A comprehensive review of the chemical-based conformance control methods in oil reservoirs

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Abstract

The production of excess water during oil recovery creates not only a major technical problem but also an environmental and cost impact. This increasing problem has forced oil companies to reconsider methods that promote an increase in oil recovery and a decrease in water production. Many techniques have been applied over the years to reduce water cut, with the application of chemicals being one of them. Chemicals such as polymer gels have been widely and successfully implemented in several oil fields for conformance control. In recent years, the application of foam and emulsions for enhanced oil recovery projects has been investigated and implemented in oil fields, but studies have shown that they can equally act as conformance control agents with very promising results. In this paper, we present a comprehensive review of the application of polymer gel, foam and emulsion for conformance control. Various aspects of these chemical-based conformance control methods such as the mechanisms, properties, applications, experimental and numerical studies and the parameters that affect the successful field application of these methods have been discussed in this paper. Including the recent advances in chemical-based conformance control agents has also been highlighted in this paper.

Keywords Foam · Polymer gel · Emulsions · Advances in chemical conformance agents · Conformance control · Water shutoff

Abbreviations

o/w	Oil in water emulsion
w/o	Water in oil emulsion
IFT	Interfacial tension
PPG	Preformed polymer gel
SAGD	Steam-assisted gravity drainage
fm-dry	Limiting capillary pressure water saturation
ep-dry	Abruptness of foam coalescence as a function of water saturation
PEG	Polyethylene glycol
BPD	Barrels per day
SDS	Sodium dodecyl sulphate
mD	Millidarcy
CIM	Conformance improved methods
mL/min	Millimetre per minute
MMSCF	Million standard cubic feet
SEM	Scanning electron microscope

GOR	Gas-oil ratio
o/w/o	Oil in water in oil emulsion
w/o/w	Water in oil in water emulsion
NVP	N-vinyl-2-pyrrolidone

Introduction

Recently, new technologies are employed to increase the level of oil recovery in a bid to meet the increasing demand for energy. These new technologies facilitate the oil recovery from challenging areas such as the deep-sea and subsea petroleum reservoirs including formations with lesser in situ oil mobility than the displacing fluid (Mandal et al. 2010). During oil production, the presence of fractures and high permeability zones in the reservoir often results in water channelling and poor sweep efficiency leading to reservoir conformance problems (Alshehri et al. 2019; Zhang and Abushaikh 2019; Abd et al. 2021). Reservoir conformance is defined as the degree to which the injected fluid uniformly displaces the hydrocarbons across the entire reservoir and up to the producing well. Conformance control is any technique applied to enhance the migration of hydrocarbons from the

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reservoir to the production well, especially those found in areas of the reservoir that are hard to move. To achieve this uniform sweep and produce more hydrocarbons, the production of water must be minimised as it causes a major drawback in oil production (Torrealba and Hoteit 2019; Sydansk and Romero-Zeron, 2011; Bai et al. 2015). Early water production can reduce the production longevity of the well and raise the expense of disposing of the produced water in an environmentally friendly and non-toxic means which is of great concern for the oil companies. The control of excess water and gas production increases the profit for the companies due to producing additional oil that will ordinarily be bypassed by the injected fluids (Azari and Soliman 1996).

The major source of poor volumetric sweep is reservoir heterogeneity which leads to the channelling of flow to thief zones as shown in Fig. 1. Other causes can be an unfavourable mobility ratio, the compartmentalisation of the reservoir and geological settings. The negative effect of poor sweep efficiency can further be aggravated by field operations such as poor well spacing, completion and stimulation (Glasbergen et al. 2014).

The most critical steps in conformance control are identifying and understanding the conformance problem from a reservoir engineering perspective and examining the flow behaviour/characteristics of the reservoir before executing a successful conformance control technique (Abd and Abushaikha 2021). Seright et al. (2001) described the conformance improvement techniques as conformance agents and conformance practice operations. A conformance agent is any chemical or material that can act as a plugging agent when injected into the reservoir. Examples include polymer gels, polymers, cement and resins. These are injected either close to the wellbore or far off in the reservoir. Conformance practice operations refer to the application of completion or mechanical methods such as casing replacement, the

serration of produced water, infill drilling and the use of completion tools.

Another classification of conformance improvement technique is mobility control agents. This depends on their application. If the technique tries to combat the drawbacks associated with the difference in density or viscosity between the displacing fluid and oil, it is described as mobility conformance control (Sydansk and Romero-Zeron 2011). Furthermore, some techniques attempt to enhance the injection or production profile by altering the reservoir permeability heterogeneity and subsequently improving the oil recovery process (Bailey et al. 2000). Conformance control measures can be further classified as:

Continuous flooding blocking agents

In this method, the sweep efficiency can be improved by continuously injecting large volumes of chemical that do not completely block the flow but instead increase the resistance. This can be done either by increasing the viscosity of the injectant or through the adsorption of the injectant which facilitates the reduction in effective permeability (Glasbergen et al. 2014).

Near wellbore blocking agents

This blocking agent will change the injection profile in the near-wellbore region. These agents can be injected into either the injectors or producers to block the flow to and from the highly conductive layers. The volume injected is typically small, but since the pressure drop at the wellbore region is very high, a very high resistance factor is required and the plugs will need to withstand the pressure differences at multiple bars (Glasbergen et al. 2014).

Fig. 1 Areal and vertical conformance problems. Adapted from Maya-Toro et al. (2015)

In-depth blocking agents

In-depth blocking agents are more suited to treat the poor conformance associated with wells with localised high permeability streaks and fractures that are at some distance from the injector and producer. After the placement and activation of the blocking agent, the consequence is a change in the streamlines, and subsequently, the injected fluids will be diverted from the blocked preferential flow path and result in other areas being swept (Glasbergen et al. 2014).

Chemicals agents are the most active aspect of conformance control research and there are over 100 different conformance control chemicals that have been developed and utilised in oil fields (Liu et al. 2016). Due to the great interest in chemical-based conformance control displayed by researchers and the oil industry, polymer gel has been widely implemented when plugging high permeability streaks in the reservoir. Foam in recent years has been successfully applied and the use of emulsions has emerged as a new agent for conformance control. As the demand for energy increases and companies are looking to maximise oil recovery, there is a need for continuous studies and advancements in technologies that will improve the effectiveness of these methods to reduce the water cut to promote the recovery of more oil. Although there have been several publications on the chemical systems of conformance control, most of the review work has focused on the application of polymer gel treatment for conformance control and the use of foam and emulsion in enhanced oil recovery processes. This paper aims to review the experimental and numerical studies on the application of polymer gel, foam and emulsion for chemical-based conformance control. Various aspects such as the mechanisms, properties and parameters affecting the application of these methods, successful field applications and recent advances will also be discussed.

The paper structure is as follows: Sect. 1 is the introduction. In Sect. 2, we discuss polymer gel treatment as a conformance control method and different types of polymer gel systems. We then proceed to review the application and factors affecting polymer gel treatment. Section 3 includes the introduction of emulsion as a chemical agent for conformance control, the water blocking and diversion mechanism of emulsion, the characterisation of the emulsion system and the application of emulsion-based conformance control methods. Section 4 includes foam usage for conformance control, foam properties, foam generation and propagation mechanisms of foam and the factors affecting foam generation and propagation. Section 5 discusses the recent advances in chemical-based conformance control agents. Finally, the conclusions from this review are presented in Sect. 6.

Polymer gel conformance control

Polymers have been employed to control the mobility of the injected water in oil recovery processes for many decades. The application of secondary enhanced oil recovery (EOR) such as water flooding to sustain reservoir pressure and to displace oil after primary depletion often leads to flow channels that can result in the bypassing of oil in heterogeneous reservoirs and premature water production. The main mechanism of polymer is to improve the mobility ratio thus leading to an efficient oil displacement (Abidin et al. 2012).

An additional application of polymers is in conformance control where a polymer gel is injected to shut off the areas in the reservoir with very high permeability. This reduces the production of water as shown in Fig. 2. There is a clear difference between polymer gel injection and polymer flooding. Polymer flooding as an EOR technique is mainly used

Fig. 2 Distinction between polymer flooding and polymer gel application. Adapted from Kazemi (2019)

to control the mobility of the injected water, whereas the polymer gel is mainly used for conformance control in situations where there is the presence of a very high permeability contrast in the reservoir (Sorbie 1991; Abdulbaki et al. 2014). Another distinction is the addition of a crosslinker which enables the polymer gel to form polymer systems that are efficient in plugging high permeability zones and creating a long-lasting permeability reduction which in turn will lead to an increased flow resistance, fluid diversion and displacing the oil out of any unswept regions in the reservoir (Sorbie and Seright 1992; Speight 2013; Abdulbaki et al. 2014; Smith et al. 2000; Norman et al. 2006a).

The primary step for a polymer gel conformance treatment is modelling the gel treatment operation using numerical simulations comprised of every valuable reservoir and well data. For instance, this includes the well logs, drilling operations, reservoir and fluid properties, production history and the point of water entry. After modelling and simulation, the next phase is to design the gel system characteristics. Certain parameters such as the viscosity, density, gel setup and injection time and the nature of the gel must be designed carefully to avoid losing the effectiveness of the gel system (Taha and Amani 2019). For a successful field application, an adequate gelation time is required to pump the gel solution into the target treatment zone. The polymer and crosslinker type and their concentrations, as well as the reservoir temperature, salinity and pH, can influence the gelation time (Nasr-El-Din et al. 1998).

Classification of polymer gel systems

Polymer gels are classified based on how they are formed, the type of crosslinker used and how they are applied. The classification into three types is centred on the conditions that they are formed in and the location where they are applied in the reservoir. They are in situ monomer gels, in situ polymer gels and preformed polymer gel systems (Bai et al. 2015).

In-situ monomer gel

In 1978, Haliburton developed a gel system from the in situ polymerisation of acrylamide monomers to form polymers. This polymer was generated in the presence and absence of a crosslinking agent. The solution of the monomer and crosslinker had a viscosity close to that of water. Due to this low viscosity, the in situ monomer gel can easily invade the in-depth regions of the reservoir. In situ monomer gel treatments have been employed in various field applications with success (Dalrymple et al. 1994; Woods et al. 1986; Townsend and Becker 1977). However, there are certain drawbacks to this gel system due to the monomer gelation being a rapidly initiated free radical process causing

difficulty in terms of controlling the gelation under high-temperature reservoir conditions and the toxicity level of the monomer acrylamide (Vossoughi 2000; Bai et al. 2015). Eoff et al. (2007) reported on a less toxic, acrylate-based temperature activated monomer system. The time of gelation was controlled up to a temperature of 93.3 °C but at high concentration of the monomer was required. Because at a low concentration, the gel formed was slightly water-soluble with lower strength. Increasing the concentration of the monomer made the application expensive and the concerns with the operational risk resulted in a decreased application.

In-situ polymer gel

This type of polymer gel is widely used for conformance treatment in the petroleum industry. The application was first reported in the oil industry in the late 50 s (Amir et al. 2018). Philips Company (currently known as Conoco Philips), in the 1970s, was the pioneers in initiating the use of in situ polymer gels for plugging high permeability zones in the reservoir (Needham et al. 1974; Borling et al. 1994). The in situ polymer gel system is essentially comprised of two elements, a high molecular weight polymer and a crosslinker. In the presence of a stimulant, the crosslinker will physically or chemically connect itself to two neighbouring polymer molecules, combining them to form a network that is three dimensional in the reservoir (Bai et al. 2015). The most widely used polymers are synthetic polymers, for example, polyacrylamide (PAM) and biopolymers such as Xanthan gum and guar gum (Dai et al. 2013). These polymers have diverse levels of hydrolysis, charge density and molecular weights, and they are typically inexpensive to produce (Al-Muntasheri et al. 2010). In situ polymer gels can be either organic or inorganic depending on the crosslinking agent.

Inorganic crosslinked polymer gels are formed as a result of the bonding between the negatively charged carboxylate group of partially hydrolysed polyacrylamide polymer and the multivalent action forming ionic bonds. Inorganic polymer gels are formed by crosslinking polymers with metal ions. Examples are chromium (III), aluminium (III) and zirconium (IV) which are widely used inorganic crosslinkers for gel preparations. They are only useful in low-temperature applications because of their speedy reaction rate, precipitation and absorption in the porous media. However, their stability can be improved by crosslinking them with low molecular weight polymers and retarding agents such as malonate, glycolates and salicylates (Ni et al. 2010; Bartosek et al. 1994; Moradi-Araghi 2000). Organic crosslinked polymer gels on the other hand are more suitable compared to inorganic crosslinked polymer gel because of their stability in high-temperature reservoirs. The covalent bond formed when the amide groups of the polymer and organic crosslinker interact provides a strong bond and stability at

elevated temperatures compared to the weaker coordinated ionic bonding in the inorganic crosslinked gel. In general, the crosslinking reaction relies on the polymer end rather than the chemistry of the crosslinkers. Phenol, formaldehyde and polyethyleneimine are the common organic crosslinkers used for polymer gels (Vasquez and Eoff. 2010; Zitha et al. 2002; Zhuang et al. 1997; Bryant et al. 1997; Amir et al. 2018).

Preformed polymer gels (PPG)

Although the application of in situ polymer gel is economical and conducive for high-temperature reservoirs, there are problems associated with their application such as a change in the gel compositions, inability to control the gelation time, shear degradation, formation water dilution and chromatographic fractionation. Considering these disadvantages, PPG was developed as an improved polymer gel system to combat the problems associated with the other gel systems (Bai et al. 2015). PPG is a particulate superabsorbent crosslinked polymer that can swell to 200 times its original size when in contact with brine. Due to its chemical and physical crosslinking, it does not dissolve. The novelty and main difference between PPG and in situ polymer gel are that the gel formation occurs at the surface before injection while in in situ gel, the crosslinking and gel formation occurs in the reservoir

(Amaral et al. 2019). The PPG system has only one component during injection, and it is injected as particles into the reservoir which makes the process of injection simpler.

The currently commercially available preformed particle gel system comes in different sizes: sub-micron (Bright water gel system), micrometres (pH-sensitive, colloidal dispersion and microgels polymer gel systems) and millimetres (preformed polymer particle gels) (Bai et al. 2013; Tavassoli et al. 2018). Micro-sized gels are primarily used to reduce the permeability in the streaks/channels that are less than one Darcy while the millimetre microgels are used for reservoirs with fractures in the form of channels or fractures with a permeability greater than a few Darcies (Bai et al. 2013; Al-Anazi and Sharma 2002).

Polymer gel for profile control

The goal of the polymer gel when injected is to maximise the gel diversion and penetration into high permeability regions as illustrated in Fig. 3. El-hoshoudy et al. (2018) discussed that gel strength code 'G' which means the polymer gel is moderately deformable and non-flowing with good resistance to high salinity. This strength code was exhibited by the hydrogel that they developed for profile control allowing it to infiltrate into the porous media easily, leading to an improved resistance factor and permeability reduction.

Fig. 3 Polymer gel injection in thief zones. Adapted from de Aguiar et al. (2020)

Several numerical and experimental studies have been conducted to examine the effectiveness of polymer gel treatment for water control. Alhuraishawy et al. (2018) conducted core flooding experiments and developed numerical models to examine the potential of combining smart water flooding with microgel polymer treatment. They reported that combining the polymer gel treatment with modified seawater (increasing concentration of sulphate ions) provided better sweep efficiency when compared to the polymer gel treatment combined with diluted seawater.

Goudarzi et al. (2015) demonstrated through laboratory and simulation studies, the transportation of PPG in fractures for water conformance control. Their investigation involved the injection of PPG into the fractures in sand pack models. Using experimental data, they developed and validated mechanistic models to design and optimise the gel treatments used for conformance control. By comparing the measured and simulated oil recovery and water cut, they achieved a favourable match indicating that the gel transport model they implemented in the simulator can accurately model gel injection behaviour and that the PPG gel can effectively plug fractures and divert the flow from high permeability streaks. Tavasolli et al. (2018) conducted experimental and numerical studies of pH-sensitive microgels for conformance control. In their study, they analysed the rheology, resistance and strength of the polymer gel before performing core flooding experiments using a cement type core with fractures. Their numerical studies included sensitivity analysis to examine the effects of polymer concentration and fracture size on polymer gel in terms of holding back the pressure gradient. They observed that a highly concentrated polymer solution is essential to abate leakage in larger fractures and to infiltrate fluid zones with an elevated pressure gradient.

Heidari et al. (2019) pointed out that fractures present in the reservoir can affect the performance of PPG treatment. To prove this, they evaluated the performance of preformed particle gel systems, namely micro-models, with varying geometries (variable mouth, step fracture, simple fracture and tiny crack fracture). They reported that after PPG treatment, the smallest amount of oil recovery was observed in the step fracture due to its tortuosity that increased the gel movement resistance. The variable mouth fracture experienced the highest oil recovery. Imqam et al. (2015) evaluated the penetration performance of PPG for the purpose of conformance control in partly opened conduits. They considered several factors such as the effect of back pressure, gel injection pressure, gel strength and matrix permeability in their analysis and concluded that a clear distinction exists between the injection and placement of PPG in partially opened and fully opened conduits. Additionally, they discussed that in partially opened conduits, PPG forms an internal and external filter cake in the matrix surface and does not wash out of

the conduit. In fully open conduits, depending on the properties of the conduit and PPG, some of the gel particles can wash out.

Jahanbani Ghahfarokhi et al. (2016) in their study of the deep in-situ injection of a green hybrid polymer gel system in layered reservoirs performed sensitivity analyses involving parameters such as polymer gel injection time, concentration and rate. They also considered the effect of injection strategy, crossflow, permeability contrast and the blockage of high permeability regions in oil recovery during the polymer gel treatment. Their results showed that a long gelation time is necessary for the gel to flow deep into the reservoir and that gel treatment is more successful in reservoirs with a low crossflow between the layers in the reservoir. Yadav and Mahto (2014) reported on a gelation study they conducted on organically crosslinked polymer system in sand packs. They prepared the polymer gel using a partially hydrolysed polyacrylamide polymer, with hydroquinone and hexamine as the crosslinkers. They injected the gel solution into sand packs at varying temperatures to simulate the Indian oil fields reservoir and examined permeability reduction with water flooding after complete gelation. They discussed that the permeability and residual resistance factor reduction which occurred in the sand pack increased with an increase in the crosslinker and polymer concentration.

Hakiki et al. (2015) studied the ability of an epoxy-based polymer to plug selective layers in water shutoff applications. They synthesised an epoxy polymer with a triethylene-tetramine crosslinker and performed displacement experiments with sandstone core samples. They showed in their results that the in situ gelation of the epoxy polymer can effectively reduce the permeability of sandstone rocks under ambient conditions. To utilise this polymer gel system in reservoir conditions, a solvent with a higher boiling point than acetone that can withstand a high temperature should be employed.

Alghazal and Ertekin (2018) used artificial intelligence to develop a neuro-simulation proxy model to examine the performance of a polymer gel treatment in naturally occurring fractured reservoirs. They built a reservoir simulator model using a commercial thermal simulator. To obtain the data for various reservoirs with production and design scenarios, they developed three artificial neural network proxy models (ANNs), one of which was a forward model used to create the production profiles for a given reservoir. The additional two were inverse models used to assess the polymer and reservoir properties that can provide the necessary production profiles. They deduced from their model that the production profile is greatly affected by the injection rate and that an in situ polymer gel with a crosslinker can effectively plug fractures and improve the sweep efficiency.

Kwak et al. (2017) examined a polymer gel system comprised of a polyacrylamide polymer and chromium

crosslinker injected in carbonate reservoirs followed by water flooding. The process was closely monitored using nuclear magnetic resonance techniques. They conducted NMR studies before and after water flooding and with and without a polymer gel injection. They observed a 41% increment in oil production when water flooding was executed after polymer gel treatment throughout the core samples. The highest recovery was achieved in zones without wormholes.

Brattekkås et al. (2019) in their study varied several properties of hydrolysed polymer gel to study the effect of pore size, heterogeneity and permeability on the leak-off rate and gel dehydration. To monitor water leak-off and verify the location and presence of a stable displacement front, they utilised magnetic resonance imaging which was able to detect wormholes present in the gel during and after gel injection. In their conclusions, they stated that the gel leak-off rate can only be related to the velocity when the water forms a stable displacement front which can be parallel to or moving away from the fracture.

Factors affecting polymer gel treatment

Several investigations have revealed that certain factors such as pH, salinity, reservoir temperature, crosslinker, polymer concentration and the presence of iron affect gel stability, strength and gelation time. These are crucial properties for a polymer gel system, and they determine its successful application for permeability reduction and water shutoff (Wang et al. 2016; Hasankhani et al. 2018). Polymer gel is formed through the process known as gelation. Adequate time for gelation is necessary to pump the polymer gel solution into the zone of interest in the reservoir. Tessarolli et al. (2019) examined the impact of polymer structure on polymer gel strength, gelation time and kinetics. Their results showed that a higher molecular weight and acrylate moieties of the polymer give rise to a short gelation time. This in turn promotes gel strength while the presence of NVP (N-vinyl-2 pyrrolidone) moieties and clay particles leads to a long gelation time and an enhancement in the final gel strength.

Al-Anazi et al. (2019) examined temperature, pH, salinity, polymer and crosslinker concentration influence on gel strength and gelation time using rheological measurements and a bottle test. They verified their experimental results by developing a mathematical model that captured the parameters examined in their experiment. Based on their analysis, it was found that increasing the temperature, pH, polymer molecular weight, polymer and crosslinker concentration decreases gelation time. There is an optimum concentration of polymer and crosslinker below which a gel cannot be formed. Farasat et al. (2017) demonstrated that temperature and salinity have a considerable effect on the swelling ratio of the preformed particle gel used in their studies.

They discussed how the PPG swelling ratio is influenced by salinity in low salinity regions and by temperature in high salinity regions.

Studies conducted by Lashari et al. (2018) showed that increasing the polymer and cross-linking concentration can lead to the formation of a strong polymer gel. They discussed that a high polymer concentration results in an increase in the crosslinking density, hence improving the structural integrity of the gel and decreasing gelation time. Zhao et al. (2015) examined the factors affecting non-ionic polyacrylamide (NPAM)/phenolic resin gel system for in-depth profile control. They investigated the effect of shearing, temperature and salt concentration on gelation performance. They demonstrated in their results that the salts with divalent ions have more of an impact on the gel strength and gelation time than the salts with monovalent ions. They added that increasing the gel shearing time will decrease the gelation time and gel strength.

The presence of iron (III) in large tanks used when preparing polymer solutions in field locations can have an impact on the polymer gel and gelation time (Willhite et al. 2005; Al-Muntasheri et al. 2007). According to Uranta et al. (2018), very reactive oxygen anion radicals produced by the oxidation of Fe^{2+} to Fe^{3+} in the tank may attach to a polymer chain and breaks the backbone by producing peroxide and causing polymer gel degradation. Jia et al. (2015) assessed the influence of contaminants such as iron (III) on polymer gelation performance by employing experimental techniques that combine rheology measurement with SEM spectroscopy. The presence of iron (III) in the polymer gel system, according to their analysis, had a negative effect on the quality of the polymer gel due to iron (III) acting as a strong oxidising agent and causing the degradation/destabilisation of the polymer gel system. They proposed that the surface equipment and tubing used should always be clean or a chelating agent should be added before the gel preparation to the well site.

Summary

Experimental and numerical studies have shown that polymer gel is effective at plugging high streaks in the reservoir. Certain conditions such as monomer toxicity, the control of the gelation time, reservoir temperature and salinity, which affects the in-situ monomer and polymer gels, have led to the development of a more advanced PPG system. The cost of the polymer gel is another hindering factor in the application of polymer gel treatment, including not being conducive for large volume treatments, harsh reservoir conditions and a limited penetration distance. For these reasons, researchers such as Ding et al. (2020) and Yu et al. (2018b) have proposed the

use of emulsions for conformance control because of the advantages demonstrated by this method. In the next section, the use of emulsion for conformance control is presented, including the mechanisms and the characterisation of emulsion systems for conformance control.

Emulsion conformance control

The study of emulsions has been of great interest in the petroleum industry. Emulsions have been used over the years as a displacing fluid for enhanced oil recovery processes (Massarweh and Abushaikh 2020). However, the application of emulsion as a blocking agent in conformance control is an emerging technique. Compared to other conformance control agents, emulsions have unique distinctions such as better injectivity, less difficult blockage removal, a wide range of channel plugging and less damage to the formation (Chen et al. 2018). Bai and Han (2000) reported that a higher oil recovery factor was obtained after an emulsion injection when compared to a polymer gel injection in their study. They attributed this to the induced formation damage caused by the polymer gel in the target areas in the reservoir and the lack of selective plugging by the gel.

Emulsions are thermodynamically unstable systems consisting of two immiscible fluids, one with a dispersed droplets phase and the other a continuous phase in the presence of surface-active agents. Hydrocarbon production from the petroleum reservoir and transportation to the surface is always in the form of a mixture containing oil, gas and water as well as inorganic and organic contaminants. These contaminants act as emulsifiers and with the continuous agitation of the mixture from the reservoirs during the flow up to surface facilities, tight emulsions can be formed. Emulsions can be intentionally formed for upstream processes such as enhanced oil recovery and acid stimulation (Maaref et al. 2017; Ahmadi et al. 2019). Depending on which phase is continuous or dispersed, emulsions can be water in oil (w/o), oil in water (o/w) as illustrated in Fig. 4 (Zapateiro et al. 2018; Mandal and Bera. 2015).

The most common type of emulsion formed in oil production is the w/o emulsion with a viscosity that is greater than that of oil. Using this, it creates a large pressure drop between the injection and production well, leading to a loss of fluids. This type of emulsion is considered to be undesirable in the oil production processes (Rezaei and Firoozabadi 2014; Lim et al. 2015). On the contrary, o/w emulsion has a very low viscosity that is very similar to water. This allows for good injectivity and it flows easily, thus making it attractive for conformance control measures.

Fig. 4 Types of emulsion system (Adapted from Khan et al. 2014)

Mechanism of conformance control by emulsion

To design emulsion systems for conformance control, a good understanding of the mechanisms and plugging ability of emulsion is required. The earliest investigation into the application of emulsions for conformance control was conducted by McAuliffe (1973a,b). He conducted experimental and field-scale investigations on emulsion flow through the porous media and its plugging capabilities in high permeability zones. In the experimental studies, he evaluated the bulk properties of the emulsion such as the droplet size distribution and rheology. He observed that the o/w emulsion reduces permeability to water if the initial permeability is less than 2 Darcies and the flow of emulsion is pseudo-non-Newtonian irrespective of the concentration of oil present in the emulsion. In the field studies, he reported a change in the flood pattern after the emulsion injection which led to a decrease in water production. Soo and Radke (1986) developed a filtration model to describe the flow of dilute and stable emulsions in an unconsolidated porous media. Their model captures the emulsion drops in the pores through straining and interception and they described the transient flow behaviour of the emulsion with parameters such as flow redistribution, filter coefficient and flow restriction. All 3 parameters control the steady state distribution, the precision of the emulsion front and the permeability reduction created by the retained drop. The filtration model was compared to the already existing retardation models for the emulsion flow. Only the results obtained from the filtration model could match the permeability reductions observed in the experiments.

Cortis and Ghezzehie (2007) argued that the filtration model proposed by Soo and Radke (1986) does not accurately model emulsion flow with a small to average droplet size ratio. This is because the model assumes that the emulsion and grain size of the porous media is homogeneous across all scales. Thus, predicting a fast-exponential

concentration decay that does not capture the slow late times of the emulsion. They introduced a continuous-time random walk model that captures small scale heterogeneity such as the dispersed phase droplet surface heterogeneity, shape and size. They recognised from their model that the pore space available for the water to flow is changed continuously as the oil droplets become stuck in the pore throats. The oil droplets move continuously, providing a moving boundary for the water phase.

Alvarado and Marsden (1979) described the flow of emulsions experimentally and mathematically by developing a bulk viscosity model that assumes that the emulsion is homogeneous and a single phase. They derived a simple correlation that described the non-Newtonian flow of o/w macro-emulsions through the porous medium. The correlation was reduced to Darcy's Law for o/w Newtonian macro-emulsions and the partial blocking that results in permeability reduction was included. They discovered that the model did not follow Darcy's law because of the shear rate effect on emulsion viscosity. Yu et al. (2018a) reported that as the pressure differential increases, the emulsion flows easily allowing for deep penetration in the reservoir. When the emulsion drop enters a pore throat, it will experience a capillary resistance force when passing through as a result of the "Jamin" effect. This "Jamin" effect will ultimately lead to flow restrictions including several other parameters such as emulsion droplet size, pore size distribution and interfacial tension. They concluded that for the effective plugging of the porous media, the emulsion droplet sizes should be slightly greater than the pore throat and this does not cause any form of damage to the formation. Figure 5 illustrates the "Jamin" effect encountered by an emulsion droplet in the pore throat.

Yu et al. (2018b) continued their studies by proposing a non-uniform capillary model that takes into consideration

the physical properties of the emulsion, the interaction between the emulsion and the porous media and the size difference between the pore throat and body of the porous media. They determined the resistance force by evaluating the plugging and adsorption characteristics of the emulsion droplet in the capillary model and they introduced a dilution factor in the model to demonstrate the flow of emulsion after water flooding. To validate their model, they executed injection experiments into sand packs and the results showed that by choosing appropriate coefficients, the most influential factor for emulsion flow resistance is the droplet size distribution. They continued by stating that the emulsion plugging strength is highly sensitive to the oil viscosity and less sensitive to the droplet effective permeability.

Moradi et al. (2014) stated that the connections between the mechanisms are at the pore level and that Darcies' level behaviour is the driving force in designing the key process that exploits the emerging responses of the flow of emulsions in the porous media. In their study, they analysed the capillary trapping of the dispersed phase droplets from the emulsion in the porous media as a function of the capillary number and droplet to pore size ratio. Their experiments involved the injection of the emulsion with a known droplet size distribution as a tertiary oil recovery process and single-phase flow experiments. They showed in their results that the emulsion blocking phenomena depends on the capillary number and is favoured by a low capillary number.

Characterisation of emulsion

The application of emulsion for conformance control is associated with the design of a suitable slug and injection scheme that is dependent on the properties of the emulsion and the distribution of the fluid and rock. Emulsions are characterised based on their stability, droplet size and rheological properties (Mohyaldinn et al. 2019; Mandal et al. 2010). Over the years, there have been several studies on the stability and characteristics of emulsions. Nevertheless, there are numerous unresolved issues involving emulsion characterisation such as understanding the flow of emulsions in the pore spaces of the petroleum reservoir, finding accurate measurement techniques to monitor the stability of emulsion or developing a correlation to account for the effect of various factors affecting the emulsion stability and the distribution of the droplet size. Although a large percentage of the emulsions formed are in the petroleum reservoir during production, the physics of the flow of emulsion in porous media is complex due to the complicated properties of emulsions and the porous media (Goodarzi and Zendejboudi 2019; Maaref et al. 2017).

Fig. 5 'Jamin' effect encountered by emulsion drop passing through the pore throat (Adapted from Moradi et al. 2014)

Stability of emulsions

A highly stable emulsion is essential for conformance control applications and the emulsion is said to be stable if separation is not achieved and the properties remain unchanged within a necessary time scale. Occurrences such as flocculation, coalescence and phase separation as illustrated in Fig. 6 are responsible for emulsion stability (Maphosa and Jideani 2018). According to Akbari and Nour (2018), emulsion stability is related to the type and concentration of surfactant present and this is prompted by the surfactants' ability to form films around the water droplets in the o/w interface. The formation of this film increases the interfacial viscosity and reduces the interfacial tension. This prevents the oil droplets from gathering.

Kokal et al. (1992) discussed that the stability of an emulsion can be affected by the reservoir pressure and the presence of surface-active agents. They stated that temperature and pressure in the reservoir affect the o/w interfacial tension in the emulsion. As the pressure and temperature increases, the interfacial tension reduces, affecting the emulsion by making it more stable. Rong et al. (2018) aimed to characterise and analyse the stability of oil in a water emulsion by employing a single exponential decay function in the Origin software. They deduced from their results that an increase in the mass fraction of SDS causes a sharp decline in the viscosity rate change and a slow reduction in the creaming velocity which leads to a more stable emulsion. The combination of SDS/Akylglycoside provides a more stable emulsion compared to the SDS/1-pentanol mixture.

The effect of electrolytes and temperature on the stability of o/w emulsion was reported by Kundu et al. (2013). They examined the impact of different kinds of salts on the electrophoretic properties, the phase inversion temperature and the stability of an o/w emulsion by measuring the zeta potential, turbidity and the electrical conductivity of the emulsion. They conveyed from their findings that a negative value for the zeta potential indicates stable oil in the water emulsion. An increase in the salt concentration leads to a decrease in the zeta potential of the emulsion. This in turn causes emulsion destabilisation. The stability was mostly observed with monovalent salts. Esmaeili et al. (2014) also demonstrated in their work that the droplet size distribution of the dispersed phase in the emulsion is related to the stability of the emulsion. They evaluated four different surfactant blends. They showed that surfactant blends with the lowest mean droplet diameter had the highest stability.

Chen and Tao (2004) investigated the effect of different parameters such as oil/water ratio, emulsifier concentration, stirring speed, temperature and stirring time on the stability of an o/w emulsion. They observed from their analysis that the stability of the emulsion increases with a decrease in the o/w ratio, an increase in emulsifier concentration and an increase in stirring time. There is an optimum time at which point a further increase in stirring time will lead to the destabilisation of the emulsion. Furthermore, they showed that an increase in temperature results in the instability of the emulsion. They proposed an optimum emulsifying condition of 0.5% emulsifier concentration, a 0.5% o/w ratio of 1:1, a stirring speed intensity of 2500 rpm and a mixing temperature

Fig. 6 Steps in emulsion instability (Adapted from Goodarzi and Zendehboudi 2019)

of 30 °C. Sarbar et al. (1987) studied the effect of chemical additives on the stability of an o/w emulsion flowing through porous media. They injected emulsion slugs with varying oil percentages of 1, 5 and 10% into sand packs, changing the pH and surfactant concentration of the emulsion. They found out that there was an optimal value for the surfactant concentration at which point the emulsions become very stable and the introduction of sodium chloride to the aqueous phase had a negative effect on the stability of the emulsion. For their o/w system, they found that the optimum value of pH was 10, which achieved the most stable emulsion.

Rheology of emulsions

A very important aspect of emulsion behaviour is their characteristic changes in rheology and flow path in porous media which is the reduction in shear viscosity with increasing shear rates. Some emulsions can exhibit limiting yield stress below which they will not flow (de Castro and Agaou 2019; Talon et al. 2014; Gómora-Figueroa et al. 2019). The ability of the emulsion to migrate, deform, coalesce and block pore throat is governed by the rheology of the emulsion. Emulsions can exhibit different rheological properties such as being a Newtonian or a non-Newtonian fluid depending on the volume percentage of the dispersed phase. For an o/w emulsion, the viscosity increases with a decrease in the size of the droplets involved. The power-law model is used to describe emulsion flow behaviour when the shearing rate is beyond the limit (Guillen et al. 2012).

Khambharatana et al. (1998) discussed that a change in the rheology of an emulsion has a similar trend to that of a viscometer in their investigation on the rheological behaviour of emulsion flow in porous media. They examined the flow of an oil/water emulsion in Berea sandstone at different velocities and analysed the rheology of the injected and produced emulsion after the experiment. They observed that the injected and produced emulsion showed pseudoplastic behaviour and that an increase in the flowrate during the emulsion injection caused the breakdown of emulsion droplets. They concluded that the loss of oil droplets in the porous media led to a decrease in emulsion viscosity. Al-Fariss et al. (1992) reported on the rheological behaviour of o/w emulsion in their study of emulsion flow in porous media. Their results indicated that an emulsion will display Newtonian behaviour when the oil percentage is within the range of 10–40%. Using the power-law model to describe the emulsion with a medium oil concentration of 40–60%, they noted that the emulsion behaved like a pseudoplastic fluid. At higher oil concentrations greater than 60%, the emulsion revealed yield stress and non-Newtonian behaviour fitting the Hershel–Bulkley model.

Clark and Pilehvari (1993) demonstrated in their study that the shear rate and shear stress on the emulsion is a

function of the oil droplet size distribution. They discussed that for a given oil volume phase, the viscosity and non-Newtonian behaviour of the emulsion increased with a decrease in droplet size. Droplet size distribution can change the behaviour of the emulsion from Newtonian responses to shear thinning. The emulsions that they presented in their study showed a high shear-thinning behaviour at very low shear rates and that the sensitivity to shear decreased with the increasing shear rate. The power-law could only describe the rheological behaviour of the emulsion over a limited range of shear rates. Omar et al. (1991) examined the effect of temperature and dispersed phase volumes on the rheological behaviour of Saudi crude oil emulsion. Based on their experimental observations and the analysis of their results, they reported that at a higher oil concentration, the heavy, light and medium crude oil in water emulsion exhibited Newtonian behaviour. The temperature variation did not have any effect on the rheological behaviour of the heavy crude emulsion with a 30% concentration and medium crude oil with a 50–80% concentration. However, it did alter the properties of the emulsion with light and extra light crude oil involved.

Alvarado and Marsden (1979) examined the rheology of o/w emulsion using a viscometer. In their study, they proposed a new model that was able to define the flow of the macroemulsion in the porous media with the inclusion of the permeability reduction caused by the emulsion plugging effect. They concluded that changes in the emulsion rheological behaviour from Newtonian to non-Newtonian depends on the concentration of the emulsifier and the increase in emulsifier concentration which causes a reduction in the oil/water interfacial tension which often leads to a significant increase in emulsion viscosity, surfactant adsorption and a rapid increase in the cost of the process. Bahmanabadi et al. (2016) proposed an approach that involves the addition of a cosolvent to the emulsion to reduce the concentration of the emulsifier. They studied the effect of the cosolvent on the rheology of the emulsion at different shear rates. They deduced from their results that the presence of a cosolvent in the emulsion can significantly control the viscosity of the emulsion by reducing the w/o interface of the droplet, thus improving the stability of the emulsion system.

Some studies have suggested that in addition to the rheology, stability and droplet size distribution, the continuous phase ionic strength and pH have a significant effect on permeability reduction capability of the emulsion. Soma and Papadopoulos (1995) presented a study on the effect of ionic strength and pH on the permeability reduction by emulsions. They found out that at high pH values, there was no entrapment of the emulsion droplets in the porous media due to the repulsion between the emulsion droplets and the sand grains. There was repulsion among the droplet themselves, but at a lower pH, an attractive interaction exists between

the droplets and the porous medium. Their analysis on the effect of ionic strength showed that at high ionic strengths, a substantial permeability reduction was observed due to the decrease in the thickness of the electric double layer and the reduction in the zeta potential of the sand grains and emulsion droplets.

Application of emulsion in conformance control

Emulsions, when used in conformance control, are known to be self-adapting. They flow into the high permeability zones and plug water channels depending on the pore throat to droplet size ratio, causing the channelling of flow to low permeability zones. The diversion of flow by emulsion in the reservoir is presented in Fig. 7.

Mendez (1999) investigated the flow of dilute emulsions in cores at residual saturation and the mechanisms associated with the reduction in permeability caused by the emulsion droplets. The results obtained showed that permeability impairment occurred in two stages. The first stage is associated with the injected droplets and then there is the second stage in which the droplets are generated in situ during which the generation of droplets is done. The presence of residual oil in the core plays a significant role in permeability decline.

Romero et al. (1996) investigated the application of o/w emulsion when plugging high permeability zones. In their work, they suggested that the plugging capability of the emulsion was due to mechanical retaining and fusing of the emulsion droplets. Results from their injection experiments in consolidated, naturally fractured and unconsolidated porous media at a permeability range of 22–2615 mD produced a reduction in injectivity, effective permeability to water and the relative injectivity index which remained unchanged after the injection of the volumes of water. Sadati

and Sahraei (2019) examined the application of o/w emulsions for water control using sand pack experiments and the reservoir conditions of an Iranian oil field that had experienced a high water cut after water flooding. They selected the optimum oil/water ratio and surfactant concentration conducive for the field application. They inferred from their experiments that a 20:80 water to oil ratio is adequate to create an emulsion with a plugging effect and enhancing the water flooding performance.

Torrealba and Hoteit (2019) proposed a novel conformance control method (CIM) that involved the cyclic injections of surfactant and brine slugs to form an in-situ microemulsion. The slugs are formulated in such a way that the viscosity is low enough not to affect injectivity and to ensure the invasion of the thief zones. The effectiveness of this method relies on the behaviour of the emulsion phase which is a function of the phase composition and salinity. UTCHEM, a chemical reservoir simulator, was used to conduct sensitivity analysis. In their conclusions, they stated that the formation of high viscosity emulsion in the high permeability zone of the reservoir led to the success of the treatment. Furthermore, the increase in reservoir resistance was maintained after water flooding, thus indicating the durability of the treatment.

Guillen et al. (2012) investigated the pore scale and macroscopic displacement of emulsion in sandstone core samples. They conducted visualisation experiments to examine the microscopic events leading to pore level flow diversions and the mobilisation of residual oil. In their results, they observed a pore-scale blocking of the pore throat by emulsion droplets during the microflow visualisation. They reported that the injection of an emulsion before the second water injection changed the macroscopic flow path in the core, allowing oil to be produced from the core with lower permeability. The emulsion droplets followed the

Fig. 7 Flow diversion caused by emulsion injection (Adapted from Zhou et al. 2018)

preferential water path in the higher permeability core and blocked the pores. Hence drastically reducing the mobility in the water phase. Followed by continuous water injection, the liquid mobility between the ratio and the cores is reduced and water flows through both cores, displacing the soil also from the low permeability core.

Ding et al. (2019) conducted parallel sand pack flow tests to investigate the performance of emulsion in severely heterogeneous models with varying permeability ratios. Their results revealed that although the emulsion had a strong plugging capability, it performed poorly when used for conformance control in heterogeneous models. Due to the interfacial tension playing a very significant role in capillary resistance and deformity of the oil droplets in the pore throats. An emulsion system with moderate interfacial tension should not only be strong enough to provide adequate flow resistance in high permeability zones but must be elastic enough to deform and pass through the pore throats in the regions of lower permeabilities. Fu et al. (2019) studied a control profile with emulsion systems and they also examined the flow of emulsions of different strength in class III reservoirs with different permeability contrasts. In their experiments, they injected weak, medium and strong emulsifiers into parallel core samples, one with a low permeability having 40% water saturation and the other with a high permeability with 50% water saturation. They deduced that for profile control, the use of emulsions is effective if the permeability contrast is small. Increasing the strength of the emulsion leads to a negative effect.

In enhanced oil recovery processes such as steam-assisted gravity drainage (SAGD) in oil sands, the heterogeneity of the oil sands has a substantial effect on the oil recovery potential. Ni (2019) developed a simulation model to study the application of oil/water emulsion when plugging high permeability zones of the oil sands before the SAGD process. In their model, they aimed to match the experimental results from Yu et al. (2018b) to their parallel sand pack emulsion conformance control experiments. Subsequently, they sought to investigate the effect of IFT, emulsion slug size, and quality and oil phase viscosity on the success of the conformance control method. They suggested that although the emulsion was able to block the water flow in high permeability zones, the effectiveness of the emulsion on the slug size, injectivity and IFT must be considered. They added that good conformance control can be achieved with moderate interfacial tension and a large slug size.

Romero (2009) presented a study on the characterisation of emulsion flow through porous media by conducting core flooding experiments and building a capillary network model. They developed the capillary network model to capture the macroscopic parameters from the microscopic flow behaviour of the emulsion. They reported that the viscosity of the injected emulsion is a function of the

capillary number. This dependence proves that the partial blocking phenomenon is a function of the ratio between the viscous and surface tension. They further explained that the partial blocking caused by the emulsion injected is a function of the pore throat size and the droplet diameter. Cobos et al. (2009) speculated that the flow of o/w emulsion through reservoir rocks could act as a mobility control agent by blocking the water pathways and diverting the flow of displacing fluid to the unswept regions of the reservoir by investigating the flow of emulsion through a pore throat model. Their study included an analysis of the effect of the dispersed phase diameter on the pressure drop and the characterisation of the blocking mechanisms present in the flow of the emulsion. They made comparisons between the average measured flow response and the continuous flow of one phase alone. Another comparison was made regarding the response of two emulsions with equal volumes for the dispersed phase and different droplet size distributions. The results showed that the blocking mechanisms are caused by the larger drops passing through the capillary throat. Hofman and Stein (1991) performed experiments to investigate the permeability reduction capability of oil in water emulsion. They estimated that 3 different forces (van der Waals, hydrodynamic and electrostatic repulsion) are encountered by the droplet when approaching the pore constrictions. They reported that the permeability reduction by the emulsion depends on the diameter of the droplet and the velocity at which the drops flow through the pore throat. The results from the force calculations show that the emulsion droplets with a smaller diameter than the pore constriction remained infinite. The hydrodynamic force experienced by the droplets is greater than the constriction that increases very strongly if the droplet retains its spherical shape.

Summary

An emulsion as a conformance control agent is relatively cheap compared to polymer gels because the oil can be sourced from the field and it has a better injectivity due to its low viscosity. The main parameters to consider when applying emulsion for conformance control are the drop to pore size ratio and the rheology of the emulsion. These parameters influence the propagation, stability and blocking effect of the emulsion. Although emulsion has shown itself in the literature to be an effective chemical agent for conformance control, it is relatively new, and research is ongoing regarding its applicability in the oil field. The next section of this paper will look at foam as a conformance control agent. The mechanism, properties, applications and factors affecting foam will be discussed.

Foam conformance control

The use of foam for conformance control is a new form of technology, especially for deep diversions into the reservoir. There has been a successful application of foam in completion operations where the foam redirects acid to less permeable zones thereby improving the result of acid stimulation. Foam has been applied for near-wellbore treatments and to abate gas coning in gas cap reservoirs (Fuseni et al. 2018). Foam consists of a gas/gas-like phase which is dispersed in a continuous liquid phase (surfactant). In a thin liquid film, known as lamellae, there is a large fraction of gas within the foam that separates the foam bubbles. For a lower gas fraction foam, the liquid lenses mostly separate into bubbles (Buchgraber et al. 2012). The surfactant is present in the foam arrays itself at the gas–liquid interface, creating a stabilised lamella and impeding the coalescence of gas bubbles to form a continuous phase (Aronson et al. 1994). In the porous media, the dispersed gas phase present in the continuous liquid phase fills the largest pores while the wetting surfactant phase fills and coats the smaller pores, hence generating liquid lamellae (Hanssen 1993; Bertin et al. 1998) as illustrated in Fig. 8.

Foam is characterised by the physiochemical properties of the phases that it is composed of such as bubble size and shape, film thickness and liquid fraction. These properties govern the propagation, generation and longevity of the foam in the porous media and studying the properties of foam, the latter of which is essential to optimise its application in conformance control (Farajzadeh et al. 2014; Ettinger and Radke 1992).

Fig. 8 Pore level foam flow in the porous media (Adapted from Zang et al. 2015)

Foam properties

Hamza et al. (2017) described three different foam properties that are essential to their application as conformance control agents. These are foam quality, foam half-life and foam bubble size and distribution. Bisperink et al. (1992) stated that the evaluation of foam bubble size distribution is necessary to understand the physical processes that promote foam breakdown. Kroezen and Wassink (1987) reported that the stability of foam depends on the bubble size distribution. They added that the drainage rate of foam is more pronounced with a large bubble size foam compared to the smaller bubble size foam. The bubble size distribution can be altered by changing the mixing rate. Osei-Bonsu et al. (2015) examined the bubble size distribution and half decay life of the foam. They showed in their results that the viscosity of the surfactant solution affects the coarseness of the foam bubble size and half-life.

Ettinger and Radke (1992) studied the effect of foam texture on foam flow in porous media. They conducted core flooding experiments by simultaneously injecting surfactant and nitrogen gas into Berea sandstone cores. They reported that the porous media shapes the texture of the foam and an increase in gas fractional flow generates fine-textured foam. Chang and Grigg (1999) investigated the effect of foam quality on foam behaviour in the porous media. In their results, they discussed that foam mobility decreases with an increase in foam quality and the foam resistance factor, which increases with an increase in foam quality. They observed that the foam qualities between 20 and 33.3% provide a minimum foam resistance factor.

Mechanism of foam generation and propagation

An insight into the role of the foam generation mechanism at the pore level is that it is essential to designing the foam processes for conformance control. To understand the generation, propagation and longevity of foam in porous media, the flow regimes encountered in the oil field application must be accounted for. The first is the flow regime at the surface and in the wells where bulk foam can be created by inertia flow. Next is the flow regime where a high flow rate and pressure is encountered, and finally, there is the formation at a distance from the injector well where there are lower flow rates and pressure. For each flow regime, there is a completely different foam generation mechanism which eventually leads to different flow behaviour being encountered (Farzaneh and Sohrabi 2013; Rossen and Zhou 1995). Ibrahim and Nasr-El-Dim (2019) discussed that foam is generated in the porous media through 3 different mechanisms as shown in Fig. 9, which are the leave behind, lamellae division and snap-off mechanism. The three main mechanisms of foam generation and

Fig. 9 Leave behind mechanism (Adapted from Ibrahim and Nasr-El-Din 2019)

Fig. 10 Foam lamellae division (Adapted from Ibrahim and Nasr-El-Din 2019)

propagation have been described below. Chen et al. (2004) in their paper described foam generation mechanisms as follows:

Leave behind mechanism

This involves the generation of stabilised films in the pore throats as the gas enters the pore body. The leave behind mechanism tends to create many lamellae even though it can sometimes it can lead to the creation of weak and ineffective foam. However, the gas will always have one

continuous pathway if it is the only mechanism in the lamella creation.

Lamellae division

In this mechanism, two or more lamellae are created from a single lamella. When a mobilised lamella flows through a pore body containing several unoccupied pore throats with a liquid or other lamella. The lamella breaks or spans into several open throats as presented in Fig. 10.

4.2.3 Snap-off mechanism

In snap-off as shown in Fig. 11, the lamellae are generated in gas-filled pore throats if there is a drop in the local capillary pressure to about half of the capillary entry pressure of the throat. This solely depends on the geometry of the throat and wettability of porous medium.

Foam application for conformance control

The application of foam in well treatment, aquifer remediation, and CO₂ EOR processes where foam is used to combat the issues associated with gas mobility ultimately leads to improved volumetric sweep efficiency. This plays a vital role in the petroleum industry (Sagir et al. 2018). Foam has the advantage of being relatively inexpensive, readily reversible and easier to apply with a low level of the associated risk of formation damage (Chabert et al. 2016; Enick et al. 2012). The major advantage of foam as a conformance control agent is the formation of robust foam in high permeability regions which can effectively divert fluids to low permeability regions (Talebian et al. 2014; Salman et al. 2019). Figure 12 demonstrates gas diversion by foam from high to low permeability zones.

Boud and Holbrook (1958) were the first to introduce nitrogen foam to oil field development for the purpose of enhancing the oil recovery processes. Bernard and Holm (1964) and Albrecht and Marsden (1970) extended the work of Boud and Holbrook by examining foam stability in porous media, the effect of pressure, foaming concentration, porous medium permeability and fluid saturation in

Fig. 11 Snap-off mechanism (Adapted from Ibrahim and Nasr-El-Din 2019)

Fig. 12 CO₂ diversion from high permeability zones by foam (Adapted from Carpenter 2018)

relation to the foam's ability to act as a restrictive agent of underground gas flow. They concluded that the reduction in gas permeability was greater in loose sands compared to tight sand. Foam, to some degree, selectively blocked the high permeability regions in the oil displacement experiments. Wu et al. (2016) expressed that foam has a good profile control ability in heterogeneous reservoirs and it can block large pores and throats in the formation which will result in diverting the fluids to lower permeability zones. Furthermore, they discussed that the flow of foam contacts the residual oil in the porous media and with a constant foam disturbance, the residual oil is stripped and channelled into the producing well which in turn improves the microscopic displacement efficiency.

Wang et al. (2019) conducted several experiments in sand packs and micro-models. They analysed the correlation between the blocking pressure and foam texture based on the measured flowing pressure and they captured foam images including the effect of temperature on the blocking capacity of foam. They found that foam blocking pressure has a strong correlation with the average diameter and variation coefficient. They stated that homogenous, dense and tiny foam has a stronger blocking capacity which declines when there is an increase in temperature. Bertin et al. (1998) reported that effective diversions by foam can occur in both layered and heterogeneous reservoirs if the permeability contrast is not very large, if the presence of oil does not affect the foam stability and if the capillary pressure in each layer is lower than the critical capillary pressure of the foam. Furthermore, they stated that when the crossflow is prohibited by an impermeable barrier, foam propagation and desaturation is observed in the lower permeability zone.

Wang et al. (2017) investigated the effect of the gas/liquid ratio, core permeability and injection rate on foam mobility control. Their results showed that 1 mL/min is the most effective flow rate and that the gas/liquid ratio is 2:1 for the best foam mobility control. In these conditions, for the foam with an increase in permeability, the foams' mobility control ability is improved. They reported that after 5 days of ageing, the nitrogen foam was still able to block the water channels. They added that under high salinity and temperature conditions, if the appropriate injection parameters are applied, then foam can be a promising and economical conformance control agent.

Chabert et al. (2016) presented a foaming formulation design and its application in a field pilot test in the US Gulf Coast. After the experimental work was conducted, they carried out a foam injection pilot test on a 6-well flood pattern made up of 6 producers, 3 injectors and targeted conformance rather than in-depth mobility control. The data from the injection logs showed an effective diversion of CO₂ from the thief zones to the poorly swept regions. Haugen et al. (2012) examined foam application in fracture transmissibility reduction and sweep efficiency improvement in a vastly fractured low permeability oil-wet limestone core. After selecting an optimum surfactant formulation by employing bottle tests, they proceeded to generate in-situ foam through the co-injection of a surfactant and nitrogen into the fracture. They reported that foam could not be generated in the fractures with a smooth wall surface. They also observed a non-reduction in gas mobility and the injection of preformed foam led to an increase in additional oil recovery.

Parameters influencing the foam application for conformance control

Foam stability and the mobility reduction properties are influenced by the reservoir rock and fluid properties as well as the design parameters such as foam quality and texture, formation permeability and the size of the chemical injection slug. To determine the potential of the foam for conformance control, these parameters need to be examined (Farajzadeh et al. 2014). According to Farajzadeh et al. (2015), to accurately model the rheology of foam on a field scale, an in-depth understanding of the relationship between the foam properties and the scalable properties of the porous media is required. In their study of the permeability effect in the foam texture model, the parameter $fm\text{-}dry$ which denotes the water saturation corresponds to the limit capillary pressure. $Ep\text{-}dry$ represents the abrupt coalescence of foam as a function of the water saturation. They observed that the foam's transition from high to low quality was more rapid in low permeability rocks. This implies that the foam generated in high permeability rocks does not collapse quickly at a single water saturation but that it will weaken when the range of water saturation varies. They also found out that the limiting capillary pressure for foam increases as the permeability of the rock decreases but not enough to reverse the increase in the foam's apparent viscosity as the rock permeability increases.

Sun et al. (2019) reported that reservoir permeability and heterogeneity affects the success of foam for conformance control significantly. In their investigation, they conducted several core flooding tests and deduced from their results that foam is more stable and effective in highly permeable porous media due to the low oil saturation and larger pore size. A bubble size population can easily be created which increases the foam propagation and resistance. In low permeability porous media, there is a higher percentage of oil saturation and this oil has a negative effect on the foam as it acts as a foam depressant. Li et al. (2011) in their analysis of a foam conformance application, examined the effect of permeability on the foam resistance factor during steam injection. They reported that the foam resistance factor improved when permeability was increased. This is useful when blocking steam channels as the foam will flow with more resistance in the high permeability region of the reservoir.

Another parameter that has been suggested to affect foam application is the slug injection rate. Al-Mossawy et al. (2011) discussed that faster flow rates generate foam with more uniform and smaller bubble sizes in their review paper. Kahrobai et al. (2017) in their results observed that increasing the injection rate and the concentration of the surfactant can lead to the creation of a strong and stable foam.

A great concern in foam application is its ability to remain stable in the presence of oil. Friedmann and Jensen

(1986) reported that oil saturation greater than 20% will have an adverse effect on foam stability. Schramm et al. (1993) suggested that the oil composition and presence of light components in oil are detrimental to the stability of foam in the reservoir. Simjoo et al. (2013) examined foam stability and generation in the presence of alkane-type oils. They discovered that foam generated with C14-16 Alpha olefin sulfonate (AOS) remained highly stable in the presence of oil and that the destabilising effect of foam in the presence of oil is more pronounced with a short hydrocarbon chain alkane. A similar observation was reported by Osei-Bonsu et al. (2017) in their study of foam stability in the existence of hydrocarbons. They concluded that foam stability in the presence of oil is highly dependent on the type of surfactant and oil properties. They discussed that short-chain hydrocarbons with low viscosity and density have a greater adverse impact on the longevity of foam in contrast to longer chain hydrocarbons. Hussain et al. (2019) analysed the behaviour of foam in the presence of oil and a mixture of pure components. In their experiments, a mixture of the following organic compounds was used to represent the oil: toluene, oleic acid, octanol, methylcyclohexane, dimethyl sulfoxide, n-octane and n-hexane. They concluded that the impact of oil on foam cannot be demonstrated by the mixture of organic compounds they used in their study. This is because the impact they observed in the bulk foam experiments and upon the injection into porous media was less detrimental when compared to actual crude oil.

When considering the stability and generation of foam in porous media, the surfactant plays an important role. Shah et al. (1978) stated that foam stability is dependent on the surfactant molecules arrangement in the gas/water interface. Thus, the hydrophilic-lipophilic balance of the surfactant which relates to the surfactant molecule arrangement and force balance on the interface plays an important role in the stability of the foam. Vikingstad et al. (2006) presented in their study the effect of the surfactant's concentration on the foam/oil interaction. They reported that the foam height increased with an increase in the surfactant concentration. They continued by stating that foam can be generated at concentrations lower than the critical micelle concentration and that a limited foam height can be attained at a certain surfactant concentration. Beneventi et al. (2001) examined the influence of surfactant structure on the properties of foam by conducting static and dynamic surface tension and interfacial complex modulus measurements using the oscillating bubble method. They concluded that the chain length of the hydrophobic part of the surfactant plays an important role in the kinetic migration to the interface, thus ensuring surface activity which can lead to foam stability. Belhaj et al. (2015) indicated that a higher surfactant concentration enhances foam stability and generates foam that is characterised by a fairly

uniform distribution and fine texture. At a lower surfactant concentration, the foam generated has a larger bubble size with broad distribution.

The biggest detrimental effect on the foam property in terms of conformance control are the conditions present in the reservoir. Maini and Ma (1986) evaluated the stability of foam under elevated temperature and pressure in reservoir conditions. Their results showed a dramatic decay of the foam's half-life with an increase in temperature. They suggested that at high temperatures, surfactants with long hydrocarbon chains will provide more stability for foam due to their performance. They couldn't explain why, at an elevated temperature and pressure, the foam's half-life and drainage increased.

Aarra et al. (2014) investigated the effect of pressure on foam properties. They discussed that increasing the pressure, nitrogen gas and alpha-olefin sulfonate (AOS) generated stable foam. They further added that alpha olefin with CO₂ could generate strong foam at lower pressures. Above the CO₂ supercritical pressure, weaker foams were generated. Farzaneh and Sohrabi (2013) stated that increasing the salinity may destabilise or have no significant effect on foam depending on the surfactant type. Liu et al. (2005) pointed out that foam stability is affected by salinity depending on the concentration of the surfactant. In their study into the effect of salinity and pH effect on CO₂ foam, they summarised from their results that foam generated with a surfactant concentration above 0.025% in weight was insensitive to salinity. Foam generated at a surfactant concentration of 0.05% in weight and below was sensitive to salinity. Yekeen et al. (2016) presented the effect of salinity on surfactant adsorption and foam properties. They discussed that the presence of salt favours foam generation when the concentration of the surfactant is less than the critical micelle concentration (CMC). They added that salts with trivalent and divalent ions tend to destabilise foam, but there is an optimum surfactant concentration beyond which the presence of ions will not affect foam stability.

Lastly, referring to the gas–liquid ratio according to Wende et al. (2019) is one of the key factors influencing foam application. In their experiments, with a gas–liquid ratio of 2.5:1, they observed maximum displacement efficiency. Yuan et al. (2018) conducted experiments to understand the blocking mechanism of foam. They reported that the blocking capacity of nitrogen foam was the greatest at a gas–liquid ratio of 1:1. Lang et al. (2020) conducted a series of single tube sand pack flooding tests consisting of an alternating injection of surfactant and gas. They observed that the foam resistance factor increased when the gas–liquid ratio was in the range of 0.5–1. A gas–liquid ratio of above 1 and below 0.5 resulted in a decrease in the resistance factor, thus generating foam with weak blocking ability.

Summary

In summary, the evidence from the literature shows that foam can be used for fluid diversion in the reservoir to improve sweep efficiency and oil recovery. However, for the successful implementation of foam for conformance control, several analyses should be conducted which are:

- An in-depth analysis of the reservoir properties such as permeability.
- The reservoir fluid interactions with the injected chemicals.
- The designing of an optimum injection strategy should be conducted.

The next section will discuss the recent advances in chemical agents for conformance control.

Recent advances in chemical-based conformance control agents

In this review, the application of polymer, foam and emulsion for conformance control has been discussed. However, the efficiency of the select chemical agents for conformance control is greatly governed by their stability in the reservoir. This has prompted several efforts to develop and improve the performance of the existing chemical agents. More complex chemical systems have been developed for conformance control which involves the combination of two or more chemical agents which has resulted in a range of properties, applications and effectiveness. Druetta et al. (2019) discussed the development of a polymeric surfactant, a new chemical agent that combines the characteristics of interfacial tension reduction and viscosifying. Mohd et al. (2018) examined the use of polymeric surfactants to stabilise CO₂ foam for conformance control. They concluded that the addition of polymeric surfactants further enhances the stability of the foam, but it must be manipulated depending on the field conditions.

Derikvand and Riazi (2016) proposed a novel formulation to improve foam quality for profile control. The formulation consisted of a low-cost carboxymethyl cellulose gum (CMC) polymer, alpha-olefin sulfonate surfactant and air. They demonstrated in their results that the foam's half-life can be improved by the addition of CMC, but this highly depends on the concentration of CMC. Li et al. (2018) studied the application of a novel gelled foam for conformance control in a high salinity, high-temperature reservoir. They reported that the novel gel foam formed a protective layer for the foam system which enhanced the

stability. The gelled foam has better reservoir adaptability with a selective plugging and profile capability compared to conventional foam. Saikia et al. (2020) developed a Pickering emulsified polymer gel system intended to combat the problem of polymer gels plugging the oil-producing zone when injected to combat excess water control. The system consisted of a polyacrylamide polymer, polyethyleneimine crosslinker, diesel and water. Their results showed that the polymeric gel had better thermal stability and when it was injected into the cores, there was no restriction in oil movement compared to water movement.

Recent studies have shown that nanoparticles can be used to promote the stability of conformance control agents. Li et al. (2019) proposed a novel technique combining zwitterionic surfactant and silica nanoparticles to enhance the stability of supercritical CO₂ foam. They found that due to the enhanced disjoining pressure and improved surface elasticity between the supercritical CO₂ and the foaming additives, the stability of the foam can be improved. Hurtado et al. (2020) attempted to optimise foam stability through the use of polyethylene glycol (PEG)-coated silica nanoparticles as an additive to nitrogen foam. They stated that the addition of PEG-coated silica nanoparticles provides a structural reinforcement of the foam bubbles in synergy with the surfactant. This improves the half-life and stability. Zareie et al. (2019) investigated the application of silica nanoparticles to improve the strength and network structure of a polymer hydrogel system as a part of conformance control. They proposed that a hydrogel polymer system containing 9wt% nanoparticles can create the desired gel strength and structure for optimal stability in a field application.

In the above literature, the experimental and numerical studies of chemical-based conformance controls have been reviewed. A presentation of the successful field applications is displayed in Table 1. From Table 1, it can be observed that only one field trial of an emulsion conformance control method was found in the literature, whereas there are a lot more field applications of polymer gel treatment that have been published compared to foam.

Supplementary discussion

This study covers an in-depth review of chemical agents for conformance control. This review will provide a comprehensive guide to petroleum engineers looking to apply chemical based conformance control measures. We can see from the literature discussed above that chemical conformance controlling agents are very effective in shutting off high permeability zones in the reservoir. Polymer gel has been the most effective since it is the widely used method. The use of foam has also shown a great potential as conformance control agents and more research and field pilot test should

be conducted to examine their feasibility in oil fields. For the application of emulsions, although it looks promising, there are situations where the formation of emulsions can cause adverse effects such as large pressure drops, and the process of de-emulsification can be daunting. More studies and field pilot tests are required to understand the application of emulsion for conformance control, their stability and de-emulsification as literature this is lacking in the literature. The discussion shows that improvements for the chemical conformance control agents are necessary to improve their stability under different reservoir conditions. Although the use of nanoparticles has been suggested in the literature, the cost of nanoparticles to obtain the optimum chemical agent for conformance control may hinder its application.

Concluding remarks

From the literature, for conformance control measures to be successful, identifying and understanding the conformance problem as well as studying the reservoir flow characteristics are very important. This includes an evaluation of the treatment mechanisms, chemical type, chemical properties and field control measures. Polymer gel treatment is the most widely used method in oil fields as presented in the field trial summary. The ability of the polymer gel to successfully plug the high permeability region in the reservoir is based on the gelation time of the polymer. Experimental studies have shown that the gelation time of polymer is strongly affected by the reservoir conditions such as temperature, salinity and pH. Polymer structure, concentration and crosslinker concentration are the other parameters that can influence the polymer gelation time and strength.

Emulsion-based conformance control is a relatively new technique and only one field pilot test could be found in the literature. Although most of the work done on emulsion application is based on laboratory experiments, they have demonstrated that an oil/water emulsion can divert fluid flow in the reservoir from the highly permeable to the low permeability areas. The distinct feature of the emulsion is its ability to selectively plug high permeability zones when injected into the reservoir. The effectiveness of the emulsion depends on the ratio of emulsion droplet diameter to reservoir pore throat. The Jamin effect encountered by the emulsion droplet when it enters the pore throat is responsible for the flow restriction in high permeability zones. The emulsion typically displays a non-Newtonian behaviour in the porous media. The rheology and stability of the emulsion play an important role in the application of the emulsion. These parameters are controlled by the droplet size distribution of the emulsion.

Compared to emulsions, foam has been utilised more in field applications for the purpose of conformance control,

Table 1 Summary of the successful field trials of chemical-based conformance control measures

References	Conformance technique	Field	Conformance problem	Treatment results
McAuliffe (1973a)	Emulsion	Midway Sunset field, California	Excessive water loss due to the presence of an aquifer	Decreased water production and volumetric sweep efficiency improvement
Aarra et al. (1996)	Foam	Oseberg field, Norway	Gas coning in the production Wells	50% reduction in GOR
Krause et al. (1992)	Foam	Prudhoe Bay, Alaska	Gas fingering and gravity override	GOR reduction by 32%
Ma et al. (2013)	Foam	SZ field, China	Quick water breakthrough due to high oil viscosity and reservoir heterogeneity	Reduction in the water cut between the range of 3.2–14.5% and a 30283 m ³ increase in oil production yearly
Chou et al. (1992)	Foam	North Ward-Estes, Texas	Poor sweep efficiency	Increase in oil production from 1 to 15 BPD and a reduction in gas production
Jonas et al. (1990)	Foam	Rangely Weber, Colorado	Poor sweep efficiency due to the presence of thief zones	Reduction in CO ₂ injectivity and an increase in oil production
Uddin et al. (2003)	Polymer gel	Wafra Ratawi field, Kuwait	Excessive water production due to leaks in the casing and the presence of high permeability streaks	20% increase in oil production and water cut decrease in the range of 2.8–14%
Liu et al. (2006)	Polymer gel	Daqing field, China	Water channelling leading to poor sweep efficiency	Improved water flow distribution into the oil pay zone
Al-Muntasheri et al. (2010)	Polymer gel		High water cut	58% decrease in water cut and an increase in the gas rate from 2.2 to 17 MMSCF
Ortiz Polo et al. (2004)	Polymer gel	South of Mexico	Excess water production	80–100% water cut reduction
Bai et al. (2013)	Polymer gel	Zhongyuan field, China	Quick linking of flow from the injector to the producer well and severe heterogeneity	Increase in oil production rate
Bai et al. (2013)	Polymer gel	Shengli field, China	Severe sand production resulting in very high permeability in water flooded areas	Improved sweep efficiency in low permeability areas
Norman et al. (2006b)	Polymer gel	Vizcacheras field, Argentina	Poor volumetric sweep efficiency	Increase in oil recovery

although not as much as polymer gel treatment. The experimental results and field application have shown that foam is an effective technique for conformance control. The presence of oil has a strong effect on the generation and propagation of foam in porous media. Oil with a higher percentage of lighter components and short-chain hydrocarbons are more detrimental to the stability of foam. Rock permeability plays an important role in the generation of a strong foam texture.

Lastly, before the application of any chemically based conformance control methods, a comprehensive analysis should be conducted on the compatibility of the chemicals and the reservoir conditions. The reason is that the successful application depends on the stability of the

chemicals in the reservoir. Additionally, more research and field pilot tests should be conducted for newly developed chemical agents to ascertain their applicability in oil fields.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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