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Experimental investigation of non-stationary motion of single small spherical particles in an upward flow with different velocities

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ABSTRACT

This experimental investigation focuses on carefully determining the drag coefficient of single spherical particles with considerable small diameters in non-stationary motion. A low-speed wind tunnel and a set of high-speed photography system are employed to confirm the displacement of each particle from its trajectory. Moreover, spherical particles of two different densities are used and the minimum diameter of these particles reaches 0.1 mm. Meanwhile, the Basset force generated from the relative acceleration in the gas-particle flow is calculated approximately. The experimental results show that the maximum proportion of Basset force does not exceed 2.2%. In addition, the relationship of $C_D - Re$ for the experimental data is also determined. This research offers fundamental experimental results for industrial applications and also contributes to the research of non-stationary gas-particle flow.

1. Introduction

China is suffering from the heavy haze weather nowadays. Thus, it is vital to purify the air and protect our environment. Thus, the tiny particles' manufacturing industries need to dramatically improve separation efficiency of the gas-particle separators, especially for the particles of diameter ranging from 1 μm to 1 mm.

The study of gas-particle flow is quite important and useful for the investigation of hydrodynamic applications, which is involved in air purification and environmental protection. In particular, the study of single spherical particles' motion is fundamental for gas-particle flow. In this area, Clift et al. [26] and Michaelides [19] reviewed the research background and previous work.

Drag force is one of the most important hydrodynamic forces in gas-particle flow, which is generated by friction and pressure gradient between the fluid and the particle [3]. Generally, the function of drag force is given as

$$F_D = C_D \frac{1}{8} \rho_f \pi d_p^2 \left(u_f - u_p\right) \left|u_f - u_p\right| \tag{1}$$

where F_D is the drag force of single spherical particle and C_D is the drag coefficient. ρ_f and d_p are fluid density and the diameter of the sphere respectively. u_f is the velocity of fluid, and u_p is the velocity of the spherical particle.

Ignoring the inertial effects, the relationship for predicting the drag force coefficient C_D of spherical particles in creeping flow ($Re < 1$) was derived by Stokes [30].

$$F_D = 3\pi\mu d_p \left(u_f - u_p\right) \qquad Re < 1 \tag{2}$$

where Re is a dimensionless parameter,

$$Re = \frac{\rho_f d_p \left|u_f - u_p\right|}{\mu} \tag{3}$$

Thus, in such range of Re, C_D can be described as

$$C_D = \frac{24}{Re} \tag{4}$$

Under most circumstances, however, Eq. (2) could not be used to predict the drag force when inertial effects exist. Thus, numerous equations were derived theoretically or experimentally to adapt more circumstances [2,3,5,8,9,11,15–17,20,34]. Combining the previous experimental data before Lapple and Shepherd [16]), these literatures were too old to collect, a standard drag coefficient curve was derived from the previous experiments and can still be used. Among these previous works, Brown and Lawler [5] collected the historical experimental

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data and reviewed the existing C_D–Re relationships. They also presented a correlation for the range of $Re < 2.6 \times 10^5$, which was very satisfactory for use. Six years later, Cheng [8] drew a function with a similar form and better accuracy for $2 \times 10^{-3} < Re < 2 \times 10^5$. Morrison [11] proposed a correlation for $Re < 10^6$, which covered the entire range of experimental data. Meanwhile, Mikhailov and Freire [20]) presented a model to predict drag coefficient using a non-linear rational fractional transform for $Re < 10^5$. Recently, Barati et al. [3] collected a complete set of historical experimental data and correlations. They developed two correlations with high accuracy and usability with an approach of multi-gene Genetic Programming procedure. We will summarize several previous empirical relationships in the next section.

Actually, most of the previous data were obtained from steady sedimentation experiments of which the fluid velocity is constant and the texting spherical particles reached their terminal velocity. However, the non-stationary motion of particles is common in engineering applications, and it is questionable of using such correlations to predict the drag force of spheres. For solving this problem, Jourdan et al. [13] reviewed previous investigation of non-stationary flow of spheres, including the work of Buckley [6], Nicholls and Selberg [22], Rudinger [27], Karanfilian and Kotas [14], Outa et al. [24]), Sommerfeld [29], Igra and Takayama [12], Boiko et al. [4], Tanno et al. [33]), Sun et al. [31]) and Parmar et al. [25]). Meanwhile, Jourdan et al. [13] presented an array of shock tube experiments of a small sphere in non-stationary flow, of which the Re ranged from 500 to 10^4. They found that the drag coefficients of particles in unsteady flow were larger than those in steady flow within certain Re numbers and the difference exceeded 50%. Besides, it is worth mentioning that Igra and Takayama [12] and Suzuki et al. [32] also found that the values of drag coefficient of sphere in non-stationary flow were significantly larger than those in steady flow. Igra and Takayama [12]) reviewed previous experiments and presented a study of drag coefficient values of spheres laid on the shock tube floor, of which the Re ranged from 6000 to 101,000. Later, Suzuki et al. [32] used a special device that can launch a single small sphere to the center of the test section of the shock tube when the shock was arrived. And the range of Re number was from 10^3 to 10^5. Finally, they found that the average difference between the result and standard drag curve was about 20%.

In the separation process of some special separators, such as gravity precipitator and cyclone separator, the particulate flow is in the non-stationary state. The dusty particles accelerate from the quiescent state to the uniform motion state in their terminal velocities. However, in the available literature, the experimental research on non-steady motion of single particle is not sufficient. Moreover, the diameter of the smallest single spheres in the previous experiments was 0.29 mm [13] which is larger than the dusty particles. There is no much evidence to confirm that the existing C_D–Re curves and models are appropriate for predicting the drag coefficient of spheres smaller than 0.29 mm in the unsteady motion. Thus, one purpose of this study is to develop an experimental device to record and measure the displacements of particles whose diameter ranges from 0.1 mm to 0.5 mm. Furthermore, another purpose is to verify whether the available C_D–Re relationships can be used in non-stationary motion of these small spheres. And the experimental investigation can provide a basis for the development of the cyclone separator. Finally, this preliminary study would be very helpful for future study of the smaller particles' unsteady motion.

2. Force analysis of a moving sphere

The force balance of a smooth single spherical particle moving in a flow can be described as,

$$\sum F_n = 0 \tag{5}$$

Considering a condition like this: Release a small spherical particle into an infinite, incompressible, homogeneous, upward gas flow field without electrification and initial velocity. On the vertical dimension, Eq. (5) can be transformed as,

$$F_i + F_g + F_b + F_D + F_{add} + F_B = 0 \tag{6}$$

The terms on the left side of Eq. (6) represent these different forces: inertial force, gravitational force, buoyancy force, drag force, add-mass force and history force. The expressions of each force are given as below.

Inertial force,

$$F_i = \rho_p V_p \frac{du_p}{dt} \tag{7}$$

Gravitational force,

$$F_g = \rho_p V_p g \tag{8}$$

Buoyancy force,

$$F_b = -\rho_f V_p g \tag{9}$$

Drag force,

$$F_D = C_D \frac{1}{8} \pi d_p^2 \rho_f \left(u_f - u_p\right) \left|u_f - u_p\right| \tag{10}$$

Drag force is generated by the friction ($Re < 1$), or hydrodynamic pressure gradient ($Re > 1000$), or both of them ($10 < Re < 1000$) of the fluid [3]. Many empirical or semi-empirical C_D–Re relationships are available with different types, and we enumerate several formulas published after 2000 in Table 1.

Table 1
Empirical or semi-empirical C_D–Re relationships published after 2000.

Author	C_D–Re relationship	Re	No.
Ceylan et al. [35]	$C_D = 1 - 0.5e^{0.182} + 10.11Re^{-2/3}e^{0.952Re^{-1/4}} - 0.03859Re^{-4/3}e^{1.30Re^{-1/2}} + 0.037 \times 10^{-4} Re\, e^{-0.125 \times 10^{-4} Re} - 0.116 \times 10^{-10} Re^2 e^{-0.444 \times 10^{-5} Re}$	$0.1 < Re < 10^6$	(11)
Brown and Lawler [5]	$C_D = \frac{24}{Re}(1 + 0.15Re^{0.681}) + \frac{0.407}{1 + 8710/Re}$	$Re < 2.6 \times 10^5$	(12)
Almedeij [2]	$C_D = \left[\frac{1}{(\varphi_1+\varphi_2)^{-1} + \varphi_3{}^{-1}} + \varphi_4\right]^{0.1}$ where $\varphi_1 = (24Re^{-1})^{10} + (21Re^{-0.67})^{10} + (4Re^{-0.33})^{10} + (0.4)^{10} \varphi_2 = [(0.148Re^{0.11})^{-10} + (0.5)^{-10}]^{-1} \varphi_3 = (1.57 \times 10^8 Re^{-1.625})^{10} \varphi_4 = [(6 \times 10^{-17} Re^{2.63})^{-10} + (0.2)^{-10}]^{-1}$	$Re < 10^6$	(13)
Cheng [8])	$C_D = \frac{24}{Re}(1 + 0.27Re)^{0.43} + 0.47\left[1 - e^{-0.04Re^{0.38}}\right]$	$2 \times 10^{-3} < Re < 2 \times 10^5$	(14)
Mikhailov and Freire [20]	$C_D = \frac{3808(1617933/2030 + 178861Re/1063 + 1219Re^2/1084)}{681Re(77531/422 + 13529Re/976 - Re^2/71154)}$	$Re < 118300$	(15)
Terfous et al. [34]	$C_D = 2.689 + 21.683/Re + 0.131/Re^2 - 10.616Re^{0.1} + 12.216/Re^{0.2}$	$0.1 < Re < 5 \times 10^4$	(16)
Morrison [11]	$C_D = \frac{24}{Re} + \frac{2.6(Re/5)}{1 + (Re/5)^{1.52}} + \frac{0.411(Re/263000)^{-7.94}}{1 + (Re/263000)^{-8}} + \frac{Re^{0.80}}{461000}$	$Re < 10^6$	(17)
Barati et al. [3]	$C_D = 5.4856 \times 10^9 \tanh(4.3774 \times 10^{-9}/Re) + 0.0709 \tanh(700.6574/Re) + 0.3894 \tanh(74.1539/Re) - 0.1198 \tanh(7429.0843/Re) + 1.7174 \tanh[9.9851/(Re + 2.3384)] + 0.4744$	$Re < 2 \times 10^5$	(18)