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Immiscible Displacement in Cross-Bedded Heterogeneous Porous Media

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Abstract Direct insight into the mechanisms of flow and displacements within small-scale (cm) systems having permeability heterogeneities that are not parallel to the flow direction (cross-bedding and fault zones) have been carried out. In our experiments, we have used visual models with unconsolidated glass bead packs having carefully controlled permeability contrasts to observe the processes with coloured fluids and streamlines. The displacements were followed visually and by video recording for later analysis. The experiments show the significance that heterogeneities have on residual saturations and recovery, as well as the displacement patterns themselves. During a waterflood, high permeability regions can be by-passed due to capillary pressure differences, giving rise to high residual oil saturations in these regions. This study demonstrates the importance of incorporating reservoir heterogeneity into core displacement analysis, but of course the nature of the heterogeneity has to be known. In general, the effects created by the heterogeneities and their unknown boundaries hamper interpretation of flood experiments in heterogeneous real sandstone cores. Our experiments, therefore, offer clear visual information to provide a firmer understanding of the displacement processes during immiscible displacement, to present benchmark data for input to numerical simulators, and to validate the simulator through a comparison with our experimental results for these difficult flow problems.

Keywords Permeability · Immiscible displacement · Capillary pressure · Cross-bedding heterogeneity · Visual studies

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1 Introduction

The flow of fluids through porous media is governed by the local effective permeability and fluid potential gradients. The fluid potential gradient at a point is dependent upon the surrounding fluid and permeability distributions, and originates from gravitational, capillary and viscous forces, so that the flow direction will frequently not be parallel to the source-sink potential. Heterogeneities in porous media cause displacement disturbances when fluids flow through them. An earlier article (Roti and Dawe 1993) discussed aspects of miscible flow through cross-bedded heterogeneities, where many interesting phenomena were identified including cross-flow and refraction effects. The effects of wettability heterogeneity have also been presented previously (Caruana and Dawe 1996; Dawe and Grattoni 2008), but the physics becomes even more complicated. This article continues the discussion of permeability heterogeneity by experimentally examining immiscible flow within uniform wettability organised heterogeneous media.

In this article, we report immiscible displacements within small-scale water-wet models (cm) with layers where there is an abrupt change in permeability and flow is not parallel to the layers. This type of cross-bedding geometry causing anisotropy of permeability is a common sedimentary structure in sandstone reservoirs especially in fluvial deposits and in fault zones, such as cataclastic faults (Al-Hinai et al. 2006, 2008). When the sedimentary layers and the direction of approaching flow are not parallel refraction and dispersion effects occur which can grossly distort the flow. An improved understanding is needed, since in reservoir simulators it is essential to ensure that the numerical simulation programmes represent the correct physics (Al-Hinai et al. 2006, 2008), and in core analysis that the effluent profiles are correctly interpreted.

This article concludes the series where we have examined experimentally miscible and immiscible flow in models that have basic heterogeneous patterns found in reservoir bodies, namely, the layer, the angled stripe, the lens (a truncated layer) and the quadrant with heterogeneities having permeability and/or wettability contrasts (Caruana 1997; Caruana and Dawe 1996; Dawe and Richardson 1983; Dawe et al. 1985, 1992; Dawe and Grattoni 2008; Evans and Dawe 1994; Lambeth and Dawe 1987, 1988; McKean and Dawe 1990; Roti and Dawe 1993; Shaw and Dawe 1987; Wheat and Dawe 1988; Wright et al. 1987). Our study has been augmented by other bead pack and core studies of the impact of cross-bedding on oil recovery (Ringrose et al. 1993; Huang et al. 1995; Muggeridge et al. 2002; Kortekaas 1985; Weber 1982).

This study uses synthetic cross-bedded models (stripes) enabling the properties of the cross beds to be characterised and the flows to be easily visualised, whereas in other studies using real sandstones (Ringrose et al. 1993; Huang et al. 1995; Muggeridge et al. 2002; Kortekaas 1985; Weber 1982), the ready visualisation and characterisation of the properties of each heterogeneity are more difficult.

1.1 Flow Through Heterogeneities

All hydrocarbon reservoirs, being natural geological systems, are heterogeneous; as such it is important that typical displacement patterns in known model heterogeneities are understood so that the knowledge can be reflected to real systems (Dawe and Grattoni 2008; Lambeth and Dawe 1987). Such effects are generally the greatest where the fluid saturations and pressure gradients change most rapidly, such as at displacement fronts of the displacing and displaced fluids or transition zones, and, the subject of this article, at permeability boundaries.

These changes in potential gradients cause the fluid displacement patterns to become highly non-uniform, making the prediction of the displacement fronts more difficult and often uncertain. Importantly and practically, if the effects of reservoir heterogeneities are not well accounted for at the planning stage of an oil recovery operation, or carbon dioxide geological storage development, they may become evident when it is too late to remedy, such as when water breaks through earlier than expected.

Geologically, heterogeneities occur at all scales (1 cm–10 km) as a result of depositional events. Centimetre scale heterogeneities are clearly seen in cores and are important because they control the movement of displacement fluids and the distribution of residual oil in swept and bypassed zones. Parameters derived from core experiments (centimetre scale) such as residual oil saturations, capillary pressures and relative permeability use theories of fluid displacement and flow measurement which normally assume homogeneous core properties. Therefore, the interpretations are likely to be unreliable if the core from which the data are derived is heterogeneous (Huppler 1970). However, core is opaque and so the heterogeneities within even a core sample can usually only be seen on the surface or by cutting (and hence destroying) the sample, except recently with CT and NMR imaging which is demonstrating the complexities within the material, (Hove et al. 1995; Al-Hinai et al. 2006).

2 Essential Physics of Immiscible Flow in Cross-Bedded Systems and Fault Zones

Immiscible displacement accounts for a large proportion of the oil recovery (e.g. waterflooding and solution gas drive) and also many EOR processes contain an immiscible stage (e.g. chase water displacing a solvent slug, water alternate gas, etc.). Different flow patterns exist between miscible and immiscible flow. Immiscible displacements also bring into any analysis the problems created by capillary pressure and relative permeability phenomena. These have the further dimension of requiring knowledge of saturation distribution, saturation gradients, wettability effects and positions of residual and mobile phases.

2.1 Capillary Pressure, Wettability and Heterogeneity

Capillary pressure is a function of fluid saturation and porous medium wettability and can considerably complicate flow behaviour during immiscible displacements. It will change the flow patterns in immiscible displacements from that observed in miscible displacements, especially at low flow rates where capillary effects dominate viscous effects, (Dawe and Grattoni 1998; Dawe et al. 2010), which will be further discussed in Sect. 5. This contrast between miscible and immiscible flows is often magnified in heterogeneous porous media.

The capillary number is the normal dimensionless group associated with this balance of forces and is defined as $N_{\mathrm{ca}} = q\mu/L\sigma d$, where $q =$ injection rate (ml/s), $\mu =$ displacing fluid viscosity (Poise), $L =$ length of the porous medium (cm), $d =$ depth of model (cm) and $\sigma =$ interfacial tension (mN/m), and within the reservoir (low flow rates) is usually of the order of 10^{-6}.

Wettability is defined as the preference of the porous medium for a particular fluid; if it is water then the medium is said to be water-wet, and if it is oil the medium is oil-wet. Imbibition is defined as an increase in the wetting phase saturation, and drainage as a decrease in the wetting phase saturation. Displacements through porous media having wettability contrasts have been discussed previously (Caruana and Dawe 1996; Dawe and Grattoni 2008), so in this study, we concentrate on permeability contrasts.

Although the basic physical concepts controlling flow in cross-bedded media have been identified for over a century, quantifying these effects to predict oil recovery from immiscible displacements is still challenging. For instance, at saturation discontinuities capillary pressures (interfacial curvatures) can change over a few grain diameters giving rise to large pressure gradients. In homogeneous media, such discontinuities may occur across immiscible displacement fronts and at porous media boundaries, such as end effects (Dawe et al. 2010). In heterogeneous media, capillary pressure effects are also created at the boundaries between areas with different properties, such as permeability, porosity or wettability changes (Dawe et al. 2010).

Consider the definition of capillary pressure, (Dawe et al. 2010) then,

$$p_c = p_o - p_w = 2\gamma \cos\theta^*/r,$$

where p_w = water phase pressure, p_o = oil phase pressure, γ = interfacial tension, θ^* = contact angle ($\theta^* < 90°$ water-wet and $\theta^* > 90°$ oil-wet), r = average pore throat size for the porous medium. In this study, the capillary pressure contrasts are due to permeability/grain size variation at constant wettability, (cos θ^* is constant), so assuming that the pore throat radius is proportional to the grain diameter, then the capillary pressure in the low permeability regions (small grains) would be higher than that in the high permeability regions (large grains), then

$$p_{\text{clow}} > p_{\text{chigh}} \text{ as } 1/r_{\text{low}} > 1/r_{\text{high}}, \quad \text{therefore, } p_{\text{olow}} - p_{\text{wlow}} > p_{\text{ohigh}} - p_{\text{whigh}}.$$

By further assuming that at the initial stage of a waterflood (water displacing an oil filled model) the oil phase pressure is initially approximately the same in both high and low permeability regions, then

$$p_{\text{olow}} \approx p_{\text{ohigh}} \text{ so } p_{\text{wlow}} < p_{\text{whigh}}$$

Therefore, the water will preferentially fill regions of low permeability and by-pass high permeability regions, as the water phase pressure is least in the low permeability regions. Similarly, during an oilflood in a water/oil system having permeability changes but uniform wettability, it may be assumed that initially the water phase pressure is approximately the same in both low and high permeability regions, then $p_{\text{wlow}} \approx p_{\text{whigh}}$ so that $p_{\text{olow}} > p_{\text{ohigh}}$. Therefore, the oil will preferentially fill regions of high permeability and by-pass low permeability regions, with the result that oil is left by-passed in the low permeability region.

Multi-phase flow in porous media is usually described through relative permeability parameters which are also related to capillary pressure and are functions of saturation values; the subject has been (and will be) continuously debated in the petroleum engineering literature (Bear 1972).

2.2 Refraction at Boundaries within Porous Media

King Hubbert (1968) and Bear (1972) both give a refraction equation to describe flow of a single fluid from medium 1 of uniform permeability k_1 into medium 2 of permeability k_2:

$$\frac{k_1}{k_2} = \frac{\tan\theta_1}{\tan\theta_2}$$

where θ_1 and θ_2 are the angles the respective flowlines make with the normal to the boundaries in media 1 and 2 of uniform permeability k_1 and k_2, respectively, Fig. 1. During flow, tan θ is needed because the fluid streamlines can bend before entering the new permeability

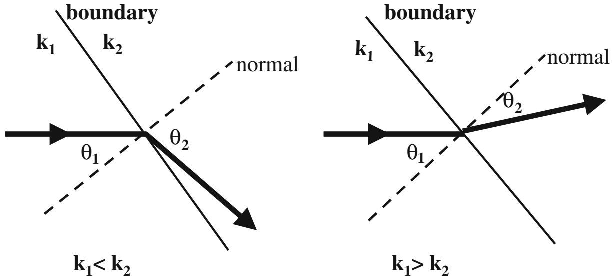

Fig. 1 Refraction of streamline when passing through a permeability boundary at an oblique angle, θ_1

(principle of conservation of matter), whereas for light, which travels in straight lines, it is $\sin\theta$ (Snell's law), so it does not change direction until it enters the second medium.

If $\theta_1 = 0$, then flow will go straight across the boundary; if $\theta_1 = 90°$ then flow will be parallel to the boundary and no fluid will cross it. If $0 < \theta_1 < 90°$, then the flowlines are oblique to the surface and the equipotential surfaces change direction abruptly and the streamlines are refracted according to this tangent rule, Fig. 1.

When k_2 tends to zero (flow from coarse to fine medium) then the streamlines will approach this now essentially impermeable boundary in such a way that the equipotential surface will terminate perpendicularly at the boundary and there will be no flow into the almost impermeable medium; whereas when k_2 tends to infinity (fine to coarse porous medium), all flowlines will terminate perpendicularly, and fluids flowing through to the more permeable rock will have streamlines nearly parallel with the interface (Bear 1972; Roti and Dawe 1993).

3 Experimental

Experimental studies were performed in specially designed visual models made with unconsolidated glass bead packs, having carefully controlled permeability heterogeneities and, in this study, water-wet beads, Fig. 2. The use of glass beads, coloured fluids and streamlines enabled the displacements to be followed visually and by video recording.

Figure 3 shows the general model used in this study which is very versatile. The ratio of permeability k_2/k_1 can be varied from zero to ∞, although in this study only the modest contrasts of 0.5 and 2 were examined; the angle of inclination α (NB α is the layer angle of inclination of the boundaries to some framework reference of the porous medium; θ is the angle of the flowlines with the normal to the boundary) can be varied over the whole range.

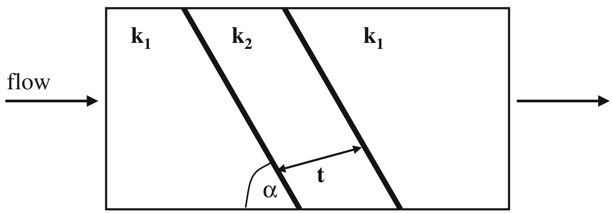

Fig. 2 The generalised stripe model. α is the stripe angle, t is the stripe thickness. The stripe can be placed anywhere within the model

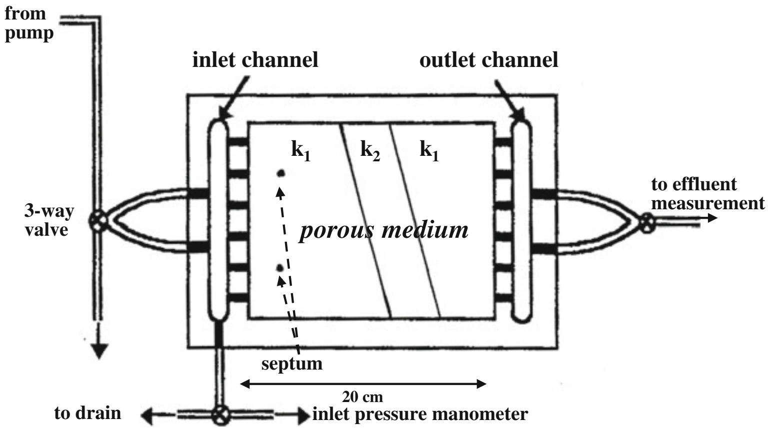

Fig. 3 Schematic of plan view of bead pack equipment

Zero θ represents the layer parallel to the flow, whilst 90° is perpendicular to the layer. The thickness of the interbedded layer, t, can be varied from zero to the whole model, but in this study was fixed at 15% of the length of the model. Also the layer length could be varied: across the whole model, as in this study, to a truncated fraction, which would then represent a lens, as in the study reported by McKean and Dawe (1990).

3.1 Experimental Set-Up

A two-dimensional, rectangular-shaped sealed Perspex box (20 × 10 × 0.6 cm) filled with Ballotini glass beads was used to carry out the flow studies. The details are given in Dawe and Grattoni (2008) but essentially two different sized beads (grade 6 = 640–750 µm and grade 9 = 310–425 µm, respectively) modelled the heterogeneity in terms of permeability contrast. Layered (Lambeth and Dawe 1987), lens (McKean and Dawe 1990) and quadrant (Dawe and Grattoni 2008) models have been presented elsewhere. In this article, we discuss the immiscible flow through 'striped' models, Figs. 2 and 3. Miscible flow within these models has been discussed by Roti and Dawe (1993).

During packing, very thin Perspex baffles were placed inside the bead pack box, at the desired inclination and spacing to separate zones of different permeability. The beads were poured into the models, which were vibrated at 100 Hz to help settle the beads and ensure a uniform packing. After dry packing and sealing the box, carbon dioxide was passed at low pressure through the packed bed to displace the air. Degassed water was then pumped into the bed, which displaced and absorbed the CO_2 (all aqueous fluids were degassed by vacuum or boiling before use). Some of the CO_2 was initially left trapped (bypassed) due to the heterogeneities, but with time this was totally absorbed by the flowing water. During the displacements, the fluids were pumped at a constant rate (between 0.05 and 6.0 ml/ min) by a dual piston pump (Altex A100) through suitable pipework and valves to the model. Schematic diagrams of the experimental setup are shown in Figs. 3 and 4.

The porosity of the glass beads was determined gravimetrically, the absolute permeability of the beads was determined by a falling head permeameter and the results are reported in Table 1. The pore volume for our standard model was approximately 48 ml. Oil/water systems were used for all the displacements, and the fluid properties are summarised in Table 2.

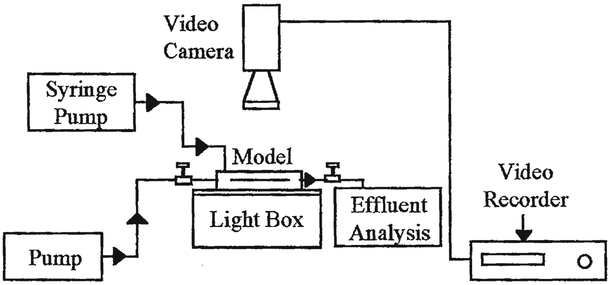

Fig. 4 Experimental set-up showing the streamline injection facility (Figure reproduced with kind permission of Springer Science and Business Media, Dawe and Grattoni 2008)

Table 1 Porous medium petrophysical properties

Porous medium	Bead size (μm)	Permeability (Darcy)	Porosity (%)
Ballotini grade 6	640–750	270	40 ± 2
Ballotini grade 9	310–425	110	40 ± 2

Table 2 Fluid properties at 20°C

Fluid	Density (g/cm^3)	Viscosity (cp)	Surface tension[a] (mN/m)	Interfacial tension[a] o/w (mN/m)
Oil (paraffin)	0.792	1.4	24.0	34.1
Water	1.0	1.0	71.1	

[a] Dyed fluids

As the density of the oil and water phases differed, immiscible displacements were conducted horizontally to minimise any influence of gravity.

Dye tracers were used for following the displacing and displaced phases. Streamline visualisation was obtained by injecting dye through septa in the top of the model (Fig. 3). These septa were made by drilling small holes into the top face of the model and filling them with self-sealing silastic rubber. Streamlines were created in some displacements by injecting dyed fluids through these septa. The dyes were chosen such that visual differentiation between the two phases and the streamlines was possible and a good contrast obtained. For water, we used Lissamine blue and red, and for oil Waxoline blue and red, obtained from ICI Chemicals. If there are wettability contrasts, then the displacements colours can become more difficult to resolve, as discussed in previous studies (Caruana and Dawe 1996; Caruana 1997; Dawe and Grattoni 2008). (From experience, methylene blue must not be used. It adsorbs strongly to both the glass and the Perspex and we could not find a way of removing the stain by solvent washing, so ruining the models for further use. However, a search of the literature showed that Bennett (1912) reported on experiments where glycerol bleaches methylene blue in bright light, such as leaving the mixture out in sunlight, or by adding acetaldehyde. This may be a rescue route for retaining the partial use of the model).

The displacements, Table 3, were observed by following the movements of the fluid, and the movement of the displacement front was recorded photographically and by sequence video recording. Immiscible displacements were continued to residual saturation, which was taken to be when less than 0.1 ml per 10 ml displaced fluid was in the effluent. During immiscible displacements, the volumes of effluent output were measured by a fluid separator and measuring cylinder. Saturations were estimated where possible by strength of colour. The injected streamlines have provided a novel technique of following individual particle flow

Table 3 Summary of the different experiments performed

Model	Permeability ratio	Injected fluid	
A. High permeability stripe	2.0	Water	Oil
B. Low permeability stripe	0.5	Water	Oil

during immiscible displacements and enabled the dynamics of flow to be better understood. It is interesting to note that after the displacement front had passed through the model, and the displaced phase became immobile the fluid streamlines reverted back to the path they took under miscible displacement conditions as shown in Roti and Dawe (1993).

Relative permeability end-points were measured by steady-state displacements, and capillary pressure curves for the water-wet glass beads by a modified porous plate method using air and water, (Caruana 1997). The wettability of the beads for these experiments was water-wet, and obtained by washing the beads in NaOH and HCl with copious rinsing in between, then drying them in an oven at 400°C.

Experimentally, we have had considerable difficulty in obtaining uniform initial saturations in our models because of the capillary pressure boundary effects, and in most cases the wetting phase (water) saturation was noticed to increase from model inlet to outlet end (capillary end effect). For instance, we were only able to get to connate water conditions for this type of displacement floods with experimental dexterity. Displacements at high injection rates were initially carried out, and due to increased viscous effects, a more uniform initial saturation was achieved before starting a low flow rate experimental run. However, we believe any gravity effects for immiscible experiments in our study were negligible from evidence from our study with CT scanning (Hove et al. 1995) and the thinness of the bead packs.

4 Results

The flow behaviour during water and oilflooding for immiscible displacements in striped models (cross-bedded systems), at low flow rates (<1 ml/ min or 2.4 m/day), is described in the following sections. The experiments performed are summarised in Table 3.

In Figs. 5, 6, 7, 8, 9, 10, 11 and 12, we present a demonstration photograph followed by four sequence drawings (for clarity) taken from the sequence photographs of each of the processes, waterflooding the high (k_1/k_2 of 2.0) and low (k_1/k_2 of 0.5) permeability stripes, and then oilflooding them.

4.1 High Permeability Stripe

Waterflooding was carried out in models filled with oil having water at irreducible saturation, whilst oilflooding was carried out in models filled with water having oil at irreducible saturation. Irreducible conditions were obtained by increasing the injection rate to 6 ml/ min (14.4 m/day) to increase viscous forces and establish an even initial water or oil saturation before the start of the next displacement.

4.1.1 Waterflooding (Figs. 5 and 6)

During waterflooding of the high permeability stripe model, the injected water entered the low permeability region and advanced within this region with a stable front, with displaced connate water moving ahead of it (determined visually using different coloured fluids), Fig. 6a. The low to high permeability boundary caused some restriction to the flow of water, whilst it enhanced the flow of oil, due to capillary pressure differences between the two permeability regions; the water phase pressure being lower in the low permeability region, Fig. 6b. Connate water leaked by film flow across the stripe boundary in this water-wet system, as shown by micromodel experiments (Dawe et al. 2010), whereas the injected water accumulated in the low permeability region upstream of the stripe.

The injected water entered the high permeability stripe only when the inlet water pressure was greater than the capillary pressure set-up by the boundary (Fig. 6c). The injected coloured water streamlines indicated that the water flowed through the stripe at an angle of around 90° to it, that is, through the shortest path. Significant movable oil was by-passed in the high permeability stripe at breakthrough (around 0.35 PV), whereas the low permeability regions were very efficiently swept, Fig. 6d.

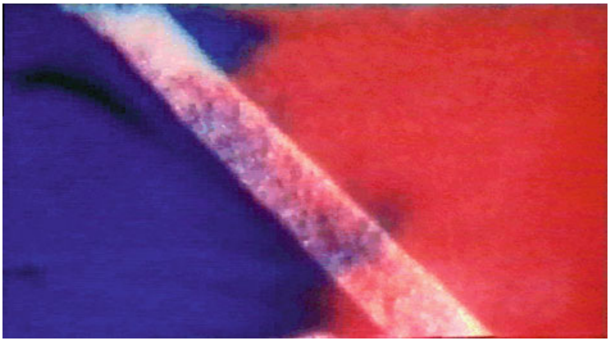

Fig. 5 Waterflooding the high permeability stripe model, *blue water* displacing clear paraffin. *Red* is connate water

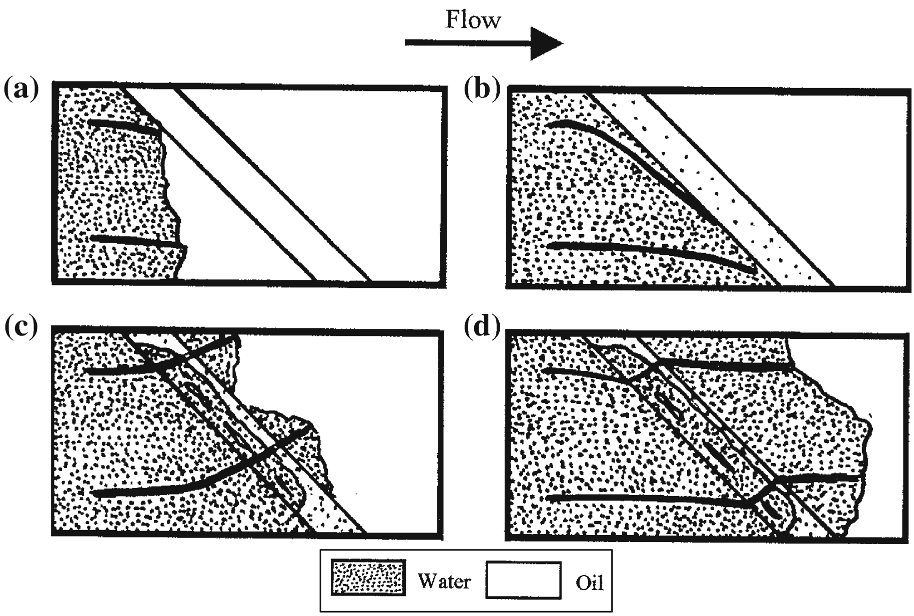

Fig. 6 Summary of waterflooding the high permeability stripe model

4.1.2 Oilflooding (Figs. 7 and 8)

During an oilflood in the presence of a high permeability stripe, the oil appeared to be sucked into the stripe. The oil displaced very little water from the low permeability region upstream of the stripe, Fig. 8a. No oil front was noticed and the oil entered the model as an unstable front, with one finger growing continuously until it reached the stripe, Fig. 8b. This was due to a lower oil phase pressure in the high permeability stripe. The injected oil coloured streamlines indicated that the oil took the shortest path to reach the stripe (Fig. 8c). The oil swept the high permeability stripe very efficiently and emerged in the region downstream of the stripe only after the stripe was filled with oil. At this point, the pressure increased to overcome the threshold pressure at the high to low permeability boundary (downstream), which was acting as a barrier to the flow of oil, but allowing the flow of water through it from the low permeability region at the inlet. Once the oil flowed out of the stripe, the pressure increased slightly to overcome capillary end effects at the outlet of the model (Fig. 8d), until

Fig. 7 Oilflooding the high permeability stripe model

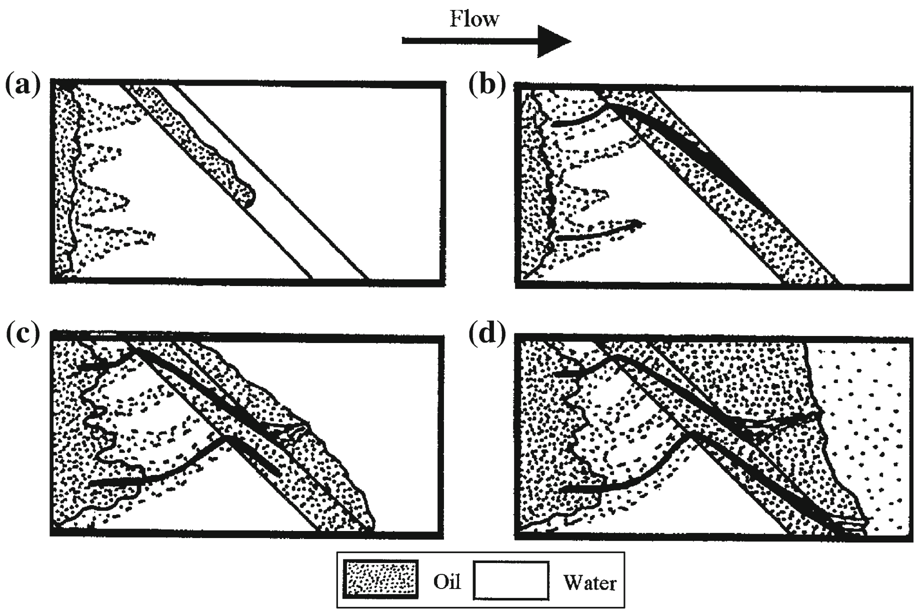

Fig. 8 Summary of oilflooding the high permeability stripe model

breakthrough was reached (0.45 PV) and the pressure remained fairly constant. At breakthrough, a large amount of water was by-passed in the low permeability region upstream of the stripe due to capillary pressure differences, whereas a high water saturation indicated by an increase in the colour intensity, remained at the outlet end of the model due to capillary end effects. These will be discussed in Sect. 5.4.

4.2 Low Permeability Stripe

4.2.1 Waterflooding (Figs. 9 and 10)

In the presence of a low permeability stripe, the water entered the high permeability region with an unstable front (Fig. 10a), and quickly moved towards the low permeability stripe due to a lower water phase pressure in the stripe, as shown in Fig. 10b. The water entered the stripe readily and displaced the oil from the stripe very efficiently (Fig. 10c). The coloured streamlines indicated that the water tried to remain in the low permeability stripe, and only when this was full, did the water emerge in the downstream high permeability region. The water moved as a front in this region and, at breakthrough, large patches of by-passed oil were

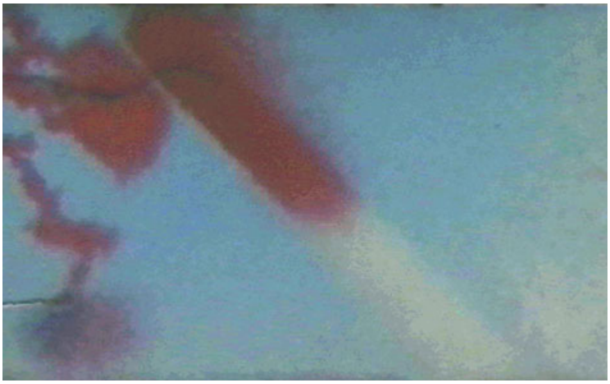

Fig. 9 Waterflooding the low permeability stripe model

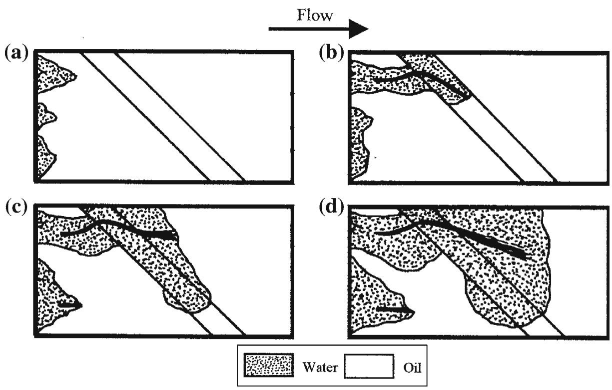

Fig. 10 Summary of waterflooding the low permeability stripe model

left in the high permeability region upstream of the stripe (Fig. 10d). Most of this by-passed oil was eventually produced.

4.2.2 *Oilflooding (Figs. 11 and 12)*

Figure 12 shows various stages of the displacement of water by oil in the presence of a low permeability stripe. In this case, the oil filled the high permeability region upstream of the stripe Fig. 12a), occurring at about 0.25 PV. When the oil displaced most of the water in this high permeability region, the pressure started to increase, as the high to low permeability boundary acted as a filter or capillary barrier letting through the water but temporarily halting the flow of oil, Fig. 12b. Since oil is the non-wetting phase, no leakage of oil occurred through film flow at the stripe boundary, and the system became permeable to only water. When the inlet high permeability region reached irreducible water saturation, the oil pressure increased sharply (Fig. 12c) to overcome the threshold pressure at the high to low permeability boundary.

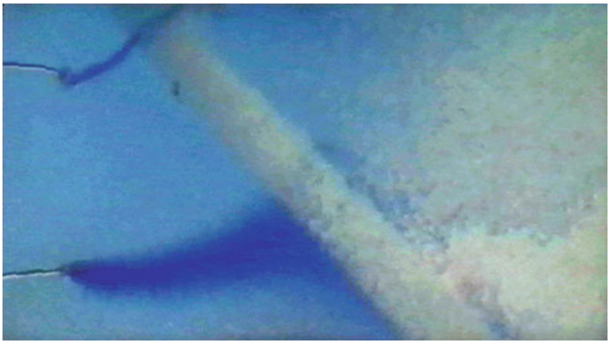

Fig. 11 Oilflooding the low permeability stripe model initially saturated with water

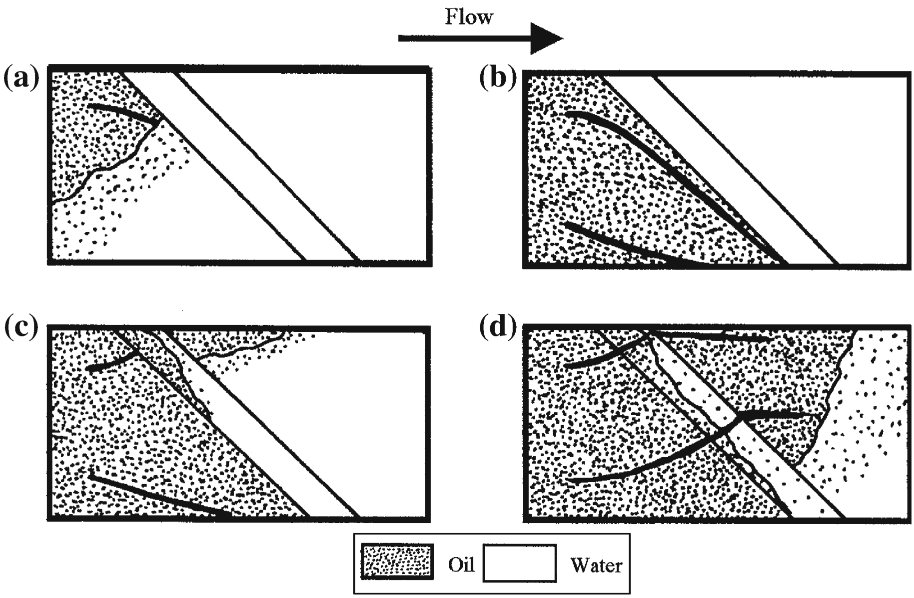

Fig. 12 Summary of oilflooding the low permeability stripe model initially saturated with water

Once the threshold capillary pressure at the boundary was overcome, the oil entered the stripe. At this stage, the injected coloured oil streamlines changed direction. The streamlines indicated that the oil took the shortest path through the stripe, that is, 90° to it. When breakthrough occurred at the outlet end of the model (Fig. 12d at about 0.65 PV), considerable amounts of water had been by-passed in the low permeability stripe. High water saturation was noticed at the outlet end of the model, due to end effects and indicated by an increase in the colour intensity.

4.3 Observations During the Displacements and Effluent Analysis

The stripe ensures non-uniform sweep of the model as can be readily seen from Figs. 5, 6, 7, 8, 9, 10, 11 and 12. One can make an overall estimate of the residual saturations (initial oil volume − produced oil volume divided by initial oil volume) but this is only an average value, it does not tell where the oil is or in what quantity is in each region, whether areas have been well swept or poorly swept or even by-passed. The colour of an area gives a qualitative estimate of the local oil saturation in that area, (Caruana 1997).

The effluent from our waterflooding and oilflooding displacements was recorded, (Caruana 1997). It must be remembered that the mechanisms governing drainage and imbibition are different. In a water-wet system, the water is located in the small pores and as a thin film on the surfaces, whereas the oil is located in the centres of the larger pores. Therefore, during a waterflood, oil is displaced from the larger pores, whilst during an oilflood water will be displaced but less effectively because of its locations, thereby making the latter process less efficient, leading to lower recoveries. There will also be by-passing of areas caused by preferential flow directions and capillary pressure differences between different permeability regions and the fluids.

During a waterflood, a high permeability stripe may cause very little loss in recovery when compared to the homogeneous case, as by-passing only occurs within the stripe, which in this study represents about 15% of the total pore volume. However, for a low permeability stripe model, we found significantly less recovery (20% less) as by-passing now takes place in the high permeability region upstream of the stripe which constituted 40% PV. Breakthrough recovery was also low as the water imbibed rapidly into the stripe due to a favourable water phase pressure, leaving bypassed oil in the high permeability region upstream. Most of the oil was eventually produced as discontinuous droplets giving rise to the slow increase of the recovery curve (Caruana 1997).

When oilflooding in water-wet porous media the presence of a low permeability stripe allowed the high permeability region upstream to be more efficiently swept than in a homogeneous model as the stripe acted as a partial barrier, however as the oil entered the stripe, water was by-passed and the ultimate recovery was slightly less than that of a homogeneous pack. On the other hand, recovery in the presence of a high permeability stripe was very low as water was by-passed in the low permeability areas and only the high permeability stripe was efficiently swept. Earlier breakthrough occurred, as the oil ‘fingers’ its way through the low permeability regions. These low recoveries are mainly due to capillary pressure boundary effects between different permeability regions, and also due to end effects, as can be observed in the figures.

5 Discussion

5.1 Imbibition and Drainage

In the case of the high permeability stripe water-wet model, connate water leaked by film flow across the stripe boundary. This reduced the barrier effect caused by the high permeability stripe. In the case of the low permeability stripe model no oil entered before the threshold pressure at the boundary had been overcome, as oil was now the non-wetting phase and no leakage occurred by film flow.

During water injection into the models, connate water displaced the oil, and that connate water itself was displaced by the injected water. The role of capillary pressure at permeability (and wettability) contrast boundaries was crucial, especially when connate water modified its potency, as it changed the flow characteristics (Dawe et al. 2010). During a waterflood under capillary dominated conditions a high permeability stripe (or an oil-wet stripe, Caruana and Dawe 1996) acted as a semi-permeable membrane, in that it allowed the flow of oil through, but temporarily halted the flow of water. A threshold capillary pressure had to be overcome at the boundary of the stripe before water entered the high permeability stripe. On the other hand, during an oilflood, the high permeability heterogeneity sucked the oil into it and caused earlier breakthrough.

5.2 Remaining Saturations and Effect of Injection Rate

In this study, the value of saturations were estimated at any location by visual inspection of the colour intensity inside the model. Higher residual oil saturations occurred in the high permeability region upstream of the low permeability stripe. This was due to capillary trapping caused by rapid water imbibition into the low permeability stripe, and the low upstream pressures that occur after breakthrough. On the other hand, following an oilflood, high water residual saturations occurred in the low permeability stripe upstream of the high permeability region, (residual saturations were estimated to be in most cases around 30%), Figs. 9, 10, 11 and 12.

In the high permeability stripe model, Figs. 5, 6, 7 and 8, an initial oil saturation caused displaced oil to enter the stripe before the oil displacement bank front had reached the stripe, whereas in a low permeability stripe model, the oil was noticed to flow into the low permeability stripe earlier when an initial saturation was present, that is, the threshold pressure at the boundary was lower. The presence of an initial oil saturation also caused the displacing oil to flow through a fine dendritic network of channels leaving previously by-passed regions unswept, whereas when no initial oil saturation was present the oil flowed as a fingered front. Capillary end effects were magnified in the presence of initial oil saturation.

Immiscible displacements are flow rate dependent because capillary forces dominate the flow at low flow rates (lower capillary number). Therefore, during a waterflood, a high water injection rate gives less time for imbibition at the heterogeneity interface, thereby reducing bypassing caused by capillary pressure differences between different permeability regions.

At sufficiently high flow rates, capillary effects on heterogeneities can be suppressed due to the increased viscous forces. Also, the effect of changing the mobility ratio could be studied experimentally using more viscous oil or viscosified water (e.g. adding glycerol) for the displacements.

5.3 Core Tests

The experimental studies carried out in this article and in previous studies (Caruana 1997; Caruana and Dawe 1996; Dawe and Grattoni 2008) have important implications for the interpretation of core floods, especially in the assessment of residual oil and relative permeabilities, and also for data input parameters for reservoir applications in grid block characterisation for numerical models, at both core plug and reservoir scales. If the core material is homogeneous, then these measurements of relative permeability could be representative, however, if the core contains heterogeneities, then the physics of displacement and flow is strongly affected by capillary forces, which are sensitive to the flooding rate, and the resulting data will be compromised.

The physics of flow must be identified within heterogeneous porous media (hopefully known heterogeneities), for instance, during a waterflood under capillary dominated conditions a high permeability stripe or an oil-wet stripe acted as a semi-permeable membrane, in that it allowed a flow of oil through but temporarily halted the flow of water. A threshold capillary pressure had to be overcome at the boundary of the stripe before water entered the high permeability or oil-wet stripe. On the other hand, during an oilflood, an oil-wet or high permeability heterogeneity sucked the oil into it and caused earlier breakthrough. Knowledge of these processes would help the core test interpretation.

On a reservoir scale, this has importance during the planning of infill wells. Such understanding of the effects of heterogeneities will ultimately lead to better predictions of reservoir performance with fewer failures in injection operations, as the adverse effects inherent in a heterogeneous system can be overcome by a better design of the injection operation.

We also found in some (aborted) runs, that even a few oil-wet beads (which had been accidentally placed) were sufficient to create a completely different flow pattern when compared to a homogeneous model, showing that the effects of even a small wettability change can be significant. Thus, heterogeneities at all scales must be considered when modelling and simulating reservoir behaviour.

Laboratory tests can use natural porous media (often specially selected ‘homogeneous’ samples) as well as reservoir fluids, but they are essentially ‘black box’ techniques giving only results on total inputs and outputs. Any interpretation of the data can be grossly distorted, often unknowingly, by artificial mixing, end effects or heterogeneities within the core. Parameters such as relative permeabilities and capillary pressures, derived from these interpretations are likely to be unreliable if heterogeneities are present within the core. Even when the distribution of heterogeneities is known the deconvolution to evaluate each relative permeability curve becomes extremely difficult. Furthermore, the methods of scaling these laboratory measurements for use in computer simulation of the reservoir behaviour will be uncertain, unless the physics is known and properly honoured.

The input and output data measurements taken in core test experiments are used to calculate the relative permeabilities to water and oil by standard methods, but must not neglect capillary pressure effects. In unsteady state core tests, the laboratory measurement of relative permeability is conducted under viscous dominated conditions as experiments are usually carried out at high rates, although Heaviside et al. (1983) carried out experiments at simulated reservoir rates, and then calculated the relative permeabilities from simulations that include capillary pressure. However, no reference is made to the internal structure of the core samples, which is usually assumed to be uniform and homogeneous (although CT scanning is showing this assumption to be false). As we have shown even the modest changes in rock permeability within a core give rise to distortions in displacement profiles and disperse the streamlines, and thereby change (usually lower) sweep efficiencies and recovery, and change effluent profiles. Such profiles are often used to determine relative permeabilites e.g. JBN or Buckley–Leveret methods (Bear 1972), so these calculated data are likely to be erroneous.

Failure to accept that the core has heterogeneities will give a totally misleading interpretation of the flood, and hence an incorrect characterisation of the porous medium. In reservoir simulators, the simulator codes must contain the correct physics, and in core analysis the effluent profiles must be correctly interpreted for sensible predictions. Thus the correct understanding is essential.

In summary, the interpretation of core tests where the inner heterogeneities are not known, or are not recognised, will usually be wrong.

5.4 End Effects

End effects were seen in our experiments as an increase in the colour intensity, particularly noticeable during oilflooding, at about 2 cm from the outlet end of the model. End effects occurred due to a discontinuity in the capillary pressure at the outflow face, as the water passes from a region of relatively high capillary pressure (the beads) into a void where the capillary pressure is zero, (Dawe et al. 2010). Capillarity in our beads (water-wet) tends to draw water into the beads from the void, which has to be overcome by the imposed pressure gradient.

5.5 Reservoir Simulation Needs

The physics used to represent the transmission of fluids from block to block during displacements must be correct in order that the reservoir simulation results do not lead to gross miscalculations and wrong recovery forecasts, (Dawe and Grattoni 2008). Even with the availability of high speed computers and numerical procedures to predict reservoir behaviour one must know what information about the reservoir is worth incorporating into the simulator, because CPU availability is not unlimited. Small-scale heterogeneities clearly have a significant effect on reservoir scale performance and therefore need to be incorporated into reservoir scale simulations, through the pseudo functions used for generating effective (relative) permeabilities and capillary pressure for grid blocks. This has been achieved in a number of model cases (Muggeridge et al. 2005). However, direct scaling of miscible and, particularly, immiscible displacements in physical models or core floods to larger dimensions e.g. reservoirs, may not be valid due to non-scaling of physical parameters.

Fine grid simulations can accurately predict the detailed flow behaviour observed experimentally, that is, for example, higher residual oil saturations remaining in the high permeability regions following a waterflood, and also predict breakthrough behaviour and recovery. However, such accurate modelling of such small-scale systems requires that the relative permeabilities and capillary pressures must be defined for each permeability and wettability region. The longer term aim of incorporating the flow characteristics caused by heterogeneities of the types described here into only a few grid blocks is still on the “wish-list”, as conventional scale-up techniques do not represent the physics of flow accurately, (Dawe and Grattoni 2008). How this will be solved is, as yet, a research topic still in its infancy.

Clearly for realistic reservoir simulation the structure of the reservoir needs to be known from the geologic interpretation point of view as well as the physics of the displacement. However, there are also the very real challenges of numerically modelling flow which is diagonal to the grid blocks in which there are permeability contrasts (Lambeth and Dawe 1988; McKean and Dawe 1990).

This study has shown that the geologic information needs to be known as well as the physics of displacement in such geometry and how it affects the flow and production profile.

5.6 Scaling

Our findings have huge implications for data input into grid block characterisation for numerical models, at both reservoir and core plug scales. This study directly models the effects of heterogeneities that occur both at the large core and the reservoir scale. In order to include the observed phenomena into a reservoir description, knowledge is required of the boundary conditions of the prototype and how to scale the results to the reservoir, or even core size, and where the boundary conditions may differ. The role of capillary pressure at permeability boundaries is crucial, especially if connate water modifies its potency. However, experimentally, it is difficult to isolate each effect so that individual and synergistic contributions can be fully evaluated.

There is also the very large problem of the real scaling rules. In order to apply the results obtained from laboratory models to field scale, it is necessary to correctly scale the physical constraints involved. This is usually by means of dimensionless groups for miscible and immiscible displacements, such as viscosity ratio, viscous/capillary ratio, gravity/capillary ratio and system ''shape'' ratios for immiscible displacements. Under certain conditions, it is possible to scale just those groups believed to most affect the processes occurring within the

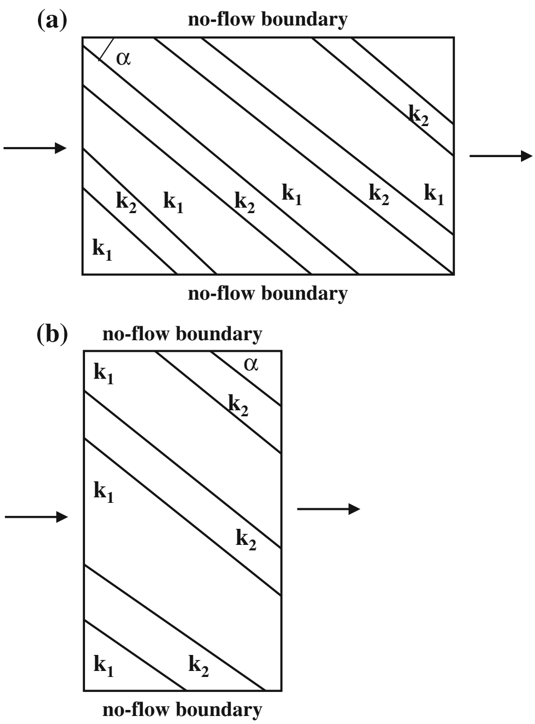

Fig. 13 The effect of boundaries on flow in a stripe model

system, (Ringrose et al. 1993; Huang et al. 1995; Muggeridge et al. 2002; Kortekaas 1985; Weber 1982).

However, there are other difficulties. An example of a heterogeneous core where the results cannot be immediately used is shown in Fig. 13. There will be different flow through the layers for cases Fig. 13a and for Fig. 13b and so their effective permeabilities will be different. The trivial case is where the layer permeability $k_1 = 0, k_2 \neq 0$. No flow is possible for set-up Fig. 13a, whilst flow will still occur for Fig. 13b. Nevertheless, provided these dangers are recognised, useful predictions can be made for displacements in heterogeneous systems.

6 Conclusions

- This article presents a visual study of the effects of small-scale cross-bedded permeability heterogeneities on the physics of flow under immiscible flow. Experiments have shown that even small variations in permeability can distort flow displacement patterns considerably.
- Fluid movements were visually observed using dyed displacing and displaced phases as well as injected streamlines, and the trapped oil or water could be located visually within the porous medium. Differences flow patterns exist between miscible and immiscible flow.
- During low rate immiscible displacements, capillary pressure effects complicate the displacements, particularly near heterogeneous boundaries, because they control the flow next to zones of different permeability (or wettability) where large saturation gradients can be created, and also at the ends of the porous medium (end effects). Capillary forces influence the saturation of swept zone and residual oil. The effects can be understood through the capillary pressure equation, which shows that during a waterflood the water phase pressure is lower in the low permeability regions, with the result that oil is left by-passed in the high permeability regions.
- For informed reservoir management decisions a full appreciation is needed of reservoir characterisation (e.g. cross-bedded heterogeneities) and the reservoir physics and its implications on recovery. These effects must be simulated and predicted to ensure accurate estimates of, particularly, water breakthrough in reservoir studies. These predictions then have to be validated. The data presented in this article provide benchmarks against which numerical simulators can be validated for these difficult flow problems for predictive modelling.

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