

# Effect of Clay Minerals on Miscible and Immiscible Viscous Fingering during Polymer Flooding

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**Abstract**—During polymer flooding a considerable amount of polymer may be lost due to adsorption into the reservoir rock. These reservoir rocks contain clay minerals, which affect the propagation of injected polymers. In this numerical study we have investigated the effect of different clay minerals on dynamics of miscible and immiscible viscous fingering. Since polymer adsorption rate is different for different clay minerals, it is important to know that how clay minerals influence the fingering pattern at both miscible and immiscible interface during polymer flooding, which is followed by water flooding. Clay minerals play a major role in oil recovery process and it affects the displacement efficiency as well. There is lack of information regarding the nonlinear adsorption effect of polymer on instability in the literature. We provide numerical results for nonlinear adsorption of polymer onto the porous matrix, since a nonlinear Langmuir sorption isotherm is more suitable model for polymer adsorption. By comparing the results for Kaolinite and Illite, it is observed that growth rate and number of miscible viscous fingers more for Kaolinite clay minerals. On contrary the number of immiscible viscous fingers at the saturation shock between connate water and oil is less for Kaolinite.

**Index Terms**—polymer flooding, adsorption, viscous fingering, clay minerals, connate water

## I. INTRODUCTION

The displacement of the oil in reservoir by the injection of less viscous immiscible water is type of secondary oil recovery process. In immiscible two phase flow, the presence of large viscosity difference between water and oil, makes the water likely to finger through the oil in more non uniform manner. This viscous instability is called immiscible viscous fingering. A large number of literatures are available on the nature of immiscible viscous fingering of two phase flow in porous medium [1]-[4]. Chouke *et al.* [5] and Peter *et al.* [6] did experiments to study the two phase immiscible displacement to show that the resident fluid was bypassed due to strong viscous fingering instability. Pavon [7] observed the dependence of fingering on the capillary number and the mobility ratio. Linear stability analysis for two phase flow in porous media is done by Yortsos *et*

*al.* [8] and Riaz *et al.* [9]. Mobility ratio across the Buckley-Leverett shock governs the instability [9]. Polymer flooding is a chemical enhanced oil recovery process that provides a favorable mobility ratio to the aqueous phase of reservoir in order to control the viscous fingering phenomena. High molecular weight and water-soluble polymer is used to improve the oil recovery efficiency as it improves the sweep efficiency of flooding process. Since this water-soluble polymer is very expensive, the cost of the oil production is optimized by injecting water behind the polymer solution. This results in the formation of polymer bank behind the oil bank. So less viscous water pushes high viscous polymer solution. This might create instability called as miscible viscous fingering (less viscous fluid displaces a more viscous fluid in miscible medium [10] [11]), this interface instability has been studied extensively over few decades [12]-[16]. These viscous instabilities are undesirable as they resulted in early breakthrough of fluid. During the propagation of polymer slug, polymer continues to get adsorbed on the rock and the concentration of polymer reduces. The effect of adsorption on the two phase flow was intensively studied in the past within the framework of polymer flooding process. Most of the studies were performed by a series of experiments in the core field [17]. These experimental studies showed that the adsorption on the porous matrix slow down the growth rate of viscous fingering and wavelength of pattern. However the effects of polymer adsorption are usually ignored while modeling the miscible viscous fingering, although this is very important in real flooding pattern. Clays present in the oil reservoir rock tend to hinder the effective propagation of the polymer molecules because of their reactivity [18]. These clays in the reservoir formations are classified into Kaolinite and Illite based on their surface activities, surface area, and swelling tendency. Thus the presence of these clay minerals causes the polymer retention, permeability reduction and formation damages [19] [20].

In this numerical study we investigate the effect of these clay minerals on miscible and immiscible instability, thus displacement efficiency. Mishra *et al.* [21] considered a linear adsorption model and found out the influence of adsorption on miscible viscous fingering. So it is important for industrial application to study the effect

of nonlinear adsorption on miscible and immiscible instabilities, which can occur simultaneously during polymer flooding. Since the clay minerals influence the nonlinear adsorption differently, we also investigate the influence of clay minerals on instability analysis and thus flooding efficiency.

## II. MATHEMATICAL MODELING

Simulation of polymer flooding in the oil reservoir is modeled including viscosity variation of the polymer solution, polymer adsorption onto the reservoir rock, and dispersion of polymer in water phase. For multiphase flow and multicomponent species transport the continuity of mass for  $k^{\text{th}}$  component is expressed in terms of overall volume of component per unit pore volume,  $C_k$  as

$$\frac{\partial \phi \rho_k C_k}{\partial t} + \nabla \cdot \left( \sum_{l=1}^{n_p} \rho_k (C_k u_l - D_{kl}) \right) = R \quad (1)$$

where the overall volume of component per unit volume is the sum over all phases including adsorbed phases,  $n_p$  the number of phases,  $r_k$  is the density of the pure component at a reference pressure, The adsorbed concentration  $\hat{C}_k$  is expressed as

$$C_k = \left( 1 - \sum_{k=1}^{n_{cv}} \hat{C}_k \right) \sum_{l=1}^{n_p} S_l C_{kl} + \hat{C} \quad (2)$$

where  $n_{cv}$  is the number of volume occupying components. the dispersive flux is assumed to be Fickian.

$$D_{kl} = \phi S_l \mathbf{K}_{kl} \nabla C_{kl} \quad (3)$$

Dispersion tensor (  $\mathbf{K}_{kl}$  ) includes the molecular diffusion. Its  $ij^{\text{th}}$  term is expressed as follows:

$$K_{klij} = \frac{D_{kl}}{\tau} \delta_{ij} + \frac{\alpha_{Tl}}{\phi S_l} |u_l| \delta_{ij} + \left( \frac{\alpha_{Ll} - \alpha_{Tl}}{\phi S_l} \right) \frac{u_{li} u_{lj}}{|u|} \quad (4)$$

where  $\alpha_{Ll}$  and  $\alpha_{Tl}$  are longitudinal and transverse dispersivities,  $\tau$  is the tortuosity factor.  $u_{li}$ , ( $i = 1, 2, 3$ ) are the components of Darcy seepage flux. The magnitude of a seepage flux for each phase is denoted as  $|u_l|$ .

The phase flux from Darcy's law is modeled as follows

$$\mathbf{u}_l = \frac{K_{rl} \mathbf{K}}{\mu_l} (\nabla \cdot p_l - \gamma_l \nabla h) \quad (5)$$

where  $\mathbf{K}$  is intrinsic permeability and  $K_{rl}$  is the relative permeability for phase ' $l$ '. The phase pressure and vertical depth are denoted as  $p_l$  and  $h$  respectively. Here  $\mu_l$  and  $\gamma_l$  are viscosity and specific weight respectively. The source term in Eq. (1) is a combination of all rate terms for particular components and expressed as

$$R_k = \phi \sum_{l=1}^{n_p} S_l r_{kl} + (1 - \phi) r_{ks} + Q_k \quad (6)$$

Nonlinear Langmuir adsorption isotherm is used to describe the rate of polymer adsorption. The adsorption modeled here is reversible with salinity and irreversible with concentration. The adsorbed concentration is given as follows.

$$\hat{C}_k = \min \left( C_k, \frac{a_k (C_k - \hat{C}_k)}{1 + b_k (C_k - \hat{C}_k)} \right) \quad (7)$$

Here the parameter ' $b_k$ ' controls the curvature of the isotherm of  $k^{\text{th}}$  component and the ratio,  $b_k/a_k$ , represents the level adsorption.

$$a_k = a_{k1} + a_{k2} C_{SEP} \left( \frac{K_{ref}}{K} \right)^{0.5} \quad (8)$$

$$C_{SEP} = \frac{C_{51} + (\beta_p - 1) C_{61}}{C_{11}} \quad (9)$$

$C_{51}$ ,  $C_{61}$  and  $C_{11}$  are anion, calcium and water concentration in aqueous phase and  $\beta_p$  is laboratory data here  $C_{SEP}$  is effective salinity of polymer.

The viscosity of solution is depend upon the concentration and viscosity is modeled as linear function of concentration as follows

$$\mu_p = \mu_w \left( 1 + A_{p1} C_{kl} + A_{p2} C_{kl}^2 + A_{p3} C_{kl}^3 \right) C_{SEP}^{sp} \quad (10)$$

$A_{p1}$ ,  $A_{p2}$  and  $A_{p3}$  are constants. In this study of polymer is the only one component that get adsorbed on the rock and controls the viscosity of the aqueous solution.

## III. RESULT AND DISCUSSION

Two-dimensional numerical simulation has been carried out to perform polymer flooding chased by water. A square domain of size 2m x 2m is considered to model the reservoir with one injection well and a production well (see Fig. 1). The domain is discretized into 200 cells in  $x$  direction and 200 cells in  $y$  direction. Reservoir is initially saturated with 10% of water. Oil viscosity is taken as 10 cp and water viscosity is kept as 1 cp. At the injection well water injected at 0.0014 m<sup>3</sup>/day. For the first 5 days the injected water contains polymer with concentration 0.20 kg/(kg of solution). Later water is used to chase the polymer solution for cumulative of 11 days. The production well is set to produce with minimum flowing bottomhole pressure of 0 Kpa and a maximum flowing bottom hole pressure of 1250 Kpa. The well radius is set to be 0.001 m for both wells. Input parameters for clay are taken from [22] and are given in Table I. Input parameters for reservoir and fluid is given in Table II. The input adsorption parameters are specified at a reference permeability,  $K_{ref}$  whose value is also given in Table II. The placement of injection and

production well is specified in the Fig. 1 in schematic diagram of domain.

TABLE I. PARAMETERS FOR CLAY MINERALS

Type of Clay	$a_{k1}$	$a_{k2}$	$b_k$	$Q_v$	$\beta$
Kaolinite	6.5	0	100	0.0054	0.015
Illite	13.5	0	100	0.0497	0.4

TABLE II. RESERVOIR AND FLUID DATA

porosity	0.22
permeability	2500 md
Oil viscosity	10 cp
Water viscosity	1 cp
initial water saturation	0.10
interfacial tension	14 dynes/cm
$A_{p1}, A_{p2}, A_{p3}$	3,3,0
Residual oil saturation	0.01
$K_{ref}$	50
$C_{SEP}$	0.01
$a_{Ll}$	.001
$a_{Tl}$	0.0001

UTCHEM is used in this numerical study for simulating multicomponent, multiphase polymer flooding followed by water flooding. It was originally developed by pope and Nelson [23]. It uses an IMPES solution to simulate several species and discretization of block centered finite difference that can simulate a wide range of displacement process at laboratory as well as field scale.

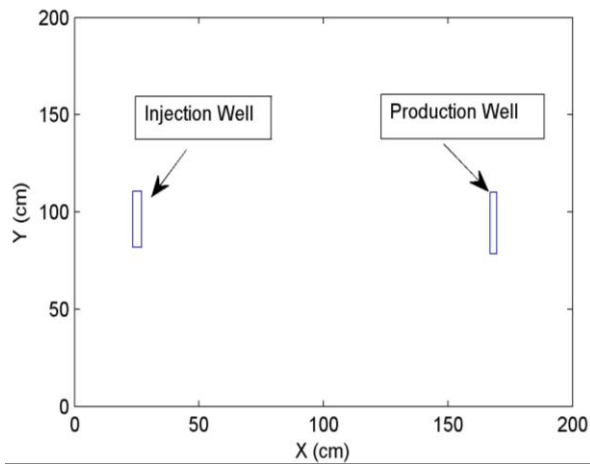


Figure 1. Schematic diagram of the domain

Numerous simulations have been performed here to investigate the effect of clay minerals on miscible and immiscible viscous fingering. We present here how nature of miscible and immiscible fingers is getting affected for different clay minerals of oil reservoir rock. Firstly we present the numerical results of miscible instability for two clay minerals such as kaolinite and Illite while keeping the other transport parameters (such as dispersion of polymer in water) and injection conditions as constants. We are showing the formation and evolution of miscible and immiscible fingers through concentration contours of polymer concentration and oil saturation contours respectively.

#### A. The Effect of Clay Minerals on Miscible Fingering Dynamics

The Effect of clay minerals on miscible viscous fingering is shown as concentration contours of polymer solution at 6, 8, 10 and 11 days. Fig. 2 shows the concentration contours of polymer for kaolinite. Red area in the polymer concentration contour indicates the amount of concentration of polymer left after its retention. So it indicates that very less amount of polymer is lost due to polymer adsorption during its propagation through oil reservoir comparatively. Results depicts that miscible fingers are formed at 8 the day and it is developing as time progress, this growth rate of formed miscible fingers are more comparatively. We can see that the lengths of formed fingers are also more. Since concentration of polymer rules the viscosity of aqueous solution, here we have higher mobility ratio which is the responsible for higher miscible fingers growth rate. Fig. 3 shows the concentration contour of polymer at 6, 8, 10 and 11 days for Illite. Results depicts the miscible fingers formation and evolution with time, here polymer adsorption is more compared to Kaolinite, resulted in less miscible instability, and smooth fingers. Growth rate of instability also get reduced due to less mobility ratio (viscosity is function of concentration). This type of clay mineral exhibit more polymer adsorption. The wavelength of fingers are more in case of more polymer adsorption rate even its growth rate is lower, Nonlinear adsorption is modeled in the entire simulation this cause change of shape in the concentration wave as distance increases. Fig. 4(a) shows the concentration plots of polymer solution at 8,9,10 and 11 days. It is also observed that here very less amount of polymer is lost due to adsorption. The disturbances in the plots are more due to formation of large number of miscible viscous fingers. Fig. 4(b) shows the concentration plots of polymer solution at 8,9,10 and 11 days for Illite clay minerals. Sorbed phase concentration is function of concentration, so retardation velocity also a function of polymer-concentration.

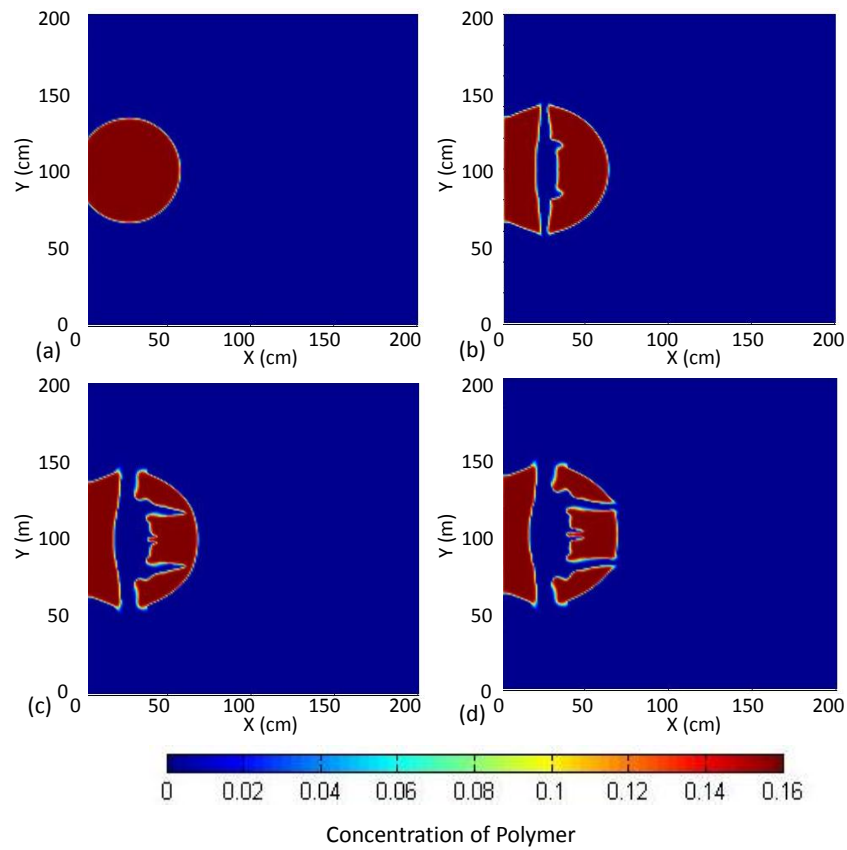


Figure 2. Contours of polymer concentration at 6, 8, 10 and 11 days for Kaolinite.

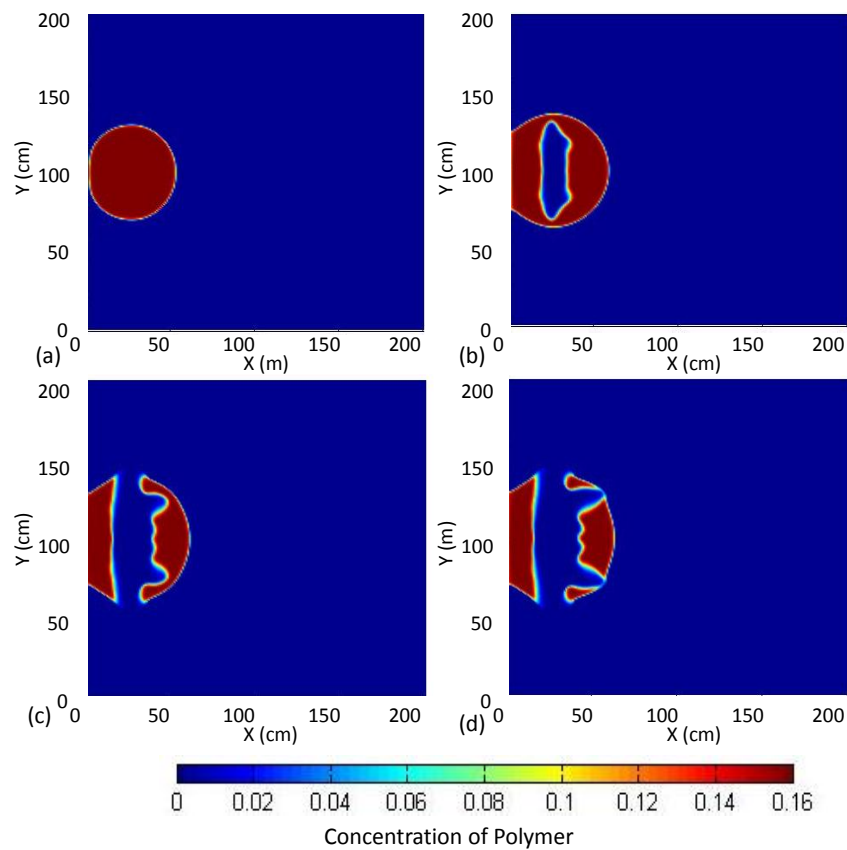


Figure 3. Contours of polymer concentration at 6, 8, 10 and 11 days for Illite.

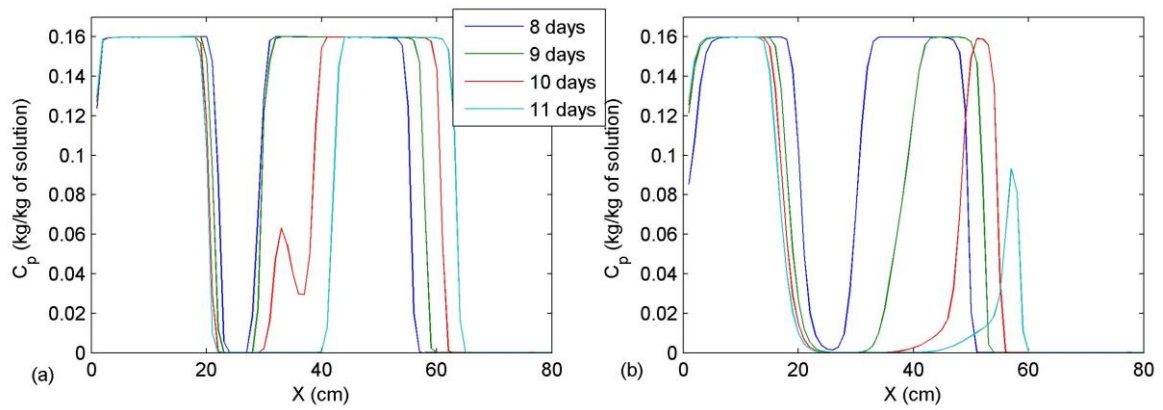


Figure 4. Concentration of polymers at 8, 9, 10 and 11 days for a) Kaolinite b) Illite

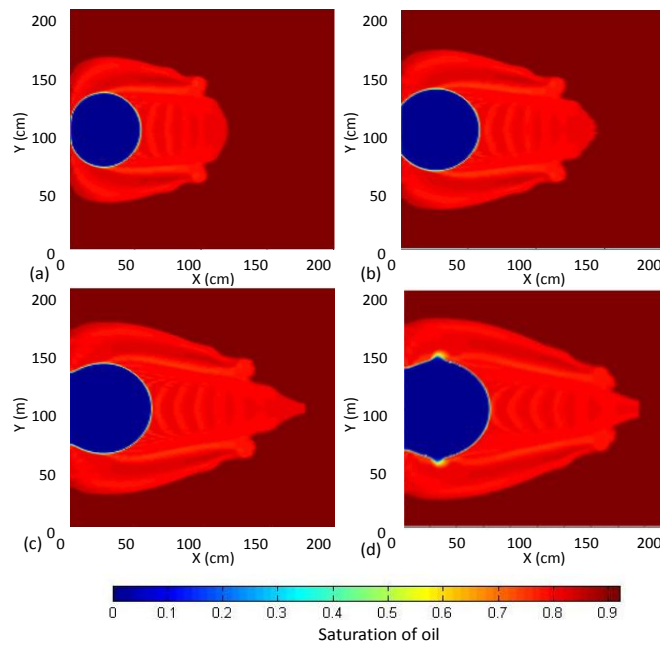


Figure 5. Contours of oil saturation at 5, 6, 7 and 8 days for Kaolinite.

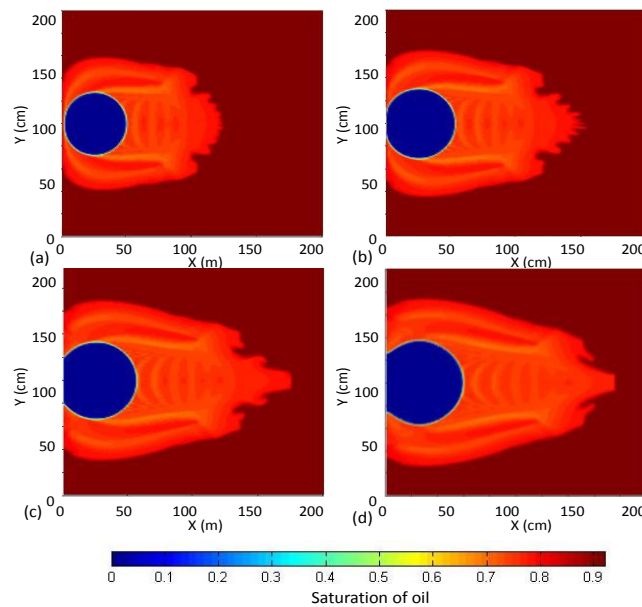


Figure 6. Contours of oil saturation at 5, 6, 7 and 8 days for Illite.

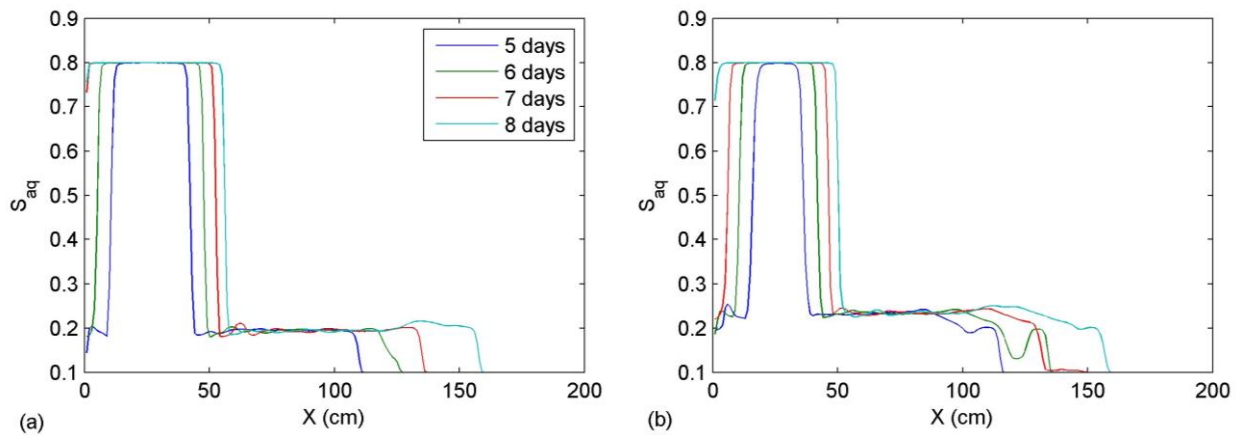


Figure 7. Water saturation plots at 5, 6, 7 and 8 days for a) Kaolinite b) Illite

Disturbance in the plots are lesser comparatively due to formation of smooth miscible viscous fingers. The concentration peak came down due to more rate of polymer adsorption. This clearly indicates that clay minerals and thus rate of polymer adsorption has great influence on characteristics of miscible fingers. More rate of adsorption results in less miscible growth rate and number of fingers but wavelength of miscible fingers are more. This is because of the concentration rules the viscosity of polymer solution and growth rate of miscible fingering is a function of mobility ratio in case of miscible displacement instability.

#### B. The Effect of Clay Minerals on Immiscible Fingering Dynamics

Polymer retention in porous matrix results in the formation of two saturation shocks. We study the influence of clay mineral and thus polymer adsorption on the immiscible fingers formed around the shock between water (which contains no polymer) and oil. Fig. 5 shows the oil saturation contour at 5, 6, 7 and 8 days for kaolinite, as we have already seen that polymer adsorption of this case is comparatively lesser. We can see there are no immiscible fingers formed at the immiscible interface between connate water and oil. Water saturation front is moving and effectively pushing the oil without having much no uniformity. Fig. 6 shows the saturation contour of oil a 5, 6, 7 and 8 days for Illite. Results depicts the more immiscible fingers formation and its evolution with time, here polymer adsorption is more compared to Kaolinite and it resulted in more immiscible viscous fingering. Growth rate of immiscible instability also get increased for higher rate of polymer adsorption. Water tries to fingers through the oil which is at higher viscosity than water. Higher growth rate of immiscible fingers at the water and oil interface is a result of higher moving water saturation velocity. This shows that the adsorption of polymer molecules onto the rock matrix also effecting the water saturation shock traveling velocity. Since chemicals are more retarded due to polymer adsorption but saturation shock at the connate water and oil moves with higher velocity. So the case where more polymer gets adsorbed will result in more

immiscible fingers at shock formed between water without polymer and oil, and resulted in higher growth rate because of the higher shock traveling velocity of saturation shock at the connate water and oil. However, there is not even a small difference in mobility ratio which is also one of important deciding factor for onset and growth of immiscible instability. Finally we can say that clay minerals have great impact on the immiscible viscous fingering at the shock formed from viscosity difference between water and oil, this rate of polymer adsorption cause changes in the saturation shock traveling velocity which is one another dependence factor for the growth rate of immiscible viscous fingers. Fig. 7a shows the water saturation plots at 5, 6, 7 and 8 days for Kaolinite. Fig. 7b represents the water saturation plots at 6, 7 and 8 days for Illite. From this plot we can understand that saturation shock traveling velocity is different for different clay minerals, water saturation front having more disturbances for Illite this is because of more formation of immiscible viscous fingers and higher shock raveling velocity For this type clay minerals where more amount of polymer get retained. Saturation front reaches early in production well, indicates higher speed of moving saturation shock, thus higher growth rate of immiscible viscous fingers at this particular shock between water which contains no polymer and oil.

#### IV. CONCLUSION

We studied miscible and immiscible instability for two clay minerals such as Kaolinite and Illite, in which Kaolinite exhibited less polymer adsorption rate and resulted in more number of miscible viscous fingers. Since growth rate of miscible viscous fingers are function of mobility ratio and the concentration of polymer rules the viscosity of solution, Kaolinite clay minerals resulted in higher growth rate of miscible viscous fingers with less wavelength of miscible viscous fingers. Illite exhibited more adsorption which results in less miscible fingers and formed fingers having large wavelength. However results depict that Illite experienced reduced miscible fingers growth rate. We have seen that these clay minerals has different rate of polymer adsorption capacity which also

affects the immiscible fingers formed at the shock the water without polymer and oil. Kaolinite resulted in less number of immiscible viscous fingers and reduced growth rate, but in case of Illite, more number of immiscible fingers are formed with higher growth rate. The water saturation shock traveling velocity is different for different clay minerals which is responsible for the change in growth rate. Higher rate of polymer adsorption into the reservoir rock will results in more immiscible viscous fingers and less miscible viscous fingers. So clay minerals have great influence on deciding the possibility of miscible and immiscible viscous fingering and have great impact on displacement efficiency.

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