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# Investigation of spore forming bacterial flooding for enhanced oil recovery in a North Sea chalk Reservoir

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ABSTRACT

Little has been done to study microbial enhanced oil recovery (MEOR) in chalk reservoirs. The present study focuses on core flooding experiments designed to see microbial plugging and its effect on oil recovery. A pressure tapped core holder was used for this purpose. A spore forming bacteria *Bacillus licheniformis* 421 was used as it was shown to be a good candidate in a previous study. Bacterial spore can penetrate deeper into the chalk rock, squeezing through the pore throats. Our results showed that injection of *B. licheniformis* 421 as a tertiary oil recovery method, in the residual oil saturation state, was able to produce additionally 1.0–2.3% original oil in place (OOIP) in homogeneous cores and 6.9–8.8% OOIP in heterogeneous cores. In addition, the pressure gradient was much higher in the heterogeneous cores, which confirms that bacterial selective plugging plays an important role in higher oil production from the heterogeneous chalk rock. In all cases, an incubation period ('shut-in') after the bacterial and/or nutrient injection was needed to give sufficient time for the bacteria to grow inside the core and to produce more oil. Our findings show potential application of bacteria as a plugging agent in heterogeneous chalk cores to improve oil production.



## 1. Introduction

To date, conventional oil recovery technologies used in the oil industry can only recover about one third to one half of the original oil in place (OOIP), leaving behind a large amount of residual oil being targeted for enhanced oil recovery (EOR) (Cusack et al., 1992; McInerney et al., 2005; Sarkar et al., 1989; Sen, 2008). Microbial Enhanced Oil Recovery (MEOR) is believed to be one of the advanced technologies enabling recovery of the residual oil due to the ability of bacteria to produce biosurfactants, biopolymers, bioacids, biomass, biosolvents, gases, and enzymes. This technology is implemented by addition of nutrients and/or bacteria to the injected fluid (Maudgalya et al., 2007; McInerney et al., 2005; Sarkar et al., 1989; Sen, 2008).

A major challenge of EOR technologies in North Sea chalk reservoirs is finding ways to mobilize the residual oil in low permeability reservoirs. During secondary oil recovery, when water is injected into a reservoir, on the microscopic level, it preferentially flows into high permeable channels, thus bypassing the low permeable, oil-filled pores parts of the reservoirs (Nagase et al., 2002; Raiders et al., 1989). Injection of nutrients/and or bacteria into these preferential pathways and stimulation of the bacterial growth in situ will block the water channels, either with bacterial cells or polymers produced in situ by the growing bacteria. Blocking of these channels will alter the water pathways to the previously unswept pore space (Crescente et al., 2005; Jenneman et al., 1996; Li et al., 2012; Nagase et al., 2002; Yakimov et al., 1997). This concept is known as microbial selective plugging as illustrated in Fig. 1. Selective plugging of the more permeable zones may result in increasing oil production, correcting microscopic and volumetric sweep efficiency and redirecting water flow to the low permeable, oil-bearing zones (Cusack et al., 1992). Even though studies of microbial plugging have been conducted by many researchers, to the best of our knowledge none has been performed on chalk. Earlier studies have been conducted in packed glass beads (Shaw et al., 1985), sandstones (Crescente et al., 2005; Cusack et al., 1992; Raiders et al., 1986, 1989; Raleigh and Flock, 1965; Yakimov et al., 1997), sandpacks (Cusack et al., 1992; Suthar et al., 2009), outcrop limestones (Al-Hattali et al., 2013; Kaster et al., 2012; Raleigh and Flock, 1965) and outcrop carbonates

*Abbreviations:* MEOR, Microbial enhanced oil recovery; OOIP, original oil in place; cfu, colony forming unit; SS, synthetic seawater; $S_{or,1st\ SS}$, residual oil saturation after 1st synthetic seawater flooding

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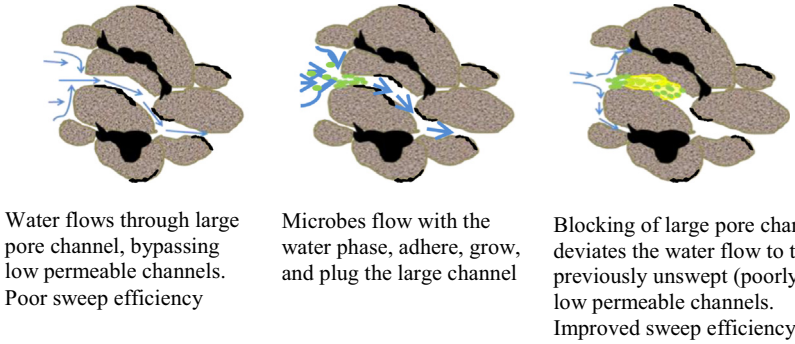


**Fig. 1.** Illustration of the selective plugging mechanism.

(Salehizadeh and Mohammadizad, 2009; Biria et al., 2013).

The phenomenon of microbial plugging has been investigated in a number of previous works where bacteria were injected into the different porous media in the water phase, without oil present. Flooding was carried out by injecting microbial culture and/or nutrient into various porous media and observing (or not observing) microbial plugging and fluid flow diversion. Shaw et al. (1985) used a sintered glass bead core to simulate the spaces and surfaces of reservoir rock and *Pseudomonas* sp. to study the bacterial plugging phenomenon. The authors observed that *Pseudomonas* sp. blocked the inlet face of a core and decreased its permeability. A dense 'bacterial mat' at the inlet face was observed using scanning electron microscopy (SEM). Raiders et al. (1986), investigated microbial plugging using Berea sandstone cores with a pressure tapped core holder along the length of the core. Indigenous microbes from the cores and *Bacillus* strain 47 were used in this study. Continuous injection of sucrose mineral salt medium resulted in a large permeability reduction (70–98%) by indigenous microbes from the core. Injection of *Bacillus* strain 47 prior to nutrient injection resulted in a more rapid plugging. Analysis of the pressure gradient along the core showed that plugging was localized at the inlet and outlet faces of the cores. The authors further tested the selectivity of the microbial plugging process by using a dual core system to create a contrast permeability layer. Two cores with different permeabilities (240 and 760 mD) were connected using a crossflow. After the system was injected with *Bacillus* strain 47 and nutrient, the flow pattern changed and about 90% of the total injected fluid was diverted to the low permeability core. Raleigh and Flock (1965), conducted core flooding using four distinct core types: Berea sandstone (homogeneous type), Cardium sandstone (less uniform sand grains compared to Berea, but a clean, well-sorted rock type), Devonian rock (a completely heterogeneous type), Indian limestone (outcrop rock, composed of oolitic porosity with secondary, small, vuggy and pinpoint porosity). *Bacillus subtilis* was used and it was observed that the majority of plugging observed in clean, homogeneous, uniformly grained, consolidated sandstone was located near the inlet face of a core. The heterogeneous carbonate behaves irregularly and plugging was observed along the entire length of the core. The authors concluded that depth of plugging within porous rock is a function of pore geometry.

The effect of microbial plugging on oil recovery was studied by injecting microbial culture into crude oil saturated core plugs. Crescente et al. (2005) conducted a series of core flooding in Berea sandstone using two types of *Rhodococcus* sp. 094. The first type was a surfactant-producing bacterium, while the second type was a non-surfactant-producing bacterium. The authors used dodecane as hydrocarbon, instead of crude oil, to saturate the cores. Different injection scenarios were studied. The bacteria were injected directly before and after water flooding. The injection of bacteria after water flooding resulted in an additional recovery of 3.1–3.4% OOIP for surfactant-producing and 5.1–9.7% OOIP for non-surfactant-producing bacteria. However, when the surfactant-producing bacteria were injected directly before water flooding, the process resulted in a higher oil recovery (67–84% of OOIP) as compared with the non-surfactant-producing bacterial injection (60–80% of OOIP). The authors concluded that when the cores were flooded with the non-surfactant-producing bacteria, the recovery was faster initially, but the recovery curves of the non-surfactant-producing bacteria and surfactant-producing bacteria would intersect and in the long run the surfactant-producing bacteria would achieve a higher recovery. A possible reason for this behavior could be that the biosurfactant produced by bacteria plays a role in addition to the selective plugging process (Crescente et al., 2005). Suthar et al. (2009) investigated the selective plugging strategy based MEOR using sandpack column and *Bacillus licheniformis* TT33, a facultative anaerobic, halotolerant, thermotolerant, and biofilm forming microorganism. Injection of a 0.6 PVI (pore volumes injected) bacterial culture at residual oil saturation, followed by a 20-day incubation period at 50 °C, resulted in an additional oil recovery of 13.0–17.8% OOIP. The bacteria produced biopolymer that increased the thickness of the biofilm. The biofilm diverted the flow to low permeability zones (a previously unflooded area) and released oil from this area. The presence of biofilm in the sandpack was confirmed by the Environmental Scanning Electron Microscope (ESEM). Al-Hattali et al. (2013), conducted core flooding experiments with Indiana limestone cores (permeability 200 mD and porosity 13%). The cores were sliced along the core using a thin blade to introduce fractures in the cores. *B. licheniformis* W16, isolated from the Omani oil field, was used in this study. The bacteria were injected in residual oil saturation condition and the cores were incubated with the bacterial culture for 18–24 h. Two different carbohydrate sources, sucrose and molasses, were tested to enhance the bacterial growth. The results showed quite a significant additional oil recovery, of 16.5–21.3% OOIP and 6.0–14.0% OOIP for sucrose and molasses, respectively. The authors speculated that lower oil recovery in the experiment with molasses could be due to slower bacterial growth in molasses as compared to sucrose. The presence of bacterial cells at the inlet, middle, and outlet of the cores was visualized by SEM at the end of the experiment. A recent publication by Kaster et al. (2012) reported core flooding experiments on bacterial plugging in low permeability Liege limestone cores (0.28–0.6 mD) and its effect on oil recovery. The enrichment bacteria consortium from the Draugen field, the North Sea, was used in the experiments. The bacteria were found to be able to penetrate, to be transported, and