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Investigations on spontaneous imbibition and the influencing factors in tight oil reservoirs

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ABSTRACT

Spontaneous imbibition has become a role on the development of tight oil reservoirs. Many oilfield cases have confirmed the validity of soaking to produce oil depending on imbibition. Considerable yield has been recovered from soaking for a period of time after hydraulic fracturing by fracturing fluid. In order to study the spontaneous imbibition and its influencing factors in tight oil reservoir with stimulated reservoir volume (SRV), we first conducted wettability and imbibition experiments with/without surfactant treatment using different tight cores. Then, we established a mechanism model of imbibition including the influencing factors in tight oil reservoirs based on the experiments. The model was also validated using the published results. After that, numerical simulation was employed to study the impacts of some essential factors on the effects of spontaneous imbibition. The results indicate that no matter mixed-wet or water-wet tight cores, water can be spontaneously imbibed into the tight cores, and consequently expel the oil. The wettability alteration agent has slight influence on contact angle and imbibition recovery for the water-wet core, but it has a distinct influence on those of the mixed-wet or oil-wet core. Natural fractures in tight rock can promote the imbibition. The size of the tight rock after hydraulic fracturing is a significant factor of imbibition recovery. Interfacial tension is crucial to imbibition in tight reservoir because capillary force becomes more significant in tight rocks than that in conventional reservoirs. Wettability intensely decides the imbibition recovery, and it is indispensable to add modifying agents to enhance imbibition for mix-wet or oil-wet rocks. The reduction of temperature in tight oil reservoir due to fracturing and huff-n-puff may decrease the recovery by more than 1% after 5–6 cycles.

1. Introduction

Tight oil resources are extensively distributed around the world, and the total reserve is about two times more than that in the deep-water environments [1]. The production of tight oil has “pushed the US crude supply to over 10% of the world total” [2]. Accordingly, it captures our attention to efficiently exploit such resources. But the permeability is overwhelmingly lower than that of the conventional reservoir. In many fields, the permeability is as low as 10^{-3} mD, so the traditional method cannot obtain economic yield [3,4]. Hydraulic fracturing has been popularly applied to improve the flowing capacity of tight oil reservoirs in recent years [5–8]. The rock around the horizontal wellbore is fractured into crushed blocks. After fracturing, depletion-drive is usually conducted. But the effect is unsatisfactory due to the irreversible permeability loss due stress sensitivity and poor natural drive; as a result, primary oil production from tight oil reservoirs is 5–10% of OOIP [9–12]. In some oilfields, water flooding has been carried out, but the injectivity is low [12–14]. In addition, water channeling through macro-fractures between injector and producer is serious [15–17]. Therefore, huff-n-puff by water has been presented and widely conducted, and the EOR effect in several oilfield cases is satisfactory [17–20].

If the matrix is strongly or partially water-wet, spontaneous imbibition is usually regarded as an important mechanism of displacing oil from matrix by water flooding or soaking in naturally fractured reservoirs with low permeability [21–27]. In fact, tight oil reservoir with SRV is fractured reservoir with much lower permeability. Therefore, imbibition is thought as the main mechanism because lower permeability means larger capillary force, which is the driving force for imbibition. Moreover, oilfield cases have shown that more oil and less water will be produced by soaking of fracturing fluid. Imbibition is affected by many factors; especially, the dominant forces for the

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Nomenclature

a	coefficient
A	surface area [m^2]
b	coefficient
C	capillary index [Pa]
C_{os}	capillary index in oil-surfactant system [Pa]
C_{ow}	capillary index in oil-water system [Pa]
C_{ow}'	capillary index in oil-water system in another media [Pa]
C_w	specific heat capacity of water [J/(m^3·°C)]
C_o	specific heat capacity of oil [J/(m^3·°C)]
C_R	specific heat capacity of rock [J/(m^3·°C)]
C_N	coefficient for Bond number
F_a	counterforce by the atmospheric pressure [N]
F_c	centrifugal force [N]
g	gravitational acceleration [m/s^2]
H	height [m]
I_o	normalized imbibed volume of oil
I_w	normalized imbibed volume of water
K	absolute permeability [mD]
K'	absolute permeability of another media [mD]
K_{rw}	relative permeability of water or wetting phase
K_{rnw}	relative permeability of non-wetting phase
K_{rwnwc}	relative permeability of water or wetting phase at end-point
K_{rnwwc}	relative permeability of non-wetting phase at endpoint
m	mass of an oil drop in an equivalent capillary [kg]
N_B	Bond number
N_{co}	Capillary number
p_a	atmospheric pressure [Pa]
P_w	water-phase pressure [Pa]
$P_c(S_w)$	capillary force at a wet-phase saturation [Pa]
P_{cow}	capillary force between oil and water [Pa]
P_{cos}	capillary force between oil and surfactant [Pa]
P_{cow}'	capillary force at a wet-phase saturation in another media [Pa]
Q_w	flow rate of wetting-phase [m^3/s]
Q_{nw}	flow rate of non-wetting phase [m^3/s]
r	radius of an equivalent capillary [m]
R	core radius [m]
S_{wc}	connate water saturation or irreducible wet phase saturation
S_{orl}	residual oil saturation at low capillary number
S_{orh}	limited value of residual oil saturation at high capillary number
S_{nwr}	irreducible non-wetting phase saturation
$\overline{S_w}$	normalized wetting phase saturation
S_{or}	residual oil saturation
T	temperature [°C]
T_1	constant
T_f	formation temperature [°C]
T_w	temperature of injected water [°C]
v_w	seepage velocity [m/s]
V_{SRV}	volume of SRV [m^3]
V_w	volume of injected fluid each cycle [m^3]
WI_w	wetting affinity index of water
WI_o	wetting affinity index of oil
x	rectangular coordinate system [m]
X_w	parameter of wetting-phase relative permeability
X_{nw}	parameter of nonwetting-phase relative permeability

Greek symbols

γ_w	gravity of wetting phase [kg/(s^2·m^2)]
γ_{nw}	gravity of nonwetting phase [kg/(s^2·m^2)]
θ_{ow}	contact angle between oil and water [°]
θ_{os}	contact angle between oil and surfactant [°]
θ_{ow}'	contact angle between oil and water in another media[°]
μ_w	water viscosity or wetting-phase viscosity [mPa·s]
μ_{nw}	nonwetting-phase viscosity [mPa·s]
ρ_o°C	oil density [kg/m^3]
ρ_w	water density [kg/m^3]
σ_{ow}	IFT between oil and water [mN/m]
σ_{os}	IFT between oil and surfactant [mN/m]
ϕ	porosity
ϕ'	porosity of another media
ψ	Constant [mN/m]
ω	angular velocity, s^{-1}

Abbreviation

EOR	enhanced oil recovery
IFT	interfacial tension
SRV	stimulated reservoir volume

transfer between matrix and fracture are usually discussed [28,29]. Tight oil reservoir is different from the conventional reservoir or naturally fractured reservoirs, so the imbibition becomes more complicated and more factors affect the oil displacement through imbibition.

In conventional reservoirs, the influencing factors of imbibition include interfacial tension, wettability, oil viscosity, and the density difference between oil and water [30–34]. However, in tight oil reservoirs, besides the above mentioned factors, some other factors should be included. In tight reservoir, natural micro-fractures are ubiquitous and play a crucial role in recovering the oil from matrix. In addition, many macro-factures are formed by fracturing to make more oil flow into wellbore. These fractures cut the tight rock into crushed blocks, which are surrounded by the fracturing fluid or water. The size of the fractured blocks will apparently affect the imbibition rate. Moreover, tens of thousands cubic meters fracturing fluids are injected into the field, therefore, the temperature will decrease due to the heat transfer in the region of SRV to some extent. Furthermore, the temperature will decrease during each cycle of water huff-n-puff. Beyond that, because the permeability in tight reservoir is several orders of magnitude lower than that in conventional reservoir, the mechanism or contribution of imbibition evaluated by Bond number may be different [35,36]. Beyond that, some more complicated mechanisms or specially properties for fluid flow in tight rock due to scale effect have been presented by researchers in the past few years. Wu et al. studied the effect of wettability and dimensions on water confined flow in nanopores [37], a simple model for the confined water flow based on the concept of effective slip was proposed. Dong et al. studied the confined behavior of hydrocarbons in organic nanopores [38]. Wu et al. reported that temperature can greatly affect the thermodynamic properties of confined fluid in nonapores [39]. Li et al. studied the capillary pressure in nanopores by molecular simulation for shale [40]. These investigations focus on the impacts of microscale effect on the fluid flow behaviors for unconventional resources.

In this work, we conducted wettability and imbibition experiments with/without surfactant treatment using different tight cores at first. Then, we established a mechanism model of spontaneous imbibition including the influencing factors in tight oil reservoirs based on the experiments. After that, the numerical method was also validated by experiments. Finally, numerical simulation was employed to discover the impacts of some essential factors on the effects of imbibition, such as natural fractures and its distribution, the size of fractured blocks,