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A new approach to calculate permeability stress sensitivity in tight sandstone oil reservoirs considering micro-pore-throat structure

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ABSTRACT

Permeability stress sensitivity has a significant effect on the development of tight sandstone oil reservoirs. The emphasis of study on mechanism of permeability stress sensitivity currently is microcosmic pore-throat structure instead of macroscopic permeability. However, existing approaches to calculate permeability reduction of stress sensitivity are still the function of permeability. As a result, the existing approaches cannot distinguish the difference of permeability stress sensitivity between different tight oil reservoirs with the same permeability. Therefore, in this paper, based on the characteristics of tight sandstone oil reservoirs, the strain of throats is characterized. Considering the effect of boundary layer and critical throat radius, a new approach to calculate liquid permeability reduction of stress sensitivity is presented. It is found when throat distribution becomes narrower or boundary layer thickness increases, liquid permeability reduction of stress sensitivity increases. Because the tight oil reservoir in Daqing Field has narrower throat distribution and larger liquid permeability reduction, the productivity of the tight oil reservoir in Daqing Field is lower than that in Changqing Field. This paper is significant to the development of tight sandstone oil reservoirs.

1. Introduction

1.1. Mechanism of permeability stress sensitivity

Stress sensitivity of petroleum reservoir rock is that its petrophysical parameters change when the effective stress acting on it changes. Permeability stress sensitivity has been a hot topic in the field of petroleum reservoir engineering and geotechnical engineering because permeability with the mutative effective stress has a more direct and important impact on petroleum development. A lot of scholars make a great contribution and have obtained many significant achievements. The research on the mechanism of stress sensitivity has experienced the following stages.

Terzaghi (1943) studied the flow behavior in the saturated deformable medium and came up with the concept of effective stress (Eq. (1)). This is the foundations of the stress sensitivity research.

$$\sigma_{\text{eff}} = \sigma - p \quad (1)$$

Fatt and Davis (1952) researched firstly in the history of reservoir rock permeability stress sensitivity. They found that the magnitude of rock permeability reduction ranges from 11% to 41%. Confining pressure acting on the rock core has a very important impact on the magnitude of permeability.

McLatchie et al. (1952) used oil to study the stress sensitivity of the cores whose permeability ranges from 3 to 102×10^{-15} m^2 and got the relational graph of permeability reduction and effective stress. It was found that the irreversible reduction for permeability is 4% in the high permeability cores while that reaches up to 60% in the low permeability cores. This indicates that the strain of the cores includes both elastic and plastic strain.

Fatt (1958) used gas to study the stress sensitivity of porosity and permeability of the cores whose permeability ranges from 3 to 630×10^{-15} m^2. When the confining pressure is 34 MPa, the degree of the reduction for porosity and permeability are 5% and 25% respectively. According to the experiments, he concluded that the stress sensitivity of porosity could be neglected while that of permeability could not in site.

Vairogs and Rhoades (1973), Kilmer et al. (1987), Jones (1988) and Osorio et al. (1997) studied permeability reduction of stress sensitivity of different cores. Especially, Kilmer et al. (1987) found that details of pore structure related to diagenetic changes appears

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Nomenclature

∇p	pressure gradient, MPa/m
A	cross-sectional area of cores, μm^2
A_{im}	area of interstitial materials, μm^2
A_p	pore area, μm^2
A_{ms}	area of microscope sight, μm^2
a, b, d, f, m and n	constants
c	strain of the effective throat, dimensionless
h	thickness of boundary layer, μm
h_i	thickness of the boundary layer of the throat whose radius is r_{effi}, μm
$h_i(\sigma_{eff})$	thickness of the boundary layer of the throat whose radius is $r_{effi}(\sigma_{eff})$, μm
H	formation thickness, m
K_g	gas permeability, $\times 10^{-3}$μm^2
$K_g(\sigma_{eff})$	gas permeability when the effective stress is σ_{eff}, $\times 10^{-3}$μm^2
$K_g(\sigma_{eff}=6.89)$	gas permeability when the effective stress is 6.89 MPa, $\times 10^{-3}$μm^2
K_{gmin}	minimal gas permeability, $\times 10^{-3}$μm^2
K_{go}	original gas permeability, $\times 10^{-3}$μm^2
K_l	liquid permeability, $\times 10^{-3}$μm^2
K_{lo}	original liquid permeability, $\times 10^{-3}$μm^2
$K_l(\sigma_{eff})$	liquid permeability when the effective stress is σ_{eff}, $\times 10^{-3}$μm^2
n_i	quantity of throats whose radius is r_{effi}, dimensionless
p	formation pressure, MPa
p_o	original formation pressure, MPa
p_{wf}	bottom pressure of oil well, MPa
q	flow quantity of the throat, $\times 10^{-9}$ cm^3/s
Q	productivity of oil well, m^3/d
r_e	supply radius, m
r_{eff}	effective throat radius, μm
$r_{eff}(\sigma_{eff})$	effective throat radius when acted by the effective stress σ_{eff}, μm
r_{effc}	critical throat radius, μm
$r_{effc}(\sigma_{eff})$	throat radius whose value becomes r_{effc} when the throat is acted by the effective stress σ_{eff}, μm
r_{effi}	effective throat radius whose number is i, μm
$r_{effi}(\sigma_{eff})$	effective throat radius of throat i when acted by the effective stress σ_{eff}, μm
r_{effmax}	maximal throat radius, μm
$r_{effmax}(\sigma_{eff})$	maximal throat radius when the throat is acted by the effective stress σ_{eff}, μm
r_{max}	maximal effective throat radius, μm
r_o	original throat radius, μm
$r_o(\sigma_{eff})$	original throat radius when acted by the effective stress σ_{eff}, μm
r_w	borehole radius, m
R_g	permeability reduction, dimensionless
R_l	fraction of permeability reduction measured with liquid, dimensionless
s_J	coefficient of permeability stress sensitivity by Jones, dimensionless
s_L	coefficient of permeability stress sensitivity by Luo, dimensionless
S_i	proportion of throats whose radius is r_{effi}, dimensionless
α_K	permeability modulus, dimensionless
α	area proportion of interstitial materials to pore area, dimensionless
β	area proportion of rigid interstitial materials to pore area, dimensionless
γ	area proportion of plastic interstitial materials to pore area, dimensionless
α'	area proportion of interstitial materials to the area of microscope sight, dimensionless
β'	area proportion of rigid interstitial materials to the area of microscope sight, dimensionless
γ'	area proportion of plastic interstitial materials to the area of microscope sight, dimensionless
ε	strain of the original throat, dimensionless
μ	fluid viscosity, mPa s
σ	overlying pressure, MPa
σ_{eff}	effective stress, MPa
σ_{effo}	original effective stress, MPa
σ_{effmax}	maximal effective stress, MPa
σ_{eff}'	effective stress acting on the rigid interstitial materials, MPa
ϕ	porosity, dimensionless
$\phi(\sigma_{eff})$	porosity when the effective stress is σ_{eff}, dimensionless

Subscript

c	critical
eff	effective
g	gas
i	number
l	liquid
max	maximal
min	minimal
o	original
wf	bottom-holeflowing

Units

mD	1 mD$=1\times10^{-15}$ m^2

to be of much greater significance to pressure sensitivity than rock composition.

Davies and Davies (1999) systematically studied permeability stress sensitivity and its affecting factors of unconsolidated and consolidated reservoir rock. They showed that rock cores with higher values of porosity and permeability are much stronger of permeability stress sensitivity in unconsolidated reservoir. However, rock cores with lower values of porosity and permeability are much stronger in consolidated reservoir. It is suggested that pore geometry is the key factor controlling the strength of permeability stress sensitivity.

Liu et al. (2002), Dong et al. (2008), He and Yang (2004) have studied permeability stress sensitivity of different lithological reservoir rocks.

Yu et al. (2007) systematically studied micro-pore-throat structure and pore-throat distribution of ultra-low permeability reservoir rock using SEM and constant-rate mercury injection technology. They proposed that rock permeability reduction due to the increase of effective stress could significantly affect oil well productivity.

Liao et al. (2012), He et al. (2012) and Li et al. (2013) consider that interstitial materials support throats and they greatly affect the strain of throats and permeability stress sensitivity.

Sun et al. (2013) compared the differences of the stress