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Predicting fiber drag coefficient and settling velocity of sphere in fiber containing Newtonian fluids

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A B S T R A C T

In petroleum industry, fiber containing fluids are widely used as drilling fluids or fracturing fluids to improve the efficiency of cuttings transport during drilling or proppant transport during fracturing. Accurate prediction of fiber drag coefficient and settling velocity of sphere in fiber containing fluids is beneficial to design and optimization of fiber drilling/fracturing fluids applications. In this paper, a visualization apparatus and high-speed camera system are used to record the settling process in fiber containing Newtonian fluids. 283 tests involving different fiber concentrations (0.00%–0.10%), sphere diameters (1–10 mm), particle densities (2680, 4450 and 7960 kg/m^3) and fluid viscosities are conducted. The fiber drag force is redefined to be suitable for spheres with different density. The effects of fiber length and fiber concentration on fluids viscosity and particle settling are investigated. The relationship between fiber drag coefficient and particle Reynolds number is obtained based on the experimental data. An explicit settling velocity equation which directly predicts settling velocity of sphere in fiber containing Newtonian fluids is proposed by correlating the total drag coefficient with the dimensionless sphere diameter. The average relative error is 4.4%, which indicates predictions of settling velocity are in good agreement with measured settling velocity. The models for predicting fiber drag coefficient and settling velocity are valid with particle Reynolds number ranging from 0.05 to 167 and fiber concentration ranging from 0.00% to 0.10%. Besides, a trail-and-error procedure and an illustrative example are presented to show how to calculate fiber drag coefficient and settling velocity in fiber containing fluids. Results of this study may provide some basis for the better field applications of fiber containing fluids.

1. Introduction

In petroleum industry, fiber containing fluids are widely used as drilling fluids or fracturing fluids to improve the efficiency of cuttings transport during drilling or proppant transport during fracturing.

During drilling in highly deviated or horizontal wells, cuttings are easy to deposit and form a cuttings bed in the lower part of the wellbore due to gravity. Insufficient hole cleaning may results in lost circulation, hindering the casing or linear to be run into its selective position, excessive bit wear and pipe sticking (GhasemiKafrudi and Hashemabadi, 2016; Guo et al., 2010; Nazari et al., 2010; Ulker and Sorgun, 2016). Different kinds of drilling fluid sweeps are used to improve hole cleaning efficiency, such as high viscosity, high density, low viscosity, combination and tandem sweeps (Hemphill and Rojas, 2002). Fiber sweeps, which improve hole cleaning efficiency and do not increase equivalent circulating density, have been the subject of research in order to design and optimize fiber applications for years. Power et al. (2000) presented detailed data from two geological side tracks drilled from the same vertical wellbore to demonstrate hole cleaning efficiency by using different sweeps. It was found that the synthetic fiberous material was very effective in boosting hole cleaning efficiency in deepwater risers. In the first extended reach well to be drilled in Abu Dhabi, fiberous LCM sweeps increased the rate of cuttings returned to surface by up to 50% and frequently resulted in major improvements in the drilling rate when coupled with pipe rotation (Cameron et al., 2003). During drilling of 10 Kharyaga wells, cleaning efficiency of different types of sweeps including high viscosity sweep, high density sweep, tandem sweeps, sweeps with special additives (carbon-based LCM material or innovative monofilament fiber sweeping agent), combined tandem sweeps was studied. Sweeps performance showed that the best hole cleaning result was achieved by circulating combined tandem sweeps, which were low viscosity sweep treated with a monofilament fiber sweeping agent followed by a treated or untreated high density sweep (Bulgachev and Pouget, 2006). Ahmed and Takach (2009) experimentally investigated hole cleaning

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performance and hydraulics of fiber sweep (0.47% Xanthan Gum and 0.04% synthetic fiber) and base fluid (0.47% Xanthan Gum). Results indicated that fiber containing sweep had better hole cleaning capability than base fluid, even though these two sweep fluids had very similar rheological properties. Besides, friction pressure loss was slightly reduced by adding fiber under turbulent flow conditions. George et al. (2014) experimentally investigated the cleaning efficiency of fiber sweeps in inclined and horizontal wellbores. Results indicated that the addition of fiber substantially improved cuttings removal when the pipe was rotated in inclined wellbore and the addition of fiber had only a small effect on cuttings bed removal when pipe was not rotated or in horizontal wellbore.

Proppant transport is important for successful fracturing. On the one hand, flowback of proppant from fracture causes many problems, such as productivity reduction, equipment damage, additional operational cost and loss of workover efficiency. By pumping a mixture of fiber and proppant during fracturing, the fibers bond with each other to create a continuous network that resists proppant flowback during oil and gas production while the effect of fiber on conductivity is negligible (Bivins et al., 2005; Burukhin et al., 2012; Card et al., 1995; Cudney et al., 1997; Ramones et al., 2014). On the other hand, insufficient proppant transport influences proppant coverage over the entire fracture surface, the final fracture geometry after fracture closure and thus production performance. A low viscosity fracturing fluid which was composed of a linear gel and a fiberous material was developed to address the serious problems related to low modulus formations. Results from the test wells indicated that proppant flowback and sanding problems were significantly reduced while production per pound of proppant placed during a treatment increased (Vasudevan et al., 2001). A new fiber containing fracturing fluid was field tested in East Texas. Field results indicated that fiber containing fracturing fluid had reduced proppant settling rates and improved proppant transport with relatively low viscosity fluids. An 11% increase in proppant pack conductivity was obtained with a 50% reduction in polymer concentration compared with conventional polymer concentration. Besides, fractured height growth was well controlled and fracture half-length was increased while production performance with fiber containing fracturing fluids outperformed both conventional crosslinked fluid and slickwater fracturing treatments (Engels et al., 2004). Many types of fibers were experimentally investigated to find appropriate fiber for proppant transport, which had the correct combination of length, diameter, flexibility and temperature stability. Two fibers were chose that cover two reservoir temperature ranges: 66 °C–121 °C and 121 °C–204 °C based on the slot test and the proppant pack conductivity test (Bivins et al., 2005). A novel fiber containing low viscosity fluid technology was developed to improve proppant transport for hydraulic fracturing in low permeability tight gas formations. The fiber based network created in the fracturing fluid dramatically reduced proppant settling, and provided a mechanical means to transport and place the proppant at greater distances from the wellbore. Besides, no damage to fracture conductivity was caused due to the fiber's degradability under bottomhole conditions (Bulova et al., 2006).

Many experimental and theoretical investigations were conducted to study the effect of fiber concentration on rheological property of fluid. The study results of Vasudevan et al. (2001) indicated the linear guar gels behaved as a standard power law fluids while the fluid assumed Bingham plastic behavior with the addition of the fiber. Engels et al. (2004) pointed that the addition of fiber at concentration up to 30 lbm/1000 gal did not have a significant effect on fluid viscosity. In the study of Card et al. (1995), the authors concluded that the fiber increased the apparent viscosity of the fluid, but this was a physical rather than a chemical phenomenon and the removal of the fiber resulted in fluid viscosity value that was identical to those of the fluid before the fiber was added. Marti et al. (2005) characterized suspensions of spheres, fibers and mixtures using rotational shear rheometry and in-line image analysis. Results indicated that the relative viscosity is a monotonic increasing function of fiber concentration at relatively low solid volumetric concentration. Rajabian et al. (2005, 2008) formulated a rheology model for fiber containing polymer fluids that took into account the fiber-fiber interactions, fiber-polymer interactions and semiflexible nature of the fibers. Consequences of the model were compared with experimental results of the rheological properties in a simple shear flow. In the study of Bulova et al. (2006), the fiber did not have serious impact on the fluid viscosity when the fluid used in the tests was composed of 30 lbm/1000 gal guar polymer and short polymer fiber. George et al. (2011) concluded that the addition of fiber up to 0.08 wt% had a minor effect on the fluid's shear viscosity profile whether at ambient temperature or 170°F. Some instances showed slightly increases in viscosity, while others showed a decrease with increasing fiber concentration. Burukhin et al. (2012) pointed that addition of fiber at concentration of 72 lbm/1000 gal did not impact the viscosity of borate crosslinked guar solution. And in the following compatibility tests, the fiber containing fluid exhibited the same viscosity as base fluid. In the experimental study of George et al. (2014), fiber concentration had little or no impact on shear viscosity.

Improving particle transport efficiency by using fiber containing fluids largely depends an additional force provided by the fiber, which is called the fiber drag force. Settling experiment is an effective way to determine drag coefficient and settling velocity of particles in fluids, and there are numerous experiments about spherical or non-spherical particles settling in Newtonian or non-Newtonian fluids for decades (Barati et al., 2014; Brown and Lawler, 2003; Cheng, 2009; Chhabra, 2007; Kelessidis, 2004; Shah et al., 2007; Terfous et al., 2013). Although there are numerous studies about the performance of cuttings transport or proppant transport by using fiber containing fluids, few settling experiments in fiber containing fluids are conducted to investigate how much does the fiber contribute to the total drag force. Elgaddafi et al. (2012, 2016) experimentally investigated the settling behavior of 2–8 mm glass sphere in both fiber containing Newtonian and non-Newtonian fluids. Results indicated that the fiber drag force was the function of the particle's projected area, settling velocity, fiber drag coefficient, and density difference between the fluid and particle. Besides, a model was developed to predict fiber drag coefficient with the particle Reynolds number ranging from 0.04 to 10 and fiber concentration ranging from 0.02% to 0.08%. However, the effect of particle density on fiber drag coefficient was not investigated in the study of Elgaddafi et al. (2012), although settling velocity of 6 mm low density bead in mineral oil was measured and compared with model predictions. In fact, in petroleum industry, particle density varies within a variety of applications, especially proppants with different density are used while fracturing in formations with different properties.

Since the rheology property of Newtonian fluid is simpler than that of non-Newtonian fluid, so the real effect of particle density and fiber on particle settling could be figured out easier by using Newtonian fluid. Besides, Newtonian fluid are also be used as drilling fluid in drilling process or flushing fluid in sand cleanout process (Li and Luft, 2006; Kolle et al., 2008; Song et al., 2014; Kamyab and Rasouli, 2016). Therefore, Newtonian fluid is used as the fluid medium in this study. In order not to make readers confused, particle in this paper does not include fiber and it only means solid used for settling.

The objectives of this paper are to: 1) investigate the effect of particle density on the fiber drag force; 2) develop a new correlation between fiber drag coefficient and particle Reynolds number, which is suitable for spheres with different density and covers a larger particle Reynolds number range; 3) propose an explicit formula to predict settling velocity of sphere in fiber containing Newtonian fluids.

2. Experimental methods

Settling experiments are conducted in a 1500 mm long, 200 mm inner diameter Plexiglas cylindrical column, as shown in Fig. 1. The movement of sphere is recorded by the high-speed camera (Phantom v310) with a recording rate of 100 frames per second, which is connected directly to a computer for data storage and analysis. The viewing zone of the high-