Visualization Investigation of the Mechanisms of Higher Quality Heavy Oil Recovery by Dense CO_2 Injection

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ABSTRACT

The efficiency of primary recovery from heavy oil reservoirs is low due to their nature of high oil viscosities and low dissolved gas contents. Because of a substantial reduction in the oil viscosity, CO_2 injection would be a potential solution to enhance recovery from heavy oil reservoirs. Many heavy oil reservoirs are shallow and likely to have a low temperature. Under the conditions of those reservoirs, CO_2 would be a dense liquid or supercritical fluid. Another benefit of dense CO_2 injection could be a favorable improvement in the physical properties of the recovered oil. It appears that the mechanism of extraction of light and intermediate components of the oil by CO_2 causes the changes in the properties of recovered oil. To identify the processes that affect the physical properties of heavy oil, the contact between CO_2 and heavy oil was visually investigated under reservoir conditions. In addition, several experiments were performed using a transparent micromodel setup to understand the impact of the extraction of oil components on the flow in porous media.

As CO_2 contacts the oil, the extraction of hydrocarbons, mostly methane at the beginning, from the oil starts immediately. The extraction of hydrocarbons by CO_2 initially leads to a sudden swelling of the oil mainly because of the liberation of the dissolved gas from the oil. Consequently, an accumulation of the light and intermediate compounds of the oil takes place in the oil phase, near the interface of the oil and CO_2. The results of the direct visualization of the flow reveal that the contact of CO_2 and heavy oil results in the formation of a different oil-rich phase. This light and less viscous oil-rich phase has a relatively lighter color than the oil in contact with CO_2 and it is significantly mobile in pore spaces.

INTRODUCTION

Heavy oils, because they constitute one of the largest reserves of fossil fuels on earth, are considered an alternative source in propping up the rising demand for oil. Heavy oil is defined as a dense (low API gravity) oil and is generally known for its high viscosity and limited mobility in porous media (Meyer, et al., 2003). Because the techniques of primary production mainly rely on natural forces within oil reservoirs, the efficiency of primary recovery by pressure depletion in heavy oil reservoirs is generally low.

Carbon dioxide is of great interest for enhancing oil recovery because of its characteristics such as high solubility in oil and oil viscosity reduction. A remarkable decrease in oil viscosity by CO_2 dissolution, in particular, for viscous oils have been reported in the literature (Miller, et al., 1981) (Klins, 1984). CO_2 dissolution in oil would also result in oil swelling which increases oil volume (saturation) in porous media and hence improves the relative permeability for oil. Another mechanism usually associated with CO_2 injection for oil recovery is the extraction of light and intermediate components of oil by the injected CO_2. However, this process is mainly considered as an active mechanism of recovery when the reservoir oil is a light oil.

The results of our coreflood investigations have shown that the concentration of light and intermediate components in the oil recovered by liquid CO_2 or supercritical CO_2 injection is higher than that of the original heavy oil in the core. Furthermore, it was observed that the oil recovered by dense CO_2 injection has a significantly lower viscosity than the original oil in the rock (Seyyedsar, et al., 2016). At first glance, the in-situ alteration of the properties of heavy oil by CO_2 would be related to the impacts of the mechanism of extraction of oil compounds by CO_2. However, the process of extraction is a slow process, in particular in porous media. That is, it is believed that the process of extraction occurs under certain conditions of temperature and pressure. Another crucial factor controlling the strength of extraction by CO_2 is the ratio of the volume of CO_2 to the volume of oil. Investigations have shown that decreasing the ratio of CO_2 to oil to a smaller ratio (but still above that required to saturate the oil) reduces the amount of oil extracted. However, the pressure at which the extraction begins remains unchanged indicating that the density of CO_2 is the dominant factor determining the extraction behavior of CO_2 (Menzie, et al., 1963) (Holm, et al., 1974).

Given the above, the oil used in the investigations regard to the extraction had usually the characteristics of the conventional (light) oil. It recurs in the literature that small hydrocarbon molecules are extracted more efficiently into a CO_2-rich phase than are large ones. For example, (Orr, et al., 1987) measured compositions of CO_2-rich and oil-rich phases. Their data confirm that small molecules partition preferentially over large molecules into a CO_2-rich phase. Thus, a combination of the mass transfer between CO_2 and heavy oil as well as the flow of CO_2 and the oil in porous media are likely to be the main reasons of the in-situ improvement of the properties of heavy oil by CO_2.

In this study, direct visualization approach was employed to investigate the contact and flow of CO_2 and heavy oil under reservoir conditions. A setup was designed to evaluate the impacts of the mechanism of extraction on the properties of heavy oil. Several experiments were performed and repeated using a transparent micromodel system to visually observe the underlying mechanisms of flow of CO_2 and heavy oil. In addition, further analysis of the fluids in the coreflood experiments was performed to evaluate the impact of CO_2 on various properties of heavy oil in porous media.

Observations, Results, and Discussion

The oil that was used in our coreflood experiments (Crude 'C') is a stock-tank oil sample and is characterized as extra-heavy oil. First, a visualization setup was used to observe the contact of CO_2 with heavy oil under reservoir conditions. Around 0.4 cm^3 of the crude oil 'J' was poured into the container using a syringe. Care was taken to ensure that no air was trapped within the oil and also to have a flat level of oil in the container. After isolating the cell, the heater was switched on and set at 28˚ *C*. Later, methane was introduced to the system and the pressure at a controlled rate increased to the test pressure. The oil in the container was only accessible from the top end of the container. It was observed that the level of oil started rising after having contact with methane due to the dissolution and diffusion of methane into the dead oil. This swelling of the oil was relatively rapid at early times of the contact of methane with the oil. The images captured during this process clearly show the swelling of the oil, Figure 1.

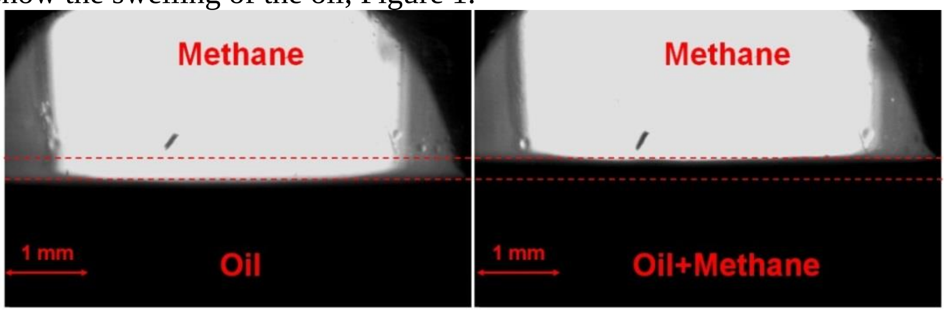

Figure 1: Level of oil in the container before the contact with methane (left) and after equilibrium with methane (right).

When the oil in the container was fully saturated with methane, CO_2 was introduced to the system from the bottom of the chamber and methane was removed from the top of the cell at constant pressure. The procedure was performed at a slow and controlled rate to ensure complete displacement of methane by CO_2 and to ensure that the pressure of the system remained constant during this displacement. This was continued until the time that CO_2 displaced methane from the chamber. Then, the chamber was kept connected to the CO_2 cell until the end of the run. It was observed that once the CO_2 contacted the oil in the container, extraction of hydrocarbons, mostly methane at the beginning, from the oil started instantly, as evidenced in Figure 2. The contact between CO_2 and the oil in the container caused to the extraction of light and intermediate components of the oil from the interface. It was seen that this phenomenon initially led to a sudden swelling of the oil mainly due to the liberation of dissolved methane from the oil. The liberation of methane and other hydrocarbon components from the oil was continued as time went on which indicates that CO_2 had also affected the oil below the surface. The process of extraction of hydrocarbon continued although the speed of it decreased dramatically after a complete liberation of light components of the oil such as methane. The similar behavior was also observed in the coreflood experiments where the liberation of methane from the oil increased the core pressure during the shut-in periods (Seyyedsar, et al., 2015).

Eventually, more hydrocarbon components were extracted from the oil by CO_2 and the level of the oil went below the original level of oil before the contact with CO_2 started. Figure 3 shows that the volume of oil in the container has decreased significantly after around 10 days of contact between oil and CO_2. At this stage, to be able to record the level of the oil in the container, the height of the camera was lowered.

A behavior similar to what was described above was also observed when the oil was dead (no dissolved hydrocarbon gas) albeit to a lesser extent, in particular at the beginning of the contact between CO_2 and dead oil, since the oil did not have solution gas (methane). In the dead oil again it was observed that the extraction of oil components continued and a significant volume of oil was gone into the CO_2-rich phase. After completing each test, the pressure of the system was decreased slightly at constant temperature and it was observed that the volume of oil was slightly decreased due to the liberation of dissolved CO_2 from the oil. Moreover, it was observed that a small amount of greasy-nature liquid was left at the bottom of the chamber after decreasing the pressure to the ambient conditions which is believed to be the extracted hydrocarbons in the CO_2-rich phase.

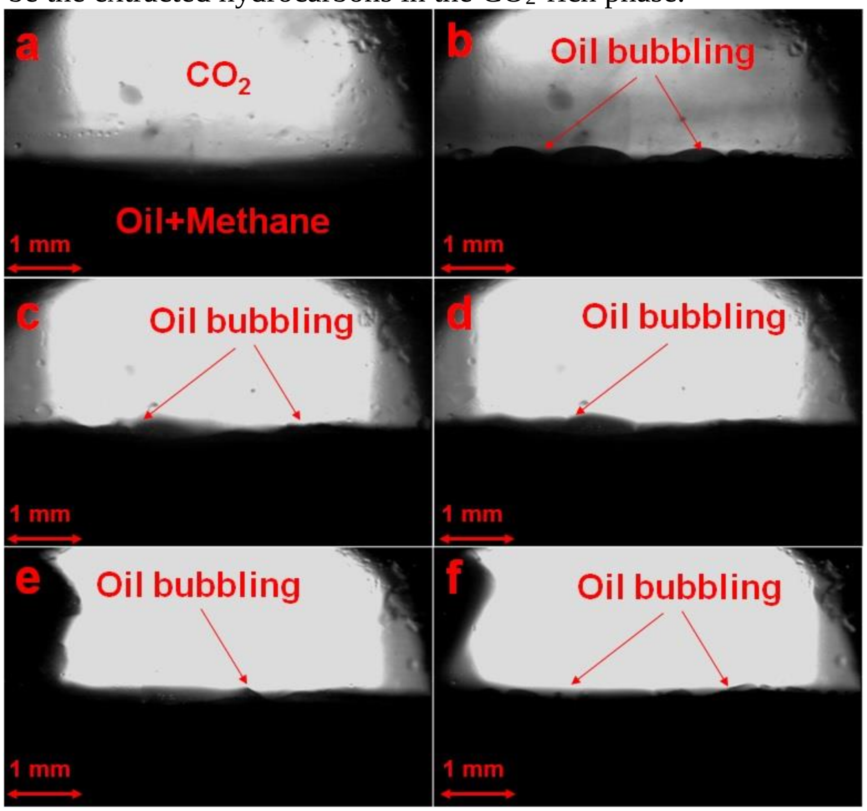

Figure 2: Extraction of oil components by CO_2 (a) first contact, (b) 1 minute, (c) 4 minutes, (d) 10 minutes, (e) 20 minutes, (f) 100 minutes after the first contact.

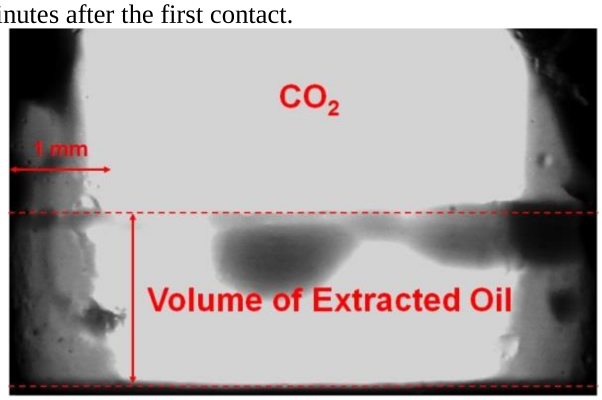

Figure 3: Shrinkage of oil volume due to the extraction of hydrocarbon components by CO_2, after 10 days.

The composition of the remaining oil after the extended contact of oil and CO_2 was analyzed and compared to the composition of the original dead oil, Figure 4. As shown, all the components up to C_{10} were completely extracted from the original oil by CO_2. Moreover, the concentration of the intermediate components up to C_{23} was reduced significantly in the remaining oil whereas the amount of the heavier components remained unchanged or changed little. The changes in the composition of the oil because of the extraction accounts for a decrease around 29% of the mass of the original oil but it was seen that that is even higher in terms of volume of oil under reservoir conditions.

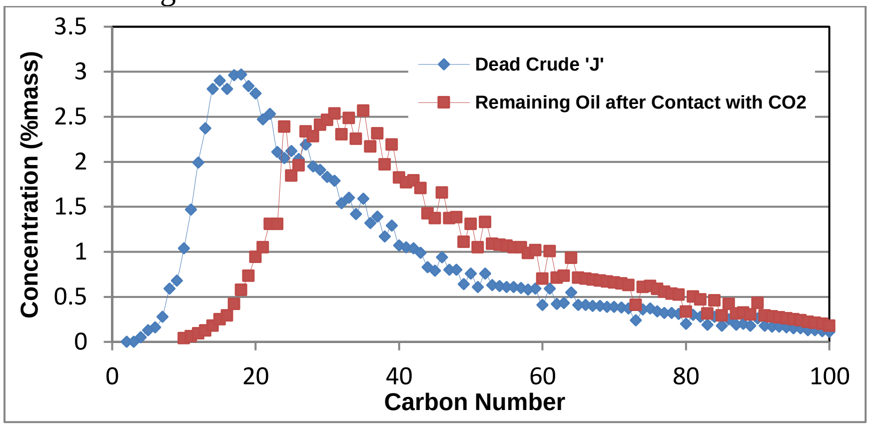

Figure 4: Compositional analysis of crude 'J' and the remaining oil after contact with (liquid) CO_2.

In a porous medium, the components extracted by the CO_2-rich phase could be easily displaced and recovered at the production outlet because of the high mobility of the carrying phase. The remaining oil that has lost a significant fraction of its light and intermediate compounds is heavier than it was before the contact with CO_2 and hence, it would have higher viscosity and density than the original oil. However, CO_2 dissolution in the remaining oil would reduce its viscosity and density and the oil can also be displaced toward the production outlet by the displacing fluid. The same procedure, which was conducted for the contact of liquid CO_2 and live heavy oil, was followed for a test under the conditions of our coreflood experiments at which CO_2 was a supercritical fluid. Similar behavior was observed during early times of the contact of CO_2 and oil.

The compositional analysis of the produced oil during the coreflood experiments revealed that from the early time of injection of CO_2 into the core, relatively higher quality oil was recovered (Seyyedsar, et al., 2016). It was shown that the speed of the mechanism of extraction decreases significantly after the sudden extraction of relatively light components (mainly methane) from the oil at early times of the process, albeit it is a continuous process. The speed of this process would further decrease in porous media due to several reasons such as the presence of water and the formation heterogeneities. Moreover, other parameters such as oil composition and oil viscosity can affect the process of extraction of hydrocarbons by CO_2. The oil used in the coreflood experiments (crude 'C') had a higher viscosity than the oil used in the visual contact experiments (crude 'J'). Also, crude 'C' has a lower concentration of light and intermediate components than crude 'J'. These factors, therefore, would have decreased the speed of the extraction of hydrocarbon compounds by CO_2 in the coreflood experiments.

An indication of oils recovered due to the extraction in fluids flow processes is their lighter color compared with that of the original oil (Holm, et al., 1974). Therefore, if the extraction mechanism was stronger in the coreflood experiments, it could have been expected to observe two different types of oils (in terms of color, viscosity, etc.) in the production outlet but that was not the case in our experiments. The produced oil in the coreflood tests was a relatively homogeneous black oil. Moreover, no considerable condensate accumulation was observed in the wet-gas-meter system during the coreflood tests. The same dead crude oil, that was used to prepare live oil for the coreflood tests, was used to prepare CO_2-saturated oil for viscosity measurements. Whilst the volume of CO_2 in the rocking cell was significant compared to the volume of oil, no considerable condensate (oil) production was also observed during removing the gas cap from the CO_2-saturated oil. The other active mechanism during the period of CO_2 injection which could potentially alter the composition of recovered oil was CO_2 dissolution and diffusion in the oil. It was shown that the dissolution of CO_2 in heavy oil results in oil swelling as well as significant reduction in the oil viscosity. Consequently, the oil saturated with CO_2 will have higher mobility than the original oil and it will also travel faster in porous media. To evaluate these phenomena and also to understand their effects on the process of oil recovery, direct visualization of the flow of CO_2 and heavy oil using a transparent micromodel was performed under the similar conditions of the coreflood experiments that CO_2 was a liquid fluid. Initially, the micromodel was fully saturated with brine and then crude oil 'J' was injected through the micromodel to establish initial water and oil distributions.
Having established the initial water and oil distributions, CO_2 was injected at 0.01 cm^3/hr through the micromodel from the bottom end of the model. Figure 5 shows a section of the micromodel before the breakthrough of CO_2. Although several branches can be seen around the stream of CO_2, only one main finger was generated in the model. Moreover, it was observed that parts of the oil which were in direct contact with CO_2 became lighter in color due to the dissolution of CO_2 in the oil.

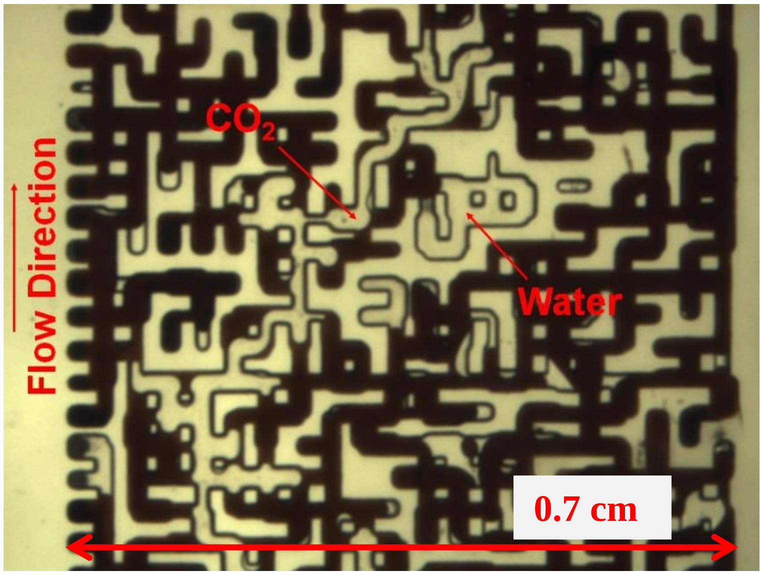

Figure 5: A magnified section of the micromodel before the breakthrough of CO_2.

After the breakthrough, oil production continued, at relatively low rates, mainly because of viscous forces and the dissolution of CO_2 in the oil and the resultant oil swelling and oil viscosity reduction. It is shown in Figure 6 that formation of a new phase with a light color in the CO_2-rich stream was observed. Although this new phase could not travel in the porous medium as fast the stream of CO_2, it was seen that this phase is significantly mobile. At first glance, this can be related to the mechanism of extraction of oil compounds by CO_2. However, the extracted compounds are essentially miscible with CO_2 and the extraction generally occurs in all parts of the interface between oil and CO_2. In addition, it was observed that this new phase was formed as a result of CO_2 and oil contact in the flow paths of CO_2. It is, therefore, believed that this new phase is a fraction of the oil in contact with CO_2 which has significantly low viscosity and probably it is rich in light and intermediate components of the oil which can explain the high mobility of this phase in pore spaces. It was shown that dense (liquid) CO_2 can extract heavy oil components. As soon as CO_2 contacts the oil in the micromodel, light and intermediate compounds of the oil are attracted by the CO_2-rich phase. Therefore, an accumulation of these components would take place in the oil phase, near the interface of oil and CO_2. That is, the similar process occurred during the period of CO_2 injection in the micromodel and hence, the displaced oil by the flow of CO_2 had a higher concentration of the light and intermediate components than the original oil in place. It is, in general, considered that when dense CO_2 is injected into an oil reservoir, three hydrocarbon phases may exist at high CO_2 concentrations. These three phases include a vapor phase, an oil-rich phase, and a CO_2-rich phase. The results of our coreflood experiments, in which dense CO_2 was injected in intermittent fashion (Seyyedsar, et al., 2015), and the visualization experiments also confirmed that at least three phases could appear in pore spaces when dense CO_2 contacts the oil. Here, it was shown that a second oil-rich phase also forms in porous media during immiscible dense CO_2 injection for oil recovery which contributes to higher quality oil production.

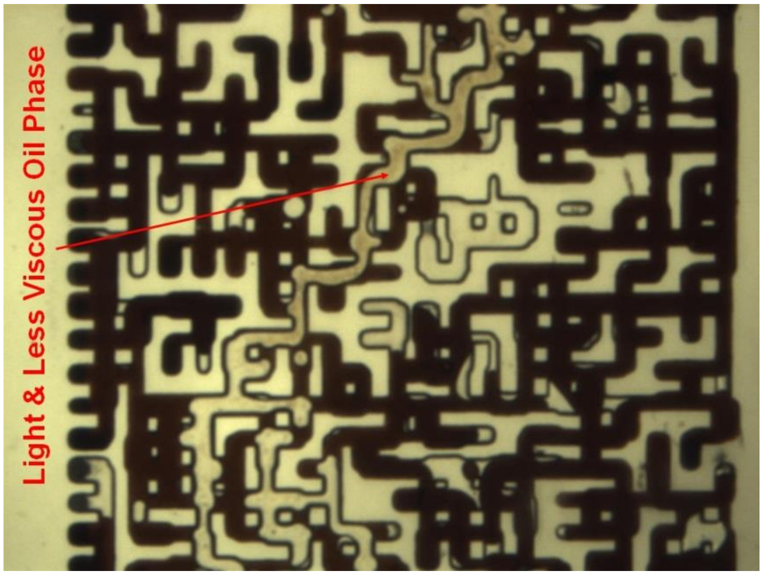

Figure 6: The same magnified section of the micromodel after a short time after the breakthrough.

Figure 7 depicts a sequence of images showing the formation of the light and less viscous oil phase as a result of the contact between the oil and CO_2. A small layer of the surface of the oil is removed and displaced by the flow of CO_2 (Figure 7a). That part of the oil has a higher concentration of the light and intermediate components than the original oil in the micromodel due to the extraction strength of dense CO_2. Hence, the light and less viscous oil phase has a high mobility and it is displaced fast (Figure 7b-f). Figure 7g-h shows that this process takes place at various locations in the porous system. However, the fact that the light and less viscous oil phase is formed in the main path of CO_2 confirms that the contact between the oil and CO_2 contributes to this process.
In another experiment, water was injected into the micromodel after the period of CO_2 injection. The tertiary waterflood was continued until there was virtually no free CO_2 in porous media, Figure 8. Three different types of oil in term of color can be seen in the image; first, the dark color oil which was the oil in direct contact with the injected CO_2 and water. The extraction of components of the oil during the period of CO_2 injection led to a darker color of the oil in the micromodel. Second, the light color oil is the fraction of oil which was not in direct contact with the flowing stream of secondary CO_2. Thus, the extraction of hydrocarbon compounds by CO_2 was not significant. The third oil type is the light and less viscous oil phase which was trapped due to the topology of the micromodel.

CONCLUSION

The results of our coreflood experiments had shown that the injection of dense CO_2 for heavy oil recovery results in higher quality oil production in addition to improving the recovery factor. In this study, to identify the mechanisms leading to the higher quality oil production, several static and dynamic fluids contact experiments were performed in micro-scale. Based on the observations and results of the experiments reported here, the following conclusions are drawn:

- As soon as dense CO_2 contacts heavy oil, extraction of hydrocarbons from the oil starts. The extraction of hydrocarbons to the CO_2-rich phase happens from the interface of the oil and CO_2.
- As a result of CO_2 and heavy oil contact in the flow paths of CO_2, the formation of an oil-rich phase in the CO_2-rich stream was observed. This oil-rich phase has a relatively lighter color than the oil in contact with CO_2 and it is significantly mobile in porous media. The light color oil in the stream of CO_2 has a higher concentration of light and intermediate components as well as a lower viscosity than the original oil in pore spaces.

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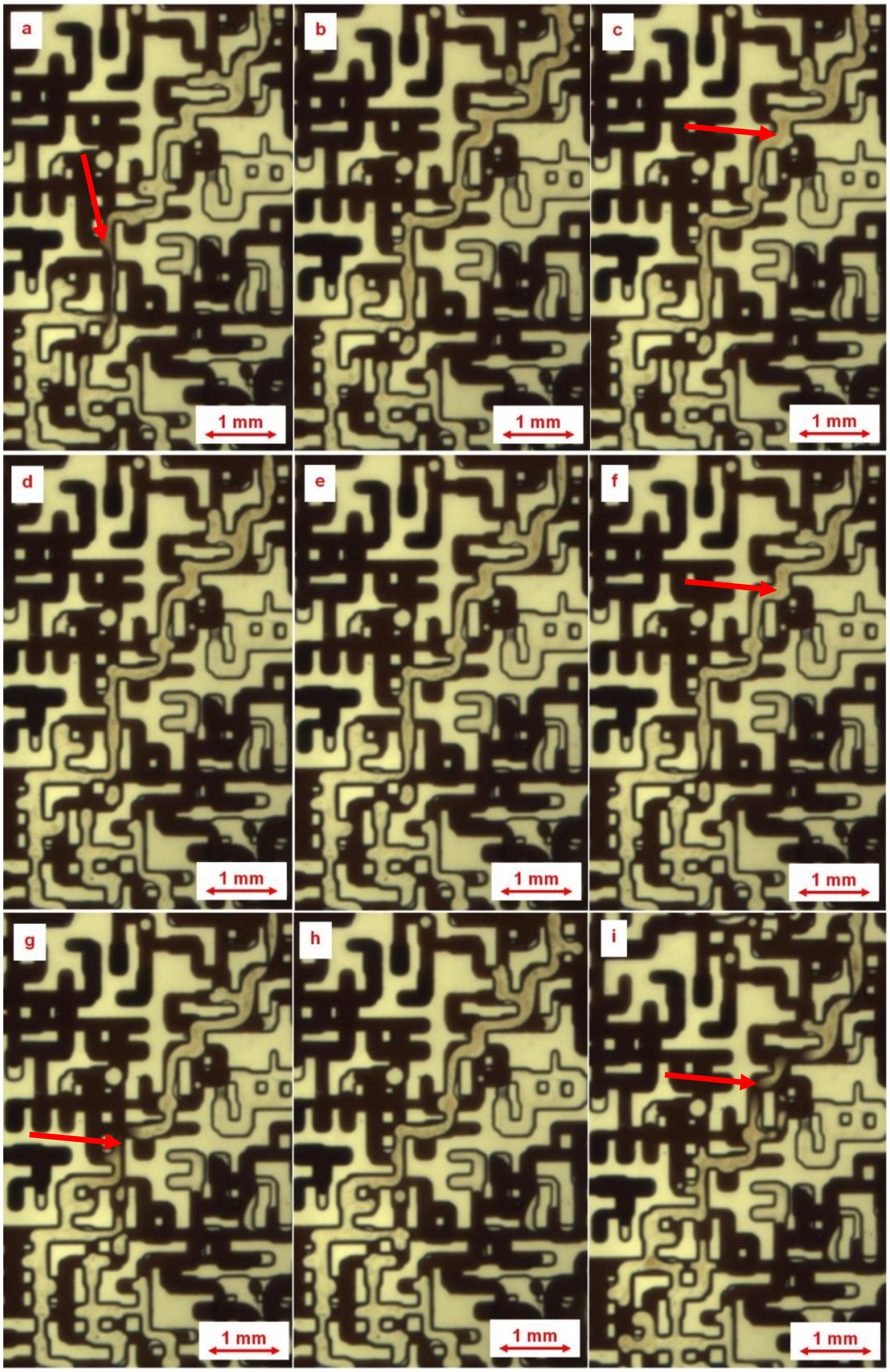

Figure 7: A sequence of images taken every 2 minutes from the same magnified section of the micromodel after the breakthrough. The formation of a light color oil phase in the CO_2-rich stream is happening due to the contact and flow of CO_2 and the oil (arrows indicate points of interest).

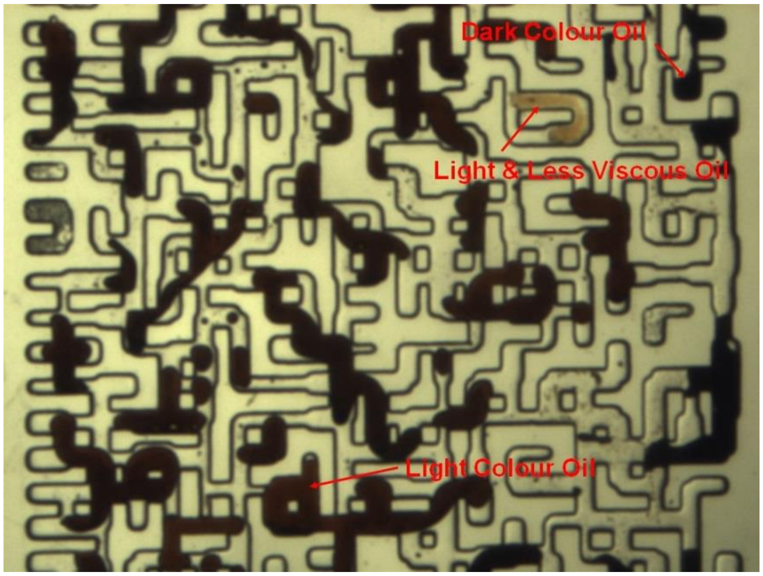

Figure 8: A magnified section of the micromodel after the extended period of tertiary waterflood.

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