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Analytical model of plugging zone strength for drill-in fluid loss control and formation damage prevention in fractured tight reservoir

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ABSTRACT

Developed fractures are beneficial for the efficient development of tight reservoir. They also lead to drill-in fluid loss and induce severe formation damage. Fracture plugging with loss control material (LCM) is the most common way to control drill-in fluid loss in fractured formation. Fracture plugging effect largely depends on the strength of fracture plugging zone, because in most cases plugging failure is caused by the strength failure of plugging zone. However, the effects of LCM mechanical and geometric parameters on plugging zone strength are still unclear. Moreover, traditional LCM selection is mainly performed by trial-and-error method, due to the lack of mathematical models. This paper develops an analytical model for plugging zone strength accounting for the frictional failure and shear failure of fracture plugging zone. Effects of LCM mechanical and geometric properties on plugging zone strength are analyzed. The proposed model is validated by laboratory data. Application procedure of the proposed model to drill-in fluid loss control is developed and successfully applied to the field case study in Sichuan basin, China. The modelling results show that particle-particle friction angle, particle-fiber friction angle, fiber tensile strength, D90 degradation rate, and friction angle between plugging zone and fracture surface are main mechanical parameters affecting the plugging zone strength. Particle size distribution, aspect ratio and initial angle of fiber, and plugging zone porosity are main geometric parameters during loss control. Single LCM parameters are applied to the selection of LCM type. Plugging zone parameters are used for the determination of optimal LCM concentration. Reasonable combination of rigid granule, fiber and elastic particle can create a synergy effect to optimize the plugging zone strength and loss control effect.

1. Introduction

Unconventional reservoir has become one of the hot points of reservoir exploration and development, since an increasing number of companies move to the exploitation of more and more challenging oil and gas reservoirs in tighter, deeper and more complex conditions (Kang and Luo, 2007; Economides and Wood, 2009). Globally, the tight reservoirs are mainly located in North America, Latin America, the former Soviet Union, Central Asia, the Middle East and North Africa (Zhang et al., 2005). In China, there is a wide range of tight reservoir distribution in Sichuan basin. The typical features of Sichuan tight reservoirs are developed natural fractures and ultra-low matrix permeability. Developed fractures are beneficial for the economic and efficient development of tight reservoir. But they also lead to drill-in fluid loss and induce formation damage (Xu et al., 2016). During drill-in fluid loss, the liquid and suspended particles deeply invade into the reservoir and cause severe formation damage (Bennion, 2002; Kang et al., 2012; Kalantariasl et al., 2014a, 2014b; Yang et al., 2016). Bedrikovetsky (2008) developed analytical models which allowed for the prediction of skin factor accumulation with time. The corresponding formation damage mechanisms mainly include particle invasion, mobilization and lifting of the reservoir fines, phase trapping damage and rock-fluid incompatibility (Bennion et al., 1999; Bedrikovetsky et al., 2001, 2011; Mahadevan et al., 2007; Civan, 2008; Windarto et al., 2012; Sacramento et al., 2015; Liu et al., 2015; Naik et al., 2015; You et al., 2015, 2016).

Fig. 1 illustrates the effect of drill-in fluid loss on gas production of the fractured tight gas reservoirs in Sichuan basin. Data of 24 gas wells shown in Fig. 1 include production layer, levels of fracture density and production, drill-in fluid loss volume, specific gas production and stimulation operation history. All these wells have the same production layer, same open hole completion type, and same stimulation operation history (acidizing with compound mud acid). Normally, higher fracture density level should correspond to higher gas production level (Kang

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Nomenclature

A	total cross-sectional area of the shear plane of fracture plugging zone, mm^2
A_f	total cross-sectional area of fibers in the shear plane of fracture plugging zone, mm^2
A_z	cross-sectional area of fracture plugging zone perpendicular to the ΔP direction, mm^2
d_f	fiber diameter, mm
d_p	particle diameter, mm
$D90$	the value of the particle diameter at 90% in the cumulative size distribution, mm
$D90_i$	the initial D90 before particle size degradation, mm
$D90_d$	the D90 after particle size degradation, mm
E	formation elastic modulus, MPa
E_f	elastic modulus of fiber in extension, MPa
f_z	friction force between plugging zone and fracture surface, N
F_c	contact force between particles in the force chain, N
$F_{\Delta P}$	force applying on plugging zone caused by the pressure difference between wellbore and formation, N
H	height of plugged fracture or fracture plugging zone, mm
k_p	stiffness of particle material, N/mm
l_f	length of fiber, mm
L_c	length of force chain, mm
L_f	length of fracture, mm
m_f/m_p	mass ratio of fiber to particle
N	average particles number of one force chain
P_z	strength of fracture plugging zone, MPa
P_{zf}	frictional strength of fracture plugging zone, MPa
P_{zs}	shear strength of fracture plugging zone, MPa
P_{zsg}	shear strength of fracture plugging zone formed with particles, MPa
P_{zsf}	shear strength increment for the addition of fiber, MPa
P_c	horizontal confining pressure perpendicular to fracture surface, MPa
P_c'	vertical confining pressure perpendicular to the shear failure direction, MPa
P_w	wellbore pressure, MPa
s	contact factor between particles
t_f	tensile strength per unit area of plugging zone, MPa
V_f	volume of fibers, mm^3
V_p	volume of particles, mm^3
V_ϕ	volume of voids, mm^3
W	width of plugged fracture or fracture plugging zone, mm
x	the horizontal shear displacement of fiber, mm
z	the thickness of the shear zone, mm

Greek letters

α	plugging zone length, mm
β	the average angle of force chain in terms of the direction of horizontal confining pressure,°
Δ	total amount of elastic deformation of a force chain, mm
ΔH	the height of the shear failure part in the plugging zone, mm
ΔP	pressure difference between wellbore and formation, MPa
ε_p	amount of deformation of single particle in the force chain, mm
ϕ	plugging zone porosity
δ_1	friction angle between particle and particle,°
δ_2	friction angle between particle and fiber,°
δ_3	friction angle between plugging zone and fracture surface,°
σ_c	average contact stress between particles in the force chain, MPa
σ_f	actual tensile stress developed in fibers at the shear plane, MPa
σ_{ft}	theoretical tensile stress developed in fibers at the shear plane, MPa
σ_{fc}	tensile strength of fiber, MPa
σ_n	the normal stress on the fiber, MPa
θ	the angle of fiber with respect to shear plane,°
θ_i	initial angle of fiber with respect to shear surface, °
ρ_f/ρ_p	density ratio of fiber to particle
τ_f	shear strength of a single force chain, MPa
v	Poisson's ratio

Abbreviations

DDR	D90 degradation rate
LCM	loss control material

et al., 2014a). However, actual gas production level of some gas wells is severely reduced due to formation damage induced by drill-in fluid loss. Only 41.7% of all the wells with high level of fracture density correspond to high production level, because of drill-in fluid loss; only 37.5% of all the wells with medium level of fracture density achieve medium production level (Fig. 1).

During the development of fractured tight reservoir, formation damage prevention and efficient drilling put forward high requirements on lost circulation pressure which refers to the maximum pressure a wellbore can withstand before lost circulation occurs (Kang et al., 2014). Several methods are available to increase lost circulation pressure including stress cage, fracture closure stress and fracture propagation resistance method (Fuh et al., 1992; Aston et al., 2004; Dupriest, 2005; van Oort et al., 2011). The stress cage method aims to create additional hoop stress in the wellbore neighborhood using loss control material (LCM) by plugging and propping the near-wellbore fractures (Wang et al., 2008). The fracture-closure stress method attempts to generate more closure stress by deliberately widening induced fractures and plugging them with sized LCMs (Dupriest, 2005). Fracture propagation resistance approach targets the fracture tip isolation with LCMs to prevent the further propagation of natural or induced fractures (van Oort et al., 2011). The strength and stability of fracture plugging zone under increasing wellbore pressure is essential for the three methods above (Xu et al., 2014a). Fracture plugging with LCMs is the most common way to control lost circulation in fractured tight reservoir (Kang et al., 2015). Fracture plugging effect largely depends on the strength of fracture plugging zone because most plugging failure is caused by the strength failure of plugging zone (Calçada et al., 2015). Strength failure of plugging zone is also one of the major reasons for fracture propagation (Xu et al., 2014b). During the drill-in process of fractured reservoir, fracture propagation can increase the loss rate and invasion depth of drill-in fluid (Majidi et al., 2010). Therefore, the improvement of plugging zone strength by reasonable LCM selection is of great importance for drill-in loss control and formation damage prevention in fractured reservoir. However, the effects of LCM mechanical and geometric parameters on plugging zone strength are still unclear. Furthermore, traditional LCM selection is mainly performed by trial-and-error method, due to lack of mathematical models (Kumar et al., 2010). To our best knowledge, very few papers have been published on the strength model of fracture plugging zone for reasonable LCM selection to control drill-in loss and prevent formation damage in fractured tight reservoir.

In the present paper, an analytical model for the strength of fracture plugging zone accounting for frictional failure and shear