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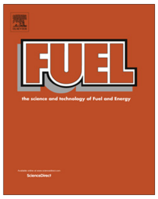

Theoretical conductivity analysis of surface modification agent treated proppant

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HIGHLIGHTS

- Analytical models are derived to compute SMA treated proppant embedment and fracture conductivity.
- Visco-elastic model is adopted to predict proppant embedment and fracture conductivity.
- Influence of SMA properties on production is analyzed.

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ABSTRACT

Proppant embedment plays a significant role in conductivity decreasing, especially for weakly consolidated sandstones, shale and coal beds. Surface modification agent (SMA) is widely used in decreasing proppant embedment and proppant crush, increasing proppant cohesive force and long term conductivity. In this study, analytical models are derived to compute SMA treated proppant embedment and fracture conductivity. A model based on coefficient adjustment is established to match the conductivity and embedment of SMA treated proppant. Application results of this method to matching fracture stabilizer treated fracture conductivity are reasonable. Visco-elastic model is adopted to predict proppant embedment and fracture conductivity. Properties of fracture filled with visco-elastic proppant is also studied, it will take a relatively long time for conductivity to reach a steady state after fracturing. With the increase of proppant viscosity, more time will be needed for conductivity to reach a steady state. Conductivity variation increases with the increase of closure pressure. There are nearly no effect of formation rock viscosity on fracture conductivity.

Q3 1. Introduction

Q4 Hydraulic fracturing is an important stimulation technology. When high-viscosity liquid is injected into a well by local surface high pressure pump unit at a speed that greatly exceeds the absorptive capacity of formation, well bottom pressure will surpass ground stress and rock tensile strength, thereby generating fractures. Then, with the injection of fracturing fluid carrying proppant, fracture supported by proppant will be generated. The fracture may change flow type from radial flow to bilinear flow, break through near-wellbore blockage, expand and communicate original micro cracks, thus increasing production remarkably. Hydraulic fracturing is a major stimulation technology for low permeability reservoirs. In recent years, it has also been widely used in unconventional reservoir such as shale gas, coal rock and unconsolidated sandstone reservoirs. Proppant embedment plays a significant role in hydraulic fracturing, a variety of SMA (surface modification agent) have been applied to enhance the effect of hydraulic fracturing. It is of great importance to study proppant embedment and SMA's effect.

A number of empirical or semi-empirical models on proppant embedment have been established [1–23]. A semi-empirical model was derived to calculate proppant embedment under the condition of known proppant concentration and overburden load [1]. Huitt and Mcglothlin [1] conducted relevant experiments to support the equation, and studied influence proppant size, concentration of proppant-paving, fluid leak-off, and overburden pressure.

Volk et al. [5] quantified factors that influence embedment, such as proppant concentration, size, distribution, rock type, and embedment surface. They formulated empirical equations based on experimental results. Lacy et al. [11] did experimental research on embedment and fracture conductivity in soft formations, results

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showed that the primary parameter that determines embedment was closure pressure, with proppant size and fluid viscosity also being important.

Lacy et al. [13] developed a new computer-controlled laboratory technique that measures propped fracture aperture and proppant embedment in soft reservoir sandstone. They investigated relationships between embedment and closure pressure, concentration of proppant-paving, proppant size, water saturation, gelled-fluid-leakoff behaviour, and core mechanical properties. Guo et al. [20] studied proppant embedment in core samples experimentally. They found that fracture aperture would be significantly reduced due to proppant embedment.

Many experimental studies on fracture conductivity have been reported [12,14–16,18,22,23,3,4,7–10].

However there have been few analytical models for calculating fracture conductivity. Existing models are mostly empirical or semi-empirical. In the study of Gao et al. [24]. Gao et al. [24], analytical models were derived to calculate proppant embedment, proppant deformation, change in fracture aperture, and fracture conductivity in ideal or experimental situations of either single-layer or multi-layer patterns in fractures under closure pressures. The new models and existing models were compared, and results showed that the new models could match experimental data in all of the cases studied.

Some SMA is high-molecular polymer and hence viscoelastic material. They will form a layer of viscous membrane with certain intensity on proppant surface, which will slightly reduce fracture conductivity, but can stop relative movement between proppant grains, hence reduce proppant embedment, restraint proppant flowback and strengthen fracture stability [25–27].

In this study, analytical models are derived to compute SMA treated proppant embedment and fracture conductivity. Application results of this method to matching fracture stabilizer treated fracture conductivity are reasonable. SMA treated proppant may show elastic-plastic properties, viscoelastic model is adopted to predict proppant embedment and fracture conductivity, properties of viscoelastic proppant is also studied.

2. Proppant embedment analytical models

In the research of Gao et al. [24], analytical models were derived to calculate proppant embedment, proppant deformation, change in fracture aperture, and fracture conductivity. Related parameters and sketch figure are shown in Fig. 1.

$$h = 1.04D\left(K^2p\right)^{\frac{2}{3}}\left[\left(\frac{1-V_1^2}{E_1}+\frac{1-V_2^2}{E_2}\right)^{\frac{2}{3}}-\left(\frac{1-V_1^2}{E_1}\right)^{\frac{2}{3}}\right]+D_2\frac{P}{E_2} \quad (1)$$

$$\beta = 1.04D\left(K^2p\frac{1-V_1^2}{E_1}\right)^{\frac{2}{3}} \quad (2)$$

$$a = \beta + h \quad (3)$$

$$\phi = \frac{D\phi_0 - 2\beta}{D - 2\beta} \quad (4)$$

$$r = \left(\frac{D-2\beta}{D}\right)r_0 \quad (5)$$

$$\tau = \sqrt{1+\left(\frac{D-2\beta}{D}\right)^2({\tau_0}^2-1)} \quad (6)$$

$$\kappa = \frac{\phi r^2}{8\tau^2} \quad (7)$$

$$F_{RCD} = c_0KW = \frac{(D\phi_0-2\beta)(D-2\beta)r_0^2}{8D^2\left(1+\left(\frac{D-2\beta}{D}\right)^2(\tau_0^2-1)\right)}(D-2a) \quad (8)$$

where h is value of embedment; D is initial fracture aperture; D_1 is diameter of proppant; D_2 is thickness of formation rock; E_1 is elastic modulus of proppant; E_2 is elastic modulus of formation rock; κ is permeability; p is closure pressure, r is radius of pore throat; r_0 is radius of pore throat when closure pressure is equal to zero; W is fracture aperture when fracture is under action of closure pressure; α is change in fracture aperture; β is deformation of proppant deformation; ϕ is porosity, dimensionless; ϕ_0 is porosity when closure pressure is equal to zero; v_1 is Poisson's ratio of proppant; v_2 is Poisson's ratio of formation rock; μ is fluid viscosity; τ is pore tortuosity; τ_0 is pore tortuosity when closure pressure is equal to zero; K is distance coefficient, equals to 1, c_0 is fitting coefficient (see Figs. 2 and 3).

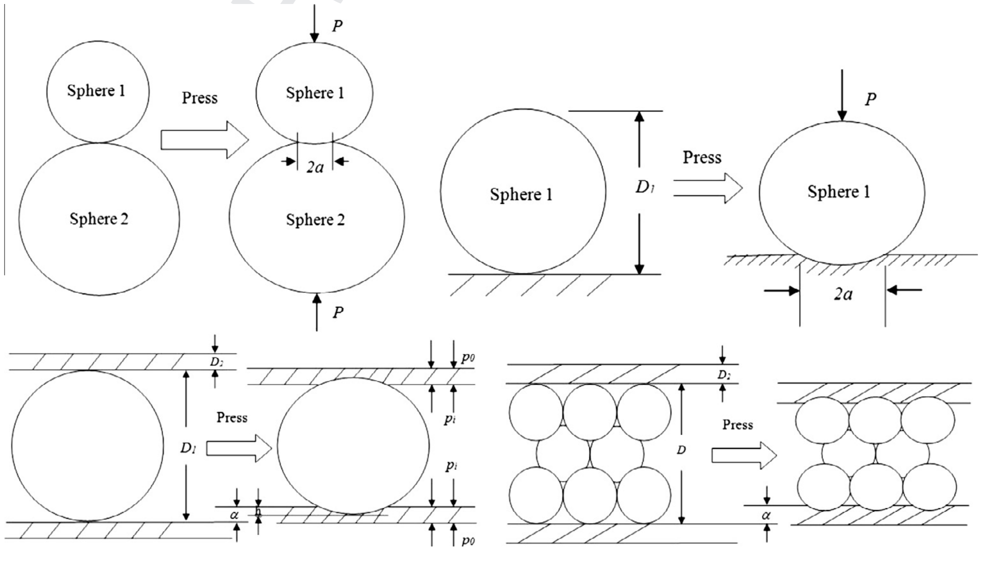

Fig. 1. The mutually squeezing sphere and fracture.

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