Comparison Study on Sag Foam Model Parameters in Different Reservoir Simulators

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Abstract: In order to model the foam behavior inside the porous media, various studies have been conducted and several models developed. Some of the commercial reservoir simulators equipped with these foam models. However, the contribution of each model parameter and their effect on the foam behavior are varied between different simulators. This study aims to compare two different well-known foam models and reveal the contribution of foam model parameters using the numerical simulation study. A synthetic model for surfactant-alternating-gas flooding in sand pack system is built using simulators. Design of expert is utilized to design different simulation scenario based on different foam models parameters. Simulations were performed for all scenarios and the results are analyzed by ANOVA to investigate the effect of different parameters on foam mobility reduction factor. The results show the effect of each parameter on mobility reduction factor in both models. Also, it illustrates that some parameters like critical water saturation are not important in ECLIPSE and CMG models however it has a moderate effect on foam mobility reduction in UTCHEM model.

Key words: Foam flooding, surfactant-alternating-gas, foam empirical model, mobility reduction factor, effect of different parameters, utilized

INTRODUCTION

Now a days, many oil field reservoirs have reached to their declined periods, therefore, Enhanced Oil Recovery (EOR) mechanisms including; chemical flooding (Hematpour *et al.*, 2012; Hematpour *et al.*, 2011), thermal flooding (Osterloh and Jante, 1992) and microbial flooding (Lake, 1996) become the essential part of field development plan. Gas flooding for sweep efficiency purpose is categorized in EOR methods. However, several drawbacks are associated with it. The gas flooding normally leads to low areal sweep efficiency due to its high mobility (cause viscous fingering) and its low density (cause gas segregation) (Hematpour *et al.*, 2016a). The foam assisted process has been introduced to overcome this problems (Hematpour *et al.*, 2016b). Foam flooding methods are categorized into three groups; pre-generated foam injection, Surfactant-Alternative-Gas injection (SAG) and co-injection flooding (Hematpur *et al.*, 2014).

Among these methods, SAG is the most common method due to its operational cost as well as its efficiency (Rossen *et al.*, 2014; Afsharpoor *et al.*, 2010).

Foam is defined as the discontinuous gas phase inside the continuous liquid phase (Hematpour *et al.*, 2016b). Considering the number of lamellae, the foam is categorized into two types: weak foam with weak texture (low numbers of lamellae) and strong foam with strong texture (high numbers of lamellae). The foam in porous media can be created by three different mechanisms: first, "leave behind" in which lamella are generated during the gas invasion and leave behind the gas flow, second, "snapped-off" in which lamella are created due to changing the capillarity of the medium, third, "lamella division" in which the number of lamellae is increased due to dividing mechanism when one lamella meet pore junction (Hematpur *et al.*, 2016).

The critical capillary pressure (P^*_c) is the main parameter in the foam coalescence phenomena. As it is depicted in Fig. 1 when the capillary pressure reaches to the critical value the foam suddenly will be collapsed. It will happen when the foam quality decrease and water saturation reaches to the critical value. The corresponding water saturation is called critical water saturation (S^*_w).

In order to model the foam flow through porous media, several models have been developed. These models are categorized into three major groups including mechanistic models, empirical models and semi-empirical models (Hematpur *et al.*, 2014). Most of these models aim to modify the gas phase mobility in the presence of gas, either change the relative permeability of gas or gas viscosity. Most of them utilize a function as "mobility

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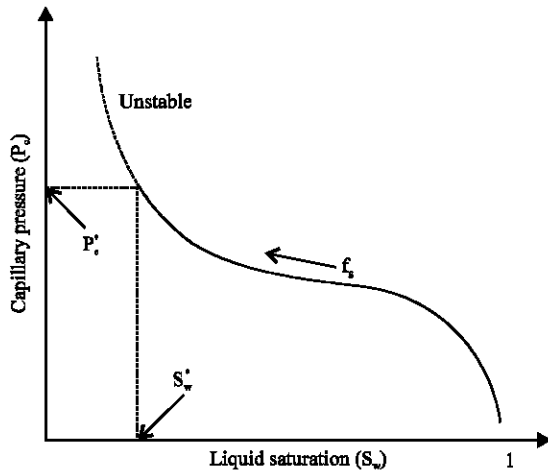
Fig. 1: Critical capillary pressure in foam (Farajzadeh *et al.*, 2015)

reduction factor" to shows the effect of foam on the gas mobility. The general definition of mobility reduction factor is illustrated in the following equation:

$$MRF = \frac{\Delta P_{foam}}{\Delta P_{no-foam}}$$

Reservoir simulators commonly utilized empirical models to simulate the foam flow through the porous media. Equation 1 illustrated three different empirical model which are implemented in commercial (CMG and ECLIPSE) and non-commercial simulators (UTCHEM) (Computer Modeling Group, 2015; Schlumberger, 2015; Volume, 2000). Different models for foam simulator. CMG:

$$
\left\{
\begin{aligned}
FM &= \frac{K_{rg}^f = K_{rg}^0(S_w)FM}{1 + fmmob.F1.F2.F3.F4.F5F6.fdry} \\
F1 &= (\frac{\text{mole fraction (ICPREL)}}{fmsurf})^{epsurf} \\
F2 &= (\frac{fmole\text{-}S_0}{(fmole\text{-}floil)})^{epoil} \\
F3 &= (\frac{fmcap}{\text{capillary number}})^{epcap} \\
F4 &= (\frac{(\text{capillary number} - fmgcp)}{fmgcp})^{epgcp} \\
F5 &= (\frac{(fmomf\text{-}X_{numx})}{fmomf})^{epomf} \\
F6 &= (\frac{(\text{mole fraction-flsalt})}{(fmsalt\text{-}flsalt)})^{epsalt} \\
fdry &= 0.5 + \frac{atan(sfbet(sfbet(S_w\text{-}SF)}{\pi}
\end{aligned}
\right.
$$

ECLIPSE:

$$
\left\{
\begin{aligned}
& K_{rg}^f = K_{rg} \times M_{rf} \\
M_{rf} &= \frac{1}{1 + (M_r \times F_s \times F_w \times F_o \times F_c)} \\
& F_w \left(\frac{C_s}{C_s^r}\right)^{es} \\
F_w &= 0.5 + \frac{a\tan(f_w(S_w - S_w^l)}{\pi} \\
F_o &= \left(\frac{S_o^m - S_o}{S_o^m}\right)^{eo} \\
F_c &= \left(\frac{N_c^r}{N_c}\right)^{ec}
\end{aligned}
\right\}
$$

UTCHEM:

$$
\left\{
\begin{aligned}
& \text{if } S_w < (S_w^* - \varepsilon) \text{ or } C_s < C_s^o \text{ then } k_{rg}^f = k_{rg} \\
& \text{if } (S_w^* - \varepsilon) \le S_w \le (S_w^* + \varepsilon) \text{ and } C_s = C_s^o \\
& \text{then } k_{rg}^f = \frac{k_{rg}}{1 + \frac{(R-1)(S_w - S_w^* + \varepsilon)}{2\varepsilon}} \\
& \text{if } S_w > ((S_w^* + \varepsilon) \text{ and } C_s \ge C_s^o \text{ then } k_{rg}^f = \frac{k_{rg}}{R} \\
& R = R_{ref}(\frac{U_g}{U_{gref}})^{\sigma-1}
\end{aligned}
\right\}
$$

These simulators employ different parameters to model foam behavior. Although, the basic concept of ECLIPSE and CMG models are same, the UTCHEM model is different. Therefore, in this study, both ECLIPSE and UTCHEM models were selected to investigate the parameter's effects on the mobility reduction factor.

Analysis of variance (ANOVA) which was developed by Ronald Fisher at 1919, aims to analyze the differences among the means of group and their related procedure (e.g., variation among and between groups) (Gelman *et al.*, 2005). ANOVA is applied on simulation results of this study to find effects of different model's parameters on the foam models.

MATERIALS AND METHODS

In order to achieve the objective of this study, a base synthetic model for SAG foam flooding into sand pack

Table 1: Static properties of the synthetic mode

Properties	Values
Sand pack diameter (cm)	6
Sand pack length (cm)	76.2
NX, NY, NZ	1.1,10
Porosity (%)	36
Absolute permeability (md)	10000
Initial water saturation (%)	1
Initial pressure (psi)	44.67

Table 2: Foam model's parameters

ECLIPSE		UTCHEM	
Parameters	Values	Parameters	Values
M_r	1-100	R_{ref}	1-1e+5
C_s^r	0.1-1	C_s^o	0.01-1
e_s	0.25-15	-	-
N_s^r	0.1-0.01	$U_{gref} = (\frac{ft}{day})$	0.5-5
e_s	0.01-1		0.5-1
f_w	0.1-10		
S_w^l	Swi-1	S_w^*	Swi-1

Table 3: Analysis of variance table for ECLIPSE

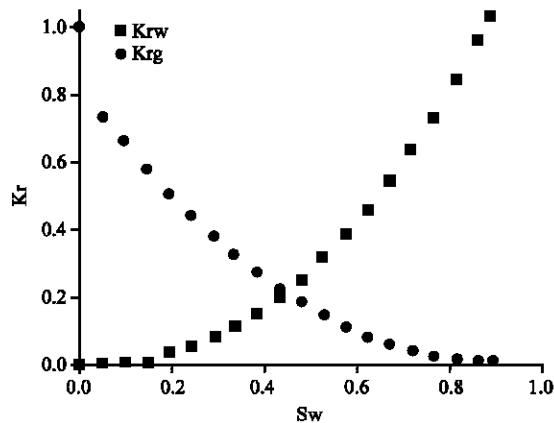| Sources	χ^2	F-values	p-values
Model	25.14	492.50	<0.0001
A-Mr	11.91	233.26	<0.0001
B-RCs	58.05	1137.16	<0.0001
C-es	24.77	485.24	<0.0001
D-RCn	0.22	4.39	0.0363
E-ec	191.42	3750.07	<0.0001
AB	1.46	28.63	<0.0001
AC	1.03	20.08	<0.0001
AD	0.27	5.24	0.0222
AE	12.10	237.09	<0.0001
BC	32.99	646.36	<0.0001
BD	0.26	5.19	0.0228
CE	1.33	26.03	<0.0001
A^2	3.59	70.31	<0.0001
B^2	7.40	145.01	<0.0001
E^2	30.29	593.46	<0.0001

Fig. 2: Relative permeability curve (gas/water)

system was built in ECLIPSE simulator as well as UTCHEM simulator. Table 1 illustrates the model's properties for the synthetic model.

The capillary pressure is assumed as zero due to its high absolute permeability. The relative permeability which has been utilized in these simulators is shown in Fig. 2.

One cycle of SAG was investigated in this study. In another word, first, four pore volume of the surfactant solution is injected into the water-saturated sand pack then three pore volume of gas is injected into the surfactant saturated core to generate the foam and the mobility reduction factors are recorded as results. The SAG behavior is studied in the absence of oil. Table 2 shows model's parameters ranges which were utilized for both simulators based on literature (Rossen *et al.*, 1999).

The DOE software is utilized to define all combinations of mentioned parameters for simulation. All parameters in Table 3 were normalized between 1-1. Three different levels are specified for each parameter: low, mid and high value. The full factorial design is proposed for all parameters combinations. Therefore, 2187 cases for ECLIPSE and 243 cases for UTCHEM are designed to cover the entire ranges of foam parameters. Mobility reduction factor is the response parameter which is recorded after four gas pore volume injection in each case. All results are analyzed using ANOVA to find the effect of foam parameters on the mobility reduction factor.

RESULTS AND DISCUSSION

All results of mobility reduction factor for both simulators are analyzed using ANOVA as following.

ECLIPSE results: Different models were fitted to all data, using ANOVA to find the least value for the residual R^2 as well as the adjacent R^2. First of all, the effect of all parameters on the response was investigated which is shown in Fig. 3.

In order to find the best model with the minimum value for R^2 and Adj. R^2, the quadratic model was selected and some parameters with high p-value were eliminated. Figure 3 depicts that dry-out function parameters (S_w^l, f_w) are not influential. Therefore, they can be eliminated from the model. The best model result is presented in Table 4 and 5. This model also includes interactions between parameters. The results of interaction between M_r and e_s is illustrated in Fig. 4.

These results show that capillary exponent (e_c) and refrence surrfactant concentration (C_s^r) has the significant effect on mobility reduction factor in SAG foam process in ELICPSE model while reference mobility (M_r) and surfactant exponent (e_s) have moderate a effect. Moreover, the mobility reduction factor is not affected by dry-out function parameters in SAG process which is not consistent with critical capillary pressure concept in foam coalescence (Farajzadeh *et al.*, 2015; Zhou and Rossen, 1995).
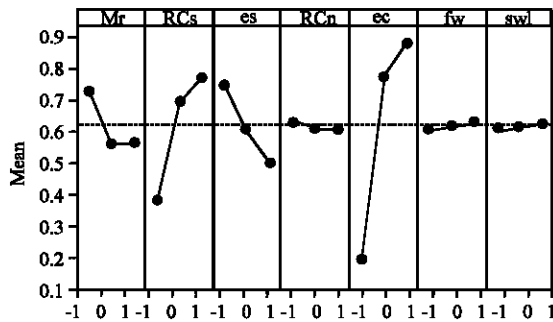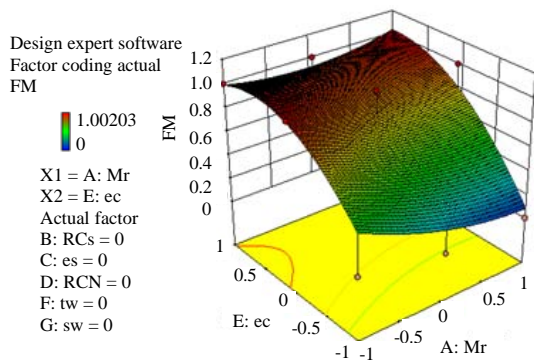
Fig. 3: The main effect plots for FM in ECLIPSE

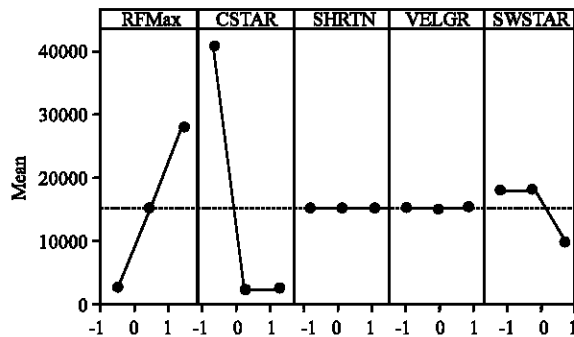Fig. 4: The model plot for M_r and e_s

Fig. 5: The main effect plot for MRF in UTCHEM

UTCHEM results: The same procedure as ECLIPSE was followed for UTCHEM simulator. Figure 5 shows effects of parameters on mobility reduction factor.

The above figure demonstrates that the shear thinning function in the normal range of gas flow in the reservoir is not the effective parameter. Hence, it can be eliminated from the model. The quadratic model also applied to these data. The best model result is presented in Table 5 and 6. This model also includes interactions between parameters. The results of interaction between
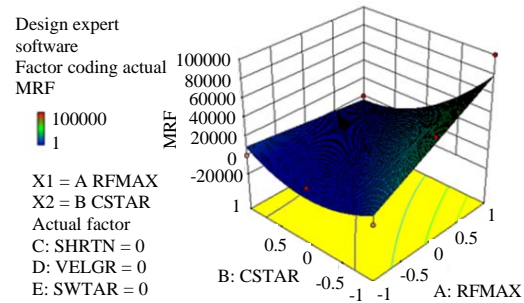

Fig. 6: The model plot for R_{ref} and C_s

Table 4: Summary of Model for UTCHEM

SD	R^2	Adj R^2	Pred R^2
0.23	0.7729	0.7713	0.7695

Table 5: Analysis of variance table for UTCHEM

Sources	χ^2	F-values	p-values
Model	2.27E+10	216.92	<0.0001
A-RFMAX	3.13E+10	298.49	<0.0001
B-CSTAR	7.04E+10	671.59	<0.0001
E-SWSTAR	2.80E+09	26.76	<0.0001
AB	4.69E+10	447.73	<0.0001
AE	1.87E+09	17.84	<0.0001
BE	4.21E+09	40.15	<0.0001
B^2	2.35E+10	223.86	<0.0001
E^2	9.35E+08	8.92	0.0031

Table 6: Summary of Model for UTCHEM

SD	R^2	Adj R^2	Pred R^2
10235.07	0.8812	0.8771	0.8714

R_{ref} and C^o_s is demonstrated in Fig. 6. These results show that in UTCHEM simulator for SAG foam process, critical surfactant concentration (C^o_s) and refrence mobility reduction (R_{ref}) factor have significant effect on mobility reduction factor while shearing thinning function parameters in the normal ranges are not affective. The critical water saturation parameter (S^*_w) has the moderate impact on the mobility reduction factor which is inline with critical capillary pressure concept (Farajzadeh *et al.*, 2015; Zhou and Rossen, 1995).

CONCLUSION

This study focuses on simulators foam's models, especially for SAG foam process. All results for the different simulators model were analyzed to find the impact of parameters on mobility reduction factors. The conclusion of this study are as following.

CMG has the highest number of parameters for foam model and ECLIPSE and UTCHEM come after it, respectively. In ECLIPSE model, the capillary exponent (e_c) and reference surfactant concentration (C^r_s) have the

highest effect on MRF, surfactant exponent (e_r) and reference mobility reduction (M_r) have a moderate effect on MRF. Other parameters are not considered as effective parameters.

In UTCHEM model, critical surfactant concentration (C^o_s) and reference mobility reduction (R_{ref}) are strongly effective parameters in MRF function, Critical water saturation has a moderate effect on MRF. In despite, both gas velocity reference and its exponent in their applied range do not show any effect on MRF.

Based on critical water saturation concept (the coalescence of foam due to critical capillary pressure) the UTCHEM model depicts the better performance because it is more sensitive to critical water saturation compare to ECLIPSE model.

Nomenclature:

K_r	=	Gas relative permeability
fmsalt	=	Critical salt mole fraction
k^f_r	=	Foam relative permeability
epsalt	=	Salt mole fraction exponent
MRF	=	Mobility reduction factor
sfbet	=	Dry out fitting parameter
∇P	=	Pressure gradient
Sf	=	Limiting water saturation
S_w		=Water saturation
C_c	=	Surfactant concentration
S_o	=	Oil saturation
C^r_s	=	Reference surfactant concentration
fmmob	=	Max mobility reduction
e_c	=	Surfactant concentration exponent
fmsurf	=	Critical surfactant concentration
fw	=	Dry-out fitting parameter
epsurf	=	Surfactant concentration exponent
S^i_w	=	Limiting water saturation
fmiol	=	Critical oil saturation
S^m_o	=	Critical oil saturation
floil	=	Lower oil saturation
e_o	=	Oil saturation exponent
expoil	=	Oil saturation exponent
N^t_c	=	Reference capillary number
fmcap	=	Reference capillary number
e_c	=	Capillary number exponent
epgcp	=	Capillary number exponent
C^o_s	=	Critical surfactant concentration
fmgcp	=	Critical generation capillary number
S^w_w	=	Limiting water saturation
fmomf	=	Critical oil mole fraction
R_{ref}	=	Reference mobility reduction
epomf	=	Critical oil mole fraction exponent
U_{gref}	=	Reference gas velocity
flsalt	=	Low salt mole fraction
σ	=	Shear thinning exponent

ACKNOWLEDGEMENT

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