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Graphical Abstract
Fundamental investigation of foam flow in porous media in the presence of oil

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Abstract

Foams demonstrate great potential for displacing fluids in porous media which is applicable to a variety of subsurface operations such as the enhanced oil recovery and soil remediation. The application of foam in these processes is down to its unique ability to reduce gas mobility by increasing its effective viscosity and to divert gas to un-swept low permeability zones in porous media. The presence of oil in porous media is detrimental to the stability of foams which can influence its success as a displacing fluid. In the present work, we have conducted a systematic series of experiment using a well-characterised porous medium manufactured by 3D printing technique to evaluate the influence of oil on the dynamics of foam displacement under different boundary conditions. The effects of the type of oil, foam quality and foam flow rate were investigated. Our results reveal that generation of stable foam is delayed in the presence of light oil in the porous medium compared to the heavy oil. Additionally, it was observed that the dynamics of oil entrapment was dictated by the stability of foam in the presence of oil. Furthermore, foams with high gas fraction appeared to be less stable in the presence of oil lowering its recovery efficiency. Pore-scale inspection of foam-oil dynamics during displacement revealed formation of a more stable front as the foam quality decreased which effectively improved the oil recovery. This study extends the physical understanding of oil displacement by foam in porous media and provides new physical insights regarding the parameters influencing this process.

Keywords

Foam, Foam flow in porous media, bubble coalescence, foam stability, foam qualitys
1. **Introduction**

Accidental spillage of petroleum-based products and contaminants can cause severe environmental hazards to the ecosystem if not remediated effectively. These contaminants can infiltrate and be trapped in ground water aquifers serving as a long term source of contamination. Trapped oil phases in petroleum reservoirs can also be economically very important. Prior to the oil reservoir becoming too depleted to drive oil out under its own pressure, more than two thirds of the total oil initially in place may remain trapped in the reservoir due to capillary forces. This remaining oil may form connected phases in parts of the reservoir and discontinuous phases in the swept zones [1-3]. Production of this trapped oil is the aim of enhanced oil recovery processes. Therefore, the economic and environmental importance of oil recovery from porous media has motivated many researchers to investigate this process using a variety of techniques [4-7].

The majority of these techniques involve the injection of a less viscous fluid (e.g. surfactant solution, CO₂ or N₂) compared to the resident oil. These scenarios typically lead to the fingering phenomenon (due to the low viscosity ratio [1, 8]) which results in early breakthrough of the injecting phase. Additional injection after breakthrough results in no further oil production as the displacing fluid continues to follow the already established flow paths [3]. Gravity override is another typical problem encountered in oil displacement processes involving gas flooding. Since the density of gas is much less than oil, it tends to rise to the top of the reservoir overriding most of the oil [9]. Additionally, selective flooding caused by reservoir heterogeneity is a common challenge associated with the gas injection process [10]. The combined effect of these conditions is a premature gas breakthrough and poor recovery efficiency.
Foam, a dispersion of gas in thin liquid films (named lamella), has been identified as a remedy for these defects due to its unique properties [11-14]. Foam exhibits apparent viscosity of a few orders of magnitude higher than its constituent gas and liquid in porous media leading to low mobility [3,15,16]. This low mobility is caused not only by trapping of bubbles within pores but also viscous dissipation associated with the moving bubbles through pore throats [17]. The trapping of gas reduces the available pathways for gas flow thereby reducing the gas relative permeability [18]. For foam to achieve its desired efficacy in oil saturated porous media, it must remain stable. However, oil has proved detrimental to the stability of foam [19] which could influence the success of foam in oil displacement applications.

The effect of oil on foam stability has been studied by many investigators at bulk [19-21] and bubble-scale [19, 22-24]. In many cases, the bulk foam test has been used as the ‘litmus test’ to determine the ability of a surfactant to generate stable foams in the presence of oil in porous media. In these experiments, the surfactant, air and oil are generally mixed in a column to produce a fixed volume of foam. The foam is then observed for a period of time and the rate of foam height decay or the half-decay time (i.e. the time taken for foam to reach half of its original height) has been considered as the measure of the foam stability. Results from these experiments have shown that light oils are more detrimental to the stability of foam. While many of the conclusions drawn from these experiments may be valid for bulk foams, direct translation of the outcomes to foam flow in porous media may be inadequate due to the complexity of the interaction between foam and oil within confined geometries.

Different observations have been reported in literature about oil-foam interaction in porous media. Some investigators have reported that the presence of light oil prevents the formation of stable foams [25, 26] while others have argued that stable foams can be produced if an appropriate surfactant or foaming agent is selected [27, 28]. The negative effect of oil may
manifest itself in porous media by prolonging foam generation and reducing foam propagation velocities [28-30]. While the type of oil plays a significant role on foam destabilisation in the bulk scale tests, Jensen and Friedmann [31] demonstrated that the oil saturation was more influential to the stability of foams than the type of oil in porous media. This observation was also reported by Mannhardt and Svorstøl [28] in their study of the effect of oil saturation on foam performance in porous media. Minssieux [25] studied the influence of the foam quality on oil displacement in a sandstone core following the gas-surfactant co-injection method. The author observed a higher oil recovery as the foam quality decreased. Osei-Bonsu et al [16] also observed more stable foam formation during oil displacement in a Hele-Shaw cell as the foam quality decreased. Ma et al [18] studied gas diversion by foam in a layered micromodel in the absence of oil. They observed more gas diversion as the foam quality increased until a point beyond which increasing foam quality decreased gas diversion.

The dynamics of oil-foam interaction especially in porous media is not fully understood and is a topic of ongoing research. There are many open questions regarding the nature and the dynamics of foam generation and propagation in porous media that need to be addressed such as how exactly the confined pore geometry of porous media influences the dynamics of foam-oil interaction or how the properties of foam affects its sweep efficiency in oil saturated porous media. Motivated by the importance of this subject, the specific objectives of this study was to delineate the effects of a) type of oil, b) properties of foam and c) foam injection rate on the efficiency of oil displacement by foam in porous media. To achieve this, a systematic series of experiments was conducted in a well-characterised porous medium manufactured using 3D printing technique that enabled us to look into the fundamental aspects of oil displacement by foam in porous media. In this paper, we present new insights and observations about how foam flow in a porous medium is influenced by oil. The rest of
the paper is laid out as follows: In Section 2 we describe in detail the experimental setup, the
materials and the experimental procedure used in this study; Section 3 provides the results
and discussion and the final conclusions are presented in Section 4.

2. Experimental Considerations

2.1. Design and fabrication of the porous medium

The porous medium was designed using ‘Rhinoceros’; a CAD software package. The 3D
representation of the pore network was created from an array of cubes of equal sizes. The homogenous model had pore size of 0.8 mm and pore throat size of 0.4 mm. The depth of the
model was 0.4 mm. The size of the entire model was 80 mm x 50 mm x 2mm. The CAD
design was converted to stereolithographic (STL) format which was then printed by a 3D printer (Objet 30 pro, Stratasys) using and acrylic based material. Fig.1 depicts the printed porous medium used in this study. The top of the printed model was sealed with a glass plate and held firmly in a Plexiglas frame with clamps. Two holes were perforated at the opposite sides of the top glass to create an inlet and outlet to allow injection of fluid into and out of the cell. The model was oil wet and had a porosity and permeability of 57.60% and 23.44 D respectively.

The porosity was calculated by measuring the amount of water required to fully saturate the model (i.e. the total pore volume). The pore volume was then divided by the bulk volume of the model to obtain the porosity. This value was also verified by image analysis. The permeability of the model was obtained in the following way: The model was first flooded by CO₂ for 10 minutes at the flow rate of 100 mL/hr to displace the remaining air in the model. The model was subsequently flooded with water until 100% water saturation was established. Different water injection rates were then applied and their corresponding pressure drops were recorded using a pressure sensor (Elveflow, France). Darcy’s law was then used to calculate the permeability of the model.
Fig. 1 Top view of the porous medium fabricated by a 3D printer used to investigate oil displacement by foam.

2.2. Materials and method

Prior to foam injection, the model was fully saturated with the oil. Two types of oil, Isopar G and Isopar V (Brenntag, UK) were used in this study. These oils belong to the same isoparaffinic series and were distinguished by their hydrocarbon chain length, viscosity and interfacial tension. The surfactant solution used to make foam consisted of a 1:1 blend of 2% (active content) Cocamidopropyl betaine and Sodium Dodecylsulfate (SDS) using 0.25M NaCl. This surfactant blend was selected because it demonstrated good stability in the presence of oil in other studies [19, 32]. Foam was pre-generated by injecting nitrogen gas and the surfactant solution though a customised foam generator. The gas was controlled by a mass flow controller (Bronkhorst, UK) while the surfactant stream was controlled by a syringe pump (Harvard Apparatus, USA). The foam flow rate and foam quality could be modified by adjusting the gas and liquid flow rates accordingly. Pre-generated foam was injected directly into the oil saturated model via a tube (diameter 0.5 mm). A microfluidic pressure sensor was connected to the inlet of the model to record the evolution of pressure drop during the course of the experiments.
The properties of the oils including the interfacial tension between the oils and the surfactant solution are provided in Table 1.

**Table 1.** Properties of oils used in this study together with the interfacial tension between oils and surfactant solution.

<table>
<thead>
<tr>
<th>Oil</th>
<th>Composition</th>
<th>Viscosity ($x 10^{-3}$ Pa s)</th>
<th>Density (g/cm$^3$)</th>
<th>Interfacial Tension (mN/m)</th>
<th>Boiling Point (ºC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isopar G</td>
<td>C10 – C12</td>
<td>0.843</td>
<td>0.749</td>
<td>0.272</td>
<td>166</td>
</tr>
<tr>
<td>Isopar V</td>
<td>C14 – C19</td>
<td>10.840</td>
<td>0.815</td>
<td>0.130</td>
<td>270</td>
</tr>
</tbody>
</table>

Three sets of experiments were conducted in this study: First, the influence of two oils (Isopar G and V) on the dynamics of foam displacement was studied to understand how the oil properties affect foam flow in porous media. Second, the effect of foam quality (gas fraction) on oil displacement was studied. Five different foam qualities between 80% and 98% were used. The foam quality was adjusted by changing the flow rate of the surfactant solution while maintaining the gas flow rate constant (5ml/hr unless specified). Finally, the performance of foam as influenced by the flow rate was evaluated. The foam flow rate was modified by changing the gas and liquid flow rates accordingly while maintaining the same ratio or foam quality.

**2.2. Image acquisition and processing**

A computer-controlled monochromic camera (Genie TS camera, Stemmer Imaging) was fixed above the model to acquire images of the displacement process at regular time intervals. A lightbox was placed under the model to illuminate and improve the quality of the captured images. The output images had a resolution of 2560 x 2048 pixels, with 8 bit gray levels giving a spatial magnification of 0.04 mm per pixel. The oil was dyed (Oil Red) to enhance
the contrast between oil and foam during displacement experiments. In order to quantify the
dynamics and efficiency of foam-oil displacement, customised codes were developed in
MATLAB to distinguish between oil, solid phase (grains) and foam. The segmentation
algorithms were similar to the ones described in Shokri et al. [33, 34] but with minor
modifications detailed as follows: The regions saturated with oil and foam was distinguished
by two main ‘peaks’ in the gray value histogram of each image. The first peak represented oil
while the second peak corresponded to foam and the solid phase (grains). A threshold was
applied to distinguish between these two peaks. The threshold was ascribed to the point on
the histogram where the derivative of the gray value changed from negative to positive [33].
In the next step, the grains were separated from foam using the picture of the empty model as
a reference. The resulting image was presented by three gray values corresponding to the
grains, foam and oil. A typical example of the raw image recorded by the camera and the
resulting segmented image is illustrated in Fig 2.

![Fig. 2](image)

**Fig. 2** (a) A typical gray-scale image recorded by the camera, (b) the resulting segmented
image with black, red and blue representing solid grains, oil and foam/gas, respectively.

3. **Results and Discussion**

3.1. **Pore-scale processes occurring during oil displacement by foam**
Fig. 3 presents a few snapshots of pore-scale interactions between foam and the oil phase observed during oil displacement by foam. These observations enable us to develop better understanding of the mechanisms controlling foam flow in porous media in the presence of oil. When foam is injected into the network, some of the bubbles burst immediately upon contact with the oil. The gas that escapes the foam network (flowing gas) as a result of phase separation propagates through the pore network while displacing some oil, Fig. 3a. The surfactant solution released after bubble collapse also contributes to oil mobilization by reducing capillary forces through lowering interfacial tension between oil and water, Fig. 3a (it is worth mentioning here that the observed phase separation of gas and surfactant solution is an important phenomenon which is often overlooked in models describing foam flow in oil bearing porous media [13,17,42]). At some point in the displacement process, stable foams begin to form, Fig. 3b, and some of the gas bubbles are temporarily trapped in various parts of the porous media. An example of this trapped bubble is indicated by the small white arrows in the images illustrated in Fig. 3. In this case for example, the trapped bubble remained stationary for over 60 seconds before moving ahead in the porous medium. The trapped gas bubbles effectively reduce the number of flow paths available for gas to travel reducing the gas relative permeability. More significantly, the presence of bubbles increases the effective viscosity of the gas phase which in turn increases the capillary number of the displacement. The result of this is an improved oil recovery from the porous medium.
Fig. 3 Close up images of foam-oil displacement showing flowing gas, trapped bubble and surfactant solution in the porous medium. The time difference between each image is 20 seconds.

3.2. Effect of type of oil on foam displacement efficiency
Fig. 4 displays the oil recovery efficiency (defined as the ratio of the displaced oil at a given
time to the initial oil saturation) and the recorded pressure dynamics during foam flow in the
presence of Isopar V and G. For the first 200 seconds of the experiment, the rate of oil
recovery is similar for both Isopar V and G. This is because oil displacement at the initial
stage is mainly controlled by the gas released from the foam network due to collapse of
bubbles in the presence of oil. However, the rate of oil recovery changed significantly after
this period such that recovery rate was higher in the presence of Isopar V (more viscous oil)
than in the case of Isopar G (less viscous oil). This is attributed to the higher foam destruction
rate in the presence of Isopar G compared to Isopar V [19, 21].

The difference in the stability of foam in the presence of oils can be explained by the strength
of the entry barrier or ‘pseudoemulsion’ film formed between the bubbles and oil [35,36].
This barrier must break before oil can spread or bridge the gas-liquid interface of foam. The
strength of this entry barrier increases with increasing carbon chain length [37]. Since Isopar
V contains longer carbon chains, foam is relatively more stable when injected into the model
resulting in a better oil displacement efficiency compared to Isopar G.

Fig. 4 (a) Recovery efficiency during oil displacement by foam and (b) pressure drop of foam
in the presence of Isopar G (C10-C12), and Isopar V (C14-C19). The recovery factor is
expressed by the fraction of the total pore volume of oil recovered at a given time.
The recorded pressure drop during oil displacement by foam in the model supports the above explanation. Fig. 4b demonstrates that under the same conditions, the pressure drop recorded across the model is higher for foam in the presence of Isopar V than Isopar G indicating that stronger and more stable foams formed in the presence of the former than the latter [38]. In the case of Isopar G, the lower pressure drop confirms the higher rate of coalescence and bubble collapse (i.e. low foam stability) as foam displaced the oil in the porous medium. Although the pressure drop in the presence of Isopar G is relatively lower in comparison to Isopar V, it is expected to be significantly higher than the pressure drop in the model for a scenario involving gas injection in the absence of foam or water – alternating – gas (WAG) process [13, 38], which is why foam is more effective as a displacing fluid.

Fig. 5 is a visual observation of foam displacing Isopar G and Isopar V at different times from the onset of the injection. One can infer from these snapshots that oil inhibits the formation of stable foam by destroying bubbles injected into the porous medium. This is evidenced by the gas fingers observed during oil displacement in the model. This phenomenon occurs as a direct result of the rapid flow of gas that escaped the foam network due to phase separation of foams upon contact with the oil in the model. As stated previously, the degree of foam destabilisation and hence fingering is influenced by the length of hydrocarbon chain and viscosity of the oil.
Fig. 5. Phase distribution and patterns of Isopar G (a-c) and Isopar V (d-f) displaced by foam after selected elapsed time from the onset of the experiment indicated on the figure. Black, red and blue represent solid grains, oil and foam/gas respectively.

Fig. 5 (b) and (e) confirms the generation of more stable foams in the presence of Isopar V compared to Isopar G. In the case of Isopar G, stable foams did not form prior to the breakthrough of gas that escaped the foam network as a result of bubble collapse while in the case of Isopar V, stable foams formed before breakthrough of the gas released. Moreover, foam permeated the entire model when saturated with Isopar V after 670 seconds such that most of the oil phase remaining in the model ahead of the stable foam front was isolated. This feature indicates that the rate of bubble collapse had significantly decreased, and the bubbles...
generated at this point in the displacement process were more stable in the porous medium compared to the initial stage of foam injection. On the contrary, most of the unrecovered oil in the case of Isopar G was still connected due to the persistence of bubble collapse and gas fingering as shown in Fig. 5(b) and (c).

Fig. 6 quantitatively describes the evolution of the isolated oil blobs over the course of oil displacement. During the initial phase of oil displacement, the number and size of the isolated blobs are identical for both oils since in both cases, the gas escaped from the foam network was responsible for oil displacement (see Fig. 4a). However, towards the end of oil displacement, the number of isolated oil blobs in the case of Isopar V was significantly more than Isopar G. As mentioned above, this feature was caused by the propagation of more stable foams in the porous medium in the presence of Isopar V as opposed to Isopar G which was characterised by gas fingering. Even after stable foams began to form in the latter, the rate of bubble collapse and coalescence at the foam front was still high enough to cause preferential flow though the porous medium. Consequently most of the oil ahead of the foam was connected. This analysis clearly illustrates the importance of foam stability not only on the efficiency of oil displacement but also on the patterns and distribution of isolated oil phase in porous media which has not been considered in the majority of predictive tools used to describe foam-oil displacement in porous media.
Fig. 6 (a) Number of trapped blobs as a function of recovered oil and (b) the average size of trapped blobs versus recovered oil. (c) and (d) shows same information except pore volume of foam injected was presented on the X-axis. The error bars represent standard deviations of three different displacement experiments conducted for each case. The red and blue dotted lines represent the number of pore volumes injected to obtain 90% oil recovery of Isopar V and G, respectively.

3.3. Effects of foam quality on oil displacement efficiency

In this section, the displacement efficiency of oil as influenced by the foam quality (gas fraction) is discussed. The displacement efficiency was expressed in terms of the pore volume of foam injected as a function of the fraction of oil recovered from the model. Fig. 7 displays the recovery efficiency for five different foam qualities (indicated in the legend of the Fig. 7a). One can conclude that oil displacement is favoured by foam with lower foam quality (higher surfactant fraction). This result could be ascribed to the nature of the bubbles.
produced when foam quality is altered. Increasing foam quality results in generation of foam with thinner lamellae and smaller Plateau borders relative to the bubble size [16]. These thin films are more susceptible to the penetration of oil into the gas-liquid interface of the bubbles. Consequently, foams with high gas fraction undergo catastrophic destruction in the presence of oil.

Fig. 7b and 7c shows qualitatively that the displacement of oil by lower quality foam (i.e. low gas fraction) is more effective compared to the higher quality foam (the latter exhibited fingering phenomena even after one pore volume of foam was injected into the model). Bubble collapse and coalescence rate increases as the foam quality increases causing more gas to escape the foam network consequently delaying the formation of stable foams. Additionally, Fig. 7 demonstrates that decreasing foam quality below 85% (i.e. 80%) results in lower recovery efficiency as more pore volumes of foam are used to recover a certain fraction of oil. It must be mentioned however that, when the recovery efficiency is plotted against time, the rate of oil recovery is higher for 80% compared to 85% foam quality. In our previous study of foam displacement in a liquid filled Hele-Shaw cell [16], we observed no influence of foam quality on displacement efficiency as the displaced fluid (water) had a minor impact (if any) on the foam stability. This is clearly not the case in the present study as the degree of foam destruction by oil is dependent on the foam quality. This is another important feature that must be taken into consideration when developing predictive models to describe foam flow in porous media saturated with oil.
Fig. 7 (a) Oil recovery as a function of foam pore volume injected. (b) and (c) shows the patterns of oil distribution at the corresponding points indicated on the curve. Red, black and blue indicate oil, grains, and foam/gas respectively.

3.4. Effects of foam flow rate on oil recovery efficiency

The injection rate of the displacing fluid affects significantly the dynamics of displacement and phase entrapment in porous media and the overall recovery of the displaced phase [7, 39, 40]. In this section, we present and analyse the influence of the flow rate of pre-generated foam on oil displacement and recovery. Within the range of flow rates tested in our experiments, no notable difference was observed in the efficiency of oil recovery by foam. To explore the possible reason for such behaviour, we calculated and compared the apparent viscosity and the (apparent) capillary number of the foam at different flow rates using the steady state pressure drop recorded by the pressure sensor. The apparent viscosity of foam $\mu_{app}$ was calculated using Darcy law $\mu_{app} = \frac{k \Delta P}{q \Delta L}$ where $k$ is the permeability of the porous medium, $L$ is the length, $q$ is the Darcy velocity, and $\Delta P$ is the pressure drop across the model [41]. The apparent viscosity was then used to calculate the viscosity ratio $M$ and the (apparent) capillary number $Ca$. Following Lenormand et al. [40], $M$ was defined as the ratio of the displacing phase viscosity (foam) to the viscosity of the displaced phase (oil). We
define the (apparent) capillary number for foam as \[ Ca = \frac{q \mu_{app}}{\gamma_{ow}} \]
where \( q \) is the flow velocity and \( \gamma_{ow} \) is the interfacial tension between the oil and surfactant solution. The influence of foam flow rate on the viscosity ratio and the capillary number is shown in Fig 8b.

Fig. 8 (a) Oil recovery as a function of foam pore volume injected under different foam flow rates indicated on the legend. (b) Viscosity ratio and capillary number as influenced by the foam flow rate.

As flow rate increases, the viscosity ratio decreases. Since the viscosity of oil is constant, the decrease in the viscosity ratio is attributed to the decrease in the apparent viscosity of foam, which is typical of shear-thinning fluids [7]. This shear thinning behaviour explains why the (apparent) capillary number of the flowing foams increased only by approximately an order of magnitude when the flow rate was changed by two orders of magnitude.

In any case, the value of (apparent) capillary numbers and viscosity ratios as shown in Fig. 8b are high in all cases (compared to typical values reported for unstable displacements) which may have contributed to the high oil recovery recorded under the investigated flow rates. We cannot generalise such a conclusion as the range of flow rates investigated in our experiments was relatively narrow. Nonetheless, the obtained results illustrate minor dependency of the oil recovery on the applied foam flow rate within the range tested in our experiments.
4. Summary and conclusions

We have conducted a comprehensive series of experiments to investigate the dynamics of oil displacement by foam under different boundary conditions in a customised porous medium fabricated by 3D printing technique. Our investigation reveals complex interactions between foam and oil under dynamic conditions that must be taken into account when describing foam flow in porous media for applications such as enhanced oil recovery or soil remediation practices. Without developing proper physical understanding of the mechanisms controlling foam flow in porous media in the presence of oil, the modelling efforts would be largely dependent on empirical relations and fitting parameters [42]. These parameterisations oversimplify the less understood physical and chemical phenomena, potentially obscuring the true nature of the dynamics of foam flow in porous media. The present study extends the fundamental knowledge required to adequately describe foam flow in oil-saturated porous media. We have demonstrated that foam-oil interaction in porous media is indeed a complex phenomenon and the dynamics of the phase distribution during displacement is influenced significantly by the boundary condition under which displacement occurs. It is essential to develop a thorough understanding of these interactions to be able to accurately model and predict the dynamics of foam-oil displacement in porous media. Based on the results obtained in this study, we draw the following conclusions:

1. The time and number of pore volumes required for stable foam to form in a confined medium is highly dependent on the properties of oil and in general, the interaction between foam and oil. Our investigation revealed that light oils are more detrimental to the stability of foams which subsequently delays the formation of stable foam in porous media. This influences significantly the dynamics of oil recovery as well as distribution of oil phases in the medium at any given time. Additionally, phase separation that occurs especially during the initial phase of oil recovery must be taken into account when
modelling foam-oil displacement in porous media. This phenomenon suggests that treating foam in porous media in the presence of oil as a single phase fluid (which is common practices in foam modelling) is not an adequate reflection of the process [13, 17, 42].

2. As foam quality increases (higher gas fraction), foams become less stable in the presence of oil due to the thinning of foam films and Plateau borders (as foam quality increase) which make it easier for oil to invade the gas-liquid interface of the foam causing bubbles to collapse [16]. This in turn delays the generation and propagation of stable foams and consequently reduces the oil displacement efficiency.

3. Within the range of flow rates tested in our study together with the type of oils and surfactant investigated, our results showed negligible impact of pre-generated foam flow rate on the oil recovery efficiency.

A relatively simple pore geometry was considered in the present study which helped us to look into the fundamental aspects of foam flow in porous media in the presence of oil. As for future research, it will be interesting to investigate foam-oil interaction under different boundary conditions in more heterogeneous and realistic porous media where the additional effects introduced by the complexity of the pore geometry and topology are present.

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References


