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Upscale methodology for gas huff-n-puff process in shale oil reservoirs

Lei Li, James J. Sheng*

Texas Tech University, Lubbock, TX, USA

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ABSTRACT

Results of recent laboratory experiment studies suggest that huff-n-puff gas injection holds great potential to increase oil recovery from shale oil cores. However, our current knowledge of the field-scale performance of this process is very limited. Reservoir simulation is required to properly upscale this process from laboratory to field conditions in order to predict oil recovery and reduce the risk of failure in field projects.

After examining the literature, the purpose of all upscale methods is to generate a single curve which can describe the relationship of oil recovery versus dimensionless time for different scales. For a gas huff-n-puff process applied in a shale oil reservoir, it is also necessary to generate one single type curve to upscale a lab experiment to field-scale production. In this paper a new expression of dimensionless pressure was generated to describe the huff-n-puff efficiency, and a new version of dimensionless time was also derived that includes dimensionless pressure, permeability, porosity, viscosity, and core length. A compositional numerical model with dynamic gridding was built and validated by matching the experimental data, and the model was then used to test the upscale methodology. Several validation tests were conducted for different fluid and rock parameters, well constraints, and operation schedules. To this end, a type curve was developed for different scales which demonstrates that all sizes yield a similar relationship between oil recovery and dimensionless operation time. It proves that the cumulative oil recovery of gas huff-n-puff EOR in shale oil reservoirs can be predicted. In a case of high-permeability, the curve between oil recovery and dimensionless time deviates from the type curve (moves to the right side). This indicates huff and puff times are too long, and the process is inefficient. In this case, the huff and puff times can be reduced so that the curve follows the generated type curve.

1. Introduction

Huff-n-puff gas injection to enhance oil recovery in conventional reservoirs has been studied in laboratory and tested in field (Sheng, 2015). The main mechanisms are the miscibility of injected gas with in situ oil so that oil viscosity is reduced and oil may swell, and pressure drive resulting from gas injection. In recent years, the gas huff-n-puff method has been demonstrated to improve oil recovery in shale oil and condensate reservoirs, and it has also been proven effective in our experimental studies (Gamadi et al., 2013, 2014; Yu and Sheng, 2015; Meng et al., 2015; Li et al., 2015; Wan et al., 2015; Meng and Sheng, 2016a) and simulation studies (Wan et al., 2013; Sheng, 2015; Wan and Sheng, 2015a, 2015b; Sheng et al., 2016; Meng and Sheng, 2016b; Wan et al., 2016). Sheng and Chen (2014) show that owing to ultra-low permeability in shale reservoirs, it is very difficult for gas and pressure propagate from an injector to a producer, therefore, gas huff-n-puff is superior to gas flooding. In terms of field application, huff-n-puff gas injection was not widely used in conventional reservoirs. In shale and tight reservoirs, huff-n-puff gas injection has been tried several fields. However, the detailed results were not reported in the literature. CO_2 huff-n-puff injection was conducted in the Bakken formation in the areas of North Dakota (Hoffman and Evans, 2016) and Montana (Sorensen and Hamling, 2016). However, the tests did showed significant oil increase.

In our previous work (Li et al., 2015), we conducted a series of experiments to test the core diameter size effect on oil recovery in laboratory conditions. The core diameters varied from 1 to 4 in.. The results illustrated that cores with bigger diameters yield a lower oil recovery in the same huff-n-puff cycle under the same operation conditions. That means we need to modify the operation conditions, such as by enlarging the huff and puff time to obtain cost-effective oil recovery in a field-scale operation. Previous work of upscaling from lab-scale to field-scale focused upon conventional reservoir studies. Geertsma et al. (1956) derived dimensionless variable groups which govern the displacement of oil in reservoirs by liquids using dimensionless analysis and inspectional analysis. They provided a complete list of dimensionless groups which are useful to design experiments in laboratory. But the list is so long that it is very difficult to use these

* Corresponding author.
E-mail address: james.sheng@ttu.edu (J.J. Sheng).

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Nomenclature

c	constant, the ratio of the gravity force to the capillary force
C	constant in dimensionless time in this study, 0.000264
c_t	the coefficient of volume compressibility, 1/psi
k	absolute permeability, mD
k_e*	effective permeability of the two phases at S_{wf}, mD
L	the characteristic length in Eq. (1) and Eq. (15), ft
L_a	the characteristic length in Eq. (6) and Eq. (7), ft
L_c	the characteristic length in Eq. (3), ft
L_f	half fracture length in Eq. (5), ft
P_c	capillary pressure, psi
P_e*	capillary pressure at S_{wf}, psi
P_D	dimensionless pressure
P_{max}	the maximum matrix average pressure in one cycle, psi
P_{avg}	the matrix average pressure at any time, psi
P_{huff}	huff process efficiency
P_{puff}	puff process efficiency
R	recovery by spontaneous water imbibition
R*	normalized oil recovery
RF	Oil recovery factor in Eqs. (12)–(14).
S_{wf}	water saturation behind imbibition front
S_{wi}	initial water saturation
t	time, hours
t_{Huff}	huff time, days
t_{Puff}	puff time, days
t_D	dimensionless time
μ_e	the effective viscosity of the two phases (but considered as one phase), cp
μ_o	viscosity of oil, cp
μ_w	viscosity of water, cp
$\varnothing$	porosity
σ	interfacial tension, psi·ft
θ	contact angle, °

groups in a practical design. Similarly, Thomas et al. (1997) derived scaling criteria for micellar flooding. Their derivations were based upon six three-phase components which flow in a porous medium.

Li and Lake (1995) developed scaling dimensionless groups for fluid flow through heterogeneous porous media. Wood et al. (2006) first presented the scaling groups to describe CO_2 flooding for a typical line-drive pattern, and then used these groups in a Box-Behnken experimental design to create a screening model most applicable to a Gulf Coast reservoirs. Handy (1960) derived an equation to predict water imbibition behavior so that the recovery increases with the square root of imbibition time under the assumption that water displaces air in a piston-like manner. Mattax and Kyte (1962) proposed an upscale equation of oil recovery vs. dimensionless time for spontaneous imbibition under the condition of using the same core sample shapes, relative permeability functions, and boundary conditions. The fluid viscosity ratios and initial fluid distributions are duplicated. And the gravity effect is neglected. They derived the following equation of dimensionless time to upscale the oil recovery behavior.

$$t = \sqrt{\frac{k}{\varnothing}}\frac{\sigma}{\mu_w L^2} \tag{1}$$

$$t_{\substack{matrix\\block}} = t_{model}\frac{\left(\sqrt{\frac{k}{\varnothing}}\frac{\sigma}{\mu_w L^2}\right)_{model}}{\left(\sqrt{\frac{k}{\varnothing}}\frac{\sigma}{\mu_w L^2}\right)_{\substack{matrix\\block}}} \tag{2}$$

where t is dimensionless time; k is rock permeability; $\varnothing$ is porosity; σ is interfacial tension; μ_w is water viscosity; and L is the characteristic liner dimension of the block.

Ma et al. (1995) improved Mattax and Kyte's equation by suggesting a new definition of dimensionless time [Eq. (3)], and they claimed this improved equation fit with different porous media, core dimensions, boundary conditions, and oil and water viscosity. Their equation is also applied to spontaneous imbibition. Basically they modified the characteristic length and viscosity term based on Mattax and Kyte's equation.

$$t_D = t\sqrt{\frac{k}{\varnothing}}\frac{\sigma}{\sqrt{\mu_w \mu_o}L_c^2} \quad , \; L_c = \sqrt{\frac{V}{\sum_{i=1}^{n}\frac{A_i}{X_{Ai}}}} \tag{3}$$

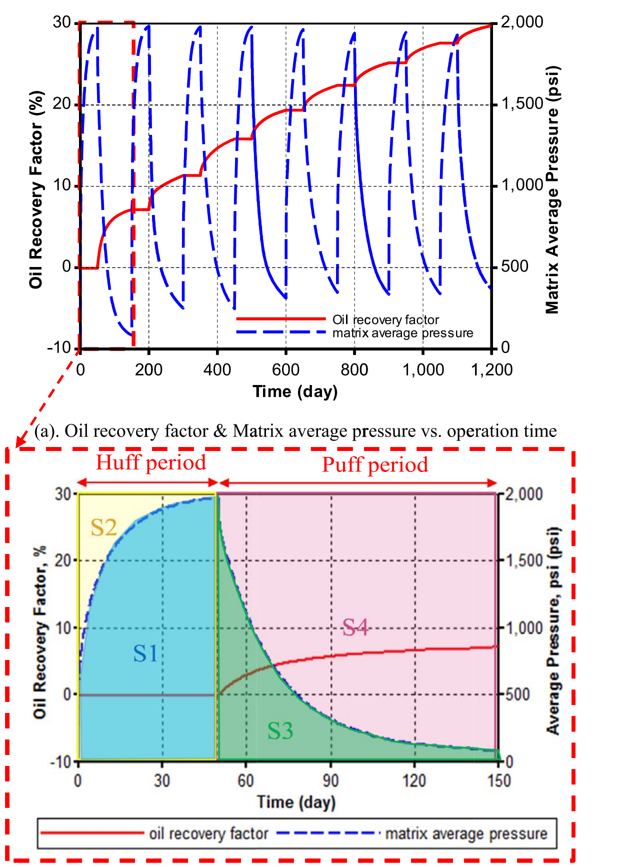
where t_D is dimensionless time; t is time; k is rock permeability; $\varnothing$ is porosity; σ is interfacial tension; μ_w and μ_o are water and oil viscosities; θ is the contact angle; L_c is the characteristic length; V is the bulk volume; X is the distance from imbibition surface to no-flow boundary; and A_i is the i$^{\text{th}}$ surface.

A classical type curve is the Gringarten type curve for well testing in fractured wells proposed by Gringarten et al. (1979). They defined two dimensionless parameters written as shown in Eqs. (4) and (5).

$$P_D = \frac{kh}{141.\,2quB}(P_i - P_{wf}) \tag{4}$$

$$t_D = \frac{0.\,000264kt}{\varnothing \mu c_t L_f^2} \tag{5}$$

where t_D is dimensionless time; t is time; k is rock permeability; $\varnothing$ is porosity; μ is fluid viscosity; B is the oil volume factor; q is the oil



(a). Oil recovery factor & Matrix average pressure vs. operation time

(b). Oil recovery factor & Matrix average pressure vs. operation time in the first cycle

Fig. 1. Oil recovery factor, average pressure change during huff-n-puff cycle.