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Full Length Article

A numerical study of the wall effects for Newtonian fluid flow over a cone

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A B S T R A C T

The effect of blockage ratio i.e. ratio of diameter of cone, d and flow channel, D on the drag coefficients due to Newtonian fluid flow over cone is studied numerically by solving the CFD equations in Ansys FLUENT. The drag coefficients (C_D) as a function of Reynolds number (Re) and d/D are reported in the range of Re: 0.01–30,000 and d/D: 0.0015–0.9. The obtained C_D values are higher for confined flow (high d/D) than unconfined flow. Validity of $C_D Re^2$ = constant is ascertained for the confined Newtonian fluid flow over the cone. The variations of angle of separation and its effect on the drag coefficients are examined and justified. The comparative studies among the drag coefficients of sphere, cylinder and cone are carried out in terms of wall effect, re-circulation length and slope of axial velocity profile. The observations revealed the order of C_D as cylinder > cone > sphere. The hydrodynamic interactions between wall and fluid medium are presented with the help of velocity contour plots. More asymmetric flow is observed around the particle at higher Reynolds number and for higher wall effect. The simulated results presented herein for unconfined flow are in good agreement with the literature data.

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1. Introduction

Drag coefficient is an important process parameter for the successful design of many industrial equipments like cyclone separators, fluidized beds, dust collectors, pulverized-coal combustors, particle separation system, electrostatic precipitator, spray drying etc. The presence of submerged objects in a channel does not only affect the hydrodynamic behaviors of fluids but also influence the heat transfer performance of the system [1–3]. In reality, particles of different shapes are present in the crushed and meshed solid particles and in the mixture of fruits and vegetables being dried in food industries. The particles may have spherical, cylindrical, cubical and cone shapes. A good amount of research work is available on the study of the drag coefficients of spherical and cylindrical particles in both the Newtonian and non-Newtonian fluids. Comparatively very less study on the drag coefficient of the cone shaped particles especially theoretical analysis has been performed till date. Although multi-particles are present in most of the solid handling industrial process, the hydrodynamics of single particle give useful information on the settling behavior of the multi-particle systems. For single particle, many correlations for the drag coefficients as a function of the particle Reynolds number, Re are available in the open literature [4–7]. It is always beneficial for the efficient designer to know with high accuracy the drag coefficients of all the possible shaped particles especially through the simulation work. The simulated drag coefficient and wall effect data are available for spherical, cylindrical and other regular shaped particles. But, unfortunately, it is unavailable for the cone shaped particles.

Mathematically, the drag coefficient is expressed as [8]

$$C_D = \frac{2F_D}{AV^2\rho} \tag{1}$$

in which V is the terminal velocity of solid particle, ρ is the density of liquid, and F_D is the drag force.

Particle Reynolds number is used to check the flow regimes around the particles, and defined as [8]

$$Re = \frac{\rho d V}{\mu} \tag{2}$$

where μ the kinematic viscosity of liquid.

In confined flow, particle flows along flow axis of the flow channel. The wall of the channel applies an additional retarding effect on the terminal velocity of the particle called wall effect. It can be represented by the wall factor, f [8,9,5,6].

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Nomenclature

C_D	Drag coefficient	Re_∞	Reynolds number based on V_∞
$C_{D\infty}$	drag coefficient at $d/D = 0$	L	length of particle (mm)
F_D	Drag force (N)	CS	corn syrup
V	terminal velocity (m/s)	θ	angle of separation (°)
V_∞	unbounded terminal velocity (m/s)	l_w	re-circulation length (mm)
V_{max}	maximum measured terminal velocity (m/s)	ρ	density of fluid (kg m^{-3})
A	projected area (m^2)	μ	kinetic viscosity (Pa.s)
d	diameter of particle (mm)	τ	shear stress, Pa
R	radius of particle (mm)	P	pressure
r	radial position (mm)	u	velocity of fluid (m/s)
D	diameter of flow channel (mm)	g	acceleration due to gravity (m/s^2)
Re	Reynolds number based on V		

$$f = \frac{V}{V_\infty} \tag{3}$$

in which V and V_∞ are the terminal velocity of the particle in bounded and unbounded fluids, respectively. For Newtonian fluids f is function of the Reynolds number and the ratio of the diameters of free falling particle and flow channel.

The presence of the tube wall makes the behavior of the bounded flow different form the unbounded flow (Singha and Sinhamahapatra [10]). The bounded flow spreads the wake, shifts the separation point in the downstream site and changes the extent and nature of vortex interaction between vortices of the flow wall and solid particles. The unconfined drag coefficient $C_{d\infty}$ was determined experimentally by many researchers [8,9] by extrapolating the confined C_D vs. d/D curve to $d/D = 0$.

1.1. Background of the work

Uhlherr and Chhabra [11] showed that the drag coefficient of sphere falling in cylindrical tubes is affected by both the falling sphere to flow channel diameter ratio and Reynolds number. They concluded that at low ($Re \leqslant 0.5$) and high ($Re \geqslant 100$) Reynolds number the wall factor, f depends only on the diameter ratio. They used the following equation along with the logarithmic plot of C_D versus Re and diameter ratio as the parameter to estimate directly the unconfined drag coefficient for the sphere [11]

$$C_D Re^2 = \text{Constant} \tag{4}$$

Chhabra et al. [12] also examined the effect of the wall on the terminal velocity of sphere settling along the axis of a cylinder filled with Newtonian fluids. In their work, only sphere to flow channel diameter ratio dependent wall factor was reported both at very low and very high Reynolds numbers. They also reported that the drag coefficient is varied with both the diameter ratio and Reynolds numbers at the intermediate Re. Similar kind of wall effect studies also had been carried out by many researchers [13–17] in non-Newtonian fluids.

Hydrodynamics behavior of laminar flow of Newtonian fluid over a hot confined sphere was theoretically studied by Krishnan and Kaman [18]. They showed that the wall effect is predominant at lower particle Reynolds number, and the accuracy of the prediction of wall effect has become better at higher blockage ratio and Reynolds number. Stalnaker and Hussey [19] studied the wall effect due to the transverse motion of long length and short diameter cylinder through a Newtonian fluid. The effect of the wall on the dimensionless drag coefficient was categorized into strong boundary and weak boundary regions. The effect was seen less in the weak boundary zone than the strong region. Unnikrishnan and Chhabra [9] studied the wall effects on the drag coefficient of cylinders falling through different Newtonian fluids with wide range of viscosity. The ratio of the cylinder to flowing tube radius was varied in the range of 0.08–0.4, cylinder length to cylinder diameter from 0.05 to 2 and Reynolds number 0.2 to 180. The unconfined terminal velocity was calculated by extrapolating the experimental terminal velocity versus diameter ratio profile to the diameter ratio equal to zero. They reported the dependency of the terminal velocity and wall factor on the length of the cylinder. Analytical expression of the unconfined drag coefficient developed by them is given below [9]

$$C_{D\infty} = \frac{17.5}{Re_\infty}\left(1 + 0.68 Re_\infty^{0.43}\right) \text{ for } 0.0513 \leqslant L/d \leqslant 2 \tag{5}$$

in which $C_{D\infty}$ and Re_∞ are the drag coefficient and Reynolds number at unconfined terminal velocity, L and d are the length and diameter of the cylindrical particle. They also suggested a linear variation (Eq. (6)) of the wall factor of the cylinder with the diameter ration for $Re < 30$.

$$f = 1 - 0.69\frac{d}{D} \text{ for } Re > 30 \tag{6}$$

Chakraborty et al. [20] carried out numerical analysis of the hydrodynamic behavior of Newtonian fluid flow over a circular cylinder confined in a rectangular channel. Reynolds number and the ratio of the cylinder diameter to flow channel width were varied in the range of 0.1–200 and 0.05–0.66 respectively. They too observed that the drag coefficient decreased with decreasing the diameter ratio and increasing the Reynolds number.

Experimental drag coefficients of the cone shaped particles settling in both the Newtonian and non-Newtonian fluids were reported by Sharma and Chhabra [8]. The study was carried out using unconfined flow Reynolds number which varied in the range of very low to 500 as the system parameter. In their study, the cone angle was varied in the range of 43°–93.7°. The flow behavior index, n was kept in the range of 1.0–0.62 with the consistency index, m of $3.73 \times 10^{-3} < m < 4$ Pa.s^n. The ratio of the cone to flow channel diameters was also varied in the range of 0.148–0.4343. The wall effect, f was found independent of the apex angle and power law index but affected by the diameter ratio and Reynolds number. Chhabra [21] reported the wall factor for a range of non-spherical particles like cubes, parallelepipeds, cylinders, needles, thin plates and circular discs sedimented in stationary Newtonian liquids. In all the cases, the wall factors were varied with the shape and size of the particles at low Reynolds number. They also developed correlations for the variations of wall factor with the particle to tube diameter ratio. They identified that all the shapes except thin cylinders ($L/d > 10$) experience smaller wall effect than sphere of equal volume. Nitin and Chhabra, and Munshi

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