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Investigating the Effect of Different Flood Patterns on Field Performance During Foam Enhanced Oil Recovery

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Abstract

Foam flooding has been successfully implemented in solving problems that arise during gas flooding as it increases gas viscosity and reduces gas relative permeability resulting in favorable mobility ratios and better volumetric sweep efficiency. This research study aims to evaluate the effect of different flood patterns on field performance during foam enhanced oil recovery. A three-dimensional reservoir simulation model was developed with a reservoir simulator and each flood pattern including normal and inverted four, five, seven, and nine-spots were modeled and simulated separately under consistent conditions of field gas injection rate, bottom-hole pressure of production wells, and surfactant concentration. Field Oil Efficiency (FOE), Net Present Value (NPV), Rate of Return (ROR), and Payout Time (POT) were used in making comparisons. An Original Oil in Place of 139.43 MMSTB was found at the initialization. Simulation results showed that a normal and an inverted five-spot pattern were more effective in their respective categories as they resulted respectively in higher FOE, lower FGOR, higher NPV and ROR, and shorter POT. An inverted five-spot resulted in an FOE of 4.36 %, an NPV of $ 83.48 million, and an ROR of 13.64% higher than that obtained for a normal five spot, and a payout time of 1.54 years shorter than that obtained for the normal five spots. The findings highlight the superior efficiency of the normal and inverted five-spot patterns, with the inverted five-spot pattern demonstrating significantly better performance in terms of FOE, NPV, ROR, and POT. Based on the presented results, an inverted five-spot pattern was recommended in this paper as the best flood pattern during foam-enhanced oil recovery applications.

Keywords: Foam Flooding, Flood Patterns, Field Oil Efficiency, Net Present Value, Rate of Return, Payout Time

1. Introduction

It is reported in the literature that about $2.0\ x\ 10^{12} bbls$ and $5.0\ x\ 10^{12} bbls$ of conventional and heavy oil respectively remains untapped in petroleum reservoirs after primary and secondary recovery processes have been implemented [1]. Untapped or bypassed oil can only be recovered using enhanced oil recovery methods. Ahmed and Meehan also reported that Primary, Secondary, and Tertiary recovery processes will result respectively in 25 %, 30 %, and 45 % of Original Oil in Place for light oils, and 5%, 5%, and 90% of original oil in place for heavy oils respectively as shown in Figure 1 [2]. A variation of flow rate and oil recovery for each oil recovery process with time is also presented in Figure 2.

Figure 3 shows a detailed classification of oil recovery processes [3]. Primary recovery of petroleum refers to the production of hydrocarbons under natural driving mechanisms present in the reservoir while secondary recovery involves hydrocarbon production in which water injection and/or immiscible gas injection strategies are used to support production after the natural energy of the reservoir has exhausted. When primary and secondary recovery processes have been implemented, Enhanced oil recovery methods are then initiated to aid in the recovery of un-swept or bypassed oil.

Enhanced Oil Recovery is the process of producing recoverable oil after primary and secondary recovery processes have been conducted, and aims at extending the productive life of a field such that oil remaining in a reservoir or oil that could not be produced by primary and secondary processes could be recovered. This paper will focus more on foam-enhanced oil recovery. Gas injection is considered an acceptable Enhanced oil recovery strategy but suffers a lot of setbacks arising from high viscosity and density differences between oil and gas. This results in unfavorable mobility ratios ranging from 10-100. Boeije and Rossen also reported that unfavorable mobility ratios gave rise to viscous fingering, gravity override, and gas segregation, all of which led to an early gas breakthrough, poor sweep efficiency, and poor recovery [4]. A disadvantage of early gas breakthroughs is the additional cost incurred in recycling and reinjection of produced gas. Gas flooding in heterogeneous oil reservoirs will result in gas channeling as the gas will flow preferentially towards the layers of high permeability causing more oil to be left un-swept by injected gas in the layers of lower permeability [5]. There is also a tendency for gas to segregate to the top of the reservoir since gas density is lower in comparison with that of oil, and as a result, more oil will be bypassed by the gas [6].

Christensen et al. (1998) Christensen et al. reported that Water Alternating Gas (WAG) reduces gas mobility, the result of which is an increase in sweep efficiency and an improvement in oil recovery [7]. Other authors [8], [9] conducted pilot tests and simulation studies on WAG, and

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their results showed that gas segregation and viscous fingering reoccurred because the reduction of gas mobility by WAG was insignificant.

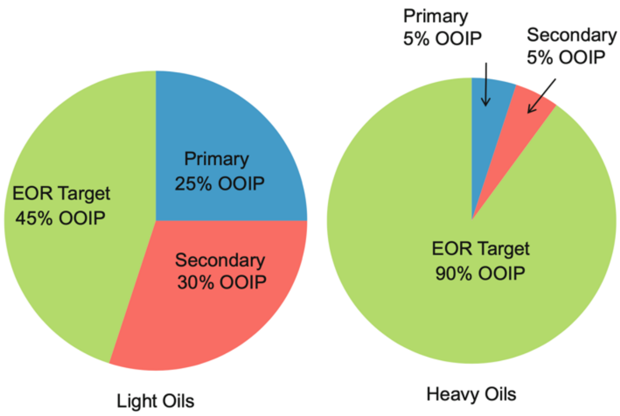


Fig. 1 Oil Recovery Target for Oil Recovery Processes for different crudes [2]

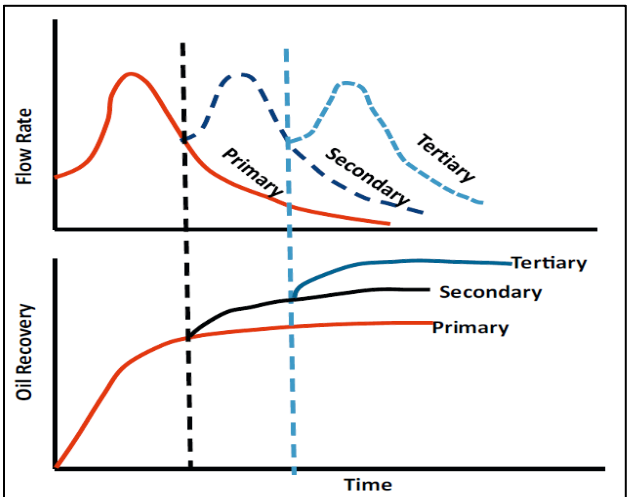


Fig. 2. Variation of flow rate and oil recovery for each oil recovery process [2]

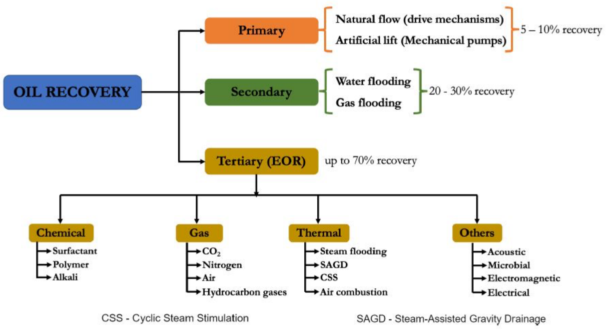


Fig. 3. Classification of Oil Recovery Processes [3]

A solution to these problems is injecting foam in place of gas. A foam is a dispersion of a non-wetting phase (gas) in a continuous wetting phase which is a liquid (water) containing surfactant at a concentration that is above the critical micelle concentration [10]. Surfactant injected with gas lowers the water-oil interfacial tension, causing the oil to become more mobile as the capillary pressure between the oil and water is reduced. The presence of foam also results in a reduction in gas mobility since it increases the apparent viscosity and reduces the relative permeability of the gas. As a result, favorable mobility ratios are achieved with foam injection which has the overall effect of achieving a uniform sweep of oil to the production wells (Figure 4), resulting in an improvement in oil recovery.

Mobility ratio is defined as the ratio of the mobility of the displacing fluid (Gas or Foam) to the mobility of the displaced fluid (oil) given mathematically by:

$$M = \frac{\lambda_{displacing}}{\lambda_{displaced}} = \frac{\lambda_{gas/foam}}{\lambda_{oil}} = \frac{K_{rg}/\mu_g}{K_{ro}/\mu_o} \quad (1)$$

Based on equation 1, having low displacing fluid mobility will result in a corresponding decrease in Mobility ratio which gives a better sweep and an improvement in oil recovery. This phenomenon is exhibited by foam. Simulation studies were performed to compare the effectiveness of gas and foam flooding as Enhanced Oil recovery strategies [11], [12], and their results showed that foam accelerated production and led to an increase in reserves in comparison with gas. This is a clear indication that foam flooding was more effective technically and economically than gas flooding as an enhanced oil recovery technique.

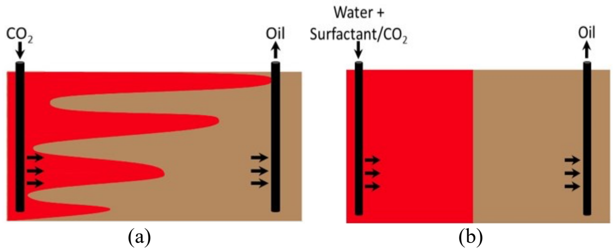


Fig. 4. Comparison of the sweep of oil between (a) gas flooding and (b) foam flooding [10]

Foam flow in porous media can be modeled using population balance and local equilibrium models [13], [14]. [13]. According to Ma et al., foam modeling techniques are designed to modify gas relative permeability and/or gas viscosity in porous media, and the viscosity and relative permeability of gas are physically separable but mathematically, they are not [13]. This is because they are tied to one another by Darcy's equation as shown in Equation 2

$$U_g = \frac{K K_{rg} \nabla P_g}{\mu_g} \quad (2)$$

Foam models have been developed for use in reservoir simulators such as UTCHEM, CMG STARS, and Eclipse 100 to aid in describing and simulating foam enhanced oil recovery processes [15]. Foam can be injected into porous media in four main ways [14]:

a) Co-injection of gas and aqueous surfactant solution involves the simultaneous injection of both fluid components from a single well into the reservoir.
b) Surfactant-alternating-gas (SAG) in which surfactant and gas are injected as separate slugs from a single well.
c) Dissolving surfactants in supercritical Carbondioxide such that as they come in contact with water in the reservoir, foam is formed
d) Injecting surfactant solution and gas into different layers of the reservoir.

The objectives of this current study will be achieved using Eclipse 100 reservoir simulator, hence, the need to present in this paper the foam model used in Eclipse [15], [16] and are presented in equations 3a to 3f

$$K_{rg}^{f} = K_{rg} \times M_{rf} \tag{3a}$$

$$M_{rf} = \frac{1}{1+(M_r \times F_s \times F_w \times F_o \times F_c)} \tag{3b}$$

$$F_s = \left(\frac{C_s}{C_s^r}\right)^{e_s} \tag{3c}$$

$$F_w = 0.5 + \frac{\operatorname{atan}\left(f_w\left(S_w - S_w^l\right)\right)}{\pi} \tag{3d}$$

$$F_o = \left(\frac{S_o^m - S_o}{S_o^m}\right)^{e_o} \tag{3e}$$

$$F_c = \left(\frac{N_c^r}{N_c}\right)^{e_c} \tag{3f}$$

Different flooding patterns for improving areal sweep efficiency during waterflooding projects as shown in Figure 5. The author distinguished between normal and inverted flood patterns identified by one producer and one injector per flood pattern respectively. These flood patterns were applied in this paper to investigate and compare their individual effects on-field performance during foam enhanced oil recovery to select an optimum flood pattern for foam flooding projects.

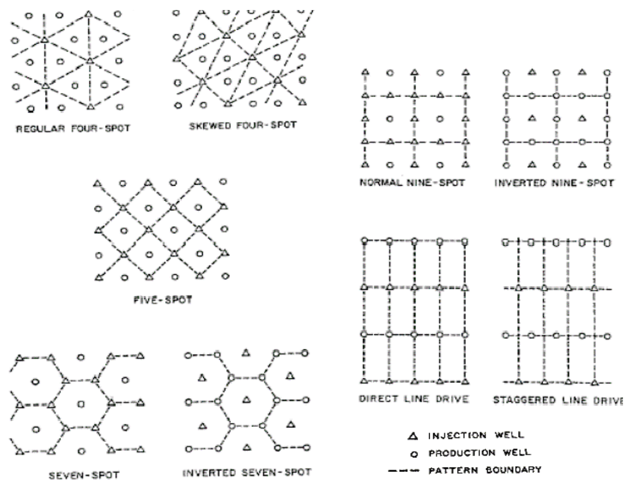


Fig. 5. Flooding patterns [17]

A proper flood pattern is that which enables the injection fluid to have maximum contact with the crude oil system within the reservoir [18]. The author reported that it may be desirable to convert production wells to injection wells or to drill new injection wells. Well arrangements were classified as irregular, peripheral, regular, crestal, and basal injection patterns [18].

Several well patterns were investigated on various secondary and tertiary recovery methods using Eclipse 100 reservoir simulator [19]. Results selected a five-spot as an optimum well pattern because, for all recovery scenarios, Field Oil Efficiency (FOE) and Distance Equality Factor (DEF) for the five-spot pattern were higher than those obtained for the other well patterns. The authors also used Field Oil Efficiency and Net Present Value in selecting an optimum recovery method for the field, and results showed that Foam Assisted Water Alternating Gas (FAWAG) method exhibited better recovery performance because of higher FOE's and NPV's that were obtained in comparison with other recovery scenarios.

Waterflooding simulation studies were conducted to determine the profitability of different flooding patterns in the Kube offshore field [20] and their results showed that a normal 5-Spot pattern provided maximum recovery in comparison with a direct line drive which was the least efficient flood pattern.

The main objective of this study is to use a numerical simulation approach in selecting a suitable flood pattern for foam flooding applications. The criteria considered in this paper are:

a. A high Field Oil Efficiency or Oil Recovery Factor
b. A low Field Gas Oil Ratio
c. A high Net Present Value
d. A High Rate of Return
e. An earlier Payout time

The flood pattern that meets the stated criteria is selected and recommended for foam flooding applications

2. Methodology

A reservoir simulator was used in conducting simulation studies to compare and evaluate the effect of different flooding patterns on Field Recovery Performance during foam enhanced oil recovery. A 3D reservoir simulation model with a porosity of 30 % and a permeability of 500 md, 50 md, and 200 md for layers 1, 2, and 3 respectively was developed and used to model the different flooding patterns proposed by Craig [17].

The reservoir model was constructed on a Cartesian grid with a block-centered geometry, having a 7 x 7 x 3 grid with dimensions of 1000 ft. x 1000 ft. x 20 ft. respectively using a Reservoir Simulator. In this paper, field gas injection rate and surfactant concentration were fixed at 100 MSCF/DAY and 1.1 LB/STB respectively. The oil production rate was controlled by bottom-hole pressure and was fixed at 2000 PSIA for all production wells. The injection and production wells for each case were completed respectively on layers one and three. The flooding patterns that were considered were normal and inverted four, five, seven, and nine spot patterns (Figure 5) and were modeled using Eclipse 100 reservoir simulator and presented in Figures 6 to 9.

For the normal flood patterns (one producer per flood pattern), the gas injection rate for each well was defined as the ratio of field gas injection rate to the number of gas injection wells (Equation 4) while surfactant concentration was the same for each injection well. Similarly, for the inverted flood patterns (one injector per flood pattern), the total gas injection rate and surfactant concentrations remained unchanged because only one gas injection well was operational for each flood pattern.

$$\text{well gas injection rate} = \frac{\text{field gas injection rate}}{\text{number of gas injection wells}} \tag{4}$$

For the two scenarios (normal and inverted flood patterns), field gas injection rate, and surfactant concentration were fixed at 100 MSCF/DAY and 1.1 LB/STB respectively. The production wells for all scenarios were controlled by bottom-hole pressure and fixed at 2000 PSIA. This approach created equilibrium between all flooding patterns such that equal volumes of gas and foam were injected for each scenario. This made it possible for oil recovery performance to be a function of a given flood pattern.

An economic analysis was further conducted in this paper to comparatively assess the profitability of each flood pattern. Output data from reservoir simulation was used as input data in the calculation of Net Present Value (NPV), Rate of Return (ROR), or Return on Investment (ROI), and Payout time (POT) defined mathematically by equations 5 to 7 [21].

$$\text{NPV} = (\text{present value of discounted cash flow at a given rate i}) - \text{capital investment} \quad (5)$$

Table *2* shows the number of injection and production wells, individual gas injection rates, bottom-hole pressure constraint of the production wells, and well surfactant concentrations per stock tank barrel for all the flood patterns considered in this paper.

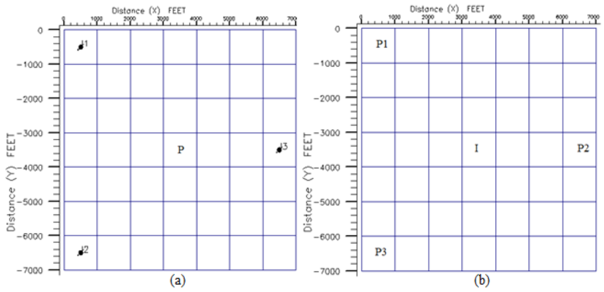


Fig. 6. (a) Normal Four Spot and (b) Inverted Four Spot

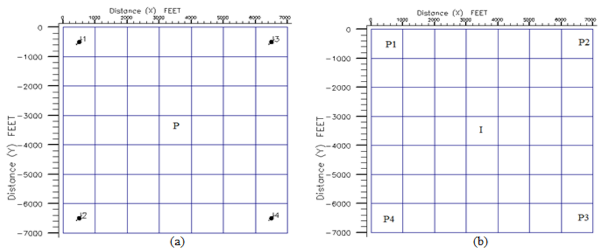
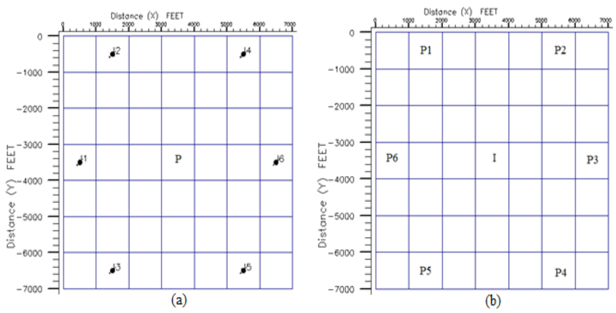


Fig. 7. (a) Normal Five Spot and (b) Inverted Five Spot



$$\text{R.O.I.} = \left(\frac{\text{annual profit}}{\text{capital investment}}\right) * 100 \quad (6)$$

$$\text{Payout Period} = \frac{\text{capital investment}}{\text{average annual cash flow}} \quad (7)$$

Table **1** shows additional data used in this paper in developing the reservoir model while

Fig. 8. (a) Normal Seven Spot and (b) Inverted Seven Spot

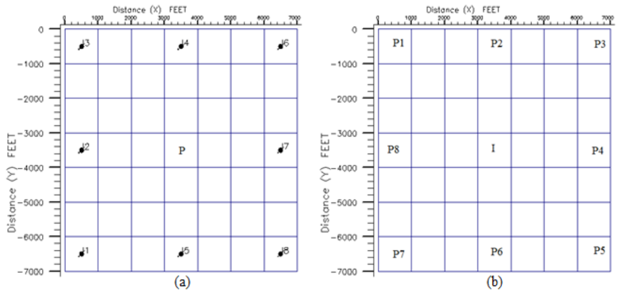


Fig. 9. (a) Normal Nine Spot and (b) Inverted Nine Spot

Where, $I_1, I_2, \ldots\ldots\ldots\ldots, I_n$ represents injection wells, and $P_1, P_2, \ldots\ldots\ldots\ldots, P_n$ represents production wells

Table 1. Reservoir Model Parameters

Property	**Value**
API Gravity	45°API
Gas Gravity	0.06054
Water Density	64.79 Ibm/ft^3
Datum Depth	8400 ft.
Pressure at Datum Depth	4800 psia
Net Reservoir Thickness	60 ft.
Depth of Oil Water Contact	8500 ft.
Depth of Gas Oil Contact	8200 ft.
Bottom-hole Pressure for Production Wells	2000 psia
Total Field Gas Injection rate	100 MSCF/DAY

Table 2. Reservoir Simulator Input Data

Flooding Pattern	**Number of Injection wells**	**Number of Production Wells**	**Gas Injection Rate per well MSCF/Day**	**Surfactant Concentration IB/STB**	**Bottom-hole Pressure for oil production wells**
Normal Four Spot	3		33.33		
Normal Five Spot	4		25.00		
Normal Seven Spot	6	1	16.67		
Normal Nine Spot	8		12.50	1.1	2000
Inverted Four Spot		3			
Inverted Five Spot		4	100		
Inverted Seven Spot	1	6			
Inverted Nine Spot		8			

3. Results and Discussion

3.1 Results

Figures 10 to 18 show simulation results for each of the normal and inverted flood patterns. Figure 14 shows that, a total of $7.81\,x\,10^{8}Lb$ of foam was injected for all flood patterns during the period of simulation. All the flood patterns considered in this paper were simulated separately and their respective effects on reservoir performance were compared.

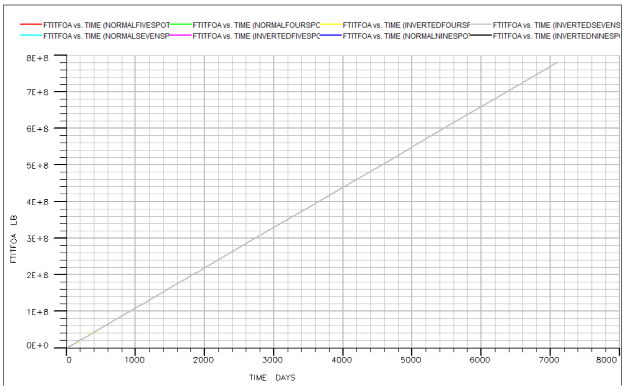


Fig. 10. Field Foam Injection Total for all Flood Patterns

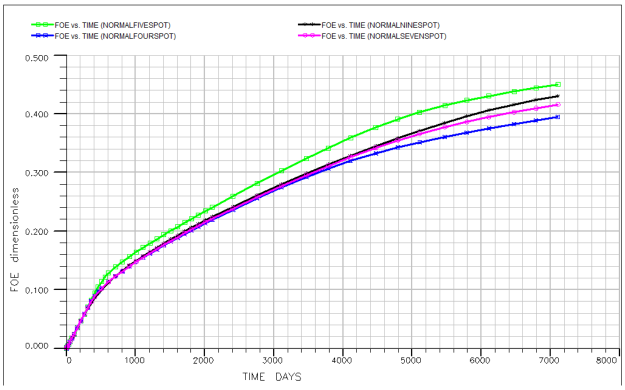


Fig. 11. Field Oil Efficiency for Normal Flood Patterns

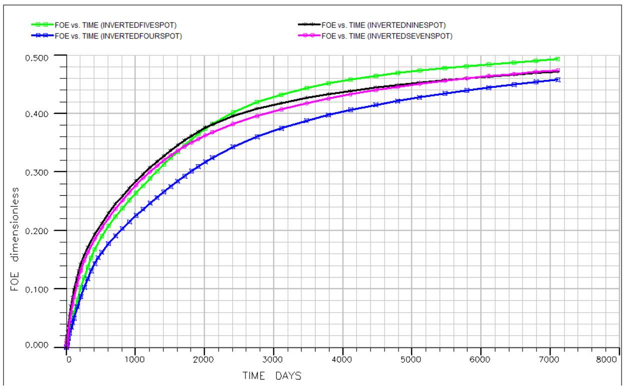


Fig. 12. Field Oil Efficiency for Inverted Flood Patterns

Table **3** shows a summary of cumulative oil and gas produced, and total foam injected for all flood patterns. The total foam injected was obtained from Fig. *10*, and was found to be the same for all flooding patterns considered in this paper. Cumulative oil produced was obtained from Fig. *15* and Fig. *16*, and cumulative gas produced from Fig. *17* and Fig. **18** for normal and inverted flood patterns respectively.

Table *4* shows the capital investment components with their respective costs. These data were used to carry out economic analysis using Net Present Value (NPV), Rate of Return (ROR), and Payout Time (POT) as economic indicators, expressed mathematically by equations 5, 6, and 7 respectively.

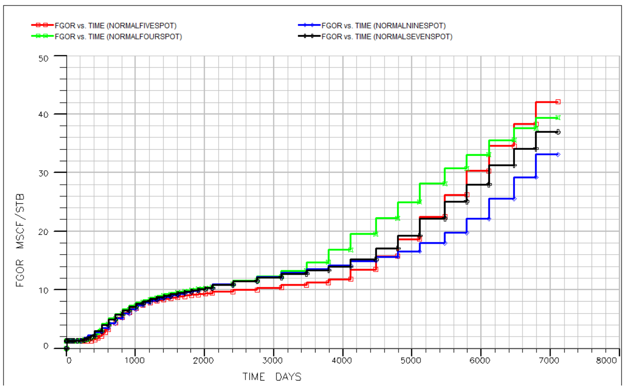


Fig. 13. Field Gas Oil Ratio for Normal Flood Patterns

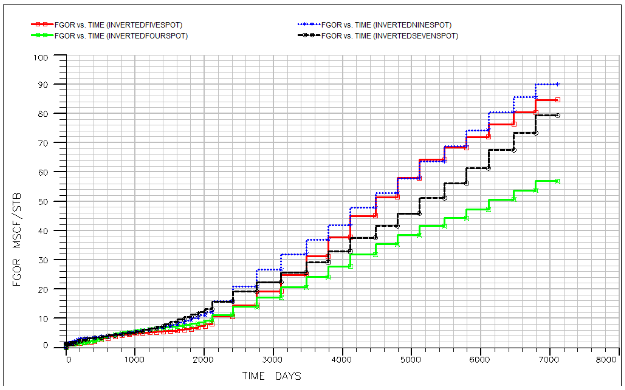


Fig. 14. Field Gas Oil Ratio for Inverted Flood Patterns

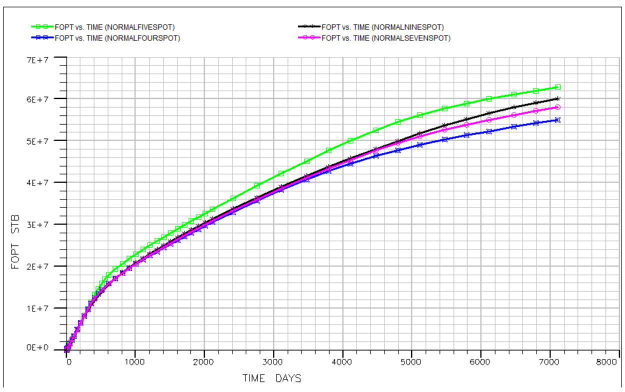


Fig. 15. Field Oil Production Total for Normal Flood Patterns

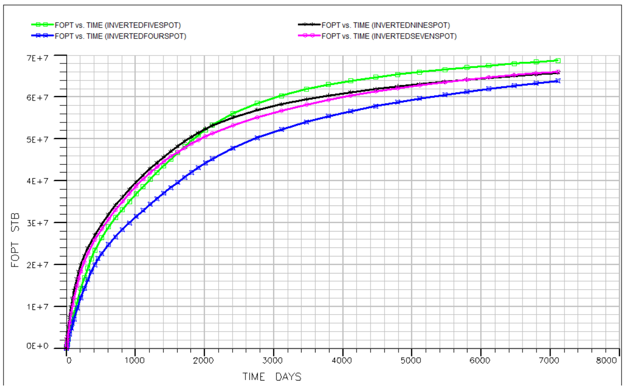


Fig. 16. Field Oil Production Total for Inverted Flood Patterns

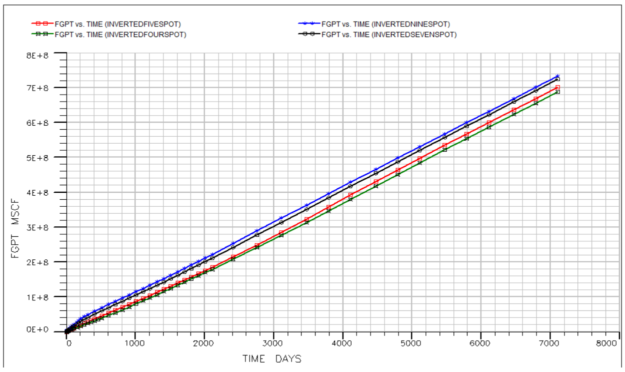


Fig. 18. Field Gas Production Total for Inverted Flood Patterns

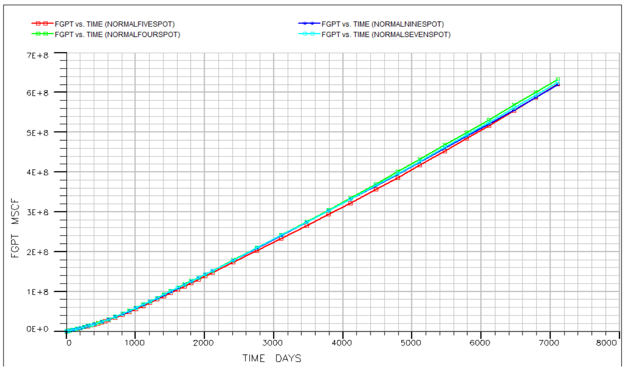


Fig. 17. Field Gas Production Total for Normal Flood Patterns

Table 3. Outputs from Reservoir Simulator

Flooding Patterns	Cumulative Oil Produced MMSTB	Cumulative gas produced MSCF	Cumulative Foam Injected LB	Number of Production Wells	Number of Injection wells
Normal Four Spot	54.99	$6.33 \, x \, 10^8$	$7.81 \, x \, 10^8$	1	3
Normal Five Spot	62.76	$6.21 \, x \, 10^8$			4
Normal Seven Spot	57.96	$6.26 \, x \, 10^8$			6
Normal Nine Spot	60.00	$6.19 \, x \, 10^8$			8
Inverted Four Spot	63.85	$6.87 \, x \, 10^8$		3	1
Inverted Five Spot	68.75	$7.00 \, x \, 10^8$		4	
Inverted Seven Spot	66.08	$7.24 \, x \, 10^8$		6	
Inverted Nine Spot	65.75	$7.33 \, x \, 10^8$		8	

Table 4. Capital Investment Components and Costs

Injection well Construction Cost ($MM)	4
Production Well construction Cost ($MM)	4
Foam Injection Cost ($/Lb.)	5
Oil Price ($/STB)	50
Gas Price ($/MSCF)	4
Interest Rate	10 %
Tax Rate	13%

Equations 8 to 15 were used in performing Calculations which led to the results presented in Table 5.

$$\text{Capital Investment} = \text{drilling and well completion cost (injectors and producers)} + \text{foam injection cost} \quad (8)$$

$$\text{Total Revenue} = (\text{cumulative oil produced} * \text{oil price}) + (\text{cumulative gas produced} * \text{gas price}) \quad (9)$$

$$\text{Income Tax} = \text{Total Revenue} * \text{Tax Rate} \quad (10)$$

$$\text{Net Income} = \text{Total Revenue} - \text{Income Tax} \quad (11)$$

$$\text{Net Operating Profit} = \text{Net Income} - \text{Capital Investment} \quad (12)$$

$$\text{Net Present Value of Operating profit} = \frac{\text{Net Operating Profit}}{(1+i)^n} \quad (13)$$

$$\text{Rate of Return} = \left(\frac{\text{Operating Profit}}{\text{Capital Investment}}\right) * 100\% \quad (14)$$

$$\text{Payout Time} = \frac{\text{capital investment}}{\text{net income}/n} \quad (15)$$

Table 5. Economic Assessment of Normal and Inverted Flood Patterns during Foam EOR

Flood Patterns	Capital Investment $MM	Cumulative Oil Produced MMSTB	Cumulative Gas Produced MMSCF	Total Revenue $MM	Income Tax @ 13% Tax rate $MM	Net Income, $MM	Net Operating Profit, $MM	Net Present Value of Operating Profit at i = 10% $MM	Rate of Return %	Payout Time Years
Normal Four Spot	3921	54.99	633	5282.0	686.60	4594.91	673.91	105.06	17.187	16.64
Normal Five Spot	3925	62.76	621	5622.0	730.86	4891.14	966.14	150.62	24.615	15.648
Normal Seven Spot	3933	57.96	626	5402.0	702.26	4699.74	766.74	119.53	19.495	16.319
Normal Nine Spot	3941	60	619	5476.0	711.88	4764.12	823.12	128.32	20.886	16.131
Inverted Four Spot	3921	63.85	687	5940.5	772.27	5168.24	1247.24	194.44	31.809	14.794
Inverted Five Spot	3925	68.75	700	6237.5	810.88	5426.63	1501.63	234.10	38.258	14.104
Inverted Seven Spot	3933	66.08	724	6200.0	806	5394.00	1461.00	227.77	37.147	14.218
Inverted Nine Spot	3941	65.75	733	6219.5	808.54	5410.97	1469.97	229.16	37.299	14.203

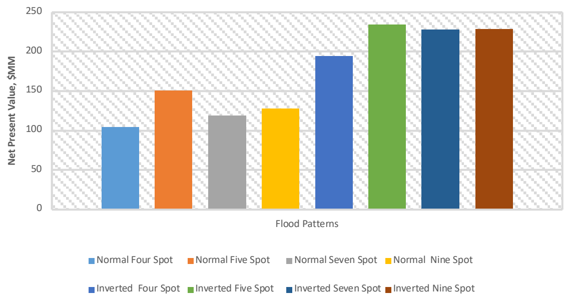


Fig. 19. Net Present Value for all Flood Patterns

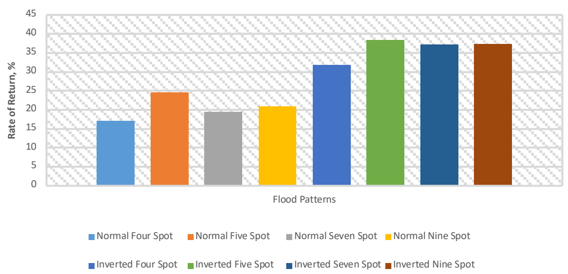


Fig. 20. Rate of Return for all Flood Patterns

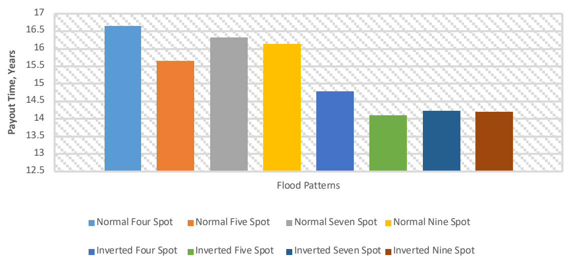


Fig. 21. Payout Time for all flood Patterns

3.2 Validation of Results

In this paper, a normal and inverted five-spot were found to be more efficient in their respective categories. This was validated by comparing the distance equality factor for the four, five, seven, and nine-spot patterns with their respective Field Oil Efficiencies (FOE's). Bagrezaie & Pourafshary [19] defined the distance equality factor (DEF) between injectors and producers by the following mathematical equation (Equation 16).

$$DEF = \left[1 - \left(\frac{Average\ D_{(i,P)} - Minimum\ D_{(i,p)}}{Average\ D_{(i,p)}}\right)\right] * 100\% \qquad (16)$$

$$Average\ D_{(i,P)} = \frac{\sum_{n=1}^{n} D_n}{n} \qquad (17)$$

Where $Average\ D_{(i,P)}$ denotes the average distance between injectors and producers for each flood pattern, and $Minimum\ D_{(i,p)}$ denotes the minimum distance between injectors and producers in each pattern.

DEF varies from 0% to 100% for unfavorable and favorable DEF's respectively, and a higher DEF delays the breakthrough of injected fluid. The overall effect of a higher DEF is an improvement of the efficiency of the well pattern, hence higher oil recovery factor or Field Oil Efficiency. Table 6 shows the distance equality factor (calculated from equation 16) for each well pattern considered in this paper and compared to the Field Oil Efficiency results of Fig. **11** and Fig. **12**.

Table 6. A comparison between Distance Equality Factor and the Field Oil Efficiency for Normal and Inverted Flood Patterns

Flood Pattern	Distance Equality Factor (DEF) %	Field Oil Efficiency for Normal Flood Patterns (Extracted from Fig. 11) %	Field Oil Efficiency for Inverted Flood Patterns (Extracted from Fig. 12) %
Four Spot	78.36	39.44	45.79
Five Spot	100.00	45.01	49.31
Seven Spot	88.14	41.57	47.39
Nine Spot	82.84	43.03	47.16

The Distance Equality Factor results show that a normal and an inverted five spot would result to better volumetric efficiency in comparison with other flood patterns because a DEF of 100% was obtained. This is shown by higher Field oil

Efficiency for the normal and inverted five spots. For the Inverted Flood Patterns, FOE increases with an increase in DEF indicating the same trend in the following order: four, nine, seven, and five spot patterns. However, a slight variation exists for the FOE in moving from a normal nine spot to seven spot.

Also, in this paper, an inverted five spot was found to be a suitable flood pattern for foam enhanced oil recovery processes. This was validated by comparing the results of this current study and the results presented by Bagrezaie & Pourafshary in which the performances of various flood patterns for numerous oil recovery processes were compared [19]. Results presented by the authors showed that an inverted five spot was preferred for all the considered oil recovery processes including Foam and Foam Assisted Water Alternating Gas injection methods. Their results are in agreement with the results obtained in this paper.

3.3 Environmental Impact of Application of Surfactants and Foams in EOR

In a study where the application and environmental risks of surfactants are documented, it can be seen that surfactants can be simultaneously useful and detrimental to the environment [22]. Other researchers suggested the withdrawal of highly toxic and non-biodegradable compounds from commercial use and replacing them with more environmentally friendly surfactants [23]. Extensive research has been conducted on identifying and evaluating the performance and environmental risks associated with the use of natural surfactants as an alternative to commercial surfactants in Enhanced Oil Recovery applications [24]–[27]. Results from their studies showed that natural or locally sourced surfactants which are proven to be environmentally friendly, met the performance requirements of commercial surfactants. Co-injection of the natural or local surfactants with gas to form foam for enhanced oil recovery has not yet been investigated and future work in this direction will critically evaluate its feasibility.

4. Discussion

Foam results from injecting a combination of gas and a liquid containing surfactant, and since the total field gas injected and surfactant concentration in the well stream for all injection well cases were the same, the total Field Foam Injected for all cases would also be the same and found to be $7.81\ x\ 10^8\ Lb$ as shown in Fig. **10**. The presence of foam reduces gas mobility which yields favorable mobility ratios, resulting in a delay in gas breakthrough, low gas production volumes, low field gas-oil ratio, and better oil recovery.

The Original Oil in Place (OOIP) or Field Oil in Place (FOIP) at initialization of the developed reservoir simulation model was found to be 139.43 MMSTB. Figure 11 and Figure 12 show respectively a comparison of Field Oil Efficiency for normal and inverted flood patterns, and results show that a normal and an inverted five-spot yielded FOE's of 45.01% and 49.37 % respectively which was higher than that obtained by respective flood patterns of the same category. This is because more contact occurred between the injected fluid (foam) and the oil zone for the normal and inverted five-spot patterns than with the flood patterns of the same category. This resulted in better macroscopic and microscopic displacement of oil, which led to an improvement in volumetric efficiency and oil recovery. Also, the distance between injector(s) and producer(s) for the normal and inverted five spots are longer than that of other flood patterns causing a delay in the breakthrough of the injected fluid, hence better recovery.

However, the inverted five spot was found to be more efficient than the normal five spot since it resulted in a Field Oil Efficiency of 4.36 % higher than that obtained for the normal five spot. This is because, for the inverted five spot, four production wells were available to drain oil from the reservoir in comparison to the normal five spot which had only one production well. Hence, the higher the number of production wells, the higher the production and oil recovery.

Results from Fig. **13** also show that, during the mid-simulation period, the normal five spot resulted in the lowest FGOR, which increased gradually thereafter, but the FGOR for the normal nine spot was found to be lowest at the end of the simulation while the normal four spot yielded the highest FGOR. For the inverted flood patterns, the four spot resulted in the lowest FGOR while the five and nine spots yielded high FGOR's .

An economic evaluation was conducted for all flood patterns and results are presented in Table 5 and illustrated in Fig. 19, Fig. 20, and Fig. 21, which shows a comparison of NPV, ROR, and POT for all flood patterns considered in this paper respectively. For the normal flood patterns, a normal five spot resulted to the highest NPV ($ 150.62 million) while the Four Spot gave the lowest NPV ($ 119.53 million). An inverted five spot also resulted in the highest NPV ($ 234.10 million) while the four spot was the lowest ($ 194.44 million). Similarly, the rate of return for the normal and inverted five spot (24.615% and 38.258% respectively) were found to be highest in their respective categories. Results also show that the payout time for the normal and inverted five spot (15.648 years and 14.104 years respectively) were earlier in comparison with others of the same category.

A comparison between a normal and an inverted five spot shows that an inverted five spot was more profitable than a normal five spot for foam flooding applications because an inverted five spot resulted to an NPV of $ 83.48 million higher, a rate of return of 13.64% higher and a payout time of 1.54 years less than the NPV, ROR, and POT obtained for a normal five spot respectively.

5. Conclusion

Since gas flooding poses a lot of problems during its implementation in the field, and because foam flooding is more effective than gas flooding [11], [12], it is recommended to explore the use of foam flooding or foam assisted enhanced oil recovery methods after waterflooding. Results from simulation and economic analysis show that a normal and an inverted five spot pattern were more effective in improving reservoir performance depicted by higher Field oil efficiencies, Low Field Gas Oil Ratios, higher Net Present Values, a higher rate of return, and an earlier Payout Time. It can also be depicted from the results in Table 5 that the least-performing inverted flood pattern (inverted four spot) was more efficient than the best-performing normal flood pattern (normal five spot). Hence, if it is decided to implement foam flooding for an enhanced oil recovery project, inverted flood patterns should be used, and most especially, an inverted five spot pattern should be selected as it will result in better field performance in comparison with other inverted flood patterns.

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Nomenclature

FOIP	Field Oil in Place
FOPT	Field Oil Production Total
FGPT	Field Gas Production Total
FGOR	Field Gas Oil Ratio
FTITFOA	Field Foam Injected
NPV	Net Present Value
ROR	Rate of Return
POT	Payout Time
K_{rg}, K_{rg}^{f}	Gas relative permeability, Gas relative permeability with foam
K_{ro}	Oil Relative permeability
μ_o	Oil viscosity
μ_g	Gas viscosity
$\lambda_{displacing}, \lambda_{displaced}$	Mobility of displacing fluid, Mobility of displaced fluid
M	Mobility Ratio
U_g	Gas Velocity
∇P_g	Gas differential pressure gradient
M_{rf}	Mobility Reduction Factor

M_r	Reference Mobility reduction factor
F_s	Mobility reduction factor dependence upon surfactant concentration
F_w	Mobility reduction factor dependence upon water saturation
F_o	Mobility reduction factor dependence upon oil saturation
F_c	Mobility reduction factor dependence upon Capillary Number
C_s, C_s^r	Surfactant Concentration, Reference Surfactant Concentration
e_s	Exponent to control steepness of transition
S_w, S_w^l	Water Saturation, Limiting Water Saturation
S_o, S_o^m	Oil Saturation, Minimum Oil Saturation
e_o, e_c	Exponent to control steepness of the transition
N_c, N_c^r	Capillary Number, Reference Capillary Number
DEF	Distance Equality Factor
$Average\ D_{(i,P)}$	Average Distance between injectors and producers
$Minimum\ D_{(i,p)}$	Minimum distance between injectors and producers
D_n	Injector-Producer well connection
n	Number of connections between injectors and producers