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Effect of waterflooding history on the efficiency of fully miscible tertiary solvent injection and optimal design of water-alternating-gas process

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ABSTRACT

Miscible gas injection is one of the most common tertiary recovery methods applied at the mature stage of a reservoir, usually after severe waterflooding. This application is typically done in the form of water alternating gas (WAG) rather than continuous injection of expensive gases. In this process, the performance of miscible gas, especially if it is water insoluble hydrocarbon gas, injection is affected by the amount of water exsiting in the reservoir.

To study this effect of preceding water injection on-fully-miscible displacement in water-wet media and propose optimal WAG patterns, a set of experiments were performed on a sand pack model. The results showed that the amount of water existing in the system significantly reduces the miscibility of gas with oil and, therby, the ultimate recovery. However, a critical amount of water was found at which this effect becomes more prominent. It was also observed that a WAG cycle starting with gas as the first injection phase results in more effective recovery than the same WAG cycle with water as the first injection phase. The effect of water in the system during the following cycles is not as critical as in the WAG cases that start with waterflooding. Finally, the optimal design constrained by the injection scheme design (gas injection whether on its own or with water), slug sizes, time to switch to gas injection after first waterflooding, and injection patterns were presented. Considerations were also given to solvent retrieval in proposing the optimal injection schemes.

1. Introduction

Waterflooding is a process conventionally used for secondary recovery in oil fields. Under ideal conditions—i.e., homogeneous water-wet reservoirs with high permeability and light oil—large amounts of water are injected for a long period of time. This may result in pores filled with water, often exceeding the amount of oil. The statistics showed considerably high amount of oil left, even under very ideal conditions, after waterflooding to be a potential for tertiary recovery.

Historically, miscible gas injection has been the most widely appplied tertiary recovery technique (Babadagli, 2007), and is typically applied in the form of WAG (Stalkup 1984; Surguchev et al., 1992; Christensen et al., 2001; Zhang et al., 2013). As seen in Fig. 1, with the exception of two cases of these mature gas injection processes, the incremental recovery averages less than 10%. This highly pessimistic outcome can be attributed to severe waterflooding preceding any of these methods and/or involvement of water during the succeeding gas injection in the form of WAG. In fact, the use of chemicals (surfactants, alkalis, or alkali-polymer-surfactants, or micellar flood) as a tertiary recovery agent yielded much more promising results (almost doubled incremental recovery of gas injection) as pointed out by Babadagli (2007).

Waterflooding may prevent proper mixing of injected solvent with reservoir oil as water occupies previously oil saturated pores reducing the overall contact area between injected gas and oil in the reservoir. Also, water traps the oil in pores and prevents miscibility of solvent with oil since water–solvent interfacial tension is higher than that of water–oil, giving rise to water spreading around the oil and preventing contact with injected gas. This was investigated by Hamedi and Babadagli (2015) visually at the pore scale and by Lin and Huang (1990) through core scale experiments. They stated the wettability is the primary reason for the blockage of oil by water to limit its contact.

Wettability controls the phase distribution and spreading of phases over each other (Chatzis et al., 1983; Jadhunandan and Morrow, 1995) along with interfacial tension. This effect was experimentally studied by Stern (1991), Øren et al. (1992), and Rao et al. (1992). In a water-wet medium, injected gas typically displaces the free water in the system from the previous waterflooding (Jones, 1985; Hamedi and Babadagli, 2015), yielding low efficiency gas injection. The suggestion was to start with gas injection rather than waterflooding (Alquriaishi and Shokir, 2011; Hamedi and Babadagli, 2015).

On the other hand, pore scale investigations showed that pre-waterflooding might even have positive effects on the succeeding miscible gas injection in the long run for oil-wet systems (Hamedi

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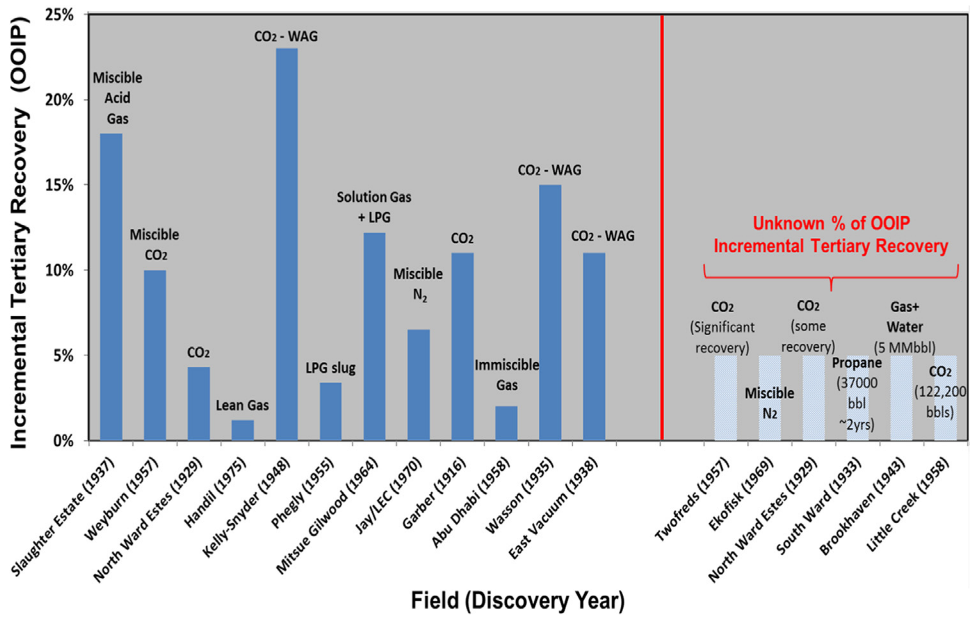

Fig. 1. Ultimate recoveries of tertiary gas injection processes (data from Babadagli 2007).

and Babadagli, 2015). This was also supported by field scale observations on miscible gas inejction results for carbonates by Christensen et al. (2001).

As seen, previous water history affects the miscible displacement performance (Raimondi et al., 1961; Kasraie and Farouq Ali, 1984; Holm, 1986; Huang and Holm, 1988; Wylie and Mohanty, 1996) and the WAG processes are required to be optimally designed (Carlson, 1988; Winzinger et al., 1991; Harpole and Hallenbeck, 1996; Kane, 1999; Sohrabi et al., 2001; Righi et al., 2004; Sohrabi et al., 2005; Mobeen Fatemi et al., 2011). Wettability is a critical factor that plays a role on determination of optimum WAG slug sizes. Jackson et al. (1985) suggested 0:1 (continuous slug) and 1:1 CO_2–water slugs as optimum for water- and oil-wet systems, respectively, through experimental studies. One also has to determine the best injection strategies, i.e. conversion time to miscible flooding from waterflooding, for optimal design of the WAG process. Srivastava et al. (1995) observed that miscible flue gas injection before water flooding yields a higher ultimate recovery than the case with preceding-secondary-waterflooding.

On the basis of these observations, the following questions regarding WAG sequences and the presence of water and its effect on injected gas miscibility can be raised:

(1) What is the optimum injection rate (or amount) for water and injected hydrocarbon solvent?
(2) How do water, injected hydrocarbon solvent, and oil interact?
(3) What is the minimal amount of hydrocarbon solvent and water to inject for an efficient process?
(4) What is the optimal injection sequence for an efficient recovery process?

Although a number of experimental studies at the pore and core scales as well as numerical models at the field scale exist, more experimentation is needed covering a wide range of injection options such as slug sizes, sequence, injection rate, etc., to give insight into the optimal design of the WAG process. This paper investigates this through core scale experimentation to eventually provide optimal application conditions of fully miscible WAG process. Note that a liquid solvent (heptane) was used, instead of a miscible gas, to represent fully miscible gas injection. Hence, the term WAG used throughout the text refers to "water alternating solvent" injection and the solvent is fully miscible with oil. Two basic schemes were followed to analyze oil–water–solvent interactions during WAG process in water-wet medium: (1) straight hydrocarbon solvent injection as a tertiary recovery technique following waterflooding, and (2) initial hydrocarbon solvent injection before water and continue the process as WAG. Note that the investigations on these were done on 1-D core flooding basis to clarify multiple interaction of phases (oil, solvent, water, and rock). Therefore, 2- and 3-D effects (mainly gravity override) are not included and this should constitute the next phase of the study.

2. Experiment and materials

Experiments were conducted at ambient pressure and temperature conditions. All experiments were carried out in a core holder with a meshed sand-pack of 9 cm in length and 3.8 cm in diameter (Fig. 2). The core holder was attached to two syringe pumps in the inlet for solvent and water injections. Outlet was linked to a graduated cylinder for sample collection at time-specific intervals.

A sand pack made of pure silica sand with an average porosity of 37% was used as porous media. The sand pack was saturated with light crude oil (14 cp at 25 °C) and for each experiment a new model was prepared. Heptane was used as a solvent since it is fully miscible at first contact with oil at experimental conditions, representing fully miscible fluids at reservoir conditions.

Note that no initial water exists in the system and it is 100% oil saturated. Despite this, the system is considered water-wet due to material used (clean and uncoated glass beads and very light oil) and as the model did not undergo any aging process. Initial contact angle tests and waterflooding performances also supported the water-wet nature of the system (figures not included).

Experiments were conducted at two flow rates (2 cc/min and 0.5 cc/min) to evaluate the effect of flow rate and to allow for sample collection in a timely manner since heptane is highly volatile. A refractometer and a density meter were used to analyze the composition of produced oil in different experiments. The refractometer was calibrated by using different weight percentages of oil and heptane mixtures.