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Full Length Article

Stochastic modelling of particulate suspension transport for formation damage prediction in fractured tight reservoir

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ABSTRACT

Developed fractures are beneficial for the efficient development of tight reservoir. But they also lead to formation damage induced by particle capture in fractures during drill-in fluid loss. Effective modelling of particle transport and capture behavior is critical to the prediction and prevention of formation damage. However, the behaviors of particulate suspension transport in fractured media are still incompletely understood and quantified. This paper develops stochastic microscale model for size-exclusion particulate-suspension transport in fractured media. The proposed model accounts for the fracture network connectivity and its subsequent evolution due to particle capture by the introduction of percolation theory. It accounts for the particle capture probability and accessible flux in the expression for particle capture and fracture plugging dynamics. The micro-stochastic model allows for upscaling and numerical solution is obtained for the macroscale equation system to predict the rate and range of formation damage induced by drill-in fluid loss. Laboratory experiments are conducted for the model validation. Modelling results exhibit preferential plugging of fractures with size equal to or below the suspended particle size. The fractures with width equal to the particle diameter decrease fastest. The captured particle concentration decreases with the improvement of the network connectivity. Higher network connectivity leads to smaller decrease of fracture concentration and network permeability during the transport and capture of the same size of suspended particles. The proposed model shows a good agreement with laboratory data.

1. Introduction

Transport, filtration, and subsequent retention of suspended particles and colloids in porous or fractured media are common phenomena in nature and in many industrial applications [1–17]. In petroleum industry, capture of suspended particles in reservoirs during the process of drill-in fluid loss leads to significant productivity decline [2–4]. Nowadays, 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 [5,6]. Globally, the tight reservoirs are mainly located in North America, Latin America, the former Soviet Union, Central Asia, the Middle East and North Africa. 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 [7,8]. Invasion of drill-in fluid into fractured tight reservoir results in severe formation damage due to particle capture and subsequent fracture plugging [9–18].

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 [19]. However, actual gas production level of some gas wells is severely reduced due to formation damage induced by particle capture in fractures during 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).

A thorough understanding and reliable modelling of particle transport and capture in fractures by mathematical models are critical to the prediction and prevention of formation damage. Up to date,

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Nomenclature

C	particle concentration distribution by sizes, L^{-4}, μm^{-4}
c	total suspended particle concentration, L^{-3}, μm^{-3}
D	decrease term in the fracture size kinetic equation
d_s	particle diameter, L, μm
f	distribution density of fracture size, dimensionless
f_{ac}	fraction of accessible flow, dimensionless
g_p	conductivity of a single fracture, L^4, μm^4
g_e	absolute permeability, L^4, μm^4
g_{ea}	accessible permeability, L^4, μm^4
F	distribution density of conductivity, dimensionless
H	fracture concentration distribution (density), L^{-4}, μm^{-4}
H^v	distribution of volumetric fracture concentration (density), L^{-5}, μm^{-5}
h	fracture concentration (density), L^{-2}, μm^{-2}
I	increase term in the fracture size kinetic equation
k	permeability, L^2, μm^2
k_1	permeability of a single fracture, L^4, μm^4
l	characteristic length, L, μm
l_f	fracture length, L, μm
l_{max}	maximum fracture length, L, μm
P	pressure, $ML^{-1}T^{-2}$, MPa
p	fraction of allowed fractures, dimensionless
p_c	percolation threshold, dimensionless
$p_s(r_s,w_f,l_f \rightarrow l_f')$	distribution of the capture probability by l_f', L^{-1}, μm^{-1}
$p_s(r_s,w_f,l_f)$	particle capture probability, dimensionless
q	flow rate through a single fracture, L^3T^{-1}, $\mu m^3 s^{-1}$
r_s	particle radius, L, μm
s_1	cross-sectional area of a single fracture, L^2, μm^2
t	time, T, s
U	total velocity of the flux, LT^{-1}, $\mu m s^{-1}$
w_f	fracture width, L, μm
x	coordinate, L
Z	coordination number, dimensionless

Greek Letters

ϕ	porosity, dimensionless
ϕ_a	allowed fraction of fracture porosity, dimensionless
ϕ_{ac}	accessible fraction of fracture porosity, dimensionless
σ	volumetric concentration of captured particles, L^{-3}, μm^{-3}
Σ	size distribution of the captured particle concentration, L^{-4}, μm^{-4}
$\underline{\Sigma}$	distribution of the captured particle concentration over the fracture and particle radii, L^{-6}, μm^{-6}
λ	filtration coefficient, L^{-1}, μm^{-1}

considerable research has been devoted to the description of transport and retention behavior of suspensions in porous media, as well as their effects on the reservoir conductance properties. The classical colloidal-suspension deep bed filtration (DBF) theory is the most commonly used approach for predicting particle transport behavior and the consequent media alterations [20–22]. The classical DBF model includes two equations for particle population balance and capture kinetics, respectively [23]. Several forms of filtration coefficient as a function of retained particle concentration for different capture mechanisms and the resultant analytical solutions have been reported in the literature [24,25]. The reported mismatch between the modeled and measured particle DBF data makes it necessary to examine the fundamental principles of the classical model for suspension transport in porous media, including its upscaling from micro- to macroscale and possible model generalizations [26,27]. Random-walk models for colloidal-suspension transport in porous media have been developed by Shapiro and Bedrikovetsky [28,29]. The distinguished feature of the obtained upscaled equation is its elliptic type, which is due to timely dispersion of the particles. Upscaling of population balance equations for colloidal-suspension transport in porous media have been performed by Bedrikovetsky [30]. The exact averaging method was developed for mono-sized particles in size-distributed pores, yielding generalization of the classical large-scale model. Population balance model was derived accounting for variation of pore and particle size distributions due to several particle capture mechanisms [31]. It is assumed that suspended particles move at the average flow velocity of the carrier fluid, and the whole porous space is accessible to particles. The particles smaller than the pores pass without straining while the particles larger than the pores are size-excluded in the medium. Particularly, these assumptions lead to independent deep bed filtration of poly-dispersed particles under the low retention conditions. However, most of these works focus on the suspension transport and particle capture behavior in porous media only. Severe formation damage has been observed in fractured reservoir due to particle capture and subsequent fracture plugging.

Particle capture results in the change of the fractured media properties, such as permeability, porosity and fracture size distribution. On the other hand, the property change affects the particle transport and capture behaviors in return [32]. Percolation theory is a branch of probability theory for predicting the properties of random media [33–35]. It is often associate with network modelling of fluid transport and used to predict medium properties [28,36,37]. However, few papers have introduced the percolation theory for the modelling of particle transport and capture behaviors in fractured media. To the best our knowledge, the behavior of particulate suspension transport in fractured media are still incompletely understood and quantified.

In the present paper, stochastic microscale model is developed for size-exclusion particulate suspension transport in fractured media. The proposed model accounts for the fracture network connectivity and its subsequent evolution due to particle capture by the introduction of percolation theory. It accounts for the particle capture probability and accessible flux in the expression for particle capture and fracture plugging dynamics. The micro-stochastic model allows for upscaling and numerical solution is obtained for the macroscale equation system to predict the formation damage induced by drill-in fluid loss. Laboratory experiments are conducted for the model validation.

The structure of this paper is as follows. Section 2 presents the percolation model of the fractured tight reservoir. Section 3 develops the stochastic microscale system of governing equations with varying fracture and particle size distributions. The upscaling and numerical solution of the micromodel for mono-dispersed suspension is derived. The captured particle concentration profiles and the evolution of the fractured network properties are presented and discussed in Section 4. In Section 5, the detailed description of experimental procedures is given, and experiment results are discussed. Field case study of drill-in fluid loss control and formation damage prevention in fractured tight reservoir is reported in Section 6. Finally, Section 7 presents the conclusions of the study.

2. Percolation model of the fractured tight reservoir

The geometric model of fractured tight reservoir for size-exclusion suspension transport is established based on percolation theory in this section. Developed fractures in the tight reservoir are connected to each other and form a network (Fig. 2). The suspension transport in the matrix can be neglected due to the low permeability of the matrix (less than 0.1 mD). As shown in Fig. 3(a) and (b), fractured medium is represented in the model as a fracture network. Bond percolation is adopted here to establish the fracture network by the assignment of all