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The effect of forces affecting the spread of oil droplets on a rock surface

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Abstract
A better understanding of the main forces that affect oil droplets is expected to play an important role in enhancing oil recovery from reservoirs. The effects of the various forces on an oil droplet on the top of a rock surface or hanging from the bottom of a rock surface are analysed. The results proved that increasing the mass of an oil droplet creates a favourable condition for interaction between the displaced and displacing fluids, which prevents the displacing fluid from bypassing the oil droplets. The results show that the mass of an oil droplet plays an important role in initiating its movement if the gravity force is greater than the capillary force. This study provides a sound understanding of the main forces affecting oil droplet movements and opportunities for future enhanced oil recovery projects.

Keywords Enhanced oil recovery · Capillary force · Gravity force · Analytical and logical analysis

List of symbols

a_x Acceleration of the fluid element in the *X*-direction
a_y Acceleration of the fluid element in the *Y*-direction
g Gravity acceleration
l Vector length
m Mass of the oil droplet
P_c Capillary pressure
P_x Pressure in the *X*-direction
P_y Pressure in the *Y*-direction
W Weight of the oil droplet
$\sum Fx$ Summation of the forces affecting oil droplet in the *X*-direction
$\sum Fy$ Summation of the forces affecting oil droplet in the *Y*-direction

Greek symbols

Δx Change in the *X*-direction
Δy Change in the *Y*-direction
θ Contact angle between the centralized capillary force and the main axis
ρ Oil droplet density

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Introduction

Enhanced oil recovery (EOR) changes the properties of a reservoir and increases the oil production. The change could occur between the displaced and the displacing fluid or the displaced fluid and the reservoir rock. The change might take the form of oil swelling, wettability alteration, reduction of interfacial tension, oil viscosity and capillary forces (Green and Willhite 1998; M.A. Samba et al. 2019a, b; Elsharafi 2018; Naser, et al. 2020).

Capillary force has a considerable effect on the oil recovery efficiency (Green and Willhite 1998; Kathel and Mohanty 2013; Romanuka et al. 2012; Elraies and Tan 2012), and many studies have focused on the mechanisms involved (Guo et al. 2020; Nobakht et al. 2007; Tola et al. 2017; Esfe et al. 2020; Rossen and Lu 1997). Nevertheless, the effect of capillary force is still under investigation, particularly its relationship with aging time, wettability type, pore throat diameter and mass of the oil droplet.

The molecules of any homogeneous material are held together by molecular attraction forces (cohesion forces). The magnitude of these forces in liquids is less than those in solids. These forces dissociate due to fluid displacement or drive mechanisms during the initial stage of oil production, whereby large oil droplets dissociate into small droplets (Hinze 1955; M J Van der Zande, Janssen, and Van den Broek 2001; Marinus Johannes Van der Zande 2000). Most of the small droplets will stick onto the surface of the pores, generating another force. This force affects the molecules of the liquid and also those of other media in contact with them, whether they are solids, liquids or gases. This force is an adhesion force, the origin of capillary force, which is generated when adhesion to the walls is stronger than the cohesive forces between the liquid molecules (Boyd 2020). Many factors affect the capillary force, such as the mass of the oil droplet and the diameter of the pore throat. Studies have shown that the effect of capillary forces is inversely proportional to the mass of the oil droplet (Andersen 2020). Thus, an oil droplet with a larger mass has smaller capillary forces (Pak et al. 2015). Also, the relationship between the oil droplet mass and the pore throat diameter has an important influence on the displacement process. Indeed, the mass of the oil droplet compared to the pore throat diameter can determine whether or not an oil droplet can be produced (Fig. 1). To illustrate the figure, water injection is considered as immiscible flooding, when the mass of the oil droplet fills the pore throat (d_1), the oil droplet is affected by the cohesive forces of the water droplet, even if there is no interaction between the molecules of the liquids (a capillary force can be established) (Fig. 1A). If the mass of the oil droplet does not fill the pore (d_2), the water droplets may bypass the oil droplet and fail to displace it (Fig. 1B).

It is also important to determine the capillary force based on the wettability of the reservoir, which has a significant influence on oil recovery efficiency. Many researchers have investigated the effect of wettability on capillary force (Guo et al. 2020; Chinedu C Agbalaka et al. 2009; Andersen 2020; Chinedu Christian Agbalaka et al. 2008; Roustaei et al. 2012). The effect of the capillary force has been noticed during the wettability change from oil-wet to water-wet (Masalmeh 2003; Jabbar et al. 2017; Al Sayari 2009). The change in wettability causes a change in capillary force based on the wetting phase. In an oil-wet reservoir, the capillary force is between the oil droplet and the rock surface, in this case more effort is needed to reduce the capillary force in order to free the oil droplet. On the other hand, in a water-wet reservoir, the capillary is primarily between the water droplet and the oil droplet if the water droplet cannot be bypassed, as mentioned previously. This capillary force is not the main hindrance to enhancing oil recovery in a water-wet because oil is not miscible with water. In a water-wet case, chemical injection could be used to create an interaction between the oil droplet and the water droplet or, in the oil-wet case, to change the wetting phase from the oil-wetting to a water-wetting phase.

Based on the empirical literature, the main recovery challenges result from the relationship between an oil droplet and the solid surface due to the multiplicity of physical phenomena involved (mass of the oil droplet, aging time, pore throat diameter, etc.). Nevertheless, some physical phenomena could be further investigated. In this study, the relationship between the different forces and the oil droplet spreading on a rock surface at the late stage of oil production is analysed. It is anticipated that the mass of the oil droplet may play an important role in displacing the remaining oil in place since the proposed theory indicates that an increase in the mass of an oil droplet helps to displace the oil droplet and reduce the capillary force, but another force is still required to displace the large oil droplets. This point will be elaborated in the second part of this work, the second part will also introduce a new material to enhance oil recovery in the order to prove the analytical investigation in this paper. Moreover, the effect of these forces could be further introduced to the reservoir simulation.

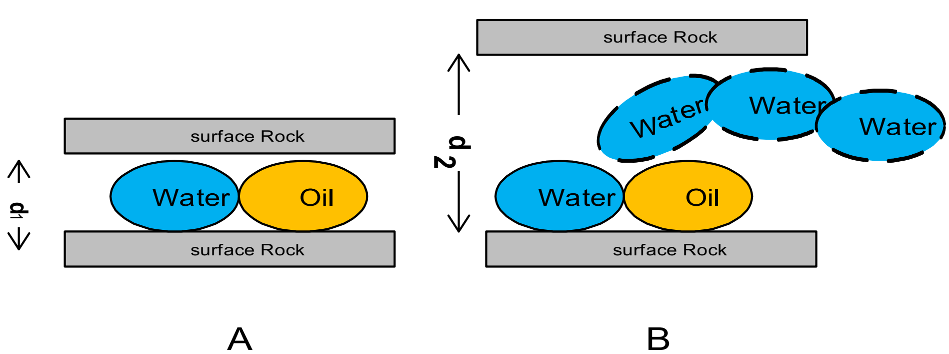

Fig. 1 How the pore diameter relative to the mass of the oil droplet can determine the fate of the oil droplet

Analytical investigation

Assumptions

1. Oil droplets are not located on a flat surface.
2. The analysis included two cases: an oil droplet on the top of a rock surface and an oil droplet hanging from the roof of the rock surface.
3. The flow direction is along the *X*-axis.
4. The contact angle **(**θ) is between the centralized capillary force and the main axis.
5. The system is in the oil-wetting phase.
6. The oil droplet is affected by two forces in the base case: gravity force, and capillary force.
7. Absence of linear streamlines (in the late stage of production).
8. The relative permeability of water and oil is a uniform function of oil and water saturation, i.e., the value does not change over time.
9. The driving mechanisms are neglected.

The oil droplet is located on the top of a rock surface

The oil droplet is located on the top of a rock surface without injection

Pressure is the force per unit area and it works as a vector. However, pressure at any point in a fluid is the same in all directions. That is, it has magnitude but no specific direction and, therefore, it is a scalar quantity. The main pressures that have an effect on the oil droplet are; pressure in *X*-direction (P_x), pressure in *Y*-direction (P_y), and capillary pressure (P_c) (Fig. 2).

From Newton's second law, a force balance in the X and *Y*-direction gives the following**:**

$$\sum F_x = \mathrm{ma}_x = P_x\Delta y - P_C l \sin_\theta = 0 \quad (1)$$

$$\sum F_y = \mathrm{ma}_y = P_y\Delta x - P_C l \cos\theta - \frac{1}{2}\rho g \Delta x\ \Delta y = 0 \quad (2)$$

where.

ρ is the density and $\mathrm{W} = \mathrm{mg} = \frac{1}{2}\rho g \Delta y$ is the weight of the oil droplet.

So

$$\sum F_y = P_y\Delta x - P_C l \cos\theta - \mathrm{mg}\Delta x = 0 \quad (2.1)$$

We have $\Delta\mathrm{x} = \mathrm{l}\cos\theta$ and $\Delta y = l\sin\theta$. Substituting these geometric relations and dividing Eq. 1 by Δ y and Eq. 2 by Δx gives

$$\sum F_x = \mathrm{ma}_x = P_x - P_C = 0 \quad (3)$$

$$\sum Fy = \mathrm{ma}_y = P_y - P_C - \mathrm{mg} = 0 \quad (4)$$

In this case, it is assumed that $\sum \mathrm{F_x}$ is smaller or equal to $\sum \mathrm{F_y}$. Thus, the oil droplet will stick to the surface of the rock and prevent forward movement. Based on Eq. 3, the mass of the oil droplet plays a significant role in allowing the oil droplet to be free, where the positive effect of the pressure in the *X*-direction (P_x) is ignored in this case because there is no injection

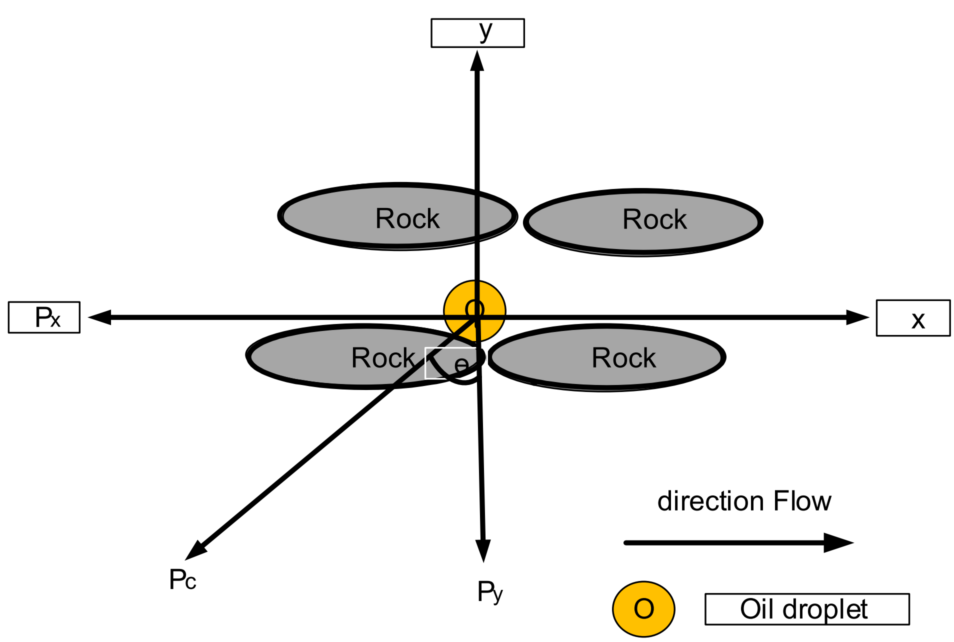

Fig. 2 Forces acting on an oil droplet located on the top of a rock surface without injection

$\left(\sum F_x = -P_C\right)$. Thus, the oil droplet in the *X*-direction is affected only by capillary force, which is against the flow direction and prevents the oil droplet from moving. As mentioned above, the smallest mass of the oil droplet has the strongest capillary force, so the increase in the mass of the oil droplet can reduce the P_c that acts on the oil droplet. Also, there are other forces that have effects on the oil droplet in the *Y*-direction, these are the capillary pressure and the gravity force $\left(\sum F_y = -P_C - mg\right)$ and both of them work against the flow direction (Eq. 4). The conclusion in this case is that the oil droplet sticks due to the gravity force in the *Y*-direction and the capillary force in both Y and *X*-direction as well. Figure 2 shows that if the mass of the oil droplet increases and is supported by the inclination of the rock surface, or the oil droplet is subjected to a positive force along the *X*-axis (P_x), the oil droplet will move forward with the flow direction.

The oil droplet is located on the top of a rock surface with water injection

The oil droplet is affected by the same forces shown in Eq. 3 and Eq. 4, even in the case of water injection. The pressure in the *X*-direction does not affect the oil droplet due to its small mass compared to the pore throat diameter. This allows the water droplet to bypass the oil droplet since gravity and capillary forces are acting on the oil droplet. In this case, the $\sum F_x$ is still smaller or equal to $\sum F_y$ because of the small size of the oil droplet, so there is a chance for the water droplet to bypass the oil droplet (Fig. 3). In addition, there is no interaction between the oil droplets and water droplets, because the pore diameter compared to the size of the oil droplet, which it does not provide a suitable condition for the water droplets to displace the oil droplets due to the capillary force. The conclusion in this case is that the oil droplet sticks due to gravity force in the *Y*-direction and the capillary force in both *Y*-direction and *X*-direction. As mentioned above, to allow the oil droplet to be free, its mass should be increased to decrease the capillary force and prevent the water droplet from bypassing it, so that it will be subjected to a positive force on the *X*-axis (P_x).

The oil droplet is located on the top of a rock surface and it is mass increases

In the case shown in Fig. 4, it is assumed that $\sum F_x$ is larger than $\sum F_y$. Thus, the oil droplet will move forward in the direction of production. Equation 3 shows that, the oil droplet moves due the pressure in the *X*-direction (P_x), where P_x is greater than the capillary pressure. Generally, P_x will have an effect on the oil droplet if its mass is increased. In any case, the effect of P_x will neglect the capillary force effect on the oil droplet due to the small value of this force compared to the P_x ($\sum F_x = Px$). In addition, the increase in the mass of the oil droplet will not only create a favourable condition for interaction between the displaced and displacing fluid but will also increase P_x and determine the direction of acceleration (Eq. 3). The conclusion in this case is that the movement of the oil droplet is due to increase of its mass, which allows the oil droplet to be pushed by the water droplet. Even though, the oil droplet remains exposed to the gravity force in the *Y*-direction and the capillary force in both Y and *X*-direction, these forces are negligible because their small magnitude compared to value of P_x. The second part of this paper will include one of the methods that can be used to increase the mass of an oil droplet.

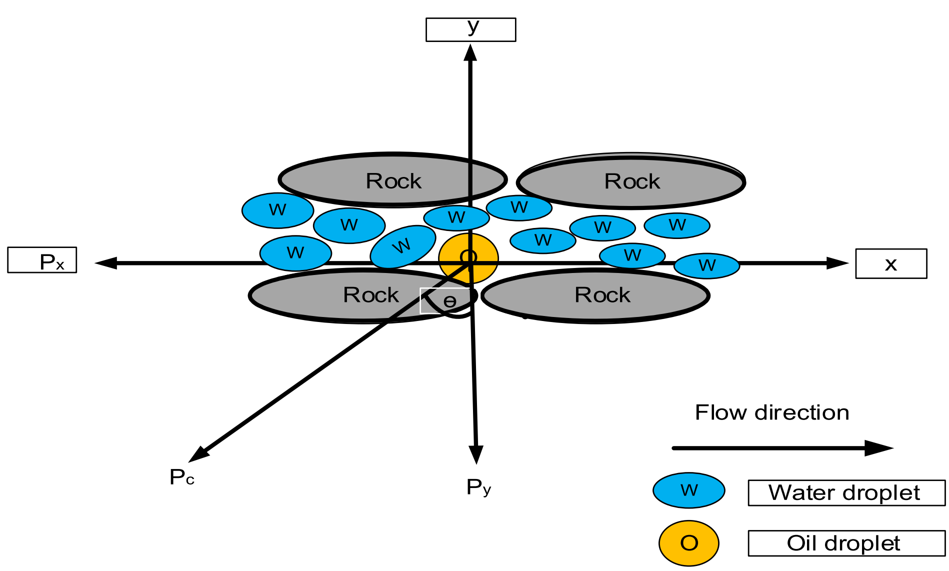

Fig. 3 Forces acting on an oil droplet when it is located on the top of a rock surface during water injection

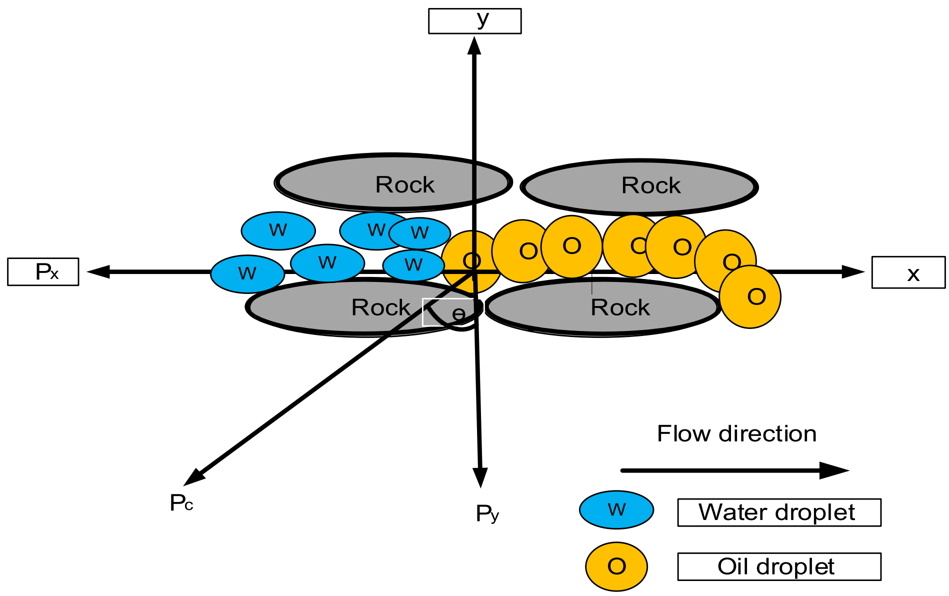

Fig. 4 Forces acting on an oil droplet on the top of a rock surface and its mass increases

The oil droplet hangs from the bottom of a rock surface

The oil droplet hangs from the bottom of a rock surface without injection

From Newton's second law, a force balance in the X and Y direction gives the following:

$$\sum F_x = \mathrm{ma}_x = P_x \Delta y - P_C l \cos\theta = 0 \tag{5}$$

$$\sum F_y = \mathrm{ma}_y = P_y \Delta x + P_C l \sin\theta - \frac{1}{2}\rho g \Delta x \Delta y = 0 \tag{6}$$

where:

ρ is the density and $W = mg = \frac{1}{2}\rho g \Delta y$ is the weight of the oil droplet.

So

$$\sum F_y = P_y \Delta x + P_C l \sin\theta - \mathrm{mg}\Delta x = 0 \tag{6.1}$$

We have $\Delta x = l \sin\theta$ and $\Delta y = l \cos\theta$. Substituting these geometric relations and dividing Eq. 5 by Δ y and Eq. 6 by Δx gives

$$\sum F_x = \mathrm{ma}_x = P_x - P_c = 0 \tag{7}$$

$$\sum F_y = \mathrm{ma}_y = P_y + P_c - \mathrm{mg} = 0 \tag{8}$$

In this case, it is assumed that $\sum F_x$ is smaller or equal to $\sum F_y$. Thus, the oil droplet will stick to the bottom surface of the rock, as shown in Fig. 5.

Based on Eq. 7, two forces affect the oil droplet along the *X*-axis; pressure in the *X*-direction (P_x) and P_C. The positive effect of the pressure in the *X*-direction (P_x) is ignored in this case because there is no injection. Thus, $\sum F_x = -P_C$, where Pc works against the flow direction. Meanwhile, the forces that affect the oil droplet on the *Y*-axis are Pc and gravity force (mg) ($\sum F_y = P_C - mg$). based on Eq. 8, it is apparent that the gravity force works against Pc and Pc works against the flow direction. Therefore, increasing the mass of the oil droplet will help to free it and allow it to move forward with the flow direction.

The oil droplet hangs from the bottom surface of a rock with water injection

In this case, it is assumed that $\sum F_x$ is smaller than or equal to $\sum F_y$. Therefore, the oil droplet will stick on the bottom surface of the rock and cannot move forward (Fig. 6). Equation 8 shows that there are three forces acting on the oil droplet in the *Y*-direction; P_y, P_c and the gravity force (mg). P_y and P_c will cause the droplet to hang, but in this case, there is no P_y effect on the oil droplet, so the oil droplet sticks due to the capillary force (P_c), and the gravity force works against the capillary force. Meaning, the capillary force is greater than the gravity force. In this case, the water droplets bypass the oil droplet in the presence of the capillary force due to the small mass of the oil droplet compared to the pore throat diameter. Furthermore, there is no interaction between the displaced and displacing fluid.

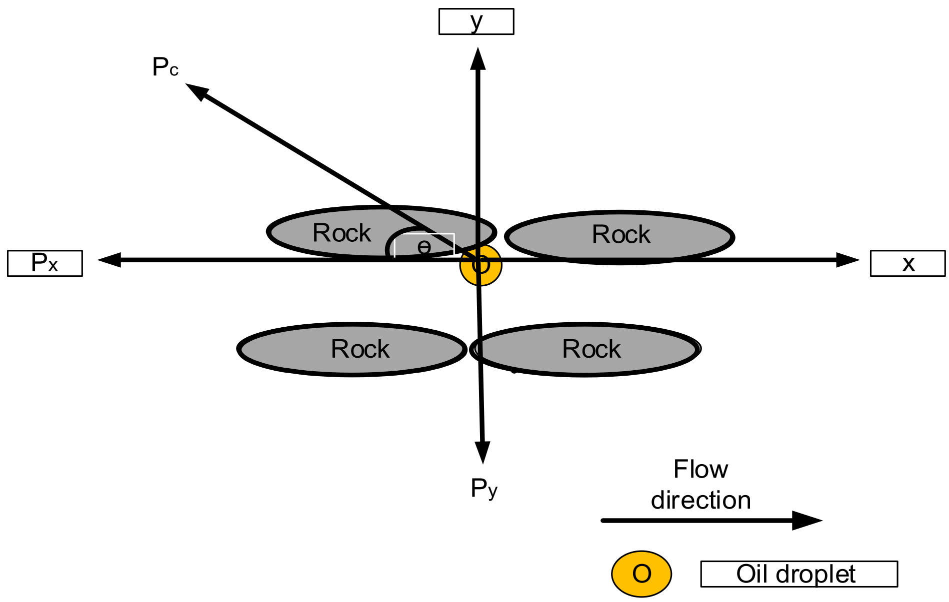

Fig. 5 Forces acting on an oil droplet when it hangs from the bottom surface of a rock without injection

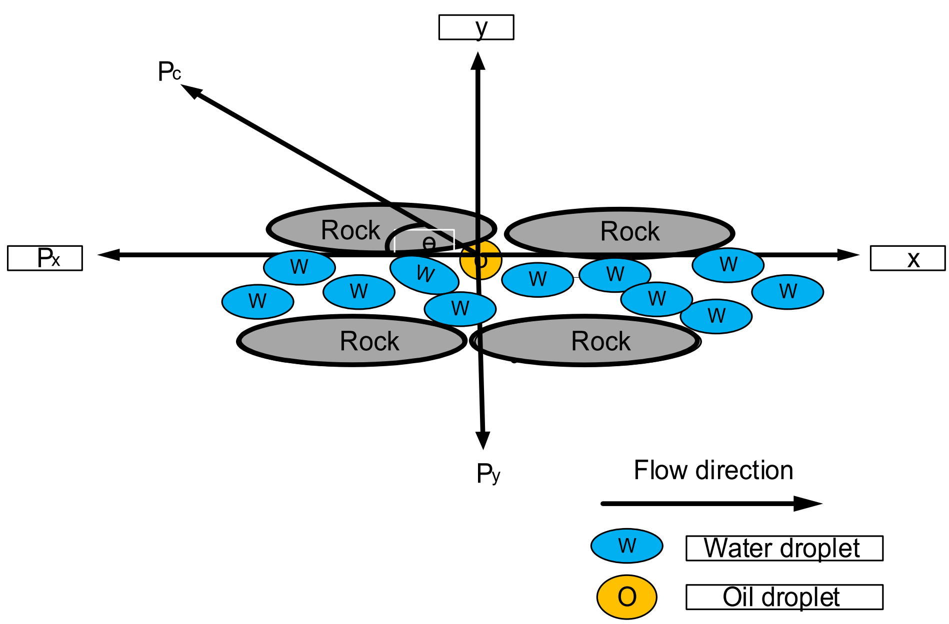

Fig. 6 Forces acting on the oil droplet when it hangs from the bottom of a rock surface with water injection

The oil droplet hangs from the bottom of a rock surface and its mass increases

Based on the previous investigation, if the mass of the oil droplet is successfully increased (Fig. 7), the oil droplet can be moved easily because the gravity force would be greater than the capillary force. Moreover, the increase in the mass of the oil droplet will not allow the water droplets to bypass it. In addition, the material that will be used to increase the oil droplet mass will help to create an interaction between the oil droplet and the water droplet.

Conclusions

In this study, detailed analysis of the forces that affect the oil droplet help to explain the oil droplet's movement in porous media. The main findings of this study can be summarised as follows:

- Increasing the oil droplet mass causes a reduction of the capillary pressure and creates the conditions for an

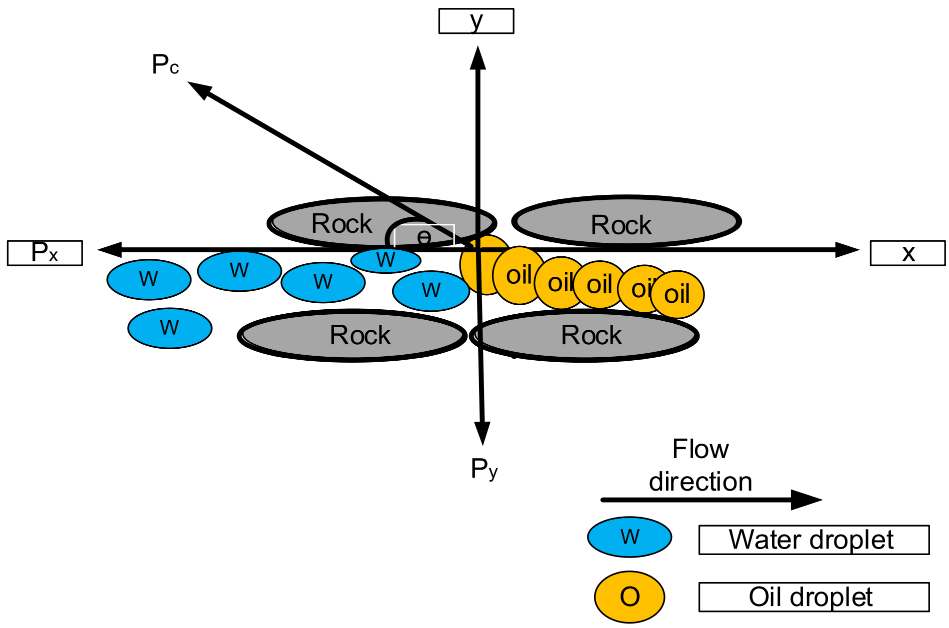

Fig.7 Forces acting on the oil droplet when it hangs from the bottom of the rock surface and its mass increases

interaction between the displacing and displaced fluid, hence movement of the oil droplet.

- The results show that the mass of an oil droplet plays an important role in initiating its movement if the gravity force is greater than the capillary force.
- The analyses confirm that the mass of the oil droplet has a systematic effect in order to recover the oil. Increasing the mass of the oil droplet will create an opportunity to displace the oil droplet and reduce the capillary force.

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Declarations

Conflict of interest We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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