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Solvent Induced Oil Viscosity Reduction and Its Effect on Waterflood Recovery Efficiency

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Abstract

WAG process is one of the techniques used for reducing gas consumption, enhancing recovery factor and achieving better profile control of displacing fluids. Recovery efficiency due to reduction of oil viscosity, simulating a WAG process, in a wide range of reservoir permeability and water injection rate was investigated. Gas viscosity reduction by miscible gas or solvent injection is mimicked by progressive dilution of a medium density crude oil with a mixture of hydrocarbon solvent. The porous media used in this study consists of a set of water wet sandstone core plugs of low to medium permeability. The experimental findings show that reduced oil viscosity has no correlation with recovery efficiency, in the normal flood velocity regime. However, in the higher flood velocity regime, recovery efficiency reduces with increasing oil viscosity, only for higher permeability cores, which is attributed to micro-heterogeneity within pore geometry. The study suggests that the additional oil recovery during miscible gas injection, is mainly contributed by the swelling factor of oil which results in increased oil saturation, higher reservoir pressure and increased relative permeability of oil in addition to the contribution from lower interfacial tension and very little, if any due to oil viscosity reduction.

Key words: WAG process; Recovery efficiency; Oil viscosity

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Nomenclature

C^* = Wettability constant, Value of C* depends on the rock wettability and it indicates the effect of imbibition on the growth of viscous fingers.
D = Diameter of the core
k_o = Effective oil permeability
k_w = Effective water permeability
k_{wabs} = Absolute water permeability
k_{wor} = Permeability to water at the residual oil saturation S_{or}
M = Mobility ratio
q_t = Total flow rate (ft^3/day)
S_{or} = Residual oil saturation
S_{wc} = Irreducible water saturation
v = Interstitial velocity, which is u/Ø, as u is Darcy velocity
W = Width of the layer in glass micromodel (ft)
WI = Amott-Harvey Index
$\frac{\partial P_c}{\partial L}$ = Capillary pressure gradient
α = Dripping angle
σ = Interfacial tension between the fluids
μ_w = Viscosity of connate and displacing fluid (water)
μ_o = Viscosity of oil
λ_w = Mobility of the displacing fluid (water)
λ_o = Mobility of the displaced fluid (oil)

INTRODUCTION AND BACKGROUND

Viscosity of crude oil is one of the most important physical properties that influences the flow of oil through porous media and affects oil recovery factor at all stages of recovery. In a secondary or waterflood recovery, the recovery factor is the product of the displacement efficiency and the volumetric sweep efficiency.

$$\text{Recovery Factor} = E_{VOL.}E_D \quad (1)$$

The volumetric sweep efficiency, E_{VOL}, is fraction of total flood water that is contacted by the displacing fluid. It is controlled mainly by the oil/water mobility ratio, flood pattern and cumulative water injected[1]. E_D, the displacement efficiency, depends on the rock characteristics and the viscosities of the displacing and displaced fluids. The ultimate oil recovery ($1 - S_{wi} - S_{or}$) is achievable only if there is a piston like displacement throughout. However, the piston like displacement phenomenon stops at the occurrence of water breakthrough, the onset of which depends on the stability of the advancing water-oil interface. An unstable interface would initiate viscous fingering and due to the change of saturation along the path of fingers, increasing amount of water will tend to flow through the path leading to larger amount of bypassed oil. Occurrence of viscous fingering is believed to be due to the instabilities at the interface between the displacing fluid and the displaced fluid when the viscosity of the displaced fluid is much larger than the viscosity of the displacing fluid[2]. Peter and Flock[3] has conceived a dimensionless number, instability number (I_{sr}), which is a function of mobility ratio, displacement velocity, system geometry and dimensions, capillary and gravitational forces, and system permeability and wettability.

$$I_{sr} = \frac{(M-1)v\mu_w D^2}{C^* \sigma k_{wor}} \tag{2}$$

Here again the mobility ratio plays a major role in deciding the stability of the oil water interface and onset of water breakthrough.

Mobility ratio is defined as

$$M = \frac{\lambda_w}{\lambda_o} = \frac{k_w \mu_o}{k_o \mu_w} \tag{3}$$

Once water breakthrough occurred, the amount of oil displaced by water would depend on the fractional flow mechanism within the pore channels. Pirson[4] derived the fractional flow formula considering capillary and gravity terms, which is given by

$$f_w = \frac{1 + \frac{k_o}{q_t \mu_o}\left(\frac{\partial P_c}{\partial L} - g\Delta\rho \sin\alpha\right)}{1 + \frac{\mu_w k_o}{\mu_o k_w}} \tag{4}$$

The fractional flow of water and hence the displacement efficiency largely depends on the oil/water viscosity ratio μ_o/μ_w.

From the above discussion it is apparent that one of the common parameters affecting oil recovery is the oil viscosity and unless viscosity of flood water is increased by additives, the mobility becomes unfavorable when oil viscosity is high[5]. During primary recovery, viscosity of oil is reduced naturally when reservoir pressure depletes and gets somewhat offset during reservoir cooling due to water flooding. The artificial way to reduce oil viscosity in-situ, starts during tertiary recovery through injection of solvent and miscible or semi miscible gases. Solvent injection being uneconomical in most cases, gas injection, particularly CO_2 injection, is a favorable industry practice[6]. In miscible gas flooding, the incremental oil recovery results from oil swelling and reduction in oil viscosity[7]. Gas injection processes are most effective when the injected gas is nearly or completely miscible with the oil in the reservoir[8] because maximum viscosity reduction is achievable when the gas and oil form a single phase. Among other gases the use of CO_2 to recover left behind oil is becoming ever more popular, eclipsing other EOR methods because of its intrinsic advantages such as low minimum miscibility pressure (MMP) with most oils, higher density (less gravity segregation), higher oil swelling factor and viscosity reduction, in addition to the obvious environmental advantages. However, laboratory or field data of oil viscosity due to gas injection is hardly available. Laboratory demonstration by Lansangan[9] with 8 crude oils of west Texas has shown that at single phase condition, CO_2 mole fraction of 0.3 – 0.9 can reduce oil viscosity by 50 – 70% or more. In case of low viscous oil, studied by Bon and Sarma[10] did not produce optimistic results. At bubble point pressure, oil viscosity reduced to 0.134 and 0.121 cP from original viscosity of 0.139 cP on mixing 20 and 40 mol% CO_2, respectively. In case of partially miscible gas (60-65 mole% CO_2), 20-30% reduction in the viscosity is reported at reservoir condition[11].

To reduce the consumption of gas, enhance oil recovery factor and better profile control of displacing fluids, almost all the commercial miscible gas floods today employ the WAG (Water alternating gas) or SWAG (Simultaneously water and gas) methods[12, 13] which take advantage of both gas and water injection process. In this work we investigated the effect of oil viscosity reduction on waterflood recovery efficiency, closely simulating a WAG process. Major experimental variables are reservoir permeability, water injection rate and oil viscosity. To eliminate the oil swelling factor, caused by miscible gas injection and to study the viscosity effect only on recovery efficiency, oil viscosity reduction is achieved by progressive dilution with a mixture of hydrocarbon solvent. The porous media used in this study consists of a set of sandstone cores, representing low to medium permeability reservoir. The recovery factors are correlated with the respective oil viscosity, types of porous media and flood water velocity. As far as possible, ideal conditions are followed to achieve reproducible results.

1. MATERIALS AND METHODS

1.1 Materials

1.1.1 Crude Oil

A medium viscosity paraffinic oil (53.6 mPa.s) with low acid number (TAN-0.04 mg KOH/gm of oil) of Middle East carbonate reservoir origin is used as the base oil. After removing associated water and bottom sediments by high speed centrifuging and filtering through a 0.45 micron high pressure filter, different quantity of light hydrocarbon (heptane, octane and toluene in 50:30:20 ratio) is mixed to prepare oil of reducing density and viscosity. The final properties of the oils used and quantity of solvent mixed are given in Table 1.

Table 1
Properties of Crude Oil Samples Used for the Study

Sample #	APIo	Viscosity* (mPa.s)	Density* (g/cc)	IFT* (mN/m)	Solvent added ml/L of crude
1	39.3	4.3	0.831	13.39	480
2	35.1	6.1	0.846	13.92	315
3	33.6	9.7	0.853	14.65	200
4	31.9	11.2	0.859	16.06	80
5	29.2	23.3	0.876	16.29	50
6	26.3	53.6	0.895	16.37	0

* The properties are measured at 25 ^{o}C.

1.1.2 Non Damaging Brine

4% ammonium chloride solution in de-ionized water, filtered through 0.45 micron filter paper is used to represent reservoir brine. Ammonium chloride brine is used to avoid clay swelling and misleading results.

1.1.3 Porous Media

Berea Sandstone core plugs are used throughout the study because of its consistency in petro-physical characteristics and homogeneity in macro level.

A set Berea sandstone core plugs (Kair - 136, 71 & 14 milliDarcy) were used to represent water wet and consolidated. The core plugs were used repeatedly after careful cleaning by non-damaging solvent immersion process to achieve maximum reproducibility of coreflooding results. The properties of these core plugs are shown in Table 2.

Table 2
Petrophysical Properties of the Core Plugs under Study

Core No.	Vp (cc)	He- Porosity (%)	kwabs (mD)	Ammot Wettability Index	Core Wettability	% of Pore area to Grain space
1	19.3	20.8	14.2	0.569	Strongly Water wet	20.12
2	18.5	21.7	70.8	0.624	Strongly Water wet	21.77
3	18.7	21.9	136.3	0.573	Strongly Water wet	24.89

1.1.4 Coreflooding Apparatus

Temco CFS-830-10000-HC reservoir condition coreflooding equipment is used to conduct the core flooding experiments.

1.1.5 Ultracentrifuge

Corelab ACES 200 model with automatic image detection ultracentrifuge is used to measure wettability of the core plugs.

1.2 Experimental Procedures

1.2.1 Saturation

Prior to commencement of waterflooding, core plugs were brought to appropriate saturation profile by flooding brine followed by crude oil to connate water saturation (Swc) condition.

1.2.2 Wettability Measurement

Wettability of the core plugs were measured by ultracentrifuge method in determining their wettability. Amott-Harvey method is applied in calculating wettability of the core plugs (Table 2).

1.2.3 Water Flooding

To understand the limit of flooding rate, a similar set of core plugs were subjected to waterflood at increasing water injection rate, starting from 0.5 ml/min till their critical velocity is reached. It is found that the critical velocity of the set is above 5.5 ml/min. In all cases the waterflood rate for the main experiments was limited to 0.9 ml/min. The core plugs were loaded in a core holder under 500 psi confining pressure, brought to oil saturation upto Swirr and water injection was conducted at flow rates which were increased stepwise, starting with 0.1 ml/min upto 0.9 ml/min with an increment of 0.1 ml/min in each step. The produced fluid is collected in an oil-water separator with acoustic interface measurement. Real time monitoring of produced oil and water volume and differential pressure across the core was done through computerized data acquisition system. All the experiments were conducted at room temperature and without any back pressure.

2. RESULTS

To investigate the effect of viscous forces and the possible contribution of oil recovery due to reduction of oil viscosity alone, due to miscible gas or solvent injection, the oil samples used in the present study are prepared by diluting with lower hydrocarbon solvent to closely represent this scenario. The base oil of 53.6 mPa.s viscosity is stepwise reduced upto 4.3 mPa.s and there are four oil samples between this range. Thus the least viscous oil has a viscosity of less than 8% of the original oil, which is possibly more than the dilution and viscosity reduction achievable by miscible gas injection or solvent injection in a reservoir case. The porous media used are consolidated Berea sandstone core plugs of 14, 71 and 136 mD permeability to represent average sandstone reservoirs. Wettability of the core plugs are measured and found to be strongly water wet. The core flood experiments were conducted at flow velocities between 0.43 to 3.87 ft/day, to represent sub-normal, normal and higher than normal flood velocity of a typical homogeneous sandstone reservoir water flood recovery process. The porous media have demonstrated strong water wettability as can be seen in table 3. Thus, it is obvious that the experimental model fall within the boundary of a typical sandstone reservoir with low to medium viscosity oil, which has undergone gas or solvent injection to reduce oil viscosity, followed by waterflood recovery.

The experimental results include linear core flow recovery conducted in three core plugs of low to medium permeability using six crude oils and water flow rate of 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8 and 0.9 ml/min corresponding to the flood velocity of 0.43, 0.86, 1.29, 1.72, 2.15, 2.58, 3.01, 3.44 and 3.87 ft/day. The ultimate oil recovery from nine different flood velocity using the six different viscosity oils are plotted in Figures 1 – 9. The recovery results are discussed considering two aspects; the effect of oil viscosity and water injection rate on water flood displacement efficiency.

Table 3
Instability Number at Sor Condition for Various Flow Rate and Oil Viscosity

Flood Velocity	μ_o - 4.3 mPa.s		μ_o - 6.1 mPa.s		μ_o - 9.7 mPa.s		μ_o - 11.2 mPa.s		μ_o - 22.3 mPa.s		μ_o - 53.6 mPa.s	
Ft/day	Isr	Rec %	Isr	Rec %	Isr	Rec %	Isr	Rec %	Isr	Rec %	Isr	Rec %
Core Plug -1												
0.43	50	64.12	105	63.25	198	65.43	250	62.34	521	63.40	1470	66.23
0.86	90	65.78	235	66.17	376	67.23	478	67.74	1084	68.98	2941	67.41
1.29	136	66.53	371	68.54	564	69.22	625	68.65	1879	70.21	4411	68.34
1.72	198	70.32	446	69.72	677	70.62	875	69.81	2252	71.29	5882	70.81
2.15	248	71.33	588	70.23	988	72.21	1196	71.82	2603	73.45	7352	72.92
2.58	297	73.12	743	72.10	1129	73.41	1250	73.17	3124	75.32	8822	73.85
3.01	317	73.41	909	72.69	1317	75.42	1603	72.83	4236	74.58	8022	73.45
3.44	431	74.34	892	75.12	1430	76.76	1749	74.92	4503	76.58	9600	75.91
3.87	485	76.41	1114	75.12	1862	76.41	2061	73.64	4686	75.98	9827	74.62
Core Plug -2												
0.43	15	56.80	35	55.23	70	57.23	79	57.71	192	58.12	470	57.24
0.86	30	60.23	70	58.29	141	59.34	157	60.13	384	59.12	940	61.34
1.29	45	62.88	106	60.76	211	61.34	236	63.45	576	61.56	1410	63.43
1.72	60	65.70	141	61.6	282	63.12	315	65.72	768	63.26	1880	64.54
2.15	75	66.53	176	67.44	352	65.72	394	67.12	960	65.62	2350	66.18
2.58	90	69.94	211	68.92	423	67.48	472	69.42	1151	67.41	2820	68.31
3.01	106	70.77	247	70.14	493	69.64	551	71.21	1343	67.52	3290	69.73
3.44	121	71.07	282	72.39	564	70.11	630	70.03	1535	68.52	3760	68.23
3.87	136	73.81	317	72.88	634	71.66	708	70.60	1727	66.36	4229	69.89
Core Plug -3												
0.43	17	48.12	19	50.23	37	48.54	41	52.30	98	51.71	240	49.43
0.86	34	53.65	38	52.14	74	50.36	82	53.70	195	54.22	480	51.88
1.29	51	55.67	57	54.62	111	53.65	123	54.89	293	56.54	720	53.89
1.72	69	57.56	76	57.43	148	55.63	164	56.76	391	58.32	960	55.78
2.15	86	59.65	94	60.56	185	58.31	204	59.21	488	61.23	1200	58.39
2.58	103	65.32	113	63.73	222	61.53	245	62.74	586	63.56	1441	62.90
3.01	120	67.13	132	65.43	258	64.48	286	63.93	684	65.13	1681	64.12
3.44	137	68.42	151	67.91	295	66.90	327	63.50	781	66.49	1921	64.88
3.87	154	71.12	170	70.41	332	68.90	368	67.43	879	67.13	2161	65.87

3. DISCUSSION

The recovery at low flood water velocity upto 2.58 ft/day given in Figures 1 – 6 show oscillation of data and no clear trend in increase or decrease of oil recovery efficiency could be seen. However, at higher flood water velocity, above 3 ft/day (Fig 7 – 9), it is apparent that recovery efficiency has followed a clear downward trend, but for medium and high permeability cores only. The oil viscosity has no apparent effect on recovery efficiency in low permeable core. Also a general observation could be made from all the flood experiments that irrespective of the viscosity of the oil, recovery efficiency is reduced with increasing permeability of core plugs.

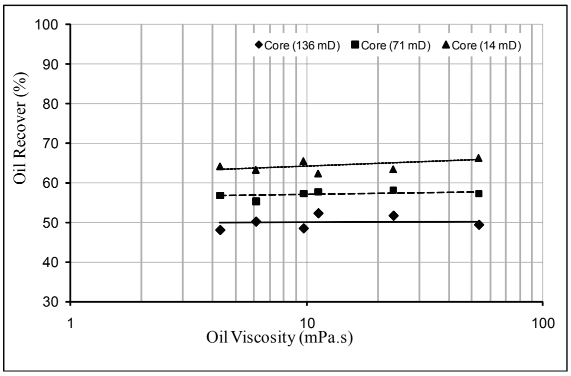

Figure 1
Oil Viscosity Effect on Displacement Efficiency (Injection Rate 0.43 ft/day)

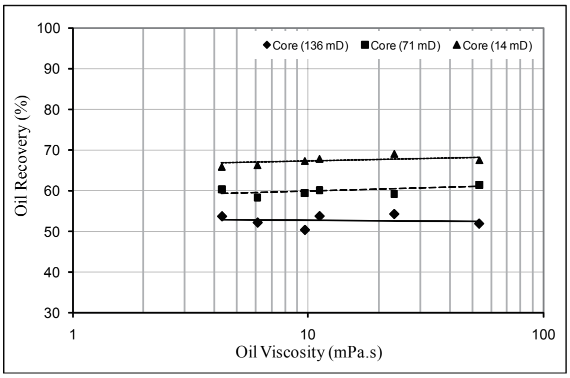

Figure 2
Oil Viscosity Effect on Displacement Efficiency (Injection Rate 0.86 ft/day)

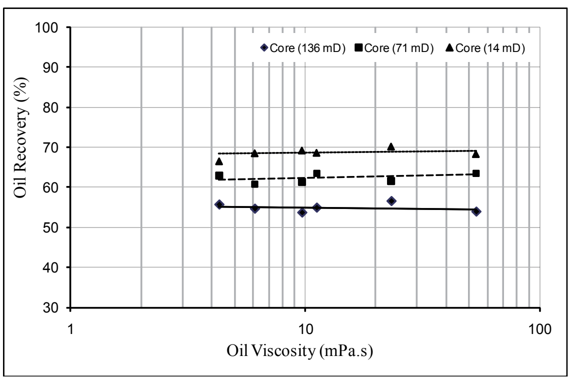

Figure 3
Oil Viscosity Effect on Displacement Efficiency (Injection Rate 1.29 ft/day)

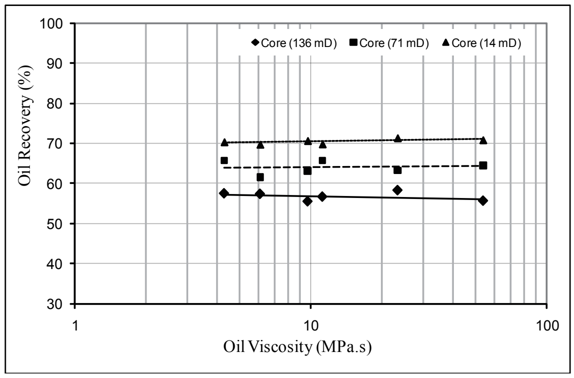

Figure 4
Oil Viscosity Effect on Displacement Efficiency (Injection Rate 1.72 ft/day)

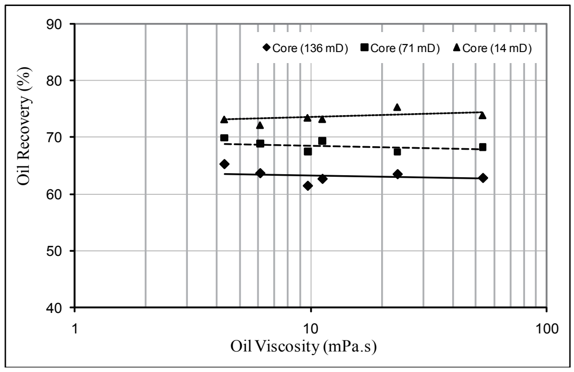

Figure 5
Oil Viscosity Effect on Displacement Efficiency (Injection Rate 2.15 ft/day)

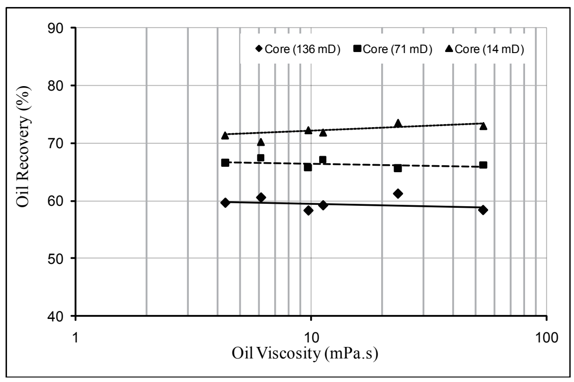

Figure 6
Oil Viscosity Effect on Displacement Efficiency (Injection Rate 2.58 ft/day)

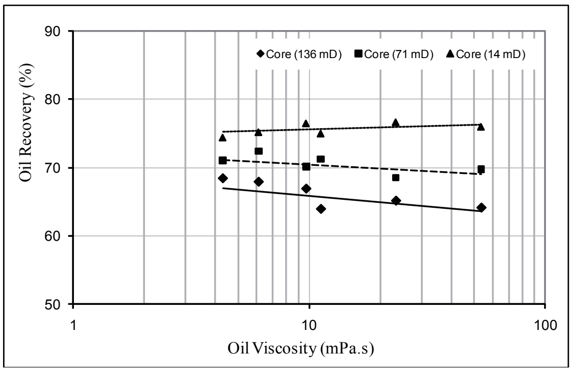

Figure 7
Oil Viscosity Effect on Displacement Efficiency (Injection Rate 3.01 ft/day)

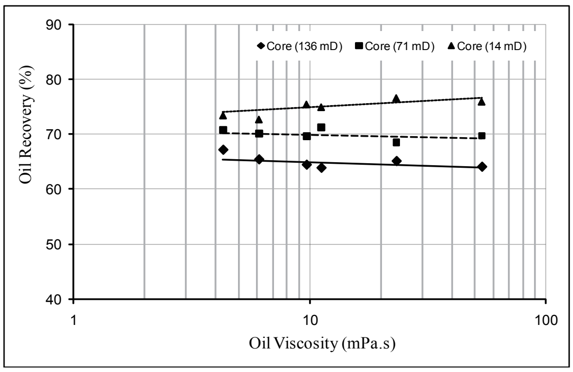

Figure 8
Oil Viscosity Effect on Displacement Efficiency (Injection Rate 3.44 ft/day)

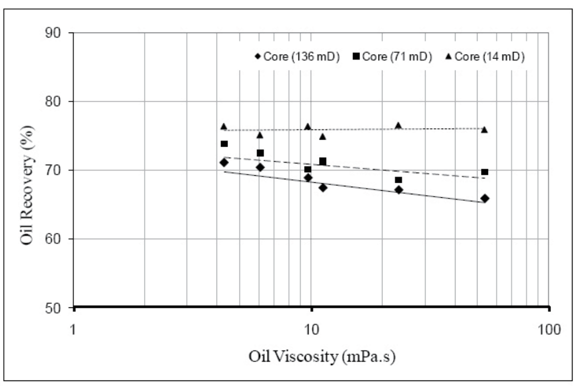

Figure 9
Oil Viscosity Effect on Displacement Efficiency (Injection Rate 3.87 ml/min)

The above observation is contrary to general belief that higher viscosity results in poorer recovery. From our investigation, it is seen that recovery efficiency is reduced with increasing oil viscosity only when the flood rate is higher than 3 ft/day. To investigate further we tried to explain the facts in terms of instability of the water oil interface by calculating instability number (Eqn - 2) using the experimental data, such as effective and end point relative permeability of oil and water. From the I_{sr} values presented in table 3 and figure 12, no correlation could be drawn between recovery efficiency, core permeability, oil viscosity and calculated I_{sr} values. In contrast to the experimentally observed results, the Isr value is seen to exceed the frontal stability limit[14] (> 1000) for the low permeability core at much lower flood rate compared to the higher permeability cores, hence the expected recovery should be much lower for low permeability core than higher permeability cores (table 3). To investigate further for the cause of unchanged recovery with increasing viscosity for low range flood rate and reducing recovery for the higher range flood rate, we investigated the pore geometry of the used core plugs through X-ray microtomography. The investigation is conducted with the help of Skyscan 1172 X-Ray microtomography system. From these scans three 2D black & white images of each core plugs are presented in Fig 11 and the pore size distribution is measured with the help of a image analysis software. The pore size distribution in terms of pixel number is presented is figure 13. It can be seen from these two figures that heterogeneity in pore body and pore throat is more for the high and medium permeability core compared to the low permeability core. Although the core plugs are initially considered as homogeneous the microtomography images and the pore size distribution shows heterogeneity at the micro level which is probably responsible for generating a few large fingers instead of desired many small fingers in the high permeability core, which becomes a progressively more dominant factor when viscosity is also higher, resulting capillary trapping of larger quantity of oil in the smaller pore passages and bypassing flood water through the larger pore passages. Similar observation is reported by Abrams[15] in some of the experimental investigation in which residual oil saturation is found to decrease with increasing waterflood rate but after some critical flood velocity the residual oil saturation has increased.

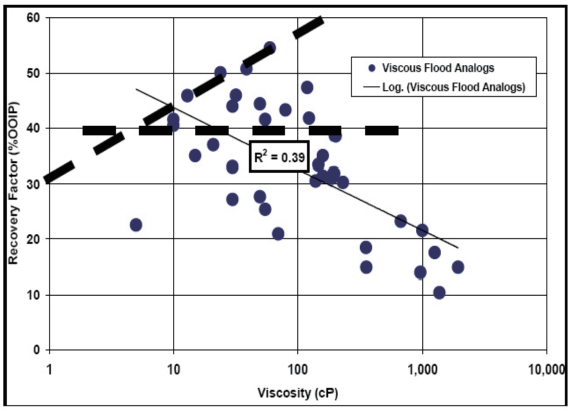

Figure 10
Oil Viscosity Effect on Recovery Factor (Ref-16)

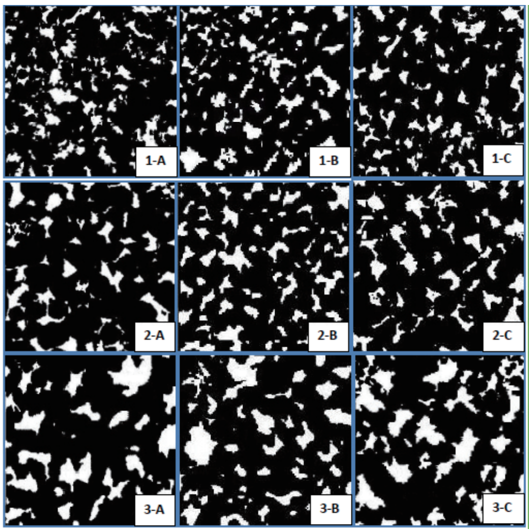

Figure 11
2D Section of the X-Ray µct Images Showing Pores in White and Pore Space in Black

1-A, 1-B and 1-C are the 2D Slices from Injection Face, Middle and End Face of Core-1. Similarly 2-A, 2-B, 2-C are for Core-2 and 3-A, 3-B, 3-C are for Core-3.

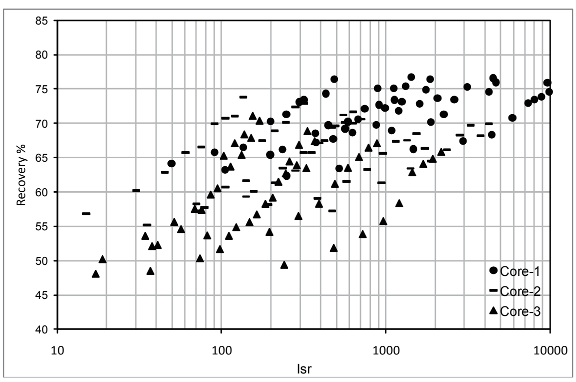

Figure 12
The Instability Number (Isr) is Plotted Against Oil Recovery Factor for Different Flow Velocity and Oil Viscosity

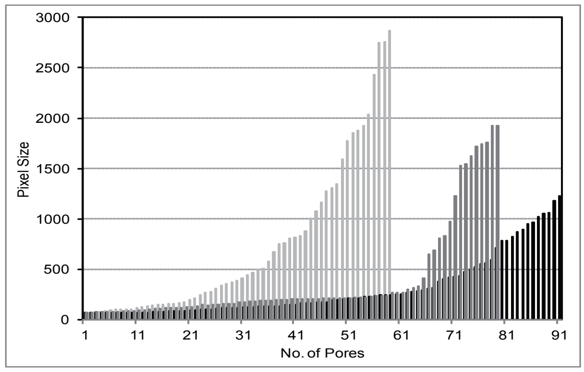

Figure 13
Pore Size Distribution of the 3 Core Plugs (in Terms of Pixel No.) Obtained From Image Analysis

From the results of this study it is evident that whether the reservoir permeability is high or low, reduction of oil viscosity by mixing solvent does not help to enhance waterflood recovery efficiency to any conclusive way. In support of our observation, the review work of Beliveau16 (2008) is presented in Figure 10. It shows that the effect of oil viscosity on recovery is more prominent in the high viscosity range. At low viscosity range (which is the present case) the recovery efficiency is scattered and can not be predicted with any certainty. A detail statistical work[17] on the effect of viscosity on recovery efficiency predicted a one fifth reduction in oil recovery for each ten times increase in oil viscosity. However from later update by Doscher[18], no such correlation could be found.

From experimental results of the detail study conducted with three major variables, it may be safely concluded that in the lower viscosity range, a small reduction of oil viscosity does not have any significant effect on oil recovery. The additional oil recovery through miscible gas injection, reported in the literature, may be due to reduction of IFT and swelling of oil which results in increased oil saturation, higher reservoir pressure and increased relative permeability to oil.

CONCLUSION

(1) The study was aimed at examining the effect of reducing oil viscosity on oil recovery in a miscible WAG recovery process in a strong water wet reservoir.

(2) To simulate the process, oil samples were diluted with hydrocarbon solvent mixture and water flood recovery is measured in a wide range of reservoir permeability and varied water velocity.

(3) Oil viscosity is seen to have no correlation with recovery efficiency in the normal flood velocity regime. However, at higher flood velocity the recovery is seen to decline with viscosity which is attributed to heterogeneity at the pore level.

(4) The recovery factor is seen to be more velocity dependent rather than oil viscosity dependent.

(5) Higher oil recovery is observed with increasing injection rate due to the dominance of viscous forces over capillary forces keeping permeability and oil viscosity parameters constant.

(6) The results suggest that the additional oil recovery during miscible gas injection is mainly contributed by the swelling factor of oil which results in increased oil saturation, higher reservoir pressure and increased relative permeability of oil in addition to the lowering of oil-water interfacial tension.

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