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A feasibility study of thermal stimulation in unconventional shale reservoirs

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ABSTRACT

Shale oil production from plays such as the Bakken and Eagle Ford, driven by advances in horizontal well drilling and hydraulic fracturing technology, has helped improve US domestic oil production. However, due to the low permeability of shale oil reservoirs, primary depletion only produces 5–10% of the original oil in place and there is a huge potential for improved recovery. Chemical and gas huff-n-puff have been piloted with varying degrees of success, but no breakthrough recovery method has been discovered.

This study examines improved oil recovery from shale reservoirs by thermal stimulation, consisting of primary depletion (early in a well's life), followed by conversion of the well to a heat injector to elevate reservoir temperature, and finally followed by a secondary depletion. The proposed method was tested using a compositional, thermal reservoir simulator (CMG STARS) and key parameters affecting recovery during thermal stimulation were investigated.

This study found that 1000 days of thermal stimulation with a 700 °F heater has the potential to economically increase oil recovery from about 7% to more than 11.5%, with potential for even greater recovery if heat injection time and temperature are optimized. The study also found that thermal pressurization of oil is the primary mechanism for the improved recovery. Kerogen decomposition into oil and gas results in a significant increase of hydrocarbons in place but is only a minor contribution to the additional recovery because production is limited by a lack of flow capacity. Furthermore, a two-fold increase in permeability is observed as a result of kerogen decomposition, but its contribution to recovery is also minor because the heated region is not well connected with the fractured region. The heating scheme may be improved in the future to better connect the heated region with the fractured region.

1. Introduction

Over the past decade, US production of oil and natural gas has increased rapidly. Oil production in 2015 was the highest in the US since the 1970s and natural gas production reached an all-time high (U.S. EIA, 2015). Recent growth in oil and gas production can be attributed to increased development of unconventional resources, particularly from shale oil and gas reservoirs; advances in drilling and hydraulic fracturing technology have provided access to oil and gas in these extremely low permeability reservoirs, previously considered uneconomic. Shale oil production increased from less than 1 MMBPD between 2002 and 2011 to 4.5 MMBPD (almost half of total US oil production) in 2015 (U.S. EIA, 2016a).

Economic production from shale oil reservoirs such as the Bakken, which extends across Montana and North Dakota, and the Eagle Ford in Texas, is accomplished by drilling long lateral horizontal wells with several stages of hydraulic fractures. However, because of the steep production decline behavior of hydraulically fractured wells (75% 2-

year well decline rate) (Adekunle and Hoffman, 2014), primary depletion produces only 5–10% of the total oil in place, necessitating enhanced oil recovery methods to increase production (Shoaib and Hoffman, 2009). Chemical and gas (produced gas or CO₂) huff-n-puff have been used to increase shale oil production with varying degrees of success (Shuler et al., 2011; Yu et al., 2014).

Here, we propose a novel approach to increase oil recovery from shale oil reservoirs by thermal stimulation. Traditional thermal recovery for heavy oil reservoirs involves cyclic steam injection (Prats, 1982), steam flooding (Hoffman, 2003), steam-assisted gravity drainage (Butler and Stephens, 1981) or in-situ combustion (Coats, 1980). Downhole heaters (electrical or electromagnetic) have also been tested to increase oil temperature, consequently reducing oil viscosity, vaporizing volatile components of the oil and improving recovery (Hascakir et al., 2010). Steam assisted heating processes are better suited for shallow and thick reservoirs because the heat loss from the wellbore and to the over/under burden is limited. If the reservoir depth is greater than about 4000 ft. (such as the shale reservoirs studied

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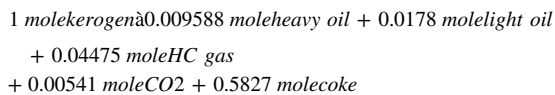
here), heat loss from the wellbore makes injection of steam from the surface uneconomical. It is possible to use down-hole steam generators for deeper reservoirs, but these generators are not commonly used because of high maintenance costs and combustion control problems downhole (Singh et al., 1988). Furthermore, as depth increases, the reservoir pressure increases and the latent heat of the steam decreases. Thus, steam processes are typically not applied to deep reservoirs. Air injection has been tested for heavy and light oil reservoirs, but the main challenge is the control of the flood front (Greaves et al., 2012). Downhole heating and air injection can be considered for deep reservoirs like shale oils.

Thermal stimulation has been used in oil shales, i.e. fine-grained rock containing significant amounts of an organic substance called kerogen, to produce oil and gas (Lee et al., 2016). Kerogen is a solid mixture of organic matter that is converted to oil and gas when exposed to high pressure and temperature during burial of its source rock; in cases where pressure and temperature are insufficient, the kerogen remains as part of the source rock and can be mined if shallow or converted to oil in the ground by injecting heat. In-situ heating at about 650 °F converts the kerogen to oil and gas that can be produced by conventional means (Fowler and Vinegar, 2009). The shale oil reservoirs studied here (Bakken and Eagle Ford) contain a small amount of kerogen – less than 10 wt% compared to greater than 20 wt% for typical oil shales (Vernik and Nur, 1990). The oil in these extremely low permeability reservoirs is also significantly less viscous (0.1 – 1 cp) than the heavy oil reservoirs (> 1000 cp) where thermal recovery is typically applied.

We utilize a compositional, thermal reservoir simulator to test the hypothesis that shale oil recovery can be increased significantly by thermal stimulation. Four potential mechanisms for thermal improved recovery are proposed. First, solid kerogen in the rock matrix can be converted through a series of chemical reactions into oil and gas at elevated reservoir temperatures, which increases oil in place. Second, matrix porosity and permeability can increase as some of the rock grain volume (i.e. kerogen) is converted to fluid pore volume. Third, reduction in oil viscosity at elevated temperatures may aid recovery. Finally, heating of the oil may result in increased reservoir pore pressure which may lead to increased production. It is presumed here that the energy for thermal stimulation can be delivered at the bottomhole without significant energy loss. We propose high frequency electromagnetic (microwave) heating at the wellbore, instead of steam or hot water injection. Microwave energy is introduced into the reservoir from a radiating element located in the horizontal section of the wellbore; this energy is converted into heat within the formation through the adsorption of electromagnetic energy by connate water in the formation (Carrizales et al., 2010). The same well is used for both production and heating; there is no production from the well during heating.

2. Model development

A reservoir model for a typical shale oil reservoir, consisting of a fluid characterization and a computational domain definition, was developed for this study. Thermal stimulation of shale oil reservoirs was simulated in CMG STARS, incorporating mass transport, heat transfer, phase equilibrium at elevated temperatures and reaction kinetics for the following kerogen decomposition reaction (Fan et al., 2010):



The kerogen and coke are considered components of the organic solid phase, heavy oil is considered the C30+ component of the oil, light oil consists of C7–C29 components and HC gas stands for the methane

in this work.

2.1. Governing equations

The mass balance equation in compositional simulations can be expressed for each fluid component i and for each organic solid component s (either kerogen or coke) as follows (Fan et al., 2010):

$$\frac{\partial}{\partial t} \left(\phi \sum_j S_j \rho_j X_{ij} \right) - \sum_j (a_{ij} - b_{ij})r + \nabla \cdot \sum_j \rho_j X_{ij} u_j + \sum_j \rho_j X_{ij} q_j = 0 \quad (1)$$

$$\frac{\partial C_s}{\partial t} - (a_s - b_s)r = 0 \quad (2)$$

where ϕ is reservoir porosity, S_j is the saturation of phase j , ρ_j is the molar density of phase j , X_{ij} is the mole fraction of component i in phase j , a_{ij} and a_s are product stoichiometric coefficients for component i in phase j and for organic solid component s , respectively, b_{ij} and b_s are reactant stoichiometric coefficients for component i in phase j and for organic solid component s , respectively, q_j is the rate of phase j as source/sink, C_s is the organic solid concentration, r is reaction rate. Velocity u_j is computed by Darcy's law:

$$u_j = -\mathbf{K} \frac{k_{rj}}{\mu_j} (\nabla P_j + \rho_j g z) \quad (3)$$

where \mathbf{K} is permeability tensor, k_{rj} is relative permeability of phase j , μ_j is viscosity of phase j , g is the gravitational constant ($g=32 \text{ ft/s}^2$), z is reservoir depth and P_j is phase j pressure. The first group of terms in Eq. (1) accounts for mass accumulation, while the other groups of terms represent mass change in each phase resulting from the reaction, mass flow and well source/sink. The first term in Eq. (2) represents the change in organic solid component (e.g., kerogen) concentration, while the second group of terms accounts for mass evolved/consumed during the reaction. The mass of each component evolved or consumed during the reaction is governed by reaction rate (r) expressed as (Fan et al., 2010):

$$r = A e^{-\frac{E_a}{k_b T}} \prod_{ij} C_{ij}^{b_{ij}} \prod_s C_s^{b_s} \quad (4)$$

where A is frequency factor, E_a is activation energy, k_b is the Boltzmann constant and C_{ij} is the concentration of component i in phase j . The kerogen decomposition reaction converts organic solid reactants into fluid products, increasing pore volume and consequently, permeability. Eq. (5) below relates porosity to the change in kerogen concentration with time, while the Carmen-Kozeny equation (Eq. (6)) relates rock permeability to changing fluid porosity.

$$\phi^{n+1} = \frac{\partial C_s}{\partial t} \frac{1}{\rho_s} + \phi^n \quad (5)$$

$$K^{n+1} = K^n \left(\frac{\phi^{n+1}}{\phi^n} \right)^{ck} \left(\frac{1 - \phi^n}{1 - \phi^{n+1}} \right)^2 \quad (6)$$

where ρ_s is solid density, superscript n is a time marker and ck is the Carmen-Kozeny coefficient, which we assume to be 0.95 in this study.

As a result of the temperature dependence of phase density, composition and reaction rate, the mass balance equation is coupled with the energy balance equation given by (Fan et al., 2010):

$$\frac{\partial}{\partial t} \left[\phi \left(\sum_j U_j \rho_j S_j \right) + (1 - \phi) U_r \right] - \nabla \cdot \left(\sum_j H_j \rho_j u_j \right) - \nabla \cdot (\kappa \nabla T) + \sum_j H_j \rho_j q_j \\ + q_h = 0 \quad (7)$$

where U_j and U_r are the internal energies of phase j and the rock respectively, H_j is the enthalpy of phase j , κ is thermal conductivity, T is temperature and q_h is heat input/output from a well. The first group of terms in Eq. (7) represents energy accumulation, the second and third

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