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Fracture closure and conductivity decline modeling – Application in unpropped and acid etched fractures

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ABSTRACT

Natural fractures, hydraulically generated fractures, and acid etched fractures have some degree of fracture face roughness that generates flow conductivity. While it has been proven both theoretically and experimentally that fracture conductivity depends on fracture face roughness, there are limited models that can predict fracture conductivity at different closure stresses for these various fracture roughness patterns. In addition, some of the models require detailed statistical and topographical surface profile parameters, which limit their field application.

A numerical model is developed to study the closure of rough surfaces in contact. Both asperities and semi-infinite half-spaces are assumed to be deformable. The mechanical interaction among asperities is accounted for and its effect on the fracture closure is investigated. Asperity failure is also considered in the model and the results are compared to that of perfectly elastic contact. Aperture profiles that are the output of the closure model are used to solve the fluid flow problem and study the effect of closure stress on fracture conductivity.

It is evident in our results that the closure behavior depends on the etching pattern as well as the elastic properties of the surface. The performance of a rough fracture depends on its initial aperture, asperity height distribution, roughness pattern, and the closure stress range. Certain fracture roughness patterns were able to withstand the closure stress while undergoing lower amounts of closure. Our model tends to predict fracture closure and conductivity behavior better than widely used correlations.

This paper discusses the closure of fractures and attempts to shed more light on the performance of such a stimulation technique by comparing the closure behavior of some particular surface patterns. Our model can be used to determine the most optimum fracture system for a given reservoir condition.

Introduction

Acid fracturing is a stimulation technique used in carbonate reservoirs. This technique is considered as an alternative to the well-known propped hydraulic fracturing. Fractures tend to close due to the in-site stresses acting normal to the plane of fracture. The closure of fracture has detrimental effects on the conductivity and therefore, should be prevented. Proppant is widely used in the hydraulic fracturing process and this material serves to keep the fracture open against closure stresses. However, the mechanism by which the fracture is being held open is essentially different in acid fracturing technique.

Acid fracturing is a complex process in which acid reacts with rock and removes some parts of it. The amount of rock removal and its general etching pattern is a function of factors such as chemical kinetics, formation heterogeneity and acid injection rate. The acid–rock reaction results in two random rough surfaces. The asperities on these surfaces act as pillars to keep the fracture open. Fracture surfaces, later on, come into contact after the pump pressure is dissipated. The success of an acid fracturing job depends on how well the asperities withstand the closure stresses. The increasing effective stress often reduces the fracture aperture and its conductivity.

Quantification of fracture closure is crucial to predicting the performance of acid fracturing. This cannot be done without detailed study of the closure mechanisms. There might be significant uncertainties involved due to the rock heterogeneity and the random nature of acid fracturing. It is worth mentioning that the actual surface data is almost impossible to acquire and this makes closure quantification more difficult.

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Nomenclature

H	asperity height, L, in
A	asperity area under axial load, L^2, m^2
E	Young's modulus, m/Lt^2, psi
f	axial load on asperity, mL/t^2, lbf
v	Poisson's ratio
C'_{ii}	asperity self-effect deformation coefficient, t^2/m
C''_{ii}	half-space self-effect deformation coefficient, t^2/m
C_{ij}	coefficient of half-space deformation due to mechanical interaction effect, t^2/m
R_i	asperity radius, L, in
r_{ij}	distance from center of asperity 'i' to asperity 'j', L, in
r_i	distance from the center of asperity 'i' within loaded area, L, in
D_{ii}	half-space deformation due to force on asperity 'i', L, in
D_{ij}	half-space deformation due to force on neighboring asperities, L, in
Re	Reynold's number
L_x	grid length in x-direction
L_y	grid length in y-direction
k_f	fracture permeability, L^2, mD
w	fracture aperture, L, in
C_f	fracture conductivity, L^3, mD ft
μ	fluid viscosity, m/Lt, Pa s
q_x	fluid injection/production rate in x-direction, L^3/t, m^3/s
q_y	fluid injection/production rate in y-direction, L^3/t, m^3/s
K_n	rough surface normal stiffness, m/t^2, MPa/m [psi/μm]
σ	normal stress, m/Lt^2, psi [MPa]
δ	rough surface closure, L, μm
UCS	unconfined compressive strength, m/Lt^2, psi [MPa]
ε	strain

Several attempts have been made to investigate the closure of rough surfaces in contact. These studies include analytical (Greenwood and Williamson, 1966; Gangi, 1978; Brown and Scholz, 1985; Cook, 1992; Adams and Nosonovsky, 2000; Myer, 1999) and numerical (Hopkins, 1991; Pyrak-Nolte and Morris, 2000; Deng et al., 2009; Lanaro, 2000; Duan et al., 2000) approaches as well as experimental works (Bandis et al., 1983; Brown et al., 1986; Marache et al., 2008; Matsuki et al., 2008). The mathematical model developed by Greenwood and Williamson (1966) is based on the Hertzian contact theory. Asperity summits are assumed to be spherical and their height is assumed to follow a known probability function. One of the most important assumptions in their study and the generalized models of such kind (e.g. Brown and Scholz (1985)) is that asperities deform independently, which might not be always true. Gangi (1978) later on proposed the "bed of nails" model to describe the fracture permeability variations under closure stress. Gangi's model more or less resembles Greenwood's expression in that, asperity heights follow a probability function and they act independently. A shortcoming of Gangi's model is that it does not include the effect of half-space deformation. It should be noted that spatial distribution of asperities are not considered in Gangi's model. A much better description of joint deformation physics is given in Hopkins' (1991) model. His model takes into account the deformation of the half-space under asperities. As another improvement to the previous models, Hopkins considers the mechanical interaction of asperities. This study is an application of some firmly established concepts of rough surface closure to acid fracturing. Except for a few cases, the literature is mainly concerned with elastic closure. However, it is of our interest in this paper to investigate the effect of asperities failure on the closure behavior of the fracture.

Hydraulic conductivity of rough surfaces is extensively studied because of its important implications in different branches of science and engineering. Inaccessibility of actual field samples and difficulties in simulating the in-situ conditions leaves the hydraulic conductivity of rough surfaces an unanswered question. The hydraulic conductivity of rough surfaces is addressed in many experimental and analytical works (Witherspoon et al., 1980; Tsang and Witherspoon, 1981; Glover and Hayashi, 1997; Gong et al., 1998).

Today, the conductivity of acid fractures and unpropped rough fractures is of interest in petroleum engineering. A successful acid fracture has to remain conductive under closure stress, otherwise it is not an economical practice. Several empirical models are proposed to predict the conductivity of acid fractures under closure stress among which, Nierode and Kruk (1973) is widely used. There are other correlations based on Nierode and Kruk's (1973) correlation, which essentially consider the rock embedment strength and the amount of dissolved rock to predict the fracture conductivity (see for example Nasr-El-Din et al. (2008)), while some others account for the effect of surface roughness on conductivity (see for example Pournik et al. (2009)).

The closure behavior of rough surfaces depends on the elastic properties of the surface as well as the topographical properties of the surfaces. The position of the asperities relative to one another has an important impact on the closure behavior. An elasto-plastic model is used in this paper and the mechanical interaction among the asperities is also considered in this study. Our results indicate that a significant portion of the closure occurs at low stress levels. As the number of contacting asperities increases, the fracture tends to stiffen.

Theory

In this paper, asperities are modeled as cylinders with different heights. As the fracture closes under the influence of farfield stresses, some of the asperities come into contact. The ones that are in contact carry the load while the non-contacting asperities have zero force acting on them. Asperities may indent the half-space and cause deformation in the half-space. Therefore, deformation is allowed in the asperities and also in the half-spaces below and above the asperities. This deformation is not limited only to the area under the asperity and spreads radially around the asperity and may affect the neighboring asperities. The fracture deformation model used in this study is a numerical model similar to that of Hopkins (1991). The total deformation has three components: (1) the deformation of asperity i due to the force f_i, (2) half-space deformation due to the force f_i, (3) the deformation of half-space under asperity i due to the force f_j on asperity j. The latter is usually termed as "mechanical interaction" and has a significant effect on stress distribution among the asperities. The change in height of asperity is calculated from Hooke's law,

$$\Delta h_i = \frac{h_i}{A_i E_i} f_i = C'_{ii} f_i, \qquad (1)$$

where h_i is the initial height of the asperity, A_i is the cross-sectional area of the asperity, and E is the modulus of elasticity. The second