Introduction

Gas flooding can be used as a method to enhance the ultimate recovery. Its utilization, however, is hampered by gas fingering and gravity segregation. This instability in the displacement process can be reduced by foaming the gas. Foam is a mixture of gas and water, whereas some portion of the gas is made discontinuous by thin liquid films called lamellae (Falls et al. 1988). Various factors can affect lamellae stability. For instance, the surfactant can stabilize the lamellae by adsorption on its surface, while oil droplets enter the lamellae and destabilize it. Generally, there are two main injection scenarios for foam generation within the porous media: (1) co-injection of gas and surfactant solution and (2) surfactant altering gas (SAG) (Ma et al. 2014). Based on previously carried out studies (Moradi-Araghi et al. 1997; Farajzadeh et al. 2015), foam is stronger in media with higher permeability and as a result, blocks them more efficiently and diverts fluid flow from high permeable zones to low permeable zones (Robin 1987; Llave et al. 1990). The pressure gradient created by foam between two communicating layers causes a crossflow called viscous crossflow. This phenomenon, which is mainly due to the inequality of fluid mobility, causes the foam to invade the low permeable layer and recovers residual oil (Zapata and Lake 1981; Bertin et al. 1998). The simulation of foam displacement can be done by either empirical modeling or mechanistic modeling. As opposed to Mechanistic models, where gas mobility is altered based on lamellae concentration, empirical models modify gas viscosity/relative permeability based on experimental studies and do not obtain foam texture (Hematpur et al. 2018). In this research, the performance of viscous crossflow was studied by simulation of foam injection in fractured media.

Method

We used the STARS model for foam flow in our simulations (Abbaszadeh et al. 2014). The single porosity model utilized in this study is a 2-D model and consists of 550 grids (25*22*1). The matrix contains 484 grids and three one-millimetre fracture is located at the left of the matrix. The length of the matrix is 220 cm and has 110 cm in width, and fracture has an overall 0.3 cm thickness (3*0.1). The matrix and fracture media were saturated with oil and gas, respectively. Foam was generated within the fracture in the quality of 65% by co-injection of N2 and surfactant solution with a flow rate of 3.6 cc/min at reservoir condition. Figure 1 illustrates the model.

Figure 1 Frame of the utilized model

In this study, three various conditions were considered for foam flow modeling. In the first scenario, foam was created in both media with identical properties. As mentioned previously oil phase can destabilize foam so, in the second condition, it was assumed that foam is highly unstable to oil and completely or partially coalesces in the matrix. In the last case, the properties of foam were different in the matrix and fracture media. Figure 2 shows foam conditions in fracture and matrix media for all cases.

Case A

In this case, a strong foam was formed in the matrix and fracture media with the same properties and it coalesced at oil saturation above 70%. Foam efficiently blocked the fracture and a pressure gradient...
was observed within the fracture. This pressure drop was transferred to the matrix and diverted gas and surfactant solution to the matrix. As foam was formed in the fracture, the fluids entered the matrix media and an arc-shaped front can be seen as a result of viscous crossflow. In the front, when oil saturation is above the critical value of 70%, no foam existed and the only available phase was water, and behind the frontline, gas (in the form of foam) is the dominated phase. This result is in good agreement with previously conducted experiments by Khoshkalam et al. (2019). Figure 3 compares the simulation and experimental results.

![Figure 3: Foam front propagation within the matrix media. Left) Simulation result for oil phase saturation within the matrix media after 10 years, the contour line indicates oil saturation above 80% and flow vectors show the flux of water phase. Right) Foam front displacement within a microdevice (Khoshkalam et al. 2019).](image)

**Case B**

To investigate the effect of the oil phase on foam behaviour it was assumed that the oil phase destroys foam totally or partially in the matrix media. Therefore, two conditions were examined: 1) foam coalesces entirely in the matrix and flow as the gas phase, 2) foam coalesces in the matrix at oil saturation above 30%. Similar to Case A, the formation of foam in the fracture caused an extra pressure drop and an arc-like front was formed in the matrix media. In this case, however, only a small amount of Nitrogen penetrated into the matrix. As foam became less oil-resistant, more water and less gas entered the matrix. Thus, it can be concluded that the creation of a strong foam in the matrix hampers the surfactant solution flow from the fracture (Farajzadeh et al. 2012). Figure 4 compares the foam front at distinct oil-resistance. As can be seen from the figure, gas displacement was non-piston-like when foam was less oil-tolerant. Figure 5 displays the gas volume in the matrix at three different states. It is clear that more gas was diverted from the fracture by rising the foamability in the matrix.

![Figure 2: Foam strength at distinct conditions](image)
Figure 4 Gas propagation within the matrix after 15 years. The contour line indicates gas saturation above 20%. Left) No foam existed in the matrix. Middle) Foam coalesces at oil saturation above 30%. Right) Foam coalesces at oil saturation above 70%.

Figure 5 Gas volume in the matrix at various conditions.

Case C

In this analysis, the mobility reduction of foam was enhanced in the fracture, while it remained constant for the matrix. As foam became stronger, more fluids (gas and water) were directed to the matrix media. Contrary to case B, when increasing foam strength in the matrix had positive effects on the gas phase, in this case, however, rising the foamability had positive influences on both fluids. Moreover, the existence of a strong foam in the fracture increased foam front propagation inside the matrix. Figure 6 illustrates foam displacement at two different foam strength.

Figure 6 Foam front propagation within the matrix media after 10 years. Left) Foam with high mobility reduction in fracture. Right) Foam with low mobility reduction in fracture. The contour line indicates oil saturation above 80%.
Conclusions

Foam can be used as a solution for poor volumetric sweep efficiency of gas injection. The behaviour of viscous crossflow was investigated in this analysis. Based on conducted simulations, foam could block media with high permeability and forced fluids to the low-permeability zone. An arc-shaped displacement front was formed as a result of pressure drop within the fracture media. It was shown that the stability of foam against the oil phase has a considerable influence on the sweep efficiency of foam injection. We also demonstrated that foam strength within the fracture and matrix media can affect viscous crossflow differently. A strong foam in the matrix hindered surfactant solution flow from the fracture, whereas a strong foam in the fracture had positive effects on the flow of both phases from the fracture.

References


