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A Simulation Study of Chemically Enhanced Water Alternating Gas (CWAG) Injection

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Abstract

Water alternating gas (WAG) injection has been a popular method for commercial gas injection projects worldwide. The injection of water and gas alternatively offers better mobility control of gas and hence, improves the volumetric sweep efficiency. Although the WAG process is conceptually sound, its field incremental recovery is disappointing as it rarely exceeds 5 to 10 % OOIP. Apart from operational problems, the WAG mechanism suffers from inherent challenges such as water blocking, gravity segregation, mobility control in high viscosity oil, decreased oil relative permeability, and decreased gas injectivity.

This paper addresses the aforementioned problems and proposes a new combination method, named as the chemically enhanced water alternating gas (CWAG), to improve the efficiency of WAG process. The unique feature of this new method is that it uses alkaline, surfactant, and polymer as a chemical slug which will be injected during WAG process to reduce the interfacial tension (IFT) and improve the mobility ratio. In a CWAG process, a chemical slug is chased by water, preceded by gas slug and followed by alternate CO_2 and water slug or chemical slug injects after one cycle of gas and water slug. Essentially CWAG involves a combination of chemical flooding and immiscible carbon dioxide (CO_2) injections. These mechanisms are IFT reduction, reducing water blocking effect, mobility control, oil viscosity reduction due to the CO_2 dissolution and oil swelling.

CMG's STARS was used to study the performance of the new method using some of the data found in the literature. It is a chemical flood simulator that can simulate all aspects of chemical flooding, and it can also handle immiscible CO_2 injection features by considering *K*-value partitioning. The sensitivity analysis shows that the new method gives a better recovery when compared to conventional WAG. This study shows the potential of CWAG to enhance oil recovery.

Introduction

Enhanced oil recovery (EOR) refers to a variety of processes to increase the amount of oil extracted from a reservoir after primary and secondary recoveries, typically by injecting liquid chemicals (e.g., surfactant) or gas (e.g., nitrogen, carbon dioxide) or the use of thermal energy. The injected fluids compliment the natural energy of the reservoir or interact with the reservoir rock/oil system to create favorable conditions for oil recovery (Green and Willhite 1998). The concept of EOR has gained popularity as the global demand for supply of oil has increased. It is generally known that about two-thirds of original oil in place (OOIP) remains unrecovered after primary and secondary recovery (pressure maintenance, water flooding). The remaining oil exists as trapped, immobile oil droplets due to high capillary forces between water and oil droplets. Hence, EOR methods are key factors to extend and maximize production from existing oil and gas fields. The economic potential of providing new methods for increased and enhanced oil recovery is significant. It therefore represents a subject of great interest as it provides a means to optimize production and resource management.

In recent years, CO_2 flooding projects have grown rapidly around the world. It is the second largest process after thermal methods in heavy oil field (Hinderaker *et al.* 1996). CO_2 is more desirable than other gases due to lower injectivity problems, lower formation volume factor, abundance of reserves, and higher incremental oil recovery (Kulkarni 2003). Nowadays the research related CO_2 sequestration for global warming issues has made this technology very interesting (Mogbo 2011). Furtheremore, CO_2 has a low miscibility pressure (multi-contacts and first contact miscibility) compared to other miscible gases (Teletzke *et al.* 2005; Al-Ajmi *et al.* 2009). Such features allow the application of CO_2 flooding on different range of crude oil, moderate to low API gravity crude oil at shallow depths. For a depleted reservoir with a low reservoir pressure is not technically or economically feasible to increase the reservoir pressure, CO_2 can still be used in immiscible conditions (Singh and Singhal 2005; Sahin *et al.* 2008). At immiscible conditions, there is a great chance of improvement of oil recovery by CO_2 flooding because CO_2 can considerably reduce the oil viscosity and swell the oil volume. The viscosity reduction helps to improve the mobility ratio in heavy oil fields and hence provides better macroscopic displacement efficiency (Hatzignatiou and Lu 1994). The swelling, the increase in volume of a crude oil when saturated with CO_2, causes oil droplets to be removed from pore spaces and hence, a lower residual oil saturation and better microscopic displacement efficiency is expected (Zain *et al.* 2001).

However, it is strongly believed that mobility ratio which controls the volumetric sweep efficiency, between CO_2 and oil is poor (Faisal *et al.* 2009). Most of the CO_2 field projects have experienced premature gas breakthrough at the producers. In heterogeneous media where there are high permeable zones, faults and fractures, the condition is even worst. The injected CO_2 can enter high permeable zones and bypass a large amount of oil in the reservoir. This makes a significant decrease in oil recovery efficiency (Martin *et al.* 1988). In addition to heterogeneity, the poor sweep efficiency of CO_2 gas injection projects is related to low viscosity and density of CO_2 gas (Maubeuge *et al.* 2005). It causes gas to rise upward in reservoir and bypass many lower portions of the reservoir. A number of researchers have shown that using gas thickener chemicals (Enick *et al.* 2000), alternative injection of natural gas liquid (NGL) for heavy oils (McKean *et al.* 1999) can help to control the mobility of CO_2 gas flood but most of these processes are still at experimental stage and are not accepted in field scale due to some issues like feasibility, cost, applicability, safety and environmental impact (Kulkarni and Rao 2005).

Caudle and dyes (1958) noticed that the sweep efficiency of a gas injection process can be increased by decreasing the mobility behind the flooding front. This is achieved by injecting a water slug along with a gas slug. The water slug can reduce the relative permeability to gas and therefore lowers the total mobility. In their proposed method, the miscible slug is driven by a simultaneous injection of water and gas in the proper ratio. To avoid injectivity problems and other operational limitations related to simultaneous injection, this method is changed to Water Alternating Gas (WAG) process. During the WAG process short slugs of gas and water are injected alternately to control the mobility of gas and reduce the residual oil saturation. The recovery is better than gas and water injection alone (Rogers and Grigg 2000) because the higher macroscopic efficiency of water combines with the higher microscopic efficiency of gas give a better recovery of oil (Poollen 1980; Christensen *et al.* 2001; Crogh *et al.* 2002; Awan *et al.* 2008). However, recent studies have shown that most of the fields could not reach the expected recovery facor from WAG process (Sharma and Rao 2008). Christensen *et al.* (2001) have reported that the average recovery factor in miscible WAG is 9.7 percent and in immiscible case it is around 6.4 percent.

Most of the research on using chemicals during gas injection is related to gas mobility control. Only a few researchers have investigated the change in the properties of water slug during WAG injection. The first simulation study on this subject was conducted by Behzadi *et al.* (2009). They introduced an EOR method which is the injection of ASP slug chased by water, preceded by a solvent slug (miscible CO_2), and finally followed by continuous miscible CO_2 injection. They have found that by this EOR method it is possible to get a higher recovery compared to only using ASP or miscible CO_2 alone. It needs less CO_2 slug size to obtain the same recovery during miscible CO_2 gas injection. It was shown that heterogenity does not have much effect on recovery and even it is much better in heterogenous environment. Zhang et. al. (2010) have used the CO_2 and polymer injection process. After four cycles it was flooded by extended water flooding. This combination gave better recovery than the polymer flood. Moreover, it had much better gas utilization than the CO_2 WAG run. They showed that the advantages of coupled CO_2 and polymer injection can effectively reduce the pressure drop across the core and can obtain encouraging recovery factor if the optimal polymer concentration is added to water. It was concluded that by using 400 ppm polymer, it is possible to obtain higher recovery compared to WAG inection. He stated that a better recovery is due to the WAG mobility control in the system during injection.

In this study the main objective is to propose a new combination method, chemically enhanced WAG (CWAG) to improve the recovery of WAG process. In the CWAG method, the concern is to solve the problems related to conventional WAG process using alkaline, surfactant, and polymer to improve the oil recovery. The main challenges in current WAG mechanism, description of CWAG method, and a worklflow of CWAG modeling are discussed next and then a simulation study is presented to demonstrate the potential of CWAG method.

A Review of Problems Related to Conventional WAG Process

Some new studies have reviewed the main issues associated with a WAG process. The main issues seem to be gravity segregation effect, water blocking phenomena, and WAG mobility control. In the following sections, these issues are discussed.

Gravity Segregation Effect. Ideally, the gas slug is followed by the water slug in WAG injection. Both gas and water slugs displace oil in a piston like manner to sweep horizontally the entire depth of the reservoir, and move the oil to the production well. However, this is impossible due to gravity effect. In near wellbore region, where CO_2 and water are alternately injected, the WAG process has a good conformance, and the sweep efficiency is fairly good, but as the injected fluids progress into the reservoir and move towards the producing well, the gas tends to rise upward due to its low density, and the water tends to descend because of its higher density (Kulkarni and Rao 2005).

Water Blocking Effect. The injected water can isolate the residual oil from contact with CO_2. In this condition, injected water blocks the contact between the CO_2 gas and residual oil. Due to the high IFT between water and oil, it is not possible for water to remove trapped oil from the pores. This phenomena is known as the water blocking effect which reduces displacement efficiency at the pore scale; i.e., it results in a larger residual oil saturation (ROS) (Green and Willhite 1998). A number of studies have shown that oil originally trapped by water is not all contacted when CO_2 is injected (Lin and Huang 1990; Muller and Lake 1991). Some of the trapped oil is mobilized by CO_2 injection, but the rest of the oil remains blocked from the mobile flowing oil phase by water in the pore throats. Water blocking is a strong function of rock wettability and more detrimental in water-wet rocks. (Lin and Huang 1990).

WAG mobility control. WAG mobility control is not feasible especially in high or medium viscosity oil. In high viscous oil reservoirs, the oil and water mobilities are low therefore the mobility ratio will be high. Mobility ratio more than one is considered as non-favorable mobility ratio which gives rise to viscous fingering problems.

Chemically Enhanced WAG (CWAG)

To overcome the issues mentioned above, a new combination method is proposed. This new method, termed as CWAG, combines features of immiscible CO_2 flooding with Alkaline-Surfactant-Polymer (ASP) flooding to produce a chemically enhanced WAG flood. Coupling of ASP with immiscible CO_2 is expected to improve the efficiency of the current WAG technology.

Alkaline and surfactant are typical additives in chemical flooding which can reduce the IFT significantly. Surfactants are organic compounds with both hydrophobic groups (tails) and hydrophilic groups (heads) in a molecule. Due to this unique ability of having two different groups available in the molecule, surfactants act on the interface of two immiscible phases and lower the interfacial tension between these two phases. During IFT lowering process, the hydrophilic part of surfactants remains in aqueous phase while hydrophobic part resides in the oil phase thus making more contact opportunities between the two phases and hence lowering interfacial tension. Alkaline can react with acidic componenets of crude oil to generate in-situ surfactants or soap. The combination of the soap and surfactant can reduce the IFT to ultralow values, i.e. 10^{-3} or 10^{-4} mN/m.

During WAG process in water-wet rocks, the water is in contact with rock grains, and it can trap oil in some parts. By having an aqueous system with ultralow IFT, it is possible for wetting phase to mobilize the trapped oil. The authors hope that by having an ultralow IFT from alkaline-surfactant system it would be possible to reduce the effect of water blocking. WAG mobility control can be enhanced further by using polymer to increase the aqueous phase viscosity. So the mobility control which is a concern for high viscosity oil will be improved. Other advantages of using the CWAG metod can be summarized as follows:

1. Better sweep efficiency in comparison with both ASP and CO_2 flooding alone
2. Less viscosity instability
3. Low IFT and higher capillary number for ASP bank
4. The more continuous oil phase the more favorable for ASP due to oil swelling

Workflow of CWAG Modeling

To the best of our knowledge, there is no study related to immiscible CO_2 combined with ASP. Immiscible CO_2 injection is more favorable than miscible injection due to being economically and technically feasible. In this study, the effects of oil swelling and oil viscosity reduction which are the two important mechanisms in immiscible CO_2 flooding are considered. The IFT reduction and the slug pattern of CWAG are studied. The commercial software STARS-CMG was used in our study. It is a thermal, *K*-value compositional, chemical reaction and geomechanics reservoir simulator ideally suited for advanced modelling of recovery processes such as injection of steam, solvents, air and chemicals. The simulator can model the flow of three-phase, multi-component fluids, in one, two, or three dimensions, including complex heterogeneous faulted structures. In a CWAG process, the main features considered in this simulation study are as follows:

- IFT reduction due to the presence of surfactant and alkali;
- Modification of relative permeability curves due to the changes in capillary number;
- Increasing water viscosity due to the polymer addition;
- Adsorption of chemical components;
- Residual resistance factor due to chemical adsorption;
- Oil swelling by dissolution of CO_2 in oil;
- Reduction of oil viscosity by dissolution of CO_2 in oil.

Synthetic Reservoir Model. The reservoir model used in this study consists of 8×8×35 grid blocks. Grid dimensions are 100 ft ×100 ft ×10 ft, resulting in a reservoir 800 ft length, 800 ft width and 350 ft thick. The reservoir is thick enough to see the effect of gravity segregation. The reservoir is located 3000 ft beneth the surface and has no dip. The reservoir is homogeneous and consists of a sandstone formation. **Fig. 1** shows the synthetic reservoir model. The vertical injection and production wells are diagonally located in the model. In all simulations the injection rate is fixed at 50000 ft^3/day for gas injection well and 3000 bbl/day for water injection well, and the bottom-hole pressure (BHP) at the production well is fixed at 200 psi. **Table 1** presents the input reservoir rock and fluid properties used for the simulation study. The reservoir oil is light oil of moderate viscosity with a reasonably high petroleum acid content, which will react with an injected alkaline solution to form natural “soaps” that can help to increase oil recovery. The reservoir rock is considered to be sandstone with rock density of 2.6 g/cm^3 with high porosity and permeability (Table 1).

CWAG control parameters. Six components were modeled to simulate the processes; water, oil, CO_2, alkali, surfactant, and polymer. CMG-STARS can handle a reduction in IFT by maximum two components. Surfactant and alkali components are responsible for IFT reduction in our simulation. The values of IFT used in the simulation model are shown in **Fig. 2**. The IFT data are used to calculate capillary numbers in the simulation model. The injections of chemicals decrease the IFT, and increase the capillary number which translates into a change in relative permeability and a reduction in the residual oil saturation. STARS can interpolate between different sets of relative permeability curves based on capillary number.

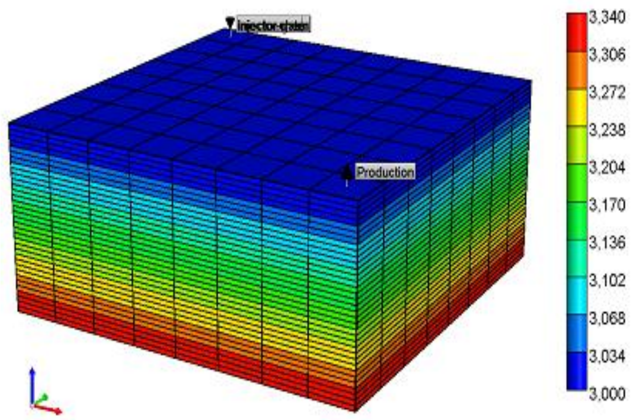

Figure 1- 3D view of the synthetic reservoir model.

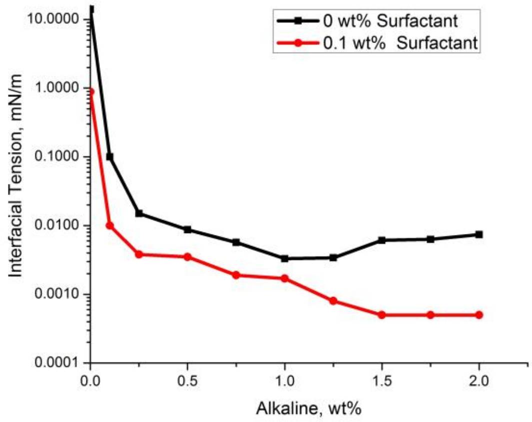

Figure 2- IFT data in simulation (Pandey *et al.* 2008).

Table 1-Reservoir rock and fluid properties.

Reservoir rock		Reservoir fluid	
Parameters	Values- units	Parameters	Values- units
Reservoir size	800×800×350 ft	Water density	62.97 lb/ft^3
Number of grid	8×8×35	Water viscosity	0.6 cp
k_x×k_y×k_z	200×200×20	Oil density	52.02 lb/ft^3
k_v/k_h	0.1	Oil viscosity range	3.2 cp
Porosity	0.2	Initial oil saturation	0.4
Initial res. pressure	900 psi	Initial water saturation	0.6
Res. temperature	100 F		

CMG-STARS allow the use of stoichiometric chemical reactions that consume injected chemicals or result in reaction products, including those that restrict fluid flow. This feature helps to model the interaction of alkali with the rock as well as reaction of the alkali with acidic components of oil to generate additional in situ surfactants. The water rheological properties which are a function of polymer concentration are handled with the polymer option in STARS. As polymer molecules are large compared to most pore throats, all pore throats may not be accessible to them. Experimentally measured values of adsorption, polymer-accessible pore volume, and residual resistance factor (RRF) were also used in the simulations (Pandey, Kumar *et al.* 2008). Injection of CO_2 at pressure lower than minimum miscibility pressure (MMP) is helpful to improve the efficiency of oil recovery through swelling of the oil, viscosity reduction and solution gas drive. The above mechanisms can be modelled via appropriately chosen p, T (and possibly composition) dependent K values describing solubility, as well as compositionally dependent densities and viscosities. The CWAG pattern is an important control parameter which should be considered in any successful project. CO_2 slug which is injected in the beginning of the process is helpful to decrease the oil viscosity and consequently improves the areal sweep efficiency of ASP flooding and its injectivity.

Sensitivity Study. To have a sensible study, we assume that the simulation model data are based on a water flooded reservoir with a 40 percent residual oil saturation and 60 percent water saturation. The base case of CWAG is defined by the injection of chemical slug which contains 0.1 wt% polymer without alkaline and surfactant, and it is chased by water alternating gas injection. The reservoir performance during CWAG process was compared with WAG and continous CO_2 injection (CGI). A sensitivity analysis is performed on critical parameters affecting the process significantly.

IFT Effect. A sensitivity study of the reservoir performance due to IFT reduction was conducted on the CWAG model by changing the concentration of the surfactant and alkali which yield different IFT values. Six simulation runs with different chemical composition slug were performed. The chemical slug compositions used in this sensitivity study are presented in **Table 2**.

CWAG Slug Pattern. To study the effect of the CWAG slug pattern, the four different patterns as presented in **Fig. 3** were considered with the composition given for Case 6 in Table 2 as a base case. This study helps to identify which pattern yields a better recovery during CWAG process.

Table 2-Chemical slug compositions for different cases.

Case	Surfactant concenration, wt%	Alkali concentration, wt%	Polymer concentration, wt%
Base	0.0	0.0	0.1
1	0.0	0.5	0.1
2	0.0	1.0	0.1
3	0.1	0.0	0.1
4	0.1	0.5	0.1
5	0.1	1.0	0.1
6	0.1	1.5	0.1

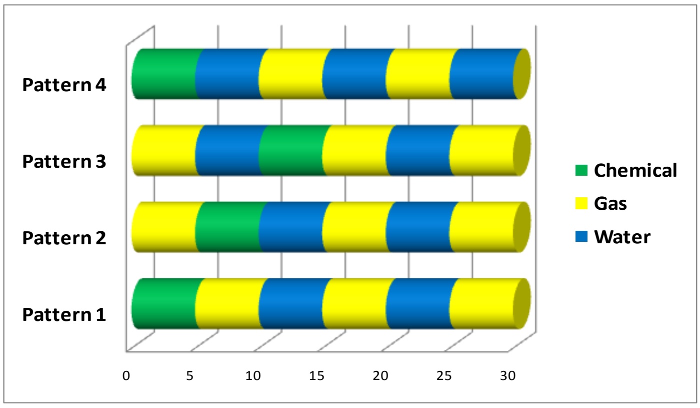

Figure 3- Chemically enhanced water alternating gas process.

Results and Discussion

The oil recovery factor of CWAG process is compared with CGI injection and WAG process in **Fig. 4**. It shows that oil recovery from CWAG process is more than WAG and CGI. During CWAG process, a chemical slug is injected into reservoir and is followed by alternating gas and water slug (pattern 1). The chemical slug contains 0.1 wt% polymer without alkaline and surfactant. It helps to see the effect of polymer slug during CWAG process. Fig. 4 shows an increase in oil recovery which is probably due to better mobility control from polymer slug during CWAG process. Polymer cannot reduce the residual oil saturation but it can reduce the time required to get the same recovery which is economically advantageous. Fig. 4 also shows that after a while CWAG and WAG have almost the same recovery factor. This means that the same residual oil saturation is achieved by both methods. **Fig. 5** shows the oil production rate from three different schemes. In the first slug a low oil production is observed during CGI and WAG processes compared to CWAG but in the second slug there is a sudden increase in oil production only for WAG process which can compensate the low production rate from last period. The CGI cannot recover much oil, compared to other schemes due to early breakthrough and gas override. The CWAG with the chemical slug of 0.1 wt% polymer without alkaline and surfactant is considered as a base case for further sensitivity analysis study.

Figure 6 shows the IFT variation between oil and water during CWAG process in the center of reservoir (grid-block 4, 4, 18) for all related cases in Table 2. As shown in Fig. 6, the IFT decreases during the first three years and it reaches its minimum values and then as the injection continues with alternative gas and water the IFT increases. As it is expected the base case which does not have any IFT reduction agents shows no changes in IFT during CWAG process. Here, Case 6 shows better IFT reduction in CWAG process. The effect of IFT on the oil recovery factor and daily oil production during the CWAG process are plotted in **Figs. 7 and 8.** As the IFT reduces, a higher recovery from CWAG is achieved. It means that by having ultralow IFT value it is possible to obtain more oil recovered from this method. Fig. 7 shows that the oil recovery factor from Case 6 is higher than other cases because this case yields the lowest IFT values. This sensitivity study shows that IFT reduction which is an important mechanism in chemical flooding works quite well in the CWAG process. By having a lower IFT it is possible to reduce the water blocking effect in the reservoir. These results indicate that all successes in chemical flooding can be applied for CWAG process. Fig. 8 shows that the Case 6 has a significant oil production rate at the producer during the chemical slug injection (1st 5 years). **Fig. 9** shows the average reservoir pressure during CWAG process for all cases. As it is expected, in the chemical slug injection period the Case 6 with higher oil production rate shows a lower average reservoir pressure compare to other cases.

The effects of slug pattern on CWAG performance are presented in **Figs. 10, 11,** and **12**. For all slug patterns, Case 6 in Table 2 is selected as a best chemical slug during CWAG process and the effect of different slug patterns are studied. There are some more possible patterns on the CWAG method but in this study only those patterns which seem to give a better recovery are selected. Fig. 10 shows that if the chemical slug inject after one cycle of the WAG it would be more beneficial compared to other patterns. Also this study shows that injection of chemical slug which is preceded by gas slug and followed by alternating gas and water injection is a good pattern for CWAG process. This is probably due to oil viscosity reduction resulted from the injection of CO_2 in front of the chemical slug. The reduction in oil viscosity consequently improves the areal sweep efficiency of chemical flooding as well as its injectivity. The same performance is shown in Fig. 11 and Fig. 12 for both Patterns 2 and 3.

Conclusions and Recommendations

A majority of WAG field projects have resulted in a lower than expected recovery factor. In this study the inherent problems of conventional WAG process like gravity segregation, water blocking and WAG mobility control are reviewed. Then a new EOR method based on chemically enhanced WAG, named as CWAG, is proposed to improve the efficiency of conventional WAG process. The CWAG is a combination of chemical flooding and CO_2 gas injection by employing WAG technique. The most important conclusions and recommendations that can be drawn from this study are:

1. The oil recovery factor for the new method was compared with those of the WAG and CGI processes through a simulation study by using CMG-STARS. The results show a significant improvement in incremental oil recovery factor during CWAG process.
2. A sensitivity analysis is shown that the CWAG process significantly reduces the IFT and provides ultralow IFT system so that it is possible to minimize the water blocking effect and hence, get higher oil recovery factor.
3. The Case 6 with the chemical composition slug, 0.1 wt % surfactant, 1.5 wt % alkaline and 0.1 wt % polymer has the lowest IFT which yields maximum oil recovery factor during CWAG process.
4. Pattern 3 with a chemical slug same as a Case 6 results in higher incremental oil recovery. The injection of chemical slug after one slug of gas and water (pattern 3) is much more effective compared to other possible patterns.
5. The effect of heterogeneity is not investigated through this study. It would be interesting to investigate the effect of heterogeneity on the performance of the CWAG method.
6. To verify the potential of CWAG it is unavoidable to do coreflood experiments to develop this method. It is recommended to test this method in different reservoir conditions to see exactly the potential of CWAG specifically in high temperature reservoir which is always a concern in chemical flooding.

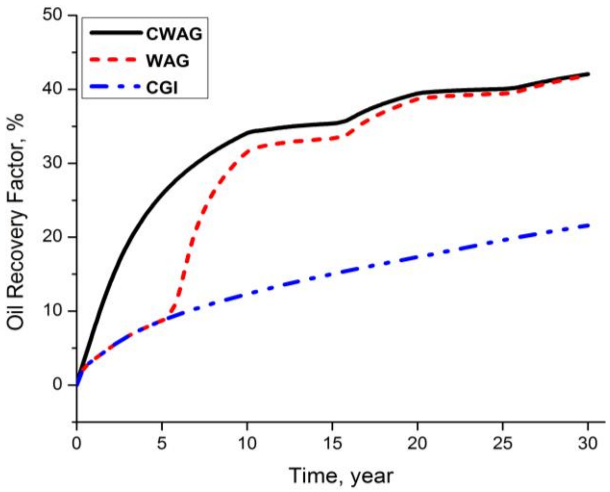

Figure 4- The oil recovery factor for CWAG, WAG and CGI.

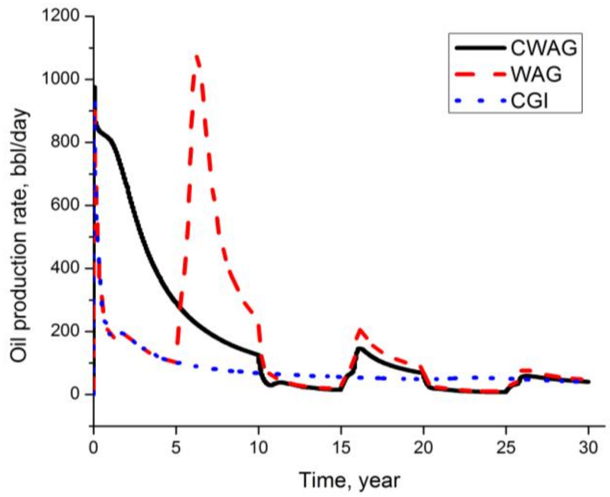

Figure 5- The oil production rate for CWAG,WAG and CGI.

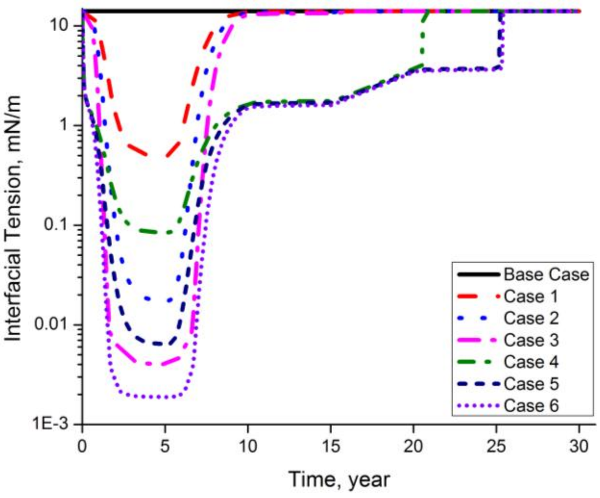

Figure 6- The IFT related to different chemical slug composition.

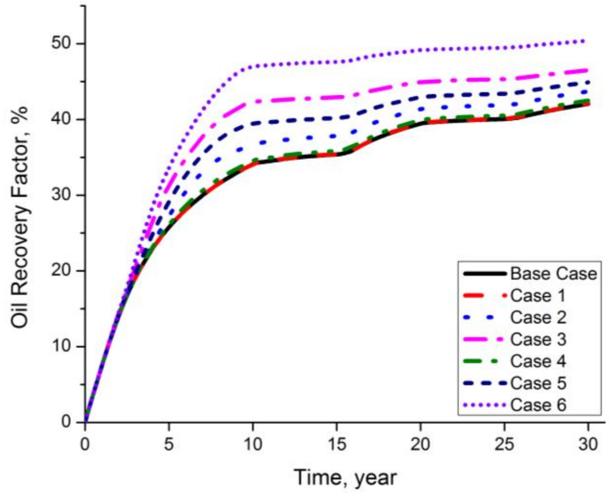

Figure 7- The effect of IFT on oil recovery factor.

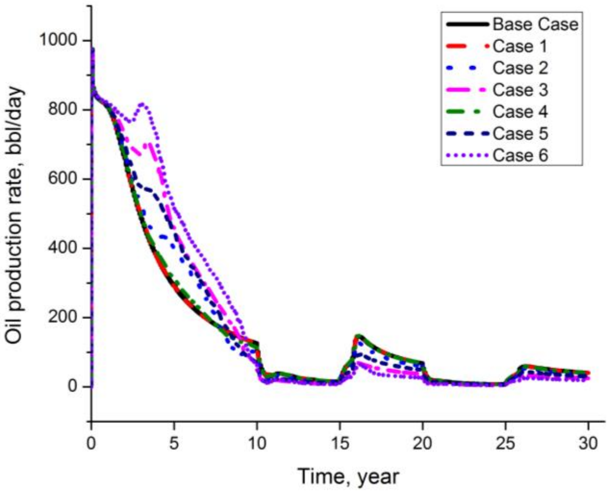

Figure 8- The effect of IFT on Oil production rate.

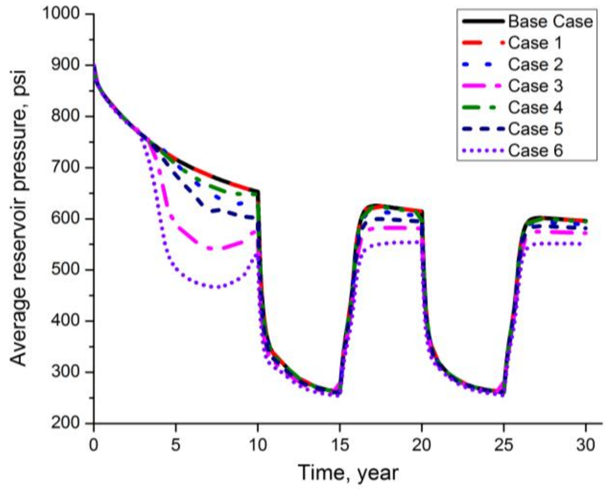

Figure 9- The effect of IFT on average reservoir pressure.

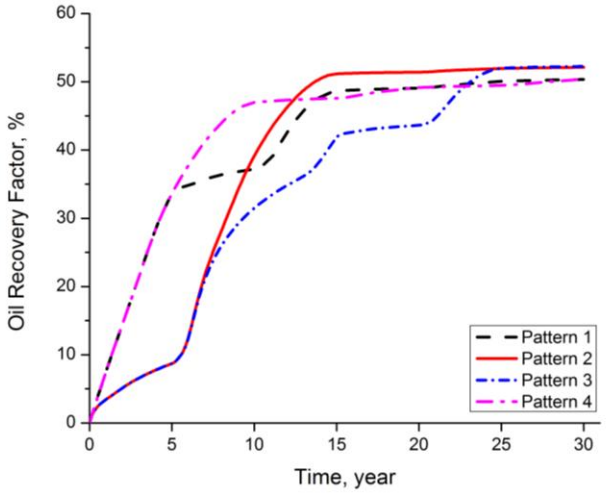

Figure 10- The effect of slug pattern on oil recovery factor

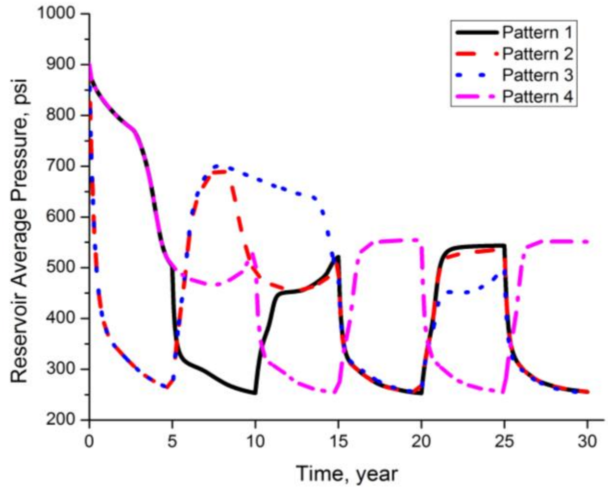

Figure 11- The effect of slug pattern on average pressure.

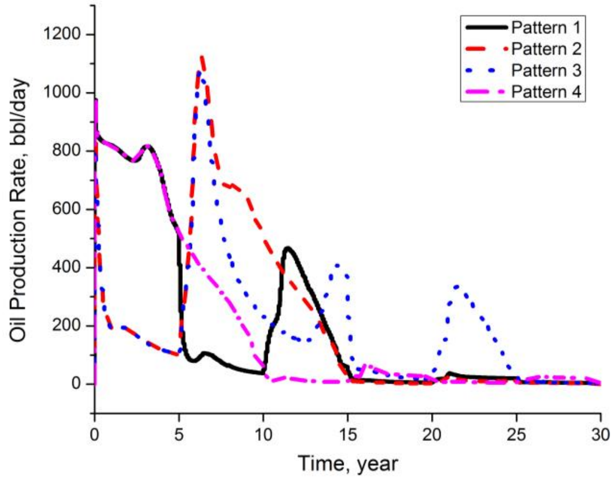

Figure 12- The effect of slug pattern on oil production rate.

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