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Displacement front stability of steam injection into high porosity diatomite rock

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Abstract

Steamflood displacement in porous media is considered to be stable, as compared to other gas-flooding techniques. Stability on the microscopic and core scale lends stability to steam movement on the reservoir scale. Initial aspects of this work use analytical methods to examine frontal stability in high-porosity rocks. Analytical methods indicate stable steam fronts for typical reservoir properties, but they also predict unstable displacement in high-porosity rock. The second portion of this work uses pattern level thermal simulation to study the stability of steam drives in high-porosity rocks. Two different permeability models (an isotropic model and a thief model) are compared at three average porosities (25%, 50% and 70%). Small thermal conductivities are shown to induce the formation of the steam fingers. More importantly, the simulation results show that as the rock porosity increases, steamfront stability decreases. This is exemplified by earlier breakthrough times for models that have greater average porosity. While the stability of a steam front does decrease, analysis indicates that the difference is likely not significant, around a 20% reduction in breakthrough time, compared to other aspects. For example, reservoir heterogeneity has a much greater impact on breakthrough time than does the relatively unstable displacement front associated with high-porosity rock.

Keywords: Displacement stability; Steam injection; Diatomite; Thermal recovery

1. Introduction

An unstable displacement occurs when an injected fluid bypasses a portion of the in situ fluid that it is trying to displace. This often occurs when a fluid of high mobility displaces a fluid of lower mobility. Therefore, a highly mobile gas such as steam would not, at first, appear to be an effective agent for recovering viscous crude oils. The condensable nature of steam, however, provides a self-stabilizing effect. As an unstable extension of the steam displacement front begins to move into the colder reservoir, heat dissipates from the extension to the reservoir. With loss of heat, the steam condenses to water and the

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displacement front is stabilized (Farouq Ali, 1982; Burger et al., 1985). The rate of heat dissipation from the finger is a function of the thermal conductivity, the volumetric heat capacity of the system, and the temperature difference between the steam and the reservoir.

The fraction of solid per unit bulk volume of rock has a major impact on both the thermal conductivity and volumetric heat capacity. The rock usually has the greatest thermal conductivity, in comparison to fluids in the pore space, and is able to transfer significant heat from the unstable steam finger. Therefore, there is concern that this self-stabilizing effect is not apparent in high-porosity rocks. One particular class of high-porosity reservoirs, diatomite, is considered in detail. Although the current work is based on diatomite, it is applicable to any high-porosity rock.

Because diatomite is used for the study, some background on the rock type is provided. Pure diatomite is a hydrous form of silica composed almost entirely of the skeletal remains of unicellular aquatic organisms called diatoms. These skeletal remains collect at the sea bottom along with silts, sands and mud. A general observation is that the fewer the impurities in the rock, the greater the porosity and permeability. Porosity ranges from 25% for silty diatomite to 65% for clean diatomite (Schwartz, 1988). An interesting property of diatomite is that it has high porosity, but unfortunately, its permeability is extremely low, ranging from 0.01 to 10 md. This is due to the extremely small size of the diatoms and diatom fragments. Another important feature is high pore-volume rock compressibility (Diabira et al., 2001), yet some formations may contain a network of more permeable natural fractures or fracture-like pathways. This apparent inconsistency is because of the brittle nature of diatomite when it encounters non-compressive loads. These fracture-like pathways are relevant to fluid flow and oil recovery in diatomite reservoirs. Typical diatomite reservoirs consist of many alternating diatomite/shale intervals where the separate productive layers are only connected through the wellbore.

Both analytical and simulation methods are utilized to understand better steamflooding high-porosity reservoirs that contain hydrocarbons. The analytical techniques are discussed first, and then a more in depth simulation study is covered.

2. Analytical

Published analytical methods (Burger et al., 1985; Miller, 1975; Yortsos, 1984) are available to determine the conditions for stable steam-oil displacement. In general, these methods relate steam front stability to rock and fluid properties.

The first method, described by Burger et al. (1985), determines steam front stability by comparing the mobility of displacing and displaced fluids. The expression begins with the Darcy-law mobility divided by the advance rate for the displaced fluid. This term is divided by the mobility upon the advance rate for the displacing fluid:

$$\frac{\dfrac{k_{rw}}{\mu_{\mathrm{w}} \cdot V_{\mathrm{w}}}}{\dfrac{k_{rs}}{\mu_{\mathrm{s}} \cdot V_{\mathrm{s}}}} > 1 \tag{1}$$

where $k_{i\mathrm{r}}$ is relative permeability, μ_i is viscosity, V_i is advance rate, and the subscripts w and s stand for water and steam phases, respectively. Eq. (1) is a statement of the pressure gradient in the steam phase upon that in the water phase. If the result from Eq. (1) is greater than 1, then the process is indicated to be stable. Upon assumption that the relative permeability for the displacing fluid is approximately equal to that of the displaced fluid, useful information is drawn from

$$\frac{\mu_{\mathrm{s}} V_{\mathrm{s}}}{\mu_{\mathrm{w}} V_{\mathrm{w}}} > 1 \tag{2}$$

Burger et al. (1985) presented an expression to calculate advance rates, V_i, as displayed in Eq. (3).

$$V_i = 1 + \frac{1-\phi}{\phi} \frac{c_{\mathrm{v}}(T_{\mathrm{s}} - T_{\mathrm{r}})}{\rho_{\mathrm{i,Ti}}\left(H_{\mathrm{s,Ts}} - H_{\mathrm{w,Tr}}\right)} \tag{3}$$

where ϕ is porosity, c_{v} is average heat capacity per unit volume of the rock matrix, T_{s} is steam temperature, T_{r} is reservoir temperature, $H_{\mathrm{s,Ts}}$ is steam vapor enthalpy at steam temperature, $H_{\mathrm{w,Tr}}$ is the liquid water enthalpy at reservoir temperature, and $\rho_{\mathrm{i,Ti}}$ is