LABORATORY STUDIES OF WATERFLOOD FROM OIL RESERVOIRS IN INDONESIA

by

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ABSTRACT

The continual shortage of domestic crude oil requires optimum oil and gas conservation practices to ensure maximum recovery from the reservoirs.

Oil production from reservoirs by natural (primary) drive mechanisms is often an inefficient process which may leave considerably more "residual" oil trapped behind the reservoirs than can be produced.

One of the primary objectives of this study is to provide additional oil recovery obtainable by waterflooding from Indonesian oil reservoirs; these then become the reference for an economic projection of the profitability of the waterflood.

Results of laboratory studies indicate that there is a significantly large quantity of oil which may be recovered by waterflood from oil reservoirs in Indonesia.

I. INTRODUCTION

Waterflooding is an application of artificial techniques to increase the proportion of oil that can be extracted from a crude oil reservoir,beyond the amount that flows naturally or is pumped to the surface through producing wells.

These artificial techniques have been used for many years by the petroleum industry. It is generally acknowledged that the first waterflood occurred as a result of occidental water injection in the Pithole city area of Pennsilvania in 1865. The practice became generally applied to oil reservoirs in the late 1920s.

The often-imagined concept of a crude oil reservoir is a vast pool of underground oil in an open cavern,into which it is only necessary to sink a bore and draw off all of the fluid. But as such is very far from the case; most oil reservoirs generally consist of sandstone or limestone and sometimes are rarely volcanic rock (like metamorf tuff),in which the oil occupies part of the microscopic pore spaces between the mineral grains, or solution voids, or occasionally a network of permeating fractures. The pore spaces, voids, or fractures must be adequately interconnected to enable the oil to flow through and out of the rock into a wellbore.

According to Rapoport and Leas (1978) only a part of crude oil (on average about 30 per cent) present in the reservoir is recovered under the action of "primary" or "endogenous" energy of the reservoir. Part of it may further be produced by methods of secondary or tertiary oil recovery.

There are five principle types of natural resevoir drive mechanisms (Table 1),ranging from water drive (the most efficient) to drive resulting from slight expansion of the reservoir rock and its fluid contents by production.

A natural water drive from an underlying aquifer is the most efficient displacing mechanism because of the generally large amount of energy resulting from the hydrostatic head of the water.

According to Mc Kay.B.A (1974),the efficiency of principle natural drive mechanism in oil reservoirs is as follows :

Table 1. Efficiency of principle natural drive mechanisms in oil reservoirs.

Natural drive mechanism type	Expected Oil Recovery (%)
Water drive	30 - 80
Combination drive	15 - 50
Gas-Cap drive	20 - 60
Solution-Gas drive	15 - 35
Rock and Fluid Expansion drive	0 - 10

In a water-drive displacement mechanism,three principle factors control the proportion of reservoir hydrocarbons remaining at depletion :

Contact factor : the contact factor of a reservoir is an expression of the amount of the reservoir that bypassed by displacing water,for various physical reasons.

If the reservoir contains sizeable zones of shale or silt, faults,extreme permeability variations,or tight zones,the contact factor will be poor.

Sweep efficiency : the mobility of fluids in a reservoir controls the sweep efficiency (mobility is the permeability of a rock to a fluid,devided by the fluid's viscosity).

Sweep efficiency is usually determined as a function of the ratio of water mobility to oil mobility, and can be improved in an oil reservoir either by raising the water viscosity using chemicals or by lowering the oil viscosity by thermal techniques.

Displacement efficiency : this is the pore system of the reservoir that principally governs displacement efficiency; production is controlled by the degree of pore interconnection, the size of the pore throats, the fluid and rock interfacial tensions, and the resulting pressure required to move the various phases (gas,oil,and water) through the system.

Figure 1 is an idealised sketch (after Herbeck et al,1976) showing residual oil becomes trapped during water displacement.

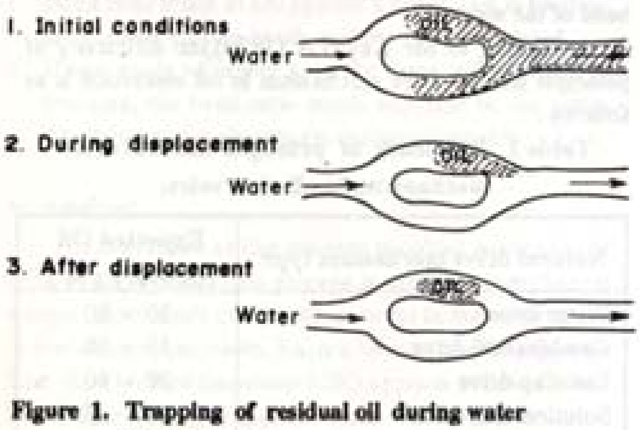

Figure 1. Trapping of residual oil during water displacement.

II. METHOD

Dynamic displacement has generally been a standard laboratory technique for waterflooding of core samples.

In particular this method expresses the characteristics of water injection into a permeable medium where oil is the displaced phase.

The oil displacement efficiency of a waterflood in the field can be calculated from the water-oil relative permeability characteristics and the water and oil viscosities.

The established procedure is to construct a plot of fractional flow of water versus water saturation.

Ignoring capillary pressure effects, fractional flow equation is as follows :

$$fw = \frac{1 - \frac{k}{Ut}\frac{kro}{\mu}\,(g.\ d\,[.\ \sin\alpha\ d)}{1 - \frac{k}{Ut}\ \frac{kro}{\mu}} \qquad (1)$$

Where :

fw	=	fraction of water in the flowing stream passing any point in the rock (i.e watercut)
k	=	formation permeability
kro	=	relative permeability to oil
krw	=	relative permeability to water
Ut	=	total fluid velocity
μo	=	oil viscosity
μw	=	water viscosity
g	=	acceleration due to gravity
dp	=	water-oil density difference
αd	=	angle of formation dip to the horizontal

In so called practical units, the equation becomes :

$$fw = \frac{1 - 0.004881 - \frac{k.kro}{Ut}\ \frac{A}{\mu}\,(\ d\,[.\ \sin\alpha\ d)}{1 - \frac{\mu w}{\mu o}\ \frac{kro}{krw}} \qquad (2)$$

Where permeability is in md ; viscosity in cp ; area (A) in sq.ft ; qt (flow rate) in BPD ; and density difference in gm/cc.

In horizontal reservoirs, the equation becomes :

$$fw = \frac{1}{1 - \frac{\mu w}{\mu o}\ \frac{kro}{krw}} \qquad (3)$$

The oil displacement efficiency (Crawford,1974) can be estimated using the equation :

$$Ed = \frac{Swbt - Swc}{1.0 - Swc} \quad (4)$$

Where :

Ed = oil displacement efficiency,dimensionless.

Swbt = average watersaturation at water break-through, fraction of pore volume.

Swc = connate water saturation,fraction of pore volume.

The maximum oil displacement efficiency by water-flooding Ed.max is :

$$Ed.\max = 1 - \frac{Sor}{1- Swc} \quad (5)$$

Where :

Sor = residual oil saturation,fraction pore volume, equivalent to 1.0 minus the maximum water saturation shown from the relative permeability data.

The prediction of additional oil recovery in the fields by waterflooding can be estimated using the basic equation :

$$Nwf = \frac{7758\, \varphi Vrf\ (Sos - Sor)\ Ev\, Ep}{Bo} \quad (6)$$

where :

Nwf = total waterflood recovery , STB oil

φ = average porosity , fraction

Vrf = reservoir volume within flooded area,ac-ft

Sos = oil saturation at flood start,fraction

Sor = residual oil saturation after waterflood, fractio

Ev = vertical invasion efficiency,fraction

Ep = areal of pattern sweep efficiency,fraction

Bo = oil formation volume factor at flood pressure, RB/STB

Sources of data information :

φ = logs or core laboratory data.

Vrf = subsurface maps.

Sos = based on difference in original OIP and oil produced prior to flood.

Sor = laboratory flood tests.

Bo = laboratory analysis of subsurface fluid sample.

Ev = experience in similar fields if data limited can be estimated as function of water-oil mobilities (k/) and permeability variation.

Ep = can be estimated as function of mobilities, flood pattern.

As an example,if data available from laboratory studies and estimation include :

φ = 0.20

Vrf = 5×10^5 ac-ft

Sos = 0.456

Sor = 0.25

Ev = 0.7

Ep = 0.6

Bo = 1.176 RB/STB at flood pressure of 1000 psia.

Required : (I). Estimate waterflood oil reserve :

$$Nwf = \frac{7758\, \varphi Vrf\ (Sos - Sor)\ Ev\, Ep}{Bo}$$

$$Nwf = \frac{(7758)(0.2)(5x10^5)(0.456-0.25)(0.7)(0.6)}{1.176}$$

$$Nwf = \frac{5.71 \times 10^7\ STB}{6}$$

Required : (II).

Estimate maximum possible reserves with Ev = 1.0 and Ep = 1.0 (all of reservoir floodable ; all of area of cross-section reduced to residual oil saturation).

$$Nwf = \frac{(7758)(0.2)(5 \times 10^{10})(0.456 - 0.25)(1)(1)}{1.176}$$

$$Nwf = 1.359 \times 10^8 STB$$

III. DISCUSSION OF LABORATORY MEASUREMENTS

In preparation for laboratory work, core samples were drilled parallel to the bedding planes from each core segment using kerosene as a bit lubricant.

Plugs were thoroughly cleaned in a soxhlet extractor using warm toluene as a solvent for residual hydrocarbons.

The plugs were then dried in a controlled humidity oven at 40 % relative humidity and 60^0 C. Such conditions were selected to avoid, or at least minimize, dehydration of swelling clay minerals that may have been present in the cores.

After cooling, permeability to gas was measured by Boyle's law porosities, using helium as the injection medium,were determined.

A plot was then made of log permeability versus porosities to facilitate selection of suitable representative sample for this study.

The selected samples were evacuated and resaturated under pressure with their respective brines,then were dynamically flushed with the oil to remove water until conditions of "irreducible water saturation" were obtained, then effectives permeabilities to oil were measured.

On completion of the preliminary described above, the plugs were all flooded with simulated formation brine.

Aparratus for measuring waterflood includes various types of accumulators, core holder, gauges, regulators and plumbing (Figure 2).

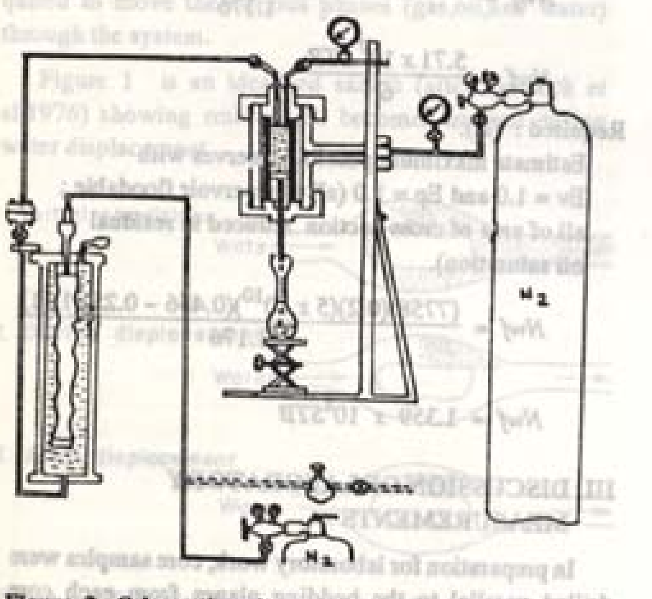

Figure 2 Schematic unit apparatus for waterflood measurements.

IV. DISCUSSION OF LABORATORY RESULTS

The initial investigations in this study have tested 339 core samples from 50 wells, from 33 oil fields from eight sedimentary basins in the Indonesian region.

The results can be reviewed from two aspects, firstly the performance within a basin as shown in Table 2 and then between fields as presented in Table 3.

In general the results show an average oil reecovery of approximately 36.7 % PV (57.3 % OIP) and remaining average residual oil saturation of 27.0 % PV (42.7 % OIP).

V. CONCLUSIONS

1. The tests showed that waterflooding can produce a significant amount of additional oil recovery from oil reservoirs in the Indonesian area, and particularly for sand formations.
2. Further properly controlled and documented laboratory data are urgently required before the feasibility of waterflooding as a secondary method can be firmly established in oil fields.
3. When deciding whether or not to use waterflooding techniques reliable estimates of recoverable oil have to be made in a comprehensive engineering eavaluation in which over all reservoir characteristics are considered in the light of current and anticipated economic factors.

Table 2. Summary of oil recovery and residual oil averages after flooding

No.	Basins	Average Oil Recovery % PV	Average Oil Recovery % PV	Average Oil Recovery % OIP	Average Oil Recovery % OIP
1.	N-Sumatra	28.1	28.5	49.6	50.4
2.	C-Sumatra	37.9	32.1	54.1	45.9
3.	S-Sumatra	47.5	19.8	70.6	29.4
4.	NE-Java	25.5	26.0	49.5	50.5
5.	NW-Java	30.1	34.4	46.7	53.3
6.	Kutei	43.9	21.0	67.6	32.4
7.	Natuna	38.2	21.3	64.2	35.8
8.	Salawati	42.1	33.0	56.1	43.9

Table 3. Waterflood laboratory data

Basins	Fields	Total Well	Ave. Depth (Ft)	Ave. K (MD)	Ave. (%)	Ave. Scw % Pv	Ave. Oil−Rec % Pv	Ave. Sor % Pv	Total Analys
N. Sumatra	A	1	5600	5	21.7	44.3	36.1	19.6	7
	B	1	3400	900	29.0	39.0	27.7	23.3	5
	C	2	900	212	24.1	46.9	20.6	32.5	4
C. Sumatra	A	1	3710	1556	21.5	32.2	40.3	27.5	29
	B	1	3650	1500	23.6	36.8	42.4	20.8	29
	C	2	3225	710	22.3	29.2	39.7	31.1	24
	D	1	5750	2180	27.7	27.4	34.3	38.3	3
	E	1	4030	229	21.9	32.3	33.3	34.4	3
	F	1	2270	1895	18.2	32.7	39.9	29.4	6
	G	3	2435	378	25.2	31.9	35.5	32.6	12
	H	2	2500	248	27.9	25.8	38.2	36.0	12
	I	1	3200	259	19.9	31.3	35.9	32.8	6
	J	1	3420	506	21.4	29.9	46.5	23.6	4
S. Sumatra	A	4	3800	99	21.6	38.8	45.5	15.7	32
	B	1	4100	290	18.5	33.8	42.6	24.1	31
	C	1	4000	32	32.2	26.0	54.3	19.7	3
	D	1	4030	229	21.9	32.3	33.3	34.4	3
	E	1	2270	1895	18.2	32.7	37.9	29.4	6
	F	3	2435	378	25.2	31.9	35.5	32.6	12
	G	2	2500	248	27.9	25.8	38.2	36.0	12
NW−Java	A	1	4800	97	10.8	36.1	17.5	46.4	5
	B	2	3200	38	28.7	42.3	38.5	19.2	6
	C	1	2920	228	27.8	27.3	36.9	35.8	6
	D	1	3000	36	30.0	30.9	29.9	39.2	4
	E	2	3400	1517	26.8	35.1	36.3	28.6	7
	F	1	3100	.19	24.6	41.6	21.2	37.2	2
NE−Java	A	2	9950	40	31.1	31.6	37.9	30.5	3
	B	2	6880	5	12.2	63.5	13.0	21.5	4
Kutei	A	3	6900	235	20.4	34.6	46.9	18.5	43
	B	3	4290	130	23.5	38.6	37.1	24.3	26
	C	1	4700	1295	26.5	37.3	49.2	13.5	6
	D	1	4650	1308	28.0	30.1	42.4	27.5	7
Natuna	A	4	5700	1500	22.5	40.5	38.2	21.3	21
Salawati	A	1	2725	10.1	22.6	28.6	42.9	28.5	3
	B	1	5500	28.0	25.4	19.4	43.1	37.5	3
	C	1	5965	47.3	21.1	26.6	40.3	33.1	3

Tabel 4. Main oil-fields in Indonesia Status 1 Jan 1985

Basin	Number of fields	Productive formation	Capacity bopd	Cumulation prod 1-1-85 mmbo
1 N. Sumatra	21	SST & LMST	118,700	530.00
2 C. Sumatra	88	SST	703,600	5,690.00
3 S. Sumatra	57	SST	62,200	1,680.00
4 NW. Jawa	50	SST & LMST	242,200	984.00
5 NE Java	1	LMST	?	0.43
6 Barito	5	SST	4,700	113.00
7 Kutei	21	SST	291,900	1,465.00
8 Tarakan	4	SST	13,000	299.00
9 Sulawati	16	LMST	36,600	280.00
10 Bula	1	SST & LMST	760	13.00
11 W. Natuna	1	SST	11,400	44.00

Tabel 5. Main gas fields in Indonesia

Basin	Field	Productive formation	Capacity MMCFPD
N. Sumatra	Arun	LMST	1800
Kutei	Badak	SST	700
Kutei	Nilam	SST	3900
Kutei	Handil	SST	170
Kutei	Attaka	SST	140

Figure 3. Some of Indonesia tertiary sedimentary basins

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