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Evaluation of oil-tolerant foam for enhanced oil recovery: Laboratory study of a system of oil-tolerant foaming agents

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ABSTRACT

The objective of this paper is to investigate an oil-tolerant foam system as a displacing agent to improve the efficiency of oil recovery. To achieve this objective, several foaming agents are examined based on foam–oil interaction models and previous studies. By measuring the interfacial and surface tensions of surfactants, we investigate the implications of the value of spreading coefficient and the lamella number in a system of foaming agents. The foamability and foam stability of the preferred foaming agents were statically tested. At last, the oil tolerance of the foaming agent system in both static and core flow experiments was investigated.

Results indicated that the oil tolerant foaming system performs best among the various surfactants tested. In static testing, both foamability and foam stability increase as concentrations of surfactant and salt increase. It was also observed that the polymer significantly increases the foam stability in the presence of oil. The oil droplets do not spread at the surface due to the properties of the oil-tolerant foam, so the foam can be stable in the presence of crude oil.

The oil tolerant foaming system exhibits much greater foaming volume and longer drainage-half time than ordinary foam, either in the presence or absence of oil. The mobility reduction factor for dynamic displacement of oil-tolerant foam is much higher than those of pure foam and polymer solutions in the presence of oil. Experiments with different remaining oil saturations reveal that when the residual oil saturation is about 40%, the oil-tolerant foam can achieve the highest oil recovery.

1. Introduction

Many improved/enhanced oil recovery (IOR/EOR) methods have been developed to increase the overall recovery of a reservoir, such as chemical flooding, surfactant EOR, gas EOR and foam EOR. With better microscopic displacement and volumetric sweep efficiency, foam flooding has been recognized as a potential method for gas enhanced oil recovery (Wang, 2007; Hirasaki et al., 2008). Foam is composed of a large number of gas/liquid interfaces or lamellae for controlling mobility, and can be formed in gas swept channels to divert the subsequently injected gas to previously upswept and oil-rich regions of the reservoir (Hou et al., 2012; Kam et al., 2007). Therefore, foam flooding can enhance oil recovery greatly (by about 10–25%) in secondary and tertiary recovery processes, and it is expected to become another potential technology for improving oil recovery in addition to water or polymer flooding (Kam and Rossen, 2003; Kam et al., 2007; Li et al., 2012; Wang, 2007).

The major challenge of foam injection is foam stability in the presence of oil. Its oilfield applications in the North Sea and Daqing oilfields have proved that the stability of foam in the presence of oil was the key factor to foam EOR in the reservoir (Feng, 2009; Vikingstad et al., 2006). Wang (2007) suggested that foam "stabilizes with water and defoams with oil", so foam breaks up easily but is hard to regenerate when the foam meets residual oil or a large "oil wall" in the formation. Experiments such as Farajzadeh et al. (2012) and Zhao (2008) demonstrated that foam could not keep stable or high flow resistance in porous media at high oil saturation.

Foam is a thermodynamically unstable system, and its stability is influenced by many factors, such as surfactant structure, properties of the bubble, disjoining pressure and oil phase (Farajzadeh et al., 2012). Garret (1980) showed that oil exerts a strong influence on foam stability. Some models predict that when foam meets crude oil, oil can reduce its lifetime and destroy its film surfaces because surfactants are adsorbed into the micelles or co-adsorbed at the gas/water interface. Another mechanism of the effect is that the transfer of surfactant causes the reduction in surfactant concentration from the gas/water interface to the oil phase or the oil/water interface (Farajzadeh et al., 2012).

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Nomenclature

EOR/IOR	enhanced/improved oil recovery
S	spreading coefficient
E	entering coefficient
B	bridging coefficient
L	lamella number
SDS	sodium dodecyl sulfate
AS	alkanolamide
MSB	modified sulfonic betaine
EO	ethylene oxide sulfonate
FC	fluorocarbon
OTF	oil-tolerant foam
N_2	nitrogen
wt%	weight percent
v%	volume percent
FCI	foam composite index
SFT	surface tension
IFT	interfacial tension
V	foaming volume
$T_{1/2}$	drainage half-life time
PV	pore volume
MRF	mobility reduction factor
S_{or}	oil saturation
S_w	water saturation
CMC	critical micelle concentration

The foam–oil stability mechanism has been mainly discussed in three models: spreading (S), entering (E) and bridging coefficients (B) (Aveyard et al., 1994; Robinson and Woods, 1948; Schramm and Novosad, 1992, 1990). They are defined as follows:

$$S = \sigma_{w/g} - \sigma_{w/o} - \sigma_{o/g} \tag{1}$$

$$E = \sigma_{w/g} + \sigma_{w/o} - \sigma_{o/g} \tag{2}$$

$$B = \sigma^2{}_{w/g} + \sigma^2{}_{w/o} - \sigma^2{}_{o/g} \tag{3}$$

where $\sigma_{w/g}$ is the surface tension between water and gas, $\sigma_{w/o}$ is the interfacial tension between oil and water, and $\sigma_{o/g}$ is the surface tension between oil and gas. When the value of the spreading coefficient is negative, the oil droplets stay captured between the two film surfaces and spreading does not occur, which means the foam remains stable in the presence of oil. The ability for oil drops to enter the gas–water interface is referred to as an "entering coefficient" (E), and if E is positive, it is favorable for oil to enter the gas–water surface, which results in a thinning of the foam film and eventually the film ruptures (Simjoo et al., 2013). The bridging coefficient is defined as a criterion for the effect of oil bridging on foam stability, and when B is positive, the foam is unstable (Farajzadeh et al., 2012).

The stability of foam also can be described by another parameter, the lamella number (L), which is defined as a ratio of capillary pressure at Plateau borders to the pressure difference across the oil–water interface (Schramm and Novosad, 1992, 1990; Vikingstad et al., 2006). The lamella number is defined as

$$L = \frac{\Delta P_C}{\Delta P_R} = \frac{R_O}{R_P}\frac{\sigma_{w/g}}{\sigma_{w/o}} = 0.15\frac{\sigma_{w/g}}{\sigma_{w/o}} \tag{4}$$

where R_O is the radius of oil droplet, and R_P, is the radius of the Plateau border. Three kinds of foam can be distinguished by the value of L, E and S (Table 1) (Simjoo et al., 2013).

These coefficients can be used to discuss foam stability mechanisms in the presence of crude oil. Many researchers have studied foam–oil interactions and oil-tolerant foam by using these models. Farajzadeh et al. (2012) reviewed the mechanisms and models for foam–oil interaction, such as the disjoining pressure, coalescence, and drainage. They also presented various ideas on the improvement of foam stability and longevity in the presence of oil. Vikingstad et al. (2006) studied the influence of oil types and oil saturations on foam generation and stability, and they also observed the effect of surfactant structure on foam–oil interactions. To gain better insight into the foam–oil interaction, Simjoo et al. (2013) investigated the effects of various surfactants and surfactant concentrations on the foamability and foam stability in the absence and presence of different oil types.

Table 1
Foam stability prediction by L, E and S.

Value of L	E	S	Foam stability to oil
$L<1$	Negative	Negative	Quite stable foam
$1<L<7$	Positive	Negative	Moderately stable foam
$7<L$	Positive	Positive	Quite unstable foam

The ultimate objective of these studies is to obtain an oil-tolerant foam, which can retain foam stability in the porous media. In recent years, many foaming agents were selected and studied to achieve the best foam stability in the presence of oil, such as a fluorinated surfactant, an AOS surfactant, an AO surfactant, and various mixed surfactant systems (Al-Attar, 2011; Kovscek, et al., 2010; Deng et al., 2012; Ashoori et al., 2011; Lai, 2007). Deng et al. (2012) and Vikingstad et al. (2006) presented the foamability and foam stability of various fluorinated surfactants in the presence of oil and they found that fluorinated surfactants can remain stable for a long time in oil. However, the field applications of fluorinated surfactants have limitations, such as higher costs and environmental problems. Cubillos et al. (2012) evaluated four surfactants (LAS, AOS C_{12-14}, AOS C_{14-16}, FBET) to establish foaminess and foam stability in the presence of oil, and their study showed that AOS C_{14-16} had the best performance of all formulations and was sufficient for field application. In contrast, other studies (Dalland et al., 1994) indicated that AOS surfactant exhibited poor blocking performance and failed to generate foam in the presence of oil.

However, most previous studies focused on the microscopic mechanisms of foam–oil interactions, as well as the foamability and stability of surfactants in static foam tests rather than in the porous media (Farajzadeh et al., 2012; Simjoo et al., 2013). Most of the research dealt with a single surfactant as a foaming agent, but neglected the effect of mixed surfactant systems. This article focuses on the study of oil-tolerant foam agent systems that have better gas blocking performance in high oil-bearing environments. First, several surfactants were selected and their IFT and SFT were measured. Second, systematic experiments were performed to evaluate the foaming performance of an oil-tolerant foam (OTF) agent in formation water and crude oil. Then the blocking ability of oil-tolerant foam in the porous media at different oil saturations was tested in the core flooding system. Finally, to evaluate the oil-tolerant foam system, the EOR effect of all the foam flooding was investigated.

2. Materials and methods

2.1. Materials

Five types of surfactants were selected and synthesized as foaming agents in this experiment, alkanolamide surfactants