

## Microgels, Bright Water, and Colloidal Dispersion Gel (CDG) Applications in Mature Reservoirs

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### Abstract

Water production is one of the most influential issues in petroleum engineering since a large number of oil and gas wells will produce water in their life time. In addition, water is the most abundant fluid in an oil field, and it is produced along with oil. Excess water production has become a significant concern for oil field operators, because it reduces hydrocarbon production even though the reservoirs still contain significant amounts of hydrocarbons. Due to long-term water flooding, excess water production has become a significant problem for oil field operations as reservoirs mature. This paper reviews recent developments in the microgels Brightwater® and colloidal dispersion gel (CDG). The review investigates properties, evaluations, and applications for water shut-off treatments. It also updates microgel criteria developed in recent years based on field applications reported in the Oil and Gas Journal and at various SPE conferences, as well as the updates of different microgels by the manufacturers. It classifies microgel methods into Brightwater® and colloidal dispersion gel technologies. Microgel technology is used in depth conformance control treatments in mature reservoirs for water shut-off and increased sweep efficiency. New developments in chemical microgels and EOR techniques and mechanisms are summarized in this paper, which clarifies the challenges and limitations for each microgel. The applications of the various microgels will be ruled out based on specific reservoir conditions (mature reservoirs). This work will establish guidelines for the selection and optimization of microgels for use as a water shut-off and conformance control agent under mature reservoir conditions.

*Keywords:* Quantitative chemical applications; water shut-off; conformance control treatments; sweep efficiency; mature reservoirs.

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### 1. Introduction

The production of hydrocarbons is typically accompanied by the production of water. This water consists of formation water and/or water that has been injected into the formation. Water production increases over the life of a reservoir, and water produced from oil reservoirs is not economical. Operators must, therefore, find ways to handle relatively large amounts of water in an environmentally acceptable manner at the lowest possible cost. Water production is thus one of the most crucial issues in petroleum engineering today. Due to long-term water flooding, excess water production has

become a major problem for operations in mature oil fields [1]. These reservoirs usually have a high water cut of more than 80. Many chemical systems have been used to control water and improve recovery from reservoirs with a high water cut. Koch and McLaughlin (1970) used an inorganic gel to change the injection profiles in waterflood injection wells. The results indicated that the material and techniques may be applied to control water breakthrough problems in waterflood producing wells [2]. Chen (1988) examined a non-polymer in-situ gelling system for water control treatments [3]. Inorganic gels have a viscosity close to that of water and can

be pumped using field mixing and injection equipment. Liang et al. (1992) found that gels reduced water permeability more than oil permeability [4]. Herbas et al. (2004) developed a model to study a polymer gel treatment in a pilot test to improve injection profiles and sweep efficiency in a water injector [5]. Recently, in-situ gels have been studied as water control systems for high-temperature reservoirs [6, 7, 8] Chauveteau et al. (2000, 2001, 2003, and 2004) developed a microgel system for water control [9, 10, 11, 12]. Microgels are colloidal particles of acrylamide crosslinked with zirconium. Microgels are classified as follows: “Brightwater®” (Popping microgel), “Colloidal Dispersion Gels” (CDG), “SMG” (Small calibrated microgels), and “PPG” (Preformed Particle Gels to plug thief zones). These are used for Conformance Injection well treatments excluding SMG.

## 2. Microgel Applications

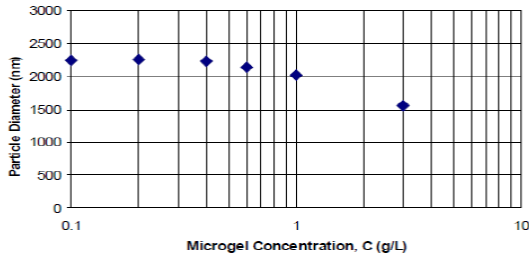
Microgels are gels that are formed at a polymer concentration below the polymer’s critical overlap concentration in the gel’s makeup brine. Polymer microgels are dominated by intra-molecular crosslinking (within the same polymer molecule). With new microgel technology, thickness and consistency of a polymer can be modified to fit the reservoir conditions. The size of microgels (polymer aggregate) can be changed during shearing. However, the properties of microgels are affected by salinity,  $pH$ , and shear rate. The resistance of microgels is weak [10, 11, 12]. Chauveteau et al. (2004) investigated new types of microgels [12]. The results include both their characteristics in solution (size, intrinsic viscosity, mutual interactions, and rheology) as well as their performances in a porous media (both model granular packs and Berea sandstones). These microgels were found to strongly reduce water permeability by forming thick adsorbing layers. They found that oil permeability is not affected by microgels [12]. Both the mechanical and thermal stability of microgels is excellent. Their shear rates can be as high as  $1.5 \times 10^4 \text{ s}^{-1}$ . Their viscosity did not change for a month at  $150 \text{ }^\circ\text{C}$ . Microgels penetrated completely into super-high permeability layers and reduced their permeability [12]. Chauveteau et al. (2000) found that microgels formed in the propagation area are isotropic [9]. Their size decreases considerably as the shear rate increases. Burcik et al. (1967, 1968) studied the mechanisms of microgels in the formation zones [13, 14]. They remarked that

the reduction of water mobility by microgel solutions occurred from increasing microgel viscosity and decreasing water effective permeability. They reported that oil displacement in mature reservoirs could be improved by increasing both the microgel viscosity and the injection flow rate. In addition, they found that the polymer retained inside the pore channels caused pseudo flow at high shear rates [13, 14]. Feng et al. (2003) determined that the microgel size decreases as the  $1/3$  power of applied shear rate [15]. The microgel’s size depends on the  $pH$  value, reservoir salinity, and temperature. Both their mechanical and thermal stability is acceptable. In addition, microgels can be injected into porous media, plugging the water source area without any problems. These results suggest that microgels would be good candidates for both water shutoff (WSO) and profile control operations [15]. Céline’s (2008, 2009) work principally aimed at studying how high salinity impacts microgel treatment efficiency [16, 17]. Solubility of microgels was first evaluated in an extended domain of brine salinities (up to  $200 \text{ g/L NaCl}$  with a high content of calcium). Viscosity measurements and filterability tests through calibrated membrane filters were performed, and led to specifications for optimum microgel dissolution. Injections in granular pack models were then carried out with microgels diluted in brines of various salinities and at various microgel concentrations. These tests allowed for an assessment of the injectivity and the permeability reductions. After injection, the packs were flushed with different brine salinities. Results showed that the hydrodynamic thicknesses of adsorbed layers did not vary significantly when microgels were injected in brines of moderate to high salinities. At very high salinity ( $200 \text{ g/L NaCl}$  with calcium), a shear-controlled over-adsorption of the microgels was observed. Results also showed that adsorbed layers were very stable when exposed, after microgel adsorption, to brines of low to very high salinity.

### 2.1. Size Characterization of Microgels

Reported in (Figure 2.1) is the concentration dependence of the microgel size as measured by the static method. The dependence observed is expected, since at high concentrations, the regime is no longer strictly diluted. Making measurements at low concentrations and extrapolating to zero concentration is thus required to obtain meaningful size estimations. The diameter found is  $2.3 \text{ }\mu\text{m}$  which is much larger than the hydrodynamic size found for linear polymers (Figure 2.2) [18].

**Figure 2.1:** Size determination. Meaningful size evaluation requires extrapolation to zero concentration[12].



**Figure 2.2:** Microgels Size Distribution

| Name                      | Developer                     | Particle Size             | Applications     |
|---------------------------|-------------------------------|---------------------------|------------------|
| Bright Water <sup>®</sup> | Chevron, BP and Nalco (Tirco) | Sub-Micro (< 1 μm)        | 60+ injectors    |
| Microgel                  | IFP                           | Micro (1-10 μm)           | 10+ producers    |
| PPG                       | RIPED/Missouri S&T            | Millimeter (10 μm to mms) | 5,000+ injectors |

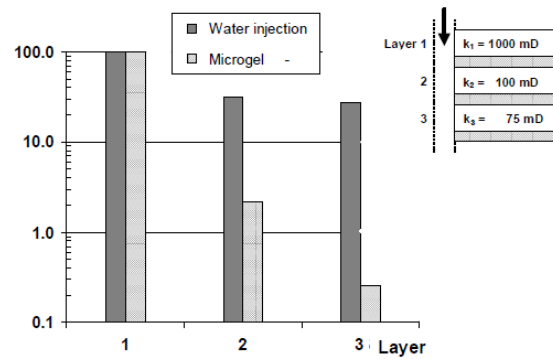
## 2.2. Placement of Microgels Around a Well

In the absence of zonal isolation (“bullhead” treatments), microgels are placed into the different layers existing around the wells according to their ability to reduce water permeability as a function of the initial permeability of each layer. When properly designed, they should significantly reduce the water permeability of the highest permeability layer around the well and penetrate almost exclusively in this layer. Chauveteau et al., (2004) mentions microgel mobility in layers having a smaller permeability will be reduced [12]. As an example, calculations were carried out for the injection of the microgels tested in their study into a well with three layers assuming no cross-flow ( $K = 1000, 100$  and  $75 mD$ ). The results, plotted in (Figure 2.3) show a negligible penetration inside the two lowest permeability layers.

## 2.3. Benefits of Microgels

There are different benefits for microgels as follows: (1) Microgel size from 0.3 to 2 μm. (2) Applicable permeability range of 10 to 10,000 mD. (3) Commercially available in emulsion and powder forms. (4) High temperature stability (up to 165 °C). (5)

**Figure 2.3:** Depth of penetration in lower permeability layer 2 and 3(in cm) when microgels with a diameter of 1.5 μm havereached 100 cm in Layer 1. [12].



Environmentally friendly. (6) High shear rate stability ( $20,000 sec^{-1}$ ). (7) High chemical stability ( $CO_2, H_2S$ , high salinity). (8) Efficient in WSO and sand control applications.

## 3. Brightwater<sup>®</sup>

### 3.1. History

Brightwater<sup>®</sup> was a BP project started in 1997. Nalco was identified as the best potential development and supply partner, and joined as an equal contributor. In 1998, Mobil, BP, Texaco, Chevron, and Nalco supported the material’s development. In late development, only BP, Chevron, and Nalco supported Brightwater<sup>®</sup>. Brightwater<sup>®</sup> has been developed by an industry group (BP, Chevron and Nalco), and is now commercialized by TIORCO (Nalco company). It was first tested in Indonesia in 2001. Brightwater has seen field applications in Minas, Indonesia (Chevron, 2001), Arbroath, North Sea, UK (BP, 2002), Milne Point and Prudhoe Bay, Alaska, USA (BP) (several, 2004-5), Strathspey field, North Sea, UK (Chevron, 2006), Argentina (several, 2006), Pakistan (BP, 2006-7), and other locations in Alaska (several, 2007).

### 3.2. Overview

Brightwater is a particle gel. The median particle size distribution is about 0.3 to 0.5 microns. Brightwater<sup>®</sup> material is a tightly surrounded, thermally activated particle gel injected as a dilute slug which flows with the water and pops open deep in the reservoir, blocking the swept zones. This allows water to be diverted into zones that remain either

unswept or poorly swept. Sub-microsized particle gels has been developed by both Pritchett et al. and Frampton et al. for in-depth division conformance control treatments [19, 20]. BP and Chevron used Brightwater® for more than 10 wells without super-high permeability or streaks. Their results determine that the oil recovery was increased after injection of sub-micro particles into the swept oil zones/areas [19, 20]. Brightwater® is a sub-micron particulate injected downhole with the injection water as a one-time batch [21]. It can be deployed with conventional chemical injection equipment and requires no modification to the existing water injection system [21]. The particle sizes are sufficiently small (0.5 micron) to propagate through the rock pores with the injected water [21]. As the sub-micron particle (polymer) passes through the reservoir it gradually warms to the reservoir temperature. As it heats up, the polymer expands to many times its original volume (a factor of four to ten depending on salinity), blocking pore throats and diverting any water following behind it [21]. The information needed to properly select the right sub-micron particulate is available and varies depending on the thief zone properties, water salinity, and reservoir temperature. A number of treatments were performed in Alaska, the North Sea and Argentina. Later treatments in Argentina give no indication of increased recovery while Alaska treatments quote a four-year gain of 60,000 *bbl* against a ten-year target of 50,000–250,000 *bbl* at less than \$5/*bbl* [21]. A North Sea application claims over 130,000 barrel of oil increase in the first 12 months at a \$4/*bbl* and estimates final incremental recovery to rise to 300,000 barrels [21].

### 3.2.1. Asia Pacific

This field marked the first deployment for Brightwater® in 2001. This proof-of-concept study showed TIORCO and the customer that Brightwater® could be successfully manufactured and deployed, and a positive oil response was soon observed. The field produced an additional 300,000 barrels of oil after the Brightwater® treatment, with a corresponding decrease in oil cut decline.

### 3.2.2. North Sea

Currently in development, this field study for a North Sea operator will use the new cold-activating Brightwater® technology, set to activate at less than 50 °C. The operator and TIORCO are jointly completing reservoir modeling work and tracer studies to un-

derstand and predict the incremental oil recovery. The expected oil recovery is large, and a sizable target exists due to fault-induced channeling. The field trial will require 100 tons of Brightwater to be injected as a solution with a seawater flood over a period of 4-5 days. It is expected to take approximately three months to form the block deep in the reservoir, and incremental oil recovery should commence after an additional three months.

### 3.2.3. North America

In this mature field, production wells were showing relatively high water cuts above 70%, even with low to medium total pore volume injection. Following a miscible injection test to determine the connectivity pattern between wells, three injection wells positioned in a triangular pattern relative to one another were chosen. The Brightwater® treatment was deployed in late 2004, and by mid-2005 the producer began to see incremental oil production. Over the course of 2005 to 2007, the offset production well had produced 410,000 barrels of incremental oil, which translated to a revenue increase of over \$20 million. The operator expects the Brightwater treatments to continue to pay dividends into the foreseeable future. Over the next 15 years, they expect to produce an additional 2 million barrels of incremental oil.

### 3.2.4. Campos Basin, Brazil

The Salema field, a waterflood development off the coast of Brazil (Campos Basin), has been suffering from early water breakthrough and poor sweep efficiency in the southern areas of the field. In an attempt to increase the sweep efficiency, Brightwater®6 has been selected. A study describes the feasibility, maturation, execution, monitoring and results of the first trial in Brazil (July 2009), which was also the first for Shell worldwide. They discuss reservoir simulation and lab work (core tests, sand-pack tests) that led to the decision of performing the operation [21].

### 3.2.5. El Bora oil field in Tunisia, North Africa

SITEP and Eni have started to evaluate certain tertiary methods of enhanced oil recovery for El Borma, a mature Tunisian field. A pilot project based on the application of Brightwater® was employed to verify its applicability and efficiency in that particular field. The technology aims to improve oil recovery and reduce water production. The methodology used is applied to mature oil fields that are subjected to water injection and suffer from heterogeneity issues.

#### 4. Colloidal Dispersion Gel (CDG) Applications

Both Chang et al. (2004) and Al-Assi et al. (2009) prepared Colloidal dispersion gels (CDG) by crosslinking a low concentration of polymer solutions with a small amount of either chromium acetate or aluminum citrate [21, 23]. Spildo et al. (2009) investigated the applicability of CDG in higher salinity (35,000 ppm) sandstone reservoirs [24]. Positive results were reported although a one-week reaction time was needed to complete the crosslinking reaction. Juntai et al. (2011) noted that CDG can be used for both conformance and mobility control [25]. Contradicting conclusions exist regarding whether or not CDG can propagate in porous media [25]. Juntai et al. (2011) studied two CDG types:

1. CDG that is performed before being injected into the porous media (preformed) and
2. CDG that is formed in-situ under reservoir conditions.

Preformed CDG is a stable microgel. Therefore, it is typically used for both conformance and mobility control [24]. Juntai et al. (2011) developed a novel viscosity model for stable microgels. Their viscosity model was a function of both the microgel concentration and the shear rate; it was confirmed by matching their results with published microgel data. CDGs have a high injectivity due to a relatively low polymer concentration. Gelation is affected by both shear and reaction of chemicals with both reservoir rocks and fluids. Predicting CDG gelation time and strength is difficult due to both the flowing and reservoir effects. CDGs easily penetrate and damage low permeability oil zones before gelling. Both their thermal and salt resistance depends on polymer properties. Liu et al. (2010) noted that typical chemicals are weak gels, preformed particle gels (PPGs), and colloid dispersion gels (CDGs) [26]. Polymer concentrations (excluding crosslinkers and other additives) usually range from 1,000 to 3,000 mg/L for weak gel and from 400 to 1000 mg/L for CDG. Polymer concentrations below 1000 mg/L cannot be used in reservoirs with either fractures or extremely high permeability channels [26].

#### 5. Conclusions

- Microgels have great applications for water shut-off and conformance control treatments in mature

reservoirs.

- Microgels have a higher stability than conventional polymers. Microgels are low cost and are of little risk to the environment. Microgels can be applied in both oil and gas wells.
- For the application of microgels, bullhead injection is recommended in both oil and gas wells.
- Sand control effects can be also obtained by using Microgels.

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