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# Viscous and Permeability Effects on Miscible Displacement in Heterogeneous Porous Media

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*Oil recovery from reservoirs requires an understanding of displacement flow through reservoir porous media. The fluids flow through the microscopic pores of the reservoir that make up the macroscopic reservoir system. Such systems are heterogeneous, particularly the permeability which can vary in any direction. These permeability variations affect the fluid displacement patterns, which in turn affect displacement efficiency. Visual models can display the displacement patterns. In this paper, we demonstrate a number of miscible displacement experiments in visual models of large core size, 20*10*0.6 cm, unconsolidated glass-bead packs having carefully controlled, but simple, permeability heterogeneities. Layered/striped/lensed/quadrant systems and miscible fluids having differing viscosities are illustrated in this paper. Our experimental visual evidence show that even small permeability heterogeneities within the reservoir can significantly affect displacement patterns. Thus, before core tests can be properly interpreted, the heterogeneity of the system needs to be known. Additionally, the displacement patterns can be used to validate the results obtained from numerical simulation, for identification of the physics of fluid flow and for engineers for scale-up to improve the design criteria for efficient recovery.*

***Keywords:*** Porous media, displacements, miscible flow, heterogeneity, cross flow, lens structure.

## 1. Introduction

Hydrocarbon reservoirs are complicated, geological, heterogeneous bodies; not the homogeneous porous blocks that are often imagined. Heterogeneity means that a property varies spatially. Well log and core analysis reports show that all reservoirs are heterogeneous with rock properties (porosity, permeability, saturation etc.) varying within the reservoir [1,2]. As we shall show, permeability heterogeneities cause variations in the fluid movements compared to the equivalent homogeneous system. Often, the effects of heterogeneities are generally not well-accounted for at the planning stage of an operation and only become evident when it may be too late and water has started to be produced before the predicted time [2].

Inside the reservoir, there can be miscible and/or immiscible flow, with one, two or sometimes three mobile phases (oil, gas and water) [3]. Miscible displacement occurs, for instance, when oil flows to the production wellbores from deep within the reservoir displacing the oil near the wellbore, or water moving within the aquifer. Oil can also move to the wellbore by immiscible displacement for instance, when the oil is displaced by water or gas [2]. There can also be mass transport across phase boundaries (e.g., gas from liquid

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to vapour in solution gas processes, liquid dropout from gas in condensate reservoirs, multi-contact processes in miscible gas enhanced oil recovery processes and transfer of chemicals such as in surfactant enhanced oil recovery). Additionally, there can be temperature changes with corresponding, physical changes as in thermal-enhanced, oil recovery and cooling during long-term waterflooding of a reservoir with cold water.

In this paper, we illustrate how the flow patterns in miscible, linear, isothermal displacements in slug flow in model heterogeneous permeability systems are modified by the heterogeneities, and discuss the implications for scale-up to reservoir scale. The physics of miscible, displacement flow is needed in order to:

- Understand the effects of heterogeneities and their boundaries on the displacement process,
- Aid interpretation of flood experiments in heterogeneous core material,
- Consider the implications for simulation of grid blocks containing known heterogeneities.

This is because:

- In reservoir simulators, the simulator codes must contain the correct physics. If a simulator can predict these model displacement patterns, then the simulator can be considered 'calibrated' and predictions may realistically predict the fluids flowing through the heterogeneous rocks. The physical processes occurring during oil and gas production must be properly represented by equations and correlations suitable for reservoir simulators.
- In core analysis, the effluent and pressure data of displacement experiments must be correctly interpreted for sensible reservoir applications and predictions. If the core is assumed homogeneous, and it is not, then no matter how clever the mathematical modelling is, it is simply modelling the wrong experiment! Or the wrong experiment has been carried out for the verification of the model.

## 2. Length Scales

Reservoirs must be considered at many length scales, ranging from the microscopic pores (1-1000$\mu m$), through the core (1-100 cm) to the reservoir (1-100 km). **(Figure 1)**.

The reservoir rock is a porous medium made up of pores conventionally envisaged as irregularly shaped holes in rock, some 1-100$\mu m$ in length and diameter connected to maybe six other pores - there can be some $10^6$ pores in 1 cc of rock and possibly over $10^{21}$ pores in a typical reservoir. Rock is sampled for the laboratory in cylindrical cores, some 3-10 cm in diameter and 10-1000 cm in length, but commercial reservoirs themselves are some 1-100 km in length, with wellbores often some 1-10 km apart. These different length scales can be observed in any cutting through a hillside or in a quarry. From a distance, one can see the heterogeneities; the many layers and undulating variations, but on moving closer, one can see smaller variations and a sample under a microscope can begin to reveal the variety in the pore shapes and size (**Figure 1**). Likewise, CAT (Computed Axial Tomography) scanning can show up the heterogeneities in real cores. The petroleum reservoir engineer has to have an appreciation of the different scales and how they affect reservoir behaviour and predictions.

## 3. Model Heterogeneities

For reservoir studies, the flow of fluids is affected by the heterogeneities. For reservoir engineers, geological variations themselves that do not affect or interfere with the flow pattern changes are not important. The heterogeneities can be permeability or wettability changes. In the work to be discussed here, only permeability heterogeneity effects on miscible displacement with varying viscosities will be considered. The effect of wettability on immiscible flow has been considered elsewhere [4,6].

Four geometries commonly occurring in natural, hydrocarbon reservoirs - layered, cross-bedded (striped), lensed and quadrant, **(Figure 2)** are the basic building blocks for studying reservoir heterogeneity. The layers can be parallel to linear flow or at an angle. For instance, the layer model represents typical,

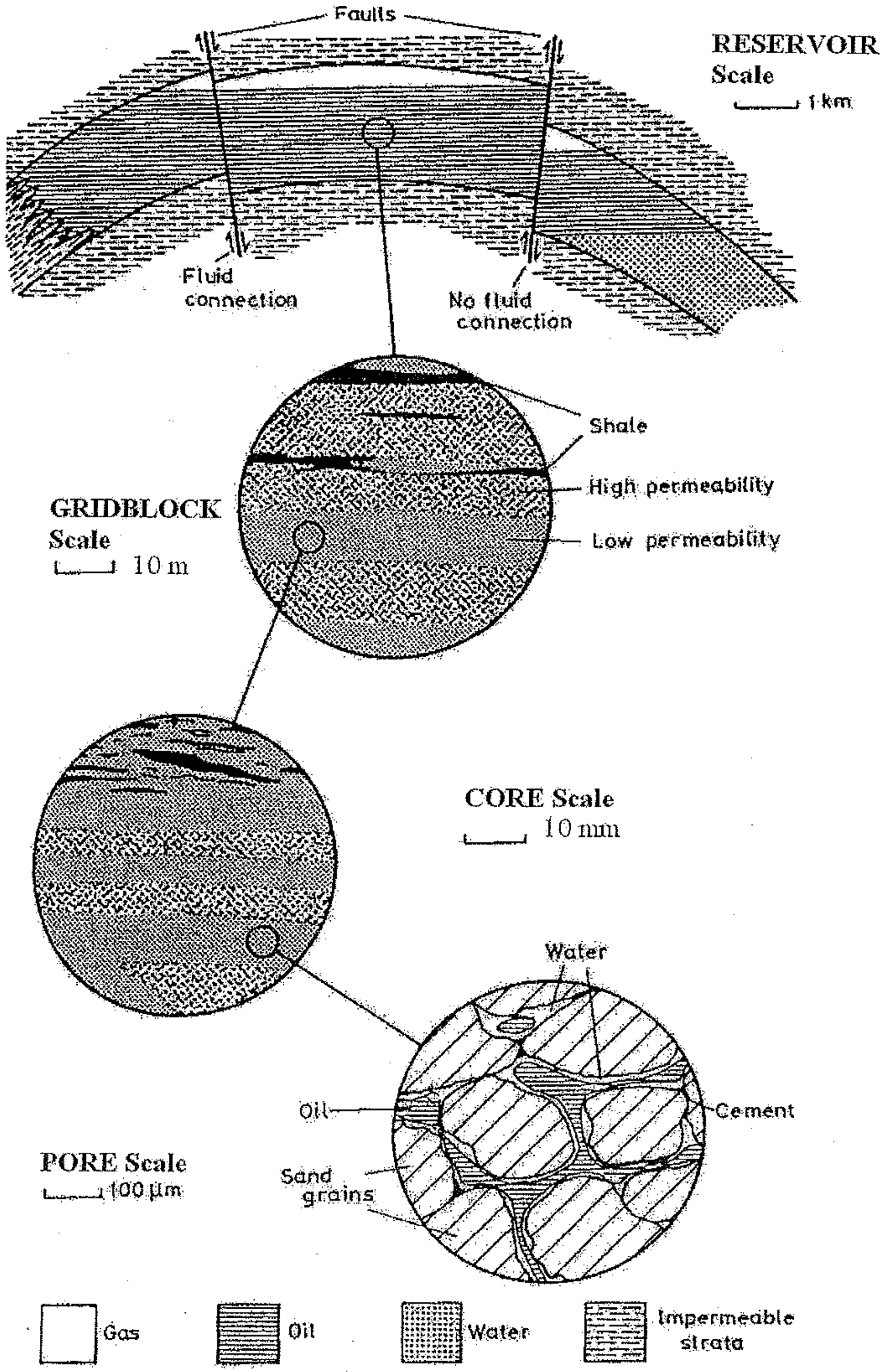

**FIGURE 1:** *Length Scales within the Reservoir*

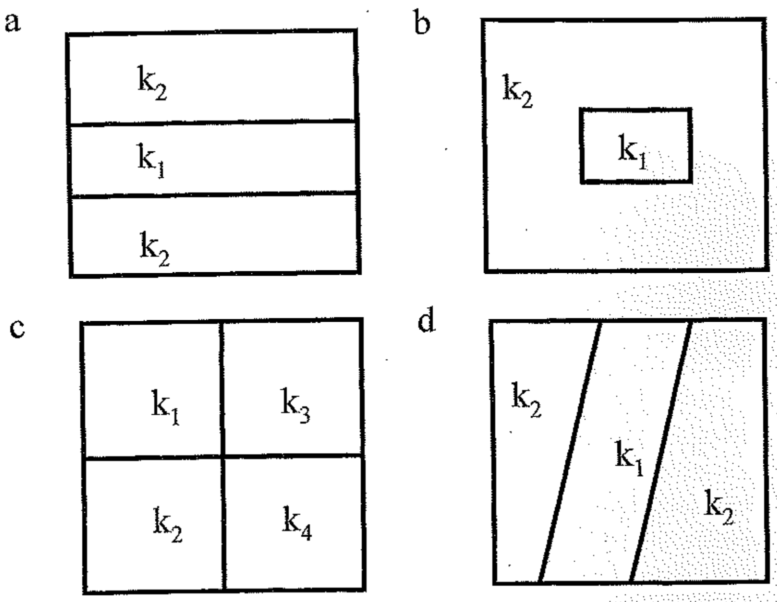

**FIGURE 2:** *Packing Patterns: (a) Layered Model (b) Lensed Model (c) Quadrant Model (d) Striped (cross-bedded) Model*

sedimentary layers, the stripe model represents cross-bedding, that is when the layers are not parallel to the flow direction and is a common sedimentary structure in sandstone reservoirs especially in fluvial deposits. Lenses are common core heterogeneities [6-9] and for modelling can be regarded as discontinuous layers. The quadrant model illustrates what might occur if layered systems were subject to faulting [9-11] and could represent sedimentary rocks containing patches of different permeability and wettability, as well as when cores are butted together as is sometimes done for long-core, flow tests.

The effects of layer-thickness, permeability contrast, angle of layer-to-flow direction, mobility ratio
and for immiscible displacements wettability and flood rate can be examined. Each of these parameters influences the displacement profiles and disperses the flood front. Such real effects must be considered in simulation studies or interpreting core tests. In this paper, we summarise by illustrations, the vast array of displacement patterns obtained from our model heterogeneities in miscible displacement and discuss their significance. The full individual experimental data are given in the cited literature [4-15].

## 4. Flow Definitions

In order to produce the hydrocarbons from the reservoir, there has to be flow of the fluids (oil and maybe gas and water) to the wellbores through the heterogeneous porous media of the reservoir. Fluid movements are governed by the local, fluid potential gradients and reservoir effective permeabilities, the injection and production points and the fluid viscosities.

The permeability of the porous media has to be determined experimentally and compared to a standard because the Navier-Stokes equation cannot be solved for porous media, except for the simplest of models. In petroleum reservoir engineering, flow through porous media is normally described by Darcy's law [16-18], where

$$Q = \frac{-k_a A}{\mu} \frac{\partial \varphi}{\partial l}$$

and $Q$ is the flowrate, $\mu$ the fluid viscosity, $A$ the cross-sectional area, $\partial \varphi / \partial l$ is the potential gradient, where the potential, $\varphi$ can be taken as $P + z\rho g$ where $z$ is a vertical distance from some datum plane, the $\rho$ fluid density, usually assumed constant, $g$ the acceleration due to gravity and $P$ the pressure. $k_a$ is termed the permeability and has the dimensions of length squared. $k_a$ is for a single fluid saturating the porous medium under laminar flow.

Darcy's law assumes that the fluid is a continuum and that there are no interactions between the fluid and the solid and that the porous medium is uniform for the particular element being considered. Care must be taken to ensure that everybody is meaning the same thing when talking about the permeability. Civil engineers use a different formulation of Darcy's law, particularly in groundwater hydraulic engineering and use head instead of pressure, $h = P / \rho g$, and the hydraulic conductivity (sometimes known as the seepage flow coefficient) where $C = k\rho g / \mu$. C has the dimensions of velocity [16]. Ultimately, the equations give the same results since we are determining flow rates against pressure.

The fluid potential gradient at any point, $\partial\varphi / \partial l$ is dependent upon the surrounding fluid distributions and originates from gravitational, capillary and viscous forces. The changes in potential gradients cause the fluid displacement patterns to become highly non-uniform and make the prediction of the displacement fronts uncertain, although often the baseline flow can be approximated to linear flow away from the well bore and radial flow close to the well bore. Flow vectors are frequently not parallel to the potential sources and sinks, causing cross flow and refraction effects. These effects are generally greatest where the fluid saturations, the viscosity contrasts and pressure gradients change most rapidly, such as at displacement fronts, transition zones of the displacing and displaced fluids and at boundaries (permeability or wettability). In this paper, we shall restrict ourselves solely to linear flow and permeability changes.

### 4.1 *Displacement*

For miscible displacement e.g., oil displacing oil, water displacing water or fluid movements in front of or behind an immiscible displacement front, the streamlines generally follow the permeability changes. If the viscosity of the initial and displacing fluids are different then, as discussed later, viscous effects are imposed on top of the heterogeneity effects. If the streamlines are not parallel to the heterogeneity, some interesting consequences can occur and the predictions can become difficult. As discussed elsewhere [3-7], interpretation of immiscible displacements is more problematic as not only are there permeability and viscous effects but also effects due to capillary forces, wettability and saturation which can become dominant. The saturation effects are particularly interesting as they are affected by pore scale wettability, which modify the relative permeability and capillary pressures, which themselves modify the displacement patterns.

### 4.2 Slug Flow

For hydrocarbon production, the hydrocarbons have to be pushed out of the reservoir by displacement, usually by expansion of rocks and fluids or by gas (gas cap expansion) or by water (aquifer encroachment) or by injected fluids (water or gas) [2, 18]. However, often the cost of materials dictates that any displacement fluid is injected in the form of a small volume, preferably much less than one pore volume followed by a cheaper chase fluid [13]. Such volumes are often referred to as 'slugs'; a typical sequence is schematically drawn in **Figure 3**.

The behaviour of each of the boundaries is governed by the reservoir characteristics mentioned above plus the fluid mobility ratio, *M* (the ratio of

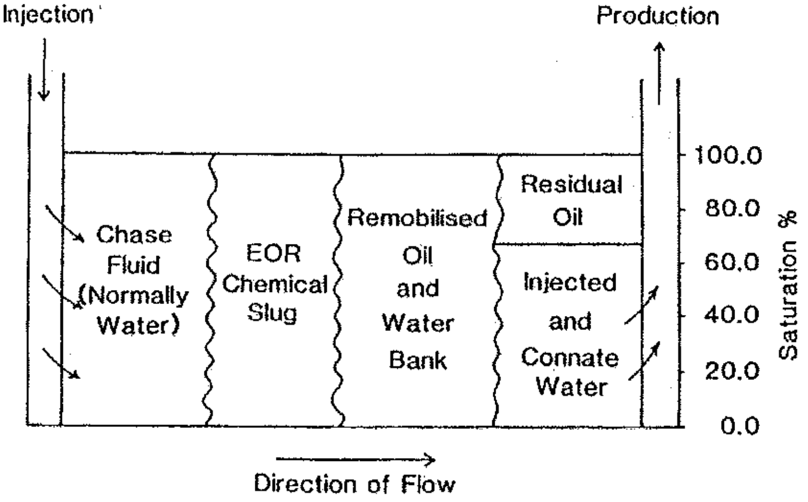

**FIGURE 3:** *Slug Mode EOR Process*

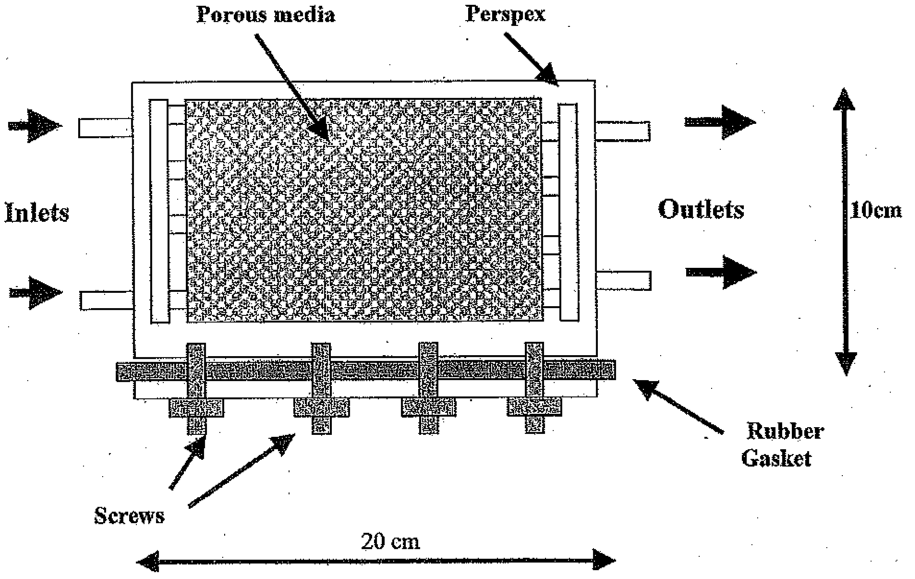

**FIGURE 4:** *Schematic of Experimental Apparatus*

mobilities of displacing (fluid 2) to displaced fluid (fluid 1)). Mobility is the effective permeability, $k_e$, divided by fluid viscosity, $M = k_{r2}\mu_1 / k_{r1}\mu_2$. For miscible processes, this simplifies to the viscosity ratio, $\mu_1/\mu$ as the permeability of the rock is the same to all phases in miscible situations.

A further complication is that because of viscosity differences, the slugs can have a different mobility ratio at the leading and trailing edges. The trailing edge contains the chase fluid (normally water), which has a low viscosity so there is usually a mobility ratio greater than unity, termed unfavourable, at this end of the slug (see **Section 5.2**), [13]. Many failed, field trial, enhanced, oil recovery are due to unfavourable mobility ratios combined with reservoir heterogeneity [13].

Any possible deleterious effects of heterogeneities and viscosity ratios on oil recovery must be effectively tackled through a good understanding of the physics.

## 5. Experimental

Our experiments are to provide visual evidence of the processes occurring within heterogeneous porous media. Here, we have used visual models with unconsolidated glass bead packs having carefully controlled permeability (but in other work wettability [4,5]) heterogeneities and miscible displacements with fluid viscosity variations [4 - 15].

A rectangular-shaped, sealed Perspex box (usually 20cm x 10 cm x 0.6cm) filled with glass beads was used to carry out the flow studies. Two different sized beads, Ballotini Grade 6 (640-750 mm) and Grade 9 (310-425 mm) model the heterogeneity effects in terms of permeability contrast. The main packing procedure was to place thin, cardboard baffles inside the 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 packing, 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 carbon dioxide (all aqueous fluids were degassed by vacuum before use). The fluids were pumped through the models at a constant rate (between 0.05 and 5.0 ml/min) by a piston pump (Altex) through suitable pipework and valves. A schematic diagram of the experimental setup is shown in **Figure 4**.

For miscible displacements, coloured fluid systems were used. In order to vary the mobility ratios, matched density aqueous solutions of sodium chloride and glycerol were made-up (matched density avoid any complicating effects due to density gradients). Slug displacements were performed by changing the injected fluid after the requisite fraction of pore volume had been injected into the model.

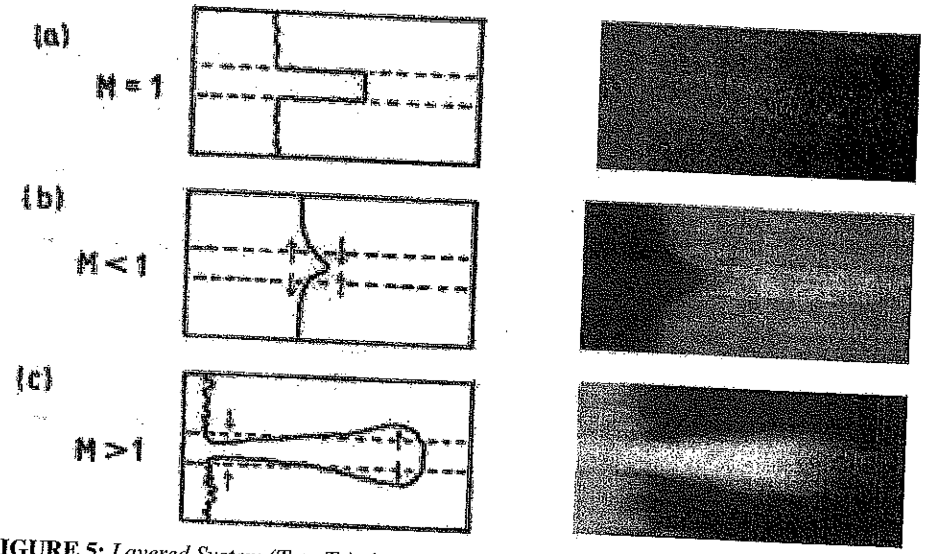

**FIGURE 5:** *Layered System ($T_A > T_B$) showing the Effect of Mobility Ratio on the Relative Frontal Advance, (a) M = 1, Equal Mobility Ratio Case. M > 1, (b) M < 1, Favourable Mobility Ratio Case. (c) Unfavourable Mobility Ratio Case*

The displacements were observed by following the movements of the fluid. The displacing and displaced phases were dyed. Streamlines tracers were created in some displacements by injecting dyed fluids through septa in the top of the model. The dyes were chosen such that visual differentiation between the two phases and the streamlines was possible and a good contrast obtained. The movement of the displacement front was recorded photographically and by sequence video-recording. During miscible displacements, the effluent output was analysed by a colorimeter and the volumes of effluent output were measured by measuring cylinder.

The porosity for both grades of beads was determined gravimetrically to be 40% ± 2%. The absolute permeability of the beads was measured by means of the falling head method and found to be 270 D and 110 D for the Grade 6 and Grade 9 beads respectively. The pore volume was approximately 48 ml.

## 6. Miscible Displacement Experiments in Layered Systems - Viscous Crossflow

### 6.1 Miscible Displacement

Consider the layered system of **Figure 5** with a central layer, *A*, being more permeable than the surrounding medium, *B*. If the conductance is defined as *T*, (the ratio of permeability *(k)* / porosity), then $T_A > T_B$ (unless the porosities are significantly different). Let miscible fluids be passed through these layers where fluid 1, of viscosity $\mu_1$, is displaced by fluid 2, of viscosity $\mu_2$.

Three cases of different mobility ratios ( $M = \mu_{1/}\mu_1$ ) can be identified:

(i) The displacing and displaced fluids are identical, $M = 1.0$. The displacement fluid will move at a relative rate equal to the conductance contrast, $T_A T_B$, (**Figure 5a**), i.e., essentially the ratio of permeabilities.

(ii) The displacing fluid ($\mu_2$) has a higher viscosity, M < 1.0, the so-called favourable mobility ratio case, when the fronts will move at a relative rate lower than (i) (**Figure 5b**). In this case, transverse pressure gradients cause the displacement boundary to be squeezed in at the front and widened at its base forming a characteristic cusp. However, the rate of channelling through the more permeable layer is reduced compared to the $M = 1$ case.

(iii) The displacing fluid is less viscous than the displaced fluid, $M > 1.0$ the unfavourable mobility case. A larger separation of frontal displacement position occurs (**Figure 5c**), which will lead to severe channelling in the high conductance layer and may cause relatively little fluid to enter the low conductance layer. Crossflow will swell the finger of the displacing fluid at its front and squeeze it at its base to form the characteristic bulbous shape. Viscous fingering will also occur although our experiments suggest that, although often considered important, it is a second order effect compared to the effect of heterogeneity permeability contrast.

## 6.2 Slug Displacement Analysis

Slug flow displacement experiments in layered systems show the significance of mobility ratio effects on slug stability. The slugs can break down during the flow through the layers if insufficient slug volume is injected (**Figure 6**). If the trailing edge of the slug's faster layer $X_{A2}$ overtakes the leading front of the slower layer, then the slug has essentially been divided into two portions. This slug breakdown is affected by the mobility of the initial, slug and chase fluids, at both the front and back slug boundaries. Dispersion can also occur across all boundaries [14]. Slugs larger than the pore volume have been estimated to be needed (up to perhaps three), which defeats in principle, the objective of slug injection. Recycling may be a solution. The effects at both ends of the slug must be considered and slug volumes may be required to be larger than expected. Viscosification promotes a flatter leading edge slug front but destabilises the rear of the slug. Nine different basic flow patterns can be identified as summarised in **Figure 7** [7, 9,12]. In particular, Patterns 2 and 6 are interesting. **Figure 8a** is essentially the favourable mobility displacement shown in **Figure 5b**, except that on closer examination, one finds further complications. In this

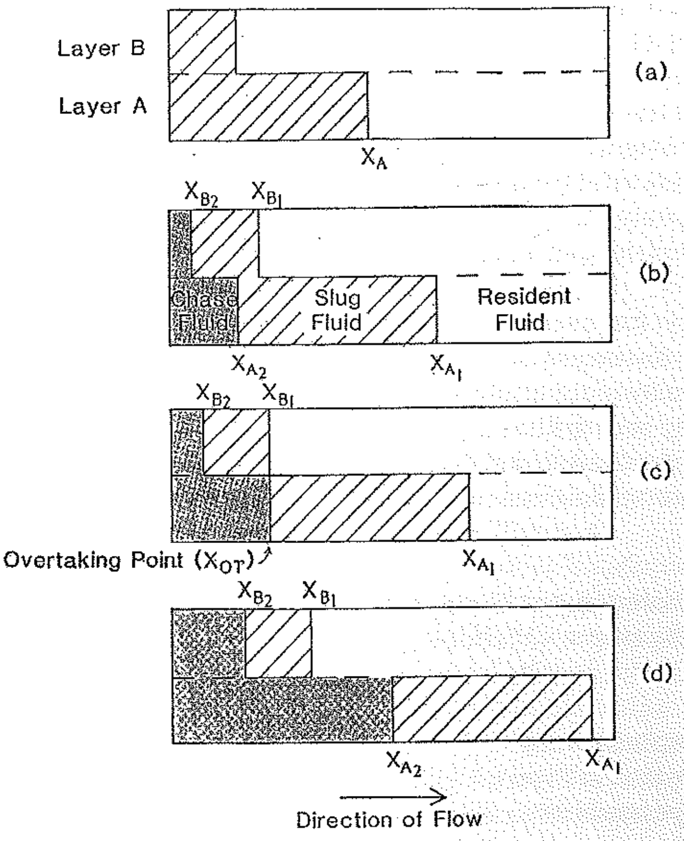

**FIGURE 6:** *Degradation of a Slug in a Layered System*

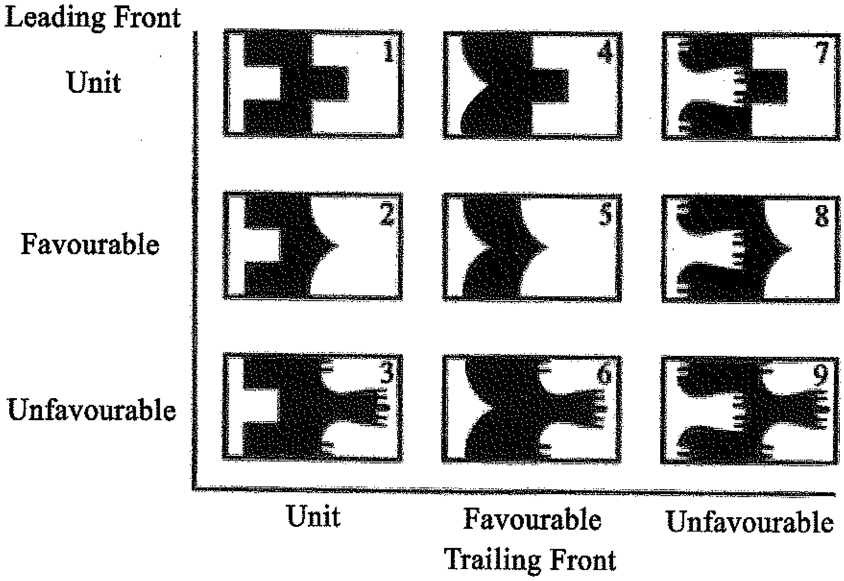

**FIGURE 7:** *Displacement Patterns through a High Permeability Layer caused by Viscous Cross Flow for a Slug having the Different Combinations of Fluid Mobility*

example, fluids 2 and 3 have the same mobility, but cross flow effects still occur within the system caused by the initial displacement disturbance due to the viscosity differences, so that the slug will breakdown. The chase fluid front will channel into the slug fluid in the high conductance layer even though the chase and slug fluids have the same mobility. Even though this is often thought to be a favourable slug mobility displacement, the slug can still be divided.

In **Figure 8b** which is pattern 6, fluids 2 and 3 have increasing viscosity; the slug, Section 2, will be forced by crossflow into the high conductivity central layer. One can see that the transverse pressures around the favourable front cause the chase fluid to cross flow out of the central layer, and the rear front to appear to have an unfavourable character. Although this effect decreases with increasing distance from the front, it is clear that small volume, chemical slugs are likely to deteriorate even under favourable mobility ratio conditions because of the porous media heterogeneity. Calculations show that as the viscosity of the slug fluid increases ( $M_{32}$ increasing), the slug size requirements is reduced but only to a certain level, as the two boundaries must be considered. Thus, viscosification may not be as effective as sometimes believed [13].

**Wright *et al.*** [13] used their experimental measurements and observations to derive a relationship between the relative displacement ratio in the layers, *U*, with the conductance (permeability/porosity) ratio of layers, *T*, and mobility ratio, *M* (which for miscible systems is the ratio of displaced to displacing fluid viscosity). Their convenient analytical expression for *U* is valid for layers of length/thickness aspect ratio greater than 10,

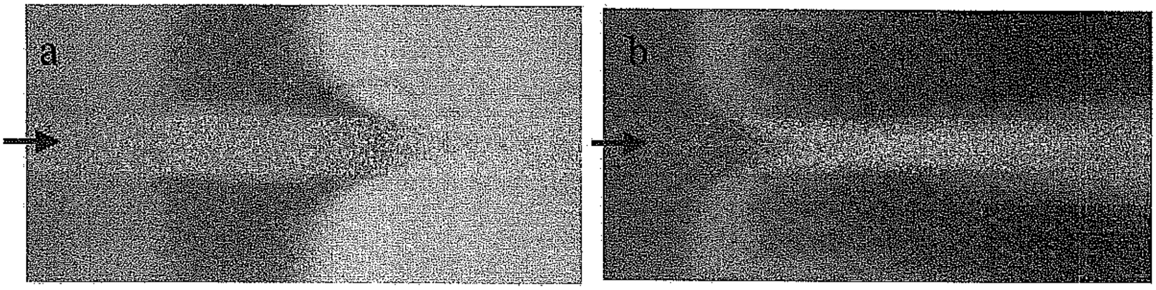

**FIGURE 8:** *(a) Pattern 2 at Slug Breakdown (b) Pattern 6*

$$U = T\left[(1 + A) / (1 / M + A)\right] > 1,$$

where

$$A = \left[(1 + T) / (1 + TM)\right]^{0.5}$$

$T$ can be determined directly from the $U$ value for the equiviscous displacement (M=1.0 case). Many practical situations approach these conditions, for instance, reservoir layers whose length is very great compared with their thickness, and which are not separated by shale beds. This correlation for $U$ which uses only $T$, fixed by the reservoir, and $M$, which can be varied by chemical additives, allows rapid screening of design options. When there are partial barriers to cross flow or low transverse permeabilities or where the layers are thick, more complex time dependent solutions are necessary [13]. The number of pore volumes needed to sweep the entire reservoir, $Q$, can be estimated if the frontal displacement rate in the low conductance layer can be evaluated after breakthrough has occurred in the high conductance layer.

$$Q = 1.0 + b\left[(1.0 - I / U)\right] U^{*},$$

where $U^{*} = TM\left(1/ M + Z^{*}\right) / \left(1+Z^{*}\right)$, and

$$Z^{*} = \left[(T + I / M) / T + 1.0)\right]^{-0.5},$$

and can be large when the conductance contrast and mobility ratio are large.

More detailed analysis [13] suggests that these studies using miscible systems will also model immiscible situations where viscous forces are dominant over capillary forces. Capillary forces are probably important only at the small scale, particularly the pore scale and maybe laboratory core tests. Therefore, capillary forces may often be regarded as negligible in reservoir structures of the order of 1 metre or more.

## 7. Miscible Displacement in Lensed Systems

The lens structure compared to the layered structure will cause additional streamline modifications, due to the permeability changes causing boundary effects both normal and parallel to the overall flow field. The parameters that now affect the displacement and recovery patterns include permeability contrast, length to width ratio and naturally, the position, number and distribution of the lenses, plus the fluid viscosity differences [8].

The displacements for a lens with a lower permeability for a miscible displacement with a mobility ratio of unity are shown in **Figure 9a**. The lens causes the interface to move around the lens trying to take the 'easier' path around it. **Figure 9b** shows the breakdown of a slug of fluid although at unit mobility, because the higher permeability encourages the fluid to flow faster through the lens. Tracer patterns for equal, favourable and unfavourable miscible mobility ratio fluids are shown in **Figure 10** for systems with lenses having higher conductance than the surrounding medium.

**McKean** and **Dawe** [8] studied miscible fluid displacement through a lens heterogeneity using a simulator and examined the effect of permeability contrast, fluid viscosity and lens size. These results show that a high or low permeability lens has significance for core test effluent profile interpretation.

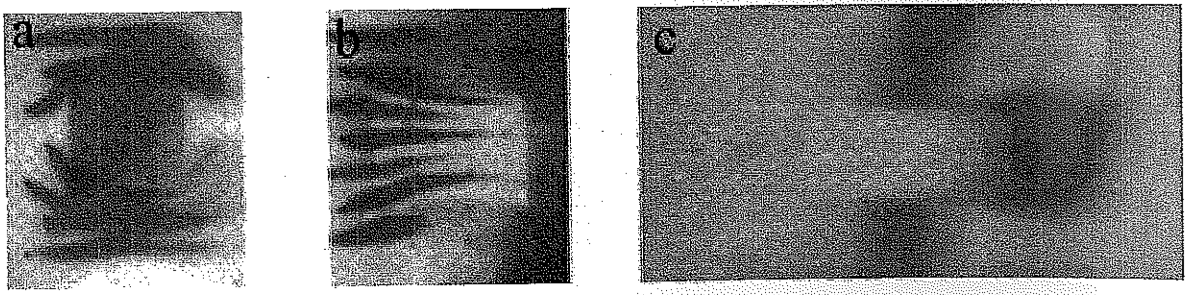

**FIGURE 9:** *(a) Streamlines flowing around a Low Permeability Lens*
*(b) Streamlines flowing through a High Permeability Lens*
*(c) Unit Mobility Slug Breakdown flowing through a High Permeabilty Lens*

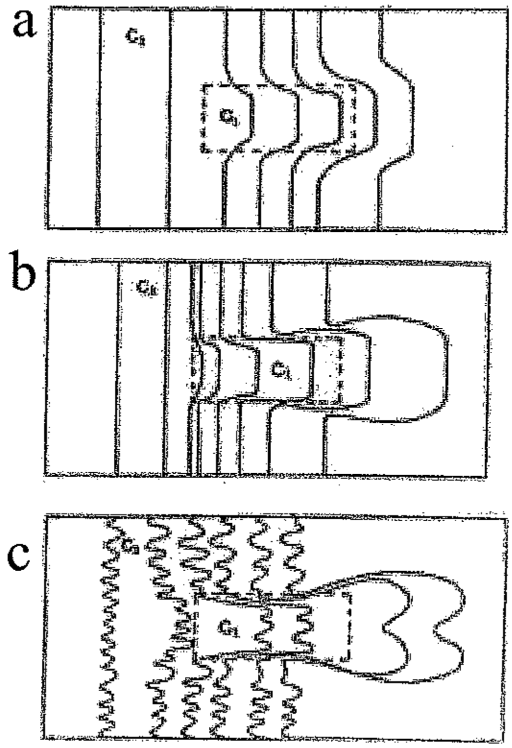

**FIGURE 10:** *Displacement Patterns in High Conductivity Lens Systems with a Mobility Ratio of (a) Favourable (M < 1) (b) Unity (c) Unfavourable (M > 1)*

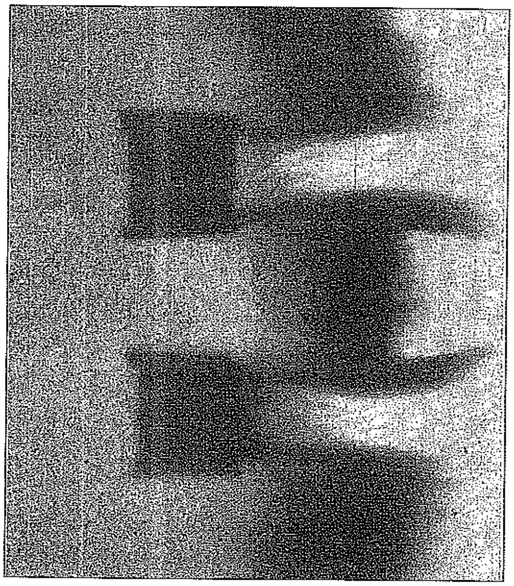

**FIGURE 11:** *Effect of Higher Permeability Patches on Displacement of a Slug of Dark Fluid. Each Patch further distorts the Displacement Front*

Simulation showed that as the permeability contrast ratio increased or decreased from unity, breakthrough sweep efficiency decreased, the size and position of the lens also has significant effect. Variations in the length of the lens altered the displacements more than the width, since the system became more like a layered system. Increased width tended to act increasingly as a permeability variation barrier.

Another difficulty is the effect of more than one heterogeneity. **Figure 11** shows a simple example. Clearly, the disturbances caused by one heterogeneity patch will affect the flow around and through the following patches.

## 8. Miscible Displacement in Quadrant Systems

The quadrant model is important for near well-bore flow, flow within faulted systems and in experiments where laminated cores have been butted together [7,10-12]. **Lambeth** and **Dawe** [10] carried out experimental and numerical studies for miscible displacements in the quadrant model and showed that even with modest conductance contrast (2.5), very early breakthrough occurs and sweep efficiency is poor.

A typical unit mobility displacement flood front pattern from their bead pack experiments is shown in **Figure 12**. The width and length of the tongue clearly will be dependent on the conductance contrast and for a given conductance contrast the tongue length and hence breakthrough time is proportional to the mobility ratio. **Figure 13** shows the various displacement patterns caused by viscous crossflow in a quadrant pattern having only two permeabilities as in **Figure 2c**.

**FIGURE 12:** *Unit Mobility Flood Pattern in a Quadrant Model with Quadrants 2 (bottom left) and 3 (top right) being 2.5 more Permeable, showing the Immense Distortion of the Front*

**Lambeth** and **Dawe** [10,12] also carried out numerical simulations to model the experimental observations in the quadrant model, using curvilinear grids to model the more complex cross flow processes that occur. When comparing the computed displacement front using standard Cartesian and curvilinear grids with the experimental data, they found that the form of the central finger was much more accurately modelled by use of the curvilinear grids, but is more expensive in terms of cpu time and so is not used in standard simulator packages because many iterations are needed for convergence criteria.

**Evans** and **Dawe** [11] carried out simulations on the radial quadrant model using a fine radial grid to model near-well bore conditions where the quadrant geometry is common. They considered two modes of flow which occur at distinct stages of petroleum production:

(a) The flow of a displacing fluid into the formation and its emplacement in the region around the well bore, and

(b) The flow of reservoir fluids from the formation and the route which they take in order to enter the well bore. They found that the presence of even small-scale heterogeneities in the near-well bore region can result in the profile of the invaded zone being significantly modified by the effects of nodal cross flow giving rise to a very different profile than for the homogeneous case. This would significantly affect placement profiles of any fluids injected into the formation, and such effects must be considered in the design and application of treatments to remedy or prevent formation damage.

## 9. Miscible Displacement in Cross-bedded Systems

**Roti** and **Dawe** [15] studied crossbedded systems in which the layers and flow are not parallel. The flow is grossly distorted by refraction and dispersion. Miscible displacements with unit and non-unit viscosity ratio were carried out and the streamlines and displacement fronts observed. The refraction equation

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

derived by **Bear** [16] and **King-Hubbert** [17] describes the flow of a single fluid from medium 1 of uniform permeability $k_1$ into medium 2 of permeability $k_2$ and $\theta_1$ and $\theta_2$ are the angles the respective flowlines make with the normal to the boundaries in mediums 1 and 2 respectively. The refraction in porous media superficially resembles the refraction of light as it transmits from one transparent medium to another, but in light theory, the refraction is proportional to sine the angle and the velocity of light (i.e. $sine\beta_1 / sine\beta_2 = vel_1 / vel_2$), rather than the permeability. The *sine* is needed because light travels in straight lines through the medium up to the boundary, whereas in porous media, the *tangent* is needed because the fluid streamlines bend to travel normal to the boundary. Unit viscosity ratio experiments confirmed the equation to within experimental precision.

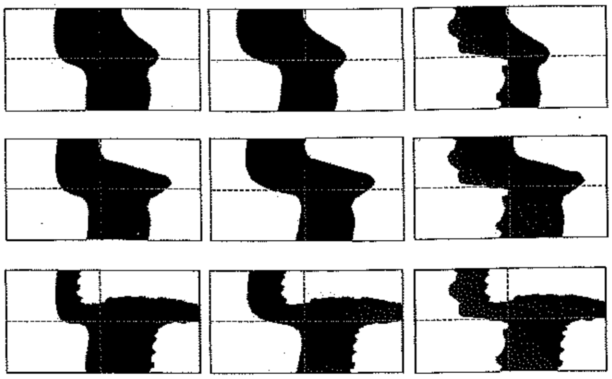

**FIGURE 13:** *Displacement Patterns caused by Viscous Crossflow for Slugs flowing through the Quadrant Model, where Quadrants 2 and 3 have Higher Permeability*

**Figure 14** shows unit mobility displacements with a permeability contrast of 2.5. In flow from a high to low permeabilities, the flow as seen by the streamlines try to remain in the more permeable medium and on crossing the interface are refracted to take the shortest path through the low permeability zone. For the low to high permeabilities case, the streamlines bent (refracted) to try to meet the interface normal to it (shortest path) and on entering the coarse medium, the streamlines changed direction to follow the lowest potential paths. On leaving the stripe and crossing into the exit zone, the fluid flowed in a linear fashion to the outlet and the streamlines gradually became less tangential and reverted to their original direction. Clearly, dispersion also occurs. Breakthrough at the exit in both cases was earlier than it would be in a homogeneous bed and the streamlines were strongly dispersed after passing through the boundary. This is of significance since, for instance, it may cause chemicals used in EOR to dilute rapidly.

Numerical simulation of these cross-bedded systems using current simulation packages is difficult because most simulators use rectangular-shaped grid-blocks in their finite difference solutions. The flow is assumed to pass perpendicularly out of these blocks into an adjacent block and not flow at an angle. To overcome this problem so that the resultant stepwise flow can appear to be diagonal, many blocks are needed to represent the stripes. Clearly, the effects of permeability contrast, viscosity ratio, stripe angle and thickness during miscible displacement in cross-bedded systems need to be investigated as each of these parameters influences the displacement performance.

## 10. Discussion on Scaling

### 10.1 Scaling Upwards

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. Reservoir heterogeneity is probably the most important reservoir parameter that affects the flow behaviour. For reservoir simulation, the geologic information needs to be incorporated effectively and efficiently into the functions used for generating effective relative permeabilities for grid blocks. This work models the flow phenomena of effects of typical heterogeneities during displacement that occur at the core scale. The implications of these findings are important for reservoir modelling data input parameters and scaling up for grid block characterisation for reservoirs.

The boundary conditions occurring in the model and how to scale the results to the reservoir size, where the boundary conditions may differ, need to be fully known. Unless the physics is known and properly honoured, the methods of scaling these laboratory measurements for use in computer simulation of the reservoir behaviour will be uncertain. Unfortunately, experimentally, it is very difficult to isolate each effect so that individual and synergistic contributions can be fully evaluated.

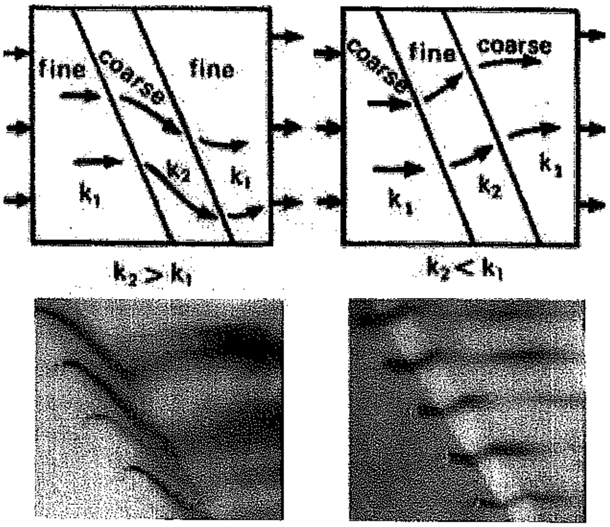

**FIGURE 14:** *Streamlines of Refracted Flow through Striped Media*

### 10.2 Core Scale Heterogeneity

In normal laboratory core tests, no reference is usually made to the internal structure of the core samples. The cores are usually assumed to be uniform and homogeneous (although CAT scanning is showing this assumption to be false). The input and output data measurements taken in core test experiments are used to calculate the permeability properties by standard methods which neglect capillary pressure effects if immiscible displacements are being used. Laboratory tests are essentially 'black box' techniques giving only results on total inputs and outputs.

If the core material is homogeneous, then these measurements could be representative of the core. However, if the core contains heterogeneities, then the physics of displacement and flow is strongly affected. Artificial mixing, end effects or heterogeneities within the core making any parameter derived from these interpretations unreliable and can grossly distort any interpretation of the data, often unknowingly. Failure to accept that the core has heterogeneities will give a totally erroneous interpretation of the flood and hence, an incorrect characterisation of the porous medium.

### 10.3 The Pore Scale - Scaling Down

The flow of fluids at the pore scale is fascinating to watch but the reservoir physics is challenging to interpret and scale. As mentioned in the introduction, there may be over $10^{21}$ pores in a reservoir, but scaling up from one pore to a reservoir is not as yet possible [3,19]. The position of fluids in the pore space will affect the ease of flow. This is currently passed onto the core scale through the relative permeabilities. If 3-phases are present and all have the potential to flow, the interpretation and prediction of flow becomes very complicated, but secondary recovery operations such as waterflooding and reservoir depressurisation and solution gas drive are strongly influenced. The values of the initial oil and swept zone residual oil saturation are essential commercial needs and have to be estimated [3,19].

### 10.4 Scaling Difficulty

There is another problem of scale-up where the results cannot be immediately scaled to simulate a larger medium. This is where the larger heterogeneous structure to be modelled has characteristic lengths greater than the short core, but has the same pattern. The trivial case is the layer permeability $k_1 = 0$, $k_2 \neq 0$. No flow is possible for setup (**Figure 15a**), while flow will still occur in setup (**Figure 15b**) even though it is the same pattern. Clearly, these dangers must be recognised before reliable predictions can be made for displacements in heterogeneous systems.

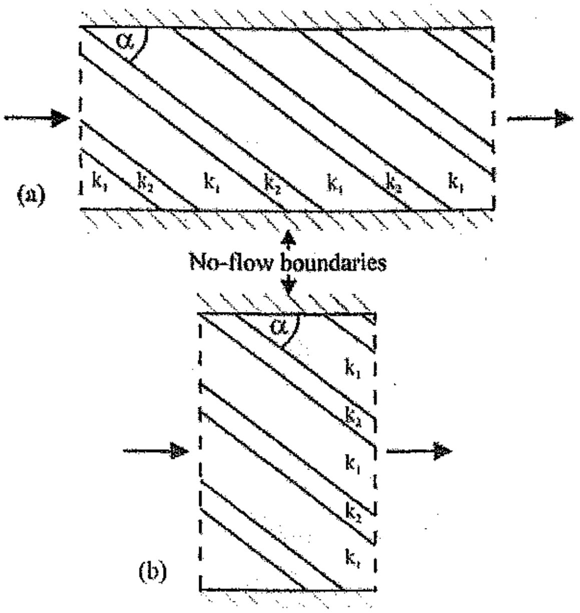

**FIGURE 15:** *Effect of Different Boundary Conditions for the Same Heterogeneity: (a) No Flow, (b) Flow*

## 11. Conclusions

- An understanding of the movement of fluids within heterogeneous porous media is fundamental to petroleum production and its efficient management. It is important for the correct interpretation of laboratory core data for the assessment of position and quantities oil and for reservoir simulation.

- Flow in heterogeneous porous media is different to that in homogeneous porous media and must be recognised when predicting breakthrough times.

- Heterogeneities in the form of layers, lenses, cross-beds and quadrants can have a profound effect on fluid displacement patterns. Even modest changes in rock permeability give rise to distortions in displacement profiles and disperse the streamlines and lower sweep efficiencies and recovery.

- Laboratory tests can use realistic 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 the heterogeneities within the core.

- If heterogeneities are present, derived parameters are likely to be unreliable as they are obtained from wrong interpretations.

- Mobility ratio is an important parameter during miscible displacement. Viscous cross flow and instabilities, (viscous fingering) in unfavourable mobility ratio cases occur and modify displacement patterns.

- Unless the physics representing the transmission of fluids from block to block is known and properly honoured, upscaling laboratory measurements to the grid block scale for use in computer simulation of the reservoir behaviour will be uncertain, with possible gross miscalculations and wrong recovery forecasts.

- Our model studies using miscible systems will model not only the miscible displacements but also immiscible situations where viscous forces are dominant over capillary forces. Such conditions are possibly approached in reservoir structures of the order of 1 metre or more, as capillary forces may sometimes be regarded as negligible at this scale.

- The reservoir model may not represent the real situation, even crudely because over-simplicity is needed to make the mathematics tractable or fit the CPU facilities available. However, if good petroleum geoscience and reservoir characterisation are available, plus a good understanding of how fluids can flow through such heterogeneities, then maybe the computer simulation will be able to represent and predict what might happen. Unfortunately, the current pragmatic situation is that many in the petroleum business (e.g., accountants, managers, shareholders, process and refinery personnel) only care about hydrocarbons producing at the wellhead! But how they flow to the wellbore is important for the reservoir engineer.

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