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Experimental investigation of the settling velocity of spherical particles in Power-law fluids using particle image shadowgraph technique

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ABSTRACT

In this study, a new experimental technique, particle image shadowgraphy, is used to measure the settling velocities of spherical particles (0.5 mm–2.0 mm) in Power-law fluids of variable viscosity and density. Different concentrations of CMC-water mixtures (0.14–0.28 wt%) are used as test fluids for the experiments. A new empirical equation, which is an improved version of the Shah et al. (2007) model, for predicting the settling velocity of a spherical particle in Power-law fluid is proposed. The new empirical model is found to give an average error of 10% in predicting the settling velocity.

1. Introduction

Particle settling velocity is a key variable affecting sedimentation and transportation processes involved in many industrial operations such as settling of drilled cuttings and proppants in drilling and fracturing fluids, design of separators and settling tanks, and hydraulic and pneumatic transportation of solid particles in mining and agriculture industry applications. Factors affecting the settling velocity of sediment particles through fluids are well known (i.e., particle size, shape and density; fluid density, shear viscosity, yield strength, gel strength, elasticity). However, the functional relationship between the particle settling velocity and controlling factors is not well defined. Traditionally, prediction of settling velocities have either been made by analytically solving the governing equations derived for some simplified conditions or using empirical equations based on experimental curves. Stokes (1851), in his classical work, presented an expression for particle settling velocity by equating the effective weight of a spherical particle to the viscous resistance of the fluid. Since Stoke's pioneer work, numerous studies have been conducted resulting several empirical formulae to predict the settling velocity of particles. Rubey (1933) presented modified version of Stokes law by considering not only the viscous resistance but also impact force of the fluid on the particle. Gibbs et al. (1971) derived the empirical equation to correlate the settling velocity and size of the spherical particles. Peden and Luo (1987) proposed the drag coefficient correlations for spheres within a limited particle Reynolds's number range. Mordant and Pinton (2000), measuring the settling velocity of solid spheres using acoustic technique, found that the velocity of the particle shows transitory oscillations while reaching a stationary limit value. Brown and Lawler (2003) reviewed different settling velocity correlations and experimental results available in the literature and, by applying corrections for wall effect, suggested two new correlations of sphere terminal velocity, one applicable for all Reynolds numbers less than 2×10^5, and the other designed to predict settling velocities with exceptional accuracy for terminal Reynolds numbers less than 4000. There exists a wide range of opinions among investigators with respect to Power-law fluid applications and, unlike Newtonian fluids, there is no universally accepted general model for determining the settling velocities of spherical particles in Power law type fluids. Two different opinions prevail among researchers regarding the use of Newtonian drag curve for non-Newtonian fluid and on the dependency of drag coefficient on flow behavior index, *n*. Shah et al. (2007), Dallon (1967), Prakash (1983), Reynolds and Jones (1989), Peden and Luo (1987), Koziol and Glowacki (1988), Machac et al. (1995), Shah (1982), and Shah (1986) have all observed the strong dependency of drag coefficient on *n*. On the other hand, studies by Lali et al. (1989), Chhabra (1990), Chhabra (2002), and Kelessidis (2004) have shown that the use of Newtonian drag curve for Power-law fluid yields equally good results.

Drag coefficient correlations developed in various studies (Acharya et al., 1976; Darby, 1996; Ceylan et al., 1999; Matijasic and Glasnovic 2001; and Graham and Jones 1994) have been found to give an average error of varying between 23% and 64% for the settling velocity of spherical particles in Power-law fluids (Chhabra, 2002). Taking the complex nature of the correlations into consideration, use of Newtonian curve is generally the preferred choice. The use of Newtonian drag curve for predicting settling velocities, however, also led to an error of about 30% (Chhabra, 2002).

Since the average error involved in the case of Power-law fluid is large, the incorporation of settling velocity of spherical particles for

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calculating pumping energy, critical lift velocity, and other design parameters can potentially lead to significant errors. The failure of correlations and of the Newtonian drag curve motivated a seminal study by Shah et al. (2007), wherein a new and more accurate model was proposed. This model has been found to be more accurate than any other correlations in the literature and predicts the values with an average error of approximately 17%, with a maximum deviation of up to 29%. The issue of variability of results from one author to another was also noted during the course of the Shah's study.

Taking into account the high error in the predicted settling velocity values and the discrepancies in the measured experimental values of the literature, a detailed and accurate study is required. Little research has been conducted in recent years to carefully explain and investigate the accuracy of Shah's hypothesis. The relatively low values for regression in Shah's model may have occurred due to experimental errors in the measured values in the various studies which Shah drew upon. In other words, there is an issue of variability in the results from one author to another, which was noted in the study by Shah et al. (2007). There is thus room for improvement with respect to these correlations.

This work aims at developing a more accurate empirical correlation for predicting a sphere's settling velocity in Power-law fluid. The effects of fluid rheological properties, Power-law index, *n*, and consistency index, *K*, on a particle's settling behavior are addressed. The correlation developed by Shah et al. (2007) is improved to increase its predictive capability. The proposed empirical model is found to give an average error of 10%, with a maximum deviation of approximately 21%. It is an improved version of Shah's original model which predicts settling velocity with an average error of 17%.

2. Experimental procedure and materials

The particle image shadowgraphy (PIS) technique used for visualizing movement of particles in fluid media is based on high resolution imaging with pulsed backlight illumination. It operates on the general principle that a shadow is cast whenever there exists a significant difference in the density of the mediums through which light passes. Using this technique, a series of shadow images of the particle falling in the fluid and in the focal plane of the camera are captured using the double-frame camera with pulsed illumination system. Fig. 1 shows a schematic of the particle image shadowgraph setup and its elements. The experimental setup mainly consists of the following parts: Image Intense CCD camera, 12× Navitar lens, cubical fluid container, a laser as a source of illumination, high efficiency diffuser, and data acquisition system.

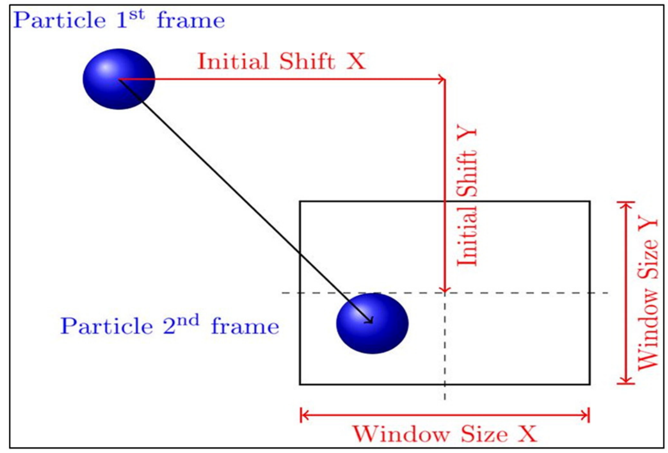

Fig. 2. Illustration of interrogation window used to determine velocities of particle (LaVision, 2010b).

The illumination source is comprised of a 50 mJ double pulsed Nd:YAG Solo III, Class 4 Laser with a frequency of 15 Hz attached to a high efficiency circular diffuser provided by LaVision. The laser beam thickness is adjustable and in this case, it is kept at the minimum value of 0.5 mm. The light produced is a pulsed green beam with a wavelength of 532 nm and 50 Hz frequency (Solo PIV, 2003). The image acquisition section consists of a double frame, CCD image intense camera provided by LaVision and a 12× Navitar lens. This is a high resolution, high sensitivity camera, which in double shutter mode can capture a pair of images in a time period as short as 500 ns. The exposure time is adjustable by using software and can be varied between 500 ns and 1 ms. The camera has a framing rate of 5 frames/s and also equipped with 12 bit CCD sensor with a resolution of 1376 × 1040 pixels pixels (LaVision, 2006).

One of the important advantages of using PIS is that it is independent of the shape and physical properties (e.g., density, size, and transparency) of the particles. It also permits investigating the particle's size down to 5 μm and freeze motions up to 100 m/s when using the appropriate imaging system and light source (LaVision, 2010b).

A carboxymethyl cellulose (CMC) mixture in water is used as the fluid medium, and different concentrations (0.14–0.28 wt%) of CMC-water mixture are prepared and used in the experiments. Polymer solution is prepared by slowly mixing the polymer in the agitating mixture. The key to preparing the homogeneous mixture is to add the polymer as

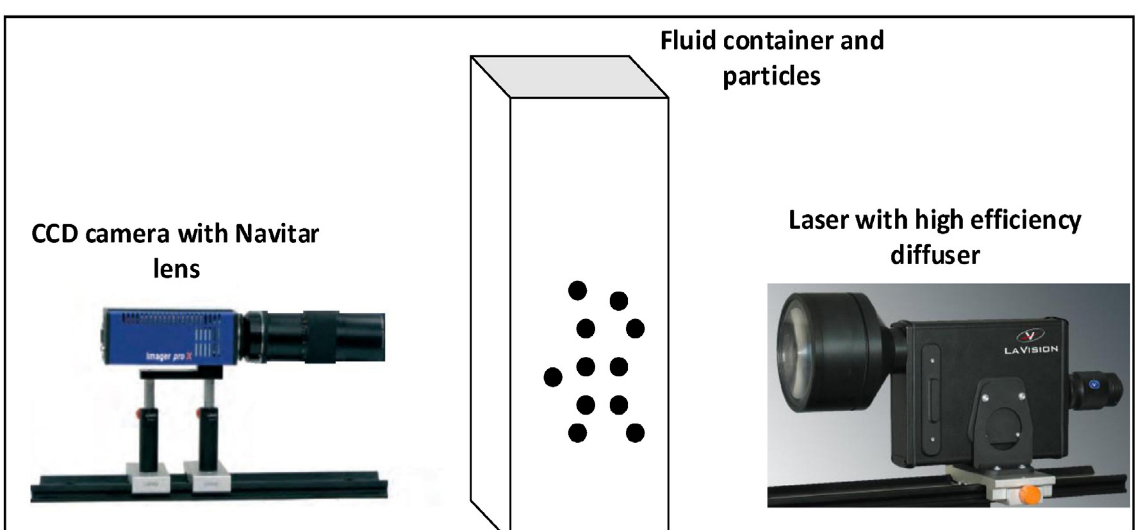

Fig. 1. Components of the experimental setup used for measuring settling velocity with particle image shadowgraphy technique.