Effects of water on light oil recovery by air injection

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HIGHLIGHTS

- Air injection for light oil recovery is modeled as a medium temperature oxidation.
- Water has positive effect on oil recovery when oil has boiling point near to water.
- High water/saturation has negative effect if oil has higher boiling point than water.
- A bifurcation-point separates solutions with the steam upstream/downstream of MTO.

ABSTRACT

We formulate a mathematical model for one dimensional flow with chemical reactions resulting from injection of air into a porous medium initially filled with gas, water and volatile oil. Our goal is to investigate the effect of water and steam on oil recovery, and we do so for a medium pressure air injection process. We show that, when the boiling point of the volatile oil is below or slightly above the boiling point of water, the hot steam region moves upstream of the medium temperature oxidation (MTO) wave (where oil vaporization and combustion occur), while the volatile oil and steam condense at the same location; it leads to considerable improvement of oil recovery by the MTO wave. Remarkably, the recovery curves (recovery fraction vs. time) depend weakly on the initial water and light oil saturations. If the volatile oil boiling point is much higher than the boiling point of water, the steam region moves downstream of the MTO wave. In this case the water effect on recovery is weaker and becomes negative for high water saturations. Numerical calculations suggest the existence of an oil boiling point at which a bifurcation occurs that separates solutions with the steam region upstream or downstream of the combustion zone.

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1. Introduction

Air injection leading to in situ combustion is generally considered applicable to recovery of heavy oils because it causes a significant reduction in oil viscosity. However, it can also be used to recover light oils by mechanisms such as combustion gas drive recovery, distillation and thermal expansion. The air injection process usually refers to "high pressure air injection" (HPAI), whereas the term "in situ combustion" traditionally has been used for heavy oil reservoirs. Our interest is in recovering relatively low viscosity oil from low permeability reservoirs that contain initially water and oil, using air injection leading to combustion, vaporization and condensation. Note that air injection can be very effective in heterogeneous light oil reservoirs as the oil evaporates away from low permeability parts to be collected in the higher mobility streaks; this occurs in HPAI (starting at ∼100 bars), for which there is a large body of literature [3,18,19,40,43,44,54], including a field example [29]. De Zwart et al. [22] conclude that air injection cannot be modeled solely as a flue gas displacement process because disregarding combustion leads to an underestimate of the recovery efficiency. HPAI is confined to reservoirs at large depths. However, at shallower depths, an alternative is to inject air at medium pressures (∼10–90 bars) in light and medium oil reservoirs, where thermal aspects play an important role. The combustion process at medium pressures is characterized by medium temperature oxidation (MTO) wave. In this wave all physical processes, reaction, vaporization, condensation and filtration are active. The name of the wave comes from the fact that the maximum temperature is bounded by liquid boiling temperature at elevated pressure and, thus, cannot be very high.

Nomenclature

A_r	MTO reaction pre-exponential factor, 1/s
α	oleic (o), aqueous (w) and gaseous (g) phase
c_α	heat capacity of phase α (o, w, g), J/(mol K)
C_m	heat capacity of porous matrix, J/(m³ K)
D_g	gas diffusion coefficient, m²/s
k	rock permeability, m²
$k_{r\alpha}$	relative permeability of phase α
n	MTO reaction order with respect to oxygen
P_α	pressure of phase α, Pa
P_{res}	reservoir pressure, Pa
Q_r	MTO reaction enthalpy per mole of oxygen at reservoir temperature, J/mol
Q_{vh}, Q_{vw}	oil and water vaporization heat at reservoir temperature, J/mol
R	ideal gas constant, J/(mol K)
s_α	saturations of phase α
s_o^{ini}, s_w^{ini}	initial saturations of oil and water phase
T	temperature, K
T^{nh}, T^{nw}	normal boiling temperature of oil and water at atmospheric pressure, K

T^{ini}	initial reservoir temperature, K
T^{ac}	MTO activation temperature, K
u_α	Darcy velocity of phase α, m/s
u_{gj}	Darcy velocity of component $j = h, \kappa, w, r$ in gas phase, m/s
u_{inj}	Darcy velocity of injected gas, m/s
W_r	MTO reaction rate, mol/(m³ s)
W_{vh}, W_{vw}	vaporization rate for hydrocarbon and water, mol/(m³ s)
x, t	spatial coordinate, m, and time, s
Y_h, Y_κ, Y_w, Y_r	gas molar fractions: hydrocarbons, oxygen, steam, remaining components, mol/mol
Y_κ^{inj}	oxygen fraction in injected gas
φ	porosity
κ_h, κ_w	phase transfer parameters, s⁻¹
λ	thermal conductivity of porous medium, W/(m K)
μ_α	viscosity of phase α, Pa s
v_l, v_g	stoichiometric coefficients in the MTO reaction
ρ_α	molar density of phase α, mol/m³

The mechanism actually responsible for oil displacement in the combustion process varies with the type of oil. In summary, we have high temperature oxidation (HTO) [45,46], in which cracking occurs forming coke, which is subsequently oxidized at high temperatures; low temperature oxidation (LTO), in which the oxygen is adsorbed or incorporated by the hydrocarbon molecules to form alcohols, aldehydes, acids or other oxygenated hydrocarbons [31,32,35,39]; and medium temperature oxidation (MTO) [27,32,33], when the oxidation reaction leads to scission of the molecules into small reaction products such as water, CO or CO_2.

A number of conceptual combustion models describing in situ combustion have been studied theoretically and experimentally in the past [1,3,8,12,16,18,19,24,40,43,44,55,54]. Most of the models assume liquid phase or coke combustion as the source of energy to sustain in situ combustion and high temperature oxidation. There are also papers that focus on numerical simulation of the combustion process [2,5,6,21,28,30,41,44,56].

It is the purpose of this paper to study the relative importance of vaporization/oxidation of light oil versus the vaporization/condensation of water in an MTO air injection process [1,16] in 1-D porous rock. Some aspects such as 2-D heterogeneity, layer thickness, the permeability contrast and heat losses can be important in ignition and extinction [4,7], but they will be kept for future work. Some HPAI projects are planned or already carried out in water flooded reservoirs [20,23,34,49]. Barzin et al. [11] observed higher fuel deposition when initial water was absent during ramped temperature experiments with light oil in combination with high flux air injection. Pascual et al. [49] performed a high pressure tube test using light crude oil to simulate the LTO process performed after waterflood of a light oil reservoir, in which the process sustained a stable front at a temperature of 250 °C. They showed that reservoir oil had excellent burning characteristics, which made the process technically feasible. When thermal losses through the rock are much higher than the heat provided by the oxidation reactions at reservoir temperature, or if the heat released by the oil is not sufficient to increase the temperature significantly (for instance in presence of large quantities of water), the oxidation reaction occurs at temperatures not far from the initial reservoir temperature [20]. In this case, oxidation reactions are slow and can be incomplete. Less carbon oxide (CO_2 or CO) is generated than in the absence of water. In this case, oxygen consumption occurs in a larger reservoir zone; the size of which depends on the oil reactivity [31] but extinction can also occur [46].

The presence of water and oil that are both mobile and can vaporize or condense represent a challenge for numerical modeling of the combustion process. Because the MTO process has been mainly studied theoretically and numerically in the absence of water in [37,38,47], it is essential that the current understanding of oxidation/vaporization/condensation mechanisms in the MTO wave is improved by studying a simple three phase model involving water, gas and a single pseudo-component oil (e.g., heptane, pentane or dodecane) in porous rock. Such oil is characterized by an average boiling temperature, density and viscosity. We assume that the oil vaporizes/condenses and reacts with oxygen, whereas water only vaporizes and condenses.

The paper is organized as follows. Section 1 describes the physical model and presents governing equations. Section 2 describes analytical and numerical solutions when water was not present initially and originated from oxidation reactions. In Section 3, the numerical solutions with several sets of conditions for the oil with different boiling temperatures in the presence of initial water are presented. Different mechanisms caused by steam condensation/vaporization are analyzed. Section 4 describes the recovery curves. We end with some conclusions.

2. Model

We study a three-phase flow problem (gas, oil and water) involving a combustion front when air is injected into thermally isolated porous rock filled with light oil and water. In this paper, we summarize the reaction process by the following reaction equation:

$$v_l \text{ (hydrocarbons)} + O_2 \rightarrow v_w \text{ (H}_2\text{O)} + v_g \text{ (other gaseous products)}, \quad (1.1)$$
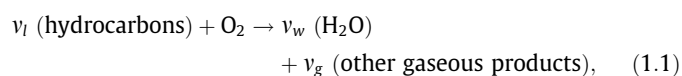
i.e., one mole of oxygen reacts with v_l moles of initial (liquid) hydrocarbons generating v_w moles of water in vapor phase and v_g moles of gaseous products (CO, CO_2, etc.). This reaction equation is an abbreviated form of a number of intermediate reactions leading to complete scission of hydrocarbon molecules (medium temperature oxidation). We disregard gas-phase reactions, though