

## Improved Heavy Oil Recovery by Non-Thermal Processes

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## 論 文 内 容 の 要 旨

Heavy oil is defined as liquid petroleum of 20 to 10 °API gravity at reservoir conditions, and the crude of which API is less than 10°API is termed as extra heavy. Heavy and extra-heavy oil reserves consist approximately of 21 and 32 % of total oil reserves respectively, while those of light to medium are estimated at 47 %. This means there is a substantial volume of heavy oil, which sits within the reach of existing oilfields. Most of these oils are trapped within the pore throats of shallow, small and thin matrices including low permeable siltstones, sandstone and carbonate reservoirs. In theory, the increment in oil, from these mature reservoirs, is obtained by implementing a technique referred as improved oil recovery (IOR). The IOR has been classified mainly into two groups that are thermal and non-thermal methods. The former, in which the heat is supplied to the reservoir in form of steam, has been preferred for heavy and extra heavy oils, because steam injection is strongly expected to decrease the mobility of the oil and augments thereby the production. To date, the production scheme is slowly disfavored primarily because of the cost of stem generation. On the other hand, a typical non-thermal method consists of injecting a fluid (slug) that reduces either the interfacial tension (IFT) or the viscosity of the residual oil. However, a poor propagation of the slug lowers the efficiency of these methods. The implementation of either of these techniques, in a candidate mature heavy oil reservoir, is inherent to its petro-physical properties and the characteristics of the residual oil.

The scope of this research considered two candidate heavy oil formations. The initial IOR screening highlights the possibility of gas-miscible (CO<sub>2</sub>) and chemical-IOR respectively to petro-physics of the candidate formations and the properties of the residual oil. The motivation was not only to evaluate their potential, but also to highlight the technical challenges. Ultimately, it was sought to propose a recovery scheme that increases the heavy oil production, while reducing associated energy cost. Both were investigated experimentally in this research.

This dissertation consists of six chapters.

Chapter 1 introduces the fundamentals of IOR, discusses on the various approaches in heavy oil recovery. Therein is also detailed the mechanisms inherent to heavy oil production and the screening criteria of IOR. The candidate formations, the properties of its untapped oils are presented.

Chapter 2 investigates the potential of CO<sub>2</sub> for the candidate formations, which was selected in respect of the petro-physical properties of the reservoir. The production was mimicked by injecting CO<sub>2</sub> both at its sub-critical and super-critical state (sCO<sub>2</sub>) in candidate heavy oils (API 11.5 and 16.6). Conducted in a PVT analyzing cell, the results showed that sCO<sub>2</sub> has a better solvating potential than CO<sub>2</sub>. The swelling of the candidate heavy oils increased in a linear fashion with the concentration of sCO<sub>2</sub> and was altered by the

presence of reservoir water. It was further shown that  $s\text{CO}_2$  promoted a stripping process of light fractions from the native oil during the development of the miscibility front, which was followed by the deposition of an appreciable amount of asphaltenes. This latter phenomenon was highlighted as major drawback for this IOR method. Further investigations in this regard revealed that not only the petro-physical properties of the candidate formation would dictate the concentration of aggregated asphaltene, but also the chemical composition of the crude oil and even the injecting conditions of  $s\text{CO}_2$ . If implemented in the candidate formation, it is shown that the injecting gas ( $s\text{CO}_2$ ) would behave either as flocculent or coagulant. Subsequently, these properties would either control or enhance the amount of deposited asphaltene. It was concluded that  $s\text{CO}_2$  was potentially viable for a heavy oilfield provided that proper injection conditions were maintained. However, given the initial concentration in asphaltene in the candidate heavy oils,  $s\text{CO}_2$ -IOR cannot be recommended.

In Chapter 3, the heavy oil production, in respect of the physico-chemical properties of the candidate heavy oils, is investigated. Therein is introduced a new class of surfactants (Gemini surfactants). Two lyophilized cationic Gemini surfactants i.e. *12-3-12* and *16-3-16* were used to formulate the aqueous micellar slugs. Their inherent physico-chemical properties were subsequently investigated. These included the critical micelle concentration (CMC), the adsorption and the surface tension. Their potential for surfactant flooding were shown as they were able to achieve (i) an ultra-IFT (order of  $10^{-3}$  mN/m), (ii) high water and oil solubilization and (iii) a relative low adsorption on sandstone and dolomite. More interestingly, those properties were found pronounced when the micellar slug, prepared from a Gemini surfactant with a longer hydrophobic alkyl chain ( $n=16$ ), was used. Additionally, the micellar slugs showed an interesting potential as corrosion inhibitor by neutralizing the acidic materials generated as by-product during  $s\text{CO}_2$ -IOR.

Chapter 4 introduces the concept of cationic microemulsions and their relevance to oil recovery. The ultra-low IFT, achieved in the microemulsions, was altered by (i) the length of the alkyl chain of the primary surfactant, and the nature of the respective cosurfactant, (ii) the presence in divalent ions in the brine solution and (iii) the acidity of the residual oil. The rheology of the microemulsions revealed a pseudo-plastic behavior, which was altered by the formation salinity. Therein is also addressed the characterization of the cationic microemulsions.

Chapter 5 introduces a hybrid recovery flooding scheme using microemulsions. The heavy production was performed by a series of core-flooding experiments, performed in Berea sandstone, representative of the formation rock. The production scheme consisted of the injection of microemulsion-gel type formulated exsitu, in water-flooded sandstone, at the trail of which low-saline water was injected. Conducted in the homogeneous Berea sandstones, up to 31% of the initial oil-in-place (IOIP) was recovered from the homogeneous water-flooded sandstone when the heaviest microemulsion formulation was injected. The oil recovery was lowered to 20.3% when the microemulsion was formulated from the micellar slugs prepared from the Gemini surfactants with the shorter alkyl chain. The microemulsion formulations prompted a series of chemical reactions with the native minerals and the residual petroleum fluids, which caused the formation of sludge in the effluent fraction. The sludge is believed to be the challenge in this recovery scheme. However, it was shown that the deposition could be mitigated by altering the composition of the preflush water.

Chapter 6 concludes this research by highlighting the feasibility of two methods. A comparative analysis and proposed solution in respect the inherent challenges are presented. Further suggestions in regard of microemulsion-flooding and asphaltene deposition are discussed.