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Lift and drag forces on an isolated cubic particle in pipe flow

*D. Laskovski**, *P. Stevenson*, *K.P. Galvin*

Centre for Advanced Particle Processing, University of Newcastle, Callaghan, NSW 2308, Australia

ABSTRACT

In this paper, the critical instantaneous lift force required to move an initially stationary magnetic cube from the wall of a cylindrical pipe was examined using a novel method in which an electromagnet was employed. The electromagnet was used to control the contact force between the magnetic particle and the pipe wall by, in effect, varying the effective particle density from 1000 kg m^{-3} to more than 12,000 kg m^{-3}. This control over the effective particle density provided a simple and non-intrusive technique of determining the critical lift force acting on the cubic particle for a broad range of fluid velocities. The cubic particle was chosen to be greater in size than the depth of the von Kármán [von Kármán T., 1930. Mechanische ahnlichkeit und turbulenz. *Math. Phys. Klasse* **5**, 58–76] viscous sub-layer for the range of fluid velocities examined. Critical instantaneous lift forces deduced from the experimental data resulted in an average lift coefficient, C_L, of 3 for pipe Reynolds numbers of $Re < 20{,}000$. A wall-corrected drag coefficient, C_{Dw}, of $C_{Dw} = 114\,Re_p^{-0.8}\,C_D$ for $100 < Re_p < 1000$ was used to calculate the critical lift force, where Re_p is the particle Reynolds number and C_D the drag coefficient. The wall-corrected drag coefficient correlation given above was determined in separate experiments in which the horizontal displacement of the cube, after its sudden release from the soffit of the pipe, was recorded. The release was achieved by firstly holding the particle in position using a magnet and then rapidly removing the magnet. This paper appears to be the first to non-intrusively evaluate the critical instantaneous lift force acting on a specific cubic particle at the pipe wall over a broad range of superficial fluid velocities.

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Keywords: Lift; Drag; Hydrodynamic; Electromagnet; Particle; Cube

1. Introduction

Recently, Laskovski et al. (2007) investigated the distribution of instantaneous hydrodynamic lift forces imposed on isolated cubic particles, which were larger in size than the depth of the von Kármán (1930) viscous sub-layer, at rest on a pipe wall. By observing the sporadic motion of the cube during its hydraulic conveying along the base of an inclined test pipe, at a set fluid velocity, Laskovski et al. (2007) were able to infer a lift force distribution using statistical analysis. In general, the instantaneous hydrodynamic lift force, L_F, which is defined as the perpendicular component of the combined shear and pressure forces acting on the surface of the immersed particle (Fox and McDonald, 1985), is expressed as:

$$L_F = \frac{1}{2} C_L \rho A_p u^2 \quad (1)$$

where C_L is the lift coefficient, ρ is the fluid density, A_p is the projected area of the particle and u is the local fluid velocity relative to the particle. Similarly, the hydrodynamic drag force, which is defined as the parallel component of the combined shear and pressure forces acting on the surface of the immersed particle (Fox and McDonald, 1985), is generally expressed as:

$$F_D = \frac{1}{2} C_D \rho A_p u^2 \quad (2)$$

where C_D is the drag coefficient. Clearly, both lift and drag exhibit a strong dependence upon the local fluid velocity, u, which in this study is defined as the undisturbed local fluid velocity at a distance equal to half the particle height away from the wall.

Particles exposed to turbulent flow tend to experience a distribution of local fluid velocities and subsequently a

* *Corresponding author at*: The University of Newcastle, Centre for Advanced Particle Processing, School of Engineering, Newcastle, NSW, 2308, Australia.

E-mail address: daniela.laskovski@newcastle.edu.au (D. Laskovski).

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Nomenclature

a_h	particle acceleration in the vertical direction ($m\,s^{-2}$)
A_p	projected area of the particle (m^2)
B	magnetic flux density (T)
B_c	critical magnetic flux density (T)
C_D	drag coefficient (–)
C_{Dw}	wall-corrected drag coefficient (–)
C_L	lift coefficient (–)
d	particle height (m)
F_D	drag force (N)
F_{Dw}	wall-corrected drag force (N)
F_F	friction force (N)
F_M	magnetic force (N)
F_{Mc}	critical or minimum magnetic force (N)
F_W	buoyant weight force (N)
g	gravitational acceleration ($m\,s^{-2}$)
I	current (A)
K_F	correction factor (–)
L_F	lift force (N)
L_{Fc}	critical lift force (N)
m	effective mass (kg)
Re	fluid Reynolds number (–)
Re_p	particle Reynolds number (–)
Re_t	terminal Reynolds number (–)
S_h	horizontal displacement (m)
S_v	vertical displacement (m)
t	time (s)
u	undisturbed local fluid velocity ($m\,s^{-1}$)
u_0	initial slip velocity ($m\,s^{-1}$)
u_p	particle velocity ($m\,s^{-1}$)
u_t	terminal velocity ($m\,s^{-1}$)
u_s	slip velocity ($m\,s^{-1}$)
U	superficial fluid velocity ($m\,s^{-1}$)
V	particle volume (m^3)
z	distance (m)

Greek letters

χ_m	magnetic susceptibility (–)
μ	dynamic viscosity (Pa s)
μ_c	coefficient of static friction (–)
μ_0	magnetic permeability in vacuum ($m^3\,m^{-3}$)
ρ	fluid density ($kg\,m^{-3}$)
ρ_s	particle density ($kg\,m^{-3}$)

distribution of lift and drag forces. Particles positioned at a pipe wall, such as those considered by Laskovski et al. (2007), experience significant Reynolds stresses if, and only if, their characteristic dimension is greater than that of the von Kármán (1930) viscous sub-layer, i.e., they extend into the buffer layer. The viscous sub-layer is defined as a narrow region of approximately laminar fluid that exists near a stationary solid boundary when in the presence of a moving fluid. This boundary layer concept, first introduced by Prandtl (1904), implicitly suggests that the fluid beyond the narrow viscous region tends to be less laminar in nature and hence more turbulent. As such, it is anticipated that particles not residing entirely within the viscous sub-layer (i.e., relatively large particles) experience a distribution of local fluid velocities and hence a distribution of lift and drag forces. It is noted that the assumption of laminar flow within the viscous sub-layer is simplistic since coherent turbulent structures (such as bursting and sweeping events) cause minor Reynolds stresses within the viscous sub-layer.

The hydrodynamic forces experienced by a stationary immersed particle, positioned at the wall of a pipe, ultimately govern the particle hydraulic conveying. In order to write a force balance, expressions for the drag and lift force imparted on the particle by the fluid at the pipe wall are required. However, much of the available drag force literature focuses on defining the drag of spheres in infinite media. In fact, relatively few studies such as those of Faxén (1923), Fayon and Happel (1960), Achenbach (1974) and Clift et al. (1978) have investigated the effect of a near pipe wall on the drag of immersed, mainly spherical, bodies. Fewer still, such as Tözeren (1983) and Ambari et al. (1984), investigate the near pipe drag of eccentrically positioned particles which again were spherical in nature. In this paper the particle considered is non-spherical, and while lift force literature for spherical particles such as the work of Saffman (1965, 1968), Halow (1973), Cabrejos and Klinzing (1992) and O'Neill (1968) exist, relatively few studies investigate the lift force of non-spherical particles. One exception is the work of Stevenson et al. (2002) who investigated the lift and drag force of small (i.e., smaller in size than the depth of the viscous sub-layer) non-spherical particles on horizontal pipe walls. An extensive search of the literature has failed to reveal a study, other than that of Laskovski et al. (2007), that considers the lift and drag force of an isolated particle that is both non-spherical and larger in size than the depth of the viscous sub-layer at a pipe wall.

An important point of difference between spherical and non-spherical particles in the context of the study is the method in which they tend to commence motion, given that spherical particles tend to begin motion via rolling whereas non-spherical particles preferably commence motion via dragging (Stevenson et al., 2002). The apparent lack of relevant lift and drag force literature for large non-spherical particles is hence a motivating factor in this study. This current study, which follows on from Laskovski et al. (2007), will determine the instantaneous drag force and critical lift force values for cubic particles in a horizontal pipe flow arrangement over a range of fluid velocities. Here, the critical lift force is defined as the minimum lift force required to initiate the hydraulic conveying of the cube. A cubic geometry was chosen as an ideal non-spherical particle because of its well defined geometry.

It is proposed that the distribution of drag forces can be measured by observing the horizontal displacement of the cube after its sudden release from the soffit of a test pipe. The sudden release was achieved by firstly holding the particle in position using a magnet, and then suddenly withdrawing the magnet. It is also proposed that the critical lift force can be measured using a novel method in which an electromagnet is used to vary the contact force between the particle and the pipe wall. The direction of the applied force depends upon the relative orientation of the magnetic poles. Varying the intensity of the magnetic field by increasing or decreasing the supplied current allows the contact force between the particle and the pipe wall to vary accordingly. In addition, the electromagnet ensures that the effective density of the particle can be manipulated. In this way a single particle, having given contact frictional properties, can be deployed over a broad range of fluid velocities.

In this study, the use of an electromagnet allows a steady hydrodynamic condition to be reached prior to the onset of particle movement. The alternative method of gradually rais-

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