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Investigating the Effect of Oil on two Foam-flow regimes (Low and High Fractional flow of Gas) for EOR - Local Equilibrium Behavior

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Abstract− Due to high energy demand and difficulties in exploring and developing new oil fields, several enhanced oil recovery methods are being developed in order to optimise production in marginal oil fields. *Enhance oil recovery (EOR)* techniques are theoretically very promising but in real life suffers the effects of many physical complications in the subsurface which are yet to be understood in detail. One such complication is the detrimental effect of oil in foam *EOR*. Current-generation reservoir simulators represent these effects in an approximate way. The *STARS*™ simulator is one such software. Though nearly 20 years old, till now there has not been a detailed study on how its parameters predict foam behaviour without oil.
The effect of oil related parameters was investigated in detail in the *STARS*™ simulator by studying the behaviour of foam in two foam-flow regimes, as identified by Osterloh and Jante and Alavrez *et* al, on steady state behaviour of foam without oil. The focus of this research work is to study the shift in the two foam-flow regimes with oil present. This is achieved by fixing oil saturation, fixing oil superficial velocity or by fixing the oil to water superficial velocity ratio. Initially Corey-type relative permeability function was employed, then the effects of oil-related parameters was investigated with fixed limiting water saturation (wet foam model) but later the effects of changing limiting water saturation was studied (dry-out foam model). The model behaviour for three-phase oil relative permeabilities was developed by implementing Stones Model II oil relative permeabilities and saturations in both the models (*STARS*™ Foam Simulator).

Index Terms— Enhanced Oil Recovery, Equilibrium Behavior, Flow Regimes, Oil and Water Saturation, Oil Relative Permeability, Foam Simulator.

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1 Introduction

1.1 Foam EOR

Enhanced Oil Recovery (EOR), as the name suggests, is the technique of recovering oil from the reservoirs by extra means, by the injection of fluids not native to the reservoir (Lake, 2010). Thus, *EOR* is the last resort left to a petroleum engineer to recover and extend the productive life of an otherwise depleted (by primary & secondary recovery) and uneconomic field. The most common and widely accepted way is the recovery by gas injection/flooding using gases such as carbon dioxide, nitrogen and various components of lighter hydrocarbon mixtures. Using these processes, one can achieve a significant amount of oil recovery, even leading to a hundred percent displacement efficiency. However, in practice, the results are much poorer than expected, mainly due to poor "sweep efficiency" of fluids (Lake, 2010). The gasses pass into the unwanted layers or suffer gravity override and thus it becomes a problem to produce the oil. The major causes of poor sweep efficiency are low viscosity of injected gases and gravity override of gas (Rossen, 2013).

Foam EOR partially overcomes the effects of poor sweep efficiency by reducing gas mobility (Schram, 1994; Rossen 1996). Foam can be classified as a mixture of gases and liquids, specifically, gas bubbles dispersed in liquid separated by liquid films called lamellae. Foam greatly increases the gas flow resistance, as it has higher viscosity and thus diverts the gas from unwanted layers. Unfortunately, the contact of foam with most crude oils destabilizes foam, which greatly limits the widespread use of foam for EOR (Mannhardt et al., 1998). Thus, it is important to understand the complexities involved in the effect of oil on foam.

1.2 Two Foam Flow Regimes

Despite the efficiencies associated with *EOR*, the results in actual field applications continue to be unpredictable. The science of foam is extremely complex as there are many contradictions in the available published foam studies: the apparent rheology of foam (either shear thickening or shear thinning), and whether foam strength increases or decreases with foam quality (Alvarez et al., 2001).

Khatib et al. (1988) defined a Pc^* regime in which foam stability in porous media is limited by capillary pressure. In this regime, foam bubbles change size accordingly to maintain foam at a fixed limiting capillary pressure, with an abrupt transition from strong foam to no foam (or weak foam) in a very narrow range of capillary pressure. This causes the water saturation Sw to stay constant and equal to Sw^* at a fixed capillary pressure Pc^*. As a result, the pressure gradient Δp is proportional to the liquid superficial velocity Uw, and independent of the gas flow rate.

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The steady-state flow behavior of foam in the absence of oil is characterized by its two foam flow regimes, illustrated in Figure 1 (Osterloh *et* al., 1994). In the figure, the pressure gradient Δp with foam is plotted as a function of the superficial velocities of water and gas, i.e. Δp (*Uw*, *Ug*). The transition zone between the two regimes is characterized by a specific value of gas fractional flow *fg*, termed as *fg**. The regime for *fg**>0.94 is the high-quality regime, or the coalescence regime. Foam in this regime obeys the *Pc** model (Khatib et al., 1988).

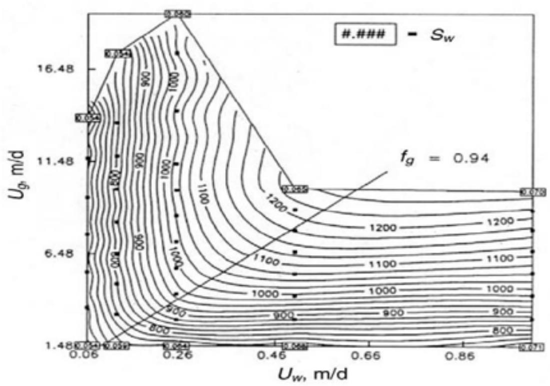

Figure 1: Pressure drop as a function of superficial gas and water flow rates (Osterloh, 1994).

Foam flow behavior is characterized by two regimes: the "*low-quality*" (low fractional flow of gas) or "*wet*" regime and "*high-quality*" (high fractional flow of gas), or "*dry-out*" or "*coalescence*" regime. In the low-quality regime, the bubble size is roughly constant, close to pore size, and pressure gradient is independent of liquid flow rate and mainly controlled by pore structure (Kam, 2003; Chen, 2010). In the high-quality regime, there exists a limiting water saturation below which foam collapses drastically and abruptly, and pressure gradient is independent of gas flow rate (Khatib, 1988).

At fixed total superficial velocity the pressure gradient Δp increases with decreasing foam quality at a fixed total flow rate U_T in high-quality regime until *fg** is reached, then Δp decreases with further decrease in foam quality in the low-quality regime.

1.3 Modelling the effect of oil on foam flow regimes for EOR: Local Equilibrium Behavior

Farajzadeh et al. (2012), tried representing at least four methods in current reservoir simulation models for the effect of oil on foam.

1. The effect of oil saturation, with two-limits (upper-limiting oil saturation for foam stability above which the oil kills foam, and lower-limiting oil saturation below which oil has no effect on foam), distinguishing whether oil destroys or harms foam.
2. The effect of oil composition, i.e. the lighter the oil, the more detrimental oil is to foam.
3. Making the limiting water saturation for foam stability depend on oil saturation.
4. Making lamella destruction rate proportional to oil saturation (Myers and Radke, 2000).

Foam stability also depends on the nature of crude oil. It is seen that lighter and lower-viscosity crude oils are more destructive to foam stability than heavier and more-viscosity crude oils. (Farajzadeh et al., 2012).

Presently, there are various foam models available which can be categorized in two types: the population balance models and the local equilibrium models. Population balance models describe the dynamic creation and the destruction of lamellae; the local equilibrium models characterize the mobility of gas trapped in the foam with some factors reflecting surfactant concentration, water saturation, oil saturation, oil composition, capillary number, and salinity. The effect of oil on foam is usually linked to wettability of rock. If surfactant adsorption and wettability alteration in the oil-wet porous media take place instantly, which indicates foam is formed instantly everywhere surfactant concentration is sufficient as in water-wet porous media, there is no need to change current foam models. Otherwise, the foam models must be modified to characterize the effect of wettability on foam. (Farajzadeh, 2012).

The most widely used model for the effect of oil on foam is the Computer Modelling Group's *STARS™* simulator, nearly 20 years old. However, there has been no systematic study of how its parameters affect the predicted foam performance.

The overall aim of this study is to: a) Investigate the effect of oil-related parameters on steady-state foam flow behavior using two foam models in *STARS™* foam simulator: Basic Empirical (Wet) & Dry-out foam option. b) Investigate the effects of different oil relative permeability functions (Corey versus Stone) on the oil effect in foam models.

2 Methodology

2.1 Main Scenarios

Based on the aims of this research work, the main scenarios for exploring the effect of oil on foam are different cases where in the oil saturation the oil and water superficial velocities are taken as a function of Δp . The Δp contours are then plotted as a function of gas and water superficial velocities. The scenarios as suggested in the experimental study of Shen and Rossen are:

1. Two foam-flow regimes without oil.
2. Two foam-flow regimes with fixed oil saturation (*So*).
3. Two foam-flow regimes with fixed oil superficial velocity (*Uo*).
4. Two foam-flow regimes with fixed oil to water ratio (*Uo*/*Uw*).

A general outline of step by step calculation for above cases is given below:

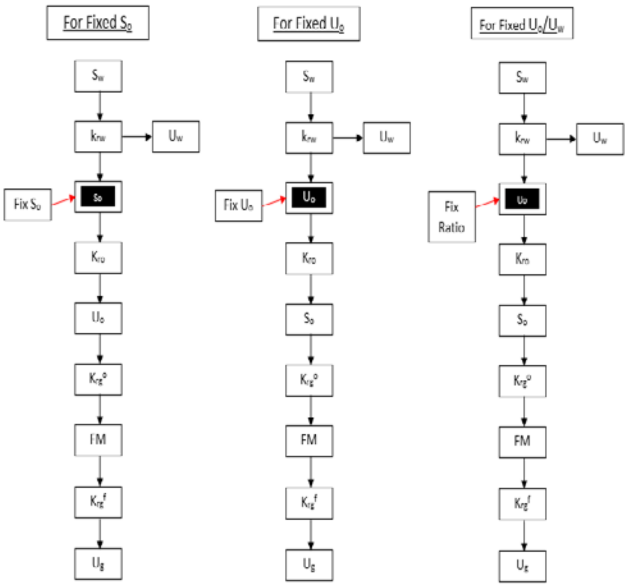

Figure 2: Schematic representation of Calculating U_w and U_g.

See text below for details of how each step is conducted.
Steps for calculating oil, water and gas superficial velocities at fixed So, fixed U_o and fixed Uo/Uw:

$Step$ 1. Set S_w (Preferably above connate water saturation) (2.1)

$Step$ 2. $Calculate$ $krw = kr_w{}^0 \left(\frac{Sw-Swc}{1-Swc-Sor}\right)^{nw}$ (2.2)

$Step$ 3. $Calculate$ $Uw = \left(\frac{Kr^o_{w*K*\Delta P}}{\mu_w}\right)$ (2.3)

$Step$ 4. Set S_o or Set U_o or Set U_o/U_w (fix) (2.4)

$Step$ 5. $Calculate$ kro $(Darcy) = \frac{U_{o*}\mu_o}{k*\Delta P}$ (Darcy's Law) (2.5)

$Step$ 6. $Calculate$ $Uo = \left(\frac{Kr^o_{o*K*\Delta P}}{\mu_o}\right)$ (use when S_o is fixed)

$Step$ 7. $Calculate$ $k^o_{rg} = k^o_{rg} \left(\frac{1-Sw-So-Sgr}{1-Sgr-Sor}\right)^{ng}$ (2.7)

$Step$ 8. $Calculate$ FM $(for\ wet\ foam\ or\ dry-out\ foam)$ (2.8)

$Step$ 7. $Calculate$ $k^f_{rg} = k^o_{rg} * FM$ (2.9)

$Step$ 9. $Calculate$ $Ug = \left(\frac{k^f_{rg*K*\Delta P}}{\mu_g}\right)$ (2.10)

2.2 STARS[TM] Wet-foam model

With the use of this model, the gas relative permeability is modified for the effect of foam by a multiplication factor called as *FM* (2.12).

$$k^f_{rg} = k^o_{rg\,(S_w,S_o)*FM} \quad (2.11)$$

where k^o_{rg} is the relative permeability without foam present.

$$FM = \frac{1}{(1+fmmob\ F1F2F3F4F5F6)} \quad (2.12)$$

Where,

F1 = *(mole fraction(icprel)) / fmsurf)^epsurf*
F2 = *(fmoil - oil saturation) / (fmoil-floil)^epoil*
F3 = *(fmcap / (capillary number))^epcap*
F4 = *(fmgcp - (capillary number)/fmgcp)^epgcp*
F5 = *(fmomf - oil mole fraction.(numw))/fmomf)^epomf*
F6 = *(mole fraction(numw)-flsalt)/(fmsalt-flsalt))^epsalt*

Equation 2.2 considers the functions reflecting the effects on foam stability on surfactant concentration, water saturation, oil saturation, capillary number, oil composition, and salinity. Only the functions for the effects of water saturation *F2* (Equation 2.13) and oil saturation *F3* (Equation 2.14) are considered in this study investigating the effect of oil-related parameters (Table 1).

$$F2 = 0.5 + \frac{arctan[epdry(S_w-fmdry)]}{\pi} \quad (2.13)$$

$$F3 = \left(\frac{fmoil-S_o}{fmoil-floil}\right)^{epoil} \quad (2.14)$$

Table 1: Oil effecting parameters (Wet Foam)

Parameter	Explanation	Allowed Range
epdry	The greater this parameter the more abrupt the fall of the *fw* (*Sw*) curve; meaning a sharper, yet still continuous, transition between the two regimes (strong foam and foam collapse).	*0 to 50000*
F2	Controls the rise of gas mobility by taking into account the effect of water saturation.	*N/A*
F3	Function describing the stability of the lamellae in the presence of oil.	*N/A*
floil	Lower oil saturation (volume fraction) below which oil has no effect.	*0 to 1*
fmdry	Water saturations around which weak foam collapses. When the transition between the regimes is abrupt (large value for epdry), fmdry is the critical water saturation, *Sw**, at which foam collapses.	*0 to 1*
fmmob	Reference mobility reduction factor.	*0 to 100000*
fmoil	Critical oil saturation (volume fraction), above which foam is completely destroyed	*0 to 1*

2.3 STARS[TM] Dry-Out model

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In the dry-out model, the limiting water saturation *fmdry* (Equation 2.15) (renamed *SF* in this model) is not constant as in the wet-foam model; it depends on other factors, such as oil saturation (*STARS*™ user's guide, 2009). Figure 6 illustrates how oil saturation and limiting water saturation depend on each other in this model. For oil saturations below *sloil*, *sfdry* is constant; oil has no effect on foam. For oil saturations above a limiting value *sfoil*, *sfdry* =1 (i.e., no foam at any water saturation). For oil saturations in between *sloil* and *sfoil*, foam mobility is a nonlinear function of oil saturation, with exponent *efoil*. Hence, oil has a detrimental effect on foam in this region.

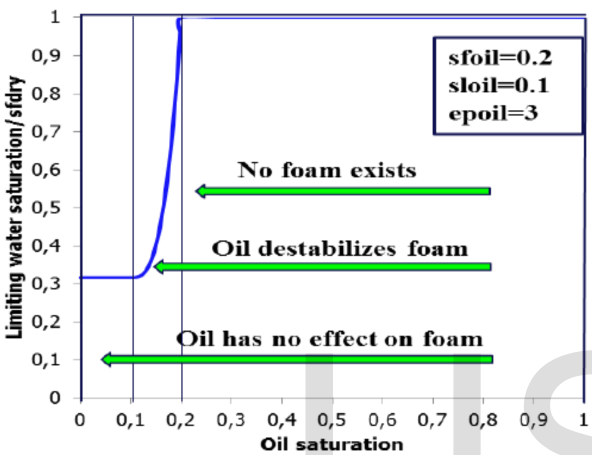

Figure 3: Limiting water saturation vs. So (dependency curve)

SF = max (G1, G2, G3<G4)

G1 = (MOLE FRACTION(ICPREL)) / SFSURF) ** EFSURF
0.0<G1<1.0
G1 * (1 – SFDRY) + SFDRY

G2 = (OIL SATURATION-SLOIL) / (SFOIL-SLOIL)) ** EFOIL
0.0<G2<1.0
G2 * (1 – SFDRY) + SFDRY

G3 = (MOLE FRACTION(NUMW) – SLSALT)/(SFSALT – SLSALT) **EFSALT
0.0<G3<1e5
G3 * (1 – SFDRY) + SFDRY

G4 = (FMCAP / (CAPILLARY NUMBER)) ** EFCAP
0.0<G4<1.0
G4 * (1 – SFDRY) + SFDRY

$$G2 = \left(\frac{(S_o - Sloil)}{(Sfoil - Sloil)}\right) \wedge efoil \qquad (\text{for } Sloil<S_o< Sfoil) \qquad (2.15)$$

The equations for *FM* (2.16) and associated oil related parameters (2.17) are given below. Table 2 consists of all the parameters we need for our model. F7 replaces F3 and F2 in the previous model. Also, if So<Sloil (G<0), SF becomes sfdry and if So>Sfoil (G>0), F7 becomes zero resulting *FM*=1.

$$FM = \frac{1}{1+fmmob*F7} \qquad (2.16)$$

$$F7 = 0.5 + \frac{\arctan[sfbet(S_w - SF)]}{\pi} \qquad (2.17)$$

Table 2: Oil effecting parameters (Dry-Out Foam)

Parameter	Explanation	Allowed Range
sfbet	Reference dry-out slope used in dimensionless foam dry-out calculation.	*1 to 5*
F7	The factor rescales the basic foam interpolation over a limited oil saturation range.	*N/A*
sloil	Lower oil saturation value used in dimensionless foam dry-out calculation. Below this, oil has no effect.	*0 to 1*
sfdry	Water saturations around weak foam collapses. When the transition between the regimes is abrupt (large value for *sfdry*), epdry is the critical water saturation, *Sw**, at which foam collapses.	*0 to 1*
fmmob	Reference mobility reduction factor	*0 to 100000*
sfoil	Critical oil saturation (volume fraction), above which foam is completely destroyed.	*0 to 1*

2.4 Stone's Model

Based on channel-flow theory, the wetting phase tends to occupy smaller pore spaces, while the non-wetting phase takes larger pores, with intermediate-wetting phase in the intermediate pore spaces. The relative permeability for wetting phase and non-wetting phase is each still a function only of its own saturation. We assume water, gas and oil are wetting, non-wetting and intermediate-wetting respectively. Normalized Stone's oil relative permeability is given in equation 2.26. An extensive explanation of how we incorporate Stone's relative permeability function into the model is given below:

Step 1. *Set U*w (Take these from previous *Corey*'s result) (2.18)

$$Step\ 2.\ Calculate\ Sw = \left[\left(\frac{\mathrm{Uw}*\mu\mathrm{w}}{\mathrm{k}*\Delta\mathrm{P}}\right)^{\left(\frac{1}{nw}\right)} * \left(1 - S_{wc} - S_{or} - S_{gr}\right)\right] + S_{wc} \qquad (2.19)$$

Step 3. Set U_o/U_w Ratio or Set U_o (2.20)

Step 4. *Calculate kro* (*Darcy*) = $\frac{U_o * \mu_o}{k * \Delta P}$ (Darcy's Law) (2.21)

$$Step\ 5.\ Calculate\ kro_w = kro_w^o \left(\frac{1-Sw-Sor}{1-Swc-Sor}\right)^{no} \quad (2.22)$$

$$Step\ 6.\ Calculate\ krw = kro_w^o \left(\frac{Sw-Swc}{1-Swc-Sor}\right)^{nw} \quad (2.23)$$

Step 7. Input Value of S_o from 0-1 in equation 2.16 (in variance of 0.0001) using excel solver

Step 8. Index Match the solution from Step 7 with kro (Darcy) which we calculated in Step 4

Step 9. Select the relative So value from Step 8 which was input in Step 7.

$$Step\ 7.\ Calculate\ k_{rog}^o = k_{rog}^o \left(\frac{(Sw+So)-Sor}{1-Sgr-Sor}\right)^{no} \quad (2.24)$$

$$Step\ 8.\ Calculate\ k_{rg}^o = k_{rg}^o \left(\frac{1-Sw-So-Sgr}{1-Sgr-Sor}\right)^{ng} \quad (2.25)$$

$$Step\ 9.\ Calculate = k_{ro} = (kro_w + kro_{wi} * kr_w) * (k_{rog}^o + kro_{wi} * k_{rg}^o) - kro_{wi}(kr_w + k_{rg}^o) \quad (2.26)$$

Step 10.*Plug the calculated three–phase saturation res STARS™ foam model*

2.5 Local Equilibrium Model – Reservoir Grid (Saturations)

The porous medium is divided into N grid cells. To calculate the saturation in the adjacent grid cells and also at the next time, the saturation formula is:

$$S_{g,i}^{t+\Delta t} = S_{g,i}^{t} + \frac{\Delta t\ Ut}{\varphi * \Delta x}\left(f_{g,i-1}^{t} - f_{g,i}^{t}\right) \quad (2.27)$$

where,

$S_{g,i}^{t+\Delta t}$ = Saturation of phase at next time-step at grid cell i

$S_{g,i}^{t}$= Saturation of phase at current time-step at grid cell i

Δt = Value of time-step (seconds)

Ut = Total superficial velocity

φ = Porosity

Δx = Length of grid cell (meter)

$f_{g,i-1}^{t}$=fractional flow of phase at i-1 grid cell at current time-step

$f_{g,i}^{t}$ = fractional flow of phase at i grid cell at current time-step

3 RESULTS & DISCUSSIONS

A base case without oil is taken as a benchmark/reference to correlate with the results. All the results are cross compared, i.e., each segment deals with Corey's and Stone's relative permeabilities and their respective saturation profiles side by side. Furthermore, the comparison between the wet foam option and dry-out foam option is studied. The base model parameters remain fixed throughout any case (Rossen and Boeije, 2013), given in the table 3 below:

Table 3: Fixed Parameters for STARS™ Foam Simulator

Swr	*Sor*	*Sgr*	*μo (cP)*	*μw (cP)*	*μg (cP)*
0.20	0.10	0.20	*5.00*	*0.70*	*0.02*
Krw	*Kro*	*Krg*	*nw*	*no*	*ng*
0.20	0.50	0.94	4.20	1.30	2.00
fmmob	*fmdry*	*epdry*	*sfdry*	*sfbet*	*K(Darcy)*
54000	0.316	20000	0.316	6000	1.30

3.1 STARS™ Wet Foam Model

3.1.1 Fixed So

Figure 4 (A-D) shows the variations in various oil parameters. Fixed *So* means that for each Δp contour the relative oil permeability, oil velocity and *F3* (Oil related parameter) would remain constant throughout the calculations. It also explains why in practical applications, it is generally difficult to monitor apparatus at fixed oil saturation with fixed relative permeabilities, oil velocity and *F3*. The oil superficial velocity, *Uw*, will increase with each incrementing pressure-gradient contour. The saturation of oil we set for our case is 0.2.

The changes in *fmoil* can be seen in Figure 4 (A and B), where-in a decrease in *fmoil* from 1 to 0.57 (with other parameter values same) will shift the pressure-gradient contours in the low-quality regime (horizontal contours) upwards. Thus the foam is weakened as the gas mobility increases with smaller values of *fmoil*. At *fmoil* = 0.21 ,the gas superficial velocities (*Ug)* shoots up compared to the relatively stagnant superficial water velocities depicting a sharp increment in gas mobility resulting in a weakened foam. As the value of *fmoil* approaches *So* the two foam flow regime would start to collapse. If the value of *fmoil* is lower than oil saturation *So*, there would be no foam present.

The lower limiting oil saturation (*floil*) when increased from 0.1 to 0.25 is shown in Figure 4 (A and C). This lowers the horizontal contours of the low-quality regime, thus the foam gets stronger (as the mobility decreases). That is, increasing the lower limiting oil saturation decreases the detrimental effect of oil on foam; below *floil*, the oil has no effect on foam and at higher *floil* the foam resilience become stronger.

In Figure 4 (A and D), *epoil* is raised from 3 to 5, shifting the pressure-gradient contours in the low-quality regime upwards, i.e., the foam gets weaker (as the gas mobility increases). When *epoil* is reduced to 1 , the foam gets

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stronger as the pressure-gradient contours are lowered down in the low-quality regime.

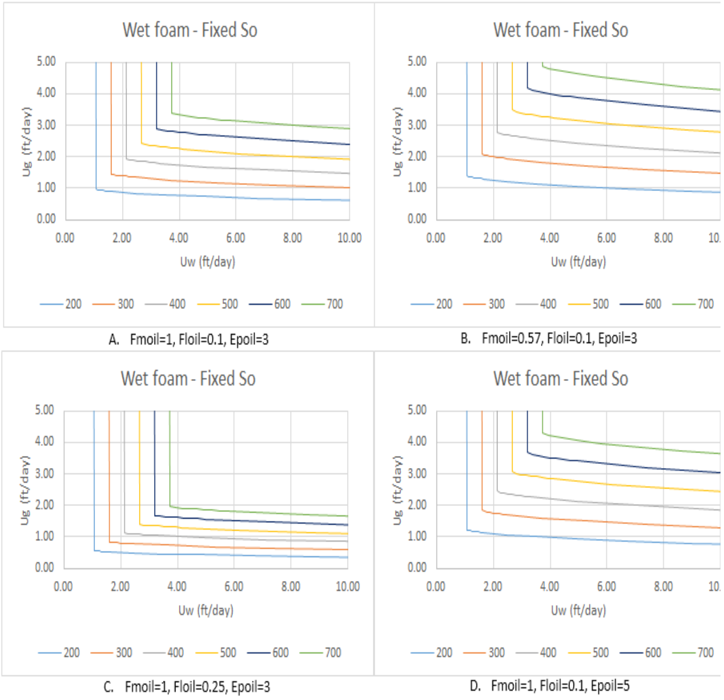

Figure 4: Wet-foam model in the presence of oil: fixed oil saturation.

3.1.2 Fixed Uo

In lab experiments, it is easier to set fixed *Uo* instead of *So* (previous case). As mentioned in the calculation steps , the *Uo* is fixed and gives a single *So* for an entire pressure-gradient contour (using *Darcy*'s law). This implies a single oil relative permeability. However, the *So* value changes for each pressure-gradient contour. In this case, we set *Uo* = 5 *ft/day*. The higher the pressure-gradient, the lower will be the So. For this case, with all the base parameters constant, *So* at Sw=0.2 is 0.187, 0.171, 0.16, 0.153, 0.15, 0.148 for Δp=200, 300, 400, 500, 600, 700 *psi/ft* respectively. This shows that with higher Δp the oil does not affect foam stability as the oil saturation already reduces with higher pressure gradient. At *fmoil*=1, the horizon of foam application (in terms of oil, water and gas saturations) is maximum. Figure 5 A, shows the base case with *fmoil*=1, *floil*=0.1 and *epoil*=3.

Lowering *fmoil* from 1 to 0.42, keeping other parameters the same (Figure 5 A and B), we see an upward shift in horizontal contours and no effect on vertical contours. The upward shift in horizontal pressure-gradient contours means that the foam has weakened, as the gas mobility increases. At *fmoil*=0.19, the Δp=200 *psi/ft* contour shoots up the values of *Ug* to approx. 2340 *ft/day* at only *Uw*=1 *ft/day* (given in appendix B.2 Fixed *Uo*). This explains that oil will kill foam if at Δp=200 *psi/ft*, *fmoil* becomes 0.19. This condition is true for all the pressure-gradients when *fmoil* ≤ *So*.

Increasing *floil* from 0.1 to 0.25 (Figure 5 A and C) results in stronger foam as the horizontal contour lines shift downwards in low-quality regime and the pressure-gradient will increase. On further increasing *floil*, *Uw* shoots down to extremely low gas velocities . At this stage, oil has negligible effect on foam sustainability.

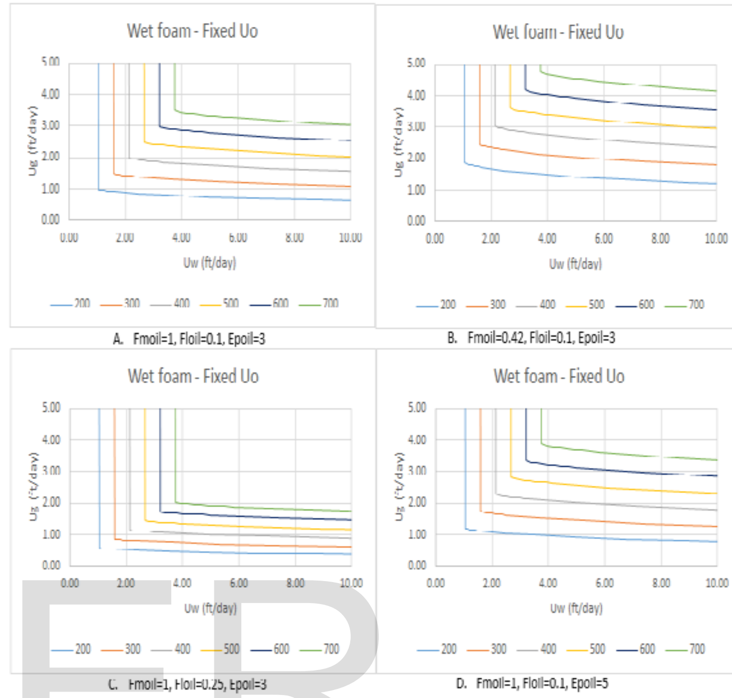

Figure 5: Wet-foam model in the presence of oil: fixed oil superficial velocity.

Increasing *epoil* from 3 to 5 in Figure 5 (A and D), shifts the horizontal contours downwards in the low-quality regime, weakening the foam and vice versa.

3.1.3 Fixed Uo/Uw Ratio

Fixing a ratio *Uo/Uw* enables us to study *Uo* as a function of *Uw*. Hence, the *So* in each pressure-gradient contour will change with the change in *Sw*, dependent on water injection rate (or *Uw*). The oil saturation will increase with the increase water saturation. The results for *Uw, Uo, Ug* (and the fractional flows) will only differ due to pressure variation between each contour. We set a *Uw/Uo* ratio of 25.

Fmoil when lowered from 1 to 0.3 in Figure 6 (A and B) keeping *floil*=0.1 and *epoil*=3, shifts the horizontal pressure-gradient contours upwards in the low-quality regime, indicating the detrimental effect of oil on foam as the pressure gradients decrease (as mobility increases). The result in this case is comparable to the previous cases where reduced *fmoil* value impacted foam strength greatly. Thus, the effect of oil on foam (in terms of *fmoil*) is relatively less in this case.

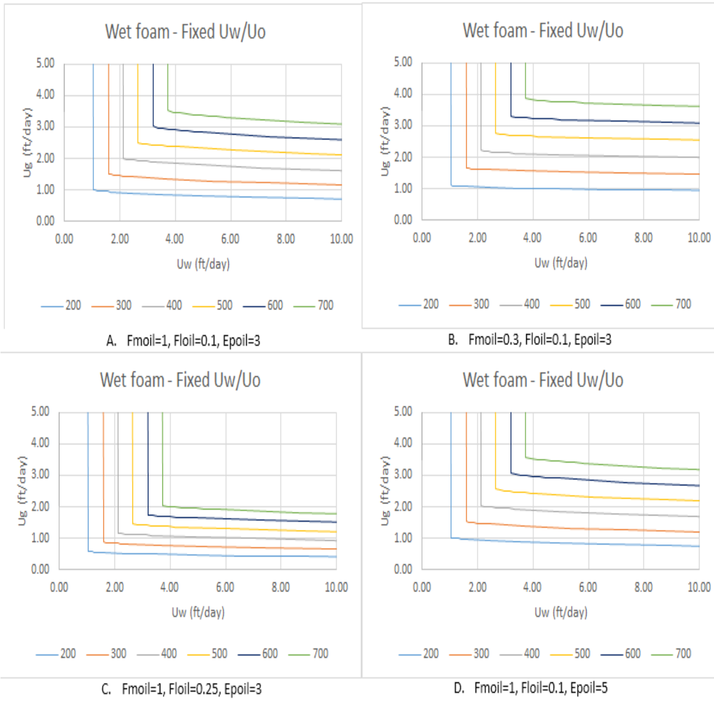

Figure 6: Wet-foam model in the presence of oil: fixed Uo/Uw Ratio

Epoil drastically weakens the foam when increased from 3 to 5 (Figure 6 A and D) as the horizontal pressure-gradient contours shifts upwards in the low-quality regime (increased mobility). Increasing *floil* from 0.1 to 0.25 (Figure 6 A and C) shifts the horizontal contours downwards in the low-quality regime making the foam stronger and tolerant to detrimental effect of oil. Increasing *floil* closer to *fmoil* will result in higher *Uw* at extremely low *Ug* or in other words collapsing high quality regime.

3.2 STARSTM Dry-Out Foam Model

3.2.1 Fixed So

With the changing limiting water saturation in dry-out model, the behavior of foam strength changes and so does the foam stability. At *sfoil*=1, sloil=0.1 and efoil=3, the transition between the high-quality and low-quality regime is gradual, depicting the water saturation (*Sw*) values in transition close to *sfdry*. When *sfoil* is decreased from 1 to 0.4 in Figure 7 (A and B), the vertical pressure-gradient contour lines shifts from left to right, making the foam unstable. The sharpness in from high-quality to low-quality regime increases with the decrease in *sfoil*. More sharper the boundary, more weakened the foam becomes. Unlike wet foam model (which impacts the horizontal pressure gradient contours in low-quality regime), dry out model only impacts on the vertical pressure-gradient (high-quality regime) contours.

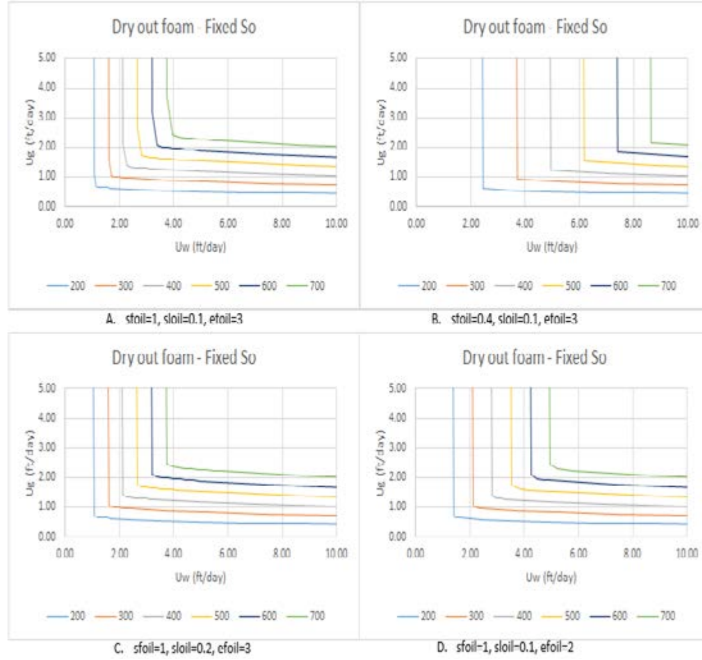

Figure 7: Dry-out foam model in the presence of oil: fixed oil saturation

At *sfoil* 0.25 (Figure 7 B) closing to *So*, the water superficial velocities (*Uw*) shoots up compared to stagnant oil superficial velocities (*Ug*), implying that the foam would either collapse or be unstable at very high *Uw*.

Sloil when increased from 0.1 to 0.2 (Figure 7 A and C) sharpens the transition zone (i.e. strengthens foam; however foam stability is still dependent on water saturations). The foam is not affected by *sloil* when it is more than *So*. In Figure 7 (A and D), *efoil* is lowered from 3 to 2, which increases the vertical pressure-gradients contours from left to right, destabilizing the foam. Unlike the wet foam model, it can be said that *efoil* when lowered, would kill the foam. The higher the value of *efoil*, the more stable the foam would be.

3.2.2 Fixed Uo

Similar to the wet foam model (fixed oil superficial velocity), we set *Uo* at 5 *ft/day*. It gives a single value of oil saturation (*So*) throughout an entire pressure-gradient contour. The oil relative permeabilities remain constant for each pressure-gradient contour but changes as the Δp contour change. The *So* values changes for each pressure gradient contour and lowers down with the increase in Δp. For Δp= 200, 300, 400, 500, 600, 700 *psi/ft*, the values of So=0.187, 0.171, 0.16, 0.155, 0.15, 0.146 respectively. *Sfoil*=1 gives the maximum region in which foam can sustain. The base case is Figure 8 A, with *sfoil*=1, *sloil*=0.1, *efoil*=3.

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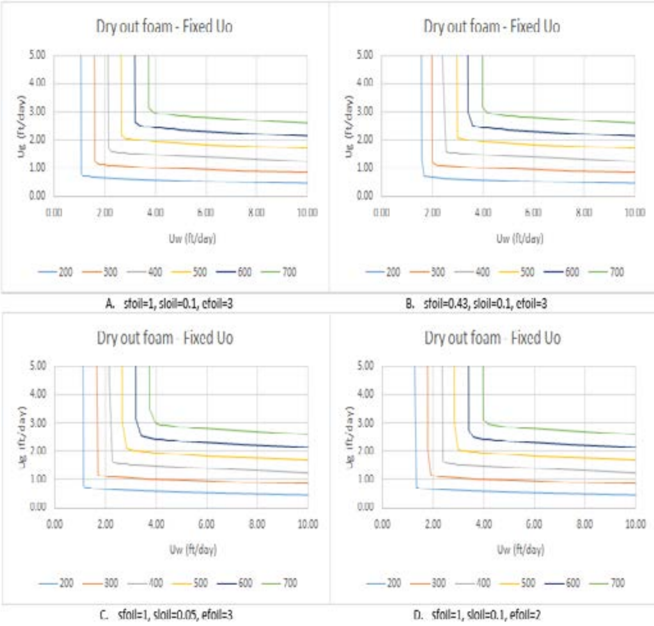

Figure 8: Dry-out foam model in the presence of oil: fixed oil superficial velocity

Lowering the *sfoil* from 1 to 0.4 and keeping the other parameters same (Figure 8 A and B), the vertical contours shifts from left to right making the foam weaker and unstable (with high *Uw* at lower *Ug*). There is no effect on the horizontal pressure-gradient contours. Further lowering the *sfoil* will distort the system, i.e., the *Uw* starts jumping abruptly for small values of *Ug*.

Sloil has minimal effect on foam stability and is only effective till the highest value of 0.15. Decreasing *sloil* from 0.1 to 0.05 in Figure 8 (A and C); the vertical pressure gradient contour shifts from left to right making the foam weaker/unstable. Effect of oil on higher values of *Sloil* is nil. Decreasing *Efoil* from 3 to 2 in Figure 8 (A and D), destabilizes foam and weakens it. Higher values of *efoil* will result in stable foam.

3.2.3 Fixed Uo/Uw Ratio

The oil saturations in each pressure gradient changes with the change in the water saturations. We set a *Uo*/*Uw* ratio of 1/25. The saturation *So, Sw, Sg* will remain constant for all Δp contours (only the fractional flow would change due to different pressure gradient). When *sfoil* is reduced from 1 to 0.144 in Figure 9 (A and B), an unexpected behavior is witnessed. The pressure-gradient contours shift from vertical in the high-quality regime to horizontal in the low-quality regime, and then switch back to vertical at higher *Uw*. The high-quality regime returns with an increase of *Uw*. In the high-quality regime (in left), limiting water saturation *sfdry* is equal to water saturation *Sw*. With the increase of *Uw*, which also indicates a rise in water saturation based on *Darcy*'s law, causes the two-foam flow regimes to switch from high-quality to low-quality regime. Since *Uo* is directly proportional to that of oil saturation, the oil saturation also increases with the increasing *Uw* in the low-quality regime. This causes the limiting water saturation *sfdry* to increase (Figure 9 B). contour lines raises a question about non unique results. If the contours cross, then they must cross in other representations as well, be it at impractical *Uw* and *Uo*.

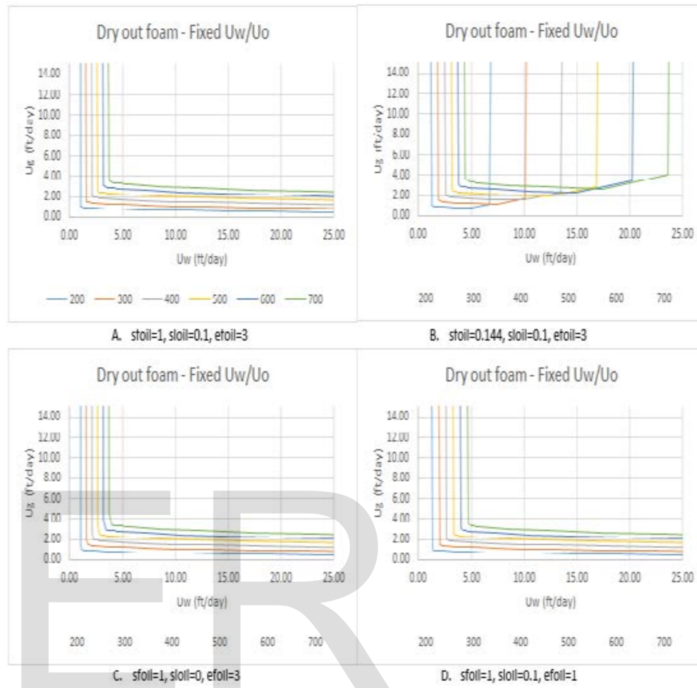

Figure 9: Dry-out Foam model in the presence of oil: fixed Uo/Uw Ratio

Increasing *Sloil* does not affect the foam stability. Lowering *sloil* to in Figure 9 C is taken for understanding that foam will weaken at low *sloil*, shifting a segment of the vertical contours from left to right. Increasing the e*foil* stabilizes and decreasing it will destabilize the foam (Figure 9 A to D).

3.3 Oil Relative Permeability Functions

Stone's relative permeability function involves the three-phase saturation unlike Corey's permeability function (Power Law) which is deemed suitable for two-phase system. The results for Stone's calculated oil relative permeability are given below (Figure 10), compared with Corey's relative permeabilities, plotted against oil saturation.

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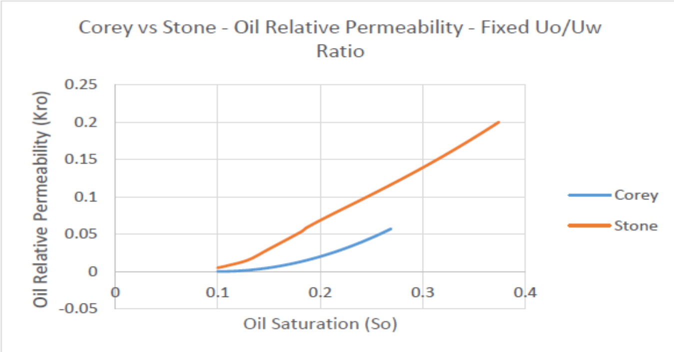

Figure 10: Comparison of Corey and Stones Oil Relative Permeabilities with saturation (Fixed Uw/Uo ratio)

Comparing Figure 11 and Figure 12, we can see the variation and error in our previous models for wet and dry-out foam for fixed *Uw/Uo* ratio. *Stone*'s model is widely accepted model for its accuracy in three phase systems.

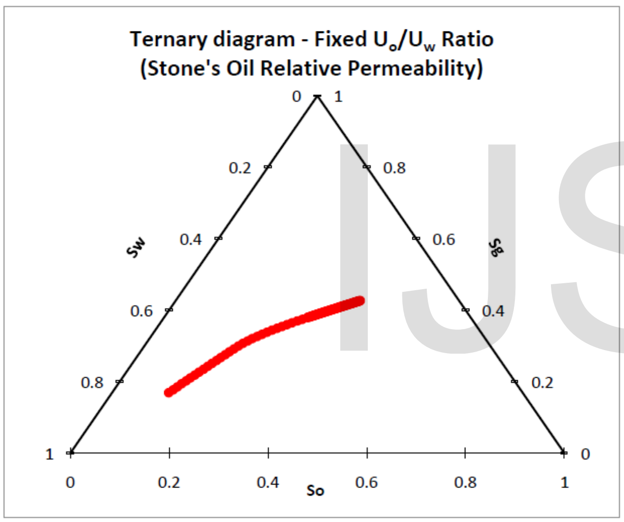

Figure 11: Ternary diagram showing Stone's saturation profile for pressure gradient at 200 psi/ft for fixed Uw/Uo ratio

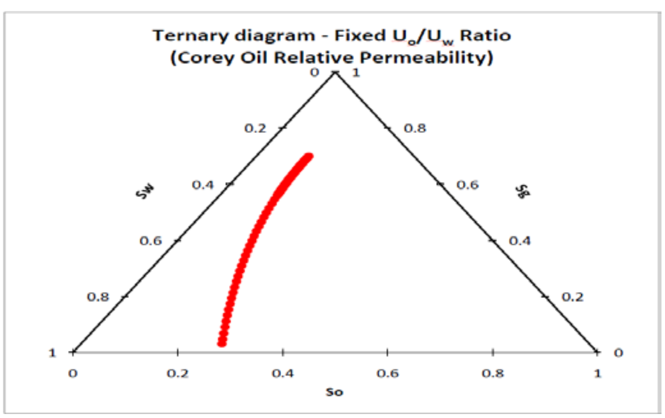

Figure 12: Ternary diagram showing Corey's saturation profile for pressure gradient at 200 psi/ft for fixed Uw/Uo ratio

In the case with fixed superficial oil velocity, Stone's saturation profile is variable at fixed relative oil permeabilities. The gas saturations are changing in such a trend that oil relative permeabilities remain constant but the oil saturation keeps changing. Figure 13 shows the above mentioned statement.

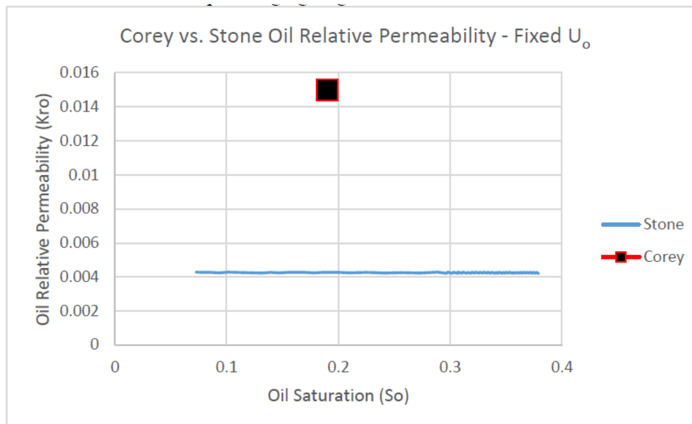

Figure 13: Comparison of Corey and Stones Oil Relative Permeabilities with saturation (Fixed Uo)

Figure 14 and Figure 15 shows the variation and error in previous model for wet and dry-out foam at fixed *Uo*. In Corey's calculations, the oil saturation determined was fixed at *So* = 0.19. In Stone's calculation, there exist a long range of oil saturations present for the same oil relative permeability.

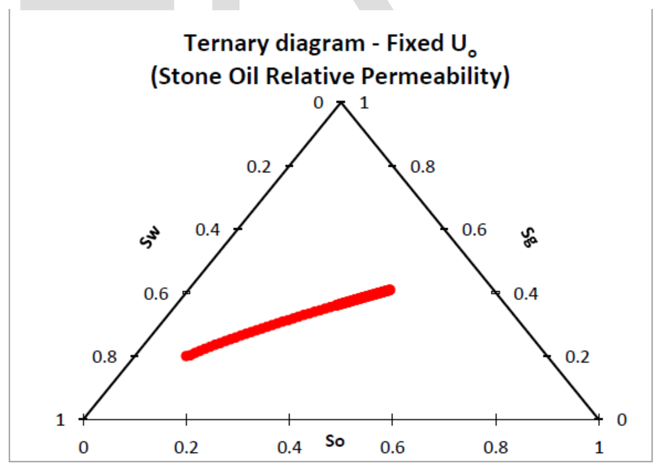

Figure 14: Ternary diagram showing Stone's saturation profile for pressure gradient at 200 psi/ft for fixed Uo

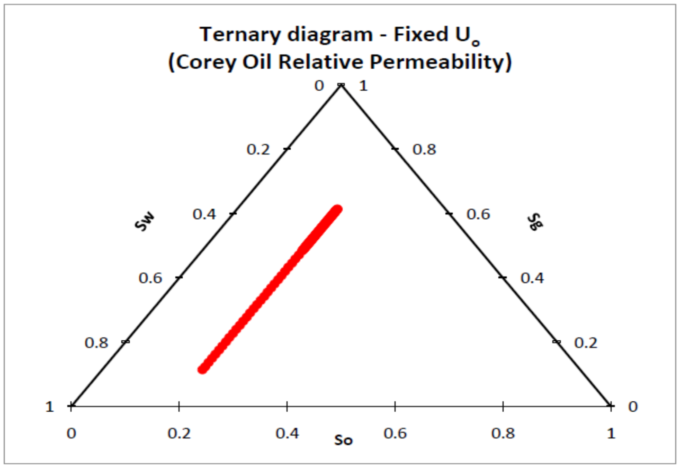

Figure 15: Ternary diagram showing Corey's saturation profile for pressure gradient at 200 psi/ft for fixed Uo

4 CONCLUSIONS

● The two foam flow-regime can be demonstrated using *STARSTM* parameters with oil in the system for both wet and dry-out foam option.

●The oil related parameters in wet-foam model only affect the low-quality regime and cause no change in the high-quality regime implying that the critical water saturation determining the flow behaviour in of foam in high-quality regime is constant under this model in the presence of oil.

● In the dry-out model, the oil-dependent function impacts only the high-quality regime.

● The increment in upper-limiting oil saturations (*fmoil* and *sfoil*) & lower-limiting oil saturations (*floil* and *sfoil*) in both the models (wet and dry-out, respectively) increases the foam tolerance to the detrimental effect of oil on foam.

● The oil exponent (*epoil*) in wet-foam model makes the foam independent of the effects of oil when lowered and vice versa. In the dry-out foam model, the oil exponent (*efoil*) negates the effects of oil when decreased and vice versa. Hence, the oil exponent behave unlike as compared to the upper-limiting oil saturation and the lower-limiting oil saturation behaving the same in both wet and dry-out foam models.

● Oil saturations below lower-limiting oil saturation has no effect on foam stability. Oil plays a destabilising role when the oil saturation lie between lower and upper limiting saturation, making the foam weaker with oil saturation approaching the upper-limiting oil saturation. If the oil saturation becomes greater than the upper-limiting oil saturation, the foam collapses totally despite the any value of water saturation.

● Incorporating Stone's model makes the foam models sensitive to oil dependent parameters as the oil saturations has a wider variance when compared to Corey's saturation profile.

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