

Research Article

Comprehensive Review of Foam Application during Foam Assisted Water Alternating Gas (FAWAG) Method

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Abstract: In the last few decades, much focus has been placed on enhancing oil recovery from existing fields. This is accomplished by the study and application of various methods. As for recent cases, the Study of fluid mobility control and sweep efficiency in gas injection process as well as Water Alternating Gas (WAG) method have demonstrated positive results on oil recovery and thus gained wide interest in petroleum industry. WAG injection application results in an increased oil recovery. Its mechanism consists in reduction of Gas Oil Ratio (GOR). However, there are some problems associated with this which includes poor volumetric sweep efficiency due to its low density and high mobility when compared with oil. This has led to the introduction of Foam Assisted Water Alternating Gas (FAWAG) technique, which in contrast with WAG injection, acts in improving the sweep efficiency and reducing the gas oil ration therefore maximizing the production rate from the producer wells. This study presents a comprehensive review of FAWAG process from perspective of Snorre field experience. In addition some comparative results between FAWAG and the other EOR methods are presented including their setbacks. The main aim is to provide a solid background for future laboratory research and successful field application-extend.

Keywords: GOR, mobility ratio, sweep efficiency, WAG

INTRODUCTION

In heterogeneous reservoirs, gas behavior is characterized by a tendency of upward movement through the layers due to its low density. In event of high mobility gas injection, gas channeling and break through occurs. In order to mitigate this problem and thus increase the gas sweep efficiency, WAG injection has had been a suitable candidate. With this process, problems such as water shielding have been reported. This is due to unfavorable mobility ratio and high mobile water saturation which results in a poor recovery (5-10% recoveries in 59 field applications) (Dullien *et al.*, 1989).

WAG injection has found applications in a variety of fields including the North Sea where similar problems of poor gas volumetric sweep efficiency due to its low density and mobility when compared with oil were observed (Blaker *et al.*, 1999; Arra *et al.*, 2002; Crogh *et al.*, 2002). When compared to water and gas injection, WAG injection has low residual oil, that is, the residual amount of oil remaining in the reservoir after WAG is lower than that after water or gas injection (Awan *et al.*, 2006).

WAG injection is performed in cycles. The first cycle is mostly efficient due to the increased miscibility

of the gas and oil which causes oil expansion that is easily swept by the water. However, in the second cycle there is reduced mass exchange between gas and oil which leads to evolution of gas saturation and thus its breakthrough in a later stage (Arra *et al.*, 2002; Awan *et al.*, 2006).

There are some problems associated with WAG injection which includes a poor volumetric sweep efficiency due to low density and high mobility of gas when compared with oil. This has led to the introduction of Foam Assisted Water Alternating Gas (FAWAG) technique, which in contrast with WAG injection, acts in improving the sweep efficiency and reducing the gas oil ration therefore maximizing the production rate from the producer wells (Arra *et al.*, 2002; Shehadeh *et al.*, 2011). Gas mobility problem is completely mitigated when applying FAWAG injection due to its high resistance to displacement (Blaker *et al.*, 1999; Arra *et al.*, 2002).

Foam mechanisms are a function of the gas, oil, water and rock parameters. Highly permeable and heterogeneous zones are responsible for foam generation which then acts by diverting the fluid flow route towards low permeability zones (Haugen *et al.*, 2010). Field applications of Foam injection have

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increased the oil rate by 1.5-5 times and reduced the water cut by 20% (Alex and Ashok, 1998).

The present study reviews the foam generation during porous media and FAWAG process in the North Sea, to seek previous efforts and emphasize the areas which are weakly recognized. For this purpose, initially a short review on generation of foam and parameters on which it depends will be presented. Afterward a review of FAWAG process case study in the North Sea will be considered.

LITERATURE REVIEW

Foam generation: Foam has been used long ago to improve the oil recovery. In the previous studies, advantages of foam utilization have been demonstrated which include increasing the sweep efficiency and decreasing the gas mobility (Krause *et al.*, 1992; Hanssen *et al.*, 1994; Hoefner *et al.*, 1994; SvorstØl, 1997). Foam utilization was first patented by Bond and Holbrook to improve the sweep efficiency of gas drives (McPhee *et al.*, 1988). Foam is a mixed phase of gas, water and foam that consist of liquid films/lamellae (Schramm and Wassmuth, 1994).

The condensation of relatively large gas molecules is what forms the Foam (Dullien *et al.*, 1989; Kovscek *et al.*, 1995). Physically, foam generation is very complex (Kovscek *et al.*, 1995). There are three mechanisms which lead to foam generation which are explained by Ransohoff and Radke (1988):

- Snap-off
- Lamella-division
- Leave-behind

The snap-off mechanism was originally explained by Roof (1970). It is characterized by the formation of lamellae due to low capillary pressure. At pore level, the water film wetting the rock walls swells and thus blocking any further gas migration through it (Fig. 1) (Roof, 1970; Falls and Hirasaki, 1988). This leads to the accumulation of gas bubbles at opposite sides of the throat thus forming lamellae. Kovscek and Radke (1994) presented plausible details this mechanism and suggested that this is the dominant foam formation mechanism.

The second mechanism for foam formation is Lamellae division. Here, further accumulation of gas causes the newly formed lamellae to enlarge. During its migration through the pores, if this large gas bubble encounters a branched point and with sufficient capillary pressure, its flow is diverted into two directions which cause its division (Fig. 2) (Kovscek and Radke, 1994). As detailed, the lamellae division depends on the bubble size (larger than pore throat), capillary pressure and the presence of a branched route. Furthermore, Lamella division is thought to be the primary foam-generation mechanism in steady gas-liquid flow (Gauglitz *et al.*, 2002; Li *et al.*, 2006).

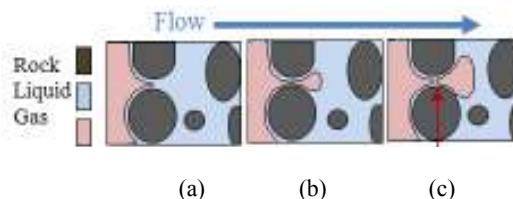


Fig. 1: (a) Gas start to push the liquid filled pore (b) liquid film swells (c) the process is repeated (figure is reproduced from Kovscek and Radke (1994))

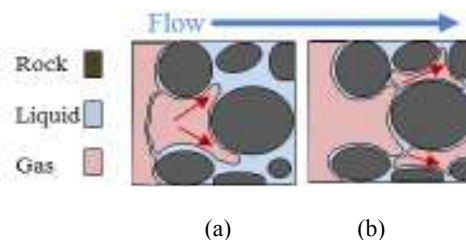


Fig. 2: Lamella-division mechanism (figure is reproduced from Kovscek and Radke (1994))

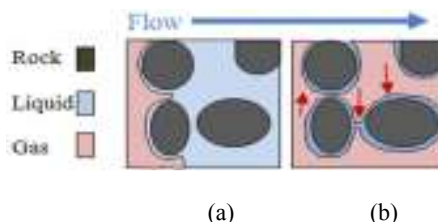


Fig. 3: (a) The non-wet phase pushed and displace wetting phase (b) wetting phase remained and bridged in the pore space and certain lamellae parallel to flow direction (figure is reproduced from Kovscek and Radke (1994))

Leave-Behind mechanism occurs when gas flowing through adjoining pore throats causes the formation of lamellae in the throat between the two pores. This is accompanied by the displacement of the wetting phase and thus the previously wet surfaces are filled with gas which leads to the formation of lamella (Fig. 3) (Kovscek and Radke, 1994). Foams generated solely by leave-behind give approximately a five-fold reduction in steady-state gas permeability (Ransohoff and Radke, 1988; Kovscek and Radke, 1994).

Hirasaki and Lawson (1985) observed that the bubbles of small size are less mobile than the bubbles of large size. Low foam density gives the fractionation of the flow whereas low foam viscosity makes tendency for fingering and channeling (Hirasaki and Lawson, 1985).

METHODOLOGY

Surfactant and surfactant adsorption: The term surfactant finds its origin from the term "surface active agent". Surfactants are organic compounds

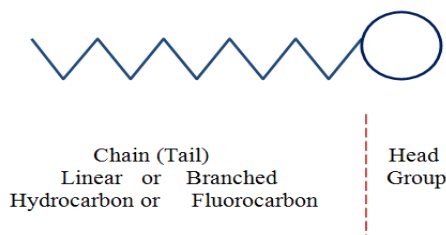


Fig. 4: Typical surfactant molecule (Willhite and Green, 1998)

that have an amphipathic nature, meaning they contain both a hydrophobic group (their tail) and hydrophilic group (their head), (Fig. 4), (Schramm and Kutay, 2000).

Surfactants have since significantly performed well in mitigating problems related to foam generation and stabilization (Hirasaki and Lawson, 1985; Schramm and Wassmuth, 1994; Gauglitz *et al.*, 2002). This performance, however, is governed by certain factors which include the brine saturation. Efficient aqueous phase solubility and thus poor oil-phase solubility is verified at low brine concentrations (Lake, 1989). However, for high brine concentrations, the surfactant flooding will exhibit decreased aqueous phase solubility due to the electrostatic forces (Lake, 1989).

Adsorption, precipitation and phase mechanical trapping are the main factors causing substantial losses of surfactant within the porous media during surfactant flooding. Each of the aforementioned factors are further triggered by certain reservoir rock or fluid parameters. Temperature, pressure and P^H are among those parameters. It has been observed that the surfactant adsorption reduces by increasing of the temperature and pH of aqueous phase (Corkill *et al.*, 1966; Connor and Ottewill, 1971). Another reduction in aqueous phase surfactant adsorption at low salinity was reported by Glover *et al.* (1979).

Foam injection mode: Generation and Injection of foam usually is divided into two main strategies:

- Co-injection
- Surfactant Alternating Gas (SAG)

Co-injection is the simultaneous injection of gas and foam into the well. SAG injection mode is generation of foam into the reservoir by alternating slugs of surfactant solution and gas injection. Here, the foam formation follows when the gas phase is in direct contact with water surfactant solution in porous media (Blaker *et al.*, 1999; Kovscek *et al.*, 1995; Crogh *et al.*, 2002). A comparative analysis based on field application of these two modes awards the SAG mode as more effective (Blaker *et al.*, 1999; Kovscek and Radke, 1994; Kovscek *et al.*, 1995; Crogh *et al.*, 2002). This attribution is worth due to the vast advantages of

the SAG mode which includes minimization of gas and water contacts in the surface facilities. Alternating slugs of gas and water can promote foam generation in the near wellbore region (Shan and Rossen, 2004).

Foam generation efficient parameters: Generation of foam depends on several factors, such as surfactant concentration, oil phase, capillary pressure, wettability, bubbles size, brine salinity, etc. However, this study just focuses on the effect of brine salinity and wettability.

Effect of water salinity on foam: Water salinity and composition of brine play an important role in the generation and performance of foam. At low salinity aqueous phase foam composition, the foam is more stable (Zhu *et al.*, 2004). Duerksen (1986) indicated that generation and performance of foam affected negatively by increasing the concentration of salt in the aqueous phase (Duerksen, 1986).

Effect of wettability on foam: Rock wettability is defined as the tendency of one fluid to spread on or adhere to a rock surface in the presence of other immiscible fluid (Craig, 1971). Parameters such as fluid distribution, capillary pressure, relative permeability and consequently hydrocarbon production are strongly affected by the wettability (Craig, 1971). In addition, wettability affects the generation and stabilization of the foam. For instance, according to a study performed by Suffridge *et al.* (1989), it was verified that foam generation is favored in water-wet porous media rather than oil-wet. Another study confirming the aforementioned condition is found in Kristiansen and Torleif (1992) work. The authors concluded that foam generation within strongly oil-wet porous medium is not possible.

EOR in North Sea: In the North Sea region, where reservoirs are characterized by high degree of heterogeneities and permeability layers, the sweep efficiency of gas is strongly affected. EOR field applications in this area were divided into three parts (Fig. 5) (Awan *et al.*, 2006):

- Norwegian Continental Shelf (NCS): 63% 12 field projects
- UK Continental Shelf (UCS): 32% 6 field projects
- Danish Continental Shelf (DCS): 5% 1 field project

North Sea oil field has experienced five projects with different field and locations (Awan *et al.*, 2006):

- Miscible Gas Injection (MGI)
- Water Alternating Gas (WAG)
- Simultaneous Water Alternating Gas (SWAG)

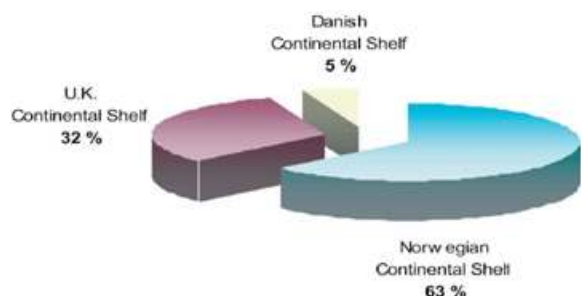


Fig. 5: Distribution by country in the North Sea (19 field projects) (Awan *et al.*, 2006)

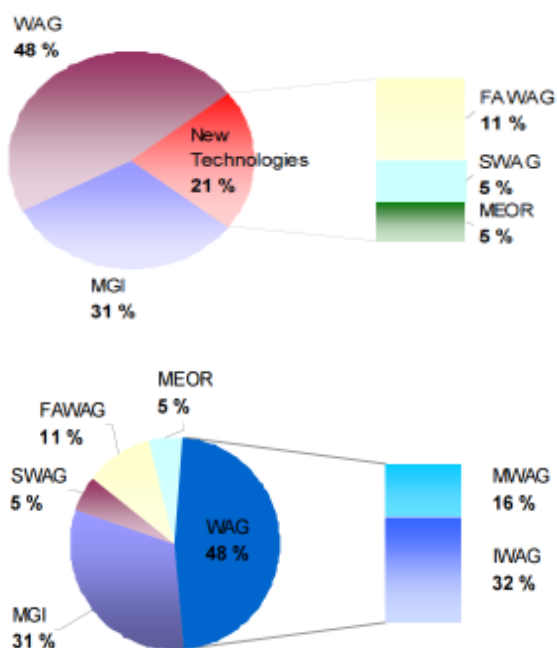


Fig. 6: Distribution by type of method in the North Sea (19 field projects) (Awan *et al.*, 2006)

- Foam Assisted Water Alternating Gas (FAWAG)
- Microbial Enhanced Oil Recovery (MEOR)

Since 1980s preference have been placed on WAG injection EOR method for the 19 fields in the north sea (Fig. 6) (Awan *et al.*, 2006):

- MGI: 6 field projects
- MWAG (WAG Miscible): 3 field projects
- IWAG (WAG Immiscible): 6 field projects
- FAWAG: 2 field projects
- SWAG: 1 field project
- MEOR: 1 field project

Snorre field of North Sea: Located at 150 km off coast Norwegian Sea, Snorre field is an important oil field on the Norwegian Continental Shelf (NCS) (Fig. 7)

(Blaker *et al.*, 1999; Arra *et al.*, 2002; Awan *et al.*, 2006). Its production was initiated in August 1996. It contains two active formations which are Statfjord and Lunde formations (Blaker *et al.*, 1999; Arra *et al.*, 2002; Awan *et al.*, 2006).

Early gas breakthrough comprises one of the major problems for a producing well. This problem has posed for Snorre field a challenge for gas control management (Arra *et al.*, 2002; Blaker *et al.*, 1999; Awan *et al.*, 2006; Skauge *et al.*, 2002). Summary of Reservoir Properties are in the following Segmentation (Arra *et al.*, 2002; Skauge *et al.*, 2002; Svorstøl, 2006):

- Production start: 1992
- Stock Tank Original Oil in Place: 520 MSm³
- Reserves: 234 MSm³
- Formation: Statfjord and Lunde
- Permeability: 100-3500 mD
- Initial Reservoir Pressure: 383 bar
- Reservoir Temperature: 90°C
- Oil: light
- API: 32 to 41
- Gas Cap: No
- Aquifer: Limited aquifer support
- Pressure maintenance: WI, WAG

FAWAG in snorre field: First developed in 1992, Snorre field relied on water injection as the main pressure maintenance mechanism. However, in the following years alternative of other methods were proposed. In 1995 a miscible WAG injection method was introduced Statoil through the two pilot test in the Central Fault Block (CFB) in order to cover the three main fault blocks in the field (Skauge *et al.*, 2002; Awan *et al.*, 2006).

The main objective of WAG application for the Snorre field was the reduction of unfavorable mobility ratio, however it has resulted in early gas breakthrough because of high permeability layers at the base of formation (Blaker *et al.*, 1999; Arra *et al.*, 2002; Skauge *et al.*, 2002; Awan *et al.*, 2006). Other problems such as tubing annulus leaks, gas or water shutoff and competition between gas injection and selling the gas were observed. This resulted in a discouragement for the continual use of WAG method and introduction of the FAWAG method (Awan *et al.*, 2006).

Foam has been applied successfully for mobility control and gas blocking in production wells (Fig. 8). FAWAG method was introduced in 1997 in the Snorre field for four pilot projects in different parts (Blaker *et al.*, 1999; Arra *et al.*, 2002; Skauge *et al.*, 2002; Awan *et al.*, 2006; Spirov *et al.*, 2012).

FAWAG technique was the world's largest application of foam in the oil industry (Skauge *et al.*, 2002). A commercial surfactant system AOS (Alpha

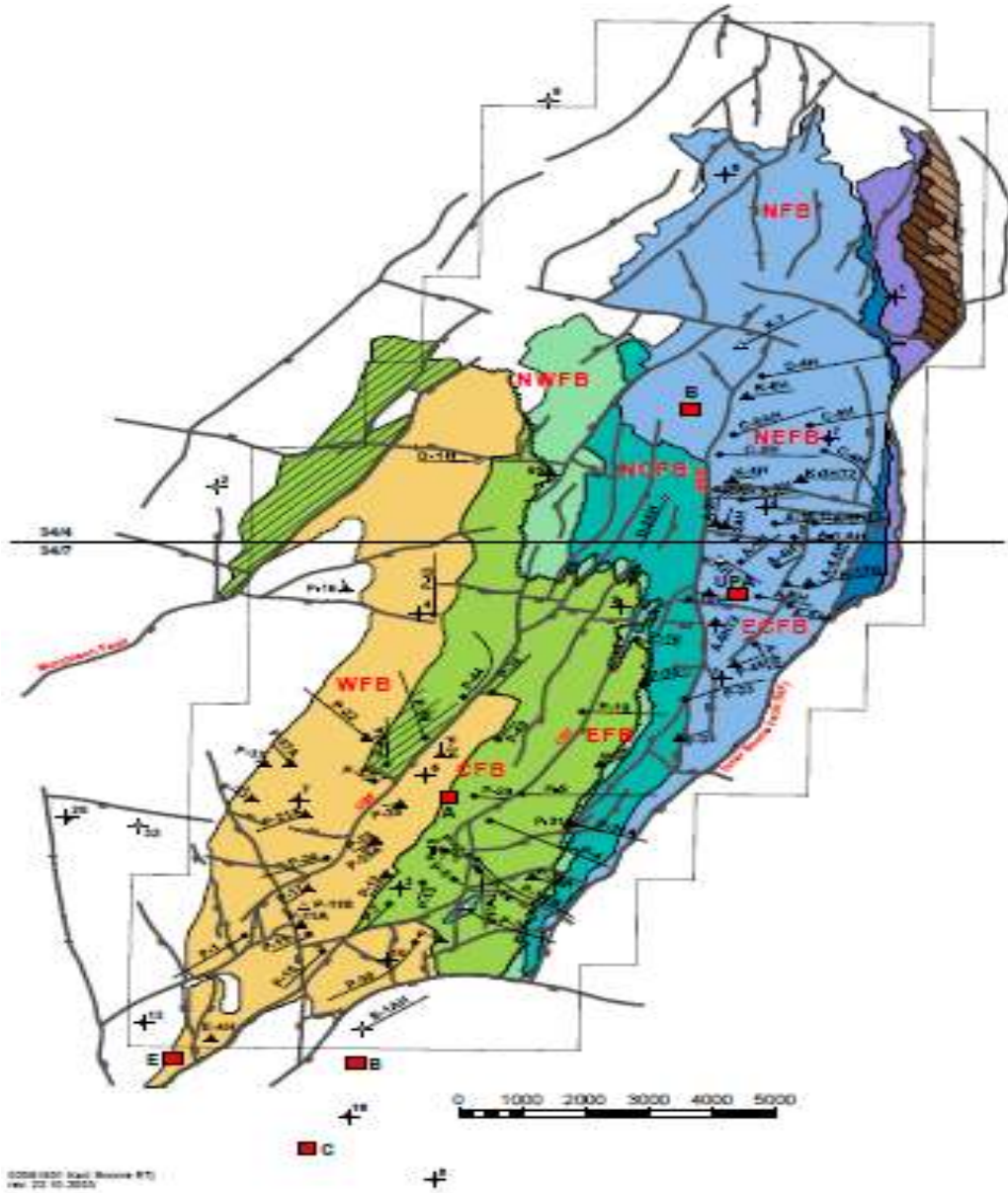


Fig. 7: Snorre field (Arra *et al.*, 2002; SvorstØl, 2006)

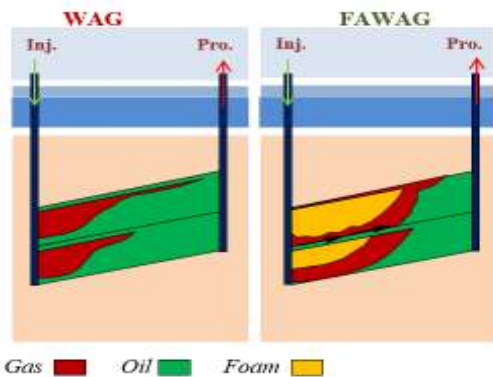


Fig. 8: Theoretical comparison of foam during WAG (SvorstØl, 2006)

Olefin Sulphonate) was chosen as the foaming agent, because it is more stable in the reservoir condition, has low adsorption factor and it is environmentally friendly (Blaker *et al.*, 1999; Arra *et al.*, 2002; Skauge *et al.*, 2002; Awan *et al.*, 2006). In FAWAG injection two modes of foam generation are practiced (Blaker *et al.*, 1999; Arra *et al.*, 2002; Skauge *et al.*, 2002; Awan *et al.*, 2006):

- Surfactant Alternating Gas (SAG)
- Co-injection

The FAWAG technique first started with SAG mode in the Central Fault Block (CFB) followed by the co-injection in 1999 (Blaker *et al.*, 1999). After 2 years

of application problems such as fracturing and gas leakage in injector well were observed. This caused that the pilot was changed to the Western Fault Block (WFB) where it performed successfully rather than CBF block (Blaker *et al.*, 1999; Arra *et al.*, 2002; Skauge *et al.*, 2002; Awan *et al.*, 2006; Spirov *et al.*, 2012).

FAWAG in central fault block: Due to the previous described problems associated with WAG injection, new methods had to be developed for efficient production oil. Foam was considered suitable for solving the problems and its implementation was performed in the CBF block in two pilots (Fig. 9) (Blaker *et al.*, 1999). The following objectives were considered:

- Producer treatment for gas shut-off
- Gas mobility control

The producer treatment was done for gas shut-off to reduce the production of GOR in producer well (P-18) (Fig. 10) and it was showed that GOR reduced more than 50% over the period of 2 month (Blaker *et al.*, 1999; Skauge *et al.*, 2002). Consequently, recovery increased due to oil production from lower reservoir zone. On the other hand the pilot of Gas mobility control was completed parallel in the same producer well (P-18) (Blaker *et al.*, 1999; Arra *et al.*,

2002; Skauge *et al.*, 2002; Awan *et al.*, 2006; Spirov *et al.*, 2012).

At CFB block of Snorre it was observed that below critical water saturation (15 to 20%) and oil saturation around 20% foam collapsed (Blaker *et al.*, 1999; Awan *et al.*, 2006). FAWAG injection in CFB stopped and changed to the Western Fault Block (WFB) in early 1999 due to the fracturing and gas leakages in injector well (P-25A) (Arra *et al.*, 2002; Skauge *et al.*, 2002; Awan *et al.*, 2006; Spirov *et al.*, 2012).

FAWAG in western fault block: The successive problems observed at CBF block demanded a change of FAWAG pilot from CBF to WFB block (Fig. 10) (Arra *et al.*, 2002; Skauge *et al.*, 2002). Foam in WFB block was injected by SAG mode from Autumn 1999 to Autumn 2001, this is because in previous pilot in CFB block it was observed that the SAG mode injection was more efficient rather than the co-injection and also it was easier to perform below fracture pressure. Injections at WFB block entailed the use of 140 tons surfactant with 0.5 and 0.2% of concentration (Arra *et al.*, 2002; Awan *et al.*, 2006; Skauge *et al.*, 2002; Spirov *et al.*, 2012). FAWAG started in WFB block with the following objectives:

- To increase sweep efficiency
- To increase storage of gas in the reservoir
- To reduce the GOR in producer well (P-39)

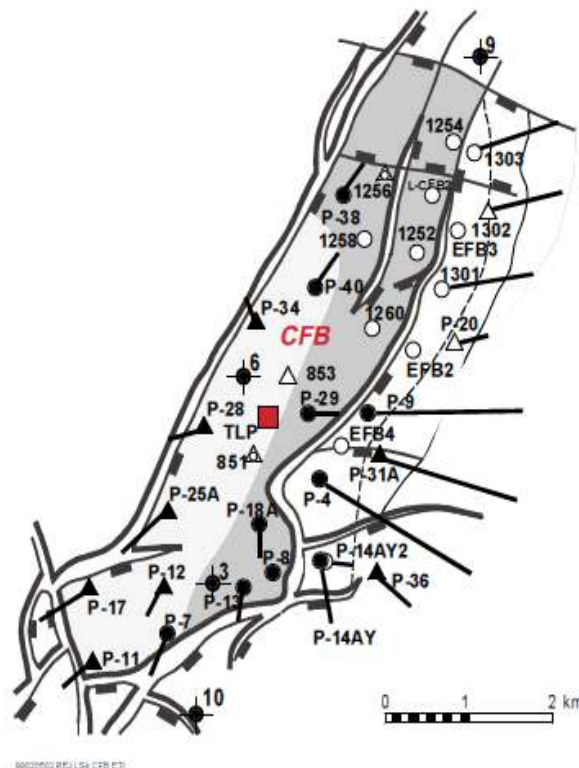


Fig. 9: Central fault block of snorre filed (Blaker *et al.*, 1999)

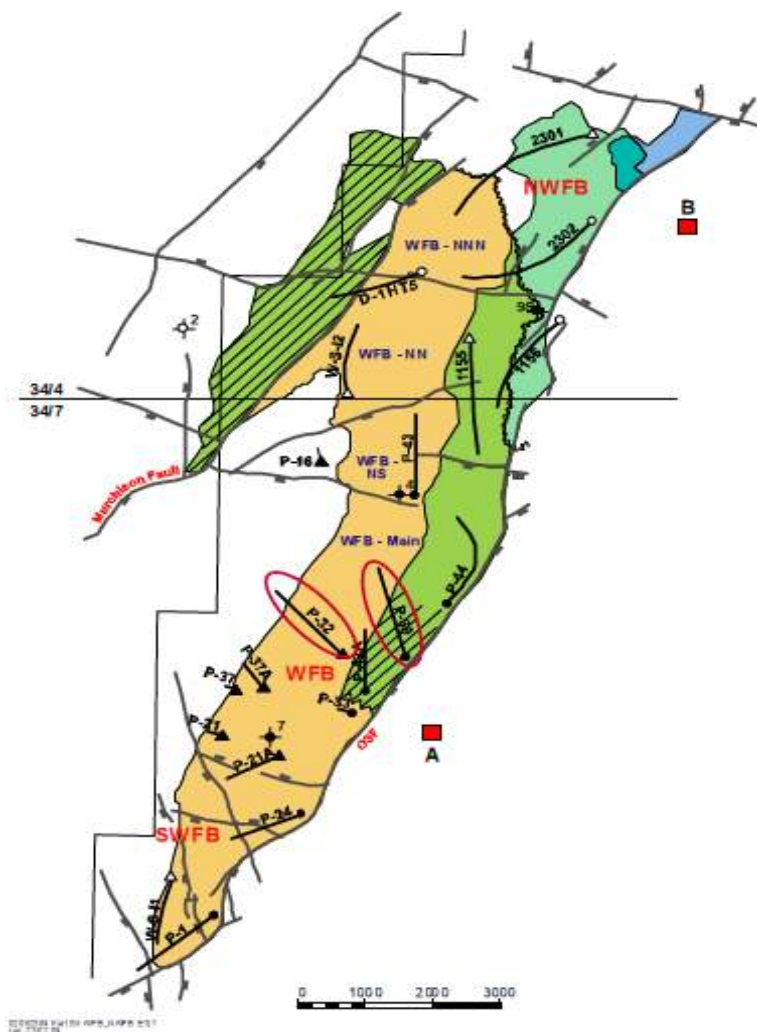


Fig. 10: Western fault block of snorre filed (SvorstØI, 2006)

After a meticulous application of FAWAG it was observed that the gas breakthrough was significantly delayed and considerable volume of gas was stored in the reservoir and consequently GOR was reduced (Arra *et al.*, 2002; Awan *et al.*, 2006; Skauge *et al.*, 2002; Spirov *et al.*, 2012). However the following problems were observed:

- Injection monitoring system
- Reservoir heterogeneities

FAWAG in Snorre WFB was successful and around 33% free back-produced gas was reduced during FAWAG process as compared to WAG injection. This successful method showed that it is possible to generate foam at large distance between injector and producer (Awan *et al.*, 2006). FAWAG was very sensitive to the reservoir heterogeneities and vertical communication (Arra *et al.*, 2002; Blaker *et al.*, 1999; Awan *et al.*, 2006; Skauge *et al.*, 2002; Spirov *et al.*, 2012). Hanssen *et al.* (1996) indicated that in

North field, range of pressure is not an important factor for generation of foam, but in contrast the temperature higher than 200°C can degrade the foam (Hanssen *et al.*, 1996).

COMPARISON BETWEEN FAWAG AND THE OTHERS EOR METHODS

Kharrat *et al.* (2012) through experimental and simulation studies compared several EOR methods including Gas Injection (GI), Water Injection (WI), Water Alternating Gas injection (WAG), Simultaneous Water Alternating Gas (SWAG) and Foam Assisted WAG (FAWAG). During secondary and tertiary recovery injection, it was observed that WAG, SAWAG and FAWAG were feasible, with FAWAG process being the most suitable process due to its high recovery (Kharrat *et al.*, 2012).

Tunio *et al.* (2012) compared Simultaneous Water Alternating Gas (SWAG) and Foam Assisted WAG (FAWAG). It was observed that the recovery at same

conditions for SWAG test was 88% and for FAWAG method was 92% which showed that FAWAG method was suitable method rather than SWAG (Tunio *et al.*, 2012).

CONCLUSION

Overall, Foam has significantly proven to be a substantial agent for application during EOR methods. Its application during the FAWAG injection has showed to improve some characteristics such as sweep efficiency during gas injection; gas storage in the reservoir and reduction in GOR (Spirov *et al.*, 2012). However, there were some problems that arose with its application encompassing the injection monitoring system and reservoir heterogeneities (Awan *et al.*, 2006).

In addition, high sensitivity to the vertical communication and reservoir heterogeneities during FAWAG were reported. This is my effect on dispersion of foam during the process (Arra *et al.*, 2002; Blaker *et al.*, 1999; Awan *et al.*, 2006; Skauge *et al.*, 2002). Oil and water saturation play important role on foam behavior. Degradation of foam is achieved below water saturation of around 15 to 20% and oil saturation of 20%.

Alpha Olefin Sulphonate may become unstable in temperature above 200°C, but the pressure is not critical (Hanssen *et al.*, 1996). SAG injection has proved to be an efficient injection rather than Co-injection because low regularity reflects the operational complexity of Co-injection.

Few studies on the FAWAG process have been conducted by simulation and consideration of foam behavior (only 2 field projects). All of which have been performed at Snorre field. This limits the implications of the results of FAWAG projects to be extended to other fields located at different regions since each field is unique in its properties. Moreover, FAWAG injection is very sensitive to the reservoir heterogeneities. Unfortunately not so many studies have focused on the foam generation in the heterogeneous porous media. On the other hand the mechanism underlying foam generation during highly heterogeneous reservoir is still unclear.

FAWAG performance presents efficient results in many worldwide fields when it is accompanied or coupled with suitable experimental and simulation runs. This requires a meticulous and rigorous supervision and conduction of the program.

The comparative results between FAWAG and the other EOR methods show that the FAWAG is more suitable method rather than the others. But, the results are almost predictable, because FAWAG has been compared with other EOR methods which are not included in the surfactant and foam. Hence, it needs to be compared with other surfactant assisted EOR methods such as SAG injection and ASP flooding.

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