Effect of Seismic Excitation on Mobilization of Trapped Oil Globule in Pore Doublet Model

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***Abstract*—Over the years, several enhanced oil recovery techniques were developed in order to recover the residual oil trapped in the reservoir. Conventional EOR techniques rely on injection of fluids and chemicals into the reservoir to improve recovery. Unconventional methods of enhancing oil recovery such as the use of flow divergent and flow pulsation have emerged. One of the unconventional EOR techniques of interest is the application of seismic wave. Despite the fact that EOR by seismic wave has shown some potential in pilot field studies as well as laboratory experiments, the working mechanism of this technique is not well understood. In this study, we aim to investigate the ability of the seismic wave excitation in releasing a trapped oil globule in a pore doublet model. We studied the ability of this model to trap oil in an imbibition process. However, the trapping did not occur. Therefore, we generated an oil globule that was already isolated in pore 2 of the pore doublet model. The inlet velocity causing the oil globule trapping was tested and determined for the given pore doublet model dimensions. A sinusoidal wave vibration was applied to the model as the seismic excitation. The positive half of the wave cycle resulted in a an adverse pressure gradient, which led to a reversed flow of the fluids in the domain. Consequently, we started the excitation at the negative half of the wave cycle, which applies a favorable pressure gradient. The favorable pressure gradient resulted in a viscous pressure that overcame the capillary pressure holding the oil globule. Consequently, the oil globule was squeezed out of pore 2 and mobilized. The trapped oil globule was successfully mobilized by the effect of the seismic wave excitation.**

***Index Terms*—Enhanced Oil Recovery, Seismic Wave, Vibration, Seismic excitation, Oil Mobilization, Pore Doublet**

I. Introduction

Any pore-level study, which attempts to investigate and find effective solutions to existing problems such as low oil recovery, should consider the reservoir rock complexity and the forces that control the multiphase flow that takes place in porous media. To understand the basic physics behind the processes, usually simple micro-models are used. Although it is difficult to predict the flow in porous media and estimate the residual oil saturation using micro-models, the flow is not random at all. The flow is usually controlled by capillary and viscous forces [1]. Residual oil trapping happens in strongly water wet rocks, when the forces exerted by the flowing water on the trapped oil globule cannot exceed the capillary forces [2].

It is nearly impossible to replicate the pore structure in the rock for research purposes. Using a simple and idealized system of capillary tubes to form the so called "pore doublet" is believed to have nothing to oil recovery in the field. However, this approach may help in understanding the basic problems that occur in the pore system, which may lead to gain some insight into developing better methods to estimate oil recovery [3].

Chatzis and Dullien [4] conducted an extensive study in a series of pore doublets to test the effect of wettability and set the conditions for oil trapping. They concluded that during drainage type of displacement, the wetting phase might be trapped in pore 1 despite the flow rate. However, during the imbibition type of displacement for low viscosity fluids and under strongly wetting conditions, the displacement of the non-wetting phase will occur in pore 1 first, then in pore 2. If ample time was given the non-wetting phase will be completely displaced [4, 5].

Meanwhile, after secondary recovery about 20-30% of oil reserve is recovered, leaving about two thirds of oil behind in the reservoir. As a result, extensive studies to recover more oil which led to introduce oil tertiary recovery or known as Enhanced Oil Recovery (EOR) [1]. Many EOR techniques such as, gas based EOR, water based EOR and thermal based EOR were studied and implemented. However, the oil recovery increased only about 30% at best cases, which means about 40-60% of initial oil in place is recovered.

When it comes to EOR, recovery factor is manipulated by two factors: macroscopic displacement efficiency and macroscopic sweep efficiency [6]. Macroscopic displacement efficiency is reduced by the capillary effect, which occurs during water and other EOR fluid based flooding leaving a portion of oil trapped in the pores.

Macroscopic sweep efficiency is affected by the reservoir geological heterogeneity "Porosity and Permeability". The distribution of the permeability

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throughout reservoirs is uncertain. When injecting fluids to sweep oil, usually fluids choose the minimum resistance path which is at the high permeability layers, leaving the oil in low permeability layers unswept. In order to sweep the oil in the low permeability layers, the injected fluids viscosity is reduced to be less than that of oil. Such as, the case in the conventional EOR by miscible gas injection and water alternating gas injection causing viscous fingering effect, which highly reduces the macroscopic sweep efficiency and leading to early gas breakthrough. Other EOR techniques, especially those by chemical flooding, face limitations due to reservoir heterogeneity. For example, alkaline surfactant polymer flooding, near well flow divergent and deep reservoir flow divergent may not be applicable in high temperature, carbonate reservoirs or those containing saline water.

In general, currently used EOR techniques suffer from flowing throughout the reservoir or at least have limited flowing distance from the injection wells. In addition, most of the unconventional EOR techniques have not shown much deference in solving the limitations that the conventional EOR techniques face.

One of the unconventional EOR techniques is the application of vibrational seismic waves, which has shown promising results. It does not pollute the reservoir with pumped chemicals. At the same time, it does not require complicated and expensive fluids to be pumped into the reservoir. Therefore, it is an environmentally friendly and relatively cheap compared to other EOR techniques to recover more oil from the reserve [7].

Several studies have been conducted since the idea of vibro-seismic started in the 1950s; it was noticed that an earthquake induced an increase in oil production [8]. Unlike the previous mentioned EOR techniques, the unconventional EOR by the application of seismic waves has shown a good potential at oscillating throughout the reservoir and increasing the oil recovery. Although throughout the years many studies were conducted in an attempt to understand the mechanism of the application of seismic vibrational waves in releasing a trapped oil globule, no theory or mathematical expression have fulfilled the question of how this technique works.

According to Kuznetsov and Simkin [9], the vibration reduces the water/oil interfacial tension. As a result, oil trapped blobs are mobilized and coalesce with each other. Moreover, vibration breaks the trapped oil into small droplets causing it to flow with flooding water. A particular low frequency wave can result in making the reservoir rock grains to produce high frequency wave and the high frequency wave may cause the trapped oil to be mobilized [10].

In the review paper by Huh [11], in the presence of vibrational excitation it was concluded that if water/oil ratio (WOR) is high then the oil production is noticeable and vice versa. In addition, there appears to be a specific optimum wave frequency, yet it is not known. On one hand, shear wave would mobilize the fluid, but on the other hand, compressional wave would squeeze the fluid out of the pore throat that is why the latter is recommended. It was proposed that in a heterogeneous reservoir, the seismic vibration propagates through high and low permeability layers that causes transient pressure between layers generating cross-flow potentially can sweep the oil from the low permeability zone. However, according to Beresnev [12], attempting to forecast the oil volume of oil released by the application of vibration of a particular frequency and amplitude in a natural rock would be unfeasible due to reservoir rock heterogeneities.

Beresnev, et al. [13] conducted an experiment on a glass micro-model utilizing a Sinusoidal wave with frequency ranging 10-60 Hz and amplitude acceleration ranging 0.5 – 7.5 mm/s2. They concluded that the rate of the organic fluid trichloroethylene (TCE) flow is proportional to the wave amplitude and inversely proportional to the wave frequency.

Beresnev, et al. [13] also conducted a numerical study using an axisymmetric capillary tube with a constriction in ANSYS fluent. Although in the presence of water flooding, the organic fluid droplet was trapped at the constriction. However, when an excitation was introduced the organic droplet was able to pass through the constriction. They observed that the droplet was not mobilized during the negative half of the wave cycle. Therefore, a complete cycle is needed to mobilize the droplet, which supported the experimental results.

Studies that attempted to understand the effect of the seismic excitation on a trapped oil globule, experimentally or numerically has used capillary tube as the field of conducting the experiment or numerical studies. So far, only one study has used an eched-glass micro-model. However, no study has used pore doublet to investigate the effect of the seismic excitation on a double channel flow. In this study, we used the pore doublet model in a numerical study.

II. Model Formulation

Most studies that investigated the multiphase flow in a pore doublet assumed that the oil and water have equal viscosities as well as equal densities to simplify calculations [1-5, 14]. According to Willhite [2], after oil is displaced from the smaller pore, pressure at (PB) in Fig. 1 drops and pressure at (PA) becomes larger. The oil in the larger pore may be displaced by the water, if water does not cutoff the oil phase in pore 2. If phase cutoff occurs, then the oil in pore 2 will be an isolated globule.

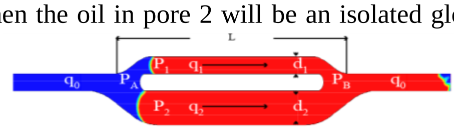

Figure 1. The pore doublet model filled with oil (red color) and water (blue color)

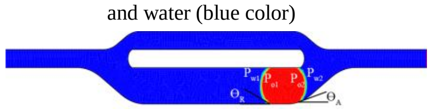

Figure 2. Isolated oil globule in pore 2 with the advancing and receding angles

The isolation of oil globule in the larger pore will lead to its trapping. The equations governing the flow in a pore doublet are adapted from SPE book [2]. If we want to get the pressure difference between points A and B in Fig. 1, then:

$$P_A - P_B = P_A - P_w + P_w - P_o + P_o - P_B \tag{1}$$

Where, Pressure drop caused by viscous forces in the water phase is given in (2):

$$P_A - P_w = \frac{8\mu_w L_w v_1}{r_1^2} \tag{2}$$

$\mathbf{P_A - P_B}$ is the Capillary Pressure given in (3):

$$\Delta P_c = P_o - P_w = -\frac{2\sigma\cos\theta}{r_1} \tag{3}$$

$\mathbf{P_{oi} - P_B}$ is the Pressure drop caused by viscous forces in the water phase is similar to (3) with changing the subscript w to o as shown in (4), which is the expansion of (1):

$$P_A - P_B = \frac{8\mu_w L_w v_1}{r_1^2} - \frac{2\sigma\cos\theta}{r_1} + \frac{8\mu_o L_o v_1}{r_1^2} \tag{4}$$

Similarly, the pressure difference in pore 2 is given in (5):

$$P_A - P_B = \frac{8\mu_w L_w v_2}{r_2^2} - \frac{2\sigma\cos\theta}{r_2} + \frac{8\mu_o L_o v_2}{r_2^2} \tag{5}$$

If we assume; $\boldsymbol{\mu_w = \mu_o = \mu}$ and $\mathbf{L_w = L_o = L}$, Then:

$$P_A - P_B = \frac{8\mu_1 L_1 v_1}{r_1^2} - \Delta P_c \tag{6}$$

The same goes to pore 2 with changing the velocity and radius to those in pore 2. According to Willhite [2], after phase cutoff occurs and an isolated globule is left in pore 2, the oil globule will be trapped, if the capillary forces holding the oil globule is equal or larger than the viscous forces in pore 1. This may occur by a small change in the curvature of the oil globule or by a change in the contact angle, as illustrated in Fig. 2. As such that, the pressure difference across the oil globule that is shown in Fig. 2, is given in (7):

$$P_{w1} - P_{w2} = (P_{w1} - P_{o1}) + (P_{o1} - P_{w2}) \tag{7}$$

Substituting that in the capillary pressure equation will give us (8) or (9):

$$\Delta P_c = P_{w1} - P_{w2} = -\frac{2\sigma}{r_A^*} + \frac{2\sigma}{r_B^*} \tag{8}$$

$$\Delta P_c = P_{w1} - P_{w2} = -\frac{2\sigma}{r_2}(\cos\theta_R - \cos\theta_A) \tag{9}$$

where, $\mathbf{r_A^*}$ and $\mathbf{r_B^*}$ are the upstream and downstream radius of curvature in the oil globule, respectively; and $\boldsymbol{\Theta_R}$ and $\boldsymbol{\Theta_A}$ are the receding and advancing contact angles, respectively. Equation (14) explains the change in capillary pressure that will occur if the curvature radius changes. Similarly, (15) explains the change in capillary pressure due to the change in the contact angles.

III. Methodology

After defining the equations that control the flow in pore doublet, we conducted a numerical study using a software named "ANSYS-FLUENT" to simulate the multiphase flow in a pore doublet model in an attempt to investigate the ability of the model to trap the oil and apply wave excitation, if oil trapping successfully occurred. We utilized ANSYS-Design-Modular to draw the pore doublet model that is shown in Fig. 1, with a total length of L= 4 mm, an inlet diameter d=d_1=0.1 mm which is similar to the pore 1's diameter and pore 2 diameter d_2=0.2 mm. We selected the inlet to be at the left end of the pore doublet and the outlet at the right end. As a result, the displacement will be from left to right. The upper and lower boundaries were defined as a wall with a no-slip condition.

TABLE I. Grid Optimization in a Convergence Test Whit Only Water Flowing Throughout the Domain

Mesh	Elements	V_{max} inlet mm/s	V_{max} Pore 1 mm/s	V_{max} Pore 2 mm/s	V_{max} outlet mm/s	No. Iterations
M1	4987	7.185	0.872	3.250	7.185	133
M2	6120	7.158	0.862	3.260	7.158	153
M3	**8970**	**7.351**	**0.868**	**3.275**	**7.351**	**331**
M4	11137	7.316	0.873	3.280	7.316	532
M5	13340	7.410	0.881	3.280	7.410	827

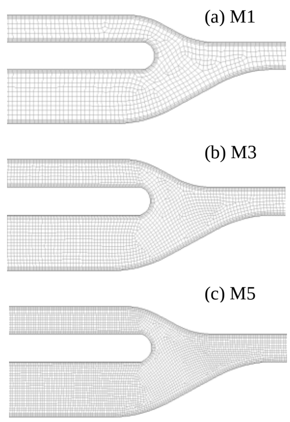

Figure 3. Grid distribution in three different meshes.

ANSYS-Mechanical was selected for mesh (grid) generation. Five different meshes were used to optimize the elements number for lower computational cost as well as higher accuracy. Velocity is a crucial variable in this study; hence, the maximum velocity along the centerline was measured in a convergence test. Four different points along the domain were selected for data collection, which are near the inlet, in the middle of pore 1 and pore 2 and near the outlet as shown in Table I. For meshes M1 and M2 in Table I, it appears that the maximum velocity changes by about 5% compared to M5. Unlike M1 and M2, M3 yields to maximum velocity change by less than

0.7%. Meanwhile, if computational cost was to be compared, then M5 takes about 60% more iterations than that of M3. From this point onward M3 in Fig. 3(b), is selected to be used for the rest of the numerical study. The inflation property in ANSYS-Mechanical was used to make the mesh near the wall finer. The mesh near the wall are made to be finer because the wave vibration is delivered using the moving wall option in ANSYS-fluent.

Since we are interested in studying the trapping of oil and its mobilization in a water filled domain, we chose the Multiphase Volume of Fluid (VOF) model as it has the ability of tracing the phases' volume fraction throughout the domain [15]. We selected water as the primary phase with a density of 998 kg/m^3 and viscosity of 0.001003 kg/m.s, and oil as the secondary phase with density of 860 kg/m^3 and viscosity of 0.0068 kg/m.s, and an interfacial tension of 0.021 N/m with 170 degree oil water contact angle. The inlet has been chosen to be a velocity-inlet with a constant velocity injection of 5 mm/s and the outlet is a pressure-outlet with a pressure of zero Pa, which is the atmospheric pressure. A stationary wall is selected when no wave excitation is utilized and a moving wall boundary is selected in the wave excitation case with a sinusoidal moving pattern defined using a user defined function (UDF). Since we are using a compressional wave, the wall movement was set to be along the x-axis.

We chose the Pressure-Implicit with Splitting of Operator (PISO) scheme for the pressure-velocity coupling, as it is faster and recommended by the FLUENT manual to be used with the VOF model.

IV. Results and Discussion

We started by simulating the trapping process as explained by Willhite [2]. The domain was filled with oil about 1 mm away from the inlet, so that we would have a fully developed flow before the water oil interface. Fig. 4, shows the volume fraction contours of the imbibition process at their respective time steps, where the red colored fluid is the oil and the blue colored fluid is the water. The water displaced the oil from pore 1 (narrower pore) first as have been illustrated in [1, 2, 4, 5]. After that, the water displaced the oil in pore 2 (wider pore). However, phase cutoff did not occur, as a result the oil in pore 2 (wider pore) was completely displaced by water.

After enough time had passed, the water displaced the oil completely as explained by Chatzis and Dullien [4] and Dullien [5]. Fig. 4, shows the displacement process with the respective time steps.

After displacing a domain filled with oil did not succeed in simulating oil trapping, we generated an oil globule in such a way that it would be isolated in pore 2. According to Willhite [2], the isolated oil globule will be trapped if the capillary pressure in pore 2 is equal or higher than the viscous pressure in pore 1. As a result, we varied the constant injection velocity and calculated the viscous pressure from (2), after the velocity value in pore 1 was extracted from the simulation results. The capillary pressure across the oil globule in pore 2 was extracted from the simulation results to determine the velocity at which the oil globule is trapped. Table II. shows that the inlet velocity 5 mm/s will cause the oil globule trapping as the capillary pressure across the oil globule is higher than the viscous pressure in pore 1. Fig. 5, Shows phase contours of the pore doublet after the oil globule was generated to be isolated in pore 2 with an inlet velocity of 5 mm/s, which is the inlet trapping velocity as shown in Table II.

Fig. 5(e), shows that the oil globule was about to be pushed out of pore 2 at time t=0.060 s, but the applied pressure was not enough. As a result, the oil globule flowed back to its initial state as shown at Fig. 5(g), which means that the oil globule was already trapped.

Now that the oil globule was trapped in pore 2 due to the capillary forces, we applied the wave stimulation through the moving wall boundary as mentioned in the methodology section. A sinusoidal wave was applied with a frequency of 10 Hz and a peak velocity of 5 mm/s, which yields to an acceleration of 314 mm/s^2. The wave was applied at time t=0.00 s. Fig. 6, shows the phase contour of the pore doublet after the wave excitation was added. The wave excitation caused the oil globule to move. However, the oil globule flowed backwards. That means that the vibration caused a reversed flow that overcame pressure exerted by the injection at the inlet. This implies that high pressure at the outlet was the result of the wave excitation. But if we would look closer at the time at which the oil globule went backward all the way back to the inlet, it would be at t= 0.016 s. The time t=0.016 s is still at the beginning of the first half of the sinusoidal wave cycle, which is the positive half of the wave cycle.

TABLE II. Viscous Pressure in Pore 1 v.s. Capillary Pressure in Pore 2.

V_{inlet} (mm/s)	ΔP_1 (Pa)	$\Delta P_c = P_{w1} - P_{w2}$ (Pa)	$\Delta P_1 - \Delta P_c$ (Pa)
5	**1.8**	**-25**	**26.8**
10	4.7	-1	5.7
20	10	23	-13
40	31.7	71	-39.3

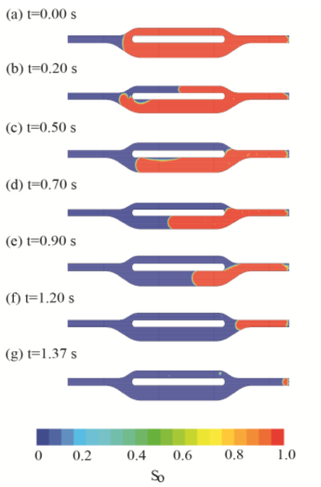

Figure 4. Time steps from (a) to (g) illustrating the pore doublet model that is filled with oil while being injected by water to displace the oil in an imbibition process.

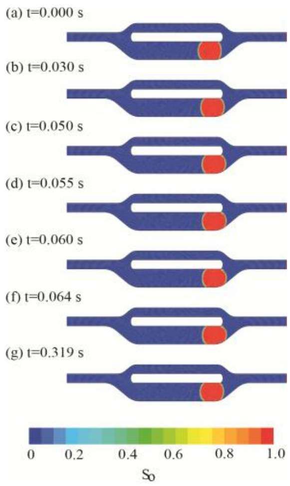

Figure 5. Time steps from (a) to (g) showing the pore doublet model being injected with water at a velocity of 5mm/s causing the isolated oil globule trapping.

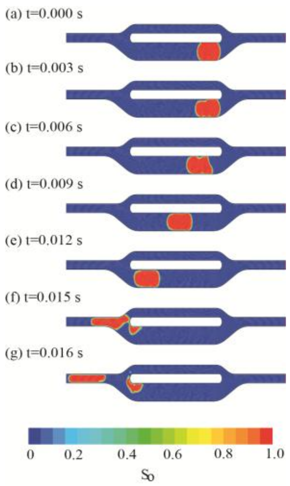

Figure 6. Time steps from (a) to (g) demonstrating the effect of wave excitation when the vibration started at the positive half of the wave cycle.

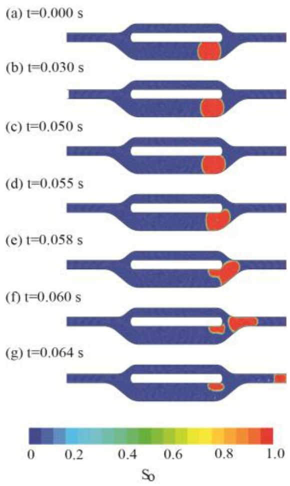

Figure 7. Time steps from (a) to (g) demonstrating the effect of wave excitation when the vibration started at the negative half of the wave cycle.

Taking into considerations the results we obtained earlier, we kept the same conditions of Fig. 6. However, we wanted to examine the effect of the negative half of the wave cycle on the trapped oil globule in pore 2 of the pore doublet. As a result, we started the wave excitation at t=0.05 s, which is at the beginning of the negative half of the wave cycle. After simulation started by t=0.05 s, which is approximately at the beginning of the negative half of the wave cycle. The negative half of the wave cycle creates a favorable pressure gradient, which applies more pressure on the trapped oil globule causing its mobilization. Fig. 7, shows the phase contour of the pore doublet with the wave excitation added after t=0.05 s. It shows that up to time step t=0.05 s the oil globule is trapped and after the wave excitation was applied, the oil globule started moving as shown at time step t=0.055 s fig. . At time step t=0.06 s a large portion of the oil globule passed from pore 2 and continued moving till it left the pore doublet.

V. Conclusion

We carried out a numerical study on the fluid flow in a pore doublet model. Apparently, it is difficult for this model to capture the physics in porous media. However, the fluid flow in porous media is controlled by the viscous and capillary forces, which can be simulated in the pore doublet model. We studied the ability of this model to trap oil in an imbibition process. However, the trapping did not occur.

We generated an isolated oil globule and patched it in pore 2. We examined the suitable inlet velocity that satisfies the condition for oil globule trapping in the pore doublet model. This velocity was determined for the pore doublet dimensions used in this study, and the oil globule was trapped. After the oil globule was successfully trapped, we applied the seismic excitation with sinusoidal wave. The positive half of the wave cycle caused a reversed flow, which would lead to further trapping the oil globule. Taking that into consideration, we applied the wave excitation starting at the negative half of the sinusoidal wave cycle. As a result, the excitation wave started after 0.05 s, which is at the beginning of the negative half of the sinusoidal wave cycle. The negative half of the wave cycle created a favorable pressure gradient. It resulted in a viscous pressure that is higher than the capillary pressure across the oil globule. That satisfies the conditions for mobilizing a trapped oil globule by a capillary constriction. As a result, the oil globule overcame the capillary constriction and was mobilized.

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