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Original Research Paper

Characterization of proppant effective settlement diameter falling in non-Newtonian fracturing fluids

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ABSTRACT

The Stokes diameter is commonly used to characterize the size of non-spherical particles, but its application is limited to Newtonian fluids. In view of this case, an equivalent hydrodynamic diameter, defined as the effective settlement diameter, has been proposed from force balance for particles settling in non-Newtonian fluids, and an iterative calculation procedure was presented. In the present work, proppant effective settlement diameters falling in non-Newtonian fracturing fluids were studied. Settling velocities of three kinds of proppants falling in glycerol solutions, uncross-linked guar solutions and slick-waters were measured, numerous random repeated experiments were conducted, the corresponding proppant effective settlement diameters were calculated and the relationships between proppant effective settlement diameter and their sieve diameter falling in different fluids were studied. Results indicate that the proppant effective settlement diameter falling in uncross-linked guar solutions is bigger than that in glycerol, while it is smaller for slick-waters. When proppants settle in glycerol solutions, the proppants effective settling diameters are constantly 1.24 times bigger than their corresponding sieve diameter. For proppants settling in uncross-linked guar solutions and slick-waters respectively, two sigmoid curves of diameter ratio are obtained followed by reaching an asymptotic value, 1. This work presented a new calculation procedure of equivalent hydrodynamic diameter for non-spherical particles settling in non-Newtonian fluids. The effective settlement diameter extends the application conditions of Stokes diameter to non-Newtonian fluids and can be used in wider engineering applications.

1. Introduction

The terminal settling velocity of particles falling in incompressible viscous medias is commonly required for process design calculations in variety of industrial applications [1–3]. Stokes first established the free settling velocity correlation of spheres settling in infinite Newtonian fluid in 1851. However, experiments have shown that the departure of a particle from a spherical surface cause a higher drag force that causes a decrease of particle terminal velocity [4–6]. The settling behavior of particles with irregular shape is essential issue in many natural phenomena and industrial applications. Typical examples include transport of fine sands in rivers and lakes, ash clouds generated during explosive volcanic eruptions, proppants transportation in hydraulic fractures, polluted water emission, manufacturing with phase change and pharmaceutical granulation. Predictably, the terminal settling velocity of an irregular particle can be strongly influenced by its shape, which is considered to be one of the essential factors affecting the flowability of particles [7].

In petroleum industry, hydraulic fracturing is arguably one of the most leveraging completion technologies, particularly in gas reservoirs. This practice has also been a key factor in unlocking the potential of unconventional gas reservoirs. Proppant is one of the key materials in hydraulic fracturing. In fracturing stimulation treatments, fracturing fluids are used to suspend proppants into the deep of fractures, and the proppants keep the created fracture open upon cessation of pumping. The productivity of fractured wells is controlled by propped fracture length, which is directly dependent on proppant settlement and transport inside the fracture. Since proppants were first used in hydraulic fracturing, the question of placement in the fracture has remained, for the most part, unanswered. Due to the proppant particles are irregular and various

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Nomenclature

Symbols

a	fitting coefficient
b	fitting coefficient
C_D	drag coefficient
C_{DCal}	calculated drag coefficient
C_{DExp}	experimental drag coefficient
C_{DINVE}	drag coefficient for visco-inelastic fluid
C_{DVE}	drag coefficient for viscoelastic fluid
d_e	effective settlement diameter (mm)
d_m	characteristic diameter (mm)
DR	diameter ratio of particle effective settlement diameter to sieve diameter
g	gravitational acceleration (m/s^2)
G'	linear storage modulus (Pa)
G''	linear loss modulus (Pa)
k	uniformity coefficient
K	consistency index (Pa s^n)
m	mode numbers
n	flow behavior index
N_1	first normal stress difference
$P(d_e)$	cumulative frequency of d_e
Re_N	particle Reynolds number of particle settling in Newtonian fluids
Re_{NN}	particle Reynolds number of particle settling in non-Newtonian fluids
V_∞	particle terminal settling velocity (m/s)
We	Weissenberg number
X	drag coefficient factor

Greek symbols

α	dimensionless parameter
α_i	the ith anisotropy parameter
β	dimensionless parameter
γ	shear rate (s^{-1})
η	absolute fluid viscosity (Pa s)
η_i	the ith partial viscosity (Pa s)
η_s	viscosity of the Newtonian solvent (Pa s)
λ_i	the ith relaxation time (s)
ρ_l	fluid density (kg/m^3)
ρ_p	particle density (kg/m^3)
σ	shear stress (Pa)
ω	dynamic oscillatory frequency (rad/s)

non-Newtonian fracturing fluids are used in hydraulic fracturing treatments, how to calculate proppant settling velocity accurately in fracturing design is still a complicated problem to be solved.

In order to calculate settling velocity of irregular particle accurately, particle characterization should be studied in advance. Current methodologies to deal with this problem mainly fall into two distinct categories. The first approach involves the development of various shape factors that are widely used to modify drag coefficients, which in turn affect terminal velocities. One of the simplest and most commonly used shape factors is the Wadell's sphericity [8], which is defined as the ratio of the surface area of a sphere with equivalent volume to that of the actual particle. Mora and Kwan [9] measured the sphericity of concrete aggregate using digital image process. Bouwman et al. [10] evaluated the performance of 9 shape factors statistically and identified an optimal combination of shape factors to measure particle's shape and roughness. In addition, the dynamic shape factor that derived from a force balance of particle settling in quiescent fluids is the most suitable parameter for flow applications [7,11,12]. Since there are three flow regimes of particle settling in Newtonian fluids, the dynamic shape factor can be further sub-classified as Stokes' shape factor, intermediate regime shape factor and Newton's shape factor [12–14].

In the second approach, efforts were made to develop size characterization of non-spherical particles. The equivalent-volume-diameter and equivalent-area-diameter have been commonly used to evaluate the physical behavior of non-spherical particles. Schmidt-Ott and Wüstenberg [15] established the relationships between different equivalent diameters and optical diameter. However, for small non-spherical particles, the equivalent-volume-diameter and equivalent-area-diameter are hard to calculate. Heywood [16] established tables to calculate the hydrodynamic diameter and terminal settling velocity, which is considered as one of the best existing methods, and then Fonda and Capes [17] fitted the tables using polynomial equations. Considering the surface fractal characteristic of rough surface particles, Tang et al. [6,18] established and validated a computational method to calculate aerodynamic diameter, which is widely used to characterize aerosol [19,20].

As mentioned above, the shape factors and equivalent diameters are easily calculated for regular non-spherical particles, such as cylinder, cube, disc and needle etc. However, for irregular particles, these parameters are difficult to obtain. Moreover, how to use the shape factors and equivalent diameters to modify the C_D–Re relationships is still a complicated problem. In contrast, due to the dynamic shape factor and hydrodynamic diameter are derived from a force balance of particle settling in quiescent fluids, they can be directly used to calculate settling velocity. However, the presented models are commonly restricted to the case of particles settling in infinite Newtonian fluids [10–12]. To the best of our knowledge, it is important to note that none work have been done to determine hydrodynamic diameter of irregular particles settling in non-Newtonian fluids. In this work, a hydrodynamic diameter defined as effective settlement diameter for particles settling in non-Newtonian fluids is proposed, and the calculation procedure is presented. The effective settlement diameter is defined as an equivalent diameter of sphere possessing the same settling velocity of the actual particle falling in the same fluid. Subsequently, based on numerous settling experiments and statistical analysis, proppant effective settlement diameter distributions are studied, and the relationships between effective settlement diameter and sieve diameter for proppants falling in different fracturing fluids are established.

2. Models

Since spheres settling velocity can be calculated using particle diameter, the sphere diameter also can be calculated with measured settling velocity according to the corresponding C_D–Re correlations. For a non-spherical particle, the calculated diameter is defined as particle effective settlement diameter, which is equal to the diameter of sphere owing the same settling velocity falling in the same fluid with the actual particle. The drag coefficient of particles settling in quiescent fluids can be calculated as follows.

$$C_D = \frac{4}{3}\frac{gd_e}{V_\infty^2}\frac{\rho_p - \rho_l}{\rho_l} \quad (1)$$