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An experimental study to determine suitable injection strategies for water-alternating-solvent process in green and brownfields☆

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ABSTRACT

Considering more than 50% of oil is left on average after primary and secondary methods in conventional reservoirs, techniques to recover the remaining oil from these proven and mature reserves is critically important to meet the future energy demand. One of the ways to achieve this is to inject miscible solvents (usually gas), which is performed in the form of water-alternating gas rather than continuous injection of this type of expensive material. In this case, the process should be optimally designed for slug sizes and proper sequences of the solvent considering several controlling parameters including past history of waterflooding (water content) and wettability.

We performed a set of experiments on vertically situated sand pack models saturated with 14cp oil. Heptane was selected as the solvent phase due to high miscibility conditions. Tests were started with waterflooding or solvent injection. Different slug sizes of solvent and water were tested on fully oil-saturated water, oil-wet samples, and samples with connate water (10 and 30%). The amounts of oil and solvent retrieved were monitored using refractometer. Using the collected data, the recovery rates and ultimate recoveries were comparatively analyzed. In addition to the technical feasibility, an economic analysis was performed considering the amount of solvent injected, oil and solvent recovered, and time for recovery.

Starting the process with heptane was technically and economically feasible (pay-out time is shorter) in the short run for both the oil- and water-wet cases. This was especially true if the rock were oil-wet, which yielded faster recovery and higher ultimate recovery. Excessive water injection (up to the plateau level) preceding the solvent injection in the oil-wet case resulted in lower recovery factor whereas this design was very effective in the water-wet case. Therefore, the time to switch to solvent injection was critical in the oil-wet case and a short initial cycle of solvent injection followed by short waterflooding cycle is suggested. In the oil-wet case, initial waterflooding resulted in an inefficient process; while it yielded high ultimate recoveries, the process time was longer than other injection options. In the water-wet case, a greater amount of solvent was needed in the first cycle.

1. Introduction

At some point during the life span of a field, enhanced oil recovery (EOR) techniques are needed. Depending on the technical reasons and economic constraints, these methods can be applied at early (green fields) or late stages (brown fields). Solvent (or miscible gas) injection is one of the most suitable candidates to be applied at any stage after primary production due to high recovery factor caused by the miscible nature of the process. In this very effective but expensive application, high amounts of oil and solvent must be recovered and/or retrieved for a profitable application.

Although miscible solvent injection has been one of the most widely applied recovery techniques at the late stages (tertiary recovery), the recovery factor was observed to be relatively low (Babadagli, 2007). Hamedi and Babadagli (2015) and Batruny and Babadagli (2015) attributed this to the selection of proper time to switch from waterflooding to solvent injection. As solvent injection is implemented in the form of water-alternating-gas (WAG) (Stalkup, 1984; Christensen et al., 2001; Surguchev et al., 1992; Zhang et al., 2013), the optimal design of slug sizes and sequences are critically important (Carlson, 1988;

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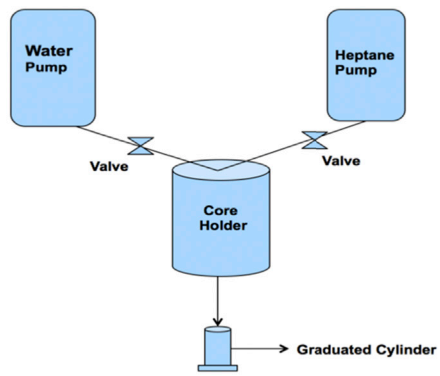

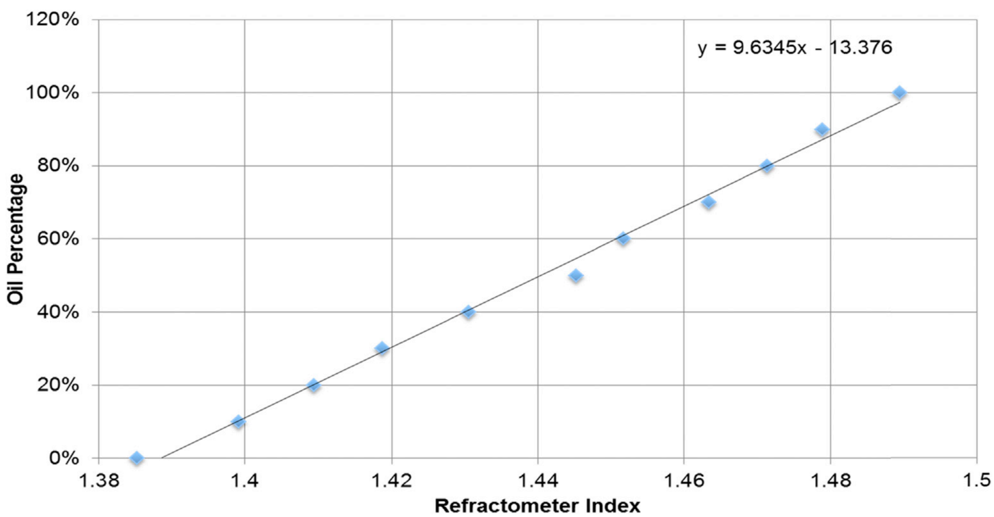

Fig. 1. **a** Experimental setup. **b** Refractometer index chart.

Winzinger et al., 1991; Harpole and Hallenbeck, 1996; Kane, 1999; Sohrabi et al., 2001, 2005; Righi et al., 2004; Fatemi Mobeen et al., 2011).

Wettability and interfacial tension governs the distribution of the phases in the pore space (Chatzis et al., 1983; Stern, 1991; Øren et al., 1992; Rao et al., 1992; Jadhunandan and Morrow, 1995). This eventually controls the mixing process between the oil trapped and injected solvent. Water may trap the oil due to its affinity to it (caused by the lower interfacial tension between these two) preventing its mixing with solvent as water-solvent interfacial tension is higher than that of water-oil (Hamedi and Babadagli, 2015; Lin and Huang, 1990). Hence, wettability becomes the controlling factor in determination of the optimal injection scheme; i.e., the sequence of injected materials (water or solvent) and -optimum- WAG slug sizes. For example, Jackson et al. (1985) showed through core scale experimentation that continuous slug without water is more effective than WAG is for water wet systems, while 1:1 solvent (CO_2)-water slugs is more desirable for oil-wet systems. This was also validated through micro-model (visual) experiments by Hamedi and Babadagli (2015). Conversion time to solvent injection (miscible flooding) from waterflooding is also critical in the optimal design of the WAG processes. Srivastava et al. (1997) and Batruny and Babadagli (2015) suggested that miscible injection before water flooding yields a higher ultimate recovery in water-wet systems compared with the case with secondary waterflooding.

Free water from previous injection stage affects the performance of solvent injection (Raimondi et al., 1961; Holm, 1986; Huang and Holm, 1988; Wylie and Mohanty, 1996). If the system is water-wet, solvent displaces the pre-injected water in the pores (Jones, 1985; Hamedi and Babadagli, 2015), yielding a low recovery factor by solvent injection. Therefore, starting solvent injection before the reservoir is water filled would yield higher ultimate recoveries (Alquriaishi and Shokir, 2011; Hamedi and Babadagli, 2015).

Hamedi and Babadagli (2015) and Batruny and Babadagli (2015) showed that if the system is oil-wet, pre-waterflooding yields a better performance of miscible hydrocarbon solvent injection. This might explain why miscible injection results in higher recoveries in carbonates at the tertiary stage (Griffith, 1981; Derochie, 1987; Christensen et al., 2001; Edwards, 2002; Duchenne et al., 2015). An interesting field application in a water-wet sandstone reservoir in Alaska showed that miscible gas injection may result in an effective recovery performance if pre-waterflooding as a secondary recovery method is not run for a long period of time before switching to the tertiary stage (Zhang et al., 2013).

In a recent attempt, Batruny and Babadagli (2015) tested solvent injection into water-wet systems on horizontally positioned core samples. The present paper is a continuation of this work. Vertical injection was adapted as a more realistic injection scheme for solvent injection and tests were performed on both water-wet and oil-wet samples. The aim was to determine the proper time to switch to solvent injection from waterflooding, as well as the slug sizes for different wettability conditions and connate water in the system. These types of clarifications and findings are useful in the design of this effective yet expensive process. The experimental data generated can also be used in field scale modeling in which larger scale heterogeneity is incorporated.

This research considered a highly effective (fully miscible solvent injection) but expensive method, which is practically applied if the reservoir conditions are suitable (Derochie, 1987; Zhang et al., 2013). Alternative methods are to use water soluble solvents such as diethyl ether (Chahardowli et al., 2013) or dimethyl ether (Al-Kindi et al., 2016; Riele et al., 2016), or more conventional methods such as miscible CO_2 alternated with water (Duchenne et al., 2015). These methods may not be