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ORIGINAL PAPER - EXPLORATION ENGINEERING

A rigorous approach to analyze bulk and coreflood foam screening tests

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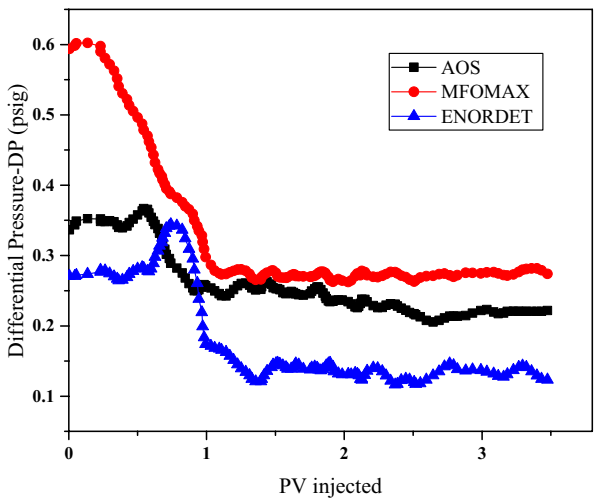
Abstract

There are many uses of foam in petroleum industry yet there is no dependable industry standard on screening a wide variety of foaming surfactants available for a particular application. This study aims to fill this gap. Three anionic foaming surfactants were characterized and tested with the two commonly used screening methods at room temperature and oil-free conditions. The results were comprehensively analyzed to compare their foaming performance. The analysis is more comprehensive than previously reported and covers many foaming attributes (peak and residual foamability, foam longevity, and rate of decay). The three surfactants for possible foaming applications in sandstone reservoirs were selected, and their foamability and foam stability performances were experimentally determined by bulk foam stability tests and coreflood tests. All methods agreed on the ratings of the three surfactants for peak and residual foaming attributes as follows in the following order of effectiveness: MFOMAX, AOS, and ENORDET. However, they broadly disagreed on ratings for other characteristics including onset of foaming, the time required for peak foaming, foam longevity, and foam decay rate. In conclusion, the screening tests revealed that the simple and faster bulk foam stability test could be cautiously used to screen out the poor performers to narrow the range of acceptable surfactants. Also, the new and rigorous analysis technique presented in this paper offers more insight than conventional half-life test.

Graphical abstract



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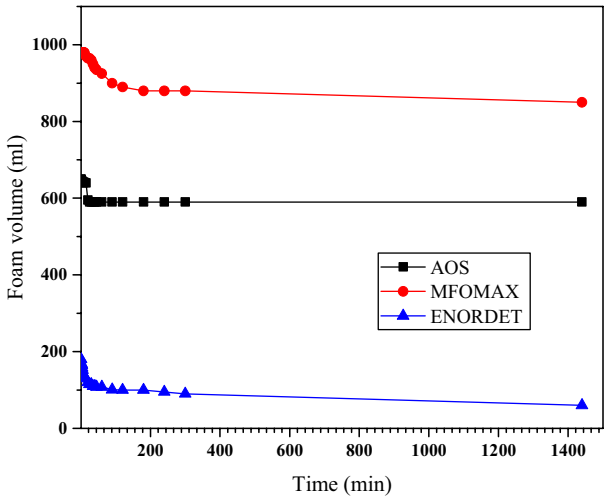
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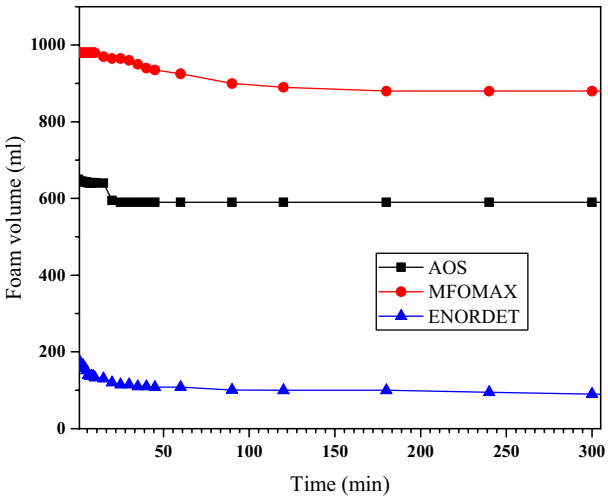
Time (min)
AOS
MFOMAX
ENORDET


Foam volume (ml)
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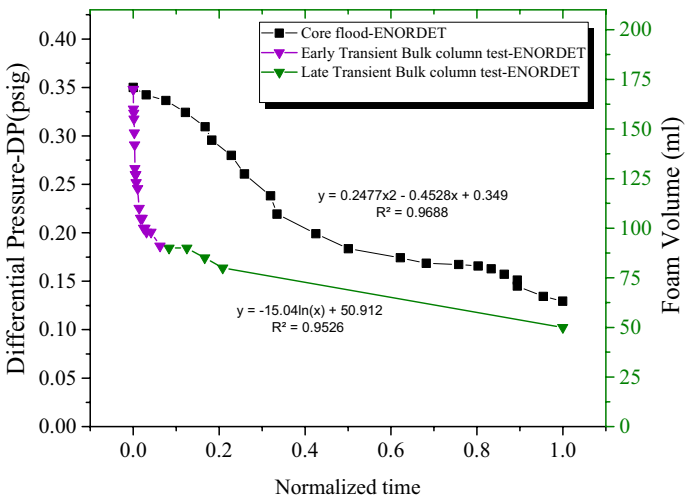
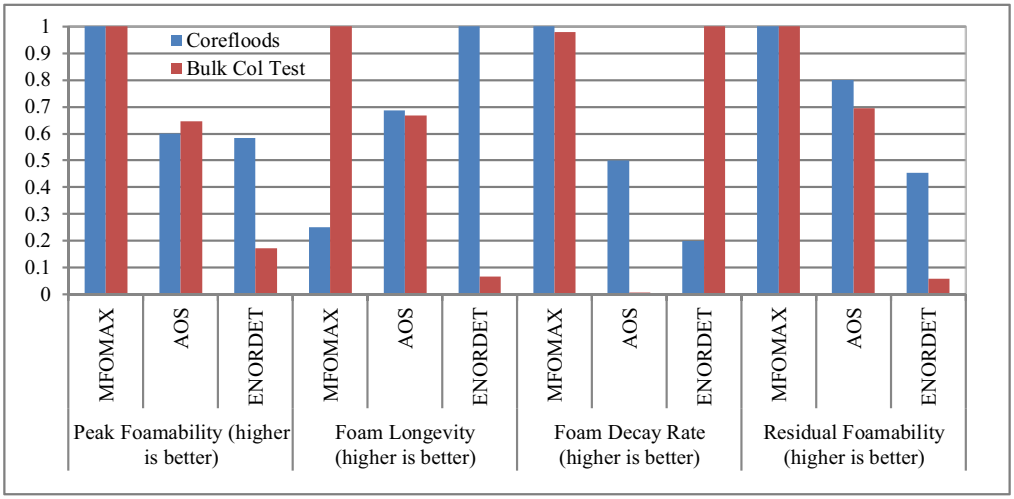

Core flood-ENORDET
Early Transient Bulk column test-ENORDET
Late Transient Bulk column test-ENORDET
y = 0.2477x2 - 0.4528x + 0.349
R² = 0.9688
y = -15.04ln(x) + 50.912
R² = 0.9526
Differential Pressure-DP(psig)
Foam Volume (ml)
Normalized time



Keywords Bulk foam stability test · Core flood · Peak and residual foamability · Foam longevity · Rate of foam decay

Introduction

The gas flooding is one of the most accepted and widely used methods for enhancing oil recovery (EOR) from oil reservoirs (Green and Willhite 1998; Lake 1996; Franklin and Orr 2007). However, since the viscosity of the gas is an order of magnitude lower than liquid, gas often fails to displace oil in a piston-like manner and tends to by-pass oil in the form of fingers and channels, especially when high permeability streaks present. Another problem encountered by gas injection is gravity segregation due to the low density of gas vs. oil, which causes gas to by-pass oil through gravity tongues (Namani et al. 2012). To overcome these problems, operators often inject a small slug of foaming surfactant before beginning gas injection with the aim of generating foam to reduce the mobility of injected gas as many studies have suggested (Bond et al. 1958), (Hirasaki 1985). This EOR method is called single-cycle surfactant-alternating-gas (SAG) or unsteady state test.

A large number of surfactants are available commercially for field applications of SAG. Also, major oil companies have developed their proprietary surfactants tailored to the specific reservoir conditions. Choosing a single surfactant that will perform best for a given reservoir is, however, not an easy and deterministic task. The process of selecting a suitable surfactant for the candidate reservoir out of a large number is non-deterministic. The coreflood tests, when conducted under reservoir conditions, are considered to be the most authentic method due to the closely matching conditions under which foam is generated and propagated in the reservoir. In these tests, a small plug of the cylindrical core (typically 3-inch long and of 1.5 inches in diameter) was saturated with reservoir fluids, after which a small slug of surfactant injected, followed by the gas injection.

Unfortunately, coreflood tests are expensive and time-consuming, hence not suitable for screening from a large number of surfactants (Jones et al. 2016). The standard industry practice is to perform the initial screening of surfactants in glassware commonly available in the lab by injecting gas into a surfactant solution to generate foam, or using a blender, in the absence of sand grains. These tests are called bulk foam stability tests because foam generates and decays outside porous media. These tests are simpler, faster, and cheaper. Some automated systems are commercially available (TECLIS FoamScan 2018) that use image analysis to determine the foam height vs. time (Li et al. 2014). Final selection of a surfactant is made by performing coreflood tests on a few outstanding performers from the bulk foam stability tests.

There is no general agreement or correlation between the foam stability in bulk foam stability tests and the coreflood tests. Several studies have suggested that the bulk foam stability tests are not as reliable as coreflood tests in accurately screening surfactants for field applications (Andrianov et al. 2012; Mannhardt et al. 2000; Farajzadeh et al. 2010; Bergeron et al. 1993). Previous studies hypothesized the reasons for the discrepancies based on the physical differences. The primary reason alluded was that foam morphology inside porous media is different than "free" foam outside porous media due to the confined and heterogeneous pore spaces (Hanssena and Kristiansen 1994). The foam in porous media encounters critical capillary pressure and critical water saturation which are highly foamicidal. In bulk foam test, on the other hand,

the gravity drainage of surfactant solution plays a dominant role as it causes the lamellae surrounding foam bubbles gets thinner, thereby the results are increasing the rate of gas diffusion from smaller bubbles (which are at higher pressure due to higher capillary pressure) to the larger ones. This diffusion causes the coarsening of bubble sizes with time as the smaller bubbles gradually coalesce into larger bubbles. Finally, the foam becomes dry and takes polyhedral structure (Jones et al. 2016). Recently, the coarsening behavior has been investigated in porous media by Jones (2018) at both pores and core scales using micromodel and sandstone core. They noted the change in bubble count over time and observed that the confining pore walls have a significant effect on foam's coarsening behavior; the coarsening was quicker (coarsening stopped earlier) in smaller pores and pore-throat environments such as the core as compared to the micromodel (Jones 2018).

Another significant difference of bulk foam stability tests is that it is performed under static conditions, whereas coreflood tests are performed at flowing conditions. Foam stability during coreflooding is thus a function of many parameters such as interstitial fluid flow velocities, the method of gas and surfactant injection, and the gas to liquid injection ratio (f_g, the foam quality) (Zhang et al. 2009).

Some studies showed a positive correlation between bulk foam stability tests and coreflood stability tests under oil-free conditions. Vikingstad and Aarra (2009) used a blender to disperse air for generating foam at a somewhat higher temperature (50 °C). They noted the decrease in foam height with time and compared results with coreflood stability tests in which N_2 and surfactant solution were simultaneously injected at a moderate rate and pressure to yield a transitional foam quality ($q_T = 40$ ml/h, $P_{inj} = 120$ bar/1764 psig, and $F_g = 80\%$). They observed that the foam stability and strength were similar in both bulk foam stability tests and coreflood stability tests in oil-free conditions. Also, Jones et al. (2015) suggested using bulk foam stability tests as a proxy to coreflood stability tests for screening foaming surfactants.

Some studies showed a positive correlation under oil-free conditions but failed to show a consistent correlation in the presence of oil (Mannhardt et al. 2000; Jones et al. 2015; Vikingstad and Aarra 2009). Whereas Van der Bent (2014) concluded that bulk foam stability tests could be used to infer surfactant performance in coreflood in the absence of oil, however, he could not find a good correlation between the two methods in the presence of oil (Bent and Der 2014). Osei-Bonsu et al. (2017) conducted a series of foam stability experiments using both micromodel and porous media and found that stability of foam in the presence of oil at bulk scale does not necessarily define its effectiveness in porous media (Osei-bonsu et al. 2017). The ambiguity of bulk foam stability tests in the presence of oil as observed by many investigators precludes them to be used as the sole method for screening surfactants for field applications.

The published studies have demonstrated the superiority of coreflood stability tests over the bulk foam stability tests. However, it is not possible to discard the later altogether because of practical reasons. It is not feasible to screen a large number of surfactants using coreflood which require expensive specialized test equipment and take a few days to conduct a single test vs. bulk foam stability tests that use glassware commonly available in laboratories and take only a few hours for a test. Because of the bulk foam stability test's simplicity and low cost, several screening systems can also run in parallel. Also, some studies show a positive correlation between the two. More studies are needed in an attempt to understand how the bulk foam stability tests can be utilized more intuitively, albeit as an initial screening tool. With this aim in mind, the current study looks into different and more in-depth ways of comparing the two methods of screening. It should be re-emphasized here that this study focuses on oil-free conditions only since studies in the past showed a positive correlation between bulk and core tests in the absence of oil while the use of bulk foam stability test for screening surfactants is ambiguous in the presence of oil.

This study shows the need to examine new attributes of foaming while analyzing both bulk foam tests and core flood results since an understanding of all possible attributes is essential for correctly selecting a suitable candidate surfactant. The "half-life" concept of the bulk test does not directly correlate with corefloods and discrepancies between individual attributes were found while analyzing the results of the two tests. Also, the delay in onset of foaming and time required to reach peak foaming were two of the attributes that could be determined in coreflood tests but not in bulk foam stability tests.

Materials and methodology

A brief description of the materials used in this study is provided here along with an elaborate discussion on the methodology of the tests.

Brine preparation

The salinity of the synthetic brine solution used for this study was 2 wt%, and it was prepared using pure sodium chloride (NaCl) provided by the Merck Company with properties listed in Table 1.

Table 1 Properties of sodium chloride

Description	Formula	Molar mass (g/mol)	Melting point (°C)	Density (g/cm^3)
Sodium chloride	NaCl	58.44	801	2.17

First, a stock solution of 10 wt% was prepared. 1000 ml of 2 wt% NaCl solution was then prepared by diluting 200 ml of the 10 wt% of the stock solution by adding 800 ml of distilled water (stirrer used for mixing correctly).

Surfactant solution

Surfactant solution preparation

Table 2 shows the properties of the three surfactants used for this study. The concentration of surfactant for all tests was 0.5 wt% and the salinity was 2 wt%.

Figure 1 shows the general structure of the first two anionic surfactants (AOS 14–16 and ENORDET 0332) which have been commercialized and employed in real fields for enhanced oil recovery (Barnes 2010; Wibbertmann et al. 2011). MFOMAX, on the other hand, is a mixture of anionic and amphoteric surfactants. It is a proprietary surfactant provided by PETRONAS Research Sdn Bhd (PRSB) which its structure has not been disclosed.

These surfactants were selected for this study due to their acceptability in the oil industry. The anionic surfactants incur lower adsorption losses in sandstones because their surface charge usually is negative, and mixed surfactants are used when some specific properties are desirable.

A stock solution of 5 wt% was prepared for each of the three surfactant solutions by adding an appropriate volume of pure surfactant to the distilled water as listed in Table 3. The amount of surfactant addition required to achieve the target concentration depended upon the active concentration of each pure surfactant.

The critical micelle concentration (CMC), an important parameter of a surfactant, was determined for the all three surfactants using the Accumet XL600 conductivity meter (by Fisher Scientific). The CMCs of the three surfactants were determined to be AOS = 0.033 wt%, ENORDET = 0.016 wt%, and MFOMAX = 0.062 wt%.

These results were utilized in selecting a safe level of surfactant solution concentration to have the surfactant concentration above the CMC value to minimize the detrimental effect of adsorption in reducing the available active percentage of surfactant affecting foamability and foam stability.

The 1000 ml of each surfactant solution (0.5 wt% surfactant concentration into 2 wt% salinity) were prepared for the surfactant characterization, core flood, and bulk foam stability tests.

Surfactant solution characterization

The density of the solution was measured at room temperature using Anton Paar DMA 4500 M (0–3 g/cm^3 range, 0.00005 g/cm^3 accuracy). Extreme care was exercised to remove all air bubbles from the testing tubes and waiting long enough for the system to stabilize. The surface tensions between nitrogen and surfactant solutions were measured

Table 2 Properties of surfactants used in this study

Name	AOS 14–16	ENORDET 0332	MFOMAX
Description	Alpha olefin sulphonate	Internal olefin sulphonate	Mixed anionic and amphoteric surfactant
Type	Anionic	Anionic	Mixed
Physical state	Liquid	Liquid	Liquid
Molecular weight average, g/mol	315	414.19	Proprietary
% Activity	33	31.30	20
pH	10	14	6–6.5

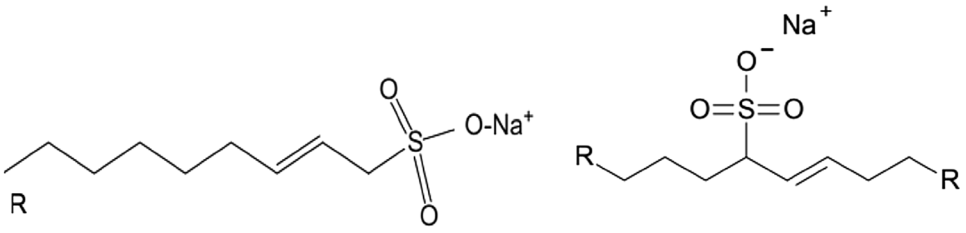


Fig. 1 General structure of Alpha Olefin Sulfonate (AOS) (left) and Internal Olefin Sulfonate (ENORDET) (right) surfactants (Barnes 2010; Wibbertmann et al. 2011)

Table 3 Volumes used for making 1000 ml of 5 wt% of surfactant stock solution

Name	AOS	ENORDET	MFOMAX
Surfactant activity (%)	33%	28.03%	20%
Distilled water added (ml)	848.5	821.6	750
Surfactant of given activity added (ml)	151.5	178.4	250

under atmospheric conditions by pendant drop method using IFT-700 Interfacial Tension Meter (by VINCI Technologies). Table 4 illustrates the results of densities and surface tension values. The density AOS and ENORDET are almost the same, whereas the density of MFOMAX is lower than the rest. Also, MFOMAX shows the highest reduction of surface tension among all.

Bulk foam stability test

The foam was generated using pure nitrogen (N_2) for this study. Though CO_2 has a broader field application, it was avoided due to significant water solubility and corrosiveness issues, though it has been used in some research studies. The literature suggests that stronger foam can be generated with N_2 which is also more compatible with different types of surfactants as compared to CO_2 (Farajzadeh et al. 2009; Farzaneh and Sohrabi 2013). Figure 2 shows the graduated cylinders used in bulk foam stability tests with a steel tube inserted from the top to the base for gas injection from the bottom of the cylinder.

TECLIS Foam Scan (2018) (bulk foam analyzer) uses a fritted disk at the bottom through which gas is introduced into a partially surfactant-filled cylinder to generate foam. This study deliberately avoided using such a disk since the texture of the foam generated in this case, was controlled by the pore sizes, and the literature shows that texture influences stability in a way that finer foam has greater foam stability. The variations in the texture of foam may explain the reason why some studies in the past showed contradictory foam stability results.

The test was performed by pouring 50 ml of the surfactant solution into a clean 1000-ml graduated cylinder of 6 cm diameter, and a steel tube was inserted to touch the bottom.

Fig. 2 The graduated cylinder used in bulk foam stability tests

N_2 gas from a cylinder was then injected at a rate of 30 cm^3/min (rate controlled by the gas regulator) through the steel tube. As the foam generation started, the height of the foam column started increasing. When the rise in foam height stops due to reaching equilibrium (new bubble generation equals bubble collapse), the N_2 injection was stopped, the stopwatch was started to begin counting the lapse time, photographs were taken intermittently, and the height of the foam column was noted periodically. This process continued for about one day after which the test was closed.

Coreflood foam stability tests

Coreflood foam stability tests were performed in a commercial coreflooding system (BPS-805 by Coretest Systems, Inc., CA, USA) using the core plug described in the next section. The system was equipped with a liquid pump, a gas mass controller for maintaining the desired gas injection rate, a differential pressure transducer, and a confining pressure system. The BPS-805 coreflooding system

Table 4 Surfactant solution characterization in term of its concentration and brine salinity

Solution	Surfactant concentration (wt%)	Brine-NaCl salinity (wt%)	Density (g/ml)	Tension (mN/m)
Brine	0	2	1.0121	72.68
AOS	0.5	2	1.0127	29.98
ENORDET	0.5	2	1.0120	29.07
MFOMAX	0.5	2	1.0090	28.25

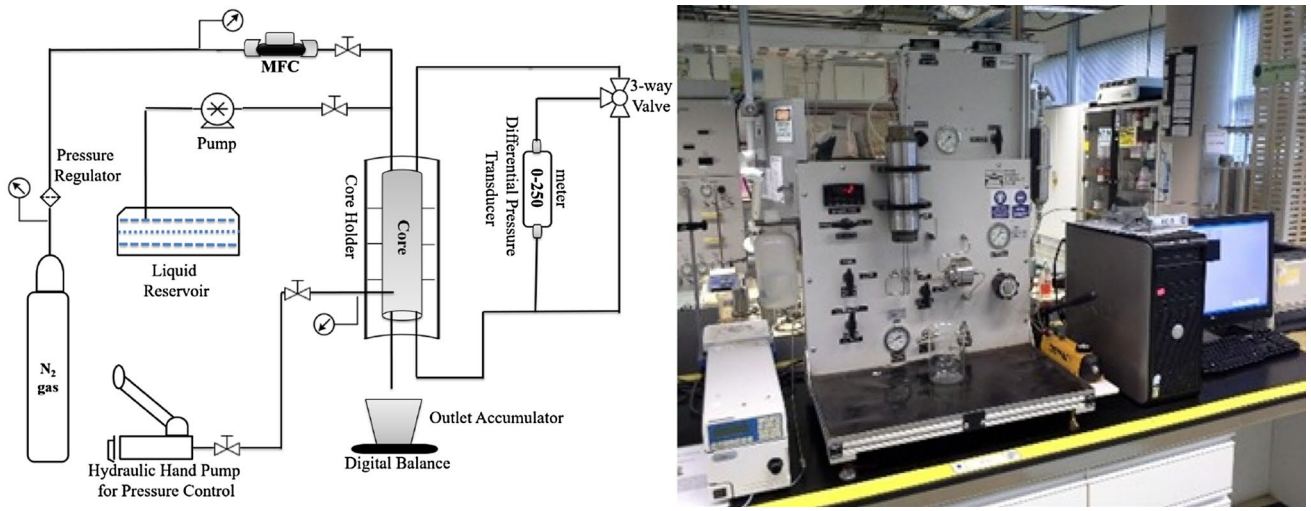


Fig. 3 Schematic and snapshot of BPS-805 coreflooding system

has been fully described by Kim and Lee (2017), except that the orientation of the core holder was vertical in this study. Figure 3 shows the schematic and the snapshot of the equipment.

The porosity and absolute permeability to gas were measured using the model M9170 poroperm system (by Grace Instrument), and the liquid permeability was determined using the BPS-805 coreflooding system with the single-phase liquid steady-state test. The residual water saturation (S_{wr}) was estimated using Timur's correlation for sandstones (Timur 1968) which correlates S_{wr} with absolute permeability and porosity, given in the following equation:

$$S_{wr} = 3.5\frac{\phi^{1.26}}{K^{0.35}} - 1, \quad (1)$$

where the porosity (ϕ) and permeability (K) are in percent and md, respectively.

In coreflood, the foaming performance was evaluated by drainage (unsteady state) experiments. The core was cleaned and saturated with a surfactant solution, and the test began by injecting N_2 into the core. The differential pressure and cumulative gas injection volumes were noted vs. time. The apparent viscosity of foam was computed using the following equation (Ma et al. 2013):

$$\mu_{foam,app} = \frac{K\nabla p}{U_w + U_g}, \quad (2)$$

where K is the permeability in Darcy, ∇p is the differential pressure gradient in (atm/cm), and $U_w + U_g$ is the total superficial velocity (cm/s).

Core plug properties

The core plug used for coreflood foam stability tests was commercially available (Kocurek Industries INC., TX, USA). The core used in this study was "Idaho Gray" sandstone cylindrical outcrop plug of 7.2 cm length and 3.7 cm in diameter. Table 5 lists the physical properties of the core plugs. The high permeability and porosity cores were chosen because of their suitability for foam studies as they are better for foam generation (Mannhardt et al. 2000) and they minimize the capillary end effects which could significantly affect the coreflooding results.

Results and discussion

Bulk foam stability tests

The bulk foam stability tests were performed on the three selected surfactants (same surfactants also used for coreflood foam stability tests) using the methods described in the previous section. The results are presented in Fig. 4 and show that the MFOMAX had the highest peak foamability since it was able to generate to a higher maximum foam volume of 990 ml with f_g of 95%, the medium performer was AOS with 640 ml with f_g of 92%, and the lowest performer was ENORDET with only 170 ml with f_g of 71%.

Residual foamability behavior was similar to the peak foamability, with MFOMAX having the highest residual foamability of 850 ml, AOS was the medium performer with 590 ml, and ENORDET was the lowest performer with only 50 ml. With regards to foam longevity, MFOMAX had the highest longevity and did not degrade before 30 min. AOS showed medium longevity and started to degrade only after

Table 5 Idaho gray sandstone core plug properties

Sample dry weight (g)	Pore volume (cc)	Porosity (%)	Absolute gas permeability (md)	Absolute liquid permeability (md)	Residual water saturation using Timur's correlation %
138.93	23.30	29.70	2974	903	14.27

20 min while ENORDET showed the lowest longevity and started to degrade just after 2 min. Regarding foam decay rate, MFOMAX and ENORDET performed almost similar and took the longest time to drop from peak to valley.

AOS was the worst performer. After 20 min of longevity, it suddenly (in 6 min) but only slightly dropped in volume by about 50 ml, after which it stayed stable until the end of the test. ENORDET had the slowest foam decay rate. After 2 min of longevity, foam began to decay non-linearly with time and dropped by 105 ml in 24 h. MFOMAX had almost similar foam decay rate as ENORDET and started to decay after 30 min and its volume reduced by 140 ml in 23.5 h. The above observations from bulk foam stability tests are summarized in Table 6 and shown in the clustered chart in Fig. 5.

A review of the peak foamability, residual foamability, and foam longevity attributes shows that the MFOMAX was the winner, the AOS was the runner-up, and the ENORDET was the least favorable. MFOMAX was also among the winners in having comparability low decay rate with ENORDET showing slightly better performance, whereas the AOS had drastically faster decay rate. Nonetheless, after a sudden drop in foam height, AOS maintained it residual foamability till the end. Thus, it can still be ranked as second best performing surfactant in these tests.

Coreflood foam stability tests

Three corefloods were performed using three different surfactants to rank them based on their foam stability. The characteristics of these surfactants were described in the previous section. The corefloods were performed using the single-slug SAG technique (the unsteady state surfactant drainage by gas injection), wherein the core was cleaned, dried, evacuated, and fully saturated with brine; which was then displaced by one of the three surfactant solutions. The tests were started by injecting gas and noting the pressure differential. All three surfactants were tested using the same core and under the same operating conditions as shown in Table 7. The coreflood foam stability results are presented in Fig. 6.

For each test, differential pressure gradient was recorded (from which the apparent foam viscosity was calculated) with respect to the gas volume injected into the surfactant-saturated porous media. The pseudo apparent viscosity of foam (μ_{foam}/K_{rg}) was derived in corefloods using Darcy's law. Since relative permeability curves for foam are not established, and the S_g varies during the test, K_{rg} could not have been determined. Under peak foaming conditions, however, f_g is only slightly less than 1, and with that high gas saturation, K_{rg} is also close to 1. Therefore, the pseudo apparent viscosity is expected to be very close or slighter higher than the apparent viscosity.

The early test data pertained to foamability behavior, i.e., pore volume injected before foaming started (delay in

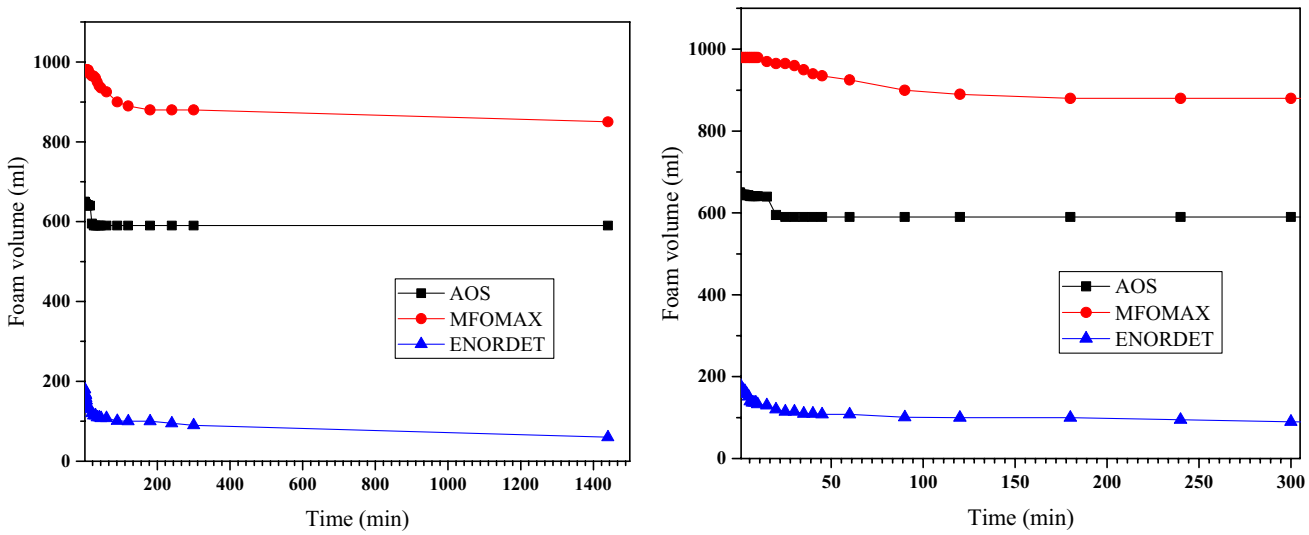


Fig. 4 The bulk foam stability tests for foam stability of the three selected surfactants, (left: complete test data, right: first 300 min of test data)

Table 6 Summary of results from bulk foam stability tests

Foam stability attribute	Observed parameter	MFOMAX	AOS	ENORDET
Peak foaming	Foam volume (ml)	990	640	170
Foam longevity	The time before decay started (min)	30	20	2
Residual foaming	Foam volume after 24 h (ml)	850	590	50
Foam decay rate	The time required to drop foam volume from peak to valley (hours)	23.5	0.1	24
Foam quality (%)	f_g at the beginning	95	92	71
Decay behavior	Qualitative observation	Early transient: non-linear polynomial; late transient: power law	Linear	Early transient: non-linear polynomial; late transient: linear
Decay behavior*	Quantitative observation	*a**	*b**	*c**

Decay behavior of bulk foam stability test was divided into two sections as early and late transient for a better understanding of trends in Figs. 8, 9 and 10.

$a*$ (Early transient): Foam volume = 2887.36 (Normalized time)^2 − 1590.83 (Normalized time) + 986.783

$a*$ (Late transient) : Foam volume = 837.89 (Normalized time)$^{-0.03}$

$b*$ (Early transient) : Foam volume = − 2874.015 (Normalized time) + 641.43

$b*$ (Late transient) : Foam volume = − 6.609(Normalized time) + 590

$c*$ (Early transient) : Foam volume = 37498.45 (Normalized time)^2 − 3239.45 (Normalized time) + 154

$c*$ (Late transient): Foam volume = − 43.0480(Normalized time) + 92.6318.

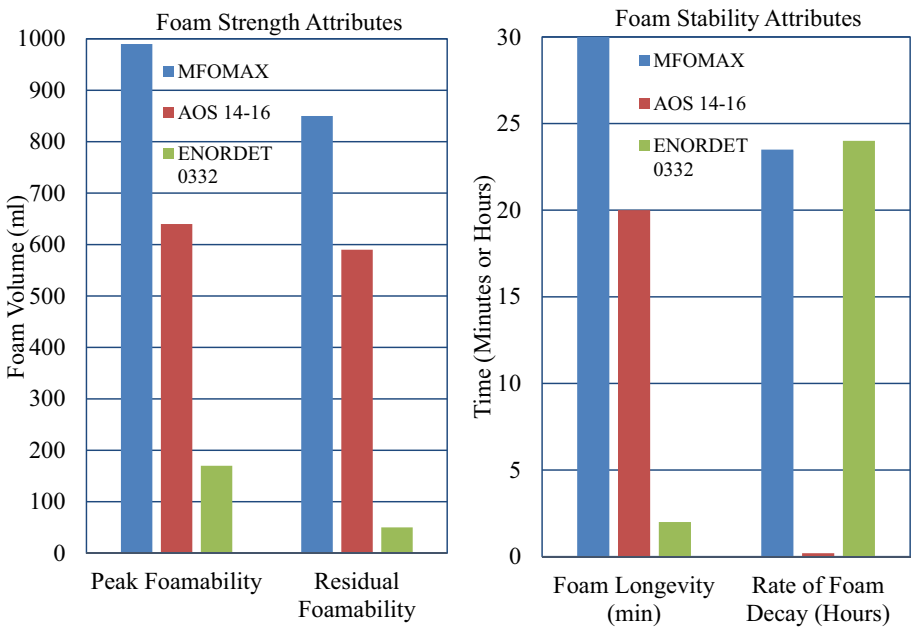


Fig. 5 The clustered column charts are displaying the results of the "bulk foam stability test" for the three surfactants. The chart on the left is for foam strength attributes, whereas the chart on the right is for the foam stability attributes

foaming) and between the start of foaming to reaching peak pressure drop (time to peak foaming). These data are not shown in Fig. 6 since those attributes cannot be determined in bulk foam stability tests. Bulk tests can only be used for testing foam stability and decay after the generation and peak foaming conditions. Therefore, to make a meaningful comparison, the pore volume injection was considered to be starting after foaming almost stabilized, i.e., zero PV injected on the figure indicates the point at which foam generation had virtually stabilized.

The coreflood foam stability tests showed that MFOMAX had the highest peak foamability since it was able to generate a pressure drop (DP) of up to 0.6 psig while AOS and ENORDET could only create pressure drop up to 0.36 and 0.35 psig, respectively. Overall, the results showed that MFOMAX is the best in foamability attributes, followed by AOS and after that ENORDET at the last. Looking at how

Table 7 Operating conditions of corefloods

Parameters	Value
Confining pressure (psi)	1000
Back pressure (psi)	14.7
Injection rate (cc/min)	2
Surfactant solution salinity	2 wt%
Surfactant concentration	0.5 wt%
Porosity (%)	29.7%
Permeability by gas (md)	2974
Permeability by liquid (md)	903

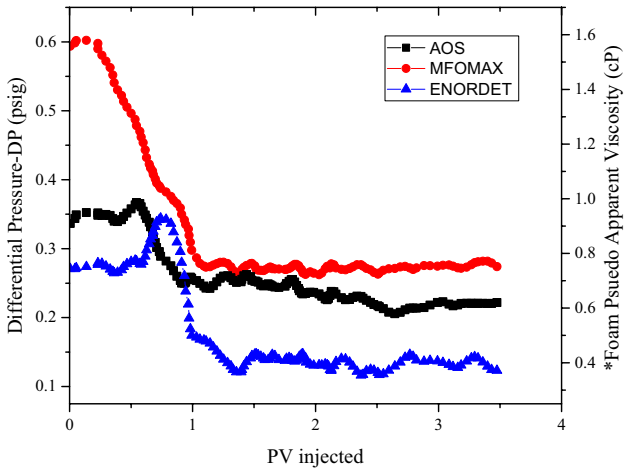


Fig. 6 The history of differential pressure change with the volume of gas injected into the core initially saturated with surfactant solution. The * indicates (μ_{foam}/K_{rg}) which is expected to be very close or slighter higher than the apparent viscosity

long the foam survived at peak foaming, ENORDET showed the highest foam longevity and did not start to decay until 0.8 PV of gas injection. AOS had the medium longevity and did not begin to decay before 0.55 PV, whereas MFOAMX could only last 0.2 PV before decay.

Regarding foam decay rate, MFOMAX had the slowest decay rate and took 1 PV of gas injection from peak foaming to drop to the residual foaming. AOS had the medium decay rate and took 0.5 PV to drop to the residual foaming, whereas ENORDET had the highest decay rate and took only 0.2 PV of gas injection to go from the peak to residual.

With regards to the lowest pressure differential (DP at the valley), MFOMAX was again had the best performance with a DP of 0.275 psig, the AOS was the second best with a DP of 0.22 psig, and the ENORDET was the lowest performer with DP of 0.125 psig. The above observations are summarized in Table 8 and plotted as a cluster chart in Fig. 7.

The MFOMAX was the winner, the AOS was the runner-up, and the ENORDET was the least favorable with regards to peak foamability, residual foamability, and rate of foam decay attributes. The ranking was reverse, however, for foam longevity attribute where ENORDET was the best performer, AOS was the runner-up, and MFOMAX was the worst. It could have been due to its peak foaming DP being 71% and 62%, respectively, higher than its competitors. Even after 0.8 PV injection after the highest longevity surfactant (ENORDET), MFOMAX had a higher DP than other surfactants. Therefore, it can be claimed that MFOMAX was overall had the best performance compare to AOS and ENORDET.

Side-by-side performance comparison of bulk and coreflood foam stability tests

In previous sections, the performance of the three surfactants was analyzed separately for each test type with the idea to rank them in overall performance as well as in each of the attributes individually. In this section, the behavior of each surfactant as observed by both tests is presented side-by-side in Figs. 8, 9 and 10.

The timescale had to be normalized to show them on the same plot. Hence, for bulk foam stability test, the time data were divided by maximum time (1440 min) to get a timescale from zero to one. Similarly, coreflood pore volumes were divided by the maximum pore volume. The two different foaming indicators, pressure drop (DP) for coreflood and foam volume (ml), however, were depicted on two separate *y*-axes.

Figure 8 shows the foaming behavior of MFOMAX by the two tests. Only the early transient (140 min) in bulk foam stability test matched well with coreflood though later, the behavior diverged. The foam decay trend reduced continuously in coreflood test but slowed down and stabilized in bulk foam test. Decay behavior in bulk foam test encountered a change in structure, from "wet-foam" in which bubbles are not interfering, and liquid drainage is faster to "dry-foam" of the highly stable tetrahedral (web-like) structure. Contrarily, the foam flow in porous media is a dynamic process, which has a different decay mechanism as the data suggest as well as the previous studies have suggested (Farajzadeh et al. 2010).

Figure 9 shows the foaming behavior of AOS by the two tests. Relative less foaming (lower DP and Foam volume) was observed in both tests as compared to MFOMAX. The early transient behavior of bulk foam stability test was very short and did not match with the coreflood. After the early transient, the foam volume change was minor in bulk foam stability tests. The coreflood, on the other hand, had somewhat similar behavior as for MFOMAX. The reasons for the discrepancy are probably the same as explained above.

Table 8 Summary of coreflood observations

Foam stability attribute	Observed parameter	MFOMAX	AOS	ENORDET
Peak foaming	Peak DP (psig)	0.6	0.36	0.35
Foam longevity	Vol. inj. before decay started (PV)	0.2	0.55	0.8
Residual foaming	DP at the valley (psig)	0.275	0.22	0.125
Foam decay rate	Vol. inj. between the start of DP drop from peak to valley (PV)	1	0.5	0.2
Foam quality (%)[a] (maximum)	f_g at the peak foaming	86	86	86
Decay behavior	Qualitative observation	Linear	Linear	Non-linear polynomial
Decay behavior**	Quantitative observation	a**	b**	c**

[a]Since it is an unsteady state test, the quality of foam keeps changing. The maximum foam quality shown above is inferred from the maximum gas saturation possible in this core based on Timur's correlation. It is likely that maximum f_g shown above pertains to the peak foaming

Following decay behavior is result of fitting curve from Figs. 8, 9 and 10.

a **: DP = − 0.3243 (Normalized time) + 0.5694

b **: DP = − 0.1626 (Normalized time) + 0.3804

c **: DP = 0.22225 (Normalized time)^2 − 0.43854 (Normalized time) + 0.3612

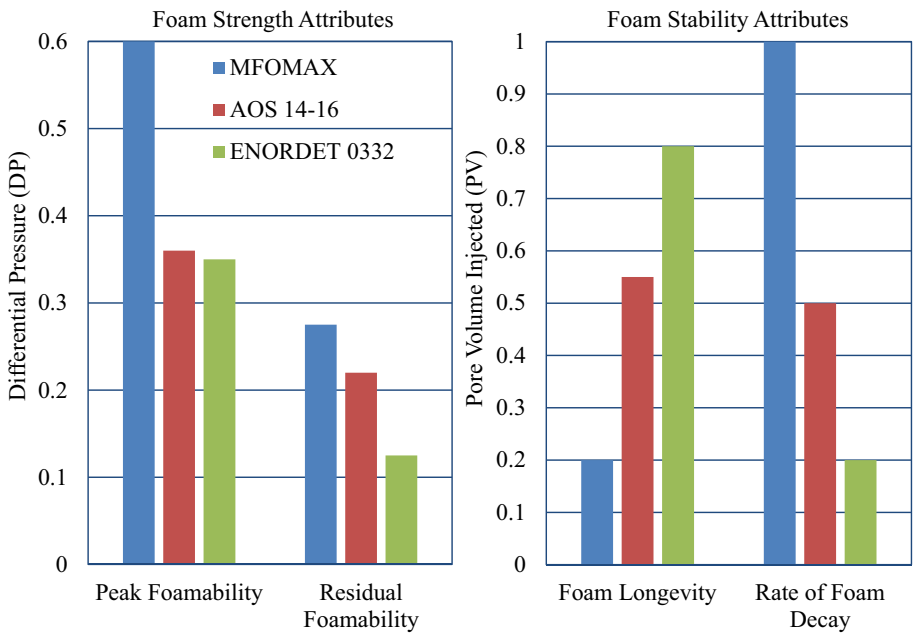


Fig. 7 The clustered column charts are displaying the corefloods results for the three surfactants. The chart on the left is for foam strength attributes, whereas the chart on the right is for the foam stability attributes

Figure 10 shows the foaming behavior of ENORDET by the two tests. The DP behavior in the coreflood test was somewhat similar and comparable to AOS coreflood test. The bulk foam stability test of ENORDET behaved differently than the previous two tests. In this case, the foam volume was significantly lower in the bulk foam stability test compare to AOS and MFOMAX. There was a sharp drop in foam volume during early transient before the decay rate significantly slowed down. This plot shows the shortcoming of using "half-life" as a screening criterion as the half-life, as shown in this chart, would have been very short and much before the "dry" foam was formed.

Normalized performance comparison of bulk and coreflood foam stability tests

The current industry practice for bulk foam stability tests is to use the half-life (the time taken for foam volume to reduce by half) is used as the primary factor distinguishing surfactant rankings. The difficulty with this practice is that bulk foam stability tests measure static stability, whereas the coreflood tests encounter dynamic stability. Because of this inherent difference, a new and more comprehensive approach will be used in comparing the two methods. In this approach, overall stability was deduced from four

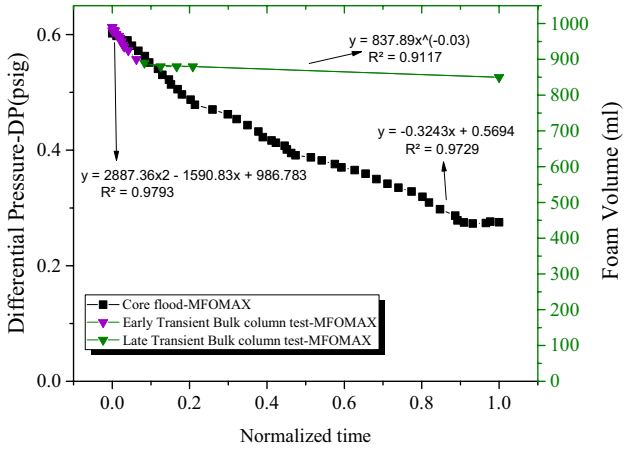


Fig. 8 Side-by-side performance comparison of bulk and coreflood foam stability tests of MFOMAX surfactant

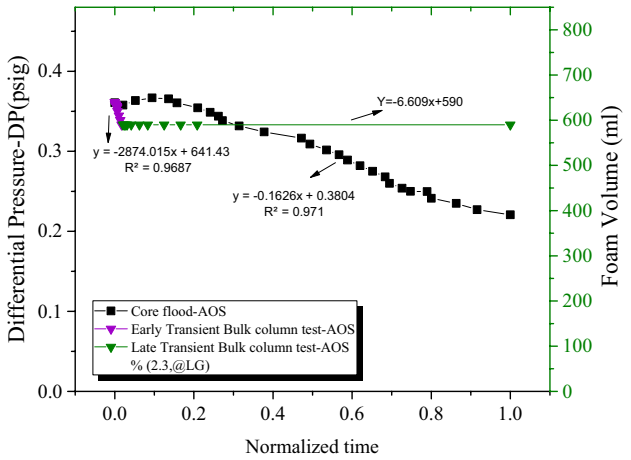


Fig. 9 Side-by-side performance comparison of bulk and coreflood foam stability tests of AOS surfactant

independent stability attributes: peak foamability, foam stability, the rate of foam decay, and residual foamability.

Above approach to ranking the surfactants were based on comparing the attributes performances of both tests individually. A side-by-side in-depth analysis of both tests together by comparing all the foaming attributes and their relative strengths among surfactant types is beneficial in screening the foaming surfactant. Since the quantitative measure of each attribute varies for each test type, such a comparison will require some intuitive techniques.

For comparing the attributes, it was necessary to normalize the data using the maximum value of each attribute from each test to yield a data range of 0–1. Figure 11 shows and Table 9 compares the normalized foaming attributes between bulk and coreflood foam stability tests.

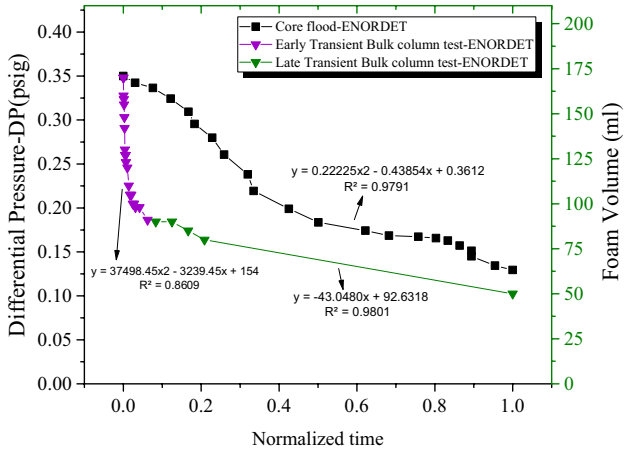


Fig. 10 Side-by-side performance comparison of bulk and coreflood foam stability tests of ENORDET surfactant

A careful side-by-side comparison of individual attributes on the juxtaposed charts (Fig. 11) reveals two shortcomings of the bulk foam stability test. First is that not all attributes are correctly ranked. Only the foamability (peak and residual) is correctly matched, whereas the foam stability attributes (longevity, decay rate) are not properly ranked. Second, even in the attributes that were correctly ranked, the relative merit is not correctly identified. AOS and ENORDET had almost similar peak foamability in corefloods but widely diverging in bulk foam stability tests. Such divergence is also evident in residual foamability.

Based on general observation from Fig. 11, ENORDET consistently showed differences between bulk and core tests, whereas MFOMAX and AOS were fairly consistent between bulk and core tests and it is due to its molecular structure that leads to a higher tendency to form micelles or aggregates in the liquid phase. This behavior results in a reduced number of surfactant molecules at the interface affecting their performance in maintaining the lamellae strength. AOS, on the other hand, is an anionic surfactant with straight carbon chain structure (no branching) leading to the better molecular arrangement at the interface. MFOMAX is a mixture of anionic and amphoteric surfactants having stronger steric interfacial forces between the surfactant molecules at the surface of lamellae which improves foam stability and strength.

Therefore, it can be inferred that the use of bulk foam stability tests should be restricted to screening out significantly lower performers. Screening out surfactants with closely matching performance by bulk foam stability tests alone is open to the risk of eliminating competent surfactants.

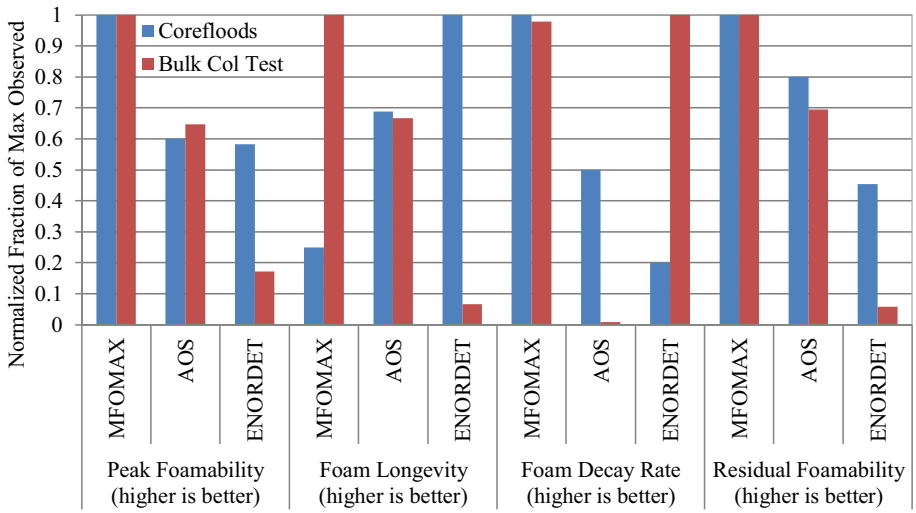


Fig. 11 The clustered column charts are comparing bulk foam test with coreflood results for all four foaming attributes: peak foamability, foam longevity, foam decay rate, and residual foamability. The data have been normalized from 0 to 1 using the maximum value of each attribute

Table 9 Comparison of normalized foaming attributes between corefloods and bulk foam stability tests

Attribute	Coreflood foam stability tests				Bulk foam stability tests			
	Observed parameter	MFOMAX	AOS	ENORDET	Observed parameter	MFOMAX	AOS	ENORDET
Peak foamability	Peak DP (psig)	1	0.6	0.58	Peak foam volume (ml)	1	0.65	0.17
Foam longevity	Onset of foam collapse (PV)	0.25	0.68	1	Stable for (min)	1	0.66	0.067
Foam decay rate	PV required to drop DP from peak to valley (PV)	1	0.5	0.2	Time required to drop foam volume from peak to valley (min)	0.98	0.01	1
Residual foamability	DP at the valley (psig)	1	0.8	0.45	Volume after 24 h (ml)	1	0.7	0.06

Conclusion

After an in-depth analysis of foaming behavior of three surfactants (MFOMAX, AOS, and ENORDET) as observed by two different foam screening methods (bulk and coreflood foam stability tests), the following can be concluded:

1. The new rigorous technique successfully analyzed the bulk foam stability performance of surfactants at ambient, oil-free conditions.
2. Bulk foam stability tests identified the highest and lowest performing surfactants correctly, though the individual attributes (peak foamability, foam longevity, foam decay rate, and residual foaming) did not always correlate well with coreflood tests. However, it can still be used as a preliminary screening tool to reduce the number of surfactants for further testing by a more reliable technique (coreflood).
3. The delay in onset of foaming and time required to reach peak foaming were two of the attributes that could be determined in coreflood tests but not in bulk foam stability tests.
4. The foam decay behaviors of coreflood and bulk foam stability tests were quite different. Foam decayed somewhat linearly in corefloods but had two distinct regimes in bulk foam tests. There was a rapid decay during early transient thought to be "wet foam" and a much slower decay during the late transient of "dry foam." Without knowing the regime, using half-life as a measure of foam quality is prone to errors.

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References

Andrianov A, Farajzadeh R, Mahmoodi Nick M, Talanana M, Zitha PLJ (2012) Immiscible foam for enhancing oil recovery: bulk and porous media experiments. Ind Eng Chem Res 51(5):2214–2226

Barnes JR, Dirkzwager H, Smit JR, Smit JP, On A, Reinaldo Navarrete C, Ellison BH, Buijse, MA (2010) Application of internal olefin sulfonates and other surfactants to eor. part 1: structure-performance relationships for selection at different reservoir conditions. Society of Petroleum Engineers, pp 1–16. https://doi.org/10.2118/129766-MS

Bergeron V, Fagan ME, Radke CJ (1993) Generalized entering coefficients: a criterion for foam stability against oil in porous media. Langmuir 9(7):1704–1713

Bond DC, Holhrook OC, Lake C (1958) States 1 2,866,507, pp 2–4

Farajzadeh R, Andrianov A, Bruining H, Zitha PLJ (2009) Comparative study of CO_2 and N_2 foams in porous media at low and high pressure-temperatures. Ind Eng Chem Res 48(9):4542–4552

Farajzadeh R, Andrianov A, Zitha PLJ (2010) Investigation of immiscible and miscible foam for enhancing oil recovery. Ind Eng Chem Res 49(4):1910–1919

Farzaneh SA, Sohrabi M (2013) SPE 164917 a review of the status of the foam applications in enhanced oil recovery. SPE J. https://doi.org/10.2118/164917-MS

Franklin J, Orr M (2007) Theory of gas injection processes. Tie-Line, Holte

Green DW, Willhite GP (1998) Enhanced oil recovery. Henry L. Doherty Memorial Fund of AIME, Society of Petroleum Engineers, Richadson

Hanssena JE, Kristiansen TS (1994) Oil interaction with foams under static and flowing conditions in porous media. Colloids Surf A 82:129–140

Hirasaki GJ (1985) Mechanisms of foam flow in porous media: apparent viscosity in smooth capillaries. Soc Pet Eng J 25(2):176–190

Jones SA (2018) Foam flow in a model porous medium: I. the effect of foam coarsening. Soft Matter. https://doi.org/10.1039/C7SM01903C

Jones SA, van der Bent V, Farajzadeh R, Rossen WR, Vincent-Bonnieu S (2015) Small core flood experiments for foam EOR—screening surfactant applications. In: 18th European symposium on improved oil recovery. https://doi.org/10.3997/2214-4609.201412126

Jones SA, van der Bent V, Farajzadeh R, Rossen WR, Vincent-Bonnieu S (2016) Surfactant screening for foam EOR: correlation between bulk and core-flood experiments. Colloids Surf A Physicochem Eng Asp 500:166–176

Kim C, Lee J (2017) Experimental study on the variation of relative permeability due to clay minerals in low salinity water-flooding. J Pet Sci Eng 151:292–304. https://doi.org/10.1016/j.petrol.2017.01.014

Lake LW (1996) Enhanced oil recovery, 1st edn. Prentice Hall, Upper Saddle River

Li J, Pan R, Guo B, Shan J (2014) Thermal stability of brine foams for shale gas drilling. J Nat Gas Sci Eng 17:131–135

Ma K, Lopez-Salinas JL, Puerto MC, Miller CA, Biswal SL, Hirasaki GJ (2013) Estimation of parameters for the simulation of foam flow through porous media. Part 1: the dry-out effect. Energy Fuels 27(5):2363–2375

Mannhardt K, Novosad J, Schramm L (2000) Comparative evaluation of foam stability to oil. SPE Reserv Eval Eng 3(1):19–22

Namani M, Kleppe J, Høier L, Karimaie H, Torsæter O (2012) Analytical model for zones distributions in non-horizontal miscible WAG injection. Energy Environ Res 2(2):159–167

Osei-bonsu K, Grassia P, Shokri N (2017) Relationship between bulk foam stability, surfactant formulation and oil displacement efficiency in porous media. Fuel 203:403–410. https://doi.org/10.1016/j.fuel

TECLIS SCIENTIFIC (2018) France, Feb. 08. https://www.teclis-scientific.com/foam-analysis.

Timur A (1968) An investigation of permeability, porosity, and residual water saturation relationships for sandstone reservoirs, vol 9. Society of Petrophysicists and Well-Log Analysts

Van Der Bent VJ (2014) Comparative study of foam stability in bulk and porous media. AES/PE:14–24

Vikingstad AK, Aarra MG (2009) Comparing the static and dynamic foam properties of a fluorinated and an alpha olefin sulfonate surfactant. J Pet Sci Eng 65(1–2):105–111

Wibbertmann A, Mangelsdorf I, Gamon K, Sedlak R (2011) Toxicological properties and risk assessment of the anionic surfactants category: alkyl sulfates, primary alkane sulfonates, and α-olefin sulfonates. Ecotoxicol Environ Saf 74(5):1089–1106

Zhang ZF, Freedman VL, Zhong L (2009) Foam transport in porous media—a review. US Dept of Energy Report no. PNNL-18918, The United States. https://doi.org/10.2172/1016458

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