

ICNMM2018-Paper No.

DRAFT: INTERFACE DYNAMICS DURING TWO PHASE FLOW IN STRATIFIED POROUS MEDIUM

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KEYWORDS

Immiscible displacement, layered porous media, flow regime.

ABSTRACT

Immiscible displacement of a non-wetting fluid by a wetting fluid is important for many fields for example, biomedical devices, paper micro-fluidics, oil reservoirs and water aquifers. In a multi-layered porous medium the displacement velocity and relative position of the layers with respect to each other is significant in determining the flow paths of the fluids. Earlier studies on two-layered porous medium indicate presence of different flow regimes in every layer depending upon the velocity. However, the effect of relative positioning of these layers in different flow regimes is still unknown. In the present work we experimentally show that at low velocity, a capillary regime is developed i.e. the wetting fluid front leads in the least permeable layer, while at high velocity the wetting fluid front leads in the highest permeability layer. At all flow rates, the least permeable layer is found to draw fluid from the high permeability layer due to capillary suction. We also show the effect of relative placement of the layers on the interphase dynamics.

NOMENCLATURE

A Cross-sectional area
 L Length of porous medium
 M Mobility ratio
 Q Flow Rate
 R_l Shape factor
 S Medium dependent constant in determining average threshold capillary pressure.
 P_c Capillary Pressure
 P_c^* Average threshold capillary pressure.

HP High permeability layer
 IP Intermediate permeability layer
 LP Low permeability layer
 $N_{CV,T}$ Transverse capillary number
 V_{in} Superficial injection velocity
 c Proportionality constant for capillary pressure
 d Diameter of glass beads in layer
 k Average permeability of layered porous media
 k_{rw} Relative permeability of water
 k_{ro} Relative permeability of oil
 Λ Constant in determining permeability
 μ_o Viscosity of oil
 μ_w Viscosity of water
 σ Interfacial tension
 θ Contact angle
 ϕ Porosity

INTRODUCTION

Immiscible displacement of a non-wetting fluid by a wetting fluid in a porous medium is of significant importance to oil reservoirs [1], ground water remediation [2], paper microfluidics [3, 4], microfluidic devices [5] and wicking [6]. Interplay of capillary force and viscous force govern the flow behavior in the porous medium. In these applications, the porous medium is naturally heterogeneous, or a heterogeneous design can be used for performance improvement of the devices. Usually the heterogeneity arises from different layers being stacked together that can hydro-dynamically interact with each other [7-10]. The studies on the flow behavior in these heterogeneous porous media generally deal with two objectives (a) upscaling the flow properties of the stratified medium for large-scale simulations (b) predicting the cross-flow behavior based on the process parameters.

For upscaling, Bertin et al. [11] experimentally studied the flow in stratified porous medium and performed large scale averaging. Dawe et al. [10] investigated the flow patterns in two layered porous media at different rates concluding that capillary forces significantly impact flow parameter determination at core scale. The focus of the present study is to predict the cross-flow behavior in the layered porous media. For predicting the cross-flow behavior in the layered porous media, McDougall et al. [12] using pore network simulations pointed out that in the viscous regime the displacement is more efficient in the layered sediments. Zhou et al. [13] and Cinar et al. [14] based on the mobility ratio, gravity number, capillary number and relative vertical displacement found the flow regime in an immiscible displacement. Chaudhari et al. [15] performed the visualization study for the layered porous media. Datta et al. [16] described, using confocal microscopy, the effect of capillary number on flow pattern during drainage. Debbabi et al. [17] compared the viscous and capillary effects analytically and found that transverse capillary number impacts the cross-flow between the layers. Ashraf et al. [18] studied the cross-flow behavior in a layered porous medium with the capillary force as the only driving force. For imbibing and resident fluids of equal viscosity, if velocity of the fluid equals $c\sigma\Lambda d/\mu L$, where c is proportionality constant for capillary pressure $P_c = c\sigma/d$, Λ is proportionality constant in determining permeability using kozeny-Carmen equation $k = \Lambda d^2$, L is the length of the porous medium, d is the diameter of beads used in the porous medium, σ is the interfacial tension and μ is viscosity of the fluid, then we may assume capillary driven flow. In all the above studies the competitive effect of different forces, namely, viscous, capillary and gravity, in a particular system is described. However, during the imbibition process in the same system, the dominant force(s) in the system keep changing due to change in the saturation of the imbibing fluid. The behavior of the flow also depends on how these forces change with time or with length traversed by a particular phase.

In the present work we use immiscible displacement of non-wetting fluid with a wetting fluid to visualize the flow behavior at different flow rates in a layered porous medium. More precisely, at different flow rates, we visualize the imbibition patterns of wetting fluid in the layered porous medium and using modified capillary number [13], we try to predict the dominant force(s) for different flow rates in a layered porous medium. We are able to use the modified capillary number and the arrangements pattern of the layers to predict the flow behavior. We have seen that in some cases, the imbibing front in the low permeability layer leads while, in others the imbibing front in high permeability layer leads.

METHODOLOGY

We consider two layered and three layered porous media to study the interplay of capillary and viscous forces during water injection in oil filled heterogeneous porous medium. Hydrophilic glass bead of sizes 5×10^{-4} m, 3×10^{-4} m and $1 \times$

10^{-4} m are used to create the porous layers parallel to each other.

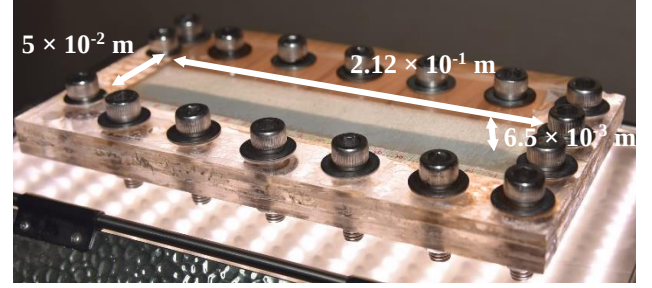


FIGURE 1. DIMENSIONS OF VISUALIZATION CELL.

Figure. 1 shows 6.5×10^{-3} m thick visualization cell used, which is 5×10^{-2} m wide and 2.12×10^{-1} m long. For two-layered porous medium, width of 5×10^{-2} m is divided in two parts, while for three-layered system, it is divided in three parts. We measure the porosity and permeability of the layers of different bead sizes separately. Table 1 shows the porosity and permeability measurement using water as fluid. We notice from the table that the porosity is approximately 36% for the three bead packs, while permeability varies significantly. Using the kozeny-Carman equation (1) for constant porosity, the permeability of the three bead sizes is given by

$$k = \Lambda d^2, \quad (1)$$

where, Λ is proportionality constant and d is the diameter of the beads. The value of Λ calculated is also listed in Table 1.

Table 1: Porosity and permeability of glass bead pack.

Diameter of glass beads (m)	Porosity	Permeability (m ²)	Λ
5×10^{-4}	0.39	39.50×10^{-12}	1.58×10^{-4}
3×10^{-4}	0.38	10.40×10^{-12}	1.16×10^{-4}
1×10^{-4}	0.33	3.33×10^{-12}	3.33×10^{-4}

Λ can be assumed to be constant in the multi-layered experiments. Figure. 2 shows the schematic of the multi-layered experimental setup. The high precision syringe pump pushes the accumulator's fluid at constant flow rate in the visualization cell. Nikon (D750) camera is used to capture the flow behavior in the multi-layered porous medium. The visualization cell has a single inlet (centrally located) and multiple outlets.

We first saturate the glass beads pack with oil of viscosity 1.64×10^{-3} Pa.s and density 784 kg/m^3 at a flow rate of $8.33 \times 10^{-9} \text{ m}^3/\text{s}$. After the cell is completely saturated with oil, we start the water injection. We color the injection water, viscosity 8.90×10^{-4} Pa.s and density 997 kg/m^3 , yellow for contrast. We inject water at constant flow rate $Q \text{ m}^3/\text{s}$, corresponding to a superficial velocity V_{in}

$$V_{in} = \frac{Q}{A}, \quad (2)$$

where, A is the cross-sectional area of layered porous media.

To predict the nature of cross-flow, we use the modified capillary number as proposed by Zhou et al. [13]. The modified capillary number (Ca) is given by

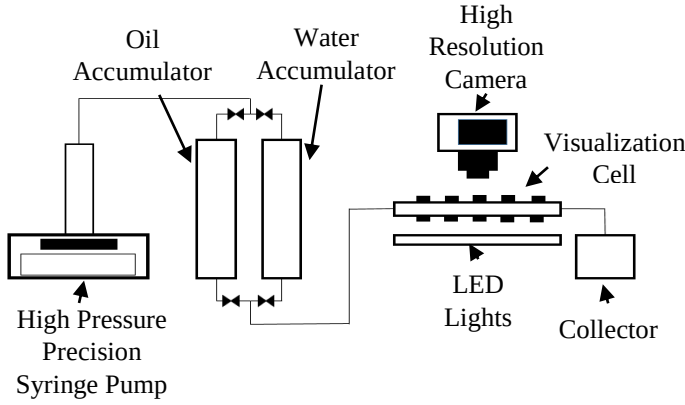


FIGURE 2. SCHEMATICS OF EXPERIMENTAL SETUP.

$$Ca = \frac{N_{CV,T} M}{(1 + M)}, \quad (3)$$

where, $N_{CV,T}$ is transverse capillary number defined as follows,

$$N_{CV,T} = \frac{LkP_c^*}{H^2\mu_o V_{in}}. \quad (4)$$

In eqn. (4), L is the length of porous medium, H is the width of porous medium, μ_o is the viscosity of oil, k is the average permeability of porous medium and P_c^* is the average threshold capillary pressure given by

$$P_c^* = 4\sigma\cos\theta\left(\frac{S\phi}{k}\right)^{0.5}. \quad (5)$$

Table 2: Schematics of two layered experimental runs.

Flow rate (m^3/s)	Arrange-ment 1	Arrange-ment 2	Arrange-ment 3	Arrange-ment 4
	LP layer HP layer	IP layer LP layer HP layer	LP layer HP layer IP layer	LP layer IP layer HP layer
1.67×10^{-10}	✓	✓	✓	✓
1.67×10^{-8}	✓			
8.33×10^{-8}	✓	✓	✓	✓

Here, S is a medium dependent constant assumed 0.02 for the glass bead-packs used in our experiments, ϕ is the porosity of medium, θ is the contact angle between water and glass beads; $\cos\theta$ is assumed 1 for hydrophilic beads and σ is the interfacial tension between oil and water, which is $24.80 \times 10^{-3} \text{ N/m}$. M is the mobility ratio defined as,

$$M = \frac{k_{rw}}{k_{ro}} \times \frac{\mu_o}{\mu_w}, \quad (6)$$

where, k_{rw} is the relative permeability of water and k_{ro} is the relative permeability of oil. The ratio k_{rw}/k_{ro} is assumed to be of the order 0.5, as measured by Ahmed et al. [19].

All experiments are conducted at room temperature and in horizontal configuration, neglecting the effect of gravity. Flow rate of water is varied in every experiment to observe different flow regimes. In Table 2 we indicate the experiments that are run for the present study.

EXPERIMENTAL RESULTS

Two layered arrangement with flow rate $1.67 \times 10^{-10} \text{ m}^3/\text{s}$

The superficial velocity at the flow rate of $1.67 \times 10^{-10} \text{ m}^3/\text{s}$ is $5.12 \times 10^{-7} \text{ m/s}$ and interstitial velocity is $14.23 \times 10^{-7} \text{ m/s}$. According to Ashraf et al. [18] for capillary driven flow the superficial velocity in the least permeable layer should be $1.75 \times 10^{-5} \text{ m/s}$ assuming $c = 4$. If we consider cross-sectional area of only one layer, then the measured superficial velocity will be $10.24 \times 10^{-7} \text{ m/s}$. Thus, the velocity in the experiment is less than the required velocity for a capillary driven flow. Therefore, we estimate that the imbibition is capillary driven in this case.

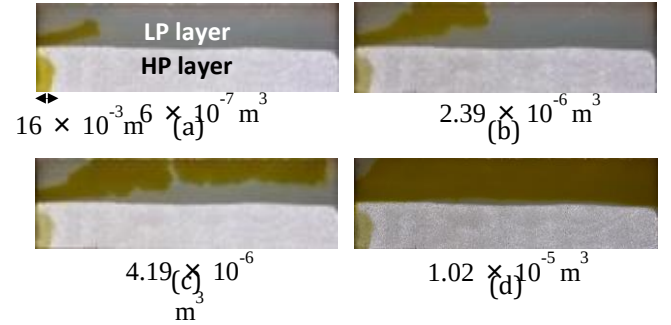


FIGURE 3. INTERFACE DYNAMICS IN ARRANGEMENT 1 AT A FLOW RATE OF $1.67 \times 10^{-10} \text{ m}^3/\text{s}$

In the present case, water first imbibes in the large permeability layer for a small length i.e. $16 \times 10^{-3} \text{ m}$ as shown in fig. 3(a) which occurs in the first 2100 s after the start of injection. This is because of the proximity of the inlet point to the high permeability layer [19]. After the wetting fluid in the high permeability layer travels a distance of $16 \times 10^{-3} \text{ m}$, the wetting fluid imbibes into the low permeability layer as shown in fig. 3(a), (b) and (c). Figure 3(d) shows that capillary suction into the small permeability layer continues till the small permeability layer is completely saturated with water. Cross-

flow from low permeability layer to high permeability layer is not observed before water breakthrough.

Two layered arrangement with flow rate $1.67 \times 10^{-8} \text{ m}^3/\text{s}$

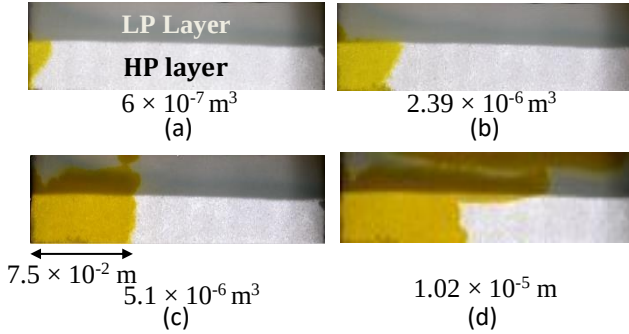


FIGURE 4. INTERFACE DYNAMICS IN ARRANGEMENT 1 AT A FLOW RATE OF $1.67 \times 10^{-8} \text{ m}^3/\text{s}$

The superficial velocity at the flow rate of $1.67 \times 10^{-8} \text{ m}^3/\text{s}$ is $5.12 \times 10^{-5} \text{ m/s}$ and interstitial velocity is $14.23 \times 10^{-5} \text{ m/s}$. If we consider cross-sectional area of high permeability layer, then the superficial velocity will be $10.24 \times 10^{-5} \text{ m/s}$, which is more than $4.15 \times 10^{-5} \text{ m/s}$ as estimated by Ashraf et al. [18] for the flow to be capillary dominant. We thus predict the flow to be governed by both the capillary and the viscous forces.

In this case, from fig. 4(a) and (b) we see that the water initially goes in the large permeability layer, till length $7.5 \times 10^{-2} \text{ m}$ and time 293 s. Water starts flowing into the low permeability layer due to cross-flow after 293 s (fig. 4(b), (c) and (d)). The cross-flow from high permeability layer to low permeability layer is capillary dominating if $\frac{N_{CV,T} M}{(1+M)} > 4.1$ [13]. The value of $\frac{N_{CV,T} M}{(1+M)}$ for the present case is 18.85. Thus, the cross-flow from high permeability layer to low permeability layer is capillary dominant. In a capillary dominating regime, the fluid front in the low permeability layer leads as shown in fig. 4(d).

Two layered arrangement with flow rate $8.33 \times 10^{-8} \text{ m}^3/\text{s}$

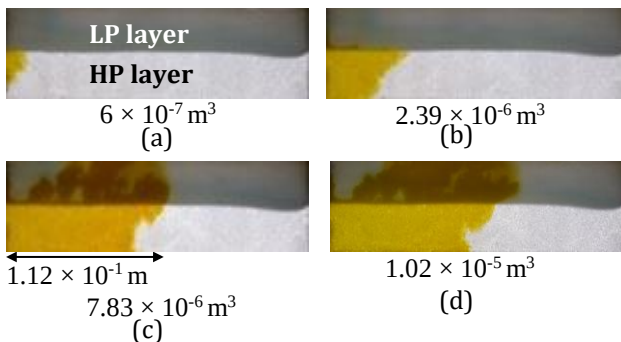


FIGURE 5. INTERFACE DYNAMICS IN ARRANGEMENT 1 AT A FLOW RATE OF $8.33 \times 10^{-8} \text{ m}^3/\text{s}$

The superficial velocity at the flow rate of $8.33 \times 10^{-8} \text{ m}^3/\text{s}$ is $2.56 \times 10^{-4} \text{ m/s}$ and interstitial velocity is $7.01 \times 10^{-4} \text{ m/s}$. The

superficial velocity is greater than the velocity for capillary dominating flow [18]. At this high velocity the imbibition would be viscous dominant.

In this case, we see that initially water starts imbibing in the large permeability layer as in the case above till a length of $5.5 \times 10^{-2} \text{ m}$ is reached as shown in fig. 5(a) and (b). After that, we see water moving into the small permeability layer at different sections through the hydro-dynamic interaction of the layers as shown in fig. 5(c). With time, the water saturation increases in both the layers till the imbibition length in the large permeability layer reaches $1.12 \times 10^{-1} \text{ m}$ as shown in fig. 5(c). As the capillary pressure of the low permeability layer is more, water is drawn from the high permeability layer to the low permeability layer as shown in fig. 5(c) and (d). The fluid front formed as a result of capillary suction from the high permeability layer to the low permeability layer leads till the water breakthrough from the low permeability layer. In this case, we see that the fluid front in the high permeability layer is viscous dominating, whereas, in the low permeability layer, it is mainly capillary driven.

The cross-flow from high permeability layer to low permeability layer is capillary dominating if $\frac{N_{CV,T} M}{(1+M)} > 4.1$ [13].

The value of $\frac{N_{CV,T} M}{(1+M)}$ for the present case is 3.8. According to Zhou et al. [13] the value of 3.8 falls in the capillary-viscous transition zone. Thus, there exists a viscous dominant regime in high permeability layer while, a capillary dominant regime in the low permeability layer for a flow rate of $8.33 \times 10^{-8} \text{ m}^3/\text{s}$.

Discussion for two layered system

At a low flow rate, the imbibition is predominantly capillary driven which causes the fluid to flow through the low permeability, high capillary pressure layer only. At a high flow rate, the viscous force drives water in the large permeability layer, which is then drawn into the low permeability layer due to capillary suction. The different regimes of flow in a layered porous medium as given by Zhou et al. [13] are plotted for $\frac{N_{CV,T} M}{(1+M)}$ versus R_l^2 , where R_l is the ratio of the length to width of the porous medium, as shown in fig. 6. It can be observed from fig. 6 that the cross-flow from high permeability layer to low permeability layer indicated by the transverse capillary number in all the above experiments except for the flow rate of $8.33 \times 10^{-8} \text{ m}^3/\text{s}$ fall into the capillary dominating zone. In a capillary pressure dominating zone, most of the wetting fluid injected into the porous medium travels through the low permeability layer. Although the fluid front in the high permeability layer progresses initially, at sufficiently longer times, the fluid front in the low permeability layer leads. For the case, in which the flow rate is $8.33 \times 10^{-8} \text{ m}^3/\text{s}$, the transverse capillary number falls in the transition zone as shown in fig. 6. In this case, the viscous forces are dominating in the layer of high permeability, whereas in the low permeability layer, the capillary forces are dominating, as predicted by Zhou et al. [13].

We performed an experiment with the same arrangement at a flow rate of $1.67 \times 10^{-9} \text{ m}^3/\text{s}$, the length at which the water front

in the low permeability layer started leading over the water front in high permeability layer is equal to 2.8×10^{-2} m.

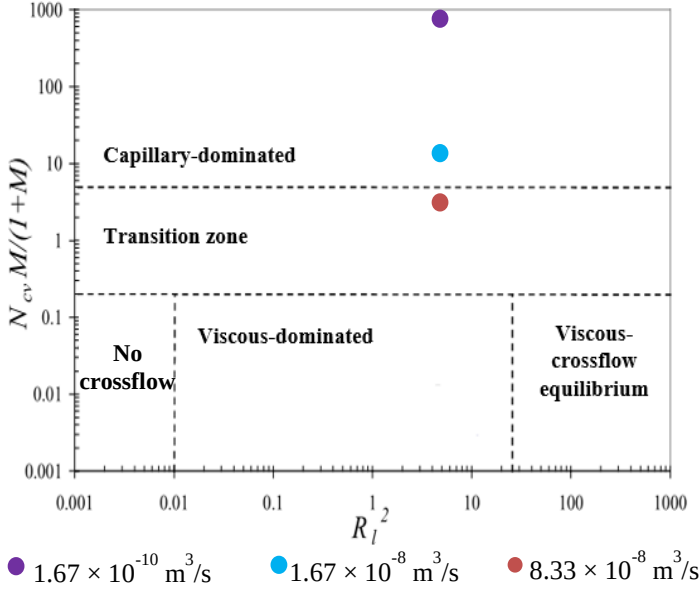


FIGURE 6. FLOW REGIONS IN IMMISCIBLE DISPLACEMENT

From the experiments with flow rates 1.67×10^{-9} , 1.67×10^{-8} and 8.33×10^{-8} m³/s, it is observed that the distance travelled by the wetting fluid in the high permeability layer increases with flow rate. Then cross-flow from the high permeability layer to the low permeability layer occurs due to capillarity. The length at which this capillary suction starts is observed to increase with increase in flow rate as shown in fig. 7.

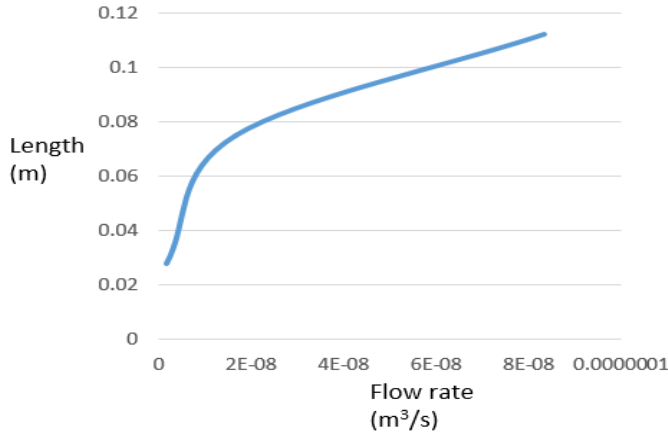


FIGURE 7. LENGTH AT WHICH CAPILLARY SUCTION IN LOW PERMEABILITY LAYER BEGINS DRAWING WATER FROM THE WATER FRONT IN HIGH PERMEABILITY LAYER VS. FLOW RATE

The two layered porous medium gives insights into the flow patterns for different regimes. Now, we observe the flow behavior in a three layered porous medium. Here, we consider three porous layers placed parallel to each other. The injection of wetting fluid into a three layered porous medium for

different flow rates shows the different cross-flow behavior. The three layers of a porous medium mentioned according to their permeability as the high, the intermediate and the low permeability can be placed in three different arrangements. Experiments are conducted on each of the arrangements for a low flow rate of 1.67×10^{-10} m³/s and a high flow rate of 8.33×10^{-8} m³/s. The following sections explain each of the arrangements.

Three layered arrangement with the low permeability layer in the middle

In this arrangement, the low permeability layer is placed between the intermediate and the high permeability layers. The superficial velocity at the flow of 1.67×10^{-10} m³/s is 5.12×10^{-7} m/s and interstitial velocity is 14.07×10^{-7} m/s. We estimate the flow to be capillary driven as the velocity is of the order 10^{-7} . In the capillary driven flow, the imbibition should be high in the layer of small beads [15]. In this case, from fig. 8(a), (b), (c) and (d), we see that the water initially goes only in the low permeability layer as the capillary pressure of low permeability layer is more than the other two layers. Cross-flow from the low permeability layer to high and intermediate permeability layers is not observed before breakthrough. This observation is similar to the case of two layered porous medium for 1.67×10^{-10} m³/s. As the inlet is centrally located, the inlet effect observed at earlier times in the two layered case is not found here.

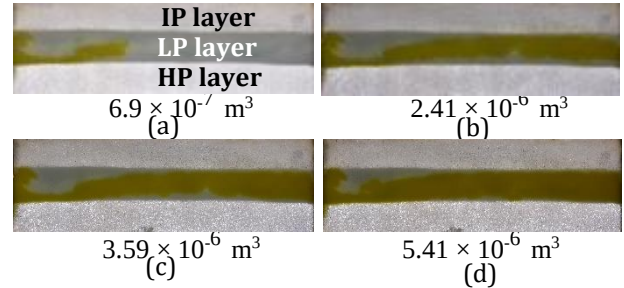


FIGURE 8. INTERFACE DYNAMICS IN ARRANGEMENT 2 AT A FLOW RATE OF 1.67×10^{-10} m³/s

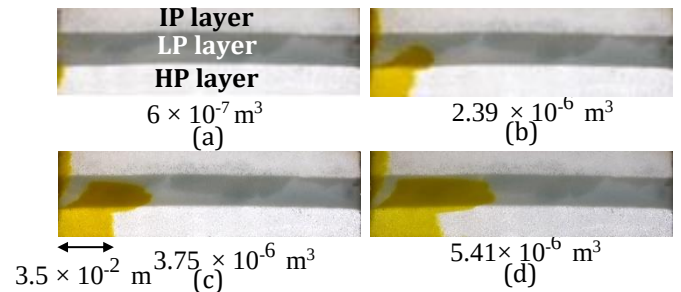


FIGURE 9. INTERFACE DYNAMICS IN ARRANGEMENT 2 AT A FLOW RATE OF 8.33×10^{-8} m³/s

Figure 9 shows the water injection in the three layered porous medium with a flow rate of 8.33×10^{-8} m³/s. At this flow rate, we see in fig. 9(b) and (c) that the injection starts in

the high permeability layer, similar to the observations made in the two layered porous medium for the flow rate of $8.33 \times 10^{-8} \text{ m}^3/\text{s}$. However, after some time, due to capillary suction the saturation in the low permeability layer begins to increase. The intermediate permeability layer has a capillary suction pressure less than the low permeability layer, hence, the wetting fluid drawn into the low permeability layer cannot be driven into the intermediate permeability layer. Therefore, the viscous forces which are dominant in the high permeability layer allow most of the injected fluid to flow through it and a very little of the injected fluid enters the intermediate permeability layer as shown in fig. 9(d).

Three layered arrangement with the high permeability layer in the middle

In this case, we show the arrangement with high permeable layer in the middle. At low flow rate, we see that imbibition pattern is similar to the case above, where low permeability layer was in the middle.

In this case, from fig. 10(a) we see that the water initially goes in the large permeability layer, till length $1.7 \times 10^{-2} \text{ m}$ and time 3540 s and in the intermediate permeability layer, till length $1.5 \times 10^{-2} \text{ m}$ as shown in fig. 10(a). After that water starts imbibing in the low permeability layer due to high capillary driving force, which can be observed from fig. 10(b), (c) and (d). This is similar to the case above, where cross-flow from low permeability layer to high and intermediate permeability layers is not observed due to the high capillary suction in the low permeability layer.

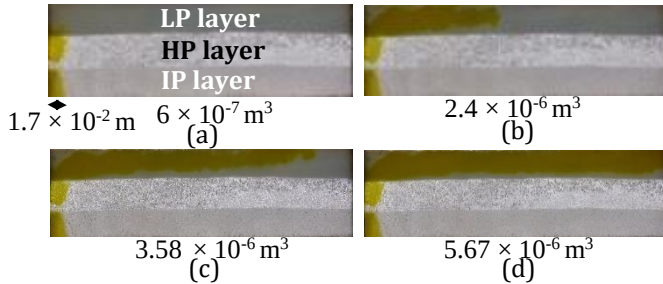


FIGURE 10. INTERFACE DYNAMICS IN ARRANGEMENT 3 AT A FLOW RATE OF $1.67 \times 10^{-10} \text{ m}^3/\text{s}$

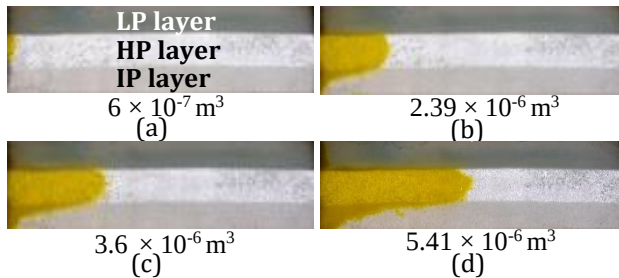


FIGURE 11. INTERFACE DYNAMICS IN ARRANGEMENT 3 AT A FLOW RATE OF $8.33 \times 10^{-8} \text{ m}^3/\text{s}$

In this case, if flow rate is $8.33 \times 10^{-8} \text{ m}^3/\text{s}$, water front leads in the high permeability layer followed by intermediate and low permeability layer as shown in fig. 11(a), (b) and (c). The saturation in the intermediate permeability layer, which has a lesser permeability as compared to the high permeability layer increases gradually, whereas the wetting fluid flow in the low permeability layer is very little. Thus, the saturation in the high permeability layer is the highest, followed by the intermediate permeability layer as shown in fig. 11(b), (c) and (d).

Three layered arrangement with the intermediate permeability layer in the middle

In this arrangement, the intermediate permeability layer is placed between the high and the low permeability layers. At a flow rate of $1.67 \times 10^{-10} \text{ m}^3/\text{s}$, we see that imbibition pattern is similar to the cases above, where low and high permeability layers were in the middle.

From fig. 12(a), we see that the water initially goes in the intermediate permeability layer, till length $2.5 \times 10^{-2} \text{ m}$ and time 3540 s as shown in fig. 12(a). Figure 12(a) and (b) show that at sufficiently long times, the wetting fluid starts imbibing in the low permeability layer due to high capillary driving force. Once the low permeability layer begins to draw the wetting fluid, the fluid front in the intermediate permeability layer halts indicating that all or most of the wetting fluid is driven into the low permeability layer as observed in fig. 12(b), (c) and (d). It can also be observed from fig. 12 that even after the wetting fluid in the low permeability layer reaches the outlet end of the porous medium, the saturation in the low permeability layer increases, indicating that the flow is predominantly capillary driven. Cross-flow from low permeability layer to high and intermediate permeability layer is not seen before breakthrough.

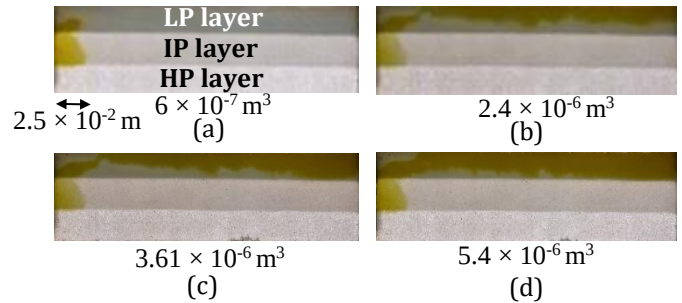


FIGURE 12. INTERFACE DYNAMICS IN ARRANGEMENT 4 AT A FLOW RATE OF $1.67 \times 10^{-10} \text{ m}^3/\text{s}$

In the case of flow rate $8.33 \times 10^{-8} \text{ m}^3/\text{s}$ for the same arrangement, from fig. 13(a), (b) and (c), we see that water front leads in the high permeability layer followed by intermediate and low permeability layer as the viscous regime dominates at initial times. And then the water flows from intermediate to low permeability layer (fig. 13(d)) due to capillary suction at a length of $3.5 \times 10^{-2} \text{ m}$ and time 83 s. Cross-flow is observed from high to intermediate permeability layer (fig. 13(c) and (d)). Thus, viscous regime is observed in high and Intermediate

permeability layers, while capillary regime is observed in low permeability layer.

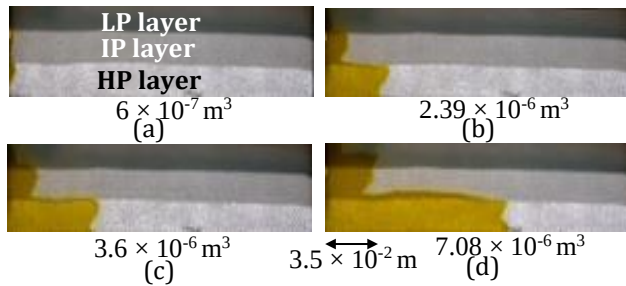


FIGURE 13. INTERFACE DYNAMICS IN ARRANGEMENT 4 AT A FLOW RATE OF $8.33 \times 10^{-8} \text{ m}^3/\text{s}$

Discussion for three layered system

In all the above cases, we see that at low flow rate the water saturation in the high permeability or intermediate permeability layer increases slightly depending upon the relative position of layer with respect to inlet [19]. However, the capillary suction dominates for the majority of imbibition process with a low flow rate. We see that, the lowest permeability layer is completely saturated, while there is no cross-flow from low permeability layer to high and intermediate permeability layer before breakthrough.

When the injection flow rate is high, the viscous regime dominates in the high and intermediate permeability layer, while a capillary driven flow is observed in the low permeability layer. This behaviour is similar to the behaviour in the two layered porous medium.

From this visualization study we see that, during the injection process the capillary and viscous forces dominate in different regions of the heterogeneous porous medium. It is important to define the space dependent or time dependent capillary number, which would help to predict the dominating driving force in different regions of the layered porous medium.

CONCLUSIONS

In this work, we use experiments to observe the different dominating driving forces for fluid flow in different regions of the layered porous medium. In two layered porous medium, we see that the fluid front in the least permeability layer leads for both the high and low flow rates. The water transfers from the high permeability layer to the low permeability layer near the inlet at low flow rate. While for high flow rate, water front in the high permeability layer progresses feeding the low permeability layer due to capillary suction.

In the three-layered porous medium, we observe similar trend in which, at low flow rates the low permeability layer is completely saturated with wetting fluid due to high capillary pressure. At high flow rate, the capillary forces and the viscous

forces both play important role depending upon the arrangement of the layers.

This work would help in finding a space or time dependent capillary number which, would help in predicting the flow behavior in heterogeneous porous media.

ACKNOWLEDGMENTS

We acknowledge Oil and Natural Gas Co. - Institute of Reservoir Studies for financial support.

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