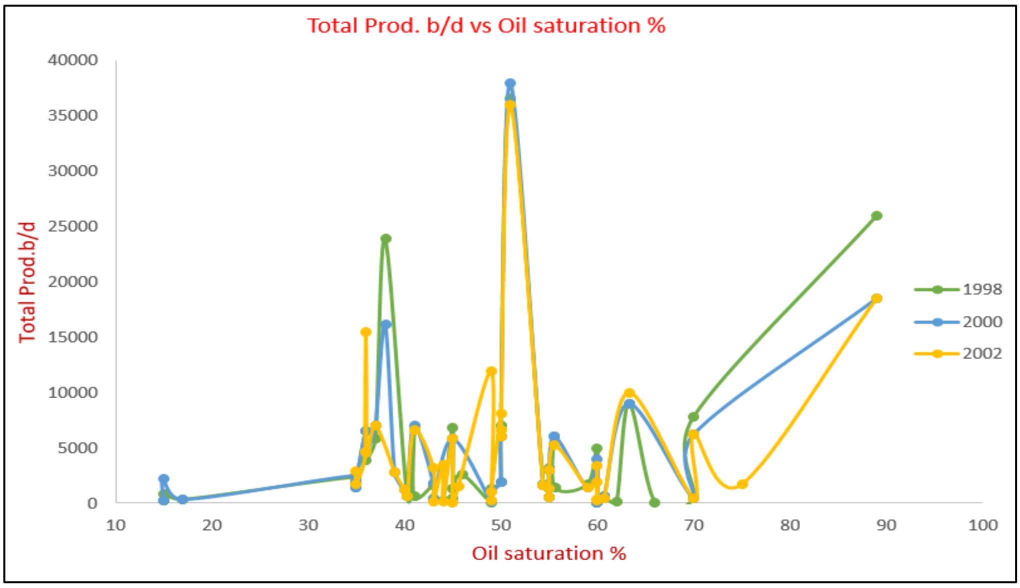

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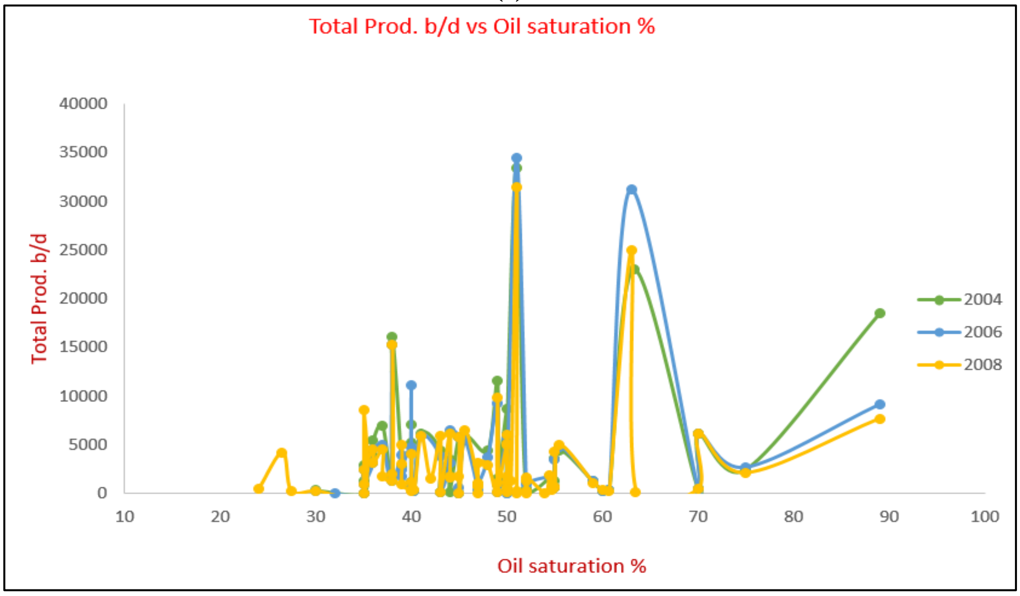

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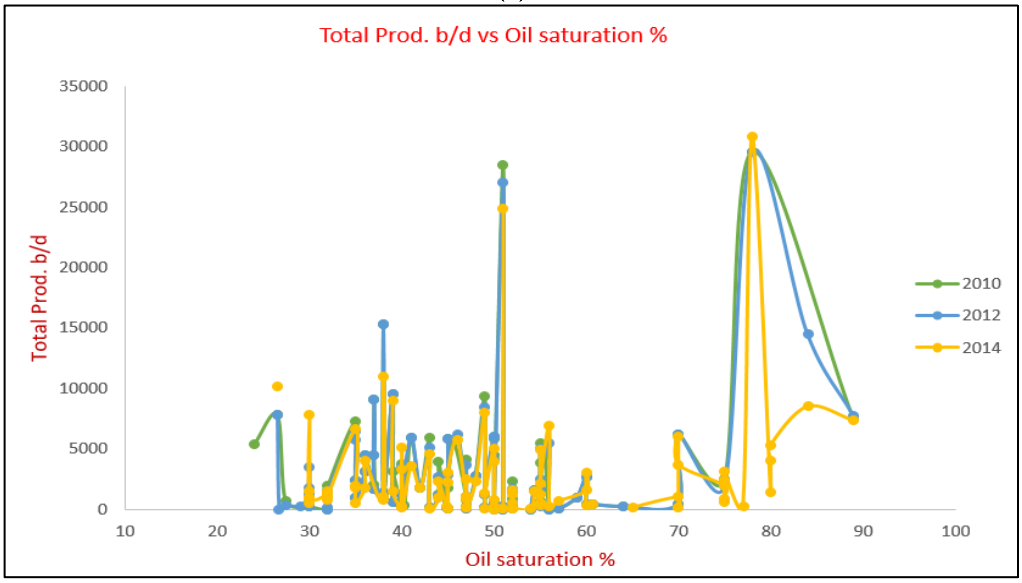

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Fig 5 Screening Base on Oil Saturation.

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After evaluating the oil and reservoir properties, for an effective screening exercise, the minimum miscibility pressure is very vital for a miscible CO_2 EOR. That is the pressure required for miscibility to be achieve between the CO_2 and the reservoir oil and this gives us direct estimate of the pressure required for CO_2 to be injected with.

➢ *Minimum Miscibility Estimation*

The minimum miscibility pressure which represents pressure at which oil recovery reaches 80% at CO_2 breakthrough time or the final recovery reaches 90-95% with 1.2PV CO_2 injection (Ghedan, 2009). It also defines the point where interfacial tension varnishes, that is point where IFT equals to zero. The MMP of the data screened is estimated here using Yellig and Metcalfe, 1978 correlation which uses temperature as the only dependent parameter. They stated that the composition of the gas has little effect on the MMP. The MMP gives a range of values from 942 to 3156 psi. These estimated MMP values falls within the recommendation of National Petroleum Council (Taber *et al.*, 1997). The accuracy of the correlation can be seen from the R^2 value obtained from the plot of MMP and temperature (figure 6). The value of 0.9968 (R^2) shows a perfect positive correlation between the MMP and the temperature. This has validated the fact that MMP increases with temperature.

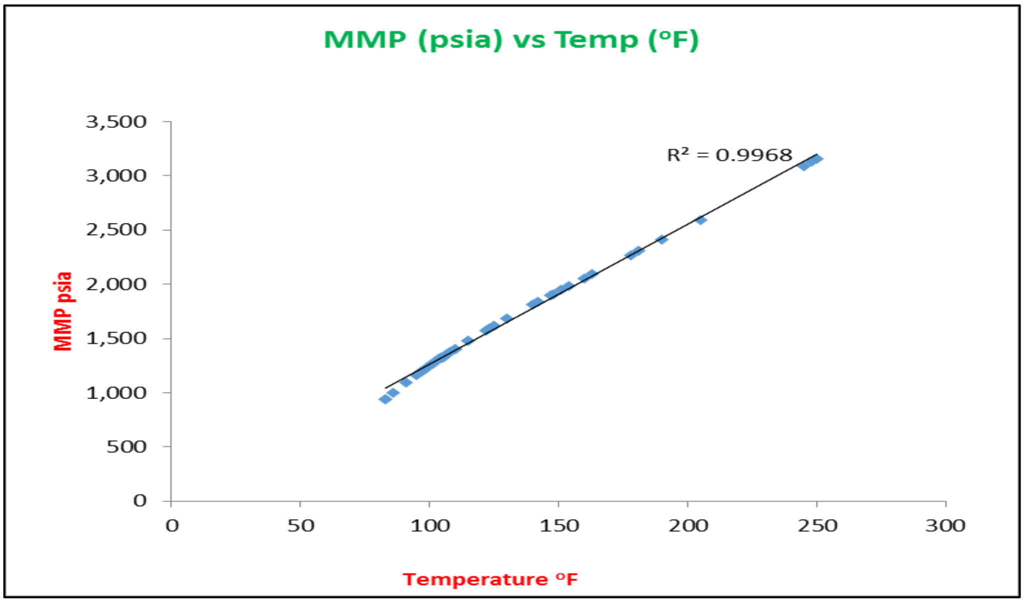

Fig 6 MMP Estimation

➢ *Evaluation Deductions*

Sequence to the evaluations and analysis conducted, figure 3 shows that for effective miscible CO_2 EOR, the oil viscosity should be less than 2cp at reservoir conditions. This validates the fact that miscible CO_2 EOR goes well and is more productive in light oil with low viscosity. The lighter the oil the more the recovery efficiency. The oil and reservoir properties which shows a more promising miscible CO_2 EOR recovery are presented in table 3 with their value ranges.

Table 3 Deductions for Oil and Reservoir Properties.

Oil/Reservoir properties	Productive value Range	Figure number
Oil viscosity	Less than 2cp	3 (a-e)
Oil API gravity	29 to 43 °API	4 (a-e)
Oil saturation	35 to 89 % PV	5 (a-e)
Depth	4000 to 7000 ft	2 (a-e)

Miscible CO_2 EOR is effective and gives a better recovery factor with light oil reservoir. High production was observed at oil API of 29 to 43 which is a good range for light crude oil. Oil reservoirs which are not only made up of oil but connate water, miscible CO_2 EOR gives a better recovery when the oil saturation percentage pore volume is 35 to 89. Light oil requires a considerable depth reservoir and hence the deduction that reservoir depth should be within the range of 4000 to 7000ft. It is pertinent to note that the values given here are not absolute and hence the range given is with respect to the reservoir fields under consideration in this research. Nevertheless, the deductions given can be considered to a large extent across the globe as the reservoir fields considered gives approximately 80 to 95 % of miscible CO_2 EOR operating fields in the world.

IV. CONCLUSION

➢ Enhanced oil recovery has become a necessary practice for the oil and gas industry in order to remain in business and to meet the global demand in energy from fossil source.

- Minimum miscibility pressure is a factor of temperature, the composition of the crude oil and the composition of the injection gas. MMP is the main play maker in CO_2 flooding. The minimum miscibility pressure increases with increasing temperature. Therefore, temperature has a direct effect on MMP.

- Effective output of the fields screened as shown in table 3 can be maximise when oil viscosity is less than 2cp at reservoir condition, oil API gravity ranging from 29 to 43^{o}API. The reservoir properties such as reservoir depth should range from 4000 to 7000ft as better miscibility is achieved in such high depths. Oil saturation is taken from 35 to 89% PV.

RECOMMENDATION

Further laboratory studies should be conducted in other to validate the findings and evaluations of the reservoir fields screened in these studies.

- *Nomenclature*

CO_2	Carbon dioxide
EOR	Enhanced Oil Recovery
OOIP	Original Oil In Place
WAG	Water Alternating Gas
MMP	Minimum Miscibility Pressure

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