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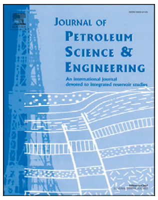

Efficiency of heavy-oil/bitumen recovery from fractured carbonates by hot-solvent injection

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ABSTRACT

This paper presents an extensive analysis of three different solvents injected through two different rock types under dynamic conditions, at elevated temperatures, to recover heavy-oil/bitumen from fractured carbonates. The main idea was to identify the optimal temperatures needed for maximal recovery by hot solvent injection for a wide range of solvents. We also considered the optimal conditions for effective solvent retrieval for the economics of this type recovery approach. In order to represent a wide range of carbon number solvents, heptane and naphtha were injected at atmospheric pressure and temperatures ranging from 70 to 120 °C and 21.5–100 °C, respectively. Propane was injected at a pressure of 1483–1511 kPa and a temperature ranging from 22 to 60 °C to be in the liquid phase. Indiana limestone (outcrop) and vuggy naturally fractured carbonate samples (outcrop core samples from a producing formation in Mexico) were selected as core samples. Hot solvent was injected continuously through artificially fractured cores followed by hot water (or steam injection) phase for solvent retrieval. The optimal temperatures for heavy oil recovery and solvent retrieval, in the subsequent hot water injection, for each kind of rock sample and type of solvent were determined. The results revealed that heavy oil recovery increase with the solvent carbon number used. Also, it was observed that when the temperature is higher than the saturation value for the given pressure curve, the recovery decreases and the lightest component of the heavy oil are dragged by the gas stream.

1. Introduction

Recovering heavy oil/bitumen from naturally fractured carbonates is challenging due to unfavorable rock characteristics (fractures, vugs, tight matrix with low porosity, and oil wet nature). Gas, water or any other fluid injected for enhancement of highly viscous oil production results in severe channeling through the fractures while the matrix tends to retain the oil due to unfavorable wettability. Therefore, oil displacement from tight matrix requires a long time for an effective transfer process by capillary imbibition or gravity drainage. To tackle these challenges, a feasible solution is to reduce the viscosity of heavy oil, which can be achieved in two ways: (1) heat transfer by steam or hot water injection, or (2) oil dilution by solvent injection.

An alternative and more efficient way is to apply both heat and solvent as a hybrid process: namely hot solvent injection, which is the subject of the present work. As injection of heated solvent is practically not efficient, pre-heating the reservoir (by steam or even hot-water) is needed to reach the desired (or optimal) temperature at which the injected solvent yields an effective diffusion into the matrix to dilute the oil in it. This can be followed by a soaking period to allow heat and mass transfer between the fluids (steam/hot water followed by solvent) injected. Obviously, the pre-heat stage can be avoided if the original reservoir is already at the desired temperature. The cycles can be continued until the economic limit is reached. Note that heat injection after the production period in each cycle preceding the next solvent injection phase, will improve not only the heavy-oil recovery but also the solvent retrieval. Fig. 1 depicts the possible application of this method at the field scale. The hybrid method is useful not only for heavy-oil recovery improvement but also to retrieve the solvent by vaporization using the heat energy to make the process economically viable. Otherwise, the retrieval of the solvent diffused into the matrix would not be effective in the “cold” injection of solvent (the only way to retrieval is gravitational segregation). The vaporized solvent can be retrieved in the hybrid application through expansion and gravitational segregation in the matrix, while the liquid solvent can easily get trapped in the pores of the matrix (Al-Bahlani and Babadagli, 2009).

In this technique, the combined effect of heat transfer and dilution yields a better result than the sole application of steam or cold solvent

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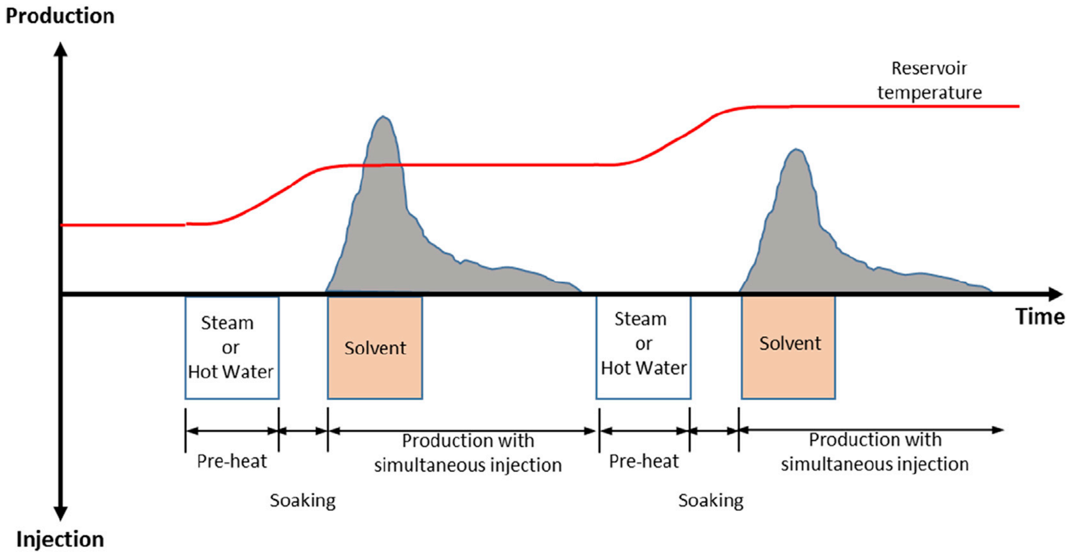

Fig. 1. Sequence of the hot solvent recovery processes.

injection alone (Butler and Mokrys, 1991, 1993, Ivory et al., 2008; Pathak and Babadagli, 2010, Pathak et al., 2011a-b, Edmunds et al., 2009; Ayodele et al., 2010; Frauenfeld et al., 2010; Deng et al., 2010; Ardali et al., 2012). For gas solvent injection, viscosity reduction effect was studied numerically by Kaneko et al. (2013). They demonstrated that higher recovery can be obtained with heavy gas solvent than with injecting light ones. This makes the process more expensive and requires effective retrieval of solvent for an economically viable process (Al-Bahlani and Babadagli, 2009).

Energy requirements and economical benefit of this kind of processes were analyzed previously through numerical simulations (Leyva-Gomez and Babadagli, 2014, 2017). They used genetic algorithms, linked to STARS simulator, as an optimization tool to obtain the best economical combination of parameters in a reservoir under hot solvent injection processes. Due to the number of parameters involved, it was necessary to carry out a high number of numerical simulations and genetic algorithms were a useful tool to reduce the computer time. Their findings showed the necessity of solvent retrieval to make this processes economically feasible. The efficiency of solvent retrieval was analyzed considering different parameters as rock wettability, temperature applied and solvent type (Mohammed and Babadagli, 2013). Also, pore visual scale experiments were carried out to understand the dynamics of solvent retrieval processes at elevated temperatures using microfluidic devices (Marciales and Babadagli, 2014).

The efficiency of this process has been studied extensively but most of these efforts were made using homogeneous sandpacks or highly permeably sandstones (Moreno and Babadagli, 2013, 2014a, Haghighat and Maini, 2013, Pathak and Babadagli, 2010, Pathak et al., 2011a,b). In the case of naturally fractured carbonate rock matrix, this kind of processes requires special attention due to poor interaction between matrix and solvent in fractures caused by unfavorable rock properties as listed above. Rostami et al. (2005) focused their studies on dual porosity systems and stated the necessity of establishing an optimum solvent injection rate. Later on, they performed simulation studies using a dual porosity system considering different injection rates at a fixed solvent injection temperature. They found that solvent flows faster through fractures and forms solvent fingers and in consequence an optimization procedure is necessary to find the optimum solvent injection rate. Rahnema et al. (2008) observed in their studies with low matrix permeability fractured systems, made of sand packs for fractured and non-fractured cases, that the presence of fractures can compensate the low matrix permeability enhancing the solvent diffusion process. Al-Bahlani and Babadagli (2009) performed static and dynamic experiments using sandstones and carbonate samples. Their objective was to study the alternate injection of steam/hot-water and solvent for heavy oil recovery from matrix. They concluded that the process depends on the solvent injection rate.

Rezaei and Mohammadzadeh (2010) studied the VAPEX process, originally suggested for unconsolidated high permeability sand reservoirs (Upreti et al., 2007 and Vargas-Vasquez, 2007), on a vuggy porous media, created by embedding wood particles in glass beads, and concluded that the presence of vugs improves the efficiency of VAPEX. Later, Naderi et al. (2013) and Naderi and Babadagli (2014) experimentally analyzed the dynamics of heavy oil recovery from heterogeneous carbonates by solvent injection alternated by steam or hot-water. Their reported values of heavy oil recovery using different solvents were highly encouraging despite unfavorable matrix conditions (oil-wet sands and carbonates).

During solvent injection processes, effective permeability will be reduced by the blockage of the pores by the asphaltene precipitation. This effect was studied by Syed et al. (2012) using packstone plugs and more recently by Moreno and Babadagli (2013, 2014a-b). The latter concluded that an optimum solvent selection not only depends on oil and rock characteristics, but also on the diffusion and mixing quality. On the basis of these observations, they recommended using different solvents throughout the recovery processes; i.e., lighter ones initially and switching to heavier ones later on. Yakubov et al. (2014) performed several experiments using C_3, C_4, C_5 and C_6 with bitumen to evaluate the efficiency of several asphaltene inhibitors during solvent injection processes. They stated that the addition of an asphaltene inhibitor is a way to prevent asphaltene precipitation and deposition in a reservoir. Taniya and Hascakir (2016) investigated the interactions between solvent and bitumen during solvent-steam injection processes. They concluded that saturated fractions of oil can precipitate asphaltenes at higher rate than n-pentane.

Leyva-Gomez and Babadagli (2014, 2016) performed dynamic experiments injecting hot heptane into artificially fractured sandstones saturated with heavy oil. They showed that temperature of injected solvent should be close to its vapour pressure in order to maximize oil recovery. The proper selection of solvent for this kind of recovery process becomes more important in low permeability rock matrix. They confirmed that heavy oil recovery is highly dependent on the solvent injection rate (Fig. 2). Lower injection rates, which allows more time for the solvent to contact with matrix in order for the diffusion process takes place, are more desirable from solvent consumption point of view. This, however, requires longer time to reach economically desirable oil