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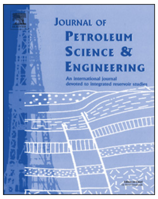

Stress arching effect on stress sensitivity of permeability and gas well production in Sulige gas field ☆

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ABSTRACT

Permeability is a fundamentally important parameter of hydrocarbon reservoir because it significantly impacts well productivity. In laboratories, it is measured under isotropic load which is equal to overburden pressure and it is often assumed to remain unchanged during production. In really however, stress arch forms above the reservoir and the overburden pressure drops during production. Consequently, there is a clear need to illustrate the stress arching effect on the stress sensitivity of permeability and well dynamic performance. Stress arching ratio, which is defined as the change in overburden pressure divided by the change of pore pressure from initial reservoir condition, is calculated for different reservoir shapes in Sulige gas field. Relationship between overburden pressure and effective stress considering stress arching effect in Sulige gas field has been established. Laboratory experiments following reservoir depletion path have been conducted under the stress arching ratio of 0.12 and 0.28 that the reservoir may follow. The results show that the stress sensitivity of permeability greatly depends on stress arching ratio. Permeability measured under nonzero stress arching ratio is larger than that obtained from the conventional experiments with the stress arching ratio of 0 under the same condition. At the pressure drop of 25 MPa, the measured permeabilities increase by 23% and 50% for the stress arching ratios of 0.12 and 0.28, respectively, compared with the values obtained by the conventional experiments when the initial permeability of the core is 0.098 md. In contrast, the permeability shows less dependence on stress arching ratio when the initial permeability of the core is large, such as 7.387 md. Furthermore, the effect of stress arching ratio is introduced into the calculation of well productivity based on the experiment results. The gas well productivities increase by 5.03%, 12.46% and 72.48% for stress arching ratios of 0.12, 0.28 and 1, respectively, when the reservoir initial permeability is 0.098 md. The impact of stress arching ratio on dynamic performance of gas well is generally incorporated via look-up tables of transmissibility multiplier in Eclipse, which is approximate to the ratio of the decreased permeability to the initial permeability for different stress arching ratio. The production decline rate and production decline type are closely related with stress arching ratio when the initial permeability is 0.098 md.

This work investigates the stress arching effect on stress sensitivity of permeability for cores with different initial permeabilities. it can provide some insights into gas productivity calculation, production forecasting, and gas recovery determination

1. Introduction

For low permeability reservoir or tight gas reservoir, it is significant to evaluate the stress sensitivity of permeability, because it greatly impacts well productivity, reservoir evaluation and management. Currently, both experiments measured under hydrostatic conditions (McLatchie et al., 1958; Vairogs et al., 1971; Jones and Owens, 1980; Brighenti, 1989; Yang et al., 2003; Abass et al. 2009; Xue and Cheng, 2011) and those measured under non-hydrostatic stress conditions (Rhett and Teufel, 1992; Schutjens et al. 1998, 2001; Teufel et al, 1991; Holt, 1990; Dautriat et al, 2009) have shown that permeability is a function of effective stress and that low-permeability rocks are more impacted by effective stress than

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☆ Research fields: rock and fluid properties, primary production, reservoir simulation.

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Nomenclatures

σ_i	the initial overburden pressure, MPa
d	the depth of the whole overburden formation layer depth, m
ϕ (x)	rock porosity of the rock at the depth of x
ρ_{ma} (x)	rock density at the depth of x, g/cm^3
$\rho(x)$	fluid density at the depth of x, g/cm^3
α	Biot's coefficient, dimensionless
P	pore pressure, MPa
$\Delta\sigma$	change of overburden pressure, MPa
ΔP	pore pressure change, MPa, which is negative for production but positive for injection
ϕ	reservoir porosity, %
k_i	reservoir initial permeability, md
$\Delta\tau$	change of shear stress, MPa
γ	stress arching ratio, dimensionless
σ	the present overburden pressure, MPa
P_i	initial reservoir pressure, MPa
σ'	the effective stress, MPa.
μ	the shear modules for the reservoir, GPa
μ^*	the shear modules for surrounding, GPa
ν	Poisson's ratios for the reservoir, dimensionless
ν^*	Poisson's ratios for surrounding, dimensionless
R_μ	the shear modulus ratio between the reservoir and surrounding rock, dimensionless
W	the width of the reservoir, m
h	the thickness of reservoir, m
e	aspect ratio, which is the ratio between the reservoir thickness h and width W, dimensionless
H	reservoir depth, m
n	the depth number, which is expressed as $n= 0.5W/H$, dimensionless
L	the length of reservoir, m
h_{eff}	the effective thickness of reservoir, m
Maxi	the maximum value of the parameters
Mini	the minimum value of the parameters
Average	the average value of the parameters;
k/k_i	normalized permeability, dimensionless
m	permeability modulus, MPa^{-1}
η	permeability increase ratio, which is equal to $(k(\gamma\neq 0)-k(\gamma=0))/k(\gamma=0)$, dimensionless
P_a	average pore pressure, MPa
P_{wf}	bottom hole flowing pressure, MPa
q_{sc}	surface production rate,10^{4}m^3/d
μ_a	The average viscosity of gas, mPa s
Z_a	the compressibility factor, dimensionless
r_e	the radius of the reservoir, m
r_w	the radius of wellbore, m
T	the reservoir temperature, K
k_x	permeability in the x direction, md
k_y	permeability in y direction, md
k_z	permeability in the z direction, md
h_t	reservoir top surface depth, m
h_d	reservoir datum depth, m
q_{scq}	production rate at constant production regime, 10^4 m^3/d
q_e	economic limit rate, 10^4 m^3/d
P_{wfp}	bottom hole pressure during constant pressure regime, MPa
G_p	cumulative gas production, 10^4 m^3
P_e	reservoir pressure during production, MPa
t_s	period of stable production, a
E_a	recovery percent of reserves in constant flow regime, %
f	bottom hole pressure decline rate in constant flow regime, MPa/a
EOR	reservoir recovery until abandoned, %
E_b	reservoir recovery increase ratio, which is equal to $(EOR(\gamma\neq 0)-EOR(\gamma=0))/EOR(\gamma=0)100$, %;
OGIP	original gas in place, 10^8 m^3
φ_r	residual friction angle, deg
c_r	residual cohesion, MPa

high permeability rocks (McLatchie et al., 1958; Vairogs et al., 1971; Yang et al., 2003; Xue and Cheng, 2011). It is worth pointing out that all the experiments assumed that the overburden pressure remained unchanged during production. However, the reservoir, unlike a free body, is attached to the surrounding rocks. Overburden pressure may change due to the internal driving forces and external constrains, which is called stress arching effect (Mulders, 2003). When stress arch is generated, partial weight of the overburden is supported by the sideburden during reservoir compaction (Hettema et al., 2009; Kristiansen et al., 2005; Hawkes et al., 2005; Soltanzadeh et al., 2007, 2009; Soltanzadeh and Hawkes, 2008, 2009; Dudley et al., 2009; Segura et al., 2011; Dusseault, 2011; Verdon, 2012). Stress arch is likely to form when the reservoir is small and soft in comparison with surrounding rock (Soltanzadeh and Hawkes, 2009; Dusseault, 2011; Segura, 2011; Verdon, 2012).

The stress arching ratio is defined as the change of overburden pressure divided by the change of pore pressure, and it is controlled by reservoir geometry, rock properties of the reservoir and surrounding rock, and pore pressure distribution within the reservoir during production (Soltanzadeh et al., 2007, 2009; Soltanzadeh and Hawkes, 2008, 2009; Dusseault, 2011; Verdon, 2012). Currently, models for calculating the stress arching ratios can be categorized as analytical models (Segall, 1992; Goulty, 2003; Holt et al., 2004; Hawkes et al., 2005), semi-analytical models (Segall, 1985; Segall and Fitzgerald, 1998; Soltanzadeh et al., 2007, 2009; Soltanzadeh and Hawkes, 2008, 2009) and numerical models (Segura et al., 2011; Verdon, 2012).

It is necessary to investigate the stress arching effect on the stress sensitivity of permeability and gas well productivity especially for low permeability gas reservoirs and tight gas reservoirs. This work describes and analyzes the stress arching effect during production. Stress arching ratios and overburden pressure are also calculated during production for elliptic cylinder shape and penny shape reservoir in Sulige gas field. To the best of our knowledge, this is the first attempt to experimentally investigate the stress arching effect on the stress sensitivity of permeability for the cores with different initial permeabilities. Experiment results are valuable for gas well production forecasting. In Eclipse, this effect is considered by introducing the stress arching ratio parameters in the transmissibility multiplier tables, and thus a more realistic production decline trend is achieved.

This paper begins with the general calculation method of overburden pressure, followed by the description of the stress arching effect and the calculation of stress arching ratios for the different reservoir shapes in Sulige gas field. After that, the stress arching effect on the stress sensitivity of permeability for different initial permeability ranges is investigated, and finally, the stress arching effect on well productivity and dynamic performance is discussed.