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Foam Application in Fractured Carbonate Reservoirs: A Simulation Study

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Abstract

Fractured carbonate reservoirs account for 25% of world's total oil resources and for 90% of Iranian oil reserves. Since calcite and dolomite minerals are oil wet, gas oil gravity drainage (GOGD) is known as the most influencing production mechanism. The most important issue within gas injection into fractured media is the channeling problem which makes the efficiency of gas injection process extremely low. As a solution, foam is used to change the mobility ratio, to increase volumetric sweep efficiency, and to overcome the fingering problem. In this work, we inspected three main influencing mechanisms that affect oil extraction from matrix, namely foam/oil gravity drainage, viscous pressure drop due to foam flow in fractures, and foaming agent diffusion from fractures into the matrixes. Foam injection simulations were performed using CMG STARS 2015, on a single matrix unit model and on some vertical cross section models. A number of sensitivity analyses were performed on foam strength, injection rate, fracture and matrix properties, matrix heights, and the initial oil saturation within matrixes. The results show that the roles of the mass transfer of the foaming agent and viscous pressure drop are significant, especially when matrix average heights are small. Moreover, the mechanism for viscous pressure drop remains unchanged, which continues to aid oil extraction from matrixes while the other two mechanisms weaken with time.

Keywords: Foam, Fractured Reservoir, Gravity Drainage, Gas Invaded Zone, CMG STARS

1. Introduction

Carbonate fractured reservoirs account for about 25% of world's oil resources and 90% of Iranian oil reserves. Two separate mediums are distinguished in fractured reservoirs: matrix units in which most of the oil is stored, and the fracture network where most of the transmissibility appears. Due to the oil-wet characteristic of carbonate reservoirs, it is often more efficient to inject natural or inert gas instead of water during the secondary recovery. The most important issue of the gas injection process into fractured reservoirs is that the high transmissible fluid prefers to pass through fracture network instead of matrix units, leaving most of original oil in place (OOIP) unswept. In addition, the injection of low viscous fluid makes it impossible to have a large invaded zone, mainly due to fingering or channeling.

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To overcome this problem, pre-generated foam is injected into the reservoir instead of natural or inert gas to reduce the mobility of displacing phase, thereby making the injection process more efficient. Three main mechanisms, namely foam/oil gravity drainage, viscous pressure drop in fracture network, and foaming agent diffusion into the matrix units, are known for oil extraction from matrix units into the fracture network during foam injection.

Unfortunately, the literature on foam application in fractured media is less frequent compared with foam application in conventional porous media and has never covered these three main mechanisms simultaneously. Kovscek et al. (1995) performed the earliest experimental study on foam application in fractures. They reported that little information was available about foam flow in fracture mechanisms until 1995. Nitrogen foam was injected into rough wall rock fracture with an aperture of 30 μm. Effective gas mobility control was reported via increscent flow resistance which was 100 to 540 times greater than those of nitrogen. Their study concerned only the viscous pressure drop mechanism. Hirasaki et al. (2006) developed a theoretical method to explain foam flow in uniform fractures. Apparent foam viscosity was presented by considering liquid lamella viscosity and the resistance of individual bubbles to pass through the throats. It was concluded that foam can divert the flow from thicker to thinner fractures, even into matrix units, and increase sweep efficiency. Their model is known as one of the valid methods for explaining foam flow in fracture networks, which considers the drop in viscous pressure to be the most important mechanism. Fjelde et al. (2008) performed an experimental study on CO_2 foam injection into fractured carbonate core samples. The main focus of their work was on the diffusion of foaming agent into the matrix blocks and its effect on the recovery curves. They reported that the oil recovery resulted from the process was slightly higher compared with pure CO_2/oil gravity drainage process. Zuta et al. (2009) performed some experimental studies of CO_2 foam injection into several fractured chalk cores, and used different concentrations of surfactant under static and flowing conditions to study the penetration rate of foaming agent into the core samples. Their work showed that diffusion process plays an important role in controlling the transfer of foam into the matrixes. Zuta et al. (2010) simulated the transfer of foaming agent solution from the fractures into the plugs with CMG commercial software STARS. A good match was observed between their previous experimental results and the simulation results. Further simulations showed that the foaming agent penetration depends on several factors such as matrix sizes, rock types, and the presence of oil. Abbaszadeh et al. (2010) also simulated the one-dimensional vertical stack of matrixes within a gas cap facing foam flow. Their work concerned the foam/oil gravity drainage mechanism in addition to viscous pressure drop mechanism. They extended their simulations to two-dimensional cylindrical as well as three-dimensional Cartesian models. A number of sensitivity analyses were conducted to investigate the effects of foam quality, foam strength, and well geometry configurations. Kiani et al. (2011) applied CMG software to simulating foam injection process on a pilot scale using 2D vertical cross section geometries. Different formulations having various approaches as well as several grid refinement methods were used in their calculations. It was concluded that using Dual Perm approach rather than Dual Poro can nicely describe viscous displacement through the porous media. Buchgraber et al. (2012) employed micromodels with smooth and rough walls to study the effects of different foam qualities and velocities on displacement efficiency. Pressure drop curves were drawn against foam quality and represented a maximum at a quality of 90%. The mobility reduction factor was reported from 10 to 600 for foam qualities from low to high. The effect of fracture roughness and aperture was also studied in their work. Pancharoen et al. (2012) modified the population balance approach to describe foam transport in fractures and numerically studied the foam flow resistance as a function of gas and liquid velocities. Their simulations covered one-dimensional and two-dimensional heterogeneous as well as radial homogeneous models. Their work mainly focused on the effects of viscous pressure drop. Haugen et al. (2012) accomplished foam flow experiment in several limestone and sandpack core samples and examined different surfactant concentrations, or rather various foam viscosities to obtain oil recoveries. Differential pressure curves along the fractures were drawn, which showed the effect of viscous pressure drop mechanism. Farajzadeh et al. (2012) magnified the effect of foam/oil gravity drainage and viscous pressure drop mechanisms by considering tall matrix unit and large injection foam flow rates. Sensitivity analyses on fracture and matrix properties, foam flow characteristics, and critical oil saturations were performed using MoReS software with insisting on the magnification of the effects of viscous pressure drop. Haugen et al. (2014) performed several experiments on immiscible N_2 and CO_2 foam injections into small core samples and found out that diffusion process was the dominant driving force perhaps due to the small scales of experimental core plugs; foam flow viscous force was reported to be the second important mechanism. The results showed high oil recovery after the injection of tens of pore volumes. Ferno et al. (2015) studied the effect of diffusion mechanism through performing CO_2 foam injection experiments on a limestone core plug. Furthermore, viscous pressure drop was added to diffusion mechanism in moving foam experiments, and the selected core sample was small enough to neglect the effects of foam/oil gravity drainage. Simulations by CMG GEM software were also performed to endorse the experimental results and reported significant recovery factors under foam flow conditions, as also demonstrated by the experiments. Chabert et al. (2016) studied foam formation advantages on a pilot scale in a layered reservoir which was previously under CO_2.injection. After several lab scale core flood experiments performed at a high pressure, surfactant was coinjected with CO_2 in a few pore volumes to increase oil sweep efficiency. Injection logs showed an efficient diversion from thief zones to previously poorly reservoir intervals. Hosseini-Nasab et al. (2017) coinjected AOS surfactant and N_2 gas into a core sample to increase extraction efficiency via sweeping oil remained after water flooding and extracted saturation profiles from X-ray images taken using some kinds of CT Scan setup in transient and steady flow conditions. It was experimentally proved that using foam after water flooding can increase oil recovery to more than about 30% OOIP. Since no study in literature simultaneously considers all the three influencing mechanisms that affect oil extraction from matrix, namely foam/oil gravity drainage, viscous pressure drop due to foam flow in fractures, and surfactant mass transfer into matrix, this paper tries to perform such calculations using a commercial reservoir simulator. Herein, we used CMG 2015 STARS module to simulate the foam injection process into a singular matrix unit and into some vertical cross sections within an assumed fractured reservoir. In order to perform calculations in CMG software, the Dual Perm approach was applied rather than the dual porosity method since it is known that it nicely describes viscous displacement through fractured porous media. The novelty of this study, compared with previous works, is that we simultaneously considered all the three main influencing mechanisms affecting the oil extraction from matrix units, namely foam/oil gravity drainage, viscous pressure drop due to foam flow in fractures, and the foaming agent diffusion into the matrixes. Furthermore, several sensitivity analyses over the foam flow characteristics, including foam viscosity and injection flow rate, matrix and fracture properties, and initial oil saturations are performed to investigate their effects on each individual oil extraction mechanism.

2. Simulation procedure

Literature review magnifies three main mechanisms for oil extraction from a matrix into a fracture network in a pay zone area which is invaded with foam. Classic foam/oil gravity drainage plays an important role in oil extraction from matrix units, especially wherever matrix heights are large. Since foam with a quality of 80 to 90% contains only 10 to 20% liquid phase, its density nearly equals the gas density, which leaves gravity drainage driving force almost unchanged. Foam flow along a fracture network is known to provide a significant drop in pressure along the flow direction. High foam injection rates will cause a significant drop in pressure, which aids classic gas/oil gravity drainage process to extract more oil from matrixes. In addition, a number of previous works reported that foaming agent diffusion from the fracture network to the matrix units largely impacts on oil extraction. A surfactant solution which stabilizes lamellas among gas globules contains a water phase plus a surfactant component as a solvent. The solution shows a high concentration of the surfactant, while the water phase within matrixes initially has a zero concentration of the surfactant, which causes the foaming agent to diffuse from the fracture network into the matrix units, thereby assisting with oil extraction process.

In order to validate our calculations, the results of the single matrix unit gas oil gravity drainage (GOGD) and the foam oil gravity drainage (FOGD) simulation results by CMG software were both compared with an analytical solution and with the simulation results of MoReS software. To this end, we firstly calculated the oil extraction rate from a matrix unit initially saturated with oil which is surrounded with gas flowing in fractures using an analytical solution. Hagoort (1980) derived formulas to calculate oil extraction rate from matrix units located in a gas invaded zone when only pure GOGD mechanism exists. In this way, Darcy's equation was used to explicate oil flow through matrix units neighboring fractures which contains injected gas on the one side.

$$Q_{Oil} = -\frac{k_{ABS} k_{Relative\ Oil}}{\mu_{Oil}} A \frac{d\emptyset_{Oil}}{dz} \tag{1}$$

Oil flow potential within matrix units was defined with respect to pressure at the lowest level and pressure differential against depth.

$$\emptyset_{Oil} = P_{Bottom} + \frac{P_{Top} - P_{Bottom}}{H} z + \rho_{Oil} g z \tag{2}$$

Since one goes upward along the matrix height, pressure within the matrix unit drops more greatly compared to the fracture, which provides a gradient from the fracture into the matrix. Conversely, when going downward, pressure in matrix increases further compared to the fracture, making an inverse gradient from the matrix to the fracture.

$$\emptyset_{Oil} = P_{Bottom} + (\rho_{Oil} - \rho_{Gas}) g z \tag{3}$$

Such a gradient causes gas to penetrate into the matrix unit from top while oil is extracted from the lowest part. This driving force is almost constant at the beginning but decreases slowly as gas penetrates through the matrix unit.

$$Q_{Oil} = -\frac{k_{ABS} k_{Relative\ Oil}}{\mu_{Oil}} A \Delta\rho_{Oil-Gas} g \tag{4}$$

Since the penetrated gas shows higher transmissibility than oil, when flowing through matrix, it channels toward the downstream outgoing oil phase. We expect the oil extraction rate curve to show a sharp decrease just after the penetrated gas starts to leave the matrix unit.

Afterwards, the same problem was simulated by CMG software, and the results were compared with MoReS simulator previously performed in the literature. The important porous media specifications, including matrix properties, fracture characteristics, multiphase relative permeability data, defined in CMG software are presented in Table 1. Corey type Rel Perm curves were utilized which specify the oil-wet characteristic of the supposed carbonate rock through two independent variables.

Table 1

Matrix and fracture characteristics defined in CMG and MoReS commercial software packages.

Matrix and fracture properties	**Matrix height**	**Matrix width**	**Matrix permeability**	**Matrix porosity**	**Fracture width**	**Fracture permeability**	**Diffusion coefficient**	
	200 ft	30 ft	5 mD	32%	10^{-3} m	10^{3} D	10^{-8} to 10^{-11}	
Relative permeability data	Corey type curve power				Corey type endpoint			
	Oil gas	Gas	Oil water	Water	Oil gas	Gas	Oil	Water
	4.5	2.1	3.2	3.2	1.0	1.0	0.75	1.0

Semi-experimental foam models use two various approaches to simulate foam flow through porous media. In the first method, all media changes as well as variations in the gaseous phase viscosity are assumed to only impact on the fluid viscosity as Hirasaki's formula (1985) presents. Conversely, in the second method, all the above-mentioned changes were supposed to affect the Rel Perm curves of the gaseous phase. CMG STARS uses the second approach which employs several independent variables to describe foam flow properties, including texture/strength at various surfactant concentrations, its decay regarding different oil saturations, non-Newtonian characteristic, etc., through some power law functions presented below.

$$k_{Relative\ Gas}^{Foam} = k_{Relative\ Gas}^{Gas} \times FM \tag{5}$$

$$FM = \frac{1}{1 + MRF_{max} \times F_{Surfactant} \times F_{Oleic} \times F_{Aqueous}} \tag{6}$$

$$F_{Surfactant} = \frac{C_{surf}}{fm_{surf}}^{ep_{surf}} \tag{7}$$

$$F_{Oleic} = \frac{fm_{oil} - S_{oil}}{fm_{oil} - fl_{oil}}^{ep_{oil}} \tag{8}$$

$$F_{Aqueous} = 0.5 + \frac{tan^{-1}(ep_{dry} \times (S_{water} - fm_{dry}))}{\pi} \tag{9}$$

Since calculations within Farajzadeh's work exclude the diffusion of the foaming agent into the matrix, in order to repeat their reported MoReS simulation results, we temporarily turned the mass transfer option off. When foam flows through the fracture network, viscous pressure drop is significant compared to gas flow, which provides an additional pressure gradient, thereby helping to extract oil from the matrix. Wherever the foam penetrates into the matrix in which oil saturation is high, it decays through separating into a surfactant solution and a gaseous phase. The STARS parameters adjusted in the simulations are listed in Table 2.

Table 2

STARS foam model parameters used to simulate FOGD in a single matrix block.

STARS parameters	MRF_{max}	**Surfactant**		**Oleic phase**			**Aqueous phase**	
		fm_{surf}	ep_{surf}	fl_{oil}	fm_{oil}	ep_{oil}	fm_{dry}	ep_{dry}
	500	0.0003	1.00	0.00	0.20	1.00	0.1	1.0

Next, we validated our results with Hagoort's work and verified foam injection into fractured media using CMG simulations with Farajzadeh's work; we also extended our simulations to more realistic two-dimensional geometries. To this end, we turned mass transfer option on again since literature mentioned its significant impact on oil extraction from matrixes. A single matrix unit is now considered to neighbor fracture network from all its sides. Furthermore, we extended CMG simulations to vertical cross section heterogeneous geometries to investigate foam injection performance in various fractured media.

All the three important mechanisms of oil extraction from matrixes reported in the literature were taken into consideration in our CMG simulations. Each mechanism plays an independent positive role in oil extraction from matrix while its inclusion depends on porous media characteristics as well as operating conditions. Individual studies on each mechanism inform us about to what extent geometric or operating conditions can affect each other and consequently the oil extraction process. Oil production rate relevant to foam/oil gravity drainage mechanism within a single matrix unit partially filled with oil is calculated by:

$$Q_o|_{Gravity\ Drainage} = \int_{H_{p_c}}^{H-z} \frac{k_{or}k_m}{\mu_o} \frac{\Delta\rho g(H-z)}{H} dz \tag{10}$$

Subsequently, oil extraction rate due to the additional drop in pressure caused by the viscous foam flow along the matrix unit perimeter is determined by:

$$Q_o|_{Frictional\ Flow} = \int_0^{Perimeter} \frac{k_{or}k_f}{\mu_o} \frac{\Delta P_{Viscous\ Flow}}{L} dL \tag{11}$$

The diffusion of the foaming agent from the fracture network at a higher concentration into the matrix unit at a relatively lower concentration causes the foaming agent to penetrate into the matrix, thereby leading oil to extract according to:

$$Q_o|_{Surfactant\ Diffusion} = \int_0^{Perimeter} D\emptyset \frac{\Delta C_{Surf}}{H/2} dL \tag{12}$$

Sum of these three oil production rates will be assumed as the total oil extraction rate from the matrix unit into the fracture:

$$Q_{o_{total}} = Q_o|_{Gravity\ Drainage} + Q_o|_{Frictional\ Flow} + Q_o|_{Surfactant\ Diffusion} \tag{13}$$

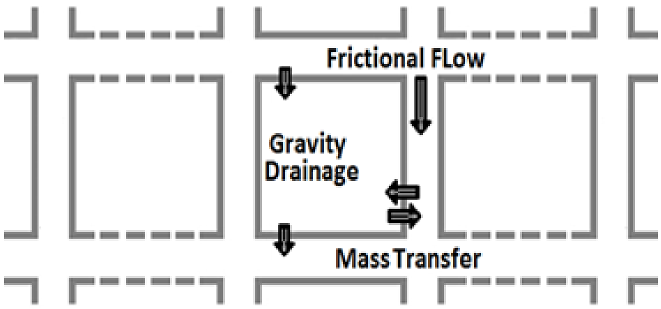

Figure 1

Main mechanisms that affect oil extraction from the matrix unit into the fracture network.

It is noticeable that the oil extraction due to frictional flow is not time-dependent, while the two other mechanisms, namely oil extraction via FOGD (foam oil gravity drainage) and oil extraction due to surfactant diffusion into the matrix, weaken with time.

In order to investigate the influences of frictional flow on oil extraction from the matrix unit, sensitivity analyses over foam texture and surfactant concentration/strength were performed. In this way, various foaming agent concentrations were supposed to form foams with different viscosities. Such foam phases were then simulated to flow through a fracture network at several assumed flow rates while frictional pressure drop was calculated. It is expected that since the foam phase strength, and therefore viscosity, enhances, frictional viscous pressure decreases, which adds an extra driving force to extract oil from the matrixes. In addition, it is expected that an increase in injection rate reduces viscous pressure along fractures, which in turn improves oil extraction from the matrix units. Thus, we performed sensitivity analyses to check out the influences of injection rate on the matrix-fracture interaction. Using foams with various strengths, and therefore various surfactant concentrations, also changes diffusion and mass transfer into the matrix unit. Since concentration differential increases, more surfactant molecules diffuse through the matrix; thus, larger rates of oil extraction due to mass transfer are expected.

Afterwards, we studied the influences of the porous media properties on oil extraction rate by changing matrix properties and fracture network transmissibility. Both matrix porosity and its permeability were simultaneously changed to cover some practical situation of real fractured reservoir's rock types. Fracture aperture, and thus its permeability, was also varied in a wide range to cover several situations from open to filled fracture. Since fracture resistance to foam flow increases, one can expect a larger drop in pressure among upstream and downstream in the fracture network.

Table 3

Various fractured media properties and injection process conditions used in the simulations.

Matrix block properties	**Vertically elongated**	**Vertical rectangle**	**Cubic shape**	**Horizontal rectangle**	**Horizontally elongated**	
Block height	50 ft	20 ft	10 ft	5 ft	2 ft	
Block width	2 ft	5 ft	10 ft	20 ft	50 ft	
Injection process specifics	**Low** r**ate** Low viscosity	High rate Low viscosity	Low rate Mid viscosity	High rate Mid viscosity	Low rate High viscosity	High rate High viscosity
Foam viscosity	10 cP	10 cP	20 cP	20 cP	30 cP	30 cP
Flow rate	150 $\mathbf{ft^3/D}$	200 $\mathbf{ft^3/D}$	150 $\mathbf{ft^3/D}$	200 $\mathbf{ft^3/D}$	150 $\mathbf{ft^3/D}$	200 $\mathbf{ft^3/D}$
Porous media properties	High $\boldsymbol{k_m}$ High $\boldsymbol{k_f}$	Mediate $\mathbf{k_m}$ High $\boldsymbol{k_f}$	Low $\boldsymbol{k_m}$ High $\boldsymbol{k_f}$	High $\boldsymbol{k_m}$ Low $\boldsymbol{k_f}$	Mediate $\boldsymbol{k_m}$ Low $\boldsymbol{k_f}$	Low $\boldsymbol{k_m}$ Low $\boldsymbol{k_f}$
Matrix permeability	45 mD	15 mD	5 mD	45 mD	15 mD	5 mD
Fracture permeability	$\mathbf{10^3}$ D	$\mathbf{10^3}$ D	$\mathbf{10^3}$ D	$\mathbf{10}$ D	$\mathbf{10}$ D	$\mathbf{10}$ D

As a result, oil extraction rate due to frictional foam flow seems to play a more important role in total oil production rate. Matrix sizes were also changed to investigate the impact of foam/oil gravity drainage on oil extraction from the matrix compared to the other mechanisms, namely pressure drop due to frictional flow and the foaming agent mass transfer mechanisms. Block heights were changed, while their volumes were kept constant, to cover several templates from a vertically elongated shape to a cubic shape and to a horizontally elongated shape. When the matrix unit shape changes from a vertically elongated shape to a cubic shape and then to a horizontally elongated shape, foam/oil gravity drainage mechanism weakens. Conversely, regarding the matrix unit perimeter, it seems that the influence of frictional pressure drop decreases when the matrix unit shape changes from vertically elongated to cubic, but it again increases when its shape changes from cubic to horizontally elongated. The different conditions of media properties and injection specifics used in the sensitivity analyses are tabulated in Table 3.

Table 4

Foam strength and injection rates used in invaded zone height sensitivity analysis.

Foam phase viscosity				
10 cP	20 cP	30 cP	40 cP	50 cP
Injection rate				
200 ft^3/D	300 ft^3/D	400 ft^3/D	500 ft^3/D	

In the case of foam injection into fractured reservoirs, in comparison to natural gas injection, the height of the invaded zone is significantly larger. Since foam phase viscosity is several times larger than the gas viscosity, the linear foam velocity within fractures are significantly smaller. If one considers the same injected volumetric flow rate through porous media, assuming fixed field area, foam will occupy a larger space, which means an invaded zone significantly thicker in the vertical direction. In order to investigate this effect, we simulated vertical cross section within some supposed fractured reservoirs which was assumed to produce oil under gas injection processes. Then, we replaced the injection gas with a foam phase with different viscosities injected at various injection rates. The details of the simulation conditions are listed in Table.4. Also, a schematic representation of such an effect is illustrated in Figure 2.

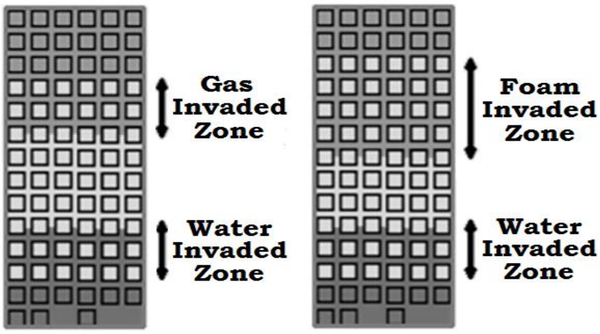

Figure 2

A schematic view of expanded foam invaded zone compared with original gas invaded zone.

Furthermore, we defined a 2D vertical cross section model within an assumed heterogeneous media with three various layers which differ in matrix properties. The matrix units within each layer are similar and exhibit the same characteristics. It was assumed that the second layer has larger matrix units, while the third one is composed of compacted grains with lower matrix transmissibility. Heterogeneous media properties, including matrix heights, porosities, permeabilities, fracture specifics, and foam phase characteristics are presented in Table 5.

Table 5

Media properties and foam phase characteristics of the heterogeneous vertical cross section model.

Pay zone characteristic	Matrix porosity	Matrix permeability	Fracture permeability	Block size	Pay zone height	Foam phase characteristics	
Top layer	0.08	10 mD	$\mathbf{10^3}$ D	10 ft	30 ft	Apparent viscosity	10 cP
Middle layer	0.08	10 mD	$\mathbf{10^3}$ D	15 ft	45 ft	Concentration	3 wt.%
Bottom layer	0.05	8 mD	$\mathbf{10^3}$ D	10 ft	30 ft	Water salinity	2% NaCl

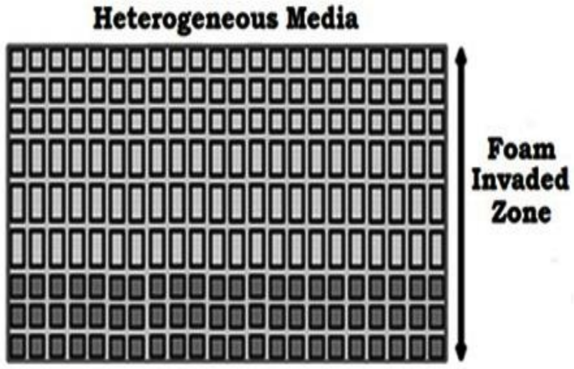

Figure 3

Cross sectional schematic representation of heterogeneous foam invaded zone.

One can compare various layers in this manner to find out which mechanism is dominant under each circumstance. A schematic view of the defined vertical cross section used in these simulations are presented in Figure 3.

Both in the single matrix unit simulations and in the stack of matrixes, we performed some sensitivity analyses on average oil saturation impact. STARS foam approach considers two limits to oil saturation, namely upper and lower limits. At oil saturations smaller than the lower limit, the existence of oil does not affect foam stability. At oil saturations higher than the upper limit, foam will completely decay into a separated gas phase and surfactant solution; at oil saturations between these two values, the decay obeys a power law function. We assumed three different initial oil saturations for the matrixes within our simulations, namely $S_o = 0.15$, $S_o = 0.30$, and $S_o = 0.45$ to investigate the influences of oleic phase on foam flow performance, and consequently on oil extraction efficiency in invaded zones.

3. Results and discussion

In order to validate our calculations, the results of single matrix unit GOGD simulation by CMG software were compared with an analytical solution and with the results of MoReS software. Considering the analytical formulas presented above, it is expected that oil extraction rate from the single matrix unit initially exhibits a relatively constant value. Since gas transmissibility is high than oil transmissibility, it channels through the matrix unit and surpasses oil phase, which leads to a less effective oil extraction process. As soon as the penetrated gas is produced in the downstream matrix unit, oil extraction rate falls significantly, which weakens GOGD mechanism. The same calculations were performed in CMG software, and the resultant graphs were compared with the analytical solution and with the results of MoReS software which were previously reported by Farajzadeh et al. (2012).

The resultant graphs of oil extraction rate and thus the recovery curves obtained by the CMG simulations show good agreement with the analytical solution and with the results reported by MoReS (see Figure 4). Small differences with relative errors up to 3-5% appeared among the graphs resulted from different approaches, which are seemingly caused due to various solution algorithms.

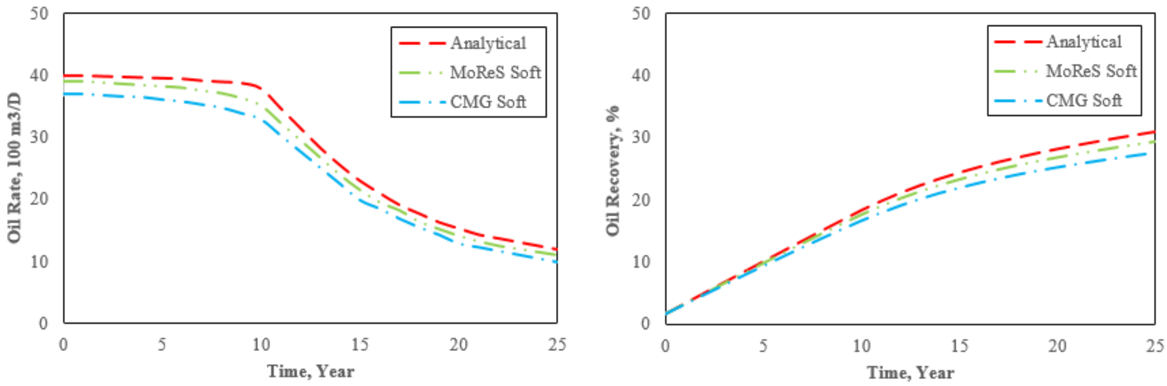

Figure 4

Comparison of CMG, MoReS, and analytical solution with pure GOGD in the single matrix unit.

In addition to previous verification which was performed on pure gas injection process within the single matrix unit surrounded with the fracture network filled with gas, we repeated all the foam injection simulations by CMG software reported in the work of Farajzadeh et al (2012). Since they supposed that only two oil extraction mechanisms, namely foam/oil gravity drainage and viscous pressure drop due to foam flow in fractures, take part in the matrix-fracture interaction, we temporarily turned off mass transfer option within our CMG simulations to match their reported conditions.

In this context, we simulated cases in which weak or strong foam were injected at various injection rates into the fracture network with various characteristics. We also simulated foam injection into the fractured media containing various oil saturations, in which foam injection was started at various times within the production life. In all the above cases, the CMG simulation results of oil extraction rates, recoveries, and calculated pressure drops well agreed with MoReS simulator. As an instance, the oil recovery curves of the cases in which the foam injection was postponed to different times are presented in Figure 5.

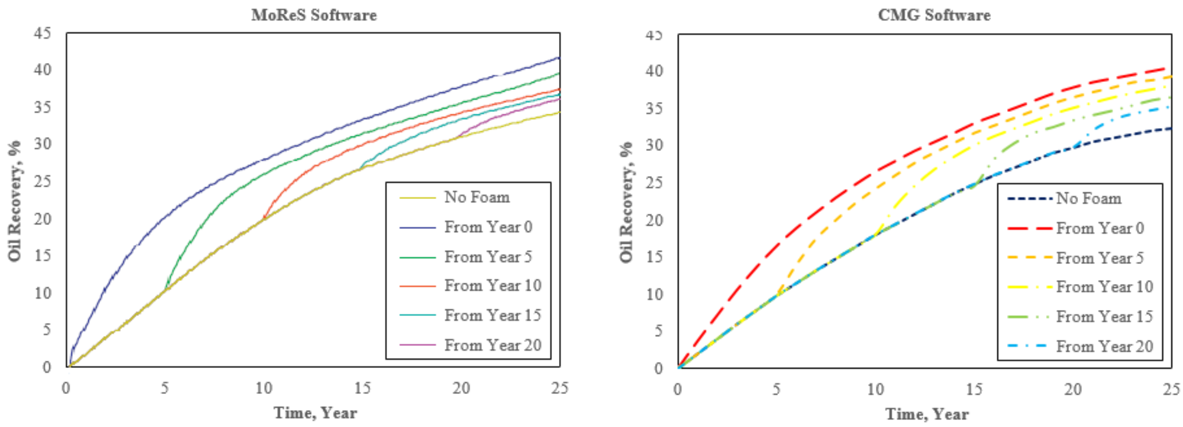

Figure 5

Comparison of CMG oil recovery with that of MoReS in the single matrix unit.

We then turned on mass transfer option within our CMG simulations to take all the three main mechanisms mentioned in the literature into account. Our CMG simulations are divided into two steps: foam injection simulations on the singular matrix unit and foam injection in a vertical cross section within an assumed fractured reservoir. In order to investigate the effect of the foam flow on oil extraction from the single matrix unit, we performed sensitivity analyses on foam flow characteristic, namely its viscosity and injection volumetric flow rate.

STARS approach like other empirical foam simulators considers a local equilibrium condition in which the rate of the foam creation and destruction is assumed equal. Water salinity and oil saturation will affect the quality of the foam via some power law functions. Furthermore, two saturation limits, namely the upper limit and the lower limit, are defined; oil saturations lower than the smaller limit will not affect foam quality, while oil saturations larger than the upper limit will completely destroy the foam into two phases, i.e. surfactant solution and injection gas. Connate water salinity has the same effect on the quality of foam, except that it has its own upper and lower limits.

Surfactant concentration within the lamella solution controls the foam viscosity. Higher concentrations will offer better control over desired mobility by increasing foam viscosity to a maximum value; further addition of surfactant will not change the foam viscosity anymore. The generated foam represents a pseudo plastic behavior, which means that higher velocities will lower the foam viscosity. Conversely, it shows high viscosity in large channels within porous media where one can expect lower shear stresses. This characteristic makes the foam useful for preventing thief zones from transmitting gas at undesirably high rates. However, in the application of foam to fracture networks, the sum of pseudo plastic effect and the higher flow rate lead to a net decrease in frictional pressure. Several foam flow rates and various viscosities were assumed in our simulations to investigate the effects of foam flow properties on oil extraction rate, and thus recovery curves, in the single matrix unit, as shown in Figure 4.

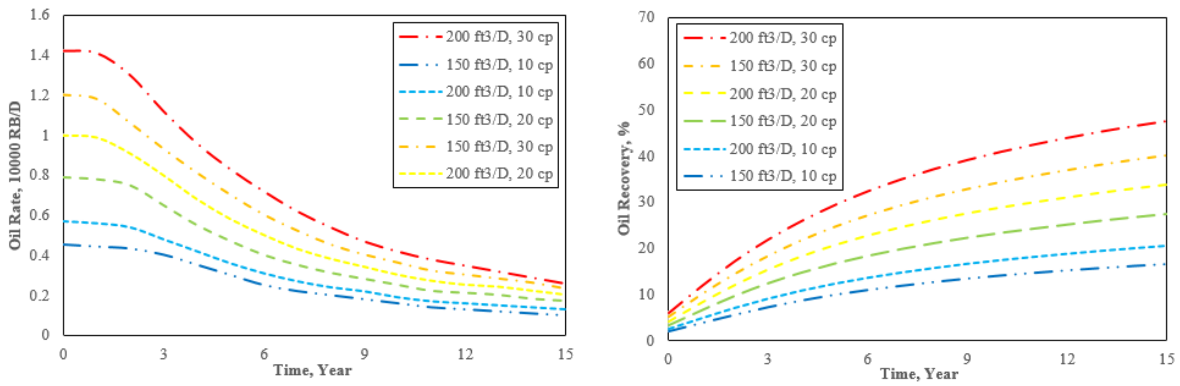

Figure 6

Oil extraction rate and recovery curves at different foam viscosities and flow rates.

Foam was injected into the fracture network around the singular matrix unit at two different rates of 150 ft^3/Day and 200 ft^3/Day. The injected foams have three various viscosities of 10, 20, and 30 cP. As foam viscosity increases at a constant flow rate, the frictional pressure drop within the fracture according to Darcy's law rises and applies a larger additional driving force to extracting oil from the matrix unit. Higher oil extraction rates will in turn accelerates recoveries. A two- or three-fold increase in foam viscosity accelerates recovery by approximately 200 and 300% respectively. An increase in foam injection rate shows a smaller impact on oil rate and recovery curve. When injection rate increases from 150 $\mathrm{ft^3/Day}$ to 200 $\mathrm{ft^3/Day}$, oil extraction rate and recovery improves by only about 20 to 30%. At higher foam viscosities, a significant decrease in oil extraction rate is seen at earlier times. At early times, foam penetrates into the matrix and only oil is extracted from the matrix unit. Later, the gas resulted from foam decay will co-exit from the matrix unit with oil, making a two-phase flow out of the matrix, which will reduce the net oil extraction rate from the matrix unit.

Moreover, the pseudo plastic behavior of the foam phase causes its viscosity to decrease at high injection rates. Nevertheless, frictional pressure decreases as flow rates increase, which will cause more oil to extract from the matrix, thereby improving recovery. Increasing foam injection velocity and foam viscosity raises the drop in pressure due to frictional flow within the fracture network. Additionally, in order to investigate the effect of the matrix height on oil extraction through various mechanisms, we simulated singular matrix units having various heights ranging from a vertically elongated shape to a cubic shape and to a horizontally elongated shape. The impact of each mechanism, i.e. gas/oil gravity drainage, frictional pressure drop in foam flow, and surfactant mass transfer into the matrix, on oil extraction from the matrix units with various shapes is calculated as tabulated in Table 6.

Table 6

Calculated oil extraction role percent by each mechanism in matrix units with various shapes.

Extraction portion of each mechanism	FOGD oil rate			Foam flow oil rate			Mass transfer oil rate		
	***Y*=0.0**	**5.0**	**10**	***Y*=0.0**	**5.0**	**10**	***Y*=0.0**	**5.0**	**10**
Vertically elongated *H*=50 and *W*=2	92%	85%	78%	5%	13%	21%	3%	2%	1%
Vertical rectangle *H*=20 and *W*=5	72%	63%	57%	15%	27%	36%	13%	10%	7%
Cubic shape *H*=10 and *W*=10	46%	39%	35%	32%	47%	56%	22%	14%	9%
Horizontal rectangle *H*=5 and *W*=20	32%	23%	15%	35%	51%	68%	33%	26%	17%
Horizontally elongated *H*=2 and *W*=50	12%	8%	5%	48%	58%	69%	40%	34%	26%

The larger the height of the matrix unit is, the more important the gravity drainage mechanism is. When the height of the matrix unit increases, the role of gravity drainage mechanism becomes more important, while the roles of the other two mechanisms, namely frictional pressure drop and surfactant mass transfer, remain unchanged. Five different matrix unit shapes were simulated at a fixed rate of foam flow, 150 $\mathrm{ft^3/Day}$, and at a foam viscosity of 10 cP. Heights of 50, 20, 10, 5, and 2 feet are adjusted while the volume of the matrix unit is kept constant. The role of gravity drainage mechanism is calculated as 92% of the total driving force in the vertically elongated shape, while it is calculated as 12% of the total driving force in the horizontally elongated shape. One must notice that when the shapes deviate from the cubic shape, the perimeter of single matrix units increases causing frictional pressure drop to further participate in the total driving force.

The most important conclusion drawn from the simulation results is that the role of frictional pressure drop in foam flow within fractures increases by 20% as time rises from the initial condition to 10 years. Second important conclusion is that the summation of the effects of two mechanisms which appeared only due to the presence of foam in the injection process increases during the process. Gas/oil gravity drainage loses its role more and more while foam (or gas plus surfactant solution) penetrates further into the matrix unit. Third important conclusion is that if the matrix height is larger than its width, 50%

to 95% of the extracted oil comes from the presence and penetration of foam into the matrix. While the matrix shape varies from the cubic to horizontally elongated shape, the mechanisms of foam flow and surfactant mass transfer will participate more than 65% in oil extraction, especially later in the process. Oil extraction rate due to mass transfer plays an important role in the foam injection process. It can be stated that the oil extraction rate due to diffusion competes with the oil extraction rate coming from frictional flow. Matrix and fracture properties like porosity and permeability also affect the oil extraction rates. Higher matrix porosity and relevant permeability increase the amount of the produced oil at constant driving forces.

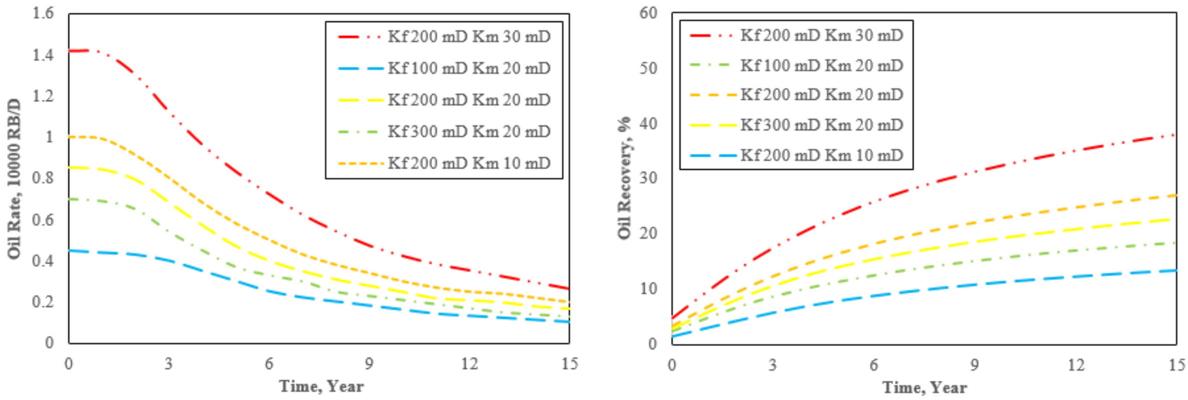

Figure 7

Oil extraction rate and recovery curves at various matrix and fracture permeabilities.

Conversely, fracture permeability influences the frictional pressure drop. The higher the fracture network permeability is, the smaller the frictional pressure drop in foam flow is. Darcy's law represents that a higher drop in pressure due to friction happens when the foam viscosity increases or fracture permeability decreases. To investigate such effects, we simulated foam injection into an invaded zone at various fracture and matrix permeabilities; the results are presented in Figure 7. A change in matrix permeability has a larger influence on oil extraction rates since it affects all the mechanisms. Conversely, a change in fracture permeability causes a smaller effect since it only includes the frictional pressure drop mechanism. An increase in matrix permeability leads to further oil extraction rates, while an increase in fracture permeability causes a decrease in oil extraction rates. As matrix permeability doubles or triples, recovery accelerates to approximately double and triple values respectively. It should be noted that in reality we cannot change reservoir porosity or transmissibility. The practical conclusion of this sensitivity analysis is that stronger foam must be injected into fractured reservoirs with a high fracture permeability. One can also conclude that foam application will increase recovery more efficiently when the porosity and permeability of matrix are higher.

Oil saturation within the matrix affects the foam stability in injection processes. In situations with high oil saturation in the matrix, more foam globules decay into separated gas phase and surfactant solution. STARS foam approach considers two limits to oil saturation, namely the upper and lower limits. At oil saturations smaller than the lower limit, the existence of oil does not affect foam stability. At oil saturations higher than the upper limit, foam will completely decay into a separated gas phase and surfactant solution, while at oil saturations between these two values, foam decay obeys a power law function. Changes in oil saturation within the simulated single matrix unit due to foam penetration after 10 years of simulation is shown in Figure 8. In this figure, all the initial oil saturations fall within the range of the upper and lower critical oil saturation limits, so foam decay obeys the power law function. The dark grids represent areas which contain original oil, while the light grids display areas invaded with foam or the released gas phase.

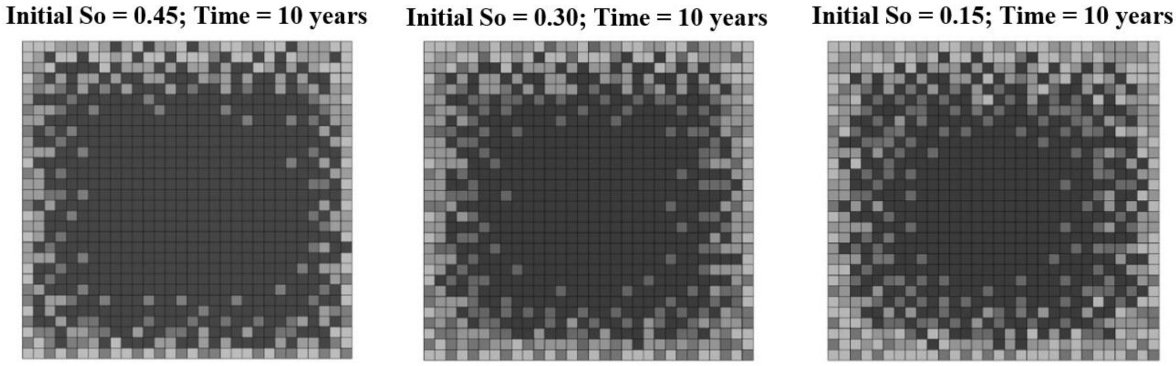

Figure 8

Foam penetration into a single matrix unit at various initial oil saturations.

All the three shapes are captured at the same time and in similar simulation conditions. In the case of high initial oil saturation, foam decay is also high, causing its quality to reduce significantly. The released gas phase then rapidly exits the matrix unit due to its high transmissibility. In this case, foam was not able to penetrate farther toward the center of the single matrix unit. Conversely, as the initial oil saturation within the matrix reduces, foam stability increases, and as a result, displacing phase mobility remains low. Foam is now able to penetrate more toward the center of the matrix unit, thereby extracting more oil.

Afterwards, we simulated an assumed vertical cross section within a fractured reservoir using CMG 2015. This vertical cross section is supposed through an assumed fractured reservoir in which water and foam injection happen. The rate of water injection is fixed, and the height of oil pay zone is great enough to study the effect of foam characteristics and its injection rates on the height of the foam invaded zone.

Table 7

Calculated the height of foam invaded zone at various foam strengths and injection rates.

The height of foam invaded zone	Viscosity 10 cP	Viscosity 20 cP	Viscosity 30 cP	Viscosity 40 cP	Viscosity 50 cP
Rate of 200 ft^3/Day	30.0 ft	35.2 ft	40.8 ft	47.0 ft	56.4 ft
Rate of 300 ft^3/Day	42.8 ft	48.6 ft	55.9 ft	62.3 ft	69.8 ft
Rate of 400 ft^3/Day	50.1 t	57.3 ft	65.0 ft	73.4 ft	80.5 ft
Rate of 500 ft^3/Day	55.3 ft	62.7 ft	70.1 ft	78.2 ft	85.6 ft

As shown in Table 7, when foam injection flow rate increases from 200 ft^3/D to 500 ft^3/D, the height of foam invaded zone rises to about 200% of the original value; this effect decreases as foam viscosity increases. An increment in foam viscosity from 10 cP to 50 cP doubles the height of the foam invaded zone. The simulations over vertical cross section show that the height of the foam invaded zone is strongly sensitive to the quality and flow rate of injected foam, which means an increase in foam viscosity and velocity in the fracture network not only reduces the frictional pressure as an important extraction mechanism, but also expands the foam invaded zone, creating more (at least twice in this case) matrix units to participate in this region. According to the presented results, one can infer that the role of expanding foam invaded zone in oil extraction from the matrix is as important as the effects of the two other mechanisms of frictional pressure drop and surfactant mass transfer into the matrix.

Table 8

The calculated oil extraction duty of each mechanism in various layers.

The portion of each extraction mechanism		**FOGD oil rate year**			**Foam flow oil rate year**			**Mass transfer oil rate year**		
	$\varphi = 0.08$	0.0	5.0	10.0	0.0	5.0	10.0	0.0	5.0	10.0
Top layer	$k = 10$ $h = 10$	46%	39%	35%	32%	47%	56%	22%	14%	9%
	$\varphi = 0.08$	0.0	5.0	10.0	0.0	5.0	10.0	0.0	5.0	10.0
Middle layer	$k = 10$ $h = 15$	67%	62%	53%	22%	31%	44%	11%	7%	3%
	$\varphi = 0.05$	0.0	5.0	10.0	0.0	5.0	10.0	0.0	5.0	10.0
Bottom layer	$k = 8$ $h = 10$	47%	38%	33%	25%	44%	52%	28%	18%	15%

Finally, we simulated vertical cross section within heterogeneous media consisting of three main layers. The top layer has the original matrix and fracture properties similar to that of the simulated single matrix unit. The middle layer has the same properties except that the height of the blocks is 50% larger. The bottom layer is assumed more compact due to overhead pressure and has less porosity and permeability. Oil production rates relevant to each mechanism are calculated at different times within the production life, as shown in Table 8. As the production life of the fractured reservoir extends, the importance of foam/oil gravity drainage decreases while the other mechanisms further participate in the oil extraction process. The comparison of the top layer with the middle one shows that the effect of gravity drainage increases by an increase in the matrix height, as expected, which makes the role of the two other mechanisms of frictional pressure drop and surfactant mass transfer less important in the middle layer. One must notice that the effect of frictional pressure drop decreases at a slower rate compared to the effect of mass transfer into the matrix, which is caused due to the fact that the perimeter of the matrix units in the middle layer is larger than that of the matrix unit in the top layer, thereby making frictional pressure drop more effective. In the same manner, comparison between the results of the top layer and the bottom layer shows that the role of frictional pressure drop along the fracture network weakens when the porosity and permeability of the matrix decrease. Conversely, the effect of the surfactant mass transfer remains unchanged, so its role in the total oil extraction enhances.

This paper included simulation studies and several sensitivity analyses on foam flow characteristics and matrix and fracture properties to investigate their effects on the foam injection into a fractured reservoir. The results will aid petroleum engineers to wisely select the foam properties with respect to the characteristics of fractured reservoirs at the initial stages of planning to inject foam for enhanced oil recovery.

4. Conclusions

The key findings of the present paper can be summarized as follows:

- The oil extraction mechanism of viscous pressure drop and the diffusion of the foaming agent into the matrix units play as important roles as the classic gravity drainage mechanism. The impacts of these two mechanisms increase as the height of the matrix decreases.

- The oil extraction mechanisms of foam/oil gravity drainage and foaming agent mass transfer weaken with time, while the mechanism of viscous pressure drop remains unchanged during the foam injection of the fractured reservoir.
- In addition to viscous pressure drop and foaming agent diffusion process which are the direct outcomes of foam application, the injection of foam will expand the invaded zone, allowing more matrix blocks to participate in production mechanisms.
- An increase in matrix permeability raises oil extraction rate which in turn accelerates the oil recovery. However, fracture permeability has an inverse effect; an increase in fracture permeability decreases viscous pressure leading to a reduction in oil extraction rates.
- An increase in foam viscosity or injection rate drops viscous pressure leading to recovery acceleration. The pseudo-plastic characteristics of foam cannot prevent the rate enhancement.

Nomenclatures

CMG	Commercial simulator
CT	Computed tomography
D	Diffusion coefficient
FOGD	Foam oil gravity drainage
$F_{Aqueous}$	Water correction factor
F_{Oleic}	Oil correction factor
$F_{Surfactant}$	Surfactant correction factor
MRF_{max}	Maximum mobility reduction factor
OOIP	Original oil in place
P_{Bottom}	Pressure at bottom
P_{Top}	Pressure at top
STARS	CMG foam approach
$\emptyset_{Oil}$	Oil flow potential

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