International Journal of Heat and Mass Transfer 112 (2017) 837–849

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Retrieval of solvent injected during heavy-oil recovery: Pore scale micromodel experiments at variable temperature conditions

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ARTICLE INFO

Article history:
Received 3 January 2017
Accepted 9 May 2017

Keywords:
Visual micro model tests
Phase distribution
Solvent injection
High temperature
Solvent retrieval

ABSTRACT

Solvent injection has been given attention to enhance oil recovery by sole use or in combination with a thermal method to develop light, medium, and heavy-oil fields. To make this process efficient, retrieval of expensive solvent efficiently is required. This can be achieved by alternative injection of water (WAG) if the reservoir is homogeneous. In case of heterogeneous reservoirs (fractured carbonates or sands with wormholes), one needs to develop techniques other than viscous displacement to retrieve the solvent diffused into less permeable matrix portion. A method of injecting steam/hot water to heat the solvent to vaporize and retrieve it was introduced recently (steam-over-solvent injection in fractured reservoirs) and tested through core experiments. Although these tests provide valuable data to design the optimal temperature of injected water to make the process viable, the mechanics of the nucleation of the solvent vapor and its entrapment in the pores at the micro scale requires further research.

A series of experiments using a 2-D etched glass micromodel (sandstone replica with a fracture) were carried out to investigate the mechanics of solvent retrieval and entrapment at variable temperature conditions. The micromodel was saturated with dyed processed oils and different solvents were injected through fracture. After the solvent was diffused into matrix completely to recover the oil, the model was heated mimicking a thermal method to reach the boiling point of the solvent and retrieve it. The wettability of the micromodel was also altered to achieve water-wet and oil-wet conditions as wettability dictates the phase distribution in the pores. Following the heating phase, water was injected to retrieve the remaining solvent in the liquid or vapor phase.

Visual observations of solvent diffusion/dispersion into matrix and its retrieval from the matrix clarified the miscibility process in the presence of an immiscible phase, interaction between different phases in a complex heterogeneous system, and phase distributions as a function of temperature. This information can be used to determine the efficiency of solvent retrieval process and optimal application conditions for EOR applications in heterogeneous sands and carbonates.

1. Introduction

Thermal processes are widely applied to develop heavy oil and bitumen reservoirs, mainly aiming to reduce the viscosity of oil. These processes may not be efficient due to heat loss in thin layers, bottom-water reservoirs and heterogeneous carbonates. The use of solvent in thermal applications to improve the efficiency of the process and to further reduce oil viscosity has been considered recently. Co-injection of solvents with steam or pre-injection of them before starting steam injection processes were tested extensively [6,20,22,9,12,13]. Solvent was also designed to inject alternately with steam [23,24]. Recovering very viscous oil through injecting superheated solvents was patented by Allen et al. [3]. The solvent performance during thermal applications is highly dependent on temperature. Pathak et al. [15–19] showed a remarkable variation of recovery with an increase in temperature for the hot solvent injection process. Steam-over-solvent injection (SOS-FR) method was proposed specifically for naturally fractured (oil-wet) reservoirs [2,25]. Later, experiments and numerical simulations were conducted to help find and design optimum solvent type, concentration and operating parameters to achieve these technologies [7,26].

Injected solvent is a much more expensive substance than the produced heavy oil or bitumen. To make solvent-aided heavy-oil recovery processes efficient, the retrieval of solvent injected at

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.05.034
0017-9310/

acceptable rates is essential for the operability and economics of these technologies. Gupta et al. [8] investigated capillary adsorption which could cause solvent retention in porous media and analyzed the importance of recycling solvents when discussing the economics of solvent aided steam injection process. Chang et al. [5] investigated different mechanisms involved in solvent retention behavior in porous media.

In light oil and homogeneous reservoirs, water injection is able to sweep residual solvent. In heterogeneous systems like fractured carbonate reservoirs, the oil is stored in the matrix but the fracture controls the flow. The method of water injection may not be efficient and making use of solvent vaporization at higher temperature was proposed for this kind situation. Al-Bahlani and Babadagli [1,2] proposed a new technology (SOS-FR) to develop the heavy oil in fractured reservoirs efficiently. At the final step of the whole process, steam or hot water was injected to heat the residual solvent at around boiling point temperature of the solvent to retrieve it thermodynamically. Mohammed and Babadagli. [10] further tested the efficiency of solvent retrieval by heating the reservoir after completing the solvent injection phase. They designed a series of static core experiments to estimate the rate and ultimate amount of solvent retrieval by hot water injection and concluded that 86–90% of the solvent introduced into rock matrix was retrieved if an optimal temperature is applied. In their work, efforts were made to clarify the physics behind this process in core scale and identify the roles of the parameters such as wettability and temperature.

More efforts are needed to clarify the effect of critical parameters (solvent type, temperature, wettability, etc.) on the solvent retrieval process, especially at the pore scale with visual evidences. Marciales and Babadagli [11] designed experiments using 2-D micromodels and vaporized the solvent diffused into porous media at elevated temperatures. They used heptane and naphtha as solvent and achieved the retrieval of them by heating at different conditions. The present paper, in a sense, is a continuation of this work. Our focus is not only on the solvent type but also oil viscosity and the wettability of the system.

We visually analyzed the vaporization and mobilization of solvent under heating. The bubble nucleation and expansion in porous media was imaged for different conditions (i.e., heating source, temperature level, heating rate, rock wettability, and oil and solvent types).

2. Experimental methodology and procedure

A series of experiments were designed using a square-shaped Berea-sandstone-replica model made by etched glass following the procedure introduced by Naderi and Babadagli [14]. The depth of the channel was 40 μm and all micromodels had a 5 cm × 5 cm matrix (porous part) and a 1 cm × 5 cm conduit to represent a fracture or wormhole. As the glass substrate is naturally water-wet, the micromodel is assumed to be initially water-wet.

An entry port and one production port were set at the opposite corners of the fracture side as seen in Fig. 1 (see micromodel on the heating plate). The visual window (the area marked by yellow[1] square on the micromodel shown in Fig. 1) to capture images was fixed in the middle of the fracture for experimental comparison and also to reduce the edge effect. Proper dying agents were chosen and added to varying liquids differently: DFSB-K175 for oil, DFSB-K43 for solvent and IFWB-C8 for water from Risk Reactor [21]. Oil, matrix grains, and solvents were classified and shown as brown, black, and cyan under filtered UV light (Fig. 2). The miscible mixture of oil and solvent is shown as color between these two and marked

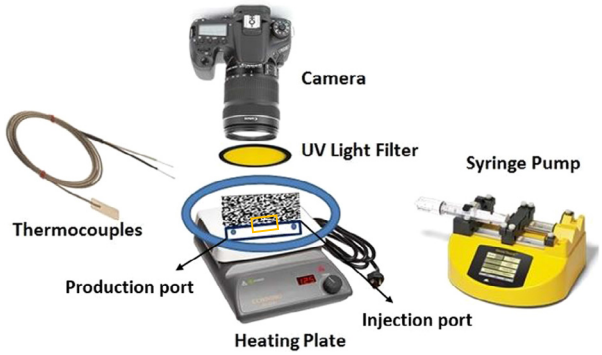

Fig. 1. Schematic of experiment set-up.

in the images. The gas phase (bubbles) is identified by black color with white outline as shown in Fig. 3. The white line represents the interface between the gas phase and the liquid phase (or matrix grains).

A Canon 7D camera recorded the images during the experiments. Syringe pump was used to inject oil and solvent at low pressure. A heating plate was controlled to heat the certain part of the micromodel to retrieve the solvent. There were two thermocouples fixed on two testing points (marked in Fig. 2) to monitor the continuous temperatures of the fracture and matrix. Temperatures were recorded every 5 min by thermocouples and a data acquisition system. The detailed set up is shown in Fig. 1.

Two kinds of mineral oils (250cp; 600cp at 25 °C) were chosen to investigate the effect of oil viscosity. Heptane and decane were injected through the fracture to be miscible with the mineral oil in the matrix. Subsequently, the system was heated to vaporize the solvent. A chemical dichlorooctamethyltetrasiloxane (SurfaSil, a siliconizing liquid) was applied to micromodel before experiments to alter wettability to more water-wet (details of this process can be found in Naderi and Babadagli [14]). The wettability alteration was validated by contact angle tests as well as through the observation of water/oil or water/solvent interfaces during experiments.

At the beginning of the experiment, the mineral oil was injected to fill the pores of the micromodel with it (Fig. 2). Then, solvent was injected at a low rate of 1 ml/h to occupy the whole fracture part. This procedure was applied for the lighter oil (250cp); but, for the heavier (600cp) oil, two options were designed. (1) Inject the solvent at 1 ml/h after around 10 h to fill the fracture and let the solvent completely mixed with the mineral oil in the matrix until equilibrium. (2) Inject more solvent for 16 h. The next step started until the solvent had sufficient time (almost 12 h) to mix with oil in the matrix and reach equilibrium as indicated in Fig. 2.

Note that this part of work was performed to reach the miscible stage. It does not target at any enhanced oil recovery assessment or so. Therefore, excess amount of solvent was injected to fully reach miscibility. Then, the solvent retrieval process, which is the main goal of this research, was initiated and the micromodel was gradually heated by continuously increasing temperature. The location of the heater (heating point) and the heating rate for each experiment are described in Table 1. Depending on the heating conditions, different boiling phenomena of solvent were observed. The detailed analysis of this process will be discussed later. The heating efficiency rate was adjusted by different heating time to reach the same final temperature. Considering the durability of the micromodel materials, the final temperature was fixed at 75 °C and 100 °C for heptane and decane, separately. Once these temperature values were reached, the heating source was shut down and the system was let down to cool to the ambient temperature.

The visualization study aimed to investigate how different parameters affect the solvent retrieval process, especially during

[1] For interpretation of color in Figs. 1, 2, 5–8, and 10–17, the reader is referred to the web version of this article.