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Low temperature air injection with solvents in heavy-oil containing naturally fractured reservoirs: Effects of matrix/fracture properties and temperature on recovery

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A R T I C L E I N F O

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A B S T R A C T

Implementation of in situ combustion process in fractured reservoirs might be risky due to quick breakthrough of unconsumed oxygen to the producers. Recently, we proposed low temperature air–solvent injection (LTASI) as an alternative process to overcome this problem (SPE 149896 and 174542). This process involved oxygen addition reactions (low temperature oxidation) rather than bond scission reactions (in situ combustion). Because increase in matrix oil viscosity is the drawback associated with oxygen addition reactions, reduction of it by adding hydrocarbon solvent into the air injected can be a solution. Determination of optimal application conditions of this kind of expensive and risky process is critically important.

Based on promising results reported in SPE 174542, we conducted new static experiments of air and hydrocarbon solvent injection at low temperature oxidation conditions that complement previous lab studies. Vertically situated sandstone and limestone samples were exposed to air + propane (or butane) mixture under static conditions mimicking huff-and-puff (cyclic injection) type injection. The main purpose was to determine the effect of change in matrix size as well as different matrix/fracture volume ratios on matrix oil recovery. This is important because this method is proposed as a cyclic injection application and the cyclic times are determined by the volume of the fractures, which are to be filled with injected air/propane and the diffusion rate of these gases into matrix.

During the experiments, the gas was injected in the annular space representing a fracture surrounding a heavy oil saturated core at certain pressure and temperature for a certain (soaking) time period. The produced gas and liquid oil were tested in different cycles using a gas chromatograph. The effect of fracture volume, matrix size, and application temperature on the produced fluid composition was studied.

An extensive experimental schedule for static diffusion experiments was accomplished in which the effect of some variables in the oil recovery and oxygen consumption was analyzed. The variables evaluated include rock type (sandstone, limestone), temperature (75, 150, 200 °C), fracture volume, solvent type (C_3, C_4), matrix size (2-in. diameter, 6-in. length; 3.2-in. diameter, 9-in. length), and injection sequences (Air/C_3/Air, C_3/Air/C_3, etc.). A total of 21 experiments were carried out for a comparative analysis and optimal application conditions yielding increased oil recovery and increased oxygen consumption through oxidation reactions in the matrix were determined. These optimal conditions will provide reduced risk due to early breakthrough of unconsumed oxygen and maximized profit, which is needed due to the high cost of propane.

1. Introduction

Although it is not a wide-spread application, field implementation of air injection at high temperature oxidation conditions, namely in situ combustion (ISC), has been successful in heavy oil recovery from non-fractured reservoirs. As one of the longest running cases, the Suplacu de Barcau field (a heavy oil reservoir of unconsolidated sands) is an example of air injection history over 50 years [14]. Field implementation of this kind of enhanced oil recovery (EOR) process in naturally fractured reservoirs is challenging due to its heterogeneous nature. Poor areal distribution of injected fluid and poor combustion efficiency due to fractures are common problems as reported by Craig and Parrish [3]

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Nomenclature

A	total area of core	LTO	low temperature oxidation
C_3	propane, C_3H_8	N_2	nitrogen
C_4	butane, C_4H_{10}	O_2	oxygen
CO	carbon monoxide	RF	recovery factor
CO_2	carbon dioxide	V	volume of core
EOR	enhanced oil recovery	V_f	fracture volume
HTO	high temperature oxidation	V_m	bulk matrix volume
ISC	in situ combustion	V_T	total reactor volume

based on the evaluation of pilot tests. Difficulty controlling the combustion front is another challenge. Alvarez et al. [1] reported this type of problem through a review of air injection pilot tests conducted in a heavy oil vuggy porosity and heavily karsted formation.

A limited number of laboratory studies on ISC process in heavy oil fractured medium (matrix + fractures) have been published. Schulte and de Vries [15] reported that oxygen diffusion into matrix governed the burning process. Stokka et al. [16] reported lab results in cores saturated with light oil and observed that air diffusion has a significant impact on recovery. Numerical simulation studies addressing air injection at high temperature oxidation conditions are also available in the literature. Lacroix et al. [7] demonstrated that gas diffusion into matrix and thermodynamic processes mainly control the global kinetics and the oil oxidation. Stokka et al. [16] numerically showed the importance of diffusion and gravity segregation for the oil production rate.

Air injection at low temperature oxidation (LTO) conditions has also been addressed. Lakatos et al. [8] determined the consequences of the low temperature oxidation experimentally. They observed asphaltene formation in the crude at LTO conditions. Lee and Noureldin [9] reported that the presence of water modified the destructive effect of LTO and both acidity and viscosity of the LTO product decreases when water is present.

Recently, Mayorquin-Ruiz and Babadagli [11] reported on laboratory tests where a heavy oil saturated core was soaked into air/propane gas mixture yields a better recovery than using only air. More promising results were also observed at high temperatures (150 and 200 °C) than at low temperature (75 °C), especially from an oxygen consumption point of view. Mayorquin-Ruiz and Babadagli [10] created a numerical simulation model of air diffusion into a single matrix and obtained diffusion coefficients through matching lab results. They also performed a sensitivity study for different matrix properties and composition of injected gas. Mayorquin-Ruiz et al. [12] modeled the injection of air at LTO conditions in a hypothetical fractured heavy oil reservoir and showed the benefits of solvent when injected alternate to air. They concluded that an optimum production time/soaking time ratio exists for different gas sequences, temperatures, and block sizes. All these efforts indicate that air diffusion into matrix is critically important in the oil recovery and oxygen consumption. This is controlled by matrix properties (lithology, size, and permeability), fracture volume filled with injected gas, cycle (soaking) periods, and temperature. Hence, additional experimental studies are needed for better comprehension of the injection of solvent and air at low temperature oxidation conditions.

2. Statement of the problem

EOR alternatives for commercial exploitation of heavy oil containing fractured reservoirs are limited (especially beyond certain depth). Air injection is an economical option for such reservoirs but it only serves as a cheap pressurizing agent, which may generate a pressure difference between fracture and matrix to drain matrix oil. While this slow process occurs, air is transferred into matrix and oxygenated compounds are generated. Transfer of air into matrix is desired to drain matrix oil and consume the oxygen for safety reasons. However, once oxygen is in contact with oil in the matrix the viscosity of oil increases at low temperatures due to polymerization effect. In order to minimize this negative effect, solvents can be co-injected with air. The solvent reduces not only the viscosity of matrix oil but also the viscosity of the oxygenated compounds. Minimization of solvent requirement for this process is essential due to its high cost.

On the other hand, air injection at high temperature oxidation conditions could be problematic not because of the thermal process itself but because of reservoir heterogeneities (low and high permeability channels), which are characteristics of naturally fractured reservoirs. To overcome these technical difficulties (uncontrollable heat front), low temperature oxidation (LTO) conditions are desired and the process can be applied in the form of cyclic (huff-and-puff) injection. Critical issues emerge for this alternative solution as listed below:

- What is the reservoir temperature at which the injected O_2 could be consumed to the safe levels without creating a large extent of polymerization for particular heavy oil characteristics?
- Could solvent injection be helpful for obtaining additional oil from the matrix and for minimizing the oil viscosity increase related to the generation of oxygenated compounds?
- What are the proper application conditions (amount of injected solvent, soaking time duration, co-injection of air/solvent, alternate air/solvent injection, etc.) at given reservoir conditions for safe limits of oxygen consumption in the matrix?

To answer these questions, a set of experiments were programmed and the results are presented in this research. The main focus is to generate a “single matrix-single fracture” condition with variable characteristics of these two media. In a sense, this study complements the previous attempt presented by Mayorquin-Ruiz and Babadagli [11], which was limited to fixed matrix and fracture size (volume).

3. Experimental procedure

A core saturated with heavy oil sample, at vacuum pressure and 80 °C, was placed into a reactor and the space between the core (matrix) and the reactor wall represented an annular fracture (a simple form of dual porosity media). After introducing a given amount of gas (air, propane or both) into the model, the reactor was left for a soaking period at a certain pressure–temperature. As no fluid was injected (or produced) continuously, the experiments can be categorized as “static”. Once the designed soaking time is reached, the gas was collected first for gas chromatography analysis. Then, the oil accumulated at the reactor bottom was removed and analyzed (density, viscosity, refractive index and