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Field scale numerical modeling of low temperature air injection with propane for heavy-oil recovery from naturally fractured reservoirs

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ABSTRACT

The alternatives for EOR in heavy oil deep fractured reservoirs are limited. Air injection is one of the options but running it in the high temperature mode, namely in-situ combustion, has technical limitations (poor areal distribution of injected air) because of highly heterogeneous characteristics of fractured reservoirs. This may also create a problem from safety point of view, i.e., there is a risk that oxygen is not completely consumed in reservoir reaching production wells quickly without fully consumed. Air, however, can be used as a pressurizing agent to recover matrix oil in the low temperature oxidation mode (LTO) even though it may result in oxidation of oil that forms asphaltenes. Our recent lab results showed that injecting a mixture of air–propane instead of pure air might reduce these negative effects. This enhanced diffusion of air and propane into matrix may also add to recovery. Hence, those lab results opened the window to think of air injection (LTO mode) as a way to produce some of the oil left in the matrix in addition to its pressurizing effect.

In the present study, a single porosity numerical simulation model, with explicit representation of fractures, was developed to analyze the injection of a mixture of gases in a naturally fractured reservoir, involving the use of air in the LTO mode. A sector model of a hypothetical fractured heavy oil reservoir was created and several air–gas injection cases such as pure air, propane–air–propane and air–propane–air cycles were analyzed. The runs were performed using the diffusion data obtained from our previous experimental studies. Different scenarios of huff-and-puff options (cycle type and duration) were tested. Attention was paid to oxygen consumption in the matrix, while fracture to matrix oxygen transfer was mainly due to voidage replacement of oil by air, and some through diffusion of air into matrix during the injection and shut off periods of each cycle.

The results obtained considering various shut in times and injection rates scenarios as well as safety aspects, showed benefits in the use of air in the LTO mode mixed with propane. This optimized air injection scheme could be considered as an alternative to develop naturally fractured heavy oil fields.

1. Introduction

1.1. Problem description

Air injection in light and medium oil reservoirs has been implemented and analyzed for decades in non-fractured reservoirs in two modes: low temperature oxidation (LTO) and high temperature oxidation (HTO). In addition, a limited number of laboratory studies on in-situ combustion in naturally fractured heavy oil reservoirs were documented. For example, Shulte and De Vries [26] showed that diffusion of fracture oxygen into matrix oil governed the burning process; Fatemi et al. [11] reported experimental results of ISC obtained from a model of crushed rock. Awoleke et al. [1] presented experimental results investigating the effects of different scales of porous medium heterogeneity on ISC and concluded that the ISC process was challenged by relatively fast transport of air through high-permeability zones.

The numerical model study performed by the same authors showed that oxygen breakthrough occurred when a critical value in air-injection rate, which was determined by fracture spacing, was exceeded. Experimental studies are needed in the LTO mode

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Nomenclature

A	Arrhenius constant, frequency factor or pre-exponential factor
yr	year
mo	month
C_3	propane
C_m	instantaneous concentration of fuel
CO	carbon monoxide
CO_2	carbon dioxide
E	activation energy
HPDSC	High Pressure Differential Scanning Calorimetry
HTO	high temperature oxidation
k	rate constant
LTO	low temperature oxidation
m, n	reaction orders
NFR	naturally fractured reservoir
N_2	nitrogen
O_2	oxygen
p_{O2}	oxygen partial pressure
R	Universal gas constant
RF	recovery factor
T	temperature
TGA	thermogravimetric analysis

for fractured heavy oil reservoirs in order to understand different aspects of the oil production mechanisms involved in this oxidation mode.

When air injection is considered for enhanced oil recovery in naturally fractured heavy oil reservoirs, it is commonly thought to be a thermal EOR process, referring to air injection at high temperature oxidation conditions, namely in-situ combustion. However, frontal heat displacement may not be possible in naturally fractured reservoirs (NFR) even if the combustion conditions are met. Therefore, the question is whether air at LTO conditions can be injected relying only on oxidation reactions with fracture oil and oil in the matrix after air is transferred into it.

Drawbacks in the use of air at LTO conditions could explain its lack of use in heavy oil reservoirs. For example, air is not an inert, non-reactive, gas; oxygen addition reactions occur when oxygen contacts hydrocarbons from which oxygenated compounds, such as asphaltenes [13] are generated increasing the oil viscosity. However, important benefits are usually disregarded, such as the unlimited availability of air and less cost compared to other fluids (nitrogen); the use of existing gas injection facilities; pressure maintenance; and the substitution for gas produced from the gas cap. Hence, if one can consume all the oxygen through kinetic reactions with oil in the fractures and in the matrix, after oxygen is transferred into it, this process may be a success. At this point, one has to make sure that the negative outcome of the reaction of oxygen in the air with oil (viscosity increase through polymerization) is minimized. Thus, one has to find out under what condition this is overcome and what is the minimal temperature to avoid this outcome. In other words, one need to determine how to minimize the drawbacks of the LTO air injection and determine conditions required for a successful application; conditions under which LTO air injection is not beneficial at all need also be determined.

1.2. Proposed solution

Mayorquin-Ruiz and Babadagli [16] reported the results of experimental studies conducted on heavy oil-saturated sandstone cores (surrounded by an annular fracture) soaked into air–solvent mixtures, also comparing the observations with the extreme cases, i.e., 100% air and 100% solvent. They concluded that a higher recovery factor was obtained by soaking the matrix cores into an air–solvent chamber at static conditions than in pure air. Note that gas was injected into annular fracture up to a certain pressure and the system was shut down for soaking. Thus, this mimics a huff & puff process (cyclic gas injection) and diffusion and gravity drainage are the controlling production mechanism rather than fluid drive. They also observed a lower asphaltene deposition in an air–solvent mixture than in 100% air. Later, Mayorquin-Ruiz and Babadagli [17] matched experimental results by means of one-matrix numerical simulations models which were then used for performing sensitivity analysis to parameters such as air–propane ratio and matrix block size. They found that the lower recovery factor was obtained when using pure air, and the higher when using pure propane, all this at lab size matrix. They concluded that the recovery process is extremely sensitive to matrix block size, especially the vertical length. The numerical simulation model was limited to a one-matrix core and further analysis is required for larger scales in order to capture all the phenomenology of the field scale recovery process.

1.3. Description of the process

The analyzed approach in this paper is a huff-and-puff process on a single matrix block at the field scale. The recovery process consisting of three phases:

Phase-1: Gas (air or solvent) is injected to fill-up the fracture system (i.e. fracture gas saturation = 100%) so that matrix blocks are soaked into gas.
Phase-2: This is a soaking period at static conditions (no fluid production nor fluid injection) during which gas components diffuse into matrix oil and oxygen reacts with it. This is a critical phase for two reasons: (1) proper oxygen consumption is intended to occur thus enough soaking time must elapse in order to reach the lowest oxygen concentration in fluids to be produced in phase-3; and (2) solvent is intended to diffuse in matrix oil and reduce its viscosity.
Phase-3: Both injected gases and gases generated from kinetic reactions are produced back as well as oil expelled from the matrix to the fracture system. Oxygen concentration in produced fluids must comply with safety regulations, to minimize the risk of explosion. Fassihi et al. [10] stated that if oxygen is found in the producers, the flammability limit needs to be compared against its concentration and the flammability limits need to be established experimentally at the pressures experienced in the production well. If found close to the limit, the producer needs to be shut in.

In this work a numerical simulation model with explicit fractures is created and used to study the effect of gas type and production-soaking schemes on recovery factor and oxygen consumption. These studies are intended to clarify the conditions for oxygen to be completely consumed in the reservoir so that it does not reach the producer well unconsumed.

2. Background data

Static diffusion experiments were performed on sandstone heavy oil – saturated cores (2 in diameter, 6 in length) immersed