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A permeability model for the hydraulic fracture filled with proppant packs under combined effect of compaction and embedment

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ABSTRACT

Hydraulic fracture is the main flow path for gas transport. The proppants are man-made material that filled in the hydraulic fractures to keep them open and allow gas flow through. The permeability change of hydraulic fracture is controlled by the combined effect of compaction and embedment. In this study, we modeled the proppant embedment as a function of effective stress by a transformed Hertz contact model and a proposed power law model which is analogous to the Oliver-Pharr model. The results illustrate that the power law relationship could better fit the experimental data, because the Hertz model becomes invalid when the embedment is large compared to the proppant size. By incorporating the power law correlation into an existing theoretical permeability model as a function of effective stress, a permeability model for the hydraulic fracture filled with proppant packs under combined effect of compaction and embedment is developed. The new model is able to adequately describe the permeability data of proppant packs confined by rock core slices. Although this study puts forward the theoretical basis of the hydraulic permeability modelling under combined effect of compaction and embedment, more fundamental studies are required to investigate the contact behaviour between the proppant packs and the fracture face under various conditions. Therefore, the permeability model could be further improved by introducing the new advanced proppant embedment correlations.

1. Introduction

The shale gas reserves distribute widely around the globe and will supply abundant fossil energy over the coming decades until a switch to renewable energy sources is made (Howarth et al., 2011). However, extraction of this source of unconventional energy is not easy, mainly attributed to the extreme low in-situ permeability (Wang et al., 2009). The hydraulic fracturing technology is required to create a man-made fracture network in shale formation to achieve economic gas production (Holditch, 2013). Hydraulic fracturing is a process of pumping specially engineered fluids at high pressure into the shale formation to create large fractures, which are then propped open with sand or ceramic proppants. The conductivity of hydraulic fractures is significantly increased by filling the fracture channels with multiple layers of proppant particles, also referred as proppant packs. The hydraulic fracture is neither a simply porous media (proppant pack), nor a fractured media, but a composite type of media, the fracture filled with porous proppant packs. The conductivity of hydraulic fracture is not only affected by proppant packs and fracture themselves, but also influenced by their interaction.

A number of experimental studies have revealed that the conductivity of hydraulic fracture can be significantly enhanced by the presence of proppants. Fredd et al. (2000) reported that the permeability varied by at least two orders of magnitude in their experiments while Kassis and Sondergeld (2010) observed that the permeability changed more than 1000 fold. Fredd et al. (2000) stated that the permeability could be proppant dominated by using high-strength proppants. Parker et al. (2005) supplemented that the fracture conductivity was greatly affected by the concentration of the packed proppants in the fracture: higher concentration yielded higher conductivity by virtue of a wider fracture. The initial permeability of the hydraulic fracture is enhanced, but the long term permeability decrease is not optimistic for shale gas production due to its strong stress sensitivity (Wen et al., 2007; Kassis and Sondergeld, 2010; Lee et al., 2010; Gaurav et al., 2012; Suarez-Rivera et al., 2013). This could be a main reason that leads to the productivity falling down for most gas shale plays in the USA (Hughes, 2013). Kassis and Sondergeld (2010) stated that the dependency does not simply obey the cubic pressure dependence law proposed by Walsh (1981).

The proppant embedment has been verified as an important factor

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that reduces the hydraulic fracture conductivity of fluid. Wen et al. (2007) verified the significant effect of proppant embedment upon the conductivity of fracture through comparing the fluid conductivity of the proppant pack compressed within the steel plateau (without embedment) and the rock (with embedment). The lower conductivity of the proppant pack confined by rock indicated that the proppant embedment played an important role in hydraulic fracture permeability change. Moreover, the proppant embedment was vividly observed by the scanning electron micrographs of the Brady sandstone wafers recovered from the quadcell stress tests where the sandstone coupon was in direct contact with proppants (Lee et al., 2010). Alramahi and Sundberg (2012) stated that the hydraulic fracture conductivity loss was controlled by stress, proppant embedment and shale properties. Based on the Hertz contact theory, Khanna et al. (2012) modeled the conductivity of narrow fractures filled with a sparse proppant monolayer, which represents the narrow secondary fractures. The proppant embedment in their work was estimated by the Hertz solution. However, the embedment should be much smaller than proppant size based on the Hertz assumption, which is not strictly consistent with the more general cases in reality.

Modelling of permeability change is complex because the permeability change is not only affected by the effective stress induced proppant packs compaction, but also influenced by the contact stress induced proppant embedment. More recently, Chen et al. (2015) proposed a general permeability model for fractured reservoir rocks including gas shale with irregular and poor connectivity fractures (Slatt and O'Brien, 2011). The model was further verified to be applicable to porous media through theoretical derivation (Chen et al., 2016). The Chen et al. model could be used to evaluate the permeability change of proppant packs under variable effective stress, however, it does not consider the impact of proppant embedment on permeability.

In this study, we modeled proppant embedment on basis of the Hertz contact model and a power law model proposed according to Oliver and Pharr (1992) model respectively. Both models are applied and further developed to describe the experimental data of proppant embedment as a function of effective stress. Their performance is compared and analysed. Then the obtained proppant embedment equation is incorporated into the permeability model developed by Chen et al. (2016). The improved permeability model is applicable to describe the permeability change in the hydraulic fracture filled with proppant packs under combined effect of compaction and embedment. The new model is verified through matching the permeability data of propped fractures. This study aims to obtain a better understanding of the permeability behaviour in the hydraulic fracture with proppant packs under combined effect of compaction and embedment.

2. Modelling of proppant embedment

The hydraulic fracture permeability is mainly affected by proppant pack compaction and embedment. To quantitatively take into account the effect of proppant embedment into the permeability model, a proppant embedment model is required. In this section, the Hertz contact model and a power law model are applied to describe the proppant embedment. The model performance is examined through matching experimental data. The models were originally proposed to relate the contact deformation to the load or force applied. In petroleum industry, stress is frequently used instead of force. The two models are further developed for analysing the proppant embedment as a function of effective stress.

2.1. Hertz contact model

According to the classic Hertz contact problem between a rigid sphere and an elastic semi-infinite half-space (Fig. 1), the vertical displacement of the surface at a distance r from the symmetry point of contact is calculated by (Fischer-Cripps, 2007):

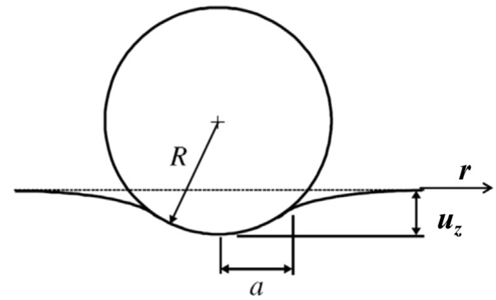

Fig. 1. Hz contact problem between a rigid sphere and an elastic semi-infinite half-space.

$$u_z = \frac{1-\nu^2}{E}\frac{3}{2}p_m\frac{\pi}{4a}(2a^2 - r^2) \quad r \le a \tag{1}$$

$$u_z = \frac{1-\nu^2}{E}\frac{3}{2}p_m\frac{1}{2a}\left[(2a^2 - r^2)\sin^{-1}\frac{a}{r} + r^2\frac{a}{r}\left(1 - \frac{a^2}{r^2}\right)^{1/2}\right] \quad r \ge a \tag{2}$$

where ν and E are the Poisson's ratio and the elasticity modulus of the half-space, respectively, p_m is the mean contact pressure and a is the radius of the contact zone which is calculated by (Fischer-Cripps, 2007):

$$a^3 = \frac{3}{4}\frac{PR}{E^*} \tag{3}$$

where P is the indenter load, E^* is the combined modulus of the indenter and the half-space given by (Fischer-Cripps, 2007):

$$\frac{1}{E^*} = \frac{(1-\nu^2)}{E} + \frac{(1-\nu'^2)}{E'} \tag{4}$$

where E' and ν' are the Young's modulus and Poisson's ratio for the sphere.

For the proppant pack, the mean contact pressure equals to the effective stress (σ_e=p_m) if the load is fully undertaken by the proppants. The relationship between the mean contact pressure p_m (or the effective stress σ_e) and the indenter load P is:

$$p_m = \sigma_e = \frac{P}{\pi a^2} = \left(\frac{4}{3}\frac{E^*}{\pi}\right)\frac{a}{R} \tag{5}$$

The radius of the contact zone a can be calculated by Eq. (5) by knowing the effective stress, the size of proppant and the combined modulus of the indenter (proppant) and the half-space (shale).

According to Eq. (1), the maximum vertical displacement (the proppant embedment) is attained when r equals to 0:

$$u_{z\ \max} = \frac{3\pi}{4}\frac{1-\nu^2}{E}\sigma_e a \tag{6}$$

Incorporating Eq. (5) into Eq. (6), we have:

$$u_{z\ \max} = \frac{(1-\nu^2)R}{EE^*}\left(\frac{3}{4}\pi\sigma_e\right)^2 \tag{7}$$

Eq. (7) can be further reduced to:

$$u_{z\ \max} = M_h\sigma_e^2 \tag{8}$$

where M_h is the composite modulus.

2.2. Power law model

In the Hertz contact problem, the depth of penetration or the maximum vertical displacement should be small relative to the radius of the sphere indenter. In a more general case in gas shale reservoir, the proppant embedment is large and the proppant would fully embed in the soft shale (see Fig. 2). Oliver and Pharr (1992) applied a power law relationship between load (P) and indenter embedment (h):