Modelling and History Matching of Foam Field Pilot, Oseberg Field

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Abstract

Gas coning and breakthrough problems in production wells are common for reservoirs under gas injection, like Oseberg. One approach to reduce gas inflow is placement of a foam region around the production well. A pilot test was initiated to evaluate if foam has a potential for reducing gas inflow to the production wells.

This paper presents history match of a foam pilot performed in June 1994 in production well 30/9-B-27 at the Oseberg field, in the Norwegian sector of the North Sea. The reservoir is a homogeneous thick, high permeability sandstone demonstrating a high productivity under up dip gravity stable gas injection. The inevitable downwards development of the global gas-oil contact in the Oseberg field resulted in gas breakthroughs into B-27 well in January 1994.

The production history of B-27 prior to foam treatment was modelled in order to determine the drainage area of the well and to match the development of the gas-oil contact and observed production gas-oil ratio. Modelling of the foam pilot was done by using a simulator incorporating an empirical foam option. Sensitivity to critical reservoir and foam parameters in the model was evaluated. Foam pilot results were modelled and better understood through the simulation allowing recommendations for further optimisation and application of the foam process in the field.

Introduction

The Oseberg field is located in the Norwegian sector of the North Sea in blocks 30/6 and 30/9, some 140 km west of Bergen. The main part of the Oseberg field has been effectively producing under up dip hydrocarbon gas injection for several years [1]. Gravity stable gas

injection in the gas cap gradually descends the gas-oil contact (GOC) and to inevitable gas breakthrough into production wells situated down dip on the structure. The plateau oil production period will be limited by increased volumes of gas due to the gas handling restrictions on the platform. Therefore, timely application of gas blocking techniques is important for expanding the production life of the wells and maintaining stable levels of oil production in the field. Foam treatment of production well is regarded as one of the potential methods to reduce the effect of gas coning, to delay gas breakthrough, and to reduce gas production [2,3]. Well B-27 experienced gas breakthrough in January 1994 and was selected for a foam treatment pilot performed in June 1994. The details on planning, design and field performance are given in reference 4. A comprehensive well monitoring program was performed in the well. Gas saturation build-up, gas coning development and production GOR in the well were monitored by logging: thermal decay time log (TDT), spinner survey/production logging tool (PLT) and production measurements.

The production history of the well and GOR production tests were modelled in order to match the development of the GOC. Modelling of the foam process applied different approaches at various stages of the project. To investigate the potential for reducing gas coning by foam, an ideal placement was simulated by an ECLIPSE near well model. The sensitivity to reservoir and foam properties was further analysed by a segment, fine grid radial model using an empirical foam description of the STARS simulator. It's foam prediction capabilities has already been successfully tested in a number of steam and carbon dioxide foam injection projects [5,6]. The B-27 foam pilot was modelled using a full 3D, fine grid radial model (STARS). This paper will briefly discuss the results of

the simulations prior to the Oseberg foam test and will focus on history match of the pilot and evaluations.

Up dip gas injection and production well behaviour

The Oseberg field is produced under gravity stable up dip gas injection. The reservoir is a thick, high permeability homogeneous sandstone demonstrating a very high productivity. The reservoir consists of the Tarbert, Ness, Etive and Oseberg formations. In the Oseberg formation the permeability is in the Darcy range.

The up dip gas injection is accompanied by downwards development of the global GOC in the field. With time the continuous descent of the GOC will inevitably lead to gas coning and gas breakthrough problems in production wells.

The foam test was performed in production well 30/9-B-27. The schematic section of the B-27 well is shown in Figure 1.

Figure 1. Schematic section of the B-27 well.

The well is perforated in 5 intervals in the lower section of the Oseberg formation, 2638.0 to 2665.9 mTVD (3339.0-3374.3 mMD). B-27 has been on production since December 1988. In the 1988-1993 period the well was producing at an average oil rate of 5000 Sm³/d

with a solution GOR of 140.3 Sm³/Sm³. By January 1993 the cumulative production of the well exceeded 7.5 million Sm³ of oil. The TDT measurements of January 1993 indicated gas saturation build-up in the top layers of the Oseberg formation in B-27. The production oil rate of the B-27 well in 1993 and beginning of 1994 was reduced and maintained at the 2500 m³/d level. A comprehensive monitoring program was carried out [4]. The TDT log measurements of static GOC position in B-27 well are given in Table 1.

Table 1. Static GOC measurement in B-27.

TDT, date	Distance to top perforation interval, mTVD
25.01.93	27.0
20.05.93	19.3
05.09.93	13.0
28.01.94	7.0

According to the TDT measurements the velocity of the GOC descent in the B-27 well area in 1993 was 1.6 mTVD/month. An increase in the well's production GOR was observed in the beginning of 1994 as a result of gas breakthrough. The TDT measurement of January 28, 1994 indicated the GOC position only 7 mTVD above the top of the upper perforation interval.

Potential evaluation of the foam pilot required a representative geological model of the well area. The near well ECLIPSE model was constructed by refining the B-27 area in the full field Oseberg model. Description of the near well model is given in the Appendix A. The objectives of these simulations were to estimate the drainage volume of the well, to match the GOC movement in the well area, gas breakthrough and production GOR development. Matching simulation parameters were the surface injection rate and voidage displacement condition. The model parameters were calibrated to achieve history match of the well data. Gas saturation distribution and GOC movement during the 26 January 1993 - 29 January 1994 production period are shown in Figures 2a and 2b and may be compared to TDT measurements and GOC position data in Table 1.

Foam process modelling

The field scale reservoir simulator STARS which incorporates an empirical set of foam functionalities and rigorous tracking of foaming agent was used in the simulations [5,6,7]. The empirical foam formulation in the K-value STARS simulator utilises the basic assumption that foam generation and coalescence mechanisms occur in the reservoir whenever gas and surfactant coexist. Foam effects on gas mobility and flow pathways are modelled via modified relative permeability curves. The model allows to account for foam sensitivity to different factors through a dimensionless interpolation parameter (IP). The gas permeability used in each particular computation is obtained by interpolating between gas

Figures 2a. Gas saturation in B-27 location - 26 January 1993.

Figures 2b. Gas saturation in B-27 location - 29 January 1994 (after 14 days of shut-in).

and foam permeability curves using the following expression for Foam Mobility (FM):

$$FM = [1 + MRF \cdot IP]^{-1} \quad (1)$$

where:

$$IP = \left(\frac{w_s}{w_s^{\max}} \right)^{e_s} \left(\frac{s_o^{\max} - s_o}{s_o^{\max}} \right)^{e_o} \left(\frac{N_c^{\text{ref}}}{N_c} \right)^{e_v} \quad (2)$$

The term MRF specifies the reference Mobility Reduction Factor (see Nomenclature section).

A fine grid STARS model was built on the basis of the ECLIPSE simulation model. Radial segment representing one tenth of the ECLIPSE near well drainage volume was constructed. Several grid blocks near the wellbore were sized as fine as 0.1 m radially. The use of such fine grid radial model was dictated by the intention to capture important gravity-viscous effects near the wellbore and to estimate their influence on foam generation, since the injection volume of 1-2 wt % surfactant solution was expected to penetrate less than 10 meters into the reservoir [4]. The model has vertical reservoir thickness of 65.9 mTVD and radius of 645 meters (equal to the radius of the well drainage volume estimated from ECLIPSE simulations).

Since the GOC position in the simulated production period was very close to the top perforation interval, the flow occurring in the blocks far away from the well was not affecting the coning processes taking place near the wellbore. The computer time required for numerous STARS sensitivity simulations to be performed was a parameter setting a limit on the number of grid blocks in the model (400-450 grid blocks).

Two aqueous- (water and surfactant) and two oleic- (oil and hydrocarbon gas) components were modelled in the STARS simulations. Component properties are given in Table 2.

Table 2. Component properties in the STARS model.

	Viscosity, cp	Molecular mass, kg/mole
Oil	0.500	0.100
Gas	0.023	0.016
Water	0.350	0.018
Surfactant	0.350	0.310

In the simulation model two sets of relative permeability curves were used. When surfactant solution is injected into a reservoir saturated with gas (leave lamella behind mechanism of foam generation), a low gas mobility (MRF=2) was used in the simulations. Foam generated by gas entering into surfactant solution will have high MRF values.

A GOR value of 500 Sm³/Sm³ was selected as a production cut-off for simulation predictions. Foam treatment in the well was taking place when the GOR was hitting a 500 Sm³/Sm³ limiting cut-off. Oil

production after treatment was also continuing until the moment when GOR was attaining the cut-off limit.

Production estimate from the segment radial model simulations may be considered as pessimistic, since the sector of the model is dipping towards the producer and does not account for the inflow into the well from the deeper reservoir zone.

Position of the global GOC at the moment of foam placement is very critical for the success of the treatment. If the global GOC approached the top perforation interval by several meters (Figure 3), an effective gas blockage (well producing with production GOR below 500 Sm³/Sm³) might be achieved by generating a strong foam with gas mobility reduction in the range of 100.

Figure 3. Foam plugging effect. Sector radial model.

However, the gas inflow was restricted considerably even at a mobility reduction of 10. The closer GOC to the perforation interval, the shorter gas blockage effect. The Figure 4 shows the difference in the oil volumes produced after foam treatment in the well with GOC position 3 and 6 meters above the top of the upper perforation interval.

Figure 4. Oil production before and after foam treatment.

Simulation with low value of gas MRF (reduced from 100 to 10) showed no effect on the length of production period after treatment with 500 Sm³/Sm³ GOR constraint, but average production GOR during this

period after foam treatment was increased by 50-150 Sm^3/Sm^3 (in comparison with MRF 100 case). The effect of the surfactant slug size becomes less significant when the current position of the GOC approaches the upper perforation interval. Simulations showed that a foam treatment in the top perforation interval of the well, even when the GOC is close to the perforations, may delay gas breakthrough and extend production at GOR equal to solution GOR.

Field pilot

In June 1994 a foam pilot test was performed in production well B-27 [4]. The upper perforation interval was selected for foam treatment and production. Reducing the production interval improved the interpretation of the foam pilot. The lower perforation intervals were isolated prior to the foam treatment.

The laboratory experiments performed indicated that the AOS surfactant generated a strong foam with MRF values exceeding 100 at Oseberg reservoir conditions [3]. The foam generation in the near well area was performed by injecting surfactant solution and hydrocarbon gas in alternating slugs. This injection scheme was selected to secure good injectivity and deep emplacement of the foam. Details of the pilot implementation are discussed by M.Aarra *et al.* [4]. Injection of surfactant solution and gas was started on June 9, 1994 and completed on June 10, 1994. The total volume of surfactant solution injected in well B-27 was 105 Sm^3 . The chemical cost of the foam pilot was about \$10,000.

History matching and evaluation of the pilot

To match the foam pilot the segment STARS model was extended to a fully 3D radial model (Appendix B). The model comprises 14 grid blocks in the radial direction with block sizes of 0.5 - 1.5 meters near the wellbore (Figure 5). Laterally, the model contains 6 segments (theta equal to 60°). Segmentation was necessary in order to model GOC in a dipping reservoir and to have dummy injection and production wells in the top and bottom segments of the model. The dummy wells allowed to imitate the global GOC movement in the reservoir independent from the B-27 shut-in and opening periods. Reservoir layering and structural dip were in accordance to the geological model. Reservoir volume representing a drainage area of the well in this model was kept similar to the volume determined in the earlier ECLIPSE simulations matching of the observed GOC development. The use of dummy wells was found to be important in the simulations of the January-April 1994 production period, prior to the setting of plug isolating the lower perforation intervals. The dummy wells allowed to match both the GOR and GOC development in B-27.

Since the foam pilot treatment in the well was performed only in the top perforation interval, the isolated lower perforation intervals were less important for the simulation in order to be represented by separate

grid blocks in the model. Therefore, the bottom model blocks were coarsened. Grid blocks in the top of the cross section, which were passed already by the descending GOC, were also coarsened. The top perforation interval zone was refined from two to six grid blocks of 1.15 m each in vertical direction. The refinement in the near well perforation zone was important for foam placement simulation and allowed more accurate modelling of segregation and foam effects in the pilot. These changes in the model did not increase the required time for each history matching and sensitivity simulation runs with calibrated foam parameters.

PRODUCER MODEL

Figure 5. 3D radial model B-27 well.

A plug was installed below the upper perforation interval in B-27 on April 8, 1994. The simulation period after setting of the plug and production from the upper perforation interval starts from April 10, 1994. Figure 6 demonstrates the sensitivity of the production GOR development during April 10-21 period to the position of the GOC. Half a meter difference in the GOC position had a significant effect on the simulated GOR development. In the best match of the base line GOR curve for the April 10-21 and May 10-13, 1994 periods

the GOC position in the model corresponds to the depth of 1 mTVD above the top of the upper perforation interval. This movement of the GOC was similar to the GOC movement in the well area estimated from the TDT log measurements.

The foam placement scenario was modelled and history matched as close as possible to the pilot procedure. The production rates of the well were averaged from the field data and used as controlling simulation parameters. Irreversible surfactant adsorption was specified at the adsorption level (0.5 mg/g) measured for the Oseberg core material in the laboratory experiments. The simulations showed that a significant amount of injected surfactant went below the top perforation interval following the segregated water (Figure 7). In the field test only 20% of injected water (20 Sm^3) were produced.

When the well was put on production after the foam placement, two base line production periods were used for history matching: June 10-30 and July 8-19, 1994. The history match of the foam pilot considered both movement of the global GOC and parameters of foam generated in the reservoir. Sensitivity to critical surfactant concentration, foam oil tolerance and critical rheology capillary number of foam shear thinning was also evaluated. In order to quantify the effect of GOC movement effect on the foam treatment performance, simulations were run with and without global GOC movement.

No global GOC movement

The producing GOR after foam treatment was gradually increasing during the June 1994 period approaching a $700 \text{ Sm}^3/\text{Sm}^3$ level (Figure 8). Simulation using the reference capillary number value calculated from laboratory data of $1.0\text{E-}6$ ($e_v=1$), and critical surfactant concentration of 1.8 weight % ($e_s=1$) did not match the beginning of the production period after foam placement. However, GOR at the end of the June production period was very close to the measured GOR. The simulation run with reference capillary number value of $1.0\text{E-}4$ ($e_v=1$), critical surfactant concentration of 1.8 weight % ($e_s=1$) and MRF equal to 100 gave a strong blockage of gas by foam persistent for both June and July production periods.

Possible GOR development in the case with no foam treatment in the well is shown in the Figure 9. The simulation without a global GOC movement gave a production GOR of $1000\text{-}1050 \text{ Sm}^3/\text{Sm}^3$ at the end of the 1994 production period, which is lower than measured GOR values after foam treatment. The simulations showed that the GOR development can not be matched by assuming a stagnant GOC (Figure 9). No movement of the GOC is also inconsistent with the TDT monitoring (Table 1), and observed GOC in neighbouring wells.

Drawdown modelled by dummy injection and production wells

Modelling of the descent of the global GOC independent from the shut-ins of B-27 was imitated by dummy wells. The previous simulations of the production period January-April 1994 allowed to estimate a necessary drawdown in the model. The production GOR of the well and measured GOC movement was matched when the well was producing from all perforation intervals at a rate of $2000\text{-}3000 \text{ Sm}^3$ of oil per day. The B-27 well oil rate after installation of plug was maintained at $450\text{-}600 \text{ Sm}^3/\text{d}$. The gas frontal movement was imitated by producing the dummy well at 2500 Sm^3 of oil per day [4]. Possible GOR development scenario without foam placement is shown in Figure 9. The history matching simulations indicated that the foam treatment in the well allowed to achieve an average of 10 to 20 times reduction in apparent gas mobility. (Figure 10). In the simulation runs which gave the GOR development shown in Figure 10 the effects of critical oil saturation and gas velocity were switched off in the simulation foam model by specifying the exponent values for their contribution equal to zero (see Eq. 1 and 2). The critical surfactant concentration was set equal to 1.8 weight %. The initial foam generated in the reservoir showed a strong gas blocking. The descending GOC in the model, similar to the field movement, gave a production GOR in the July production period 2-3 times higher without foam treatment.

Two history match simulation runs with MRF of 10 and 30 (critical capillary number of $1.0\text{E-}4$ ($e_v=1$)) and other parameters as specified in Table 3 are shown in Figure 11.

Table 3: Input to history match simulations.

MRF	$w_s \text{ max}$ weight % (e_s)	$S_o \text{ max}$ fraction (e_o)
10	1.8 (1)	0.45 (1)
30	1.8 (2)	0.5 (1)

The best match of the GOR was achieved in the simulation run with gas mobility reduction by foam equal to 30, critical surfactant concentration of 1.8 weight % and exponent value for surfactant concentration contribution equal to 2.0. The key factor in the empirical foam model which allowed to achieve this acceptable match of the pilot production GOR after foam treatment was a critical surfactant concentration component. It gave a possibility to match the observed GOR development in the initial June 11-25 production period after foam treatment having a decreasing MRF value (foam decay) as a power function of surfactant concentration. The reduction in surfactant concentration is due to adsorption, back production and segregation of surfactant.

Foam potential for B-27 well producing without plug

Two scenarios, with and without foam present, were simulated for B-27. In these simulations the plug isolating lower perforation intervals was removed after foam placement and the well was producing from all perforation intervals. The same geological model as in the previous simulations was used. The simulations applied a constant oil rate of 2500 Sm³/d (Figure 12). The first scenario considered a reference case with no foam. The production GOR in this case increased up to a level of 500-600 Sm³/Sm³ and maintained at this level for more than 150 days (Figure 12). The second simulated scenario was based on foam properties from the pilot history match. The objective was to evaluate the foam potential without isolation of the lower perforation intervals. The simulation runs were stopped at the moment when a rapid increase in the producing GOR from 250 Sm³/Sm³ up to 400 Sm³/Sm³ was observed in the foam treatment case. The results show that the foam reduced the average GOR from 587 Sm³/Sm³ to 266 Sm³/Sm³ and the cumulative gas production from 247 10⁶ Sm³ to 112 10⁶ Sm³.

Based on the test evaluation, the Oseberg foam pilot is considered as successful and opens new technical opportunities for controlling gas cut in production of high permeable reservoirs. In addition, production well foam treatment is a very cost efficient process.

Conclusions

1. The STARS simulator incorporating an empirical foam model was able to history match the foam pilot at the Oseberg field.
2. Control of the gas-oil contact movement was important for tuning the simulation models.
3. The field pilot showed that foam treatment and production from the upper perforation interval reduced production GOR in the range of 50% for about half a year.
4. The best history matching simulation case had a reference value of gas mobility reduction by foam equal to 30. The effects of oil tolerance, critical gas velocity, surfactant adsorption and surfactant concentration on the foam generation were also incorporated in the history matching simulation.
5. Field foam mobility reduction estimated from history match was lower than MRF measurements in the laboratory.
6. Both the field test and simulations have shown that a mobility reduction factor of 30 and a foam treatment radius of 10 m may be sufficient for a gas blocking design in a gas coning situation.

7. The Oseberg foam pilot opens new technical and economical opportunities for controlling gas cut in production of high permeable reservoirs.

Nomenclature

FM	=	Foam Mobility
MRF	=	Mobility Reduction Factor
IP	=	Interpolation Parameter
w_s	=	Surfactant concentration in mole fraction.
w_s^{max}	=	The maximum surfactant concentration where it is relevant.
e_s	=	Parameter for the influence of surfactant concentration.
S_o	=	Oil saturation.
S_o^{max}	=	The maximum oil saturation above which no foam can exist.
e_o	=	Parameter for the influence of oil saturation.
N_c	=	Capillary number.
N_c^{ref}	=	Capillary number at reference foam.
e_v	=	Parameter for the influence of capillary number.

Capillary number is determined according to the following formula:

$$N_c = \frac{v\mu}{\gamma\phi}$$

where:

v	=	gas velocity
μ	=	gas viscosity
γ	=	interfacial tension
ϕ	=	porosity

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Appendices

A. 3D near well ECLIPSE model

The 3D three phase near well ECLIPSE model represents a refined element of the B-27 well area in the full filled model.

The main characteristics of the model are given below:

Number of grid blocks:

21 x 21 x 23 (10143 grid blocks)

Block dimensions:

X (821 m):

150 100 50 50 25 15 10 5 3 2 1 2 3 5 10 15 25
50 50 100 150

Y (1621 m):

400 200 100 50 25 15 10 5 3 2 1 2 3 5 10 15
25 50 100 200 400

Z (65.9 m):

2*6.25 2*2.1 2*2.5 2*2.1 2*3.3 2*2.9 2*3.45 3.9 1.3
4.7 2.3 1.6 1.4 1.2 2.3 1.9

Horizontal X-permeability in layers, mD:

2*2000.0 2*2859.0 2*2137.0 2*2908.0 2*3962.0
6*2874.0 7*3672.0

Lateral Y-permeability in layers, mD:

2*2000.0 2*2859.0 2*2137.0 2*2908.0 2*3962.0
6*2874.0 7*3672.0

Vertical Z-permeability in layers, mD:

2*1000.0 2*1000.0 2*1363.7 2*1692.0 2*2610.0
6*877.0 7*367.0

Production well position in the model: i=5, j=11

Well radius: 0,108 m

B. Full 3D radial STARS model

The full 3D radial near well STARS model was used for the foam pilot history matching and evaluation.

The main characteristics of the model are given below:

Number of grid blocks:

14 x 6 x 19 (grid blocks)

Block dimensions:

I (620 m):

0.5 1.0 1.5 2.0 3.0 5.0 7.0 10 15 25 50 100 150 250

J (6 sectors):

Theta=60°C

K (65.9 m):

12.5 4.2 5.0 4.2 6.6 2.9 2*1.0 0.9 6*1.15 2*1.95 1.3
15.4

Horizontal I-permeability in layers, mD:

2000.0 2859.0 2137.0 2908.0 3962.0 8*2874.0 3672.0

Lateral J-permeability in layers, mD:

2000.0 2859.0 2137.0 2908.0 3962.0 8*2874.0 3672.0

Vertical K-permeability in layers, mD:

1000.0 1000.0 1363.7 1692.0 2610.0 8*877.0 367.0

Production well position in the model: i=1, j=1

Well radius: 0,108 m

Skin factor: 2.0

Figure 6. GOR sensitivity to GOC position. Production from the upper perforation interval prior to the foam treatment.

Figure 7. Surfactant adsorption in the near wellbore area. B-27 well.

Figure 8. GOR simulation without global GOC movement in the B-27 area.
Critical gas velocity effect.

Figure 9. Effect of decending GOC on production GOR. B-27 well. GOR development without foam treatment in comparison with measured GOR.

Figure 10. Foam pilot simulation with global GOC movement. MRF effect.

Figure 11. Foam pilot history matching with global GOC movement.

Figure 12. Simulation of foam potential for B-27 well producing without plug after foam treatment.