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**EFFECTS OF BUOYANCY FORCES ON IMMISCIBLE  
OIL/WATER DISPLACEMENTS IN POROUS MEDIA**

by

**Subramanian R. Thirunavu**

A thesis submitted to  
the School of Graduate Studies and Research  
in partial fulfilment of the requirements for the  
degree of Master of Applied Science  
in the  
Department of Chemical Engineering  
**UNIVERSITY OF OTTAWA**

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## Abstract

The effects of buoyancy forces on liquid-liquid displacement processes occurring in porous media are important in a variety of practical situations, in particular during the displacement of oil from partially-depleted underground reservoirs by means of aqueous solutions.

Most previous studies involving the visualization of water/oil displacements in porous media have been undertaken in horizontal two-dimensional porous medium cells. The objective of this work was to determine the effects of buoyancy forces on the fingering pattern and oil recovery by conducting immiscible displacement experiments in two-dimensional porous medium cells aligned in the vertical plane. A consolidated porous medium cell was utilized to perform the displacements, which permitted a wide range of experiments to be carried out within an identical porous medium.

In order to obtain a clear understanding of the effects of buoyancy forces (both favourable and unfavourable) experiments were carried out in three different modes, namely horizontal, vertical upward, and vertical downward. As the effects of buoyancy forces are almost negligible, in the horizontal mode, recoveries obtained in this mode are used as a reference and compared to those obtained in the other two modes. For the system studied in this work, as the displacing liquid in all cases had a higher density than the displaced liquid, buoyancy forces were always favourable in the vertical upward mode

and always unfavourable in the vertical downward mode.

The immiscible system employed consisted of heavy paraffin oil and glycerol solution as the displaced and displacing phases respectively. The viscosity ratio was varied by changing the concentration of the glycerol solution. Displacements with five different viscosity ratios were studied. Breakthrough time was measured and fractional oil recovery was calculated. The effects of buoyancy, viscous and capillary forces as well as the injection flow rate were also observed. The results obtained indicate that the buoyancy forces are highly effective at very low flow rates and low viscosity ratios (or high density ratios), and even with a slight increase in the flow rate, buoyancy forces lose their importance quickly.

## ACKNOWLEDGEMENTS

I would like to thank my research supervisor, Dr.G.Neale, for his guidance and the invaluable suggestions he offered during the course of the preparation of this thesis.

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# Contents

| <u>CHAPTER</u> |  | <u>PAGE</u> |
|----------------|--|-------------|
|                | Abstract .....                             | i           |
|                | Acknowledgement .....                      | iii         |
|                | Table of contents .....                    | iv-vii      |
|                | List of Tables .....                       | vii         |
|                | List of Figures .....                      | vii-ix      |
| <b>1</b>       | <b>Introduction</b>                        | <b>1</b>    |
| <b>2</b>       | <b>Literature Review</b>                   | <b>4</b>    |
| 2.1            | Stages of Oil Recovery .....               | 4           |
| 2.1.1          | Primary Oil Recovery .....                 | 4           |
| 2.1.2          | Secondary Oil Recovery .....               | 4           |
| 2.1.3          | Tertiary Oil Recovery .....                | 5           |
| 2.2            | Viscous Fingering .....                    | 7           |
| 2.2.1          | Mechanism of Viscous Fingering .....       | 7           |
| 2.2.2          | Historical Note on Viscous Fingering ..... | 9           |
| 2.3            | Immiscible Displacement .....              | 10          |
| 2.3.1          | Radial Displacement .....                  | 10          |
| 2.3.2          | Linear Displacement .....                  | 16          |
| 2.4            | Mathematical Simulations .....             | 22          |

|          |  |           |
|----------|--|-----------|
| 2.5      | Effect of Buoyancy Forces .....                  | 23        |
| <b>3</b> | <b>Theory</b>                                    | <b>28</b> |
| 3.1      | Driving Forces .....                             | 28        |
| 3.1.1    | Pressure Difference Forces .....                 | 28        |
| 3.1.2    | Viscous Forces .....                             | 28        |
| 3.1.3    | Capillary Forces .....                           | 29        |
| 3.1.4    | Buoyancy Forces .....                            | 30        |
| 3.1.5    | Inertial Forces .....                            | 30        |
| 3.2      | Definitions .....                                | 31        |
| 3.2.1    | Viscosity Ratio .....                            | 31        |
| 3.2.2    | Density Ratio .....                              | 31        |
| 3.2.3    | Interfacial Tension .....                        | 31        |
| 3.2.4    | Permeability .....                               | 32        |
| 3.2.5    | Porosity .....                                   | 33        |
| 3.2.6    | Wettability .....                                | 34        |
| 3.2.7    | Breakthrough and Breakthrough Oil Recovery ..... | 34        |
| 3.3      | Dimensional Analysis .....                       | 36        |
| <b>4</b> | <b>Experimental</b>                              | <b>39</b> |
| 4.1      | Experimental Set-Up .....                        | 39        |
| 4.1.1    | Cell Manufacturing .....                         | 39        |
| 4.1.2    | Properties of the Cell .....                     | 40        |
| 4.1.3    | Apparatus .....                                  | 40        |

|          |   |            |
|----------|---|------------|
| 4.1.4    | Specifications of the System . . . . .                | 41         |
| 4.2      | Experimental Method . . . . .                         | 43         |
| 4.2.1    | Saturation Process . . . . .                          | 43         |
| 4.2.2    | Displacement Process . . . . .                        | 43         |
| 4.2.3    | Cleaning and Drying Process . . . . .                 | 44         |
| 4.3      | Experiments Performed . . . . .                       | 45         |
| 4.3.1    | Preliminary Experiments . . . . .                     | 45         |
| 4.3.2    | Reproducibility Experiments . . . . .                 | 45         |
| 4.3.3    | Immiscible System Experiments . . . . .               | 48         |
| <b>5</b> | <b>Results and Discussion</b>                         | <b>50</b>  |
| 5.1      | Horizontal Displacement . . . . .                     | 48         |
| 5.1.1    | Effects of Flow Rate . . . . .                        | 50         |
| 5.1.2    | Effects of Viscosity Ratio . . . . .                  | 61         |
| 5.2      | Vertical Upward Displacement . . . . .                | 68         |
| 5.2.1    | Effects of Flow Rate . . . . .                        | 68         |
| 5.2.2    | Effects of Viscosity Ratio . . . . .                  | 78         |
| 5.3      | Vertical Downward Displacement . . . . .              | 84         |
| 5.3.1    | Effects of Flow Rate . . . . .                        | 84         |
| 5.3.2    | Effects of Viscosity Ratio . . . . .                  | 91         |
| 5.4      | Effects of Density Ratio in Different Modes . . . . . | 99         |
| <b>6</b> | <b>Conclusions</b>                                    | <b>110</b> |
| <b>7</b> | <b>Recommendations</b>                                | <b>112</b> |

|              |     |
|--------------|-----|
| NOMENCLATURE | 114 |
| BIBLIOGRAPHY | 116 |

## List of Tables

| <u>Table</u>  | <u>Page</u> |
|---|-------------|
| 4.1 Cell Properties .....   | 40          |
| 4.2 Specifications of the Systems Used .....                      | 41          |
| 4.3 Immiscible System Experiments .....                           | 48          |
| 5.1 Percentage Recoveries in Horizontal Displacement .....        | 52          |
| 5.2 Percentage Recoveries in Vertical Upward Displacement .....   | 70          |
| 5.3 Percentage Recoveries in Vertical Downward Displacement ..... | 86          |

## List of Figures

| <u>Figure</u>  | <u>Page</u> |
|--|-------------|
| 1.1 Typical fingering phenomena observed during the displacement of a higher viscous fluid by a less viscous fluid ( $\mu_{ratio} = 11.11$ ) ..... | 3           |
| 2.1 Patterns of well placement for water flooding .....  | 6           |
| 3.1 Wetting and non-wetting behaviours .....   | 35          |
| 4.1 Experimental set-up .....  | 42          |

|      |  |    |
|------|--|----|
| 4.2  | Homogeneity test . . . . .   | 46 |
| 4.3  | Reproducibility test . . . . .   | 47 |
| 5.1  | Breakthrough recovery as a function of flow rate, for displacements in the<br>horizontal mode . . . . .        | 51 |
| 5.2  | Effect of flow rate in horizontal mode displacements, $\mu_{\text{ratio}} = 143.5$ . . . . .                   | 54 |
| 5.3  | Effect of flow rate in horizontal mode displacements, $\mu_{\text{ratio}} = 11.11$ . . . . .                   | 55 |
| 5.4  | Effect of flow rate in horizontal mode displacements, $\mu_{\text{ratio}} = 1.72$ . . . . .                    | 56 |
| 5.5  | Effect of flow rate in horizontal mode displacements, $\mu_{\text{ratio}} = 1.72$ . . . . .                    | 59 |
| 5.6  | Effect of viscosity ratio in horizontal mode displacements, $Q = 0.91$ ml/hr . . . . .                         | 62 |
| 5.7  | Effect of viscosity ratio in horizontal mode displacements, $Q = 15.5$ ml/hr . . . . .                         | 64 |
| 5.8  | Effect of viscosity ratio in horizontal mode displacements, $Q = 107.5$ ml/hr . . . . .                        | 66 |
| 5.9  | Breakthrough recovery as a function of flow rate, for displacements in the<br>vertical upward mode . . . . .   | 69 |
| 5.10 | Effect of flow rate in vertical upward displacements, $\mu_{\text{ratio}} = 49.0$ . . . . .                    | 72 |
| 5.11 | Effect of flow rate in vertical upward displacements, $\mu_{\text{ratio}} = 3.3$ . . . . .                     | 74 |
| 5.12 | Effect of flow rate in vertical upward displacements, $\mu_{\text{ratio}} = 1.72$ . . . . .                    | 76 |
| 5.13 | Effect of flow rate in vertical upward displacements, $\mu_{\text{ratio}} = 1.72$ . . . . .                    | 77 |
| 5.14 | Effect of viscosity ratio in vertical upward displacements, $Q = 0.91$ ml/hr . . . . .                         | 80 |
| 5.15 | Effect of viscosity ratio in vertical upward displacements, $Q = 21.5$ ml/hr . . . . .                         | 82 |
| 5.16 | Effect of viscosity ratio in vertical upward displacements, $Q = 221.8$ ml/hr . . . . .                        | 83 |
| 5.17 | Breakthrough recovery as a function of flow rate, for displacements in the<br>vertical downward mode . . . . . | 87 |

|      |   |     |
|------|---|-----|
| 5.18 | Effect of flow rate in vertical downward displacements, $\mu_{\text{ratio}} = 143.5$ . . . .  | 88  |
| 5.19 | Effect of flow rate in vertical downward displacements, $\mu_{\text{ratio}} = 11.11$ . . . .  | 90  |
| 5.20 | Effect of flow rate in vertical downward displacements, $\mu_{\text{ratio}} = 1.72$ . . . . .   | 92  |
| 5.21 | Effect of flow rate in vertical downward displacements, $\mu_{\text{ratio}} = 1.72$ . . . . .   | 93  |
| 5.22 | Effect of viscosity ratio in vertical downward displacements, $Q = 0.91$ ml/hr  | 94  |
| 5.23 | Effect of viscosity ratio in vertical downward displacements, $Q = 15.5$ ml/hr  | 97  |
| 5.24 | Effect of viscosity ratio in vertical downward displacements, $Q = 168$ ml/hr   | 98  |
| 5.25 | Effect of flow mode variation for a high density ratio displacement . . . . .   | 100 |
| 5.26 | Effect of flow mode variation for a low density ratio displacement . . . . .  | 102 |
| 5.27 | Breakthrough recovery as a function of flow rate, for all the three modes,<br>at a low density ratio, $\rho_{\text{ratio}} = 1.228$ . . . . . | 104 |
| 5.28 | Breakthrough recovery as a function of flow rate, for all the three modes,<br>at a high density ratio, $\rho_{\text{ratio}} = 1.39$ . . . . . | 105 |
| 5.29 | Breakthrough recovery as a function of viscosity ratio, for all the three modes,<br>at a very high flow rate, $Q = 221.8$ ml/hr . . . . .     | 106 |
| 5.30 | Breakthrough recovery as a function of viscosity ratio, for all the three modes,<br>at an intermediate flow rate, $Q = 15.5$ ml/hr . . . . .  | 107 |
| 5.31 | Breakthrough recovery as a function of viscosity ratio, for all the three modes,<br>at a very low flow rate, $Q = 0.91$ ml/hr . . . . .       | 108 |

# Chapter 1

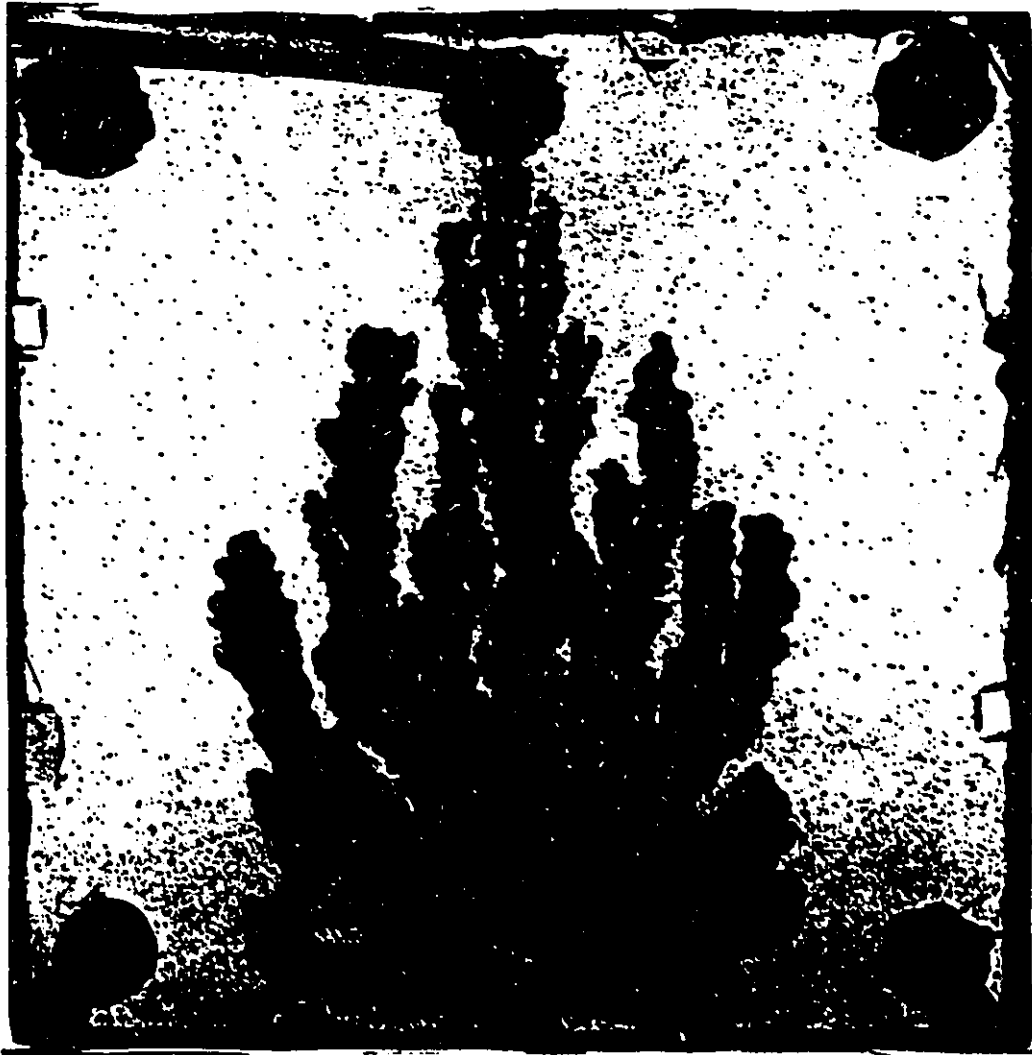
## Introduction

Oil reservoirs are volumes of porous rock containing a combination of oil, natural gas and water under pressure. When a well is initially drilled into the reservoir, natural forces tend to drive the oil to the surface. This is the "primary recovery" stage. In this stage the flow of oil through the reservoir rock to the well is caused by various natural forces 'stored' in the reservoir. When naturally occurring forces can no longer drive the oil to the producing wells, some form of artificial drive is introduced to supplement them. Water flooding is the most widely used artificial drive. The widespread application of water flooding has led to this process being referred to as "secondary recovery".

The immiscible displacement of one viscous fluid (oil) by another (water) within a porous medium forms the basis of most secondary recovery schemes. The objective of this work was to determine the effects of buoyancy forces on immiscible liquid-liquid displacements in porous media. A two-dimensional consolidated porous medium cell was utilized to perform the displacements, which permitted a wide range of experiments to be carried out within an identical porous medium. Displacements were performed with ten different flow rates ranging from 0.91 to 369.6 ml/hr and for five different viscosity ratios in the range of 1.72 to 143.5.

When a less viscous fluid (water) displaces a fluid of higher viscosity (oil), the fluid-fluid interface usually becomes unstable, and 'fingering' or 'channelling' occurs. This causes premature "breakthrough" of the displacing fluid and hence lower oil recovery. The fingering phenomenon is of considerable importance especially at very high viscosity ratios, as this causes a significant decrease in the amount of oil recovered before breakthrough. Figure 1.1 shows the fingering phenomenon occurring in a horizontal mode displacement.

One other important factor is the injection flow rate. The effects of flow rate depend on the mode of displacement. In this respect, horizontal and vertical downward displacements have similar characteristics. Both these modes have a "capillary region", a small "transition region" (in some cases) and a "viscous region". In the capillary region the percentage oil recovered increases with the flow rate, and the rate of increase depends on the viscosity and density ratios. The transition region is characterized by a constant oil recovery, while in the viscous region the oil recovery decreases with an increase in flow rate. In vertical upward displacement favourable buoyancy forces and unfavourable viscous forces act together. Thus, the displacement patterns are completely different and the results indicate that buoyancy forces are highly significant at very low flow rates.



**Figure 1.1 :** Typical fingering phenomena observed during the displacement of a higher viscous fluid by a less viscous fluid ( $\mu_{\text{ratio}} = 11.11$ ).  
Cell dimension : 154 x 154 x 2.8 mm

# **Chapter 2**

## **Literature Review**

### **2.1 Stages of Oil Recovery**

Production of oil from the reservoir follows three phases, namely

- . primary recovery
- . secondary recovery
- . tertiary recovery

#### **2.1.1 Primary Oil Recovery**

Petroleum occurs in nature within the pores of certain underground rock formations. Once an oil well has been drilled, a proportion of the oil originally in place flows naturally to the surface as a result of the very high pressure of the oil. This process is called "primary recovery". The most common primary recovery mechanisms are dissolved gas drive, gas cap drive and water drive (37).

#### **2.1.2 Secondary Oil Recovery**

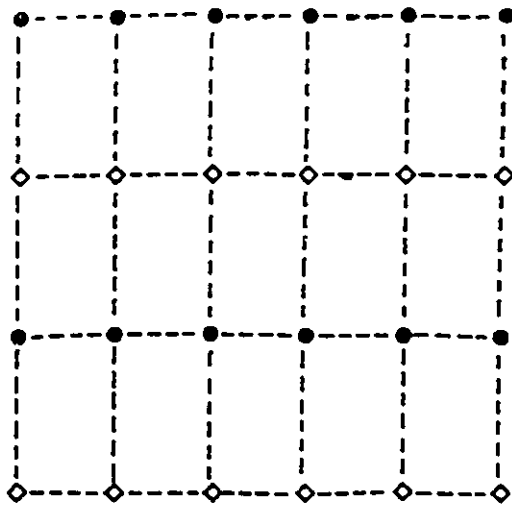
After the primary recovery stage, when the production of the oil is not spontaneous and the natural forces are no longer sufficient to drive the oil to the surface, some form of

artificial drive has to be introduced. Artificial drives include water or gas injection, but the most common method of secondary recovery is 'water flooding'. In a water flooding operation injection wells are drilled in a certain pattern around the production wells. Some typical patterns of well displacement are shown in Figure 2.1. The most common pattern is the "five-spot", which is actually a staggered line drive with the spacing between adjacent production wells and injection wells being the same.

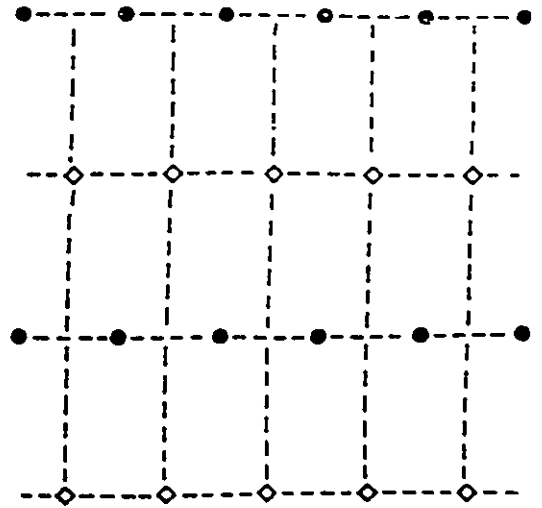
Secondary recovery techniques extract about 15 to 20% of the oil in the reservoir. Even after the secondary recovery 60 to 70% of the original oil in the reservoir is still unrecovered. This remaining oil can then be recovered by various other methods, collectively known as "tertiary recovery" techniques.

### **2.1.3 Tertiary Oil Recovery**

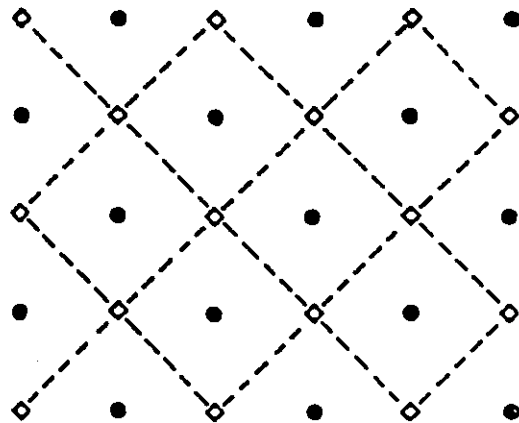
Tertiary recovery is any technique applied after secondary recovery (the term 'enhanced oil recovery', EOR, includes both secondary and tertiary recovery processes). The three major types of tertiary recovery operations arise from chemical processes, miscible displacement processes and thermal processes. The optimum application of each type is dependent upon the individual reservoir characteristics.



DIRECT LINE DRIVE



STAGGERED LINE DRIVE



FIVE-SPOT

- PRODUCTION WELL
- ◇ INJECTION WELL
- PATTERN BOUNDARY

**Figure 2.1 :** Patterns of well placement for waterflooding in oil wells

## 2.2 Viscous Fingering

Viscous fingering in porous media has been extensively studied in the past. This phenomenon has a very significant practical importance in the recovery of oil. When oil is displaced from a porous medium by water, having a viscosity lower than the oil, the oil-water interface is essentially unstable and has a tendency to break up into what are called "fingers" or "streamers". This fingering phenomena results in premature breakthrough of the less viscous displacing fluid and consequently a lower overall recovery.

### 2.2.1 Mechanisms of Viscous Fingering

"Viscous fingering" generally refers to the onset and evolution of instabilities that occur in the displacement of fluids in porous materials. In most but not all cases, the mechanism of instability is intimately linked to viscosity variations between phases or within a single phase containing a solute - hence the term "viscous fingering".

An excellent review of viscous fingering mechanisms in both porous media and Hele-Shaw cells has been given by Homsy (1). If we consider a displacement in a homogeneous porous medium, characterised by a constant permeability  $K$ , the flow will typically involve the displacement of a fluid of viscosity  $\mu_1$  and density  $\rho_1$  by a second fluid of viscosity  $\mu_2$  and density  $\rho_2$ . These differences in physical properties may result from using two different, immiscible phases, or from injection of a solvent fully miscible with fluid 1. It is the *variation* of these properties across some front that is important.

Homsy explains the basic mechanism of the instability as follows. Under suitable continuum assumptions, the flow may be taken to satisfy Darcy's law, which for a one-dimensional steady flow may be written as

$$\frac{dp}{dx} = \frac{-\mu U}{K} + \rho g \quad (1)$$

Now, if we consider a sharp interface or zone where density, viscosity, and solute concentration all change rapidly, then the pressure force ( $p_2 - p_1$ ) on the displaced fluid as a result of a virtual displacement  $\delta x$  of the interface from its simple convected location is

$$\delta p = p_2 - p_1 = \left[ \frac{(\mu_1 - \mu_2) U}{K} + (\rho_2 - \rho_1) g \right] \delta x \quad (2)$$

If the net pressure force is positive, then any small displacement will amplify, leading to an instability. This explains how a combination of unfavourable density and/or viscosity ratios and flow direction can conspire to render the displacement unstable. For example, for downward vertical displacement of a dense viscous fluid by a lighter, less viscous one, we have

$$(\mu_1 - \mu_2) > 0, \quad (\rho_2 - \rho_1) < 0, \quad U > 0.$$

Thus, gravity is a stabilizing force, while viscous forces are destabilising, leading to a critical velocity  $U_c$  above which there is instability (1):

$$U_c = \frac{(\rho_1 - \rho_2) g K}{(\mu_1 - \mu_2)} \quad (3)$$

Extending this argument there are three other obvious cases depending upon the signs of  $\Delta\rho$ ,  $U$  and  $\Delta\mu$  : one in which gravity drives the instability and viscosity stabilizes it, and the two cases in which both basic forces are either stabilizing or destabilizing.

When the gravity force is absent, as in a horizontal displacement, a simpler system is observed. In this case, the instability *always* results when a more viscous fluid is displaced by a less viscous one, since the less viscous fluid has the greater mobility (mobility is defined as the ratio of effective permeability to viscosity). Thus, we see that the two basic forces responsible for the instability are gravity and viscosity. Previous works on immiscible displacement also show that the surface tension can modify but not stabilize a flow characterised as unstable by this simple criterion.

### **2.2.2 Historical Note on Viscous Fingering**

It is interesting to trace the literature in order to establish priority for the discovery and understanding of viscous fingering, in terms of the fluid mechanics involved. Despite the fact that this instability is discussed in many fluid-mechanics textbooks and literature papers as the "Saffman-Taylor Instability" and is attributed to Saffman and Taylor (2), the phenomenon had been noted and recorded in many earlier works, although not always with a clear understanding of the mechanics and the basic mechanisms.

According to Homsy (1), the first scientific study of viscous fingering can reasonably be attributed to Hill (3), who not only published a simple "one-dimensional" stability

analysis, but also conducted a series of careful and quantitative experiments to verify it.

## **2.3 Immiscible Displacement**

Immiscible displacement forms the basis of most secondary recovery operations, and hence a considerable amount of both theoretical and experimental studies have been done in this field. Previous work in immiscible displacement can be classified into two main groups, namely radial displacement and linear displacement. In both radial and linear displacements, experiments have been conducted with Hele-Shaw cells, 2-D porous medium cells and 3-D porous medium cells. The main disadvantage in using three-dimensional porous medium cells is that they are not generally amenable to visual observation of the frontal instabilities. Also, in the case of porous medium cells, both consolidated and unconsolidated media have been used. Consolidated porous media possess the inherent advantage that the constituent particles are rigidly fixed and cannot migrate during the displacement process, thereby permitting a wide range of experiments to be carried out within an identical porous medium.

### **2.3.1 Radial Displacement**

#### **Hele-Shaw cell**

The Hele-Shaw cell is a device for investigating two-dimensional flow in porous media (1). It is based on the similarity between the differential equations governing saturated flow in a porous medium and those describing the flow of a viscous fluid in a narrow space between two parallel plates. In practice, when fluids are injected into the ground,

they are injected through a well which, in effect, is a point source and at least initially the displacement is in the radial direction. Based on this argument, Paterson argues that the radial model is more appropriate to practical situations than the linear displacement model. He also performed a detailed study on radial fingering in a Hele-Shaw cell (4). He examined the width of the fingers, and proposed an approximate equation for the growth of the fingers. His net result was, when the circumference of the injected 'bubble' is less than the critical wavelength, the displacement is stable and the interface remains a circle centred on the injection point, but once the circumference becomes greater than the wavelength, then fingers are able to grow. He also showed that the equation

$$r^{\alpha} = \cos(n\theta) \quad (4)$$

fits the shape of long fingers.

### Porous Media

An elaborate study of radial fingering in porous media was conducted by Ni et al (5), who extended the theory of immiscible radial displacement in a Hele-Shaw cell to the case of a porous medium contained between two closely spaced parallel plates. The principal difference between the two systems is that in the Hele-Shaw cell the displacing fluid occupies the entire cross-section of the cell and can therefore be treated as a two-dimensional system, whereas in a porous medium the fingers, being three-dimensional, do not generally occupy the entire cross section. This creates particular difficulties when attempting to calculate the mean-pore velocity in the fingers since their exact cross-

sectional areas are unknown. However, in their study, Ni et al (5)., considered that if the plate separation is small enough then it is reasonable to assume that the fingers in the porous medium occupy the entire cross-section and, further, that they can be treated as two-dimensional. Another difficulty encountered when extending the Hele-Shaw cell theory to a porous medium concerns the boundary condition involving pressure at the interface between the two fluids, and arises as a consequence of the use of macroscopic equations and boundary conditions to describe interfacial effects which inherently take place at the microscopic level. For slow viscous flow (i.e., with negligible inertial effects), the pressure discontinuity across the continuous interface in a Hele-Shaw cell is given by the classical Laplace expression

$$P_1 - P_2 = \gamma \left[ \frac{1}{r} + \frac{2}{h} \right] \quad (5)$$

where  $r$  denotes the principal radius of curvature of the finger tips (in the plane of the plates) and  $h$  is the plate separation. In the case of a porous medium, Ni et al., followed Chouke et al (6)., and employed the analogous macroscopic equation :

$$P_1 - P_2 = \gamma^* \left( \frac{1}{r} + \frac{1}{r'} \right) \quad (6)$$

where  $\gamma^*$  represents a macroscopic or effective interfacial tension, and  $r$ ,  $r'$  represent the principal radii of curvature of the finger tips.  $\gamma^*$  is also customarily assumed to be directly proportional to the actual interfacial tension  $\gamma$  and their relation can be expressed as

$$\gamma^* = C^* \gamma \quad (7)$$

where  $C^*$  is an empirical parameter known as the wettability number.  $C^*$  is also related to the Chouke parameter  $C$ , through the expression

$$C = 2\pi\sqrt{3C^*} \quad (8)$$

The first radial displacement data illustrating the variation of recovery and the number of fingers with the flow rate was presented by Ni et al (5). The results they obtained were qualitatively very similar to those reported by other workers for immiscible linear displacement in unconsolidated porous media. They also found that the values of  $C$  (Chouke parameter) determined for the radial displacement are very close to those previously reported for linear displacement. This fact supports the assertion that the wettability number  $C^*$  depends primarily upon the structural characteristics of the porous medium rather than upon the characteristics of the displacement process.

Experiments for radial fingering in a water-wet porous medium were conducted by Nasr-El-Din et al (7)., following Ni et al.'s (5) study. In their experiments, they used a perfectly circular cell. This was an improvement over Ni et al.'s work where a square cell was utilised. In the square cell the pressure drop is not symmetrical and it leads to dead zones at the cell corners which in turn distorts the interface shape (from circular to square) close to the cell exit. All of these problems were overcome using a circular cell. Nasr-El-Din et al.'s study showed that the wettability of the porous medium plays a very important role in oil displacement, as it determines the manner in which interfacial tension and injection flow rate affect recovery. It then became obvious that in comparing

the results obtained with media of different wettabilities, two points should be considered : (1) the relationship between recovery at the breakthrough condition, and (2) the displacement pattern. Early work in linear displacement with oil-wet porous media showed that recovery increases with flow rate towards a stabilized value, after which the recovery is independent of flow rate. Nasr-El-Din et al.'s study showed that this relationship is somewhat different for displacement in water-wet porous media, especially at low flow rates. Kyte and Rapoport (8) previously explained this difference in terms of boundary effects at the outer edge of the cell. They reported two values for the recovery, one corresponding to the first arrival of the displacing fluid at the outer edge of the cell, and the other at its actual breakthrough. They found that the former followed the same trend as in displacement in an oil-wet medium, whereas the latter exhibited a completely different trend which was a function of viscosity ratio, i.e., at low flow rates and high viscosity ratios breakthrough recovery decreases as the flow rate increases.

Wettability also affects the displacement pattern. In linear systems, Peters and Flock (9) observed that fingers in water-wet media were approximately eight times wider than those in oil-wet media. A similar observation was also reported by Paterson et al (4). In radial displacement, Ni et al (5), have reported some differences in displacement patterns at low and high flow rates.

Mathematical modelling of radial water/oil displacement processes in water-wet porous media was conducted by Agharazi-Dormani et al (10). They used response surface

methodologies to study the effects of five important variables on oil recovery and finger formation during immiscible radial displacement of oil by water in a consolidated water-wet porous medium. In their study, using a modified central composite experimental design, the following operating variables were investigated : flow rate of injection fluid, radial distance from the injection point, viscosity difference between the displaced and displacing phases, permeability of the porous medium, and oil/water interfacial tension. They developed empirical models based directly on the operating variables and indirectly on pertinent dimensionless terms to describe fractional recovery and number of fingers at breakthrough. The final models provided valuable new information about the individual and the joint effects of the operating variables.

Studies involving numerical simulations of radial displacement of a wetting fluid by a non-wetting fluid (oil-wet media) in a porous medium were performed by Kiriakidis et al (11). Three distinct statistical models were developed to describe the three distinct behaviours observed in the immiscible displacement : (a) the DLA (diffusion-limited aggregation) model for viscous fingering at low viscosity ratios, (b) the anti-DLA model for stable displacement, and (c) the invasion percolation model at very low capillary numbers. The numerical results obtained using these models were in very good agreement with the experimental results.

### **2.3.2 Linear Displacement**

Most of the previous studies in immiscible linear displacement have utilised three-dimensional consolidated / unconsolidated porous samples. In the literature, in some of the very early works, we can also see the Hele-Shaw cells being used to study linear displacement. Hele-Shaw cells were used by Perkins and Johnston (12) to study the fingering occurring during the immiscible displacement. They found that, with highly unfavourable viscosity ratios and relatively high injection rates, viscous fingers were formed readily. They also observed that numerous fingers were induced at the inlet, but as the displacement progressed the fingers coalesced. It was also seen that, at lower flow rates and more favourable viscosity ratios, displacements were considerably influenced by capillary forces.

In their work, Perkins and Johnston (12), found that, as a result of the heterogeneity of wettability of the glass surfaces, an uneven front developed and wandered erratically through the model. Previously, Chuoke et al. (6) reported that treating the glass surface to make it oil-wet will minimize this effect. With the brief experiments in Hele-Shaw cells and in packed beds, Perkins and Johnston concluded that Hele-Shaw cells are not adequate for modelling all the significant phenomena influencing immiscible fingering. According to them, although there is an analogy (with respect to potential flow) between flow in a Hele-Shaw cell and flow in a porous medium, there are also noticeable differences, particularly with regard to dispersion phenomena and two-phase flow. In their experiments with porous media, two types of initial saturation were studied. In the

first group of experiments, the porous medium was completely saturated with a single phase which was then displaced by an immiscible phase. In the second group of experiments, initial water saturations approaching irreducible minimum values were established before displacing oil with water. From these two groups of experiments, they concluded that the fingering studies will be most meaningful with respect to water-wet reservoir behaviour if the porous medium contains a residual connate-water phase. Perkins and Johnston also performed experiments to determine the effect of the particle shape. They found that the change in the particle shape does not significantly alter the fingering characteristics or the percentage recovery.

Other early works in linear displacement include studies carried out by Scott et al. (13), Chouke et al (6), Hill (3) and Van Meurs et al (14). Scott et al.(13), performed a model study to determine the influence of flow rate, viscosity ratio and interfacial tension on the waterflood recovery efficiency of viscous crude oil from sands. They carried out their experiments on a long sand pack. They plotted their results on a semi-log plot with recovery and viscosity ratio as the coordinates. Through the application of Buckley-Leverett principles (13), they determined the influence of viscosity ratio on recovery from the relative permeability curve. These theoretical predictions from the relative permeability data were found to be lower than the experimental recoveries. Their results showed a decrease in recovery with an increase in viscosity ratio.

Channelling in packed columns was first observed by Hill (3), who performed

experiments on the displacement of sugar liquors by water from columns of granular bone charcoal. Their study showed that the existence or absence of a tendency towards channelling depends upon the linear velocity of flow. They also found that the critical velocity could be defined in terms of the viscosities and densities of the two fluids.

Chouke et al (6), presented both theoretical and experimental evidence for the occurrence of macroscopic instabilities in immiscible displacement of one viscous fluid by another. They used visual models of two kinds to obtain observations, i.e., (i) displacement of oil by water-glycerine solutions through the flow channel formed by closely spaced parallel plates, and (ii) displacement of oil by water with and without initial interstitial water through unconsolidated glass powder packs. In all cases they observed macroscopic instabilities or fingers when the theory predicted their occurrence to be favourable. They also showed that a quantitative prediction of finger spacing is possible in a porous medium which is macroscopically homogeneous and isotropic throughout. In their experiments with the parallel plate model, oil was introduced first, the flow channel was tilted to about  $45^\circ$  from the horizontal, and finally the dyed water-glycerine mixture was injected at the lower end. After injection of a small amount of the glycerine mixture, injection was stopped and the fluids were allowed to equilibrate under the action of gravity. They found that at low flow rates of injection the moving interface remained essentially stable and no fingers were formed. For their experiments in packed powder models, they used an oil having a refractive index identical to that of Pyrex glass, to make it transparent. As the injection fluid (water) had a different refractive index from

that of the glass grains and the oil, light scattered wherever water penetrated. They observed that at higher viscosity ratios and lower interfacial tensions smaller fingers were formed.

A study to determine the effects of wettability and interfacial tension on immiscible liquid-liquid displacements occurring in porous media was made by Mungan (15). He used polytetrafluoroethylene (TFE) cores prepared by compressing TFE powder under different pressures as his porous medium. His study showed that the displacement of a wetting liquid by a non-wetting liquid is always less efficient than the displacement of a non-wetting liquid by a wetting one, all the other things being equal. He also found that for a non-wetting liquid displacing a wetting liquid, the recovery efficiency can be increased substantially by either reducing the interfacial tension or by increasing the viscosity of the displacing fluid. His final results show that the lowering of interfacial tension has more effect in increasing recovery from oil-wet porous media than from water-wet media. Mungan's experiments also indicated that recovery of oil could be increased by increasing the viscosity of the injected water.

Transparent three-dimensional models for studying the mechanisms of flow processes in oil reservoirs was first used by Van Meurs (14). He used a model having glass walls filled with finely powdered glass. This model became completely transparent when the powdered glass pack was saturated with an oil having the same refractive index as the glass. When water or gas, having a refractive index different from that of oil (glass) is

injected, the model became opaque in the space occupied by the water (gas). This made visual observation and photography possible in the three-dimensional model. Van Meurs carried out experiments in three different models, i.e., (1) linear water-drive displacements in both homogeneous and stratified formations were performed in a rectangular model; (2) the second model was used to simulate part of an oil field drilled according to a five-spot well pattern. It consisted of one injection well in the center of the apparatus surrounded by four producing wells at the corners; (3) the third model was to simulate the solution-gas drive displacement, and it was carried out in a cylindrical tube. The results from these three-dimensional models showed that only for uniform sands is the water drive process very efficient at low oil/water viscosity ratios. In stratified sands with interconnected layers of different permeabilities this efficiency is greatly reduced owing to the trapping of oil in the less permeable layer. In the case of high oil-to-water viscosity ratios the recovery of the oil was adversely affected due to viscous fingering. At higher viscosity ratios the effect of stratification was comparatively small. It was also seen that the ultimate recovery in five-spot flooding did not differ appreciably from those in a linear-drive at a high viscosity ratio. Finally, from the results of the third model, it was observed that in laboratory solution gas drive experiments, the occurrence of separate gas bubbles largely increases the production rate.

Recently, another three dimensional model was used to observe and measure viscous fingering in large, natural consolidated porous samples. This work by Pavone (16) utilised a molding technique, and he studied immiscible two-phase flow instabilities in

porous media under drainage conditions (i.e. nonwetting fluid displacing a wetting fluid). As the porous medium was going to be dissolved by acidizing, he chose a carbonate sample. For the liquid in place, silicon oils were used as they had a wide range of viscosities. Epoxy resin was used as the injected liquid. The experiments took place in an air bath thermoregulated at 40°C. After breakthrough, the sample was taken out of the cell and put in an air bath thermoregulated at 120°C for 2 days. This solidified the epoxy resin. Finally, the sample was placed in a hydrochloric acid bath until all the carbonate free of epoxy resin was dissolved. As the sample was placed horizontally, and the density difference between the oil and the epoxy resin was very low, gravity had almost no effect on these displacements.

The results of Pavone's work showed instabilities that looked like fingers and stable displacements behind the unstable front. He defined two dimensionless groups, namely a capillary number difference,  $\Delta N_c$ , and a viscosity ratio,  $F_\mu$  :

$$\Delta N_c = (\mu_o - \mu_r) v / \sigma \quad \text{and} \quad F_\mu = \mu_o / \mu_r$$

where  $\mu_o$ ,  $\mu_r$  are oil and resin viscosities,  $v$  is the displacement velocity and  $\sigma$  is the interfacial tension .

All data, including breakthrough recovery, stable zone length, mean local saturation and pressure drop slope, were plotted against  $(F_\mu - 1) \Delta N_c$ . Finger width was scaled against

$\Delta N_c$ . In conclusion, he describes three kinds of displacement that could occur in his physical model. Displacement is stable at low  $(F_\mu - 1) \Delta N_c$  values. Slight increase in  $(F_\mu - 1) \Delta N_c$  results in macroscopic viscous fingering. This causes a decrease in breakthrough recovery as the swept macroscopic volume is decreased. Increasing  $(F_\mu - 1) \Delta N_c$  further does not create more macroscopic fingers, but sweep efficiency decreases at the pore level, and reduces the recovery.

## **2.4 Mathematical Simulations**

Different models, both deterministic and stochastic, have been developed to simulate two-phase flow in porous media. Some of the viscous fingering studies were based on the "Diffusion Limited Aggregation" (DLA) model developed by Witten and Sander (17). Capillary fingering was studied by a number of researchers [Larson et al., (18,19) ; Chandler et al., (20) ; Wilkinson and Willemson, (21) ; Wilkinson, (22)] according to the percolation theory. Lenormand and Zarcone (23) conducted experiments and confirmed the results of the above studies. Later, Lenormand et al.,(24) also developed a deterministic model to simulate immiscible displacement of a wetting fluid by a non-wetting one. In the same year, Leclerc and Neale (25) employed a stochastic approach by using Monte Carlo decision making and random walks to simulate radial displacement of a wetting fluid in a porous medium.

Work on the mathematical simulation of the linear displacement of a wetting fluid by an immiscible non-wetting fluid in a two-dimensional porous medium was performed by

Kirikidis et al (26). This algorithm involves Monte Carlo decision making, random walks and principles of the percolation theory. The algorithm described in their work successfully predicts the three distinct behaviours of immiscible displacement in porous media. The numerical results were tested against the experimental results in the literature, and a very good agreement was observed.

Computer simulations of immiscible linear displacement in a porous medium containing regions of different wettabilities was also performed by Kirikidis et al (27). In that work they used a deterministic model based on a microscopic approach to determine the flow pattern of the invading fluid. The porous medium was represented by a two-dimensional square network of interconnected channels. Results of these computer simulations showed that the effects of the heterogeneity of the wettability on the behaviour of the invading fluid are very strong when capillary forces are significant and even stronger when there is a wettability contrast from an oil-wet to water wet-zone in the porous medium.

## **2.5 Effect of Buoyancy Forces**

Although a considerable amount of work has been done in both radial and linear displacements, very few of the studies considered the effects of buoyancy forces. The effects of gravity forces on the displacement of oil by surfactant solutions was studied by Hornof and Morrow (28). In their experiments, for systems with interfacial tension greater than 1 mN/m, they observed sharp interfaces and generally stable displacements,

whereas the experiments conducted at lower interfacial tensions showed a considerable degree of instability. At lower interfacial tensions, the interface became fuzzy, and there was distinct evidence of gravity override by the displacing phase. They successfully related the onset of gravity segregation with decreasing interfacial tension to capillary and viscous forces operating within the system.

Other researchers who studied the effects of gravity forces in horizontal two-dimensional cells include Craig et al., (29) and Crane et al., (30). Craig et al., used scaled reservoir models to study the effects of gravity forces on oil recovery performance in frontal drive operations, such as water, gas, or solvent flooding. During the displacements they observed non-uniform advance of the fluid front, which reduced the volumetric sweep efficiency. The non-uniform advance of the fluid front is caused by various factors including gravity effects, well arrangements and variations in rock permeability within the reservoir. The effects of well arrangement and permeability variations have been studied extensively. The gravity effects are due to the displacing fluid being of different density than the reservoir oil. Even though gravity effects were recognized as being present in the frontal drive operations, the reason they could not be studied is because the problem did not lend itself to simple experimental or mathematical analysis. Craig et al. first presented a progress report on the laboratory investigation of gravity effects in fully liquid saturated, horizontal, uniform and non-uniform systems. They obtained their results from scaled experiments on both linear and five-spot systems within the range of conditions normally encountered in secondary recovery operations. From their results they

concluded that in linear gas or water injection operations in flat formations of uniform rock texture, segregation of the fluids due to gravity effects can reduce the oil recovery to as low as 20 percent of those in the absence of gravity forces. For five-spot injection operations in flat uniform systems, they found that breakthrough oil recovery can be as low as 40 percent of those predicted by methods which assume negligible gravity effects. In the case of stratified rock formations, the experiments showed that the breakthrough oil recovery may be affected to a greater degree by fluid segregation due to variations in rock properties than by gravity effects.

Following Craig et al (29)., Crane et al (30)., performed some experiments to study the flow of miscible fluids of unequal density through porous media. As the density difference is increased from zero there is first a change in mode from multiple fingers to a single finger. Further increase in density difference results in a more rapid growth of the single finger. Miscible displacement with multiple fingers was studied in detail by Blackwell et al (31)., in vertical three-dimensional packed beds, and the miscible displacement with a single finger was discussed by Craig et al (29). The main objective of Crane et al's work was to bridge the gap between these two extreme cases.

The effects of gravity segregation, were also studied in vertical three-dimensional packed beds. The most significant studies done in three-dimensional beds include those of Blackwell et al (31), Slobod and Howlett (32), and Dumoré (33). From their experimental investigations Blackwell et al. concluded that in reservoirs with adequate

permeability and dip, gravity segregation can prevent channelling. Slobod and Howlett (32) studied the effects of gravity segregation in vertical unconsolidated porous media. They classified their experiments into four logical groups: (1) favourable viscosity ratio and favourable density difference; (2) favourable viscosity ratio and unfavourable density difference; (3) unfavourable viscosity ratio and favourable density difference; and (4) unfavourable viscosity ratio and unfavourable density difference. The study of the behaviour of these four systems at various rates of flow was conducted by measuring the length of the mixing or transition zone which developed between the displaced and the displacing phases. The results indicated that gravity segregation could act to shorten the mixing zone when the displacing material was the less dense phase (for downward flow), and lengthen the zone for unfavourable density differences. They plotted the change in the length of the mixing zone with density difference, rate, and viscosity ratio. The resultant graphs showed that the length of the mixing zone was clearly dependent upon the ratio of the viscous to gravity forces. They also found that when the ratio of these two quantities is used as a parameter, the plots of mixing zone length vs. the dimensionless quantity  $v/v_c$ , yield a very simplified presentation of the data. From these plots, Slobod and Howlett (32) confirmed the importance of the ratio of the viscous to the gravity forces in analyzing the flow behaviour of vertical systems.

In the same year, following Slobod and Howlett, Dumoré (33) studied stability considerations in downward miscible displacements. The main objective of his work was to generalize the stability criterion by accounting for the transition zone which developed

as a result of diffusion and mixing. This generalization led to the definition of another characteristic rate, called the stable rate, which in actual miscible drives is less than the critical rate. For such drives, it was observed that the entire transition zone was stable at rates less than the stable rate. At rates between the stable rate and the critical rate, the displacement was only partly stable, and for rates greater than the critical rate the displacement was completely unstable and viscous fingers developed more strongly.

Very recently, a preliminary study on the visualization of the effects of buoyancy forces on liquid-liquid displacements in vertically-aligned two-dimensional porous medium cells was performed by Page et al (34). They were the first people to study the effects of buoyancy forces in vertical two-dimensional cells. The results of their work suggested that buoyancy forces can have significant effects on the stability of liquid/liquid displacement processes in porous media. Their work also proved the effectiveness of using vertically aligned two-dimensional cells in studying the effects of buoyancy forces.

# Chapter 3

## Theory

### 3.1 Driving Forces

There are several different driving forces involved in liquid-liquid displacement processes occurring in a porous medium. The most common ones are pressure difference forces, viscous forces, capillary forces, buoyancy (or gravity) forces, and inertial forces.

#### 3.1.1 Pressure Difference Forces

When a displacing liquid is injected with an applied force into an oil reservoir, a pressure difference is created between the injection and the production wells, causing the oil to flow towards the production well. This is the primary driving force involved in any displacement process.

#### 3.1.2 Viscous Forces

Viscous forces arise due to frictional or viscous effects between the fluid phases, and are very much related to an important fluid characteristic called 'viscosity'. Viscosity, by definition, is related to the internal friction within a moving fluid. Due to this viscosity, a force is required whenever one layer of fluid slides past another or when a surface slides past another with a layer of fluid between the surfaces. These types of forces are called 'viscous forces'. Viscous forces play a vital role in liquid-liquid displacement

processes occurring in porous media, and their importance increases as the velocity increases.

### 3.1.3 Capillary Forces

When two immiscible fluids are in contact, the interface separating the two fluids is curved, and the curvature of the interface depends on the pressure discontinuity existing across the fluid/fluid interface. This pressure difference, which is commonly referred to as the capillary pressure ( $P_c$ ), is defined by the Laplace equation :

$$P_c = \sigma \left( \frac{1}{R_1} + \frac{1}{R_2} \right) \quad (6)$$

where  $P_c$  is the pressure across the curved interface,  $\sigma$  the interfacial tension, and  $R_1$  and  $R_2$  are the principal radii of curvature of the interface. The radii of curvature  $R_1$  and  $R_2$  are functions of the pore geometry and the contact angle which the interface makes with the pore wall.

These capillary forces are influenced by the size and shape of the pores and the general topology of the pore network. Along with the wettability of the solid surface, these capillary forces affect significantly the distribution of gas, oil and water in the reservoir rock pores throughout the different parts of a geological structure.

### 3.1.4 Buoyancy Forces

Buoyancy or gravity forces arise due to the difference of density between the two fluid phases. In liquid-liquid displacement processes, the buoyancy forces could be either favourable or unfavourable depending upon the mode of flow and the density of the two liquids involved. For example, in vertical downwards displacement, if the displacing liquid is of lower density compared to the displaced liquid, then the buoyancy forces are said to be favourable (with respect to recovery). The four limiting favourable/unfavourable situations in this context are summarized below:

| <u>Mode</u>       | <u>Densities</u>                                     | <u>Buoyancy Forces</u> |
|-------------------|--|------------------------|
| Vertical Downward | $\rho_{\text{displacing}} < \rho_{\text{displaced}}$ | Favourable             |
| Vertical Downward | $\rho_{\text{displacing}} > \rho_{\text{displaced}}$ | Unfavourable           |
| Vertical Upward   | $\rho_{\text{displacing}} < \rho_{\text{displaced}}$ | Unfavourable           |
| Vertical Upward   | $\rho_{\text{displacing}} > \rho_{\text{displaced}}$ | Favourable             |

As the density difference between the two fluids decreases, the effect of buoyancy forces also decreases.

### 3.1.5 Inertial Forces

Inertial forces become important only at high velocities and high Reynolds numbers. They are not considered here since such situations are rarely if ever encountered in practical oil recovery situations.

## 3.2 Definitions

### 3.2.1 Viscosity Ratio

Viscosity ratio, as defined in this study, is the ratio of the viscosity of the displaced liquid to that of the displacing liquid.

$$\mu_{ratio} = \frac{\mu_{displaced\ liquid}}{\mu_{displacing\ liquid}}$$

If  $\mu_{ratio} < 1$ , then the displacement is said to have a favourable viscosity ratio, and if  $\mu_{ratio} > 1$  it is said to be unfavourable.

### 3.2.2 Density Ratio

Density ratio in this study is defined as the ratio of the density of the displacing liquid to that of the displaced liquid, i.e.

$$\rho_{ratio} = \frac{\rho_{displacing\ liquid}}{\rho_{displaced\ liquid}}$$

Density ratio could be either favourable or unfavourable, depending upon the 'flow mode' under consideration.

### 3.2.3 Interfacial Tension (IFT)

When a liquid is in contact with another substance (gas, liquid, or solid), there is an

excess interfacial free energy present between the two phases. This implies that a certain amount of work has to be performed in order to separate the liquid from the second phase. The excess interfacial energy arises from the inward attraction of the molecules in the interior of a substance upon those at the surface. Since a surface possessing excess free energy contracts spontaneously if it can do so, the free interfacial energy manifests itself as an interfacial tension.

The interfacial tension is generally denoted as  $\gamma$ . Previous experimental studies have shown that a reduction of interfacial tension generally causes an increase in oil recovery, all other factors being the same.

### **3.2.4 Permeability**

The definition of permeability follows from Darcy's law. According to the definition, the permeability of a homogeneous porous material is said to be 1 Darcy if a liquid having a viscosity of 1 cP can flow through a porous medium of 1 cm length and 1 cm<sup>2</sup> cross section at a rate of 1 cm<sup>3</sup>/sec when the pressure differential between the inlet and the outlet is 1 atmosphere.

Permeability has the dimensions of an area (i.e. length<sup>2</sup>). The above defined permeability is also referred to as 'absolute permeability' and is valid only when there is a single phase fluid flowing through the porous material. When we have two or more different phases present in a porous medium, the presence of the additional phases decreases the flow of

the first phase and hence reduces its permeability. This reduced permeability is called the 'effective permeability'. The ratio of the effective to absolute permeability gives the 'relative permeability' of any given phase. As a rule, relative permeabilities are always expressed as a decimal fraction or as a percentage of the absolute permeability.

### 3.2.5 Porosity

Porosity is the ratio of the void or pore volume to the macroscopic or bulk volume. The bulk volume,  $V_b$ , of a porous material is made up of its matrix volume,  $V_m$ , and its pore volume  $V_p$ :

$$V_b = V_m + V_p \quad (9)$$

and the porosity,

$$\phi = \frac{V_p}{V_b} = \left(1 - \frac{V_m}{V_b}\right) \quad (10)$$

The total porosity,  $\phi$ , can be divided into the interconnected (or effective) porosity which is accessible to fluid flow, and the disconnected porosity which is inaccessible to fluid flow. Disconnected porosity is clearly of no interest in enhanced oil recovery operations. The porosity of a permeable medium is a strong function of the variance of the local pore or grain size distribution and a weak function of the average pore size itself.

### **3.2.6 Wettability**

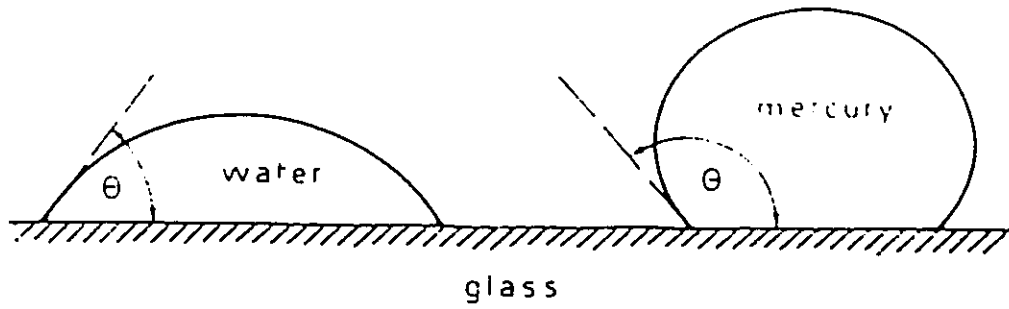
When a liquid or gas comes into contact with a solid object, cohesion forces (the attractive force between like molecules) and adhesion forces (the attractive forces between molecules of different materials) act together. Thus, while the fluid is in contact with a solid body, it either spreads out over the whole body, "wetting" it, or it forms a well-rounded drop and wets the body either very little or not at all. So far, contact angle is the most universal measure of the wettability of surfaces. As seen in Figure 3.1, if the contact angle,  $\theta$ , between the solid body and the fluid is smaller than  $90^\circ$ , then the fluid "wets" the contacted body, but if it is greater than  $90^\circ$ , the fluid is said to be non-wetting.

In the context of oil recovery operations, the reservoir wettability is not a simply defined property. It is determined by complex interfacial boundary conditions acting within the pore space of sedimentary rocks. So, it would be a gross oversimplification to classify reservoirs simply as oil-wet or water wet. Studies show that the reservoir wettability can cover a wide spectrum of conditions, including mixed or intermediate wettability.

### **3.2.7 Breakthrough and Breakthrough Oil Recovery**

When the displacing fluid first reaches the outlet port, "breakthrough" is said to have occurred. Breakthrough oil recovery is defined as the amount of oil recovered before the breakthrough occurs.

Initially, as the cell is completely saturated with the oil, and as both the displacing and



**Figure 3.1** Wetting and Non-wetting behaviours

Water "wets the glass surface, as the contact angle is less than  $90^\circ$

Mercury is "non-wetting", as its contact angle with glass is greater than  $90^\circ$

the displaced phases are incompressible, we can define the percentage of oil recovered as follows :

$$\% \text{ oil recovery} = t Q / V$$

where  $t$  = breakthrough time, sec

$Q$  = flow rate of the displacing liquid, ml/sec

and  $V$  = pore volume of the cell, ml.

### 3.3 Dimensional Analysis

A dimensional analysis was carried out to determine the important dimensionless groups involved in immiscible displacement systems. Dimensional analysis is a valuable aid for setting up experiments and interpreting data. It facilitates the presentation and analysis of the data as well as reduces the number of experiments required. It is also useful in checking the consistency of the units in equations, in converting units, and in the scale-up of data obtained in physical models to predict the performance of full-scale equipment.

Rayleigh's method, also known as the Buckingham- $\pi$  theorem, may be employed. The method is based on the concept of dimensional formulas. This is a very powerful method, however its disadvantages include the uncertainty as to whether all relevant quantities are included and the method does not provide explicit numerical predictions, whence experimental data are required.

For an immiscible system, it is considered that :

$$\text{oil recovery, sweep efficiency etc.} = f ( \Delta\rho, \mu_o, \mu_w, \gamma, v, d_p, g ) \dots\dots\dots (i)$$

$$= A \Delta\rho^a \mu_o^b \mu_w^c \gamma^f v^f d_p^h g^k \dots\dots\dots (ii)$$

The equation (ii), written in terms of the fundamental dimensions (mass, length, time) :

$$[1] = [ML^{-3}]^a [ML^{-1}T^{-1}]^b [ML^{-1}T^{-1}]^c [MT^{-2}]^e [LT^{-1}]^f [L]^h [LT^{-2}]^k \dots\dots\dots (iii)$$

If the exponents on both sides of the equation are equated, we have

$$[L] : 0 = -3a - b - c + f + h + k \dots\dots\dots (iv)$$

$$[M] : 0 = a + b + c + e \dots\dots\dots (v)$$

$$[T] : 0 = -b - c - 2e - f - 2k \dots\dots\dots (vi)$$

As we have three equations and seven unknowns, we can eliminate three unknowns and express them in terms of the other four unknowns. Let the four arbitrary unknowns be a,b,e and k.

$$\text{From (v) : } c = -a - b - e \dots\dots\dots (vii)$$

$$\text{From (vi) : } f = -b - c - 2e - 2k$$

combining (vi) and (vii), we get

$$f = a - e - 2k \dots\dots\dots (viii)$$

$$\text{From (iv) : } h = 3a + b + c - f - k$$

using (vii) and (viii), we have

$$h = a + k \dots\dots\dots (ix)$$

Now, grouping the exponents together, we obtain

$$\text{oil recovery} = A (\Delta\rho v d_p / \mu_w)^a (\mu_o / \mu_w)^b (\gamma / \mu_w v)^e (g d_p / v^2)^k \dots\dots\dots (x)$$

From (x), we obtain four independent dimensionless groups, i.e.

(I)  $\Delta\rho v d_p / \mu_w$

(II)  $\mu_o / \mu_w$

(III)  $\gamma / \mu_w v$

(IV)  $g d_p / v^2$

These groups may be combined together (by multiplication or division) to form different although not independent groups. For an immiscible system, the following convenient groups were determined :

(a) Modified Reynolds number (ratio of inertial to viscous forces)

(I)  $\Delta\rho v d_p / \mu_w$

(b) Viscosity Ratio (ratio of the viscosity of oil to viscosity of water)

(II)  $\mu_o / \mu_w$

(c) Capillary Number (ratio of viscous to capillary forces)

(III)<sup>-1</sup>  $\mu_w v / \gamma$

(d) Bond Number (ratio of buoyancy to inertial forces)

(I x III<sup>-1</sup> x IV)  $\Delta\rho g d_p^2 / \gamma$

# Chapter 4

## Experimental

### 4.1 Experimental Set-Up

#### 4.1.1 Cell Manufacturing

The porous medium cell employed consisted of a 0.28 cm thick sintered consolidated porous medium of pore volume 21 ml and porosity 0.316 constructed from almost monosized spherical glass particles of average diameter 0.0786 cm sandwiched between and sintered to two identical square glass plates of dimensions 15.4 x 15.4 x 0.5 cm. To prepare this consolidated porous medium the glass beads were first packed in between the glass plates and kept in an oven whose temperature was raised to 660°C. It took two hours to reach this pre-set temperature (660°C) and the temperature of the oven was maintained at this set temperature for two hours so that the glass beads could be sintered together. The oven was then shut off and the cell remained inside overnight before being taken out.

The next step was to seal the outer edges of the cell with an epoxy resin, and two trios of equally spaced ports of 0.2 cm internal diameter were drilled on opposite sides of the cell, 1.5 cm from the outer perimeter. Any two of the six ports could be used for the injection and recovery of the fluids during the experiments, while all six were employed

during the cleaning process that followed each experiment.

### **4.1.2 Properties of the Cell**

The following table gives the properties of the cell used in this project.

**Table 4.1: Cell Properties**

|                                    |   |                  |
|------------------------------------|---|------------------|
| Thickness of the porous medium (H) | = | 2.8 mm           |
| Particle Diameter (D)              | = | 0.786 mm         |
| H/D ratio                          | = | 3.56             |
| Porosity of the Medium             | = | 0.316            |
| Pore Volume                        | = | 21 ml            |
| Size of the glass plates           | = | 154 x 154 x 5 mm |

### **4.1.3 Apparatus**

The experimental set-up consisted of the following main components:

- a) the porous medium cell
- b) a camera
- c) a constant flow rate syringe pump
- d) 20 ml and 30 ml syringes
- e) a timer
- f) a pressure gauge
- g) vacuum tubing

- h) a vacuum pump
  - i) a 50 ml burette
- and j) a fluorescent light source.

For the experiments performed in the horizontal mode, the camera was mounted overhead and the cell was laid above the light source. In the vertical mode, the camera was mounted on a tripod and the cell was supported in a wooden holder in front of the light source. The setup of the apparatus is shown in Figure 4.1.

#### 4.1.4 Specifications of the System

The specifications of all the chemicals and the equipments used in this project, are shown in Table 4.2.

**Table 4.2: Specifications of the Systems Used**

| <u>Name</u>           | <u>Specification</u>                                  |
|-----------------------|---|
| 1) Water              | Distilled   |
| 2) Glycerol           | BDH, Analytical reagent                               |
| 3) Heavy Paraffin Oil | BDH, Analytical reagent                               |
| 4) Propanol - 2       | BDH, Analytical reagent                               |
| 5) Acetone            | BDH, Analytical reagent                               |
| 6) Methylene Blue Dye | Mallinckrodt Canada Inc., Organic reagent             |
| 7) Syringe Pump       | Sage Instruments, Model 341B                          |
| 8) Syringe            | Becton, Dickinson & Co., Franklin Lakes,<br>NJ, U.S.A |



Figure 4.1 : Experimental set-up showing vertical upward displacement in progress

|                                      |   |
|--------------------------------------|---|
| 9) Timer                             | Precision Scientific Co.                          |
| 10) Camera                           | Minolta XG-M                                      |
| 11) Glass Beads                      | Rouville Inc.                                     |
| 12) Epoxy resin & hardeners          | Smooth - on, MT - 13, Gillette, NJ                |
| 13) Silicone Rubber Adhesive Sealant | GE Silicones, White RTV 102, Pickering,<br>Canada |

## **4.2 Experimental Method**

### **4.2.1 Saturation Process**

The porous medium cell is first evacuated with the help of a vacuum pump, and is then completely saturated with the heavy paraffin oil. The heavy paraffin oil which is used for the saturation is initially placed under vacuum and stirred in order to remove any dissolved gases present. Once the cell is completely saturated with the medium to be displaced, i.e., with the heavy paraffin oil, the vacuum pump is then disconnected.

During the saturation process the amount of heavy paraffin oil required to completely saturate the cell gives the pore volume of the cell.

### **4.2.2 Displacement Process**

The displacing liquid, glycerol solution, is placed in a syringe and kept in a constant flow rate syringe pump. The flow rate selector in the syringe pump is set at a particular value.

The syringe is connected to the inlet port of the porous medium cell through a tube. The outlet of the cell is connected to a separate container to collect the displaced liquid.

As the glycerol solution starts to displace the heavy paraffin oil the patterns of the fingers formed are observed, and photographs of the moving front are also taken. When the glycerol solution first arrives at the outlet port, the so-called breakthrough time is recorded. From the breakthrough time, breakthrough recovery may be calculated.

### **4.2.3 Cleaning and Drying Process**

After breakthrough the injection of the glycerol solution is stopped and the syringe is disconnected from the cell. The cell is then flushed with water, two pore volumes of propanol-2, and two pore volumes of acetone, under vacuum. This flushing process cleans the cell completely and removes even the last traces of the two liquid phases present in the cell.

Once the cleaning operation is over, the cell is then dried first with air and then with the nitrogen gas. Nitrogen gas is passed slowly through the porous medium for about 10 minutes. After the passage of the nitrogen gas the cell is then ready for the next displacement experiment. The same sequence of cleaning and drying operations is carried out at the end of each run to ensure good reproducibility.

## **4.3 Experiments Performed**

### **4.3.1 Preliminary Experiments**

Preliminary experiments were performed to determine the homogeneity of the cell, to establish proper cleaning and drying procedures, and to become familiar with the system. Preliminary experiments showed that the homogeneity of the cell was excellent. Homogeneity of the cell was tested by displacing water by dyed water. Figure 4.2 shows the moving front at different times. As expected there is absolutely no fingering and the displacement front is seen to be perfectly smooth indicating very good homogeneity.

### **4.3.2 Reproducibility Experiments**

In order to test the reproducibility of the experiments a few specific displacements were duplicated. Figures 4.3a and 4.3b show the displacement of heavy paraffin oil by 60% glycerol solution at a flow rate of 15.5 ml/hr. Both pictures were taken at the breakthrough time. As we can see, the breakthrough time and the breakthrough recovery in the two cases differ by only 3.6%. The reproducibility of the cell was also tested in the vertical upwards mode at a viscosity ratio of 143.5 and a flow rate 107.5 ml/hr (Figures 4.3c & 4.3d). In this case the difference between the breakthrough time and the percentage recovery was seen to be 2.2%. Thus, the reproducibility of the cell was verified.

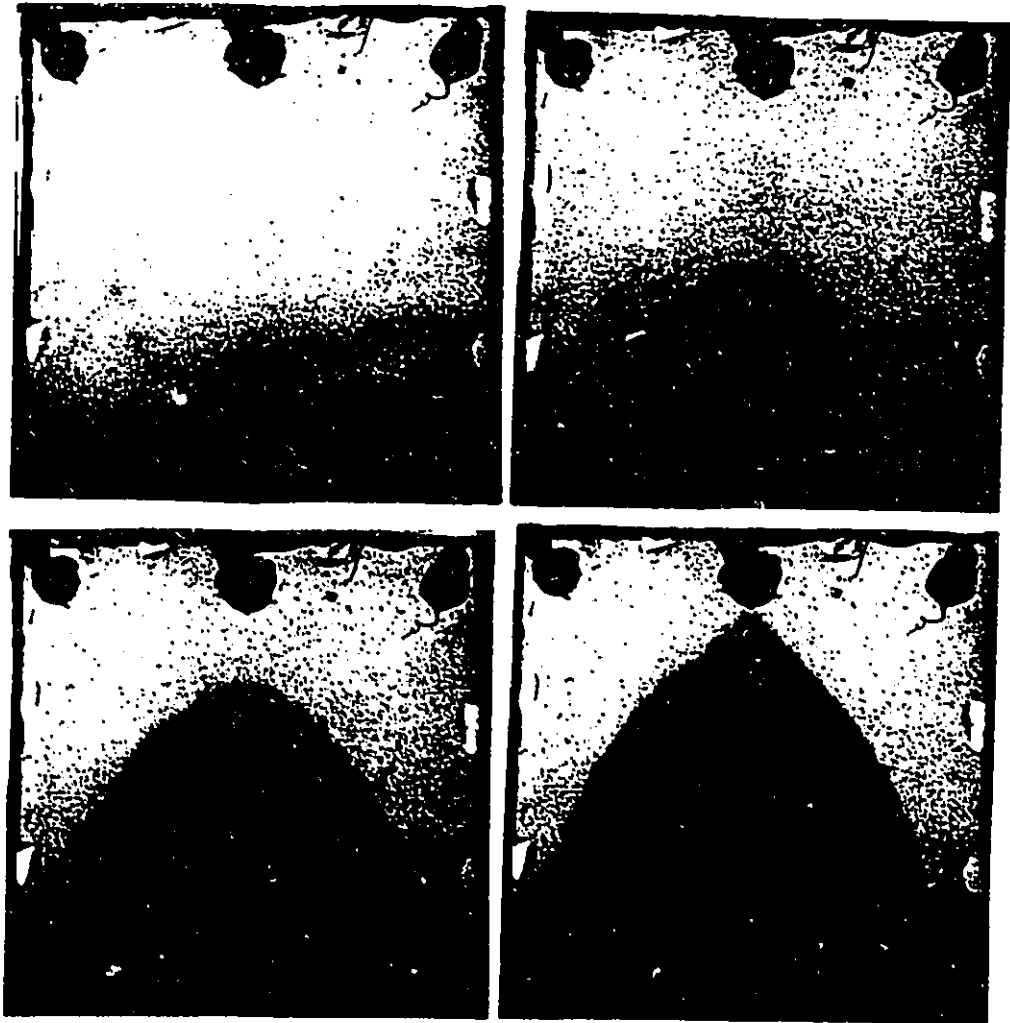


Figure 4.2 : Homogeneity test



Figure 4.3a



Figure 4.3b



Figure 4.3c

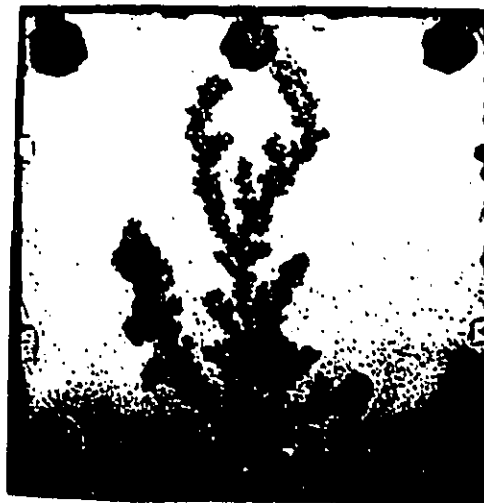


Figure 4.3d

Figures 4.3a & 4.3b : Horizontal mode,  $\mu_{ratio} = 11.11$ ,  $Q = 15.5$  ml/hr  
4.3a)  $t_{br} = 1343.4$  sec,  $R = 27.465\%$ ; 4.3b)  $t_{br} = 1391.1$  sec,  $R = 28.44\%$

Figures 4.3c & 4.3d : Vertical Upwards mode,  $\mu_{ratio} = 143.5$ ,  $Q = 107.5$  ml/hr  
4.3c)  $t_{br} = 37.1$  sec,  $R = 5.276\%$ ; 4.3d)  $t_{br} = 37.9$  sec,  $R = 5.39\%$

### 4.3.3 Immiscible System Experiments

Immiscible displacement experiments were performed in three different orientations, namely, horizontal, vertical upward and vertical downward. In all three modes the displaced phase was heavy paraffin oil and the displacing phase was glycerol solution. Five different concentrations of glycerol solution were used to alter the viscosity ratio.

In all three modes studied, for each of the five different viscosity ratios, displacement experiments were performed with ten different injection flow rates. Breakthrough time was observed for all of the displacements and from the breakthrough time the breakthrough recovery was also calculated.

Photographs of the moving front were taken periodically to analyze the fingering occurring during the displacement process.

Table 4.3 indicates the number of experiments performed with different glycerol solutions in different flow modes.

**Table 4.3: Immiscible System Experiments**

| Concentration of the experiments displacing glycerol solution | Flow orientation  | Number of performed |
|---|-------------------|---------------------|
| 0 %   | Horizontal        | 10                  |
| 0 %   | Vertical Upward   | 10                  |
| 0 %   | Vertical Downward | 10                  |

|      |                   |    |
|------|-------------------|----|
| 30 % | Horizontal        | 10 |
| 30 % | Vertical Upward   | 10 |
| 30%  | Vertical Downward | 10 |
| 60 % | Horizontal        | 10 |
| 60 % | Vertical Upward   | 10 |
| 60 % | Vertical Downward | 10 |
| 75 % | Horizontal        | 10 |
| 75 % | Vertical Upward   | 10 |
| 75 % | Vertical Downward | 10 |
| 82 % | Horizontal        | 10 |
| 82%  | Vertical Upward   | 10 |
| 82%  | Vertical Downward | 10 |

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Total number of experiments performed = 150

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# Chapter 5

## Results and Discussion

### 5.1 Horizontal Displacement

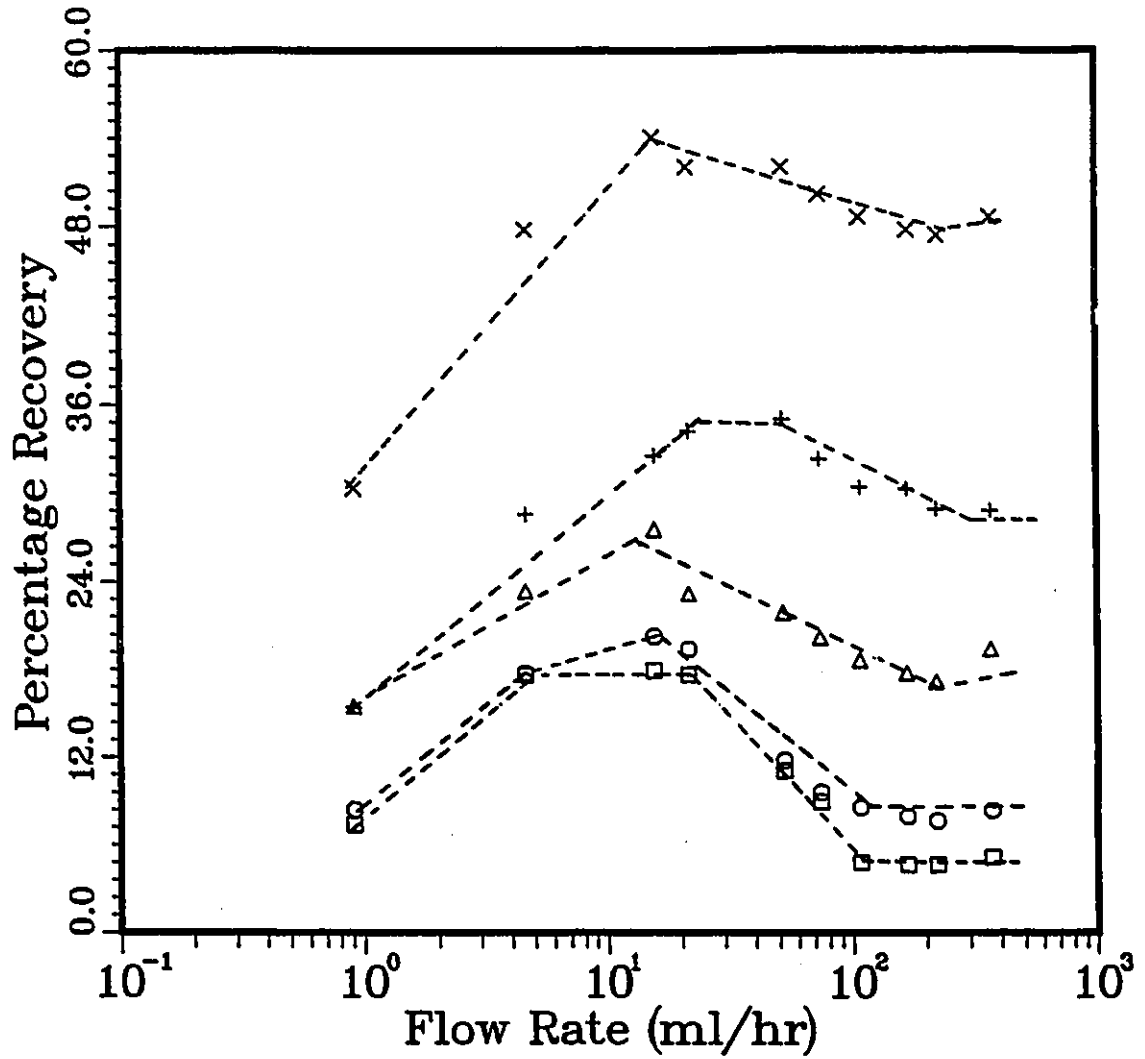
#### 5.1.1 Effects of flow rate

The experimental results obtained in the horizontal displacement show that the flow rate is one of the most important factors which affects the amount of oil recovered at the breakthrough condition. Figure 5.1 shows the percentage recovery versus flow rate relationship in the horizontal displacement. Table 5.1 shows the percentage of oil recovered for ten different flow rates and five different viscosity ratios.

At very high viscosity ratios the recovery versus flow rate plot (Figure 5.1) shows four distinct regions, namely, the capillary flow region, the stabilised flow region, the viscous flow region and a constant recovery region. The lowest flow rate studied was 0.91 ml/hr and as the flow rate was increased from this lowest value the percentage recovery always increased for all the viscosity ratios studied. This region where the recovery increases with an increase in flow rate is called the 'capillary region' and the capillary forces are said to dominate the displacement. When the viscosity ratios are 143.5 and 49.0 the capillary region is observed for flow rates less than 4.6 ml/hr. But as the viscosity ratio is decreased the capillary region is observed even up to flow rates as high as 21.5 ml/hr.

# HORIZONTAL DISPLACEMENT

- x :  $\mu_o/\mu_w = 1.72$  ,  $\rho_w/\rho_o = 1.3911$
- + :  $\mu_o/\mu_w = 3.3$  ,  $\rho_w/\rho_o = 1.3558$
- $\Delta$  :  $\mu_o/\mu_w = 11.11$  ,  $\rho_w/\rho_o = 1.3341$
- o :  $\mu_o/\mu_w = 49.0$  ,  $\rho_w/\rho_o = 1.2281$
- $\square$  :  $\mu_o/\mu_w = 143.5$  ,  $\rho_w/\rho_o = 1.1403$



**Figure 5.1 :** Breakthrough recovery as a function of flow rate, for displacements in the horizontal mode.

Table 5.1: Percentage recoveries in horizontal displacement

| <b>Viscosity Ratio ▶</b>   | <b>143.5</b> | <b>49.0</b> | <b>11.11</b> | <b>3.3</b> | <b>1.72</b> |
|----------------------------|--------------|-------------|--------------|------------|-------------|
| <b>Flow Rate ▼ (ml/hr)</b> |              |             |              |            |             |
| <b>369.6</b>               | 5.13         | 8.31        | 19.36        | 28.80      | 48.69       |
| <b>221.8</b>               | 4.66         | 7.66        | 17.16        | 28.95      | 47.43       |
| <b>168.0</b>               | 4.66         | 7.96        | 17.73        | 30.29      | 47.80       |
| <b>107.5</b>               | 4.78         | 8.55        | 18.57        | 30.36      | 48.72       |
| <b>73.90</b>               | 8.92         | 9.58        | 20.13        | 32.33      | 50.33       |
| <b>52.40</b>               | 11.05        | 11.73       | 21.85        | 35.06      | 52.18       |
| <b>21.50</b>               | 17.58        | 19.32       | 23.10        | 34.18      | 52.19       |
| <b>15.50</b>               | 17.86        | 20.20       | 27.47        | 32.45      | 54.20       |
| <b>4.600</b>               | 17.63        | 17.76       | 23.37        | 28.53      | 47.86       |
| <b>0.910</b>               | 7.40         | 8.413       | 15.50        | 15.41      | 30.31       |

Figures 5.2 to 5.5 show the effects of flow rate in horizontal mode displacements. Figure 5.2a shows the picture taken at the breakthrough time when the viscosity ratio is 143.5 and the flow rate 0.91 ml/hr. As is obvious from the photograph, it can be seen that the fingering in the capillary region (also termed 'capillary fingering') does not have any uniform displacement pattern. 'Capillary fingering' occurs at low capillary numbers when the viscous forces are negligible in both fluids and the principal force is due to capillarity.

Figures 5.3a & 5.4b also show the breakthrough time pictures for the flow rate 0.91 ml/hr, when the viscosity ratios are 11.11 and 1.72 respectively. Figure 5.4a is a picture taken during the displacement (before breakthrough). Comparing Figures 5.4a and 5.4b we can observe the backward movement of the fingers. This backward movement in the capillary region has been explained by many previous workers as due to lateral imbibition. According to Lenormand et al. in the capillary region the fingers spread and grow in all directions including backward (i.e., towards the entrance).

For higher viscosity ratios, following the capillary region a stabilised flow region with constant recovery is observed. For the viscosity ratio 143.5 the stabilised region is seen to occur between 4.6 ml/hr and 21.5 ml/hr. In the stabilised flow region both the capillary and the viscous forces have comparable effects and the recovery remains constant at a maximum value. For lower viscosity ratios,  $\mu_{ratio} = 49.0$  and 11.11, there is no clear stabilised flow region but a point with maximum recovery was observed. For still lower viscosity ratios,  $\mu_{ratio} = 3.3$  and 1.72, a small stabilised flow region with



Figure 5.2a



Figure 5.2b



Figure 5.2c



Figure 5.2d

**Figure 5.2 :** Effect of flow rate in horizontal mode displacements,  $\mu_{ratio} = 143.5$   
 5.2a)  $Q = 0.91$  ml/hr,  $t_{br} = 6167$  sec,  $R = 7.4\%$ ;  
 5.2b)  $Q = 15.5$  ml/hr,  $t_{br} = 874$  sec,  $R = 17.86\%$ ;  
 5.2c)  $Q = 52.4$  ml/hr,  $t_{br} = 159.4$  sec,  $R = 11.05\%$ ;  
 5.2b)  $Q = 107.5$  ml/hr,  $t_{br} = 33.6$  sec,  $R = 4.78\%$ .



Figure 5.3a



Figure 5.3b



Figure 5.3c



Figure 5.3d

**Figure 5.3 :** Effect of flow rate in horizontal mode displacements,  $\mu_{ratio} = 11.11$   
 5.3a)  $Q = 0.91$  ml/hr,  $t_{br} = 12913$  sec,  $R = 15.5\%$ ;  
 5.3b)  $Q = 15.5$  ml/hr,  $t_{br} = 1343$  sec,  $R = 27.47\%$ ;  
 5.3c)  $Q = 52.4$  ml/hr,  $t_{br} = 315.1$  sec,  $R = 21.85\%$ ;  
 5.3d)  $Q = 168$  ml/hr,  $t_{br} = 79.8$  sec,  $R = 17.73\%$ .



Figure 5.4a



Figure 5.4b



Figure 5.4c



Figure 5.4d

**Figure 5.4 :** Effect of flow rate in horizontal mode displacements,  $\mu_{ratio} = 1.72$   
5.4a)  $Q = 0.91$  ml/hr,  $t_{br} = 11148$  sec;  
5.4b)  $Q = 0.91$  ml/hr,  $t_{br} = 25260$  sec,  $R = 30.31\%$ ;  
5.4c)  $Q = 15.5$  ml/hr,  $t_{br} = 2651$  sec,  $R = 54.2\%$ ;  
5.4d)  $Q = 21.5$  ml/hr,  $t_{br} = 1835$  sec,  $R = 52.19\%$ .

approximately constant recovery was seen. But the stabilised region which was observed at these viscosity ratios was between 21.5 ml/hr and 52.4 ml/hr. Scott et al. (13) have previously suggested that the plateau region, i.e., the stabilised flow region, is a function of the dimensions of the system, and hence for short systems can merely become a maximum. So the disappearance of the stabilised flow region for some of the viscosity ratios studied was not completely unexpected.

Figure 5.2b shows the breakthrough picture for  $\mu_{ratio} = 143.5$  and flow rate 15.5 ml/hr. This is in the stabilised flow region and hence the displacement pattern is different from that of the capillary region. As both the capillary and viscous forces are equally important in the stabilised region the displacement pattern is also influenced by both of these forces. The displacement pattern in this region is neither fully non-uniform as in Figure 5.2a (capillary forces dominate) nor fully uniform as in Figures 5.2c and 5.2d (viscous forces dominate), but is seen to be partly uniform and partly non-uniform. Similar to Figure 5.2b, 5.3b also has a displacement pattern which is influenced by both viscous and capillary forces.

After the stabilised flow region we have a viscous region where the viscous forces are predominant and the recovery decreases as the flow rate increases. From Figure 5.1 we can see that for the viscosity ratio 143.5 the viscous region starts when the flow rate exceeds 21.5 ml/hr. The origin of the viscous region is approximately the same for all the high viscosity ratio displacements, but for lower viscosity ratios, i.e., when  $\mu_{ratio} = 3.3$

and 1.72, the viscous region begins only after 52.4 ml/hr. Figures 5.2c and 5.2d show displacements in the viscous region. If we compare Figures 5.2c & 5.2d with Figures 5.2a & 5.2b it is easy to notice the difference in the displacement patterns. In the viscous region the fingers are seen to be more uniform than in the other two regions.

One other important behaviour observed in the viscous region is the decrease in the percentage recovery with the increase in the flow rate. From Figures 5.2c & 5.2d we can see that as we increase the flow rate from 52.4 ml/hr to 107.5 ml/hr the recovery drops drastically from 11.05% to 4.78%. This is because when the viscosity ratio is very high, increase in flow rate in the viscous region causes more fingers to develop which in turn acts to reduce the percentage recovery. Figures 5.3c & 5.3d also show the breakthrough pictures in the viscous region. Here the viscosity ratio is 11.11 and the drop in percentage recovery with increase in flow rate is less when compared to the viscosity ratio of 143.5. Regarding the displacement pattern in the viscous region, from Figure 5.3d, we can observe that well defined, uniform tree-like fingers are formed with high viscosity ratios and very high flow rates.

All pictures in Figure 5.5 show displacements in the viscous region. As the viscosity ratio here is very low ( $\mu_{ratio} = 1.72$ ), unlike previous figures we do not see any tree-like viscous fingers present other than a single 'tongue' of the displacing glycerol solution. Within the viscous region as we gradually increase the flow rate from 52.4 ml/hr (Figure 5.5a) to 369.6 ml/hr (Figure 5.5d), the single tongue which is observed in all the four



Figure 5.5a



Figure 5.5b



Figure 5.5c

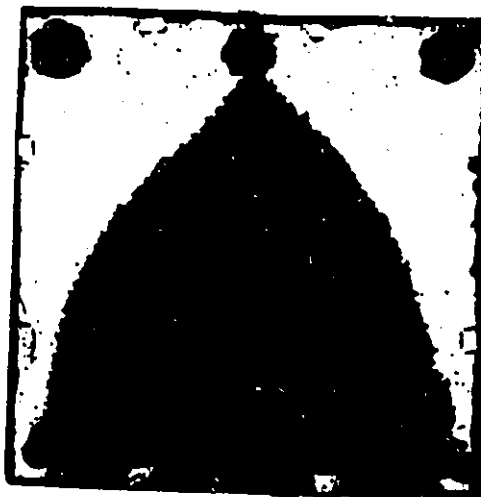


Figure 5.5d

**Figure 5.5 :** Effect of flow rate in horizontal mode displacements,  $\mu_{ratio} = 1.72$   
5.5a)  $Q = 52.4$  ml/hr,  $t_{br} = 752.6$  sec,  $R = 52.18\%$ ;  
5.5b)  $Q = 73.9$  ml/hr,  $t_{br} = 514.7$  sec,  $R = 50.33\%$ ;  
5.5c)  $Q = 107.5$  ml/hr,  $t_{br} = 342.6$  sec,  $R = 48.72\%$ ;  
5.5d)  $Q = 369.6$  ml/hr,  $t_{br} = 99.6$  sec,  $R = 48.69\%$ .

cases becomes more and more smooth along the edges. Again if we compare with  $\mu_{ratio} = 11.11$ , for  $\mu_{ratio} = 1.72$  the drop in percentage recovery is less, with increase in flow rate in the viscous region.

In the viscous region, once the recovery drops to a certain minimum value further increase in flow rate does not cause any significant change in the amount of oil recovered. Scott et al, (13) called this region as the 'constant recovery region'. For some of the viscosity ratios studied the percentage recovery actually increased slightly after reaching the minimum. This very slight increasing trend following the viscous region was also observed previously by Ni et al. (5).

All the above results obtained in the horizontal displacement are consistent with previously published results in radial & linear horizontal displacements. Scott et al. (13) presented a general representation of breakthrough recovery as a function of flow rate, for immiscible displacements in a linear water-wet system. According to them, in the region where the percentage recovery keeps on increasing with the volumetric flow rate, capillary forces trapping the oil are more important than the viscous forces. And as the volumetric flow rate increases the effect of capillary forces goes on decreasing and more and more oil is mobilised. They also observed that at slightly higher flow rates the capillary and viscous forces are comparable and the recovery remains essentially constant at a maximum value. Rapoport and Leas (35) also obtained a similar dependence between percentage recovery and flow rate, and they termed it as 'stabilization of flooding

behaviour'.

The results obtained in the horizontal mode experiments are also in very good agreement with the findings of Ni et al., who reported the recovery of glycerine using paraffin oil in radial oil-wet system.

### **5.1.2 Effects of Viscosity Ratio**

The second important factor which affects the percentage oil recovery in horizontal mode displacements is the viscosity ratio between the displaced and the displacing phases. As the results from the previous section indicated, for a constant viscosity ratio, variations in flow rate can cause variations in the percentage oil recovery. In a similar way, for a particular given flow rate, changes in the viscosity ratio can cause extreme changes in the percentage oil recovery. In the horizontal displacement for all the flow rates studied percentage recovery *always* increases with decrease in the viscosity ratio.

Figure 5.6 shows the effect of viscosity ratio in horizontal mode displacements for a very low flow rate, 0.91 ml/hr. Figures 5.6a & 5.6b show the breakthrough pictures for viscosity ratios of 143.5 and 49.0 respectively. As can be seen from these figures the increase in recovery is only 1%, even though there is a huge drop in the viscosity ratio. In Figures 5.6c & 5.6d, we have breakthrough pictures for viscosity ratios 11.11 and 1.72. Comparing Figures 5.6b & 5.6c we see that the recovery in the latter case is



Figure 5.6a



Figure 5.6b



Figure 5.6c



Figure 5.6d

**Figure 5.6 :** Effect of Viscosity ratio in horizontal mode displacement

$Q = 0.91 \text{ ml/hr}$

5.6a)  $\mu_{\text{ratio}} = 143.5$ ,  $t_{\text{br}} = 6167 \text{ sec}$ ,  $R = 7.4\%$ ;

5.6b)  $\mu_{\text{ratio}} = 49.0$ ,  $t_{\text{br}} = 7011 \text{ sec}$ ,  $R = 8.4\%$ ;

5.6c)  $\mu_{\text{ratio}} = 11.11$ ,  $t_{\text{br}} = 12913 \text{ sec}$ ,  $R = 15.5\%$ ;

5.6d)  $\mu_{\text{ratio}} = 1.72$ ,  $t_{\text{br}} = 25260 \text{ sec}$ ,  $R = 30.31\%$ .

approximately twice that of the former. And in Figure 5.6d, where the viscosity ratio is 1.72 the recovery is again twice that of Figure 5.6c. So from these observations it is clear that at high viscosity ratios, even though there is a slight increase in the recovery with decrease in the viscosity ratio, the relationship is not very sensitive. But on the other hand, at lower viscosity ratios the recovery-viscosity ratio relationship becomes very sensitive even to small changes in the viscosity ratio.

As the flow rate is only 0.91 ml/hr, all displacements in Figure 5.6 are in the capillary region. In the capillary region the displacement pattern is different for different viscosity ratios. For very high viscosity ratios like 143.5 and 49.0 the effect of lateral imbibition is very small and the displacing fluid usually tends to move directly towards the outlet port. As the viscosity ratio decreases, the lateral imbibition starts to become more and more pronounced. The effect of lateral imbibition is very clearly seen at the lowest viscosity ratio 1.72 (Figure 5.6d). Lateral imbibition combined with the backward movement produces loops which trap the displaced fluid in clusters. As can be seen from Figures 5.6c & 5.6d the size of these trapped clusters can range from the pore size to macroscopic dimensions.

Figure 5.7 shows the effect of viscosity ratio in horizontal mode displacements for an intermediate flow rate, 15.5 ml/hr. Figures 5.7a & 5.7b show displacements for viscosity ratios 143.5 and 49.0 respectively. From Figure 5.1 we can see that these two displacements are in the stabilized flow region. Figures 5.7c & 5.7d are both in the



Figure 5.7a



Figure 5.7b



Figure 5.7c



Figure 5.7d

**Figure 5.7 :** Effect of Viscosity ratio in horizontal mode displacements,  
 $Q = 15.5 \text{ ml/hr}$

5.7a)  $\mu_{\text{ratio}} = 143.5$ ,  $t_{\text{br}} = 874 \text{ sec}$ ,  $R = 17.86\%$ ;

5.7b)  $\mu_{\text{ratio}} = 49.0$ ,  $t_{\text{br}} = 988.2 \text{ sec}$ ,  $R = 20.2\%$ ;

5.7c)  $\mu_{\text{ratio}} = 3.3$ ,  $t_{\text{br}} = 1587 \text{ sec}$ ,  $R = 32.45\%$ ;

5.7d)  $\mu_{\text{ratio}} = 1.72$ ,  $t_{\text{br}} = 2651 \text{ sec}$ ,  $R = 54.2\%$ .

capillary region and the viscosity ratios for these displacements are 3.3 and 1.72 respectively. As before at higher viscosity ratios we can only see a slight increase in percentage recovery with decrease in viscosity ratio (Figures 5.7a & 5.7b). And at lower viscosity ratios even a small decrease in viscosity ratio causes a large increase in percentage recovery (Figures 5.7c & 5.7d). Comparing Figures 5.6a & 5.6b with 5.7a & 5.7b respectively, we can find that for the same viscosity ratio the displacement in the stabilized region causes wider and more uniform fingers than those formed in the capillary region. For higher viscosity ratios the fingers are very narrow in the capillary region and there is also no backward movement observed during the displacement process. By comparing Figures 5.7c & 5.7d with 5.6c & 5.6d one can also observe that increasing the flow rate in the capillary region largely reduces the amount of oil trapped as loops between the displacing phase. This is because increasing the flow rate in the capillary region tends to increase the viscous forces and this in turn forces the displacing liquid into larger pores. So, as the displacing liquid starts to invade the larger pores the amount of trapped oil decreases and the percentage oil recovery increases.

Figure 5.8 shows the effect of viscosity ratio in horizontal mode displacements for a very high flow rate, 107.5 ml/hr. All four displacements in Figure 5.8 are in the viscous flow region where the viscous forces dominate the displacement. In the viscous region viscosity ratio is a crucial factor determining the percentage oil recovery. In both the capillary and stabilized flow regions, when the viscosity ratio is decreased from 143.5 to 1.72 the recovery increases by 3 to 4 times. But in the viscous region, for the same



Figure 5.8a



Figure 5.8b



Figure 5.8c



Figure 5.8d

**Figure 5.8 :** Effect of Viscosity ratio in horizontal mode displacements,  
 $Q = 107.5 \text{ ml/hr}$

|       |                               |                                      |                |
|-------|-------------------------------|--------------------------------------|----------------|
| 5.8a) | $\mu_{\text{ratio}} = 143.5,$ | $t_{\text{br}} = 33.6 \text{ sec},$  | $R = 4.78\%;$  |
| 5.8b) | $\mu_{\text{ratio}} = 11.11,$ | $t_{\text{br}} = 130.6 \text{ sec},$ | $R = 18.57\%;$ |
| 5.8c) | $\mu_{\text{ratio}} = 3.3,$   | $t_{\text{br}} = 213.5 \text{ sec},$ | $R = 30.36\%;$ |
| 5.8d) | $\mu_{\text{ratio}} = 1.72,$  | $t_{\text{br}} = 342.6 \text{ sec},$ | $R = 48.72\%.$ |

change in the viscosity ratio the recovery increases by approximately 10 times. If we observe Figure 5.8 this could be explained very easily. When both the flow rate and the viscosity ratio are very high (Figure 5.8a) the viscous fingering is extremely high and hence the recovery is very low. Also from Figure 5.8a we can see that in the viscous region at very high viscosity ratio a large number of tiny fingers develop during the displacement and when the viscosity ratio is gradually decreased the fingers become more wide and also fewer in number. From Figures 5.8b & 5.8c it is easy to observe the extent to which the fingering is damped when the viscosity ratio is reduced. For the lowest viscosity ratio, 1.72, there is practically no fingering other than a single 'tongue' which is observed as in Figure 5.8d.

The viscosity ratio-percentage recovery relationship observed in this work agrees well with the earlier results obtained in three-dimensional beds. Scott et al. (13) performed displacement tests on a long sand pack and they plotted their results as recovery versus viscosity ratio using a semi-log plot. Their results showed a decrease in recovery with an increase in viscosity ratio. Following Scott et al., Mungan (15) investigated the influence of viscosity ratio in immiscible liquid-liquid displacements in porous media. From his experiments with polytetrafluoroethylene (TFE) cores he concluded that the recovery could be increased or made more efficient by increasing the viscosity of the injecting water, or in other words by decreasing the viscosity ratio.

## 5.2 Vertical Upward Displacement

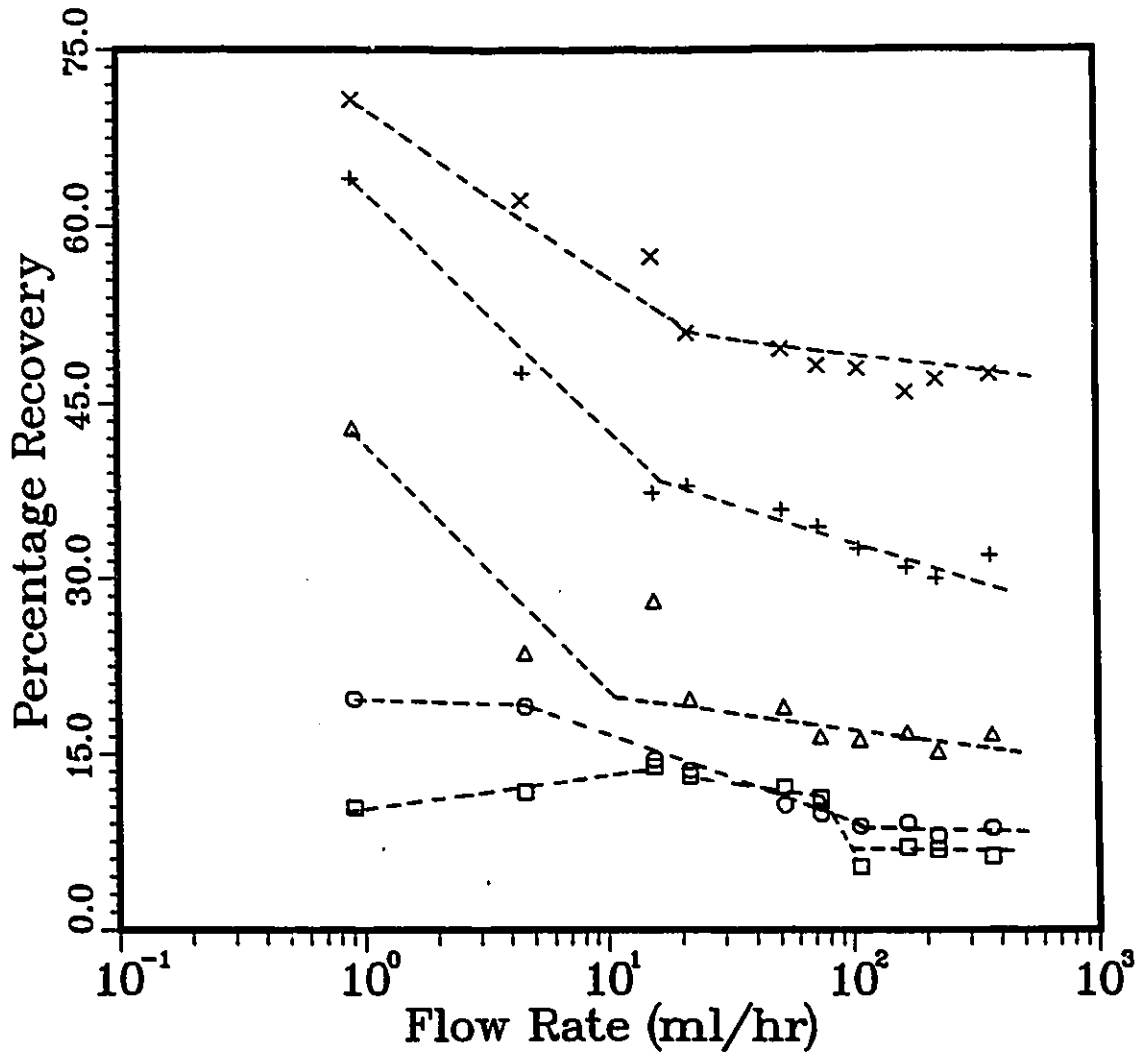
### 5.2.1 Effects of flow rate

To perform displacements in the vertical upward flow mode the cell is aligned in a vertical plane and the displacing liquid, glycerol solution, is injected at the bottom of the cell through the centre port. Experimental results obtained in the vertical upward mode indicate that the flow rate again plays a very important role in determining the breakthrough oil recovery. Figure 5.9 shows the percentage recovery versus flow rate relationship in the vertical upwards mode. Table 5.2 shows the percentage oil recovery for ten different flow rates and five different viscosity ratios.

Unlike horizontal displacement there is no stabilized flow region observed in the case of vertical upward displacement. From Figure 5.9 we can observe that the whole range of flow rates studied, 0.91 ml/hr to 369.6 ml/hr, can be divided into three regions, namely a capillary region at low flow rates, a viscous region at high flow rates, and a constant recovery region at very high flow rates. In the vertical upward displacement mode the percentage recovery almost always decreases with increase in flow rate in both the capillary and viscous regions. This is due to the presence of buoyancy or gravity forces and is explained later in the section. It was also noticed that the different regions were clear and distinct only at lower viscosity ratios. At higher viscosity ratios,  $\mu_{ratio} = 143.5$  and 49.0, the distinction between different regions was not very clear.

# VERTICAL UPWARD DISPLACEMENT

- x :  $\mu_v/\mu_w = 1.72$  ,  $\rho_w/\rho_o = 1.3911$
- + :  $\mu_v/\mu_w = 3.3$  ,  $\rho_w/\rho_o = 1.3558$
- $\Delta$  :  $\mu_v/\mu_w = 11.11$  ,  $\rho_w/\rho_o = 1.3341$
- o :  $\mu_v/\mu_w = 49.0$  ,  $\rho_w/\rho_o = 1.2281$
- $\square$  :  $\mu_v/\mu_w = 143.5$  ,  $\rho_w/\rho_o = 1.1403$



**Figure 5.9 :** Breakthrough recovery as a function of flow rate, for displacements in the vertical upward mode.

Table 5.2: Percentage recoveries in Vertical Upward displacement

| <b>Viscosity Ratio ▶</b>   | <b>143.5</b> | <b>49.0</b> | <b>11.11</b> | <b>3.3</b> | <b>1.72</b> |
|----------------------------|--------------|-------------|--------------|------------|-------------|
| <b>Flow Rate ▼ (ml/hr)</b> |              |             |              |            |             |
| <b>369.6</b>               | 6.21         | 8.65        | 16.67        | 31.92      | 47.37       |
| <b>221.8</b>               | 6.78         | 8.04        | 15.19        | 29.95      | 46.93       |
| <b>168.0</b>               | 7.01         | 9.09        | 16.82        | 30.84      | 45.87       |
| <b>107.5</b>               | 5.39         | 8.86        | 16.26        | 32.50      | 47.96       |
| <b>73.90</b>               | 11.29        | 9.90        | 16.50        | 34.37      | 48.21       |
| <b>52.40</b>               | 12.19        | 10.69       | 19.02        | 35.83      | 49.70       |
| <b>21.50</b>               | 13.14        | 13.58       | 19.61        | 37.81      | 50.91       |
| <b>15.50</b>               | 13.92        | 14.53       | 28.03        | 37.16      | 57.37       |
| <b>4.600</b>               | 11.80        | 19.09       | 23.63        | 47.60      | 62.32       |
| <b>0.910</b>               | 10.44        | 19.74       | 42.86        | 64.08      | 70.76       |

Figure 5.10 shows the effect of flow rate in vertical upward displacements, when the viscosity ratio is 49.0. Displacements in Figure 5.10a & 5.10b are both in the capillary region, Figure 5.10c is in the viscous region, and Figure 5.10d is in the constant recovery region. As can be seen from Figure 5.10 the percentage recovery *always* decreases with the increase in the flow rate. From Table 5.2 we can see that for the  $\mu_{ratio} = 49.0$  the maximum recovery is obtained for the lowest flow rate, 0.91 ml/hr. This could be explained by taking into account the buoyancy forces acting during the vertical upward displacement process. In the vertical upward displacement the buoyancy forces are always favourable as the density of the displacing glycerol solution is always higher than the density of the paraffin oil being displaced. When the flow rate is very low at 0.91 ml/hr the viscous forces are negligible and the capillary forces dominate the displacement. In the capillary region the buoyancy forces are highly effective and efficient even though they can be regarded as favourable for all the flow rates when the displacement is in the vertical upwards mode. For the lowest flow rate the buoyancy forces are highly effective and this explains the high recoveries obtained for the flow rate 0.91 ml/hr.

For the viscosity ratio 49.0 and flow rate 0.91 ml/hr the recovery is 19.74%. When the flow rate is increased to 4.6 ml/hr the recovery drops slightly to 19.09%. The corresponding recoveries in horizontal displacement are 8.41% and 17.76%. By this comparison we can notice that the buoyancy forces are highly effective for the lowest flow rate 0.91 ml/hr and with an increase in the flow rate they lose their effectiveness very quickly.



Figure 5.10a



Figure 5.10b



Figure 5.10c



Figure 5.10d

**Figure 5.10 :** Effect of flow rate in Vertical Upward displacements,  $\mu_{ratio} = 49.0$

5.10a)  $Q = 0.91$  ml/hr,  $t_{br} = 16451$  sec,  $R = 19.74\%$ ;

5.10b)  $Q = 15.5$  ml/hr,  $t_{br} = 710.6$  sec,  $R = 14.53\%$ ;

5.10c)  $Q = 52.4$  ml/hr,  $t_{br} = 154.1$  sec,  $R = 10.69\%$ ;

5.10d)  $Q = 107.5$  ml/hr,  $t_{br} = 62.3$  sec,  $R = 8.86\%$ .

Observing the displacement patterns in Figure 5.10 we can see the effects of lateral imbibition and capillary fingering in Figures 5.10a and 5.10b. In Figures 5.10c & 5.10d viscous forces dominate the displacement and in the viscous region an increase in flow rate causes more narrow fingers to be developed.

Figure 5.11 shows the effect of flow rate in vertical upward displacements for the viscosity ratio 3.3. Figures 5.11a & 5.11b are both in the capillary region and Figures 5.11c & 5.11d are in the viscous region. When the viscosity ratio and the flow rate are 3.3 and 0.91 ml/hr the recoveries in the horizontal and vertical upward displacements are 15.41% and 64.08% respectively. In the vertical upward displacement, as the density ratio is favourable the buoyancy forces tend to keep the displacing glycerol solution in the bottom of the cell (away from the outlet port at the top). And while the buoyancy forces tend to keep the displacing liquid in the bottom of the cell the capillary forces promote the lateral imbibition which causes the displacing liquid to spread until it reaches the side walls of the cell. This combined effect of the capillary and buoyancy forces acting during the vertical upward displacement explains the very high recoveries obtained at very low flow rates.

For the same viscosity ratio 3.3, when the flow rate is increased from 0.91 ml/hr to 15.5 ml/hr the recovery drops from 64.08% to 37.16%. The corresponding horizontal mode recovery for viscosity ratio 3.3 and flow rate 15.5 ml/hr is 32.45%. Thus, it is very obvious that the buoyancy forces lose their importance rapidly with even small increase



Figure 5.11a



Figure 5.11b



Figure 5.11c



Figure 5.11d

**Figure 5.11 :** Effect of flow rate in Vertical Upward displacements,  $\mu_{\text{ratio}} = 3.3$

5.11a)  $Q = 0.91$  ml/hr,  $t_{\text{br}} = 53400$  sec,  $R = 64.08\%$ ;

5.11b)  $Q = 15.5$  ml/hr,  $t_{\text{br}} = 1817.4$  sec,  $R = 37.16\%$ ;

5.11c)  $Q = 52.4$  ml/hr,  $t_{\text{br}} = 516.8$  sec,  $R = 35.83\%$ ;

5.11d)  $Q = 107.5$  ml/hr,  $t_{\text{br}} = 228.5$  sec,  $R = 32.5\%$ .

in the injection flow rate. This huge drop in recovery in the capillary region can be explained as follows. At the lowest flow rate the capillary forces are completely dominant over the viscous forces and this coupled with the favourable buoyancy force helps to produce very high recoveries. But when the flow rate is slightly increased, even though the capillary forces are still dominant the viscous forces also start to become more important. As the viscous forces start to compete with the capillary and the buoyancy forces the effect of lateral imbibition and spreading is reduced and the displacing liquid is no longer allowed to move up to the cell walls; instead, it is forced to move towards the outlet port. This behaviour of the displacing liquid can be easily understood by comparing the Figures 5.11a & 5.11b.

For the low viscosity ratios 3.3 and 1.72, increasing the flow rate in the viscous region (i.e., after 21.5 ml/hr) causes only very slight decrease in recovery. This is because in the viscous region buoyancy forces lose their importance completely and the displacement is controlled purely by viscous forces. Figures 5.11c & 5.11d show displacements in the viscous region.

Figures 5.12 & 5.13 show the effects of flow rate in vertical upward displacements for the viscosity ratio 1.72. All displacements in Figure 5.12 are in the capillary region. Figure 5.12a is very similar to Figure 5.11a except that the recovery is higher because of the lower viscosity ratio. As before, in the capillary region, we notice a rapid decrease in percentage recovery with increase in the injection flow rate. Figure 5.13 shows



Figure 5.12a



Figure 5.12b



Figure 5.12c

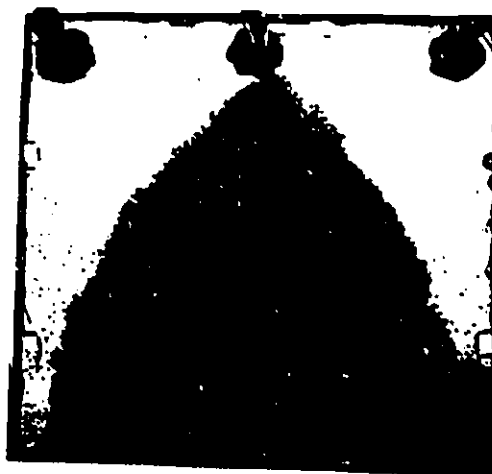


Figure 5.12d

**Figure 5.12 :** Effect of flow rate in Vertical Upward displacements,  $\mu_{ratio} = 1.72$   
5.12a)  $Q = 0.91$  ml/hr,  $t_{br} = 58969$  sec,  $R = 70.76\%$ ;  
5.12b)  $Q = 4.6$  ml/hr,  $t_{br} = 10260$  sec,  $R = 62.32\%$ ;  
5.12c)  $Q = 15.5$  ml/hr,  $t_{br} = 2806$  sec,  $R = 57.37\%$ ;  
5.12d)  $Q = 21.5$  ml/hr,  $t_{br} = 1790$  sec,  $R = 50.91\%$ .



Figure 5.13a

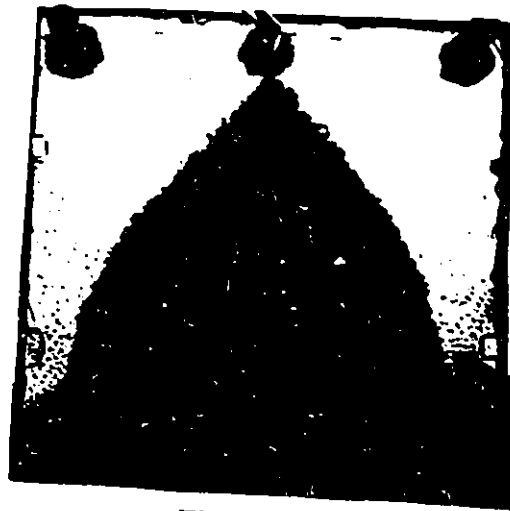


Figure 5.13b

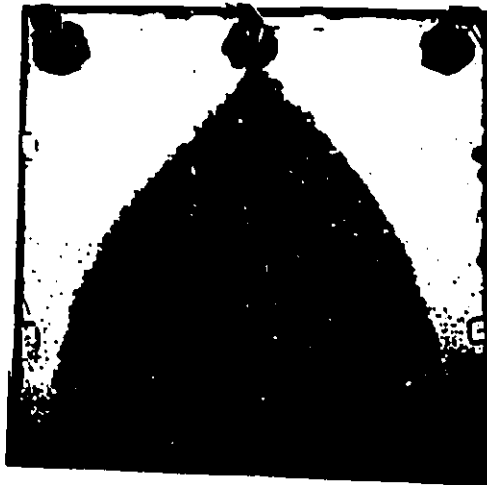


Figure 5.13c



Figure 5.13d

**Figure 5.13 :** Effect of flow rate in Vertical Upward displacements,  $\mu_{ratio} = 1.72$

5.13a)  $Q = 52.4$  ml/hr,  $t_{br} = 716.8$  sec,  $R = 49.7\%$ ;

5.13b)  $Q = 73.9$  ml/hr,  $t_{br} = 493.1$  sec,  $R = 48.21\%$ ;

5.13c)  $Q = 107.5$  ml/hr,  $t_{br} = 337.2$  sec,  $R = 47.96\%$ ;

5.13d)  $Q = 369.6$  ml/hr,  $t_{br} = 96.9$  sec,  $R = 47.37\%$ .

displacements occurring in the viscous region. In the viscous region as the flow rate increases from 52.4 ml/hr (Figure 5.13a) to 369.6 ml/hr (Figure 5.13d) the percentage recovery drops only slightly from 49.7% to 47.37%.

As discussed earlier in this section, in vertical upward displacements buoyancy forces are important in the capillary region only at very low flow rates. The extent to which the buoyancy forces are favourable depends on the density ratio between the two liquids involved in the displacement process. The higher the density ratio the more is the effect of the buoyancy forces. When the viscosity ratio is 143.5 the corresponding density ratio is only 1.14. For the density ratio 1.14, from Figure 5.9 we can observe that in the capillary region at low flow rates the recovery actually increases slightly with the flow rate instead of decreasing, and also unlike displacements with higher density ratios the maximum recovery is not obtained for the lowest flow rate. The recovery-flow rate relationship is thus very similar to that for the horizontal displacement. This can be explained by the fact that for the lowest density ratio studied the buoyancy forces are not strong enough to produce high recoveries even at very low flow rates and hence the displacement is controlled only by the capillary and viscous forces as in the case of horizontal displacement.

## **5.2.2 Effects of Viscosity Ratio**

Similar to the horizontal mode displacements, after flow rate, the viscosity ratio again plays a crucial role in determining percentage oil recovery for displacements in the

vertical upwards mode. Figure 5.14 shows the effect of viscosity ratio in vertical upward displacements for the very low flow rate of 0.91 ml/hr. As the viscosity ratio is reduced from 143.5 (Figure 5.14a) to 1.72 (Figure 5.14d) the percentage recovery increases by almost 6.7 times from 10.44% to 70.76%. The corresponding increase in recovery in the horizontal displacement is seen to be only 4.1 times (Figure 5.6). When the flow rate is 0.91 ml/hr for the highest viscosity ratio 143.5, the recoveries in the horizontal and vertical upward displacements are 7.4% and 10.44% respectively. The difference in percentage recoveries between the two modes is not very great at high viscosity ratios. For the same flow rate with the lowest viscosity ratio 1.72, the corresponding recoveries obtained in the two modes are 30.31% and 70.76% respectively. This shows that the buoyancy forces present in the vertical upwards mode, even though always favourable at the lowest flow rate, are highly effective only for low viscosity ratios (or high density ratios).

All pictures in Figure 5.14 are in the capillary region. As can be seen, in the capillary region a decrease in the viscosity ratio produces an increase in the percentage recovery. This is because at lower viscosity ratios the corresponding density ratios are high, which in turn creates more strong buoyancy forces. For the intermediate viscosity ratios of 11.11 and 3.3 we can observe patches of oil left trapped inside the displacing glycerol solution. By comparing Figures 5.14b & 5.14c we can see that when the viscosity ratio is reduced the amount of oil trapped also becomes less. For the lowest viscosity ratio 1.72, the amount of oil trapped between the displacing liquid is considerably less because



Figure 5.14a



Figure 5.14b



Figure 5.14c

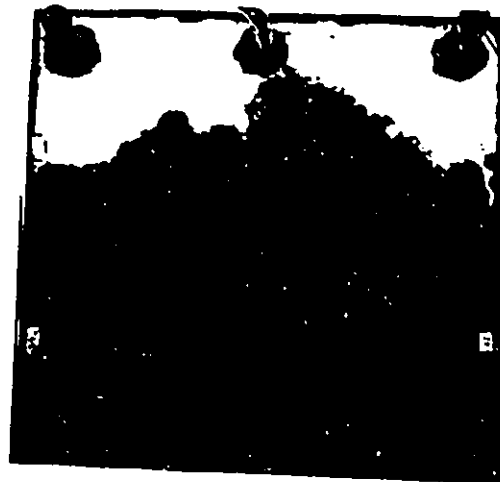


Figure 5.14d

**Figure 5.14 :** Effect of Viscosity ratio in Vertical Upward displacements,  
 **$Q = 0.91$  ml/hr**

5.14a)  $\mu_{ratio} = 143.5$ ,  $t_{br} = 8702$  sec,  $R = 10.44\%$ ;

5.14b)  $\mu_{ratio} = 11.11$ ,  $t_{br} = 35717$  sec,  $R = 42.86\%$ ;

5.14c)  $\mu_{ratio} = 3.3$ ,  $t_{br} = 53400$  sec,  $R = 64.08\%$ ;

5.14d)  $\mu_{ratio} = 1.72$ ,  $t_{br} = 58969$  sec,  $R = 70.76\%$ .

of the strong buoyancy forces acting.

Figure 5.15 shows the effects of viscosity ratio in vertical upward displacements for an intermediate flow rate of 21.5 ml/hr. As discussed in section 5.2.1, in vertical upward displacements an increase in flow rate almost always causes a reduction in the recovery. This becomes obvious by comparing Figures 5.14 & 5.15. For all the viscosity ratios studied, the recoveries in Figure 5.15 with flow rate 21.5 ml/hr, is less compared to Figure 5.14, where the flow rate is 0.91 ml/hr. This is primarily because of the reduction in the effectiveness of the buoyancy forces and the less lateral imbibition occurring at higher flow rates. Similar to Figure 5.14, in Figure 5.15 as we move from Figure 5.15a ( $\mu_{\text{ratio}} = 49.0$ ) to Figure 5.15d ( $\mu_{\text{ratio}} = 1.72$ ) the percentage recovery increases due to high density ratios and strong buoyancy forces at low viscosity ratios.

Figure 5.16 shows the effects of viscosity ratio in vertical upward displacements for a very high flow rate, 221.8 ml/hr. All four displacements in Figure 5.16 are in the viscous region. In the viscous region buoyancy forces are completely dominated by the viscous forces and hence the percentage recoveries in horizontal and vertical upward displacements are almost identical. In the viscous region the displacement patterns observed in vertical upward displacement are also very similar to those patterns observed in the viscous region for horizontal displacement.



Figure 5.15a



Figure 5.15b



Figure 5.15c



Figure 5.15d

**Figure 5.15 :** Effect of Viscosity ratio in Vertical Upward displacements,  
**Q = 21.5 ml/hr**

5.15a)  $\mu_{\text{ratio}} = 49.0$ ,  $t_{\text{br}} = 477.5$  sec,  $R = 13.58\%$ ;

5.15b)  $\mu_{\text{ratio}} = 11.11$ ,  $t_{\text{br}} = 689.4$  sec,  $R = 19.61\%$ ;

5.15c)  $\mu_{\text{ratio}} = 3.3$ ,  $t_{\text{br}} = 1329.6$  sec,  $R = 37.81\%$ ;

5.15d)  $\mu_{\text{ratio}} = 1.72$ ,  $t_{\text{br}} = 1790$  sec,  $R = 50.91\%$ .



Figure 5.16a

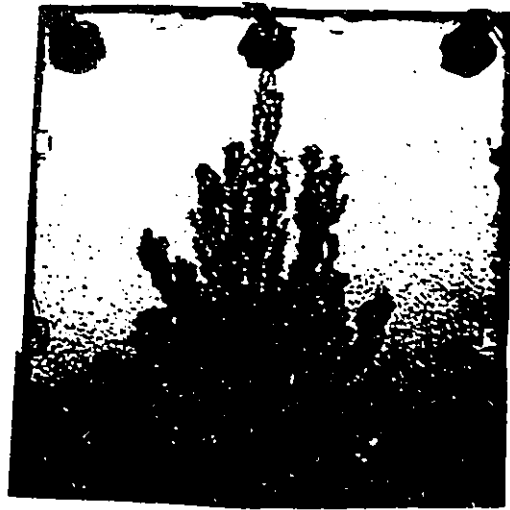


Figure 5.16b



Figure 5.16c



Figure 5.16d

**Figure 5.16 :** Effect of Viscosity ratio in Vertical Upward displac-

**Q = 221.8 ml/hr**

5.16a)  $\mu_{\text{ratio}} = 143.5$ ,  $t_{\text{br}} = 23.1$  sec,  $R = 6.78\%$ ,

5.16b)  $\mu_{\text{ratio}} = 11.11$ ,  $t_{\text{br}} = 51.8$  sec,  $R = 15.19\%$ ;

5.16c)  $\mu_{\text{ratio}} = 3.3$ ,  $t_{\text{br}} = 102.1$  sec,  $R = 29.95\%$ ;

5.16d)  $\mu_{\text{ratio}} = 1.72$ ,  $t_{\text{br}} = 160$  sec,  $R = 46.93\%$ .

## **5.3 Vertical Downward Displacements**

### **5.3.1 Effects of Flow Rate**

For vertical downward displacements the cell is again aligned in the vertical plane but the displacing liquid, glycerol solution, is injected through the centre port at the top of the cell. For displacements in this mode the buoyancy forces play an exactly opposite role, i.e., they have a negative influence on the percentage oil recovery at breakthrough. This is because for the buoyancy forces to be favourable in vertical downward displacements the density ratio should be less than one, or in other words the density of the displacing liquid should be less than the density of the displaced liquid so that the displacing liquid can stay at the top of the cell, away from the outlet port located at the bottom. But in the present system being studied, as the density of the displacing glycerol solution was always higher than the density of the displaced paraffin oil, the displacing liquid was forced to move towards the bottom of the cell where the outlet port is located and this caused a decrease in the breakthrough oil recovery.

For the same flow rate and viscosity ratio, due to the negative influence of the buoyancy forces, the percentage recovery at breakthrough in vertical downward displacement is lower than that in horizontal displacement. But it is important to note that the above statement is true only for low and intermediate flow rates where the buoyancy forces are dominant over capillary and viscous forces. For higher flow rates in the viscous region, viscous forces are completely dominant over the buoyancy forces and hence there is very little difference observed between the recoveries in different modes. By comparing Table

5.1 with Table 5.3 one can observe that the recovery in vertical downward displacement is always lower than that in horizontal displacement for all flow rates less than 52.4 ml/hr. Between 0.91 ml/hr and 52.4 ml/hr the lesser the flow rate the more is the difference between the recoveries in the two modes. This shows that the buoyancy forces, even though always unfavourable in vertical downward displacements, are highly destructive only at very low flow rates indicating their dominance over capillary and viscous forces at these flow rates.

In vertical downward displacements, similar to vertical upward displacements, no stabilized flow region is observed. From Figure 5.17 we can see that the whole range of flow rates studied can be broadly classified into two regions, namely the capillary region at low flow rates and the viscous region at high flow rates. In the capillary region both the capillary and the buoyancy forces are important. At the lowest flow rate of 0.91 ml/hr the unfavourable buoyancy forces are completely dominant over the capillary forces and hence the recovery is extremely low. But as the flow rate increases in the capillary region, capillary forces gradually overcome the negative influence of the buoyancy forces and thus the recovery increases very rapidly to a maximum value. After reaching the maximum recovery further increase in flow rate causes the recovery to drop slightly as the viscous forces start to control the displacement at higher flow rates.

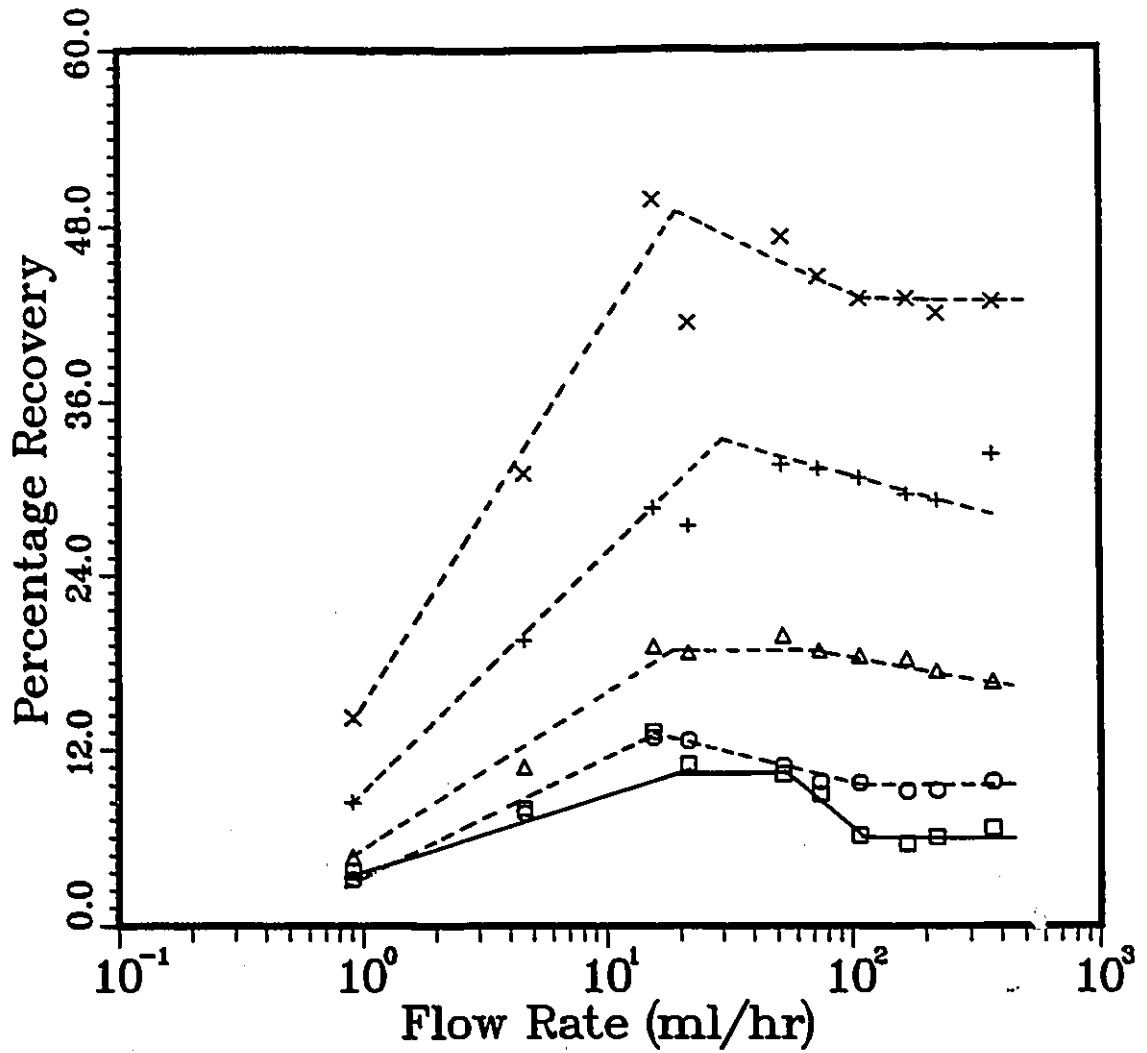
Figure 5.18 shows the effect of flow rate in vertical downward displacements for a very high viscosity ratio, 143.5. Figures 5.18a & 5.18b are both in the capillary region and

Table 5.3: Percentage recoveries in Vertical Downward displacement

| Viscosity Ratio ▶<br>Flow Rate ▼<br>(ml/hr) | 143.5 | 49.0  | 11.11 | 3.3   | 1.72  |
|---|-------|-------|-------|-------|-------|
| 369.6                                       | 6.60  | 9.78  | 16.62 | 32.22 | 42.61 |
| 221.8                                       | 6.01  | 9.21  | 17.37 | 29.04 | 41.86 |
| 168.0                                       | 5.56  | 9.16  | 18.20 | 29.49 | 42.82 |
| 107.5                                       | 6.13  | 9.71  | 18.42 | 30.58 | 42.82 |
| 73.90                                       | 8.96  | 9.78  | 18.77 | 31.24 | 44.39 |
| 52.40                                       | 10.30 | 10.87 | 19.76 | 31.55 | 47.15 |
| 21.50                                       | 10.97 | 12.60 | 18.64 | 27.31 | 41.26 |
| 15.50                                       | 13.19 | 12.82 | 19.07 | 28.55 | 49.68 |
| 4.600                                       | 7.97  | 7.66  | 10.85 | 19.51 | 30.94 |
| 0.910                                       | 3.68  | 3.12  | 4.68  | 8.42  | 14.20 |

# VERTICAL DOWNWARD DISPLACEMENT

$x : \mu/\mu_w = 1.72 \quad , \quad \rho_w/\rho_o = 1.3911$   
 $+ : \mu/\mu_w = 3.3 \quad , \quad \rho_w/\rho_o = 1.3558$   
 $\Delta : \mu/\mu_w = 11.11 \quad , \quad \rho_w/\rho_o = 1.3341$   
 $\circ : \mu/\mu_w = 49.0 \quad , \quad \rho_w/\rho_o = 1.2281$   
 $\square : \mu/\mu_w = 143.5 \quad , \quad \rho_w/\rho_o = 1.1403$



**Figure 5.17 :** Breakthrough recovery as a function of flow rate, for displacements in the vertical downward mode.

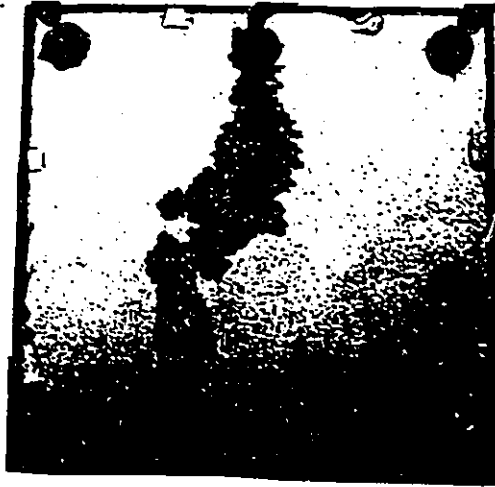


Figure 5.18a

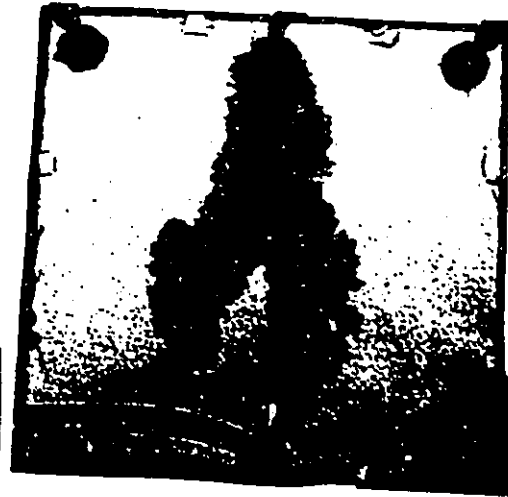


Figure 5.18b



Figure 5.18c



Figure 5.18d

**Figure 5.18 :** Effect of flow rate in Vertical Downward displacements,  $\mu_{ratio} = 143.5$

5.18a)  $Q = 0.91$  ml/hr,  $t_{tr} = 3067.2$  sec,  $R = 3.68\%$ ;

5.18b)  $Q = 15.5$  ml/hr,  $t_{tr} = 645.3$  sec,  $R = 13.19\%$ ;

5.18c)  $Q = 52.4$  ml/hr,  $t_{tr} = 148.5$  sec,  $R = 10.3\%$ ;

5.18d)  $Q = 107.5$  ml/hr,  $t_{tr} = 43.1$  sec,  $R = 6.13\%$ .

Figures 5.18c & 5.18d are in the viscous region. As we can see from Figure 5.18a in the capillary region at the lowest flow rate 0.91 ml/hr, the unfavourable buoyancy forces are completely dominant over the capillary forces, thereby greatly suppressing the effects of lateral imbibition and spreading. This destructive effect of the unfavourable buoyancy force is the reason for the extremely low recovery (3.68%) observed in Figure 5.18a. Figure 5.18b shows the breakthrough picture for the flow rate 15.5 ml/hr. Even though still in the capillary region the percentage recovery increases by almost 4 times to 13.19%. The reason for the higher recovery in the present case can be explained by comparing the displacement patterns in Figure 5.18a & 5.18b. In Figure 5.18b the recovery is higher because of the higher lateral spreading that has occurred compared to Figure 5.18a. More lateral spreading also indicates that the capillary forces are stronger than the buoyancy forces at this flow rate. Once the recovery reaches the maximum value further increase in flow rate in the viscous region causes a drop in recovery as seen in Figures 5.18c & 5.18d. This is because of the large number of viscous fingers formed with the increase in the flow rate.

Figure 5.19 shows the effects of flow rate in vertical downward displacements for an intermediate viscosity ratio, 11.11. Similar to Figure 5.18a, Figure 5.19a is also in the capillary region and as the flow rate is very low the unfavourable buoyancy forces dominate the displacement causing an extremely low recovery of only 4.68%. As the flow rate is only 15.5 ml/hr, Figure 5.19b is also in the capillary region. As before, in the capillary region recovery increases with an increase in the flow rate. Figures 5.19c

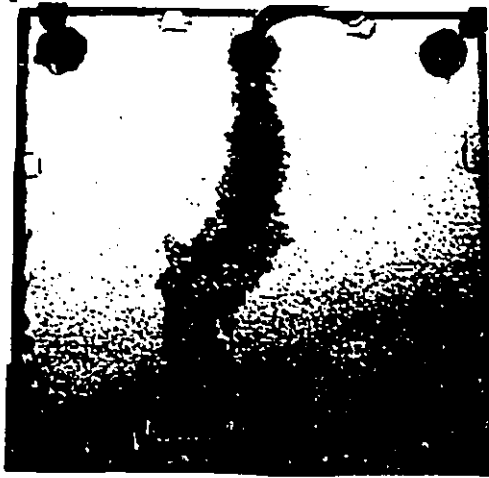


Figure 5.19a

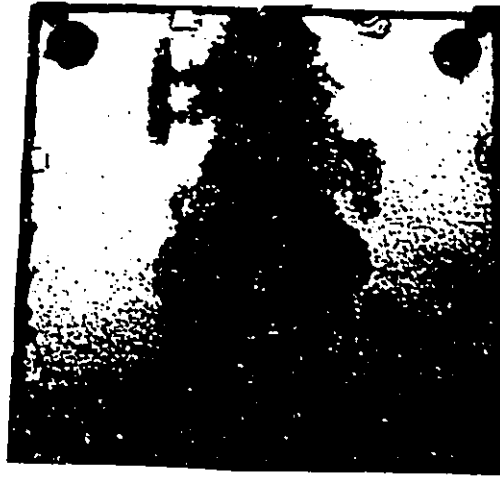


Figure 5.19b



Figure 5.19c



Figure 5.19d

**Figure 5.19** : Effect of flow rate in Vertical Downward displacements,  $\mu_{ratio} = 11.11$

5.19a)  $Q = 0.91$  ml/hr,  $t_{br} = 3900$  sec,  $R = 4.68\%$ ;

5.19b)  $Q = 15.5$  ml/hr,  $t_{br} = 933$  sec,  $R = 19.07\%$ ;

5.19c)  $Q = 107.5$  ml/hr,  $t_{br} = 129.5$  sec,  $R = 18.42\%$ ;

5.19d)  $Q = 221.8$  ml/hr,  $t_{br} = 59.2$  sec,  $R = 17.37\%$ .

& 5.19d are in the viscous flow region. As can be observed from these two figures, increase in flow rate in the viscous region causes the recovery to decrease slightly due to the higher fingering occurring at larger flow rates.

Figures 5.20 & 5.21 show the effects of flow rate in vertical downward displacements for a very low viscosity ratio, 1.72. The displacements in Figures 5.20a, 5.20b, 5.20c are all in the capillary region. As with all other viscosity ratios previously discussed recovery in the capillary region increases with an increase in the flow rate. Figure 5.20d is in the viscous region and so the recovery starts to decrease slightly. All displacements shown in Figure 5.21 are also in the viscous region and a very slight decrease in recovery is observed with the increase in flow rate. As would be expected for displacements with low viscosity ratios, in the viscous region many viscous fingers were not formed, instead a single 'gravity tongue' as in Figure 5.21 was observed. Comparing all four displacements in Figure 5.21 it can also be seen that the single gravity tongue, which is observed in all the cases, gets more smooth along the edges with an increase in the flow rate.

### **5.3.2 Effects of Viscosity Ratio**

Figure 5.22 shows the effects of viscosity ratio in vertical downward displacements for a very low flow rate, 0.91 ml/hr. All four displacements in Figure 5.22 are in the capillary region. In the previous section it was observed that small increases in the flow rate in the capillary region cause the recovery to increase considerably for displacements



Figure 5.20a



Figure 5.20b



Figure 5.20c



Figure 5.20d

**Figure 5.20** : Effect of flow rate in Vertical Downward displacements,  $\mu_{\text{ratio}} = 1.72$

5.20a)  $Q = 0.91$  ml/hr,  $t_{\text{br}} = 11836$  sec,  $R = 14.2\%$ ;

5.20b)  $Q = 4.6$  ml/hr,  $t_{\text{br}} = 5093$  sec,  $R = 30.94\%$ ;

5.20c)  $Q = 15.5$  ml/hr,  $t_{\text{br}} = 2450$  sec,  $R = 49.68\%$ ;

5.20d)  $Q = 52.4$  ml/hr,  $t_{\text{br}} = 680$  sec,  $R = 47.15\%$ .

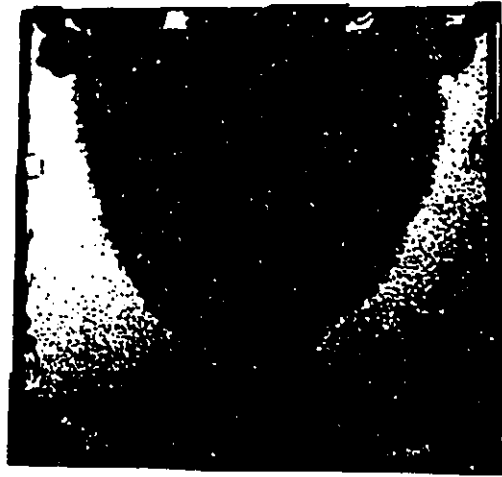


Figure 5.21a



Figure 5.21b



Figure 5.21c



Figure 5.21d

**Figure 5.21 :** Effect of flow rate in Vertical Downward displacements,  $\mu_{ratio} = 1.72$

5.21a)  $Q = 73.9$  ml/hr,  $t_{br} = 454$  sec,  $R = 44.39\%$ ;

5.21b)  $Q = 107.5$  ml/hr,  $t_{br} = 301.1$  sec,  $R = 42.82\%$ ;

5.21c)  $Q = 221.8$  ml/hr,  $t_{br} = 142.7$  sec,  $R = 41.86\%$ ;

5.21d)  $Q = 369.6$  ml/hr,  $t_{br} = 87.15$  sec,  $R = 42.61\%$ .

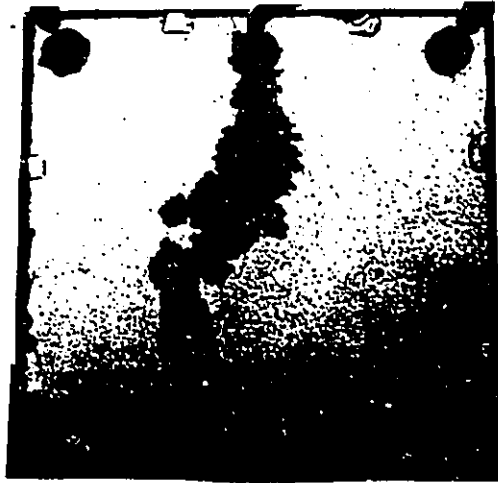


Figure 5.22a



Figure 5.22b



Figure 5.22c



Figure 5.22d

**Figure 5.22 :** Effect of Viscosity ratio in Vertical Downward displacements,

**$Q = 0.91$  ml/hr**

5.22a)  $\mu_{\text{ratio}} = 143.5$ ,  $t_{\text{br}} = 3067.2$  sec,  $R = 3.68\%$ ;

5.22b)  $\mu_{\text{ratio}} = 11.11$ ,  $t_{\text{br}} = 3900$  sec,  $R = 4.68\%$ ;

5.22c)  $\mu_{\text{ratio}} = 3.3$ ,  $t_{\text{br}} = 7014$  sec,  $R = 8.42\%$ ;

5.22d)  $\mu_{\text{ratio}} = 1.72$ ,  $t_{\text{br}} = 11836$  sec,  $R = 14.2\%$ .

in the vertical downward mode. In a similar way a decrease in the viscosity ratio also causes an increase in percentage recovery for all the flow rates. In the capillary region (0.91 ml/hr to 21.5 ml/hr) when the viscosity ratio is reduced from 143.5 to 1.72 the recovery increases by approximately 3.7 to 3.9 times. In the viscous region, at intermediate flow rates (52.4 ml/hr to 73.9 ml/hr) the recovery increases by 4.5 to 5 times and at very high flow rates the increase in recovery is about 7 times.

Figures 5.22a & 5.22b show the breakthrough pictures for the viscosity ratios 143.5 and 11.11 respectively. The recovery increases by approximately 27% when the viscosity ratio is reduced from 143.5 to 11.11. From Tables 5.1 & 5.2 we can find that in horizontal and vertical upward displacements for the same reduction in the viscosity ratio the recovery increases by about 109% and 310% respectively. As buoyancy forces do not play any significant role for 2-dimensional porous media in horizontal mode displacements, the recoveries obtained can be taken as the reference. In the vertical upward mode, as discussed in section 5.2, buoyancy forces are highly favourable at very low flow rates and low viscosity ratios, which explains the huge 310% increase in recovery observed. In vertical downward displacements for the lowest flow rate 0.91 ml/hr the buoyancy forces are highly unfavourable for all the viscosity ratios and that is the reason the recoveries increase only very slightly with a decrease in the viscosity ratio.

Figures 5.22c & 5.22d show the breakthrough pictures for the viscosity ratios 3.3 & 1.72 respectively. When the viscosity ratio is decreased from 11.11 to 3.3 (Figures 5.22b &

5.22c) recovery increases by approximately 80%. If the viscosity ratio is decreased further to 1.72 the recovery again increases by about 70%. This shows that in vertical downward displacements for the lowest flow rate studied, even though the actual recoveries obtained are always very low, the viscosity ratio - percentage recovery relationship is still sensitive, and large changes in recovery can be observed if two low viscosity ratios are compared. This behaviour is very similar to that of the horizontal displacement and is also discussed in section 5.1.2.

Figure 5.23 shows the effects of viscosity ratio in vertical downward displacements for an intermediate flow rate, 15.5 ml/hr. This is still in the capillary flow region of the displacement. As we can see from Figure 5.23, in the capillary region with decrease in the viscosity ratio the percentage recovery increases due to more lateral spreading. Figure 5.24 shows the effect of viscosity ratio in vertical downward displacements for a very high flow rate, 168 ml/hr. With a decrease in the viscosity ratio the percentage recovery increases as for all other flow rates. The displacement patterns with various viscosity ratios can be very clearly observed when the flow rate is very high. In Figure 5.24 all four displacements are in the viscous flow region and hence the viscous forces completely dominate the buoyancy effects. In vertical downward displacements, as in the other two modes, for very high flow rates with the decrease in the viscosity ratio fewer and more wider fingers are formed. With the lowest viscosity ratio a single 'gravity tongue' is observed.



Figure 5.23a

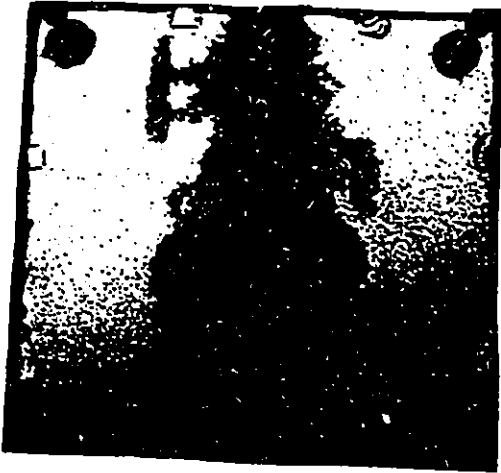


Figure 5.23b



Figure 5.23c



Figure 5.23d

**Figure 5.23 :** Effect of Viscosity ratio in Vertical Downward displacements,  
 $Q = 15.5 \text{ ml/hr}$

- 5.23a)  $\mu_{\text{ratio}} = 143.5$ ,  $t_{\text{br}} = 645.3 \text{ sec}$ ,  $R = 13.19\%$ ;
- 5.23b)  $\mu_{\text{ratio}} = 11.11$ ,  $t_{\text{br}} = 933 \text{ sec}$ ,  $R = 19.07\%$ ;
- 5.23c)  $\mu_{\text{ratio}} = 3.3$ ,  $t_{\text{br}} = 1396.4 \text{ sec}$ ,  $R = 28.55\%$ ;
- 5.23d)  $\mu_{\text{ratio}} = 1.72$ ,  $t_{\text{br}} = 2430 \text{ sec}$ ,  $R = 49.68\%$ .



Figure 5.24a



Figure 5.24b



Figure 5.24c

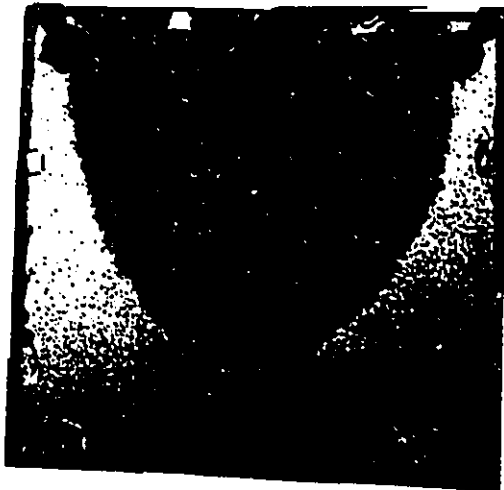


Figure 5.24d

**Figure 5.24 :** Effect of Viscosity ratio in Vertical Downward displacements,  
**Q = 168 ml/hr**

|        |                        |                  |      |                 |
|--------|------------------------|------------------|------|-----------------|
| 5.24a) | $\mu_{ratio} = 143.5,$ | $t_{br} = 25$    | sec, | $R = 5.56\%$ ;  |
| 5.24b) | $\mu_{ratio} = 11.11,$ | $t_{br} = 81.9$  | sec, | $R = 18.2\%$ ;  |
| 5.24c) | $\mu_{ratio} = 3.3,$   | $t_{br} = 132.7$ | sec, | $R = 29.49\%$ ; |
| 5.24d) | $\mu_{ratio} = 1.72,$  | $t_{br} = 192.7$ | sec, | $R = 42.82\%$ . |

## **5.4 Effects of Density Ratio in Different Modes**

In the earlier three sections, the effects of flow rate and viscosity ratio in different modes were considered. However, since the density and viscosity of the displacing glycerol solution are both dependent on the glycerol concentration, with a change in the viscosity ratio the density ratio also changes. Density ratio plays a significant role in determining the displacement patterns and the percentage oil recovery in vertical upward and vertical downward displacements. As can be understood the higher the density ratio the more would be the effects of buoyancy forces in vertical upward/downward displacements. In horizontal mode displacements, except for the gravity under-ride which sometimes occurred at very low flow rates, the effects of buoyancy forces are otherwise negligible and hence the density ratio variations do not cause any significant changes in either the recoveries or the displacement patterns.

In the system being studied, as both viscosity and density ratios are dependent variables, it is difficult to observe the effects of density ratio separately from those of the viscosity ratio. The study of the effects of density ratio becomes considerably more easy if displacements in different modes having the same flow rate and viscosity ratio are compared together. This comparison facilitates an understanding of the role played by the density ratio in different modes of displacement.

Figure 5.25 shows the effects of flow mode variation for a very high density ratio of 1.391, when the flow rate is 0.91 ml/hr. In the previous sections it was seen that the



Figure 5.25a



Figure 5.25b



Figure 5.25c

$$Q = 0.91 \text{ ml/hr}$$

$$\mu_{\text{ratio}} = 1.72$$

$$\rho_{\text{ratio}} = 1.391$$

- Figure 5.25 :** Effect of flow mode variation for a high density ratio displacement
- 5.25a) Vertical upward mode,  $t_{\text{tr}} = 58969 \text{ sec}$ ,  $R = 70.76\%$ ;
  - 5.25b) Vertical downward mode,  $t_{\text{tr}} = 11836 \text{ sec}$ ,  $R = 14.2\%$ ;
  - 5.25c) Horizontal mode,  $t_{\text{tr}} = 25260 \text{ sec}$ ,  $R = 30.31\%$ .

buoyancy forces are highly effective for very low flow rates and low viscosity ratios (or high density ratios). In Figure 5.25 as both these conditions (lowest flow rate and highest density ratio) are met, the effects of density ratio in different flow modes is very clearly observed. Figure 5.25a shows the displacement observed in the vertical upward mode. In the vertical upward displacement as discussed in section 5.2 the buoyancy forces are as such favourable at low flow rates. In Figure 5.25a along with the lowest flow rate, as the density ratio is also high, this supplements and reinforces the favourable effect of the buoyancy forces and hence the recovery is extremely high at 70.76%. In vertical downward displacements (Figure 5.25b) an exactly opposite situation is observed. Low flow rate coupled with the high density ratio causes an extremely low recovery of only 14.2%, as the buoyancy forces are highly unfavourable at these conditions. In horizontal displacement (Figure 5.25c), as expected, the recovery is in between those of the other two modes (30.31%) as the buoyancy forces do not play any significant role.

Figure 5.26 shows the effects of flow mode variation for a lower density ratio of 1.228, when the flow rate is 15.5 ml/hr. By comparing Figures 5.26a & 5.26c we can see that the recovery in the vertical upward displacement is actually lower than that obtained in the horizontal displacement. This indicates that the buoyancy forces do not have any significance at lower density ratios even if the flow rate is increased to intermediate values. But in the vertical downward displacement (Figure 5.26b) the recovery, as expected, is still lower than that for the horizontal displacement. From this observation we can conclude that in vertical upward displacements for the buoyancy forces to be



Figure 5.26a

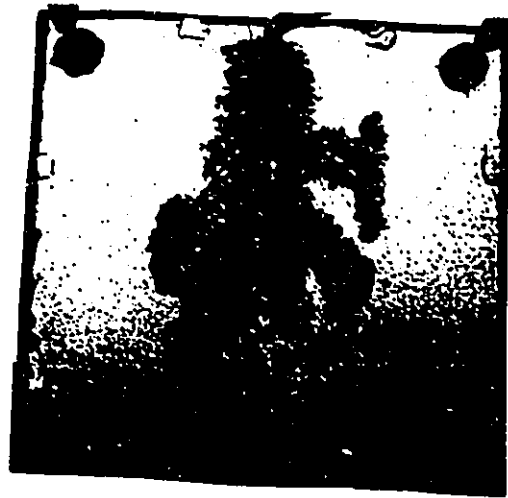


Figure 5.26b



Figure 5.26c

$$Q = 15.5 \text{ ml/hr}$$

$$\mu_{\text{ratio}} = 49.0$$

$$\rho_{\text{ratio}} = 1.228$$

**Figure 5.26 :** Effect of flow mode variation for a low density ratio displacement

5.26a) Vertical upward mode,  $t_{\text{tr}} = 710.6 \text{ sec}$ ,  $R = 14.53\%$ ;

5.26b) Vertical downward mode,  $t_{\text{tr}} = 626.9 \text{ sec}$ ,  $R = 12.82\%$ ;

5.26c) Horizontal mode,  $t_{\text{tr}} = 988 \text{ sec}$ ,  $R = 20.2\%$ .

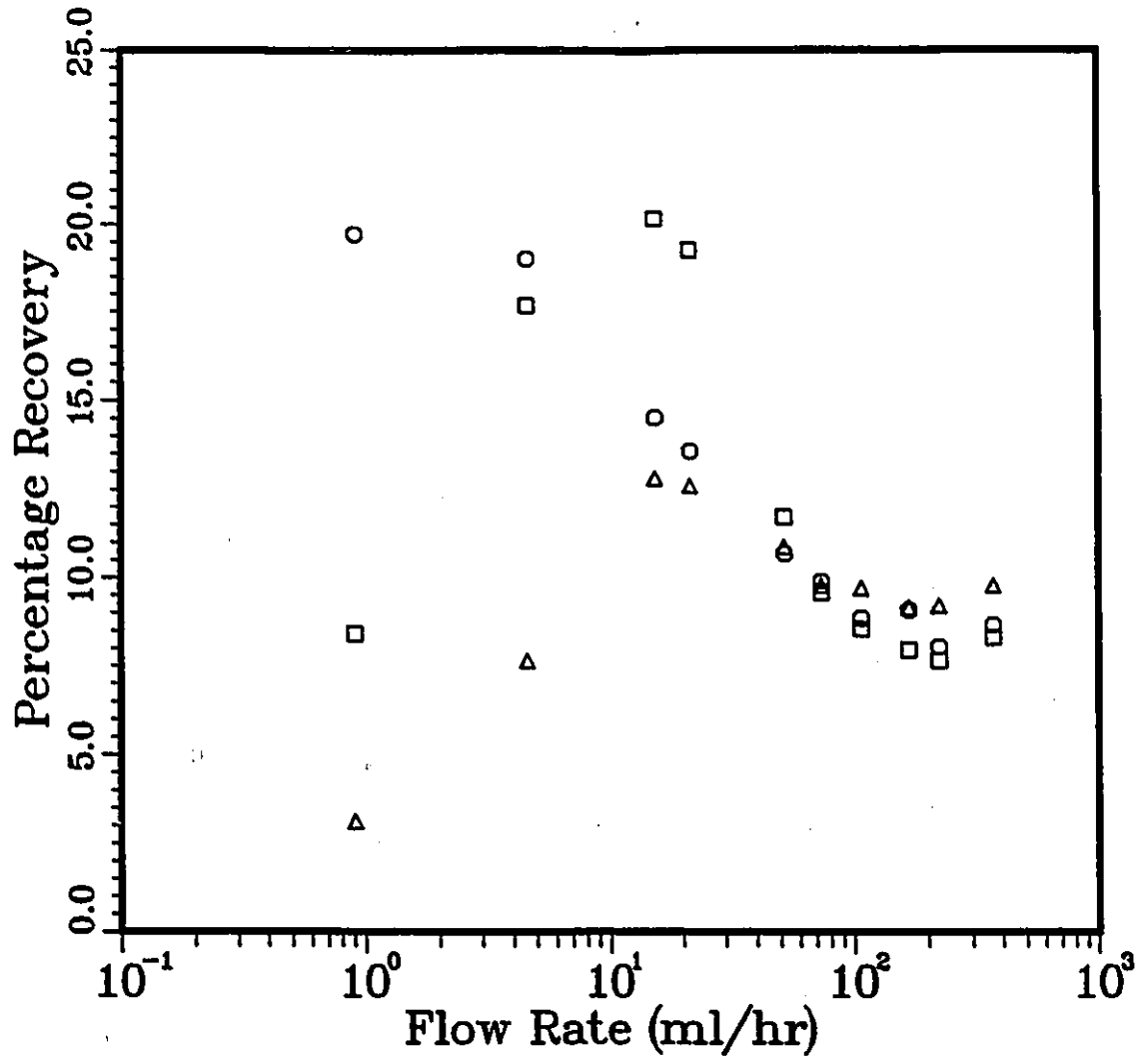
favourable at intermediate flow rates such as 15.5 ml/hr, the density ratio should at least be greater than 1.228. The displacements performed in the vertical upward mode for the next higher density ratio 1.334 and the flow rate 15.5 ml/hr do in fact indicate that the buoyancy forces are favourable and the recovery higher than in the horizontal displacement.

Figure 5.27 shows the percentage recovery versus flow rate relationship for the three different modes when the density ratio is 1.228. From this Figure we can see that at higher flow rates there is no great difference between the recoveries obtained in the different modes. When the low and intermediate flow rates are considered, the recoveries obtained at very low flow rates ( $< 5$  ml/hr) are higher in vertical upward displacement compared to the horizontal displacement, but on the other hand for intermediate flow rates (5 to 50 ml/hr) better recoveries are obtained with the horizontal displacement. Figure 5.28 shows the percentage recovery-flow rate relationship for different modes of displacement, with the density ratio in all cases being 1.391. As can be seen from Figure 5.28 the percentage recovery in vertical upward displacement is always higher than in horizontal displacement for all flow rates less than 15 ml/hr. By comparing Figures 5.27 and 5.28 we can observe that the range of flow rates over which the buoyancy forces are dominant increases with an increase in density ratio.

Figures 5.29, 5.30 & 5.31 show the percentage recovery versus viscosity ratio relationship in different modes with very high, intermediate and very low flow rates respectively.

# 30% SOLN: DENSITY RATIO 1.228

- : Vertical Upward Mode
- : Horizontal Mode
- △ : Vertical Downward Mode



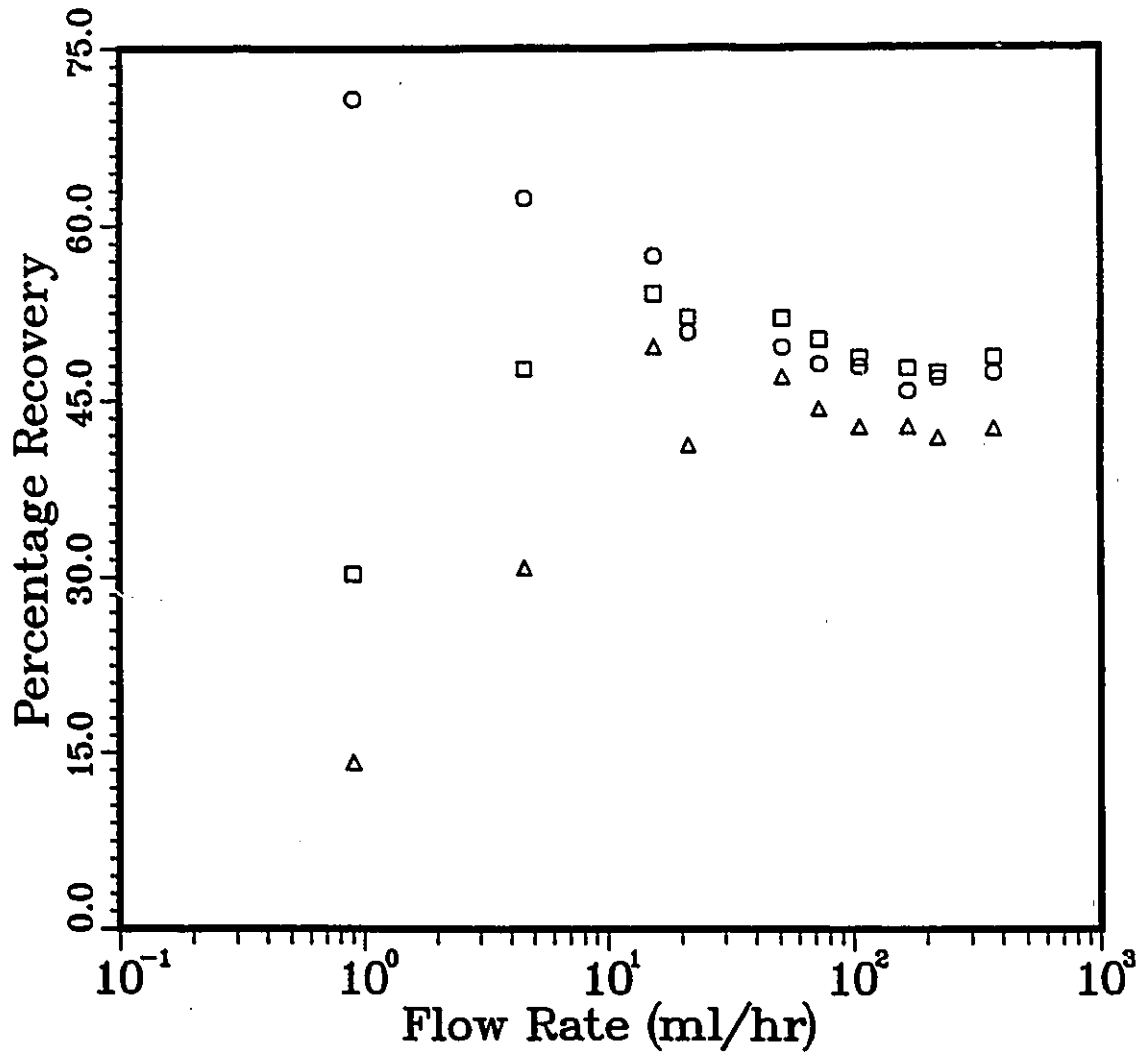
**Figure 5.27 :** Breakthrough recovery as a function of flow rate, for all three modes, at a low density ratio 1.228.

# 82% SOLN: DENSITY RATIO 1.39

○ : Vertical Upward Mode

□ : Horizontal Mode

△ : Vertical Downward Mode



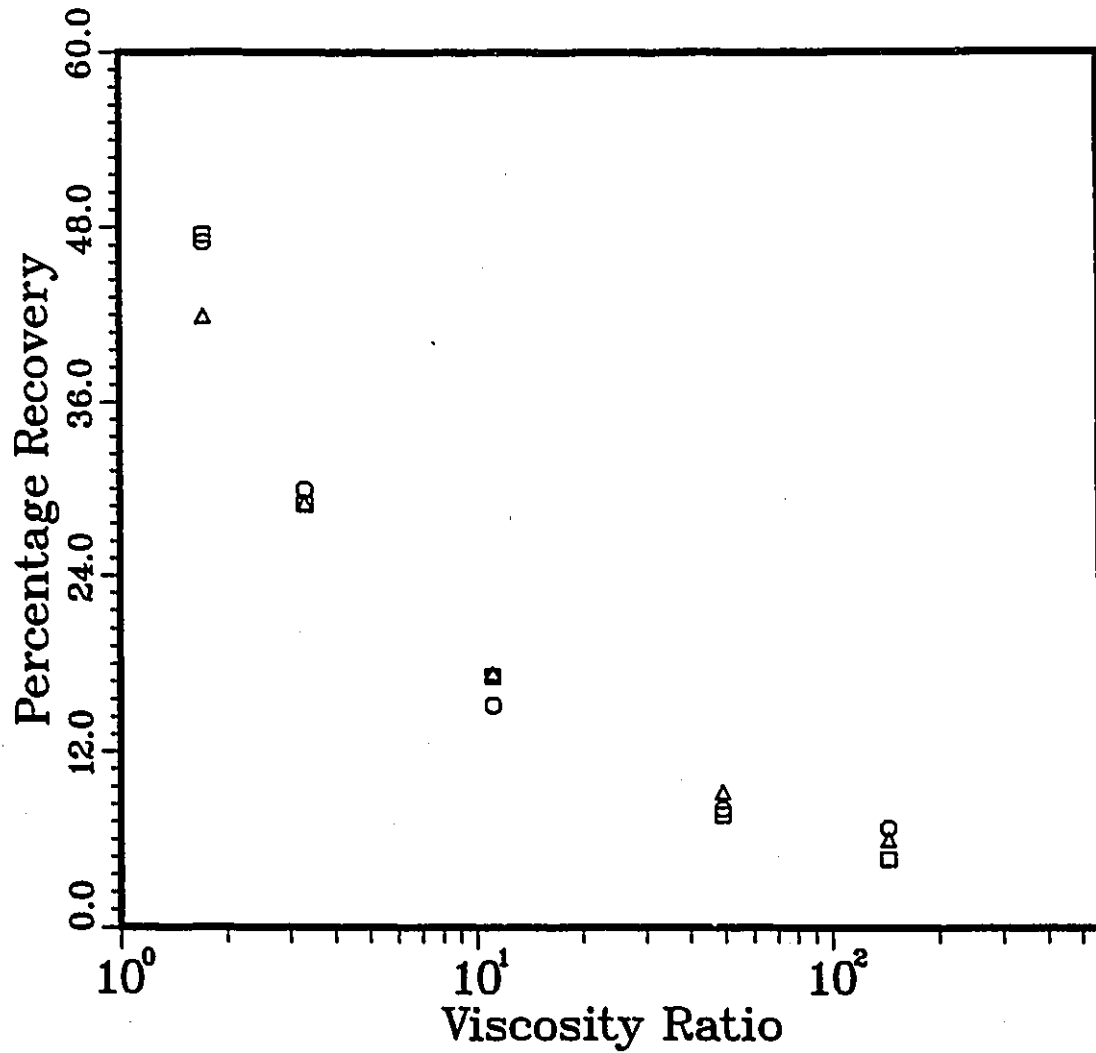
**Figure 5.28 :** Breakthrough recovery as a function of flow rate, for all three modes, at a high density ratio 1.39.

FLOW RATE : 221.76 ml/hr

○ : Vertical Upward Mode

□ : Horizontal Mode

△ : Vertical Downward Mode



**Figure 5.29 :** Breakthrough recovery as a function of viscosity ratio, for all three modes, at a very high flow rate 221.8 ml/hr.

FLOW RATE : 15.456 ml/hr

○ : Vertical Upward Mode

□ : Horizontal Mode

△ : Vertical Downward Mode

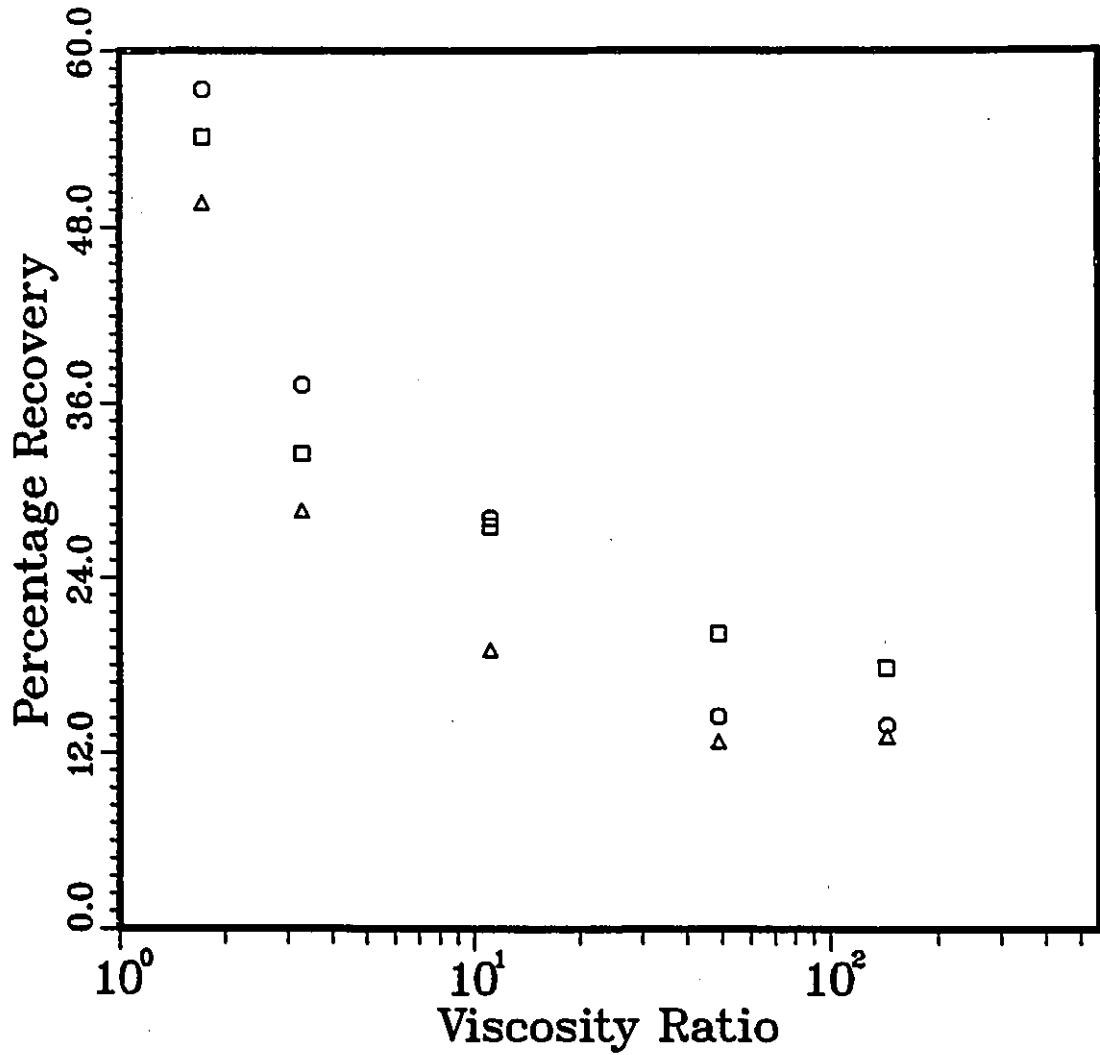
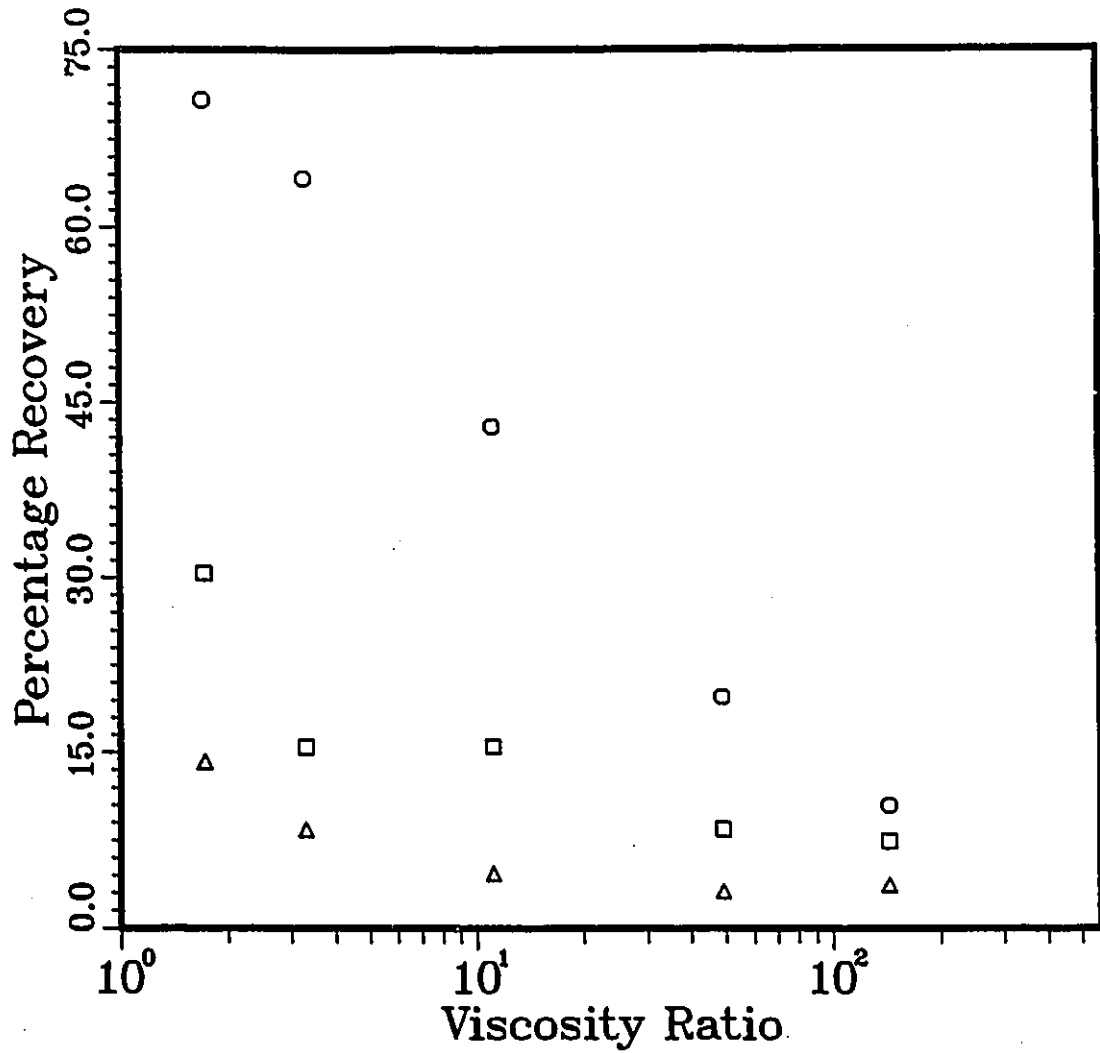


Figure 5.30 : Breakthrough recovery as a function of viscosity ratio, for all three modes, at an intermediate flow rate 15.5 ml/hr.

FLOW RATE : 0.91 ml/hr

- : Vertical Upward Mode
- : Horizontal Mode
- △ : Vertical Downward Mode



**Figure 5.31 :** Breakthrough recovery as a function of viscosity ratio, for all three modes, at a very low flow rate 0.91 ml/hr.

From Figure 5.29 we can again see that at very high flow rates there is no great difference between the recoveries obtained from different modes, regardless of the viscosity ratio under consideration. Figure 5.30 shows a similar relationship for an intermediate flow rate. From this figure we can observe that there is a definite increase in the recovery in vertical upward displacement compared to horizontal displacement when low viscosity ratios are considered. At higher viscosity ratios, as discussed before, again the horizontal displacement gives better recoveries than vertical upward displacement due to low density ratios and weak buoyancy forces. Figure 5.31 also shows the same relationship for the lowest flow rate, 0.91 ml/hr. At this lowest flow rate, for *all* the viscosity ratios the percentage recovery in vertical upward displacement is *always* higher than in horizontal displacement. This is because when the flow rate is extremely low, even for the lowest density ratio studied the buoyancy forces are still strong enough to improve the recovery.

# Chapter 6

## Conclusions

The following conclusions may be drawn from this study :

- (1) In horizontal mode displacements, for most of the viscosity ratios studied, the percentage recovery-flow rate relationship shows three distinct regions, namely (i) a capillary region at very low flow rates, (ii) a stabilized flow region at intermediate flow rates, and (iii) a viscous region at very high flow rates. In the capillary region the recovery increases with an increase in flow rate, in the stabilized flow region the recovery remains constant at a maximum value, and in the viscous region the recovery decreases with an increase in flow rate.
- (2) The stabilized flow region which is observed in the horizontal mode at high viscosity ratios gradually disappears and becomes part of the capillary region for low viscosity ratio displacements occurring in the horizontal mode.
- (3) In horizontal mode displacements the critical flow rate for transition from the capillary region to the viscous region is generally between 15 and 20 ml/hr.

- (4) Buoyancy forces are highly effective at very low flow rates and low viscosity ratios (or high density ratios). For all density ratios, vertical upward displacement always yields the highest recovery at the lowest flow rate studied (0.91 ml/hr).
- (5) At very low flow rates, where buoyancy forces are highly effective, there is a large difference between the recoveries obtained in the different flow modes at low viscosity ratios. However, as the viscosity ratio increases the difference in recoveries between the different modes decreases.
- (6) For low density ratios and intermediate flow rates, horizontal displacement produces higher recoveries than vertical upward displacement.
- (7) At very high flow rates, irrespective of the density and viscosity ratios, buoyancy forces become increasingly insignificant.

# Chapter 7

## Recommendations

- (1) In this work, the density and viscosity ratios could not be varied independently as both were dependent on the concentration of the displacing glycerol solution. However, in future studies, in order to understand the effects of density and viscosity ratios separately, it is recommended that methods be found to vary them independently.
- (2) In real oil reservoirs, viscosity ratios could be anywhere in the range of 1500 to 1. In the present work, as the maximum and minimum viscosities of the displaced and the displacing phases were fixed, the highest viscosity ratio that could be studied was only 143.46. In future, displacements with still higher viscosity ratios could be performed so that the effects of viscosity ratio could be analyzed in more detail.
- (3) Displacements could also be performed in the vertical-transverse mode and the results compared with the existing results in the other three modes.
- (4) In the present study, even though the density ratio was favourable in vertical upward displacement and unfavourable in vertical downward displacement, viscosity ratios were always unfavourable for all the cases studied. Thus, the other two possible cases, i.e. (i) both viscosity and density ratios favourable and (ii)

viscosity ratio - favourable and density ratio - unfavourable, should be studied and the results compared with the results of the present study.

## NOMENCLATURE

|                  |  |
|------------------|--|
| $t$              |  |
| $C$              | Chouke parameter                                       |
| $C^*$            | wettability number                                     |
| $d_p$            | particle diameter, [m]                                 |
| $g$              | gravitational acceleration, [m/s <sup>2</sup> ]        |
| $K$              | permeability, [m <sup>2</sup> ]                        |
| $\Delta N_c$     | capillary number difference                            |
| $P_c$            | capillary pressure                                     |
| $Q$              | flow rate, [ml/hr]                                     |
| $r, r'$          | principal radii of curvature of finger tips, [m]       |
| $R$              | percentage recovery                                    |
| $t_{br}$         | breakthrough time, [s]                                 |
| $U$              | velocity, [m/s]  |
| $U_c$            | critical Velocity, [m/s]                               |
| $V$              | pore volume of the cell, [ml]                          |
| $V_b$            | bulk volume, [m <sup>3</sup> ]                         |
| $V_m$            | matrix volume, [m <sup>3</sup> ]                       |
| $V_p$            | pore volume, [m <sup>3</sup> ]                         |
| $\sigma, \gamma$ | interfacial tension, [N/m]                             |
| $\gamma^*$       | macroscopic (or effective) interfacial tension, [N/m]  |
| $\mu_o$          | viscosity of the displaced heavy paraffin oil, [mPa-s] |

|                |   |
|----------------|---|
| $\mu_w$        | viscosity of the displacing glycerol solution, [mPa-s]            |
| $\mu_{ratio}$  | viscosity ratio, ( $= \mu_o/\mu_w$ )                              |
| $\phi$         | porosity  |
| $\Delta\rho$   | density difference, ( $=\rho_w-\rho_o$ ), [kg/m <sup>3</sup> ]    |
| $\rho_o$       | density of the displaced heavy paraffin oil, [kg/m <sup>3</sup> ] |
| $\rho_w$       | density of the displacing glycerol solution, [kg/m <sup>3</sup> ] |
| $\rho_{ratio}$ | density ratio, ( $=\rho_w/\rho_o$ )                               |
| $\theta$       | contact angle   |

## Bibliography

- (1) Homsy, G.M.: Viscous Fingering in Porous Media, *Ann.Rev.Fluid Mech...* 19: 271-311 (1987).
- (2) Saffman, P.G., Taylor, G.I.: The penetration of a fluid into a porous medium or Hele-Shaw cell containing a more viscous liquid, *Proc.R.Soc.London Ser.A.*, 245: 312-329, (1958).
- (3) Hill, S.: Channelling in packed columns, *Chem.Eng.Sci.*, 1: 247-253, (1952).
- (4) Paterson, L.: Radial Fingering in a Hele Shaw Cell, *J.Fluid Mech.*, 113: 513-529, (1981).
- (5) Ni, L.W., Hornof, V., and Neale, G.: Radial Fingering in a Porous Medium, *Revue de l'Institut Francais du Petrole*, 41: 217-228, (1986).
- (6) Chouke, R.L., Van Meurs, P., and Van der Poel, C.: The instability of slow, immiscible, viscous liquid-liquid displacements in permeable media, *Trans AIME*, 216: 188-194, (1959).
- (7) Nasr-El-Din, H., Hornof, V., and Neale, G.: Radial Fingering in a Water-wet Porous Medium, *Revue de l'Institut Francais du Petrole*, 42: 783-795, (1987).
- (8) Kyte, J.R., Rapoport, L.A.: *Trans AIME*, 213: 423-426, (1958).
- (9) Peters, E.J., Flock, D.L.: The onset of instability during two-phase immiscible displacement in porous media, *Soc.Pet.Eng.J.*, 21: 249-258, (1981).
- (10) Agharazi-Dormani, N., McLean, D.D., Hornof, V., and Neale, G.: Modelling of

radial water/oil displacement processes in water-wet porous media, *Journal of Canadian Petroleum Technology*, **32**: 22-33, (1993).

- (11) Kiriakidis,D.G., Neale,G.H., and Mitsoulis,E.: Numerical simulations of radial displacement of a wetting fluid by a non-wetting fluid in a porous medium, *J.Phys.A: Math.Gen.*, **23**: 5089-5094, (1990).
- (12) Perkins,T.K., Johnston,O.C.: A study of immiscible fingering in linear models, *Soc.Pet.Eng.J.*, **9**: 39-46, (1969).
- (13) Scott,G.R., Collins,H.N., and Flock,D.L.: Improving water flood recovery of viscous crude oils by chemical control, *Journal of Canadian Petroleum Technology*, **4**: 243-251, (1965).
- (14) Van Meurs,P.: The use of transparent three-dimensional models for studying the mechanism of flow processes in oil reservoirs, *Soc.Pet.Eng.J.*, **210**: 295-300, (1957).
- (15) Mungan,N.: Interfacial effects in immiscible liquid-liquid displacement in porous media, *Soc.Pet.Eng.J.*, **6**:245-253, (1966).
- (16) Pavone,D.: Observations and Correlations for Immiscible Viscous-Fingering Experiments, *SPE Reservoir Engineering*, 187-194, (May 1994).
- (17) Witten,T.A., Sander,L.M.: Diffusion Limited Aggregation, *Phys.Rev.B.*, **27**: 5686-5697, (1983).
- (18) Larson,R.G., Scriven,L.E., and Davis,H.T.: Percolation Theory of Two-Phase Flow in Porous Media, *Chem.Eng.Sci.*, **36**: 57-73, (1981).

- (19) Larson,R.G., Scriven,L.E., and Davis,H.T.: Percolation Theory of Residual Phases in Porous Media, *Nature*, **268**: 409-413, (1977).
- (20) Chandler,R., Koplik,J., Lerman,K., and Willemsen,J.G.: Capillary Displacement and Percolation in Porous Media, *J.Fluid Mech.*, **119**: 249-267, (1982).
- (21) Wilkinson,D., Willemsen,J.: Invasion Percolation: A New Form of Percolation Theory, *J.Phys.A: Math Gen.*, **16**: 3365-3376, (1983).
- (22) Wilkinson,D.: Percolation Effects in Immiscible Displacement, *Phys.Rev.A.*, **34**: 1380- 1391, (1986).
- (23) Lenormand,R., Zarcone,C.: Two-Phase Flow Experiments in an Etched Network: Measurement of Fractal Dimension, *Phys.Rev.A.*, **34**: 1380-1391, (1986).
- (24) Lenormand,R., Touboul,E., Zarcone,C.: Numerical Models and Experiments on Immiscible Displacements in Porous Media, *J.Fluid Mech.*, **189**: 165-187, (1988).
- (25) Leclerc,D.F., Neale,G.H.: Monte Carlo Simulations of Radial Displacement of Oil from a Wetted Porous Medium: Fractals, Viscous Fingering and Invasion Percolation, *J.Phys.A: Math.Gen.*, **21**: 2979-2994, (1988).
- (26) Kiriakidis,D.G., Mitsoulis,E., and Neale,G.H.: Linear Displacement of a Wetting Fluid by an Immiscible Non-Wetting Fluid in a Porous Medium: A Predictive Algorithm, *The Canadian Journal of Chemical Engineering*, **69**: 557-563, (1991).
- (27) Kiriakidis,D.G., Mitsoulis,E., Neale,G.H.: Computer Simulations of Immiscible Displacement in a Porous Medium Containing a Region of Different Wettability,

*Journal of Canadian Petroleum Technology*, 32: 21-25, (1993).

- (28) Hornof, V., Morrow, N.R.: Gravity Effects in the Displacement of Oil by Surfactant Solutions, *SPE Reservoir Engineering*, 2: 627-633, (1987).
- (29) Craig, F.F., Sanderlin, J.L., Moore, D.W., Geffen, T.M.: A Laboratory Study of Gravity Segregation in Frontal Drives, *Trans AIME*, 210: 275-282, (1957).
- (30) Crane, F.E., Kendall, H.A., Gardner, G.H.F.: Some Experiments on the Flow of Miscible Fluids of Unequal Density through Porous Media, *Soc. Pet. Eng. J.*, 3: 277-280, (1963).
- (31) Blackwell, R.L., Howlett, W.E.: The Effects of Gravity Segregation in Laboratory Studies of Miscible Displacement in Vertical Unconsolidated Porous Media., *Soc. Pet. Eng. J.*, 4: 1-8, (1964).
- (32) Slobod, R.L., Howlett, W.E.: The Effects of Gravity Segregation in Laboratory Studies of Miscible Displacement in Vertical Unconsolidated Porous Media., *Soc. Pet. Eng. J.*, 4: 1-8, (1964).
- (33) Dumoré, J.M.: Stability Considerations in Downward Miscible Displacements, *Soc. Pet. Eng. J.*, 356-362, (December 1964).
- (34) Page, C.A., Brooks, H.J., and Neale, G.H.: Visualization of the Effects of Buoyancy on Liquid-Liquid Displacements in Vertically-aligned Porous Medium Cells, *Experiments in Fluids*, 13: 472-474, (1993).
- (35) Rapoport, L.A., Leas, W.J.: Properties of Linear Waterfloods, *Trans AIME*, 198: 139-148, (1953).

- (36) Tayal,P., Narayan,K.A.: Visualization of Water and Surfactant Floods in Oil-Saturated Porous Media, *Experiments in Fluids*, 9: 337-344, (1990).
- (37) Mayer-Gürr,A: Petroleum Engineering, Volume 3, John Wiley & Sons, NewYork-Toronto, (1976).
- (38) Scheidegger,A.E: The Physics of Flow through Porous Media, Third Edition, University of Toronto Press, Toronto, (1974).