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DOI
10.1021/acs.iecr.9b01589

Publication date
2019

Document Version
Final published version

Published in
Industrial and Engineering Chemistry Research

I&EC research
Industrial & Engineering Chemistry Research

Article

Cite This: Ind. Eng. Chem. Res. 2019, 58, 12766−12772

pubs.acs.org/IECR

Impact of Different Oil Mixtures on Foam in Porous Media and in Bulk

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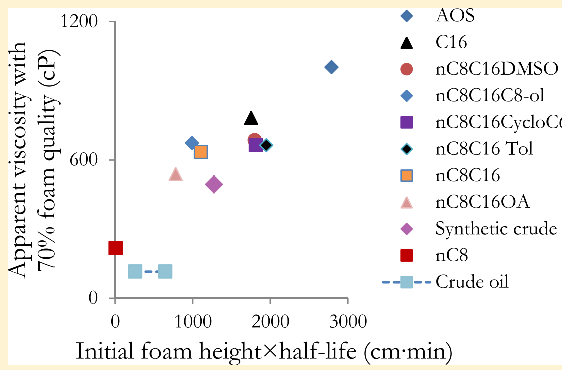
ABSTRACT: Foam can be applied to enhance oil recovery from a reservoir. Currently, to understand and model the behavior of foam in an oil reservoir, experiments need to be conducted in the presence of the specific crude oil, and extrapolating from one crude oil to another is not possible. It is therefore desirable to model the impact of a crude oil on foam solely based on the crude-oil composition. This would allow one to efficiently screen reservoirs for foam application. Here we investigate the behavior of foam in the presence of a crude oil and in the presence of mixtures of pure components, which we choose based on the gas chromatography analysis of the crude oil as well as its total acid number and total base number. To analyze the impact of an oil mixture on bulk foam we shake test tubes with surfactant solution and either a mixture of pure oil components or crude oil and analyze foam height and liquid height over time. We also conduct experiments in a porous medium, where we coinject mixtures of pure components, surfactant solution, and gas. We fix the oil injection rate and vary the ratio of the gas to surfactant solution. We use the following organic compounds (OC) to represent the crude oil: toluene (an aromatic), oleic acid (an organic acid), octanol (an organic base), methylcyclohexane (a cycloalkane), dimethyl sulfoxide (an organosulfur), *n*-octane, and hexadecane. However, when one or all of the first components is added to a 50/50 (vol %) mixture of *n*-octane and hexadecane, in proportions similar to their presence in the crude oil, the impact of the oil mixture on foam (both in bulk and in porous media) is only slightly different from the impact of the *n*-octane and hexadecane mixture. We formed a "synthetic" crude oil, with its composition mimicking the composition of a crude oil and its total acid/base number. Although the pure OC and synthetic crude oil weaken foam in bulk and in porous media, their impact on foam was less severe than the impact of the crude oil on the foam. Based on the composition of an oil mixture and the impact of its components, separately, on foam, it is not clear how to predict the impact of the oil mixture on foam in bulk or porous medium. However, in our case we find a good correlation between the foam apparent viscosity in porous media and the product of the bulk foam half-life and initial volume. One implication is that if either the half-life or initial volume of bulk foam is poor, the foam performs poorly in the porous medium.



■ INTRODUCTION

Currently, to understand and model the behavior of foam in an oil reservoir, experiments need to be conducted in the presence of the specific crude oil in a porous medium, and extrapolating from one crude oil to another is not possible. This can be a time-consuming process. It is therefore desirable to model the impact of a crude oil on foam solely based on the crude oil composition. This would allow one to efficiently screen reservoirs for foam application.

Currently there is not a published model that can predict the impact of a crude oil on a foam from the crude oil composition based on gas chromatography (GC), its total acid number (TAN), total base number (TBN), or its saturate, aromatic, resin, and asphaltene (SARA) fractions. There are various reasons why it is difficult to make such a model. These include scarcity of data on oil composition, countless different compounds in the crude oil,[1] and some compounds weakening and others stabilizing foam.[2] Here we create a "synthetic" crude oil from seven pure organic compounds (OC). Its composition is based on the most prevalent components of the actual crude oil, its TAN and TBN, and an organosulfur concentration common in "sweet" crude oils.

Previous attempts to relate the impact of crude oil on foam focused on the SARA content. Jensen et al.[3] conducted steam-foam experiments in porous media in the presence of four different crude oils, and they found that the pressure drop across their core was a function of only the oil saturation, irrespective of the crude oil. Pu et al.[4] and Vikingstad et al.[2] conducted bulk-foam experiments with different crude oils and observed that the

Received: March 22, 2019
Revised: June 17, 2019
Accepted: June 20, 2019
Published: June 20, 2019

different crude oils impacted their foams differently. However, they did not find an obvious relationship between the SARA composition of their crude oils and the impact on their bulk foam.

Others have examined the impact of different pure compounds present in crude oils (alkanes, organic acids, alcohols, and aromatics) on foam in bulk and in porous media.[2,5−9] Tang et al.[8] coinjected different pure alkanes (C_{16}, C_{10}, C_8, C_6) with foam in a sandstone; however, none resulted in an apparent viscosity as low as we observed with our crude oil; see below. Moreover, it is not clear how the impact of pure oils on foam relate to the impact of crude oils or oil mixtures on foams in bulk and in porous media.

Here we look at how OCs, predispersed (as a separate phase) in the surfactant solution, impact bulk foam generation and collapse; that is, we investigate the antifoaming properties of different pure OCs.[10] The antifoaming impact of an OC can be different from the destabilization by an OC scattered over an already-formed bulk foam (i.e., defoaming), which is tested in other studies.[11] An antifoamer ruptures foam films in two steps; the OC drop first enters the air−water interface, after which it spreads over the foam film, causing it to rupture.[10] The foamability of the foam can be reduced by OC drops, as they induce foam bubbles to coalesce during foam generation.[12] Moreover, natural cationic surfactant in the crude oil can react with anionic surfactant of the foaming solution, leading to a larger aggregate without a hydrophilic head, which is often not water-soluble.[13] Surfactant solution and an OC can also form high-viscosity emulsions, which stabilize bulk foam.[14]

A benefit of bulk-foam experiments is that the different ways in which an OC impacts foam can be observed visually. In contrast, with foam in an opaque porous medium, only the pressure gradient and the saturation of the different phases can be determined. Although the effluent from the porous medium can be inspected visually for clues on the foam characteristics in the porous medium, it does not necessarily reflect the foam characteristics in the porous medium, for example, due to foam generation at the outlet by the capillary end effect. Foam behavior in the presence of an OC is not necessarily the same in bulk and in a porous medium. Jones et al.[15] showed a strong correlation between maximum apparent viscosity of foam in a porous medium and bulk-foam half-life for foam in absence of oil but a weak correlation for foam in the presence of oil. However, we believe conducting both porous-media experiments and bulk-foam experiments gives more information on how foam interacts with an OC in a porous medium. We do not consider here the interfacial tensions (IFT) between OC, surfactant solution, and gas. It has been shown that foam-stability predictions based on IFT values are unreliable, both in bulk and in porous media.[2,16]

With this study we investigate two screening methodologies: forecasting the impact of a crude oil on a foam based on the crude oil composition and forecasting the impact of an oil on foam in a water-wet porous medium based on bulk-foam experiments. To relate the impact of a specific crude oil on foam to the crude oil composition we assemble a synthetic crude oil, with its composition based on the GC analysis, the TAN and TBN of the crude oil. We also include an organosulfur in the synthetic crude oil, because it is a common component of crude oils.[1] For this study we assume that the composition of the crude oil defines how it impacts foam, both in bulk and in porous media. We conduct both bulk-foam experiments and porous-media experiments and investigate different ways to correlate the results.

In the next section we describe the materials used in our experiments and the experimental procedures. This is followed by a section with the experimental results and discussion, and finally we give the conclusions and recommendations based on our findings.

■ MATERIAL AND PROCEDURES

Table 1 outlines our brine composition in mass per volume, which we use to make our surfactant solution, using the surfactant Alpha Olefin Sulfonate $C_{14/16}$ (AOS). The surfactant concentration was set to 0.5 wt % AOS, which is more than 100 times the critical micelle concentration (CMC) value.[17]

Table 1. Brine Composition

ions	concentration (mg/L)
Na^+	11 250
K^+	353
Mg^{2+}	1214
Ca^{2+}	400
Cl^-	20 000
SO_4^{2-}	2593

Table 2 lists relevant physical and chemical properties of these organic components and their fraction in the synthetic crude oil. Its composition is based on the crude oil's GC analysis, TAN and TBN; see Table 3 and Table 4. Although we do not know the sulfur content of the crude oil, we include an organosulfur compound in our synthetic crude oil at a concentration common in "sweet" crude oils.[1,18] *N*-Octane (nC8) and hexadecane (C16) were used to represent the lighter and heavier alkanes in the crude. Toluene, dimethyl sulfoxide (DMSO), methylcyclohexane (MCH), oleic acid (OA), octanoic acid, and 1-octanol were used to represent the aromatics, the cycloalkanes, organosulfur compounds, organic acids, and organic bases, respectively, in the crude oil.

We investigate the impact of the pure OCs on bulk foam and of pure *n*-octane and hexadecane on foam in porous medium. We also investigate the impact of the OCs in mixtures with the alkanes. To investigate the impact of OCs at concentrations in line with the crude oil composition, we conduct experiments with a 50/50 vol % *n*-octane/hexadecane mixture to which we add one other OC. See Table 2 for the concentration of the additives in the alkane mixture. We also conduct foam experiments in bulk and in a porous medium with the synthetic crude, using oleic acid as the organic acid.

We conduct our bulk-foam experiment with 25 mL tubes, filled with 5 mL of surfactant solution and, when the impact of an OC on foam is tested, also 1 mL of OC. The bulk-foam experiments were conducted at ambient conditions. For each experiment we put four test tubes in a rack, with one tube filled only with 5 mL of surfactant solution, as a benchmark. We shake the tube rack 20 s manually and measure the foam volume, total liquid volume, and, if possible, the OC volume over time. By looking at the initial foam volume we gain information on the foaming capacity in the presence of a specific OC. The time until foam volume has reached half its initial volume (half-life) gives information on foam stability. We stop the experiment after the foam volume has reached half its initial value or at the latest after 300 min, except for the experiment with crude oil, which was stopped after 120 min. Bulk-foam experiments conducted in this

DOI: 10.1021/acs.iecr.9b01589
Ind. Eng. Chem. Res. 2019, 58, 12766−12772

Table 2. Physical and Chemical Properties of Oil Components at 25 °C[20−22]

component	vol fraction in synthetic crude oil (−)	purity (%)	molecular weight (gram)	specific gravity (−)	viscosity (mPa·s)	surface tension (mN/m)
n-octane (nC8)	0.4467	99	114.230	0.702	0.537	21.1
hexadecane (C16)	0.4467	99	226.440	0.773	3.545	27.1
toluene (Tol)	0.05	99.8	92.140	0.867	0.582	27.9
dimethyl sulfoxide (DMSO)	0.005	99.9	78.130	0.845	0.286	42.9
methyl cyclohexane (CyclC6)	0.05	99	98.190	0.771	0.727	23.3
oleic acid (OA)	0.000 86	99	282.468	0.894	37.070	32.8 (at 20 °C)
1-octanol (C8-ol)	0.000 74	99	130.23	0.83	7.36	26.4
octanoic acid[a]	0.000 44	99	144.21	0.907	5.74	23.7 (at 20 °C)

[a]Octanoic acid was only used to investigate its impact on bulk foam, separately and mixed with the alkane mixture.

Table 3. Crude Oil Acid and Base Number

acid number (mg KOH/g)	0.17
base number (mg KOH/g)	0.32

Table 4. Crude Oil Composition

component	mol %	wt %
nitrogen	0.12	0.025 755
carbon dioxide	0.07	0.023 606
methane	3.18	0.390 84
ethane	1.1	0.253 451
propane	3.23	1.091 462
isobutane	1.49	0.663 559
n-butane	3.21	1.429 546
neopentane	0.02	0.011 057
isopentane	2.39	1.321 301
n-pentane	2.37	1.310 244
hexanes	4.81	3.176 283
methylcyclopentane	2.31	1.489 654
benzene	0.61	0.365 093
cyclohexane	2.77	1.786 295
heptanes	5.05	3.877 276
methylcyclohexane	6.19	4.657 207
toluene	0.27	0.190 625
octanes	9.23	8.078 849
ethylbenzene	1.04	0.846 063
meta+*para*-xylene	0.53	0.431 167
ortho-xylene	0.61	0.496 249
nonanes	7.09	6.967 951
1,2,4-trimethylbenzene	2.32	2.136 781
decanes	5.84	6.367 293
undecanes	5.5	6.587 446
dodecanes	4.17	5.442 774
tridacanes	4.4	5.933 801
tetradecanes	3.91	5.692 434
pentadecanes	4.77	7.456 176
hexadecanes	2.75	4.593 638
heptadecanes	2.03	3.608 707
octadecanes	2.25	4.241 166
nonadecanes	0.91	1.812 936
eicosanes plus	3.45	7.243 313

way are much faster than detailed foam-column tests of the Ross-Miles test and give qualitatively similar results.[19] We checked our results for consistency both by the inclusion of the benchmark sample without oil in each rack and by conducting two experiments with each oil additive.

Our experiments in a porous medium were conducted in a Bentheimer sandstone core, with 0.01 m diameter and 0.22 m length. The reported apparent viscosities are calculated from pressure measurements over a section that is 0.07 m in length, 0.05 m downstream from the inlet, and 0.10 m upstream from the outlet. By water-flooding the core we determined the average permeability of the core to be $(2.0 \pm 0.2) \times 10^{-12}$ m^2 and the permeability of the 0.07 m section of interest to be $(2.2 \pm 0.2) \times 10^{-12}$ m^2. The setup is similar to the one used by Jones et al.[15] We use two piston pumps to control our surfactant and OC injection. Nitrogen gas is supplied from a cylinder and connected to a mass-flow controller. The backpressure regulator is set at 40 bar. The core holder is put into an oven at 30 °C. The combined flow rate of OC, surfactant solution, and gas is set at 0.1 mL/min (6.75 ft/d or 2.04 m/d). The OC fractional flow is set to 1% in all experiments, and the surfactant solution and gas fraction are varied. We coinject OC with our surfactant solution and gas so that we can control the steady state at which we collect our data. Without coinjecting OC, we could otherwise enter into the cycle of foam recovering some of the oil, resulting in stronger foam and greater capillary number, which in turn results in a lower oil saturation, and so on.[3]

RESULTS AND DISCUSSIONS

Bulk foam in the absence of OC has an initial volume of 9 mL and a half-life longer than 300 min (Figure 1). In the porous medium we find that apparent viscosity can be as high as 1500 cP and is 1002 cP at 70% gas fraction (Figure 2). We consider this foam to be stable. Bulk foam generated in the presence of crude oil has an initial volume of ∼2 mL, and a half-life exceeding 120 min (after which we stopped the experiment). When coinjecting surfactant, gas, and 1 vol % crude oil, we find the apparent viscosity to be approximately one-tenth of that without OC (114 cP) (Figure 2).

Both hexadecane (C16) and *n*-octane (nC8) weaken foam in the porous medium and in bulk, reducing the initial foam volume, half-life, and apparent viscosity in the porous media, though not as severely as crude oil; see Figure 1A,B and Figure 2. The apparent viscosity observed with 70%-quality foam and nC8 (217 cP) is of roughly the same magnitude as with crude oil (114 cP), which is much less than what we observed with 70%-quality foam and C16 (782 cP). Surprisingly, the apparent viscosity of 70%-quality foam with our C16/nC8 (633 cP) mixture is greater than the average of the apparent viscosities with 70%-quality foam and C16 and with nC8. This shows that the impact of an OC mixture on foam is not necessarily the average of the impact of its components, or skewed toward its most damaging component(s), as was observed with oleic acid;[8] see Figure 3.

DOI: 10.1021/acs.iecr.9b01589
Ind. Eng. Chem. Res. 2019, 58, 12766−12772

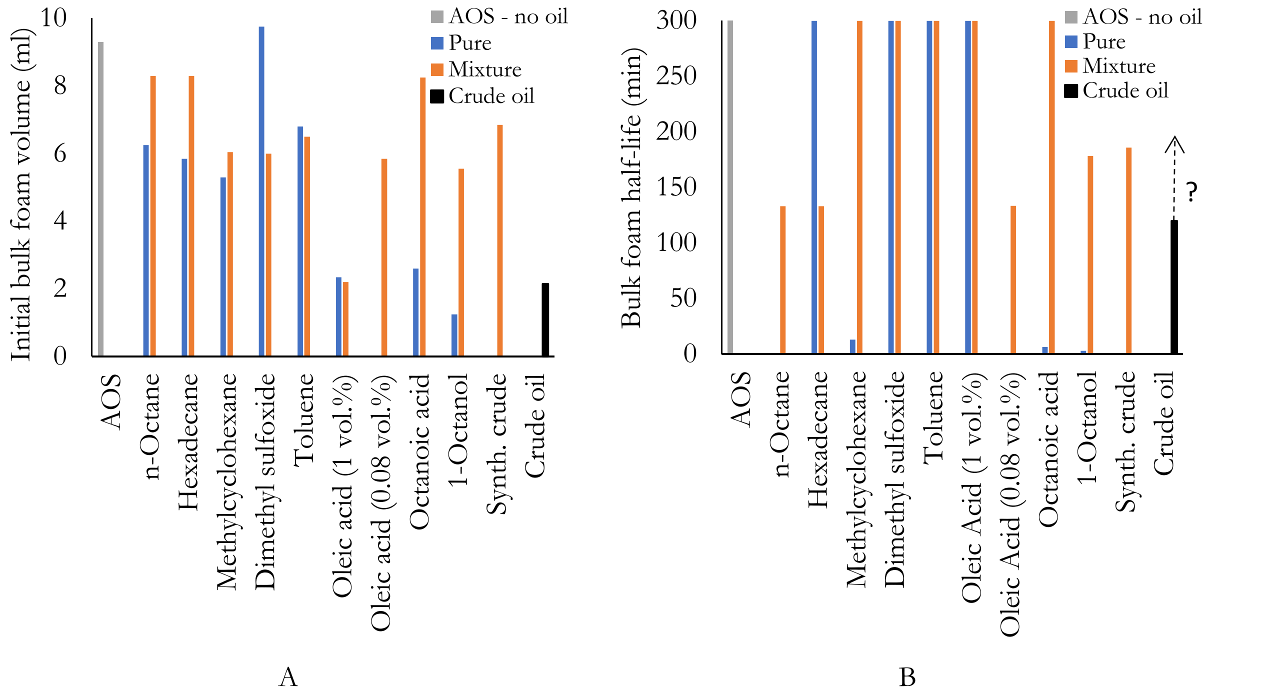


Figure 1. (A) Initial bulk-foam volume generated with AOS surfactant in the presence of different pure OC or alkane mixtures with an additive. (B) Time until the bulk foam volume collapsed to half its initial volume, i.e., the foam half-life, in the presence of different pure OC or alkane mixture with additive. Note that all the given values are the average values obtained over two experiments and that the experiment with crude oil was stopped after 120 min.

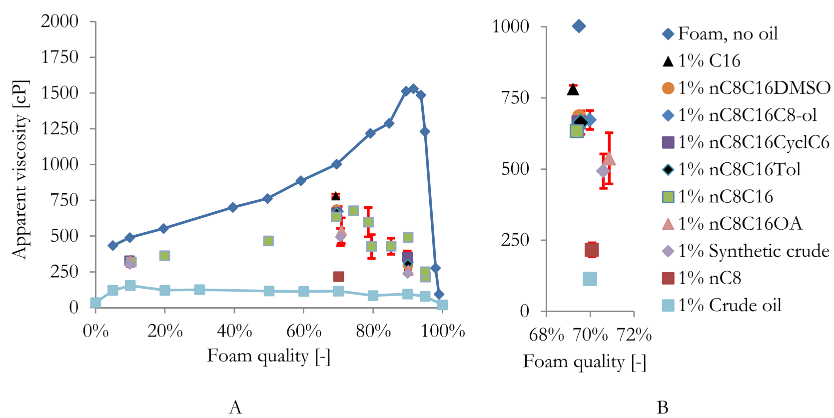


Figure 2. (A) Apparent viscosities in the porous medium, as a function of foam quality, for foam in absence of OC and in the presence of a pure OC or OC mixture at 1% fractional flow. Legend is at the far right. (B) The same data, but only over a range of foam quality between 68% and 72%. For foam without OC, we observed an apparent viscosity of 1002 cP at 69% foam quality.

Thus, even if one knows how the constituents of an OC mixture impact foam separately, correctly predicting the impact of a mixture of those OCs on foam is not obvious.

With pure oleic acid (OA) and with OA at 0.1 vol % in the alkane mixture, we observe a smaller initial foam volume in bulk and a shorter half-life, similar to what we observe with crude oil (Figure 1A,B). However, the impact of the alkane mixture on bulk foam is not changed by the addition of 0.008 vol % OA, a concentration that is in line with the TAN of the crude oil. At 0.008 vol % OA in the alkane mixture, we observe a greater fluctuation in the apparent viscosity of 70%-quality foam than without OA in the alkane mixture (Figure 2). It is not immediately clear what physical phenomena occur in the porous medium causing the larger fluctuation in pressure readings. We also conduct bulk-foam experiments with octanoic acid, which has the same pK_a as oleic acid but a shorter aliphatic chain compared to oleic acid (8 carbons vs 18 carbon atoms). Pure octanoic acid reduces the initial foam volume and half-life (Figure 1A,B). However, the bulk foam generated in the presence of the alkane mixture with octanoic acid has a longer half-life and larger initial volume than foam generated in the presence of the alkane mixture with oleic acid. This demonstrates that the aliphatic chain length of an organic acid plays a role in its impact on bulk foam. Zhang et al.[9] demonstrate that a mixture of hexadecane and 10 wt % oleic acid weakens foam. This is facilitated by formation of small solid soap particles, formed by reaction of oleic acid with the calcium ions in the water, which reside on the hexadecane-drop surfaces. It is possible that we formed small solid soap particles with the organic acid and calcium ions in our solution (Table 1); however, we did not check for the presence of solid soap particles in our experiments. Our findings show that the impact

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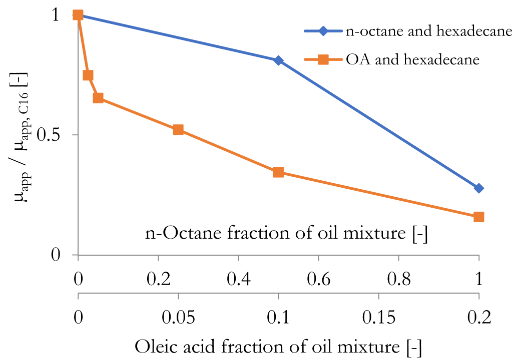

Figure 3. Ratio of apparent viscosity observed with an OC mixture to the apparent viscosity observed with pure hexadecane, as a function of the *n*-octane and OA fraction in a mixture with hexadecane. The experimental data for apparent viscosity in the presence of a mixture of oleic acid and hexadecane are from Tang et al.[8] The lines are to guide the eye.

of organic acid, and possibly present solid soap particles, do not play a dominant role in how our crude oil impacts foam, in line with the observations by Vikingstad et al.[2]

Our alkane mixture with octanol, which represents organic bases in the crude oil, has a similar impact on bulk foam as our alkane mixture with oleic acid, which represents the organic acids in the crude oil. However, in porous media, the impacts of the alkane mixture with and without octanol are not significantly different. This indicates that alcohols and organic bases in this crude oil do not play a significant role in the weakening of foam in porous media.

Pure methylcyclohexane (MCH) significantly reduces the half-life and the initial bulk foam volume. The bulk foam generated in the presence of the alkane mixture with MCH has a smaller initial volume but longer half-life than foam generated in the presence of the alkane mixture without MCH. The alkane mixtures with and without MCH do not impact foam in porous media significantly differently. This indicates that cycloalkanes of this crude oil do not play a significant role in the weakening of this foam in porous media.

The alkane mixture with toluene resulted in a slightly smaller initial bulk foam volume (7 mL) than the alkane mixture without toluene (8 mL) but a longer half-life (300+ min vs 133 min) (Figure 1A,B). However, the apparent viscosities achieved with the alkane mixture with and without toluene were not significantly different. Because the molecular structure of toluene and MCH are so similar, it is surprising that the impact of toluene on bulk foam resembles the impact of hexadecane, while the impact of MCH on bulk foam resembles that of *n*-octane. These experimental results indicate that simple aromatics and cycloalkanes, such as toluene and MCH, do not play a significant role in the impact of the crude oil on foam. On the basis of these experiments, however, we cannot say how a larger molecule, with multiple benzene rings, would impact foam, in bulk or porous media.

In our bulk-foam experiments with dimethyl sulfoxide (DMSO), it is completely soluble in the aqueous solution and does not impact the initial bulk foam volume and half-life. A smaller initial bulk foam volume is generated in the presence of DMSO in the alkane mixture (6 mL) than in the presence of the alkane mixture without additives (8 mL). However, this foam has a longer half-life than foam generated in the presence of the alkane mixture without DMSO (300+ min vs 133 min). For foam in the porous medium, there is no significant difference between the apparent viscosity achieved in the presence of the alkane mixture with and without DMSO. This indicates that such organosulfur compounds in crude oil, at least by themselves, do not play a significant role in the interaction between foam and crude oil in a porous medium.

Comparing the impact of synthetic crude oil on foam to the impact of the alkane mixture on foam, we see a 15% smaller initial bulk foam volume but a 40% longer foam half-life (Figure 1A,B). In a porous medium we see a 20% lower apparent viscosity (Figure 2). The longer bulk foam half-life could be caused by the presence of MCH, DMSO, toluene, OA, or octanol. The apparent viscosity of 70%-quality foam in the presence of synthetic crude (493 cP) is significantly greater than in the presence of the crude oil (114 cP). These experiments indicate that our synthetic crude oil does not impact foam (in bulk or porous media) like the crude oil, even though the synthetic crude oil composition is based on the crude oil composition.

It would be useful to be able to forecast foam behavior in porous media based on bulk-foam experiments due to the relative ease in which bulk-foam experiments can be conducted. However, correlations observed in absence of oil do not always hold in the presence of oil.[15] Here we plot the apparent viscosity of 70%-quality foam in porous medium as a function of the initial bulk foam volume (Figure 4A) and foam half-life (Figure 4B). These figures show there is a correlation between the apparent viscosity and bulk-foam behavior, though with a large scatter in the trend. We also investigate the relation between the apparent viscosity in porous media and the product of initial bulk-foam volume and bulk foam half-life (Figure 4C). The product of

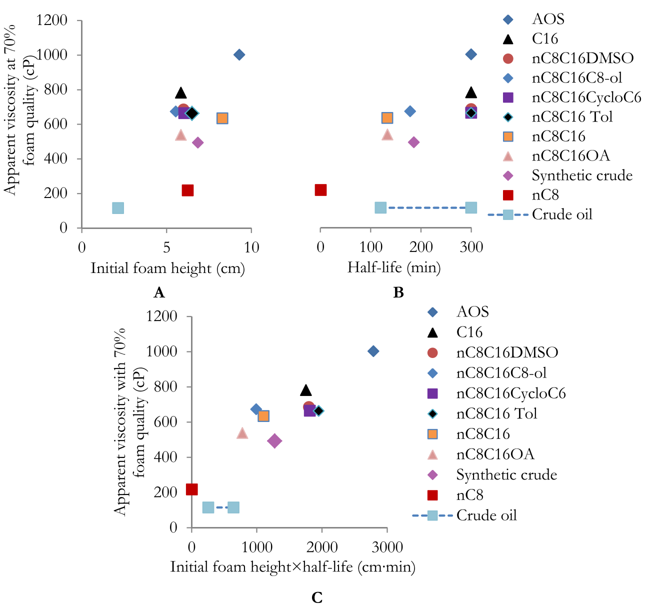

Figure 4. (top left) Apparent viscosity of 70%-quality foam in a porous medium with different OC mixtures, graphed as a function of initial bulk foam height (cm). (top right) Apparent viscosity of 70%-quality foam in a porous medium with different OC mixtures, graphed as a function of bulk foam half-life (min). Half-life values greater than 300 min are plotted as 300 min. The half-life of determination with crude oil was discontinued after 120 min. (bottom) Apparent viscosity of 70%-quality foam in a porous medium with the different OCs, graphed as a function of the product of initial bulk foam height (cm) and bulk foam half-life (min).

DOI: 10.1021/acs.iecr.9b01589
Ind. Eng. Chem. Res. 2019, 58, 12766−12772

initial bulk-foam volume and bulk foam half-life was introduced as the *Foam Composite Index* (FCI) by Pu et al.[4] to describe bulk foam in the presence of different crude oils.

The FCI of AOS foam and these oils could have been used to benchmark the apparent viscosity of the foams in the presence of these oils in porous media. We observe a good correlation in Figure 4C and a smaller scatter in the trend than in Figure 4A,B. This is in line with previous observations for foam in absence of oil; Chevallier et al.[23] used an approach similar to the FCI to correlate bulk foam behavior to foam behavior in porous media. One implication is that if either the half-life or initial volume of bulk foam is poor, the foam performs poorly in the porous medium. Further research is needed to evaluate this correlation for different OCs, foams, and porous media with different wettability.

Solely based on the GC analysis,TAN, and TBN of a crude oil, it is not clear how a mixture of those components impact foam, in bulk or in porous media. Similarly, Pu et al.[4] and Vikingstad et al.[2] find there is no obvious way to predict the impact of a crude oil on foam based on its SARA fractions. This suggests that, even for a relatively simple mixture of three pure OCs, for which we know the impact of the pure OCs on bulk foam, there is no obvious way to predict the impact of a mixture of those OCs on the foam. Thus, even if one knows the concentration of all the thousands of different components in a crude oil[1] and how these components impact foam separately, there is no obvious way to fully predict the impact of that crude oil on foam.

CONCLUSIONS

We mix several pure organic compounds (OC) to create a "synthetic" crude oil, with its composition based on the GC analysis of the crude oil and on its TAN and TBN. The pure OCs represent the following chemical species in the crude oil: light and heavy alkanes, aromatics, cycloalkanes, organosulfur compounds, organic acid, and organic base. The impact of the pure OCs and the synthetic crude oil on foam (in bulk and in porous media) is compared to the impact of the crude oil. Compared to foam without OC, the crude oil results in ~80% lower apparent viscosity in a porous medium and 80% smaller initial foam volume in bulk.

For foam in the presence of different oils we find a good correlation between the foam apparent viscosity in a porous medium and the product of the bulk foam initial volume and half-life. Further research is needed to evaluate this correlation and its predictive power for different OCs, foams, and porous media with different wettability. If this correlation holds for other OCs, foams, and porous media this correlation can be used as part of the screening procedure for foam application for enhanced oil recovery purposes.

We conclude that the effect of this crude oil on foam cannot be modeled by our synthetic crude oil. The impact of our synthetic crude oil is significantly less detrimental to foam than the actual crude oil, both in bulk and in a porous medium. The impact of our synthetic crude oil is almost the same as our mixture of *n*-octane, hexadecane, and oleic acid. The other OCs added to our alkane mixture barely influenced the impact of our synthetic crude oil on foam, both in bulk and in a porous medium.

Furthermore, we conclude that it is not obvious how to correctly predict the impact of the OC mixture on a foam based on a complete composition of an OC mixture. This holds even if the impacts of all its components, separately, on foam are known. The impact of an OC mixture on foam is not necessarily the weighted average of the impact of the pure components, nor is its impact on foam necessarily skewed toward the impact of the most harmful component.

To our knowledge, the impact of crude oil on foam in porous media has not been reproduced with a synthetic oil mixture. We suggest that screening of crude oil for foam application should be conducted with the crude oil itself and not a synthetic crude oil. If our tests were successful, our results could have been used to screen crude oils for foam application. However, before a field application, experiments would have to be conducted with the actual crude oil.

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Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

The authors thank and acknowledge both the sponsorship and advice of Universiti Teknologi Petronas. R.K.B. thanks PETRONAS for their permission for publication. S.V.-B. thanks Shell Global Solutions International B.V. especially for their permission for publication.

REFERENCES

(1) Speight, J. G. *The Chemistry and Technology of Petroleum*, 5th ed.; CRC Press, 2014.

(2) Vikingstad, A. K.; Skauge, A.; Høiland, H.; Aarra, M. Foam−oil Interactions Analyzed by Static Foam Tests. *Colloids Surf., A* **2005**, *260* (1−3), 189−198.

(3) Jensen, J. A.; Friedmann, F. Physical and Chemical Effects of an Oil Phase on the Propagation of Foam in Porous Media. *Society of Petroleum Engineers*, **1987**. DOI: 10.2118/16375-MS

(4) Pu, W.; Pang, S.; Wang, C. Experimental Investigation of Foam Performance in the Presence of Crude Oil. *J. Surfactants Deterg.* **2017**, *20* (5), 1051−1059.

(5) Dalland, M.; Hanssen, J. E.; Kristiansen, T. S. Oil Interaction with Foams under Static and Flowing Conditions in Porous Media. *Colloids Surf., A* **1994**, *82* (2), 129−140.

(6) Laskaris, G. *Effect of Surfactant Concentration, Water Treatment Chemicals, Fatty Acids and Alcohols on Foam Behavior in Porous Media and in Bulk*. M.Sc. Thesis, Delft University of Technology, 2015 DOI: 10.4233/uuid:ad56c73d-4986-4358-9dd2-2929004cea6f.

(7) Osei-Bonsu, K.; Grassia, P.; Shokri, N. Investigation of Foam Flow in a 3D Printed Porous Medium in the Presence of Oil. *J. Colloid Interface Sci.* **2017**, *490*, 850−858.

(8) Tang, J.; Vincent-Bonnieu, S.; Rossen, W. Experimental Investigation of the Effect of Oil on Steady-State Foam Flow in Porous Media. *SPE J.* **2019**, *24*, 140.

(9) Zhang, H.; Miller, C. A.; Garrett, P. R.; Raney, K. H. Mechanism for Defoaming by Oils and Calcium Soap in Aqueous Systems. *J. Colloid Interface Sci.* **2003**, *263* (2), 633−644.

(10) Pugh, R. J. Foaming, Foam Films, Antifoaming and Defoaming. *Adv. Colloid Interface Sci.* **1996**, *64*, 67−142.

(11) Simjoo, M.; Rezaei, T.; Andrianov, A.; Zitha, P. L. J. Foam Stability in the Presence of Oil: Effect of Surfactant Concentration and Oil Type. *Colloids Surf., A* **2013**, *438*, 148−158.

(12) Arnaudov, L.; Denkov, N. D.; Surcheva, I.; Durbut, P.; Broze, G.; Mehreteab, A. Effect of Oily Additives on Foamability and Foam Stability. 1. Role of Interfacial Properties. *Langmuir* **2001**, *17* (22), 6999−7010.

DOI: 10.1021/acs.iecr.9b01589
Ind. Eng. Chem. Res. 2019, 58, 12766−12772

(13) Antón, R. E.; Andérez, J. M.; Bracho, C.; Vejar, F.; Salager, J.-L. Practical Surfactant Mixing Rules Based on the Attainment of Microemulsion−Oil−Water Three-Phase Behavior Systems. In *Interfacial Processes and Molecular Aggregation of Surfactants;* Narayanan, R., Ed.; Advances in Polymer Science; Springer Berlin Heidelberg: Berlin, Germany, 2008; pp 83−113.
(14) Koczo, K.; Lobo, L. A.; Wasan, D. T. Effect of Oil on Foam Stability: Aqueous Foams Stabilized by Emulsions. *J. Colloid Interface Sci.* **1992**, *150* (2), 492−506.
(15) Jones, S. A.; van der Bent, V.; Farajzadeh, R.; Rossen, W. R.; Vincent-Bonnieu, S. Surfactant Screening for Foam EOR: Correlation between Bulk and Core-Flood Experiments. *Colloids Surf. Physicochem. Eng. Asp.* **2016**, *500*, 166−176.
(16) Mannhardt, K.; Novosad, J. J.; Schramm, L. L. Foam/Oil Interations at Reservoir Conditions; *Society of Petroleum Engineers*, **1998**. DOI: 10.2118/39681-MS
(17) Jones, S. A.; Laskaris, G.; Vincent-Bonnieu, S.; Farajzadeh, R.; Rossen, W. R. Effect of Surfactant Concentration on Foam: From Coreflood Experiments to Implicit-Texture Foam-Model Parameters. *J. Ind. Eng. Chem.* **2016**, *37*, 268−276.
(18) Mitra-Kirtley, S.; Mullins, O. C.; Ralston, C. Y.; Sellis, D.; Pareis, C. Determination of Sulfur Species in Asphaltene, Resin, and Oil Fractions of Crude Oils. *Appl. Spectrosc.* **1998**, *52* (12), 1522−1525.
(19) Drenckhan, W.; Saint-Jalmes, A. The Science of Foaming. *Adv. Colloid Interface Sci.* **2015**, *222*, 228−259.
(20) Chumpitaz, L. D. A.; Coutinho, L. F.; Meirelles, A. J. A. Surface Tension of Fatty Acids and Triglycerides. *J. Am. Oil Chem. Soc.* **1999**, *76* (3), 379−382.
(21) Kirk-Othmer. *Encyclopedia of Chemical Technology*, 5th ed.; 2004; Vol. 5.
(22) Lide. *CRC Handbook of Chemistry & Physics*, 96th ed.; 2015.
(23) Chevallier, E.; Demazy, N.; Cuenca, A.; Chabert, M. Correlation Between Foam Flow Structure in Porous Media and Surfactant Formulation Properties. *Transp. Porous Media* **2019**. DOI: 10.1007/s11242-018-01226-2

DOI: 10.1021/acs.iecr.9b01589
Ind. Eng. Chem. Res. 2019, 58, 12766−12772