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Identification of Fluid Dynamics in Forced Gravity Drainage Using Dimensionless Groups

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Abstract A number of forced gravity drainage experiments have been conducted using a wide range of the physical and operational parameters, wherein the type, length, and permeability of the porous medium as well as oil viscosity and injection rate were varied. Results indicate that an increase in the Bond number has a positive effect on oil recovery whereas the capillary number has an opposite effect. These trends were observed over a two-order of magnitude change in the value of the dimensionless groups. Furthermore, it was found that use of each number alone is insufficient to obtain a satisfactory correlation with recovery. A combined dimensionless group is proposed, which combines the effect of all the three forces. Recoveries from all the experiments conducted in this study show a very good correlation with the proposed group. The exponent of the Bond number in the proposed group is larger than the capillary number suggesting a larger importance for the former. We then show that the same group provides a good correlation for recovery from additional experiments conducted in this study (in the presence of connate water) with that of another set of experiments in the literature.

Keywords Forced gravity drainage · Dimensionless groups · Capillary number · Bond number

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Nomenclature

A	Scaling factor
B	Scaling factor
g	Gravitational constant $((\mathrm{m})/(\mathrm{s})^2)$
k	Absolute permeability (Darcy)
N_B	Bond number, ratio of gravity to capillary forces
N_c	Capillary number, ratio of viscous to capillary forces
N_{co}	Combined dimensionless number
Q_i	Injection rate $(\mathrm{cm}^3/\mathrm{min})$
v	Displacement velocity (cm/ min)
v_c	Maximum gravity drainage velocity (cm/ min)

Greek Symbols

ϕ	Core porosity, dimensionless
σ	Interfacial tension (mN/m)
$\Delta\rho$	Density difference between gas and oil $(\mathrm{kg/m}^3)$
μ_g	Gas viscosity (cP)
μ_o	Oil viscosity (cP)
μ_r	Gas/oil viscosity ratio
μ_w	Wetting-phase viscosity (cP)
ΔP_{cap}	Differential pressure imposed by capillary forces (bar)
ΔP_{grav}	Differential pressure imposed by gravity forces (bar)
ΔP_{vis}	Differential pressure imposed by viscous forces (bar)

Conversion table

cP $\times$ 1.0E-03 = Pa.s
Darcy $\times$ 9.869E-13 = m^2
$\mathrm{cm}^3 \times$ 1.0E-06 = m^3
cm^3 /min $\times$ 1.66E-08 = m^3/s
bar $\times$ 1.03E+05 = Pa

1 Introduction

Gas injection has been considered as a very attractive oil recovery process especially when it is assisted by gravity drainage. For immiscible flow, displacement efficiency could depend on the wetting properties of the fluids, the rate of gas injection and oil production, the difference of oil and gas density, their viscosity ratio, and the oil relative permeability. Investigations in the laboratories and in the field (Hagoort 1980; Chatzis et al. 1988; Da Sle and Guo 1990; Bangla et al. 1991; Kantzas et al. 1998; Rao et al. 2004; Kulkarni and Rao 2006; Jadhawar and Sarma 2008) suggest the importance of the gas–oil gravity drainage process in improving the recovery characteristics of gas injection EOR methods.

Majority of studies investigate the effect of dimensionless groups on recovery performance (Grattoni et al. 2001; Gharbi 2002; Kulkarni and Rao 2006; Wood et al. 2008; Jadhawar and Sarma 2008). In this way, the large number of factors affecting recovery can be reduced to a limited number of dimensionless groups. Moreover, use of dimensionless groups allows establishing a relation between the laboratory and the field. In the study of free-fall gravity drainage, Grattoni et al. (2001) suggested a new dimensionless group combining the effects of gravity and viscous forces with the capillary forces. Gharbi (2002) made use of dimensionless groups for scaling of miscible flooding in a 2D heterogeneous anisotropic reservoir. Kulkarni and Rao (2006) presented the effect of important dimensionless groups on the final oil recovery obtained from a number of miscible and immiscible gas gravity drainage experiments. Wood et al. (2008) introduced ten dimensionless groups to describe CO_2 flooding in a dipping waterflooded reservoir, and used them for experimental design purposes to develop screening criteria applicable to Gulf Coast reservoirs. Similarly, the relationship between the scaling groups and their effects on the overall performance of immiscible gas-driven gravity drainage were investigated by Jadhawar and Sarma (2008) through the use of uncertainty assessment techniques.

The objective of this article is to study forced gravity drainage in synthetic and natural porous media. A number of forced gravity drainage experiments are conducted with various permeability, oil viscosity, and gas injection rate. These parameters are changed extensively to obtain a wide range of dimensionless groups, where the viscous, capillary, and gravity forces compete. The results have been analyzed using the capillary number and the Bond number. These dimensionless groups will be defined later. This is followed by description of the experiments and their results. The relation between the dimensionless groups and the recovery is then examined. It is found that neither the capillary number, nor the Bond number is sufficient to explain the full range of behaviors observed. The analysis of the results is followed by introduction of a combined dimensionless group and examination of its applicability to the experiments reported here and elsewhere in the literature.

2 Dimensionless Groups

In forced gravity drainage, the effectiveness of displacement depends not only on the relative magnitude of viscous force and gravity forces, but also on their relative magnitude with respect to the capillary force. In gravity drainage, the gravity force is a driving force, while the capillary is resistive. In order to quantify the relative magnitudes of the prevailing forces, the following set of dimensionless groups are usually suggested: (I) the Bond number, N_B, is the ratio of the pore scale hydrostatic pressure drop to the capillary pressure. Here, we used the modified Bond number to include the macroscopic parameters such as permeability and porosity. This number is also defined as Dombrowski–Brownell number (Singh et al. 2001), (II) the capillary number, N_c, is the ratio of the pore scale viscous pressure drop to the capillary pressure.

$$N_\mathrm{B} = \frac{\Delta P_\mathrm{grav}}{\Delta P_\mathrm{cap}} = \frac{\Delta \rho g (k/\phi)}{\sigma} \tag{1}$$

and

$$N_\mathrm{c} = \frac{\Delta P_\mathrm{vis}}{\Delta P_\mathrm{cap}} = \frac{\mu_\mathrm{w} v}{\sigma} \tag{2}$$

where μ_w is the wetting phase viscosity, v is the Darcy velocity, σ is the interfacial tension, k and ϕ are the permeability and porosity of the porous medium, respectively, $\Delta\rho$ is the density difference between two fluids, and g is the gravity acceleration in the direction of flow.

Scaling of miscible and immiscible displacement in porous media using dimensionless groups not only reduces the number of parameters to be studied, but also allows differentiating between different flow regime, e.g., as flow regime transitions from gravity dominated to viscous dominated with increased flow rate (Shook et al. 1992).

One utility of dimensionless groups is that they allow scaling from field conditions to the laboratory conditions, so that the flow regimes in the laboratory are similar to those in the field. This is achieved by reproducing experiments with a relative magnitude of the forces that is the same as those in the field. For this study, we used the values of dimensionless numbers (the capillary and the Bond numbers) in nine gravity stable field projects reported by Kulkarni and Rao (2006) as a basis for our experimental design. In order to capture a larger range of dimensionless groups, the operating parameters were varied extensively.

2.1 Selection of Experimental Variables

In the experiments reported in this article, in addition to operating conditions, we varied rock and fluid properties. The main variables include permeability, oil viscosity, displacement rate, rock type, and pressure. The details are reviewed in the following.

Bond number: From Eq. 1, the Bond number depends on permeability, interfacial tension and the density difference between the gas and oil. While the density difference and interfacial tension between oil and the gas could be changed over a limited range, permeability is selected as the main parameter. We changed this parameter to study the effect of the Bond number on oil displacement.

Capillary number: From Eq. 2, the capillary number is a function of displacement velocity, oil viscosity, and interfacial tension. In order to obtain the capillary numbers over a wide range, we varied the gas flow rate and oil viscosity. For varying gas flow rate, we used the concept of critical gravity drainage velocity, which is defined by Blackwell and Terry (1959) and Dumore (1964) in Eq. 3. The critical gravity drainage rate represents the rate at which unfavorable viscous fingering effects are overcome by gravity forces, such that a larger v_c/v would represent better displacement efficiency.

$$v_c = \frac{k}{\mu_o}(\Delta \rho g) \tag{3}$$

The injection rates are changed from below to many times above the critical rate, which itself varied as the type of porous medium and viscosity varied.

3 Experiments

The forced gravity drainage experiments reported in this article employed a bead-pack (glass beads and sand-pack) and a sandstone core. The characteristics of the two types of porous medium and the procedure used in the experiments are described in this section.

3.1 Synthetic Porous Medium Experiments

These experiments are divided into three groups: (I) six experiments were conducted in a 120-cm long porous medium made up of sintered glass beads with average grain size of 120 μm, where the permeability ranged between 8 and 18 Darcy. The glass beads were sintered because different permeable media with various grain sizes were needed for further analysis. The first three experiments were performed with grain size ranged between 212 and 150 μm, and the other experiments in this category were performed with grain size ranged between 150 and 106 μm. (II) Three experiments were performed in a 60-cm long porous

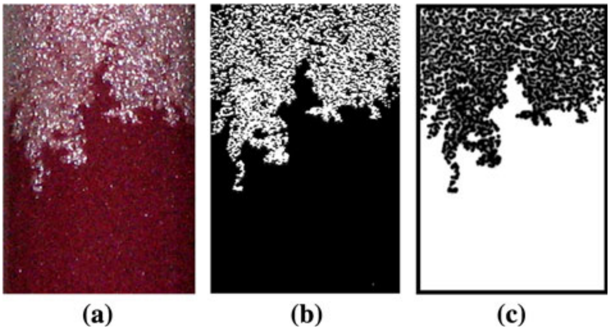

Fig. 1 Filtering process: (**a**) the raw image (**b**) black and white image (**c**) image in reverse colors

medium made up of sands. The grain size of the sieved sands ranged between 106 and 53 μm, and the permeability was around 3.5 Darcy. The crushed sand is primarily calcified in quartz group. It is usually well sorted and rounded, and strongly water-wet. (III) Three experiments were conducted in a 60-cm long porous medium using glass beads with the average permeability of 20 Darcy, where the oil viscosity was much higher than that in other experiments. The average porosity for all the experiments conducted in synthetic porous medium was around 37%. Despite their simplified pore structure, some experiments (described in group "I") allowed visual study of the displacement of oil by the gas. For this purpose, pictures were taken at regular intervals during the experiments. These raw pictures were filtered to clearly separate the wetting from the non-wetting phase and to extract the invasion front. Successive steps of this filtering process are presented in Fig. 1. The raw image (a) was not clear enough, so it was turned to black and white where the two phases are clearly distinguished (b). This displacement image is best viewed in reverse colors (c).

3.2 Natural Porous Medium Experiments

The coreflood experiments were conducted in a 60-cm long high-pressure core holder using outcrop sandstone cores. The outcrop sandstone cores come from the Aghajary formation in Ahwaz anticline located 7 km away from Ahwaz city in southwestern Iran. The porosity and absolute permeability were 16.5% and 70 mD, respectively. The experiments were conducted with and without connate water saturation. Brine (5g/L Nacl) was used as the connate water. After each experiment, the core was flooded with diluted brine, distilled water, toluene, and isopropyl alcohol, and dried in air bath before it was used in a new experiment. The experiments with connate water will be compared with other ones in the literature, to examine the validity of the dimensionless group that will be proposed in this study.

In all the experiments, nitrogen was utilized as the displacing fluid, and n-Decane and paraffinic synthetic oil were used as the displaced phase. Tables 1 and 2 give more details about the experiments, which are characterized by alphabets from "a" to "f" described as follows: a—experiments are conducted in 120-cm long sintered glass beads with permeability of approximately, 18 Darcy; b—experiments are similar to "a" except that permeability is approximately 8 Darcy; c—experiments are conducted in sand-pack of 60–cm length with ∼3.5 Darcy permeability; and d—experiments are similar to "a" except that the length is 60 cm, and the oil type is different. Experiments "e" and "f" are conducted using the 60–cm sandstone core at 30 bars, where permeability is approximately, 70 mD; and f—experiments are conducted in the presence ofconnate water saturation, where effective permeability to

Table 1 The key properties for the selected pairs of forced gravity drainage experiments

Synthetic porous medium					Natural porous medium					
Exp number	ϕ (fraction)	A (cm^2)	K_o(mD)	Q_c* (cm^3/min)	Exp number	ϕ (fraction)	A (cm^2)	K_o(mD)	Q_c^* (cm^3/min)	S_{wir}
a1	0.38	7.06	18500	6.69	e1	0.165	11.4	70	0.038	0
a2	0.375	7.06	17800	6.44	e2	0.165	11.4	70	0.038	0
a3	0.378	7.06	17000	6.15	e3	0.165	11.4	70	0.038	0
b1	0.365	7.06	8800	3.18	e4	0.165	11.4	70	0.038	0
b2	0.37	7.06	9000	3.26	f1	0.165	11.4	55	0.028	0.28
b3	0.375	7.06	8500	3.07	f2	0.165	11.4	55	0.028	0.28
c1	0.375	12.56	3700	2.38	f3	0.165	11.4	55	0.028	0.28
c2	0.38	12.56	3500	2.25	f4	0.165	11.4	55	0.028	0.28
c3	0.37	12.56	3800	2.44						
d1	0.365	12.56	20000	0.57						
d2	0.37	12.56	21000	0.6						
d3	0.375	12.56	18000	0.51						

* Critical gravity drainage rate defined by Eq. 3

Table 2 Fluid properties

	Oil density (kg/m^3)	Oil viscosity (cP)	Gas density (kg/m^3)	Gas viscosity (cP)	IFT (mN/m)
Synthetic porous medium experiments (a, b, c), 1 bar	740	0.85	1	0.018	20
Synthetic porous medium experiments (d), 1 bar	830	23	1	0.018	20
Natural porous medium experiments (e, f), 30 bar	743	0.9–0.95	32	0.02	12

oil is ~55 mD. Within each group of the experiments, a number of different flow rates were used.

3.3 Experimental Procedure

Synthetic porous medium experiments are conducted under ambient laboratory conditions, wherein the outlet face of the model was open to atmosphere. Thus, the inlet face (gauge) pressure gives the differential pressure during the displacement process. In the case of coreflood experiments, the operating pressure was, approximately, 30 bars.

In order to differentiate specific mesh sizes from the wide ranges of beads or sands, shaking table with standard sieves were used. After sorting and grouping the glass beads and crushed sands, the physical column was packed. The models vertically positioned on the screening table and all the inlet and outlet points were provided by meshed units except one which was used for glass bead or sand entrance. Then, the sand or glass beads were allowed

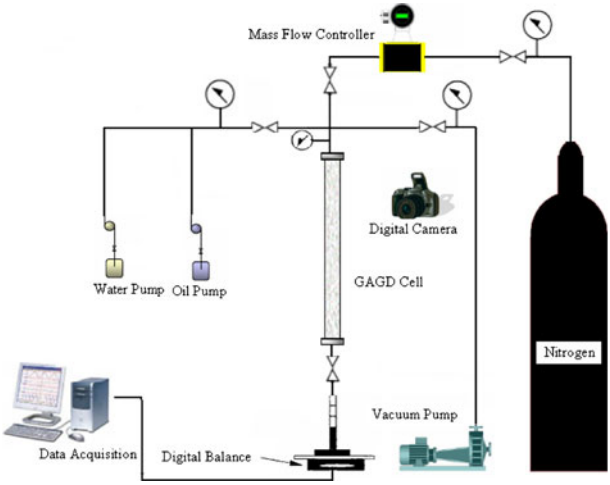

Fig. 2 Schematic representation of the experimental set up

to pour from the top portion of the model. During shaking, all the probable cavities should have disappeared.

The apparatus was then assembled with the porous medium in vertical gravity stable condition. A leak test was then performed by applying gas pressure and verifying that pressure was maintained for a certain duration. Before starting the experiments, each porous medium was vacuumed, and then fully saturated with the oil. Dead volumes and porosity were then measured by sequential filling of each component in the flow loop from bottom to top. The absolute permeability was then measured. In experiments with initial water saturation, the model was fully saturated with brine, then oil was injected at high flow rates to displace water down to irreducible water saturation, and the effective permeability was then measured. This high flow rate was 60 cc/h (1 cc/ min) in each experiment. In order to overcome the capillary-end effect, higher rates were applied at each step when no water was produced.

While the core used for each experiment is similar, the values of the connate water were approximately the same. High precision syringe pumps were used to inject different liquids and the gas was injected using a mass flow controller (MFC). The schematic drawing of the equipment used in the laboratory experiments is shown in Fig. 2

The forced gravity drainage experiments were conducted by injecting gas at the top of the porous medium at different, controlled rates. Oil production was monitored continuously using the data acquisition system.

4 Experimental Results

The experimental results and the investigation of their dependence on selected dimensionless groups are discussed in this section. Experimental results in the presence of initial water saturation are presented in Sect.5.2. The dimensionless groups corresponding to each experiment are reported in Table 3.

Table 3 The key dimensionless numbers for forced gravity drainage experiments

Synthetic porous medium						Natural porous medium					
Exp number	Q_i/Q_c	N_c (10^{-5})	N_B (10^{-5})	RF @ 2 PV & Final RF (% IOIP)	ΔP @ B.T (Psi)	Exp number	Q_i/Q_c	N_c (10^{-7})	N_B (10^{-7})	RF @ 2 PV & Final RF (% IOIP)	ΔP @ B.T (Psi)
a1	0.46	0.31	1.76	79–90	0.21	e1	7.78	3.29	2.56	44–56	2.82
a2	1.24	0.81	1.72	70–86.5	0.41	e2	13.49	5.70	2.56	43–55.5	3.34
a3	2.68	1.65	1.63	65.5–85	0.92	e3	23.32	9.87	2.56	37.5–50	7.61
b1	1.57	0.5	0.87	67–85	0.71	e4	31.10	13.1	2.56	34.5–49	8.48
b2	3.10	1.0	0.88	62–84	1.83	f1	2.81	1.12	2.42	50–57.5	2.45
b3	5.20	1.6	0.82	58–80	3.41	f2	5.28	2.11	2.42	48–56	4.87
c1	0.84	0.11	0.36	64.5–85.5	0.53	f3	21.11	8.42	2.42	44–51	11.54
c2	2.44	0.31	0.33	55–79.5	1.76	f4	52.78	21.1	2.42	38.5–48	20.1
c3	3.88	0.53	0.37	54–78.5	2.23						
d1	1.58	1.31	2.28	57.5–79	0.66						
d2	2.00	1.75	2.26	51–77	0.92						
d3	3.11	2.33	2.00	47.5–73	1.12						

4.1 Bond Number

As mentioned earlier, variations in the Bond number were primarily created by varying the permeability of the porous medium, where reduction in permeability leads to a reduction in the Bond number.

Permeability was changed by using different bead sizes and using natural sandstone cores. As seen in Eq. 2, changing permeability does not affect the capillary number, thus allowing investigation of the effect of the Bond number at a constant capillary number. Recovery factor after two pore volumes injected as a function of the Bond number is shown in Fig. 3a–c.

Results in Fig. 3a indicate that recovery at a constant capillary number increases with the Bond number. This behavior is in line with our expectation about the effect of capillarity on oil drainage by gas injection when the oil is the wetting phase. As the Bond number increases i.e., the importance of the capillary force with respect to the gravity force decreases, the oil recovery improves. A similar behavior is observed, when recovery at gas breakthrough was plotted (results are not shown here).

Results in Fig. 3b and c are for larger values of the capillary number. The capillary number varied slightly between different experiments shown in each of Fig. 3a–c. The variations in the capillary number will be accounted for later in this article, when the interaction between the Bond and capillary numbers is taken into account. Once again, results indicate that recovery at a constant capillary number increases with the Bond number. However, the slopes of correlated lines in Fig. 3a–c show that the effect of the Bond number on oil recovery is less pronounced at higher values of the capillary number. The interaction between the Bond number and the capillary number is discussed later in this article.

In order to examine the universal dependence of oil recovery on the Bond number, oil recovery from all gravity drainage experiments, shown in Table 3, are plotted against their Bond numbers in Fig. 4.

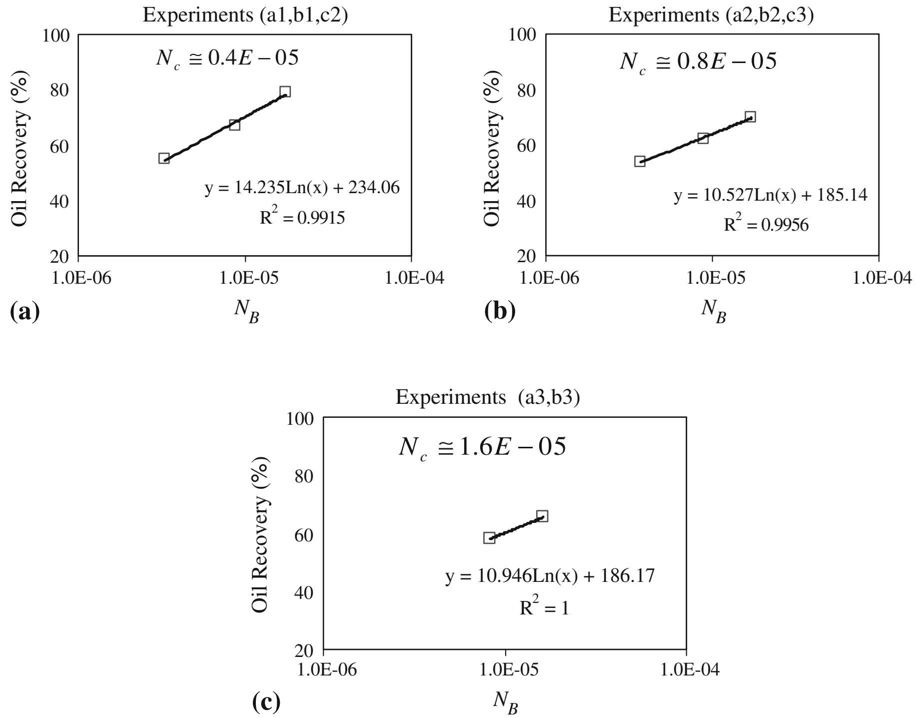

Fig. 3 Correlation of Bond number with oil recovery: (**a**) experiments a1, b1, c2 (**b**) experiments a2, b2, c3 (**c**) experiments a3, b3

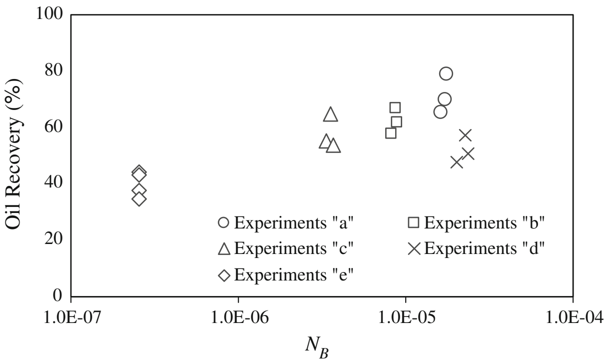

Fig. 4 Oil recoveries from all experiments against Bond number

While an overall trend may be observed, no satisfactory correlation was found between the oil recovery and the balance between the gravity and capillary forces. The estimation of oil recovery using the Bond number has two major limitations: (I) The effect of viscous force is not included; for example, by changing the gas injection rate, the oil recovery may be changed drastically, while the Bond number is kept unchanged; (II) The effect of viscosity ratio is not included; for example, when the gas/oil viscosity ratio changes leading to a change

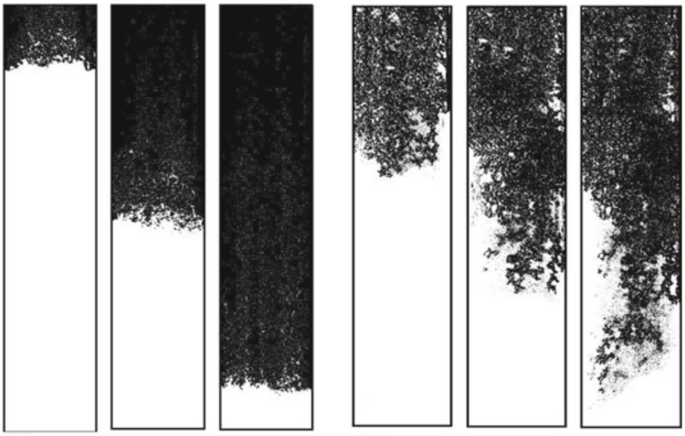

Fig. 5 Displacement structure of the invading wetting fluid for (**a**) slow displacement $v_c/v = 2$ (**b**) fast displacement and viscous fingering $v_c/v = 0.75$

in stability of the front, the Bond number remains unchanged. The effect of viscous forces and viscosity ratio are incorporated in the following sections.

4.2 Capillary Number

The capillary number, which expresses the ratio of the pore-scale viscous force to capillary force, is an important parameter in determining the stability of the gas displacement processes. In any gas injection process, the mobility ratio is typically unfavorable, and the development of unstable fingers during gas displacement is likely. Large viscous forces in the high-rate gas injection experiments, characterized by higher capillary numbers, may result in unstable flood fronts and the oil bypassing and trapping events, a mechanism that is enhanced at higher flow rates. In general, an increase in the value of the viscous forces reduces the oil recovery because the microscopic displacement efficiency suffers.

Figure 5 shows the distribution of the gas and oil recorded at regular intervals during the experiments at two different gas injection rates. At lower injection rate, (Fig. 5a, the flood-front is quite stable, while at the higher injection rate, (Fig. 5b, much bypassed oil remains behind the gas front.

Results are shown in Fig. 6a–e, where oil recovery after two pore volume injection is plotted against the capillary number. Results in each figure are characterized by the Bond number that remain approximately constant. Results in all the cases indicate that oil recovery improves as the capillary number decreases (i.e., the viscous force reduces as compared to the capillary force, and the flow stability improves).

The Bond numbers given in Table 3 for experiments “a”–“e” are characterized by continuously decreasing values of the Bond number, with the exception of “d” experiments that have the largest Bond number. The slope of the correlation lines shown in Fig. 6a–e indicates a decreasing trend with the Bond number. This suggests that the negative effect of the capillary number on oil recovery could depend on the Bond number. In order to explore for an appropriate correlation that describes the dynamics of the recovery characteristics, oil recoveries from all the experiments are plotted against their capillary numbers (Fig. 7).

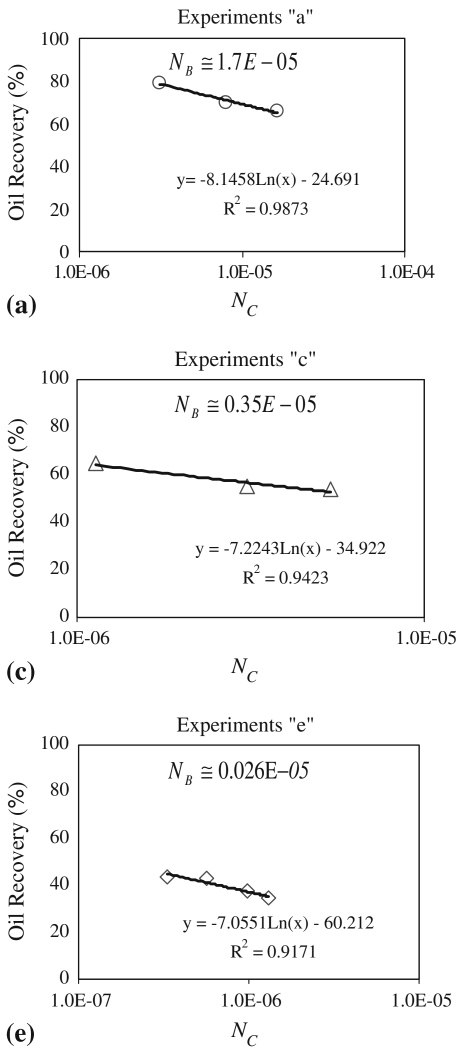

Fig. 6 Effect of capillary number on oil recovery at constant Bond number

Again, no satisfactory correlation is observed. This confirms that the capillary number alone is insufficient to predict the oil production during the forced gravity drainage.

4.3 Stability of the Invasion Front

In this section, factors that affect the stability of the front are investigated. For top-down drainage with high viscosity contrast between gas and oil, theoretical arguments based on critical gravity drainage velocity (e.g.,Dumore 1964) suggest the following criterion for the displacement under stabilized condition.

$$v_c > v \tag{4}$$

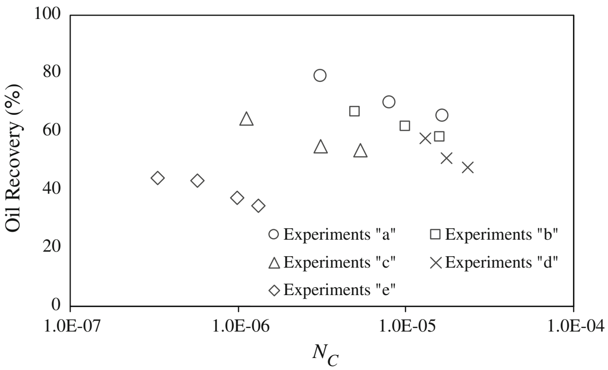

Fig. 7 Oil recoveries from all experiments against capillary number

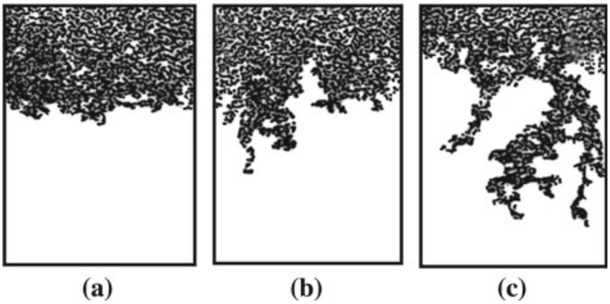

Fig. 8 Front stability analyses from displacement structures for (**a**) $v/v_c = 0.5$ (**b**) $v/v_c = 1.5$ (**c**) $v/v_c = 2.6$

This definition is in line with the studies of Meheust et al. (2002) and Lovell et al. (2005). Those authors employed the percolation theory in a stabilizing gradient (Wilkinson 1986; Birovljev et al. 1991; Auradou et al. 1999), and to characterize the invasion front instability.

$$\Delta\rho g k/\mu_o > v \tag{5}$$

Equations 4 and 5 are obtained using two independent approaches, and suggest that a stable displacement requires $v_c > v$. However, the critical gravity drainage velocity includes both gas and oil viscosities; in the gravity drainage, the gas viscosity is negligible in comparison with oil viscosity. The validity of this can be confirmed using the visual observations of gas saturation shown in Fig. 8, where experiments a, b, and c correspond to displacement velocities that are, approximately, 0.5, 1.3, and 2.6 times the critical velocity.

The results in Fig. 8 indicate that the displacement front has a stable form when the above criterion is met. In contrast, when the displacing velocity is higher than the critical velocity, the displacement front becomes unstable.

5 A Combined Dimensionless Group

Examination of oil recoveries as a function of dimensionless groups suggests that none of the above scaling groups individually can define the oil recovery.

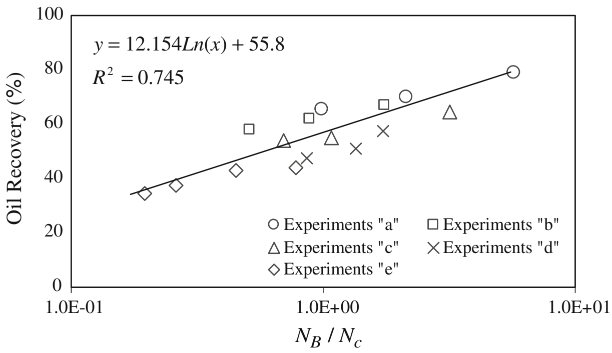

Fig. 9 Oil recoveries versus ratio of the Bond to capillary number

In the following section, we search for a new group that could capture the dependence of oil displacement over the whole range of variables investigated.

5.1 Physical Significance of the Proposed Group

In this section, we explore the utility of a combined dimensionless group that combines the above dimensionless groups. According to the experimental results shown in Figs. 4 and 7, oil recovery has a direct relation with the Bond number and inverse relation with the capillary number. Fig. 9 shows the results of all the experiments, when ratio of the Bond number over capillary number is used. Results in Fig. 9 show that when the recovery values from the high viscosity-oil experiments (“d”) are excluded, the plot of oil recovery against the ratio of the Bond to capillary number would show a better correlation. This confirms that the oil recovery is a function of viscosity ratio and should be considered accordingly. When the gas/oil viscosity ratio decreases, the flow instability increases resulting in poorer sweep efficiency. In order to account for the effect of viscosity ratio ($\mu_r = \mu_g/\mu_o$) and proper ratio of the Bond to capillary number, a combined dimensionless group, N_{Co}, is proposed

$$N_{Co} = \frac{N_B \times (\mu_r)^A}{N_c^B} \tag{6}$$

where subscript Co stands for the term “combined,” and the parameters A and B are the scaling factors. We found that the values of $A = B = 0.5$ provide a good correlation. The small values of exponent suggest that the effect of the capillary number and the viscosity ratio is less than the importance of the Bond number. It is found that if recovery at a higher PV-injection was used, other values of A and B are needed to obtain a good match. Nevertheless, in all the cases the A and B exponents were smaller than 1.

The results for the above are shown in Fig. 10, where the recovery values of all the 16 experiments are plotted against N_{Co}. This dimensionless group successfully combines the effect of the three main forces that affect forced gravity drainage. The results suggest that within the range of experiments conducted here, there is a logarithmic relationship between the oil recovery and proposed group. As stated earlier, we do not believe N_{Co}—as suggested in this article—is unique. The significance of this study lies in that it suggests that neither the capillary number nor the Bond number is sufficient for correlating recovery, and that the importance of the Bond number is more than the capillary number.

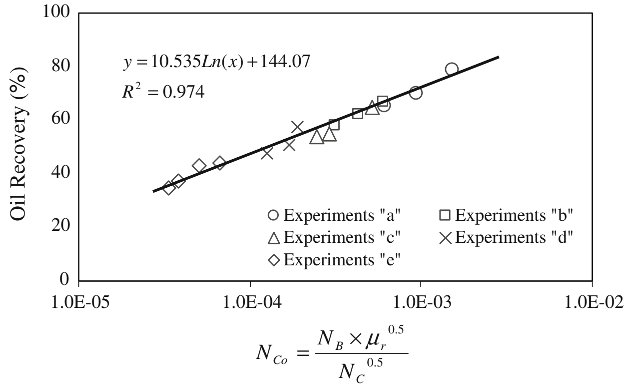

Fig. 10 Oil recoveries versus the combined dimensionless group for all forced gravity drainage experiments

5.2 Validation

In order to validate the applicability of the new group proposed, we have examined the recovery of the experiments in the presence of initial water saturation (group "f" in Table 3). Figure 11 shows the relation between oil recovery and the combined group. We have also incorporated experimental results from the long core experiments of Skauge et al. (1997). Recovery values at 2 and 4 PV gas injections are shown. A good correlation is observed in both cases. Here, it should be pointed out that for validation of the proposed number, the experiments under forced gas injection velocity are only suitable. For example, in Grattoni et al. (2001) article, experiments were conducted under spontaneous gas invasion and the capillary number is varied over the time. Hence, the oil recovery from the so-called free fall gravity drainage experiments could not be predicted by the proposed number.

Figure 11a also includes the correlation that was obtained in the absence of connate water saturation (see dashed line). The correlation in the presence of connate water saturation provides a higher recovery. This is consistent with the distribution of oil between the connate water and the invading gas, leading to lower remaining oil saturation. The difference between the two correlations is more at lower recovery factors.

6 Summary and Conclusion

A series of forced gravity drainage experiments were conducted to study the competition between the gravity, viscous, and capillary forces, through use of the Bond and capillary numbers.

The results presented in this article indicate that the oil recovery increases with the Bond number. Analysis of oil recovery against the Bond number at the same capillary number shows a good correlation, but when the capillary number changes, the dependency of oil recovery with the Bond number decreases. In contrast, and at a constant Bond number, oil recovery decreases with increasing capillary number (as a result of higher viscous forces and flow instability).

Analysis of the front instability by using the critical gravity drainage rate definition shows a good agreement with investigations based on percolation theory. It is perhaps not surprising that our experimental results and displacement structures are consistent with the stabilization criterion (Eq. 4).

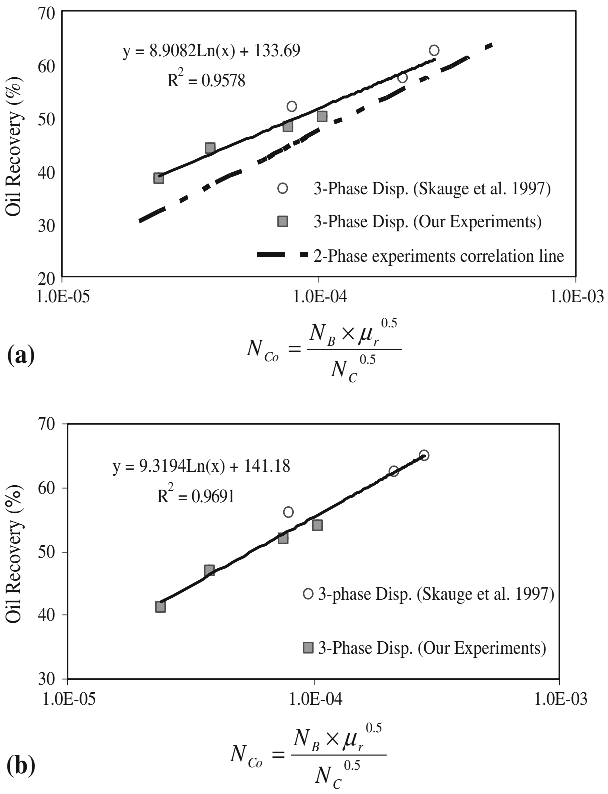

Fig. 11 Oil recoveries versus three phase gravity drainage experiments (**a**) after 2 PV injection (**b**) after 4 PV injection

Results presented in this study (Figs. 4 and 7) suggested that the Bond and capillary numbers alone could not predict the oil production characteristics. A combined dimensionless group was defined to correlate the competition between the three forces affecting oil recovery over a wide range of petrophysical and operational properties. This allows a good correlation between oil recovery and the newly proposed group in the ranges of dimensionless groups studied in this research where oil recovery varied between 30 and 80%. A logarithmic relationship was observed between the proposed group and oil recovery. Applicability of the proposed correlation beyond the range of experiments is reported, and needs to be further examined, especially when the value of the proposed dimensionless group is significantly reduced below the values investigated in this study.

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