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Frictional behavior of sliding shale rock-silica contacts under guar gum aqueous solution lubrication in hydraulic fracturing

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ABSTRACT

Over the past decades, hydraulic fracturing has been adopted extensively in the petroleum field to stimulate the growth of shale gas production. To better understand hydraulic fracturing, the frictional behavior of shale rock-silica contacts was investigated. Data from experiments show that friction coefficient of the contact gradually increases from 0.2 to somewhere in the range of 0.3–0.4, and then reaches steady state with increasing load, which is directly related to the transformation from the mixed to the boundary lubrication regime of guar gum aqueous solutions. Moreover, the friction coefficient of the contact has no trend with the increasing concentration of guar gum aqueous solution, which is attributed to rheological performances of guar gum in contacts.

1. Introduction

Over the past decades, high economic efficiency has been made possible by the exploitation of global shale gas because of advances in hydraulic fracturing (HF) [1,2]. HF is a process by which a fracture is initiated and propagated to create networks of highly conductive pathways for hydrocarbon from reservoir to well [3,4]. During the fracturing process, a fracturing fluid that includes proppants is injected into a reservoir rock at high pressure; This fluid hydraulically cracks the rock open when the breakdown pressure of the rock is achieved, and the proppants in the fluid enter the fractures [4]. Proppants fill in the gap to prevent the fractures from closing after the withdrawal of high-fracturing pressure that is caused by the pumping of fracturing fluids at the end of the HF process [4,5]. Fig. 1 shows a schematic graph of HF and the function of the proppant. The particles filling in the cracks are the proppants. The friction of the proppant in the fractures, which determines the distance of proppant transported, plays a significant role in shale gas productivity [5,6]. River sand, as proppant, was initially used in HF. A 20/40 mesh sand is the most widely used currently, and the proportion of this size of sand comprises 85% of the proppants [4]. Hydraulic fracturing has been used in the petroleum industry to stimulate shale gas production growth since 1947 [7]. Fracturing fluids have three types of solutions: oil-based, water-based and liquified natural gas. Because of their environmental and safety properties, water-based fracturing fluids play a significant role in HF. To transport proper proppant, ensure the uniform distribution of proppant and fluids with wall-building characteristics, and prevent further leak-off of fluids into the surrounding formation rock, polymers are required to increase the viscosity of the fracturing fluids. For more details and a current study of this technique, the reader is referred to [5].

The tribological properties of polymer aqueous solutions have been widely investigated. Cassin et al. [8] investigated the lubrication performances of guar gum and pig gastric mucin aqueous solutions by rolling hard stainless-steel ball and sliding soft silicone rubber flat contact for biological interest, and found that both could notably reduce friction. The friction properties of many polymers in aqueous solutions, such as polyethylene oxide, guar gum, xanthan gum and sunflower oil, were investigated over a broad range of entrainment speeds between elastomer and steel by Vicente et al. [9–11] for foodstuffs, home, and personal care industries. The results indicated that the dependence of friction on the entrainment speed of these polymers behaves as a classical Stribeck curve. Additionally, friction reduces with increasing polymer concentration in the mixed-regime for polyethylene oxide, guar gum, and xanthan gum. However, friction of sunflower oil in the mixed-regime is independent of oil content. Zhang et al. [12,13] studied the elastohydrodynamic lubrication (EHL) behavior of replacing water with polyalkylene glycols (PAGs) aqueous solutions as base stocks and found that PAGs solutions could form an EHL film and have excellent lubrication properties when organic phosphate ester is added. Recently, Wang et al. [14] obtained superlubricity by using PAGs aqueous solution. Liu et al.

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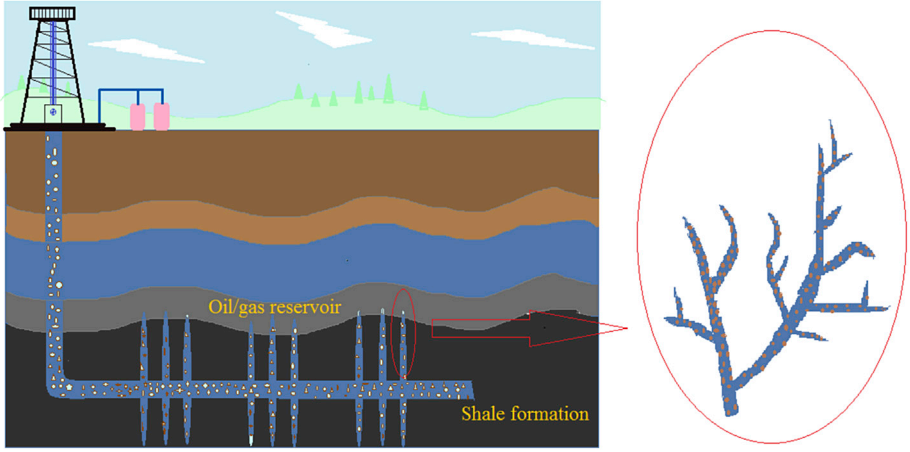

Fig. 1. Schematic illustration of hydraulic fracturing treatment and the function of the proppant which is the particles filling in the cracks for shale gas production.

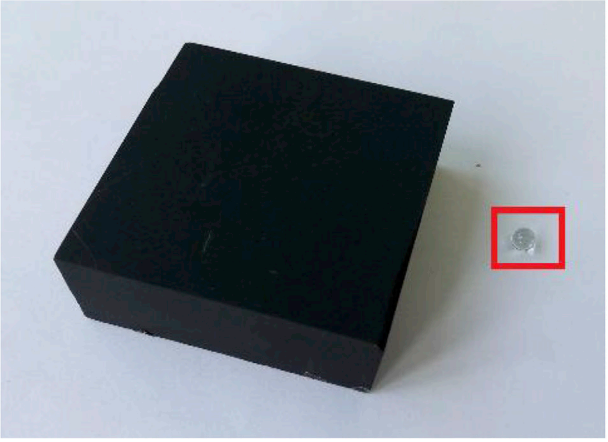

Fig. 2. Shale rock and silica ball in red box used in this study (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

[15,16] explored film-forming and the lubrication performances of linear polymer poly (ethylene glycol) in an aqueous solution by using a thin film interferometry and a ball-on-disk tribometer. They suggested that the poly molecular weight affected the lubrication film thickness. Poly rheological properties and surface-lubrication interaction determined lubrication behaviors in soft lubrication. The tribological properties of the polymer aqueous solution PPO-PEO-PPO as a lubricant on Si and Ti surface have been studied by Lin et al. [17–20]. It was found that polymer molecular structure, concentration, and loading pressure affected lubrication properties.

The oldest and widely used viscous polymer of water-based fracturing fluids in the industry is guar gum (GG), which is a high molecular weight polysaccharide. Because the silica content of river sand (silica content 80%–90%) is close to that of silica ball (silica content > 99%), the proppant used in this study are spherical silica balls. The spherical silica balls were substituted for river sand particles for simplification. There have been relatively few studies of the frictional behavior of shale rock-silica contacts under GG aqueous solutions lubrication. In the current work, the frictional properties of the contact between shale rock and silica ball were investigated. These were further evaluated by the lubrication properties of GG aqueous solutions. The experimental results in this paper help to understand the sliding mechanism of proppant particles during HF processes. The study also provides significant information for the design of HF.

2. Experimental

2.1. Materials

Shale rocks were extracted from the shale formation in Chongqing, China, the dimension of which is 48 mm × 48 mm × 18 mm. Silica balls (silica content > 99%) were bought from the East China Sea Colorful Mineral Corporation (Jiangsu, China), the diameter of which is 3 mm. Fig. 2 shows photos of the shale rock and silica ball used in the current work. The elastic modulus for the shale rock and the silica ball are 35 GPa and 84.9 GPa respectively, and their respective Poisson's ratios are 0.25 and 0.2 [21,22]. The shale rocks were polished with 400-mesh sandpaper. Before each experiment, the shale rocks and silica balls were washed with acetone and ethyl alcohol to remove impurities respectively, and they were cleaned by deionized water, and then they were dry thoroughly in an oven. Fig. 3 shows the macroscopic surface morphology of shale rock and silica ball measured by a surface profilometer (KEYENCE VK-X100 series). According to Fig. 3, the surface roughness R_q of shale and silica ball are: $R_q = 1.7$ μm, and $R_q = 1.3$ μm, respectively. In this work, GG was purchased from Sigma-Aldrich (Shanghai) Trading Corporation. GG is a macromolecular carbohydrate and weighs about 1–1.5 × 10^6, which is made by galactomannan units [9,10].

2.2. Friction measurements

In order to investigate the effects of the concentration of GG in water-based fracturing fluids on the frictional properties of shale rock-silica contact, thirteen mass fractions, 0.1 wt %, 0.3 wt %, 0.5 wt %, 0.7 wt %, 0.9 wt %, 1.1 wt %, 1.3 wt %, 1.5 wt %, 1.7 wt %, 1.9 wt %, 2.1 wt %, 2.3 wt %, and 2.5 wt % were prepared by adding the proper amount of GG to deionized water to dissolve first. To make GG completely dissolve in water and prevent it into accumulating into lumps, it was stirred gradually in water until it was smooth. According to Tjon-Joe-Pin [23], in practical HF operations, GG concentrations ranged from 0.12 wt % to 0.96 wt %. Specific mass factions were selected to simulate the concentration of GG close to that of water-based fracturing fluids used in the petroleum industry. In addition, it was considered better to investigate the effect of higher mass fractions.

A reciprocating tribometer was used to the measure the coefficient of friction (COF), which is the ratio of frictional force to normal load of contact between shale rock and silica under a series of GG aqueous solution lubrications, as schematically described in Fig. 4. The silica ball was bonded on a pin by a nut, and the pin was fixed. The shale rock slid linearly in the horizontal direction with the lower sample platform moving. That is, the shale rock provided fully automated traction. The contact was immersed in an aqueous solution of guar gum and fully lubricated by that solution during the test. Eight normal loads, 0.1 N,