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Full Length Article

Combined benefits of capillary barrier and injection pressure control to improve fluid recovery at breakthrough upon gas injection: An experimental study

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ABSTRACT

Formations with interconnected pathways of fractures (or high permeability regions) between the production and injection wells suffer from early breakthrough and low cumulative recovery during gas injection process due to the contrast in the capillary pressure of matrix and fractures. A methodology is developed to modify the production well by a high breakthrough capillary pressure skin and by controlling the injection pressure. Consequently, the liquid recovery at the gas breakthrough is significantly enhanced. This flow manipulation prevents the gas pressure to exceed the breakthrough capillary pressure plus pressure drop of the skin. The experiments are conducted in a sintered heterogeneous glass bead model using air-liquid (e.g., water and CMC solutions) systems. Tests are initially performed without the pressure control to obtain the injection pressure at which the gas breakthrough occurs. In the experiments, the gas injection flow rate is reduced to half successively, whenever the gas injection pressure reaches within 10% of the skin breakthrough capillary pressure. We continuously measure the cumulative liquid production weight and the gas injection pressure over time; pictures are continuously captured from the process to track the advancement of air-liquid interface in matrix, fracture, and skin. The effects of flow rate, drainage direction (vertical or horizontal), and fluid viscosity on the process performance are investigated. Without the use of a skin and pressure control, the recovery at breakthrough from the horizontal model is only limited to that from the fracture which is about 9% of the pore volume. The overall recovery increases to more than 90% in the presence of the skin and injection pressure control. The recovery in the vertical gas injection benefits from additional driving force provided by gravity; the recovery factors (RF) as high as 93% are achieved in the vertical drainage tests using the skin, and even without the pressure control. The proposed methodology is successfully tested, implying its promising features such as delayed gas breakthrough in a highly heterogeneous porous medium where fractures interconnect the injection and production wells. This method has potential applications in enhanced oil recovery, remediation of contaminated porous media, and membrane separation processes.

1. Introduction

Naturally fractured reservoirs constitute a major share in worldwide oil production [1]. However, it is challenging to produce hydrocarbons from fractured formations because of the contrast in the permeability and capillary pressure of fractures and matrix. For this reason, the injected fluids can flow into the fracture network, bypassing a major volume of the matrix at the breakthrough. Gravity drainage processes have been proposed as alternatives to the conventional pressure-driven recovery methods for hydrocarbon production from fractured oil formations [2]. In both the pressure- and gravity-driven recovery methods, the flow communication between the matrix and fracture can govern the flow in the fractured porous media. Zendehboudi et al. investigated this flow communication between matrix and fracture systematically, in free-fall and controlled gravity drainage processes, through experimental and theoretical studies [3–7]. They studied the impacts of different parameters and variables such as fracture properties (aperture, length, and orientation), matrix properties (porosity, permeability, and wettability), fluid properties (viscosity and interfacial tension), and process variables (production rate and pressure) on in-situ fluid recovery behavior.

The fracture network (or faults), interconnecting the production and

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injection wells impose additional challenges to the fluid recovery processes. Among all the applications of flow in percolating fractured networks in porous media, the problem of water conning from aquifer to a horizontal well through interconnecting vertical fractures is more extensively investigated in the literature. Polymer gels are proposed for the water cut-off application from inter-well channeling through fractures or faults [8–12]. The gels redirect the flow pathway by blocking the high permeability channels. However, extreme cases of fracture apertures (too narrow or too wide) can limit the use of gels, considerably [11]. The subject of percolation in a fracture network is important due to the damage to the oil recovery upon fracture network percolation, which is studied comprehensively in the literature [13–15].

The processes of immiscible and miscible gas injection in hydrocarbon reservoirs were used for the improved oil recovery for the majority of the past century [16]. The gas injection process is efficient in secondary and tertiary oil recovery processes in fractured formations in which significant residual oil is trapped in the matrix [17]. Researchers have comprehensively investigated important aspects (e.g., production mechanisms and gas/oil/rock interactions) of the gas injection into homogeneous and heterogeneous porous media in processes such as enhanced oil recovery of conventional [18–21] and heavy oil [22–24], CO_2 storage [25–27], and remediation [28–30]. The displacement mechanisms of gas injection into fractured porous media have also been studied through theoretical pore-scale modeling [31–33] and micromodel experiments [34–40].

In this study, a methodology is proposed to improve the recovery from a porous medium with percolating fracture network. Such a medium features early breakthrough of the injected fluid (gas), resulting in low ultimate recovery. This idea is initiated from our previous work on the capillary end-effects in water injection [41], and also from the concept introduced in Dullien et al. patent [42] in which a skin was created at production well to prevent gas breakthrough, and to maximize the oil production upon gas injection. In the current work, a skin is utilized at production well, followed by pressure control through injection flow manipulation. We conduct experiments in a sintered glass bead model with features such as matrix, model-long fracture, and skin. Tests are conducted in horizontal and vertical drainage modes to comprehend the effect of gravity on the recovery performance. The proposed methodology is useful for applications where the maximum recovery is desired. Of potential applications are the recovery of contaminants and toxics from underground (through remediation operations) and selective separation of oil from oily wastewater by functionalized membranes. Our research team is currently working on the application of proposed methodology in oil-water separation by advanced membranes.

2. Experimental aspects

2.1. Test fluids

DI-water (W) and air (A) are used as the wetting and non-wetting phases, respectively. We de-aerate fresh DI-water before each run to avoid the formation of air bubbles (exsolved) in the porous medium. To study the effect of fluid viscosity, Carboxy Methyl Cellulose (CMC) is dissolved in DI water to make 1% and 2% of solutions as the aqueous phase.

The CMC dissolution does not appreciably increase the mixture density. Adding CMC to DI-water also does not change considerably the surface tension; however, it substantially increases the viscosity as observed in Table 1.

Table 1
Test fluids' physical properties.

Fluid	μ (mPa.s)	ρ (g/cm^3)	σ (mN/m)
DI-Water	1.0 ± 0.2	1.00	72.0 ± 0.4
CMC 1% in DI-Water	4.8 ± 0.3	1.05	73.2 ± 0.6
CMC 2% in DI-Water	11.9 ± 0.4	1.07	74.1 ± 0.5

2.2. Porous medium fabrication and characterizaiton

A heterogeneous sintered glass bead model, comprising of three main elements: matrix, fracture, and skin (or barrier) is fabricated as shown in Fig. 1 (top view of the porous model).

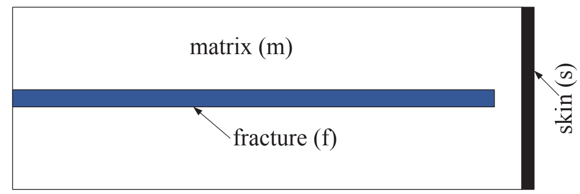

Fig. 1. Schematic of the sintered glass bead model.

A summary of model fabrication procedure is as follows. A 3-mm sheet glass is used for the top and bottom parts of the model. The spacing between the top and bottom plates is also controlled by two 3 mm glass ribbons lightly glued on the top and bottom of the model. After temporarily sealing the sides of the model, the glass beads are packed in the spacing created by 3 mm glass ribbons. The two sides of the model are temporarily sealed with masking tape, and the model is placed horizontally in the high temperature furnace where the temperature is gradually increased to 730 °C in a period of 5 h, then it is allowed to stay at this temperature for 1 h, and finally cooled overnight. Because of the size difference of glass beads BT2, BT4, and BT13, they reach the glass transition temperature at different times. The smaller beads used in skin (BT13) allow the heat transfer to their core much faster and tend to control the sintering process. If the temperature and residence time are more than the optimum values, the BT13 beads will be over-fused, resulting in shrinkage, and consequently loss of sealing in the barrier upon gas injection. If the temperature is less than the optimal value, the larger beads (BT2) will not be fused and will stay loose in the packing.

After the model is sintered, the two sides are cut using a diamond saw and sealed. Holes are drilled on the top plate for the injection and production ports. The properties of glass beads (bead type and average particle size $< d_p >$ in micron), and the dimensions and pore-volume (PV) capacities of each element are summarized in Table 2. A matrix of BT4 glass beads with an average bead size of 506 μm is used. The fracture is simulated by embedding larger glass beads (BT2) with an average particle diameter of 1125 μm in the continuum of BT4 beads. The skin (barrier) is provided as a capillary trap with significantly smaller pore sizes, created by the BT13 glass beads with an average particle diameter of 38 μm. All glass beads are preferentially hydrophilic and no surface modification is performed on the glass beads.

The pore volume of the model is measured by the saturation method. Before saturating the model, acetone is injected into the model, and dried using the vacuum. Then, dry air is injected for a period of 2 h to completely dry the model prior to saturation. The injection and production ports are altered for efficient drying. A 3-way valve is provided at the model inlet. The model outlet is initially

Table 2
Properties of matrix, fracture, and skin in the heterogeneous sintered glass bead model.

Part	Dimensions (cm)		PV (ml)	Beads	$< d_p >$ (μm)
	Length	Width			
Matrix (m)	26.87	9.46	36.4	BT4	506
Fracture (f)	25.48	0.96	3.5	BT2	1125
Skin (s)	1.37	9.46	1.2	BT13	38