Fuel 194 (2017) 129–143

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

Capillarity characters measurement and effects analysis in different permeability formations during waterflooding

Ying Li [a,b,*], Haitao Li [a,*], Shengnan Chen [b,*], Ernest Mbia [b], Ke Wang [a], Houlin Ren [c]

[a] State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu 610500, China
[b] Department of Chemical and Petroleum Engineering, Schulich School of Engineering, University of Calgary, Calgary T2N 1N4, Canada
[c] Sinopec Group Southwest Oil and Gas Branch Company, Guangxi Oil Production Plant, Deyang 618100, China

HIGHLIGHTS

- Both static and dynamic capillarity characters are examined experimentally.
- Sensitivity analysis in different permeability cases are performed.
- The underlying mechanism of capillarity in production is explored.
- A method to clarify the condition where dynamic capillarity should be considered.

ARTICLE INFO

Article history:
Received 29 September 2016
Received in revised form 22 November 2016
Accepted 24 December 2016
Available online 9 January 2017

Keywords:
Dynamic capillarity
Different permeability
Waterflooding
Effect
Numerical simulations

ABSTRACT

In the description of multiphase flow in porous media, dynamic capillarity is typically ignored. While some studies suggest that dynamic capillarity can be ignored in high permeability rock, it cannot be overlooked in low permeability rock. In this work, dynamic capillarity, in various permeability formations, was investigated through specially designed experiments and the impact on field production is simulated. First, capillarity characters (capillary pressure-saturation relationships and relative permeability curves) were obtained during the static and dynamic waterflooding process conducted in different permeability core samples under in-situ reservoir conditions. The dynamic coefficients were calculated locally and compared. Then experimental results were subjected to sensitivity analyses, through numerical simulation studies using CMG (IMEX), to determine the dynamic capillary effects on different permeability cases. The results show that (a) a low permeability formation constitutes a much larger dynamic coefficient, thus resulting in a significant difference between dynamic and static capillary pressures; (b) the lower the rock permeability, the larger the difference between static and dynamic relative permeability curves; (c) the dynamic capillary pressure in low permeability formations, compared with static capillary pressure, can be notably large, causing irregular differences in phase behavior and pressure distribution. This work demonstrates the importance of considering dynamic capillarity in low permeability reservoirs.

1. Introduction

In reservoir engineering, capillarity affects the fluid distribution and flow mechanism in porous media. Capillarity characters, as referenced in this work, include the capillary pressure-fluid saturation relationship and relative permeability curves. These characters are the main characters affecting the oil recovery of waterflooding and are, in turn, affected by multiple factors, including wettability, interfacial tension, particle size and distribution [1–3].

1.1. Static and dynamic capillarity characters

Early in 1945, Hassler and Brunner [4] began to examine the relationship between capillary pressure (P_c) and wetting phase saturation (S_w). Numerious researchers measure this relationship under static conditions [5–7], where fluid flow has completely

---

* Corresponding authors at: State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu 610500, China (Y. Li and Haitao Li); Department of Chemical and Petroleum Engineering, Schulich School of Engineering, University of Calgary, Calgary T2N 1N4, Canada (Shengnan Chen).

E-mail addresses: yingingli@163.com (Y. Li), lihaitao@swpu.edu.cn (H. Li), snchen@ucalgary.ca (S. Chen).

http://dx.doi.org/10.1016/j.fuel.2016.12.088

Nomenclature

P_c^s	static capillary pressure, M/(T2L)
S_w	wetting fluid phase saturation, dimensionless
P_c^d	dynamic capillary pressure, M/(T2L)
P_{nw}	nonwetting fluid phase pressure, M/(T2L)
P_w	wetting fluid phase pressure, M/(T2L)
τ	dynamic coefficient, M/TL
S_{water}	water phase saturation, dimensionless
$\frac{dS}{dt}$	time derivative of fluid phase saturation, T-1
P_{water}	water phase pressure
$\mathrm{P}_o^{average}$	volume averaged oil phase pressure
$P_w^{average}$	volume averaged water phase pressure
$P_C^{average}$	averaged dynamic or static capillary pressure
φ	porosity
K	absolute permeability (isotropic)
u_w	viscosity of wetting phase (referring to oil in this work)
ρ_w	density of the wetting phase (referring to oil in this work)
g	gravity constant
T_B	redistribution time
K_{ro}	oil relative permeability
K_{rw}	water relative permeability
S_w^{total}	entire core water saturation
S_{wi}	irreducible water saturation
V_{on}	measured oil outflow at time t_n
V_{wn}	measured water outflow at time t_n
S_n	water saturation at time t_n
V_p	pore volume
P_Δ	pressure difference between the core inlet and outlet ends
T_B	redistribution time
$\frac{\mu_c}{l_c}$	maximum observed desaturation rate
α	reservoir dip angle
q	total production rate
M	mobility ratio

stopped and the saturation of fluid phases ($\frac{\partial S_w}{\partial t}$) no longer changes. Static capillary pressure, obtained by the fluid phase pressure measured at the same fluid saturation, is expressed as:

$$P_c^s = P_{nw} - P_w = f(S_w) \tag{1}$$

where P_c^s is the static capillary pressure; P_w stands for the average wetting fluid phase pressure; P_{nw} represents the average nonwetting fluid phase pressure; S_w is the wetting phase saturation.

In 1949, Kirkham and Feng [8] found that the dynamic relationship between P_c^d and S_w in the porous media multiphase flow is not equal to the static condition shown in Eq. (1). In 1982, Ngan and Dussan [9] suggested the dynamic capillary pressure-fluid saturation relationship in experiments conducted at the pore scale. Hassanizadeh [10] demonstrated that the macroscopic capillary pressure is related to the change in the free energy of phases and interfaces as a result of a change in saturation. It is proposed that the transit multiphase flow is governed by a dynamic relationship between P_c^d and S_w, especially at high flow rates [11,12]. The following equation quantifies the difference between the dynamic and static capillary pressure as [13,14]

$$P_c^d = P_{nw} - P_w = P_c^s - \tau \frac{\partial S_w}{\partial t} \tag{2}$$

where τ is the dynamic coefficient, regarded as always positive; $\frac{\partial S_w}{\partial t}$ means the time derivative of the wetting phase saturation. From Eq. (2), it follows that if the wetting phase is water, the dynamic capillary pressure is larger than the static capillary pressure for water drainage ($\frac{dS_w}{dt} < 0$) and smaller for water imbibition ($\frac{dS_w}{dt} > 0$) [14]. If the wetting phase is oil and S_{water} is used to represent water saturation with positive τ values, Eq. (2) should be changed to Eq. (3) [15,16]

$$P_c^d = P_{water} - P_{oil} = P_c^s + \tau \frac{\partial S_{water}}{\partial t} \tag{3}$$

Therefore, during water flooding ($\frac{dS_{water}}{dt} > 0$), the dynamic capillary pressure is larger than the static capillary pressure, which reflects the reality in field production. Fig. 1 illustrates the interface in oil-wet porous media under static and dynamic conditions, which corresponds to both the static and dynamic capillarity characters. As Fig. 1 shows, in dynamic conditions, the increase in curvature of the interfacial shape leads to a higher capillary pressure than that in the static condition, based on Young's equation. From Eq. (3), the difference between the dynamic and static capillary pressure depends on the dynamic coefficient. Factors influencing the dynamic coefficient, therefore, will also influence the difference between the dynamic and static capillary pressures.

Some studies have proposed that the dynamic coefficient is affected by multiple parameters, such as fine-scale heterogeneities, interfacial tension, dynamic contact angle, wettability and viscous fingering macroscopic heterogeneities [17]. Stauffer [18] has presented an equation to show the relationship between the dynamic coefficient and its impact factors as:

$$\tau = \frac{0.1\varphi\mu_w}{\lambda k}\left(\frac{P^d}{\rho_w g}\right)^2 \tag{4}$$

where u_w means the viscosity of the wetting phase; φ is the porosity of the porous media; K is the absolute permeability of the material; ρ_w is the density of the wetting phase; P^d and λ are both Brooks-Corey constitutive model [19] parameters, depending primarily on pore structures; g is the gravity constant. According to this relationship, permeability, which characterizes pore structure and porous media heterogeneities, correlates with the dynamic coefficient and dynamic capillary pressure. Early in 1958, Wyllie and Gardner [20] have suggested that during the flooding process, the effect of the capillary pressure on the relative permeability is:

$$K_{ro} = \left(\frac{1 - S_{water}}{1 - S_{wi}}\right)^2 \frac{\int_{S_w}^{1} \frac{dS_{water}}{dP_c^2}}{\int_{S_{wi}}^{1} \frac{dS_{water}}{dP_c^2}} \tag{5}$$

$$K_{rw} = \left(\frac{S_{water} - S_{wi}}{1 - S_{wi}}\right)^2 \frac{\int_{S_{wi}}^{S_w} \frac{dS_{water}}{dP_c^2}}{\int_{S_{wi}}^{1} \frac{dS_{water}}{dP_c^2}} \tag{6}$$

where K_{ro} is the oil relative permeability; K_{rw} is the water relative permeability; S_{wi} is the irreducible water saturation; P_c is the capillary pressure. These two equations represent a typical parametric model for the relative permeability and capillary pressure relationship. The nonparametric model which describes a closer relationship between capillary pressure and relative permeability, uses a piecewise function form to interpolate such a relationship with splines, by a series of control knots [21]. As the static capillary pressure increases with smaller pore sizes [22], even to nearly 7 MPa