

Drag Force Analysis for an Inertial Microfluidics Device

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Abstract

In the current article, the effects of drag force on the three-dimensional motion of particles in an inertial microfluidic channel are analytically studied. The drag force has an important role to play in the motion of particles in this class of microscale channels. Analytical expressions are given for determining the drag force exerted on a spherical rigid particle when there is relative motion between the particle and fluid. Furthermore, the influences of particle diameter on the drag force and drag coefficient are analyzed in detail. It is predicted that the present paper would help engineers and researchers to better understand the motion of particles in microfluidic channels.

Keywords: Inertial microfluidic; Particle motion; Drag force; Drag coefficient

Introduction

Microelectromechanical and nanoelectromechanical systems (MEMS and NEMS) made of ultra-small structures have shown many fascinating functions and abilities in recent years [1-8]. More specifically, new promising techniques have been proposed in medicine to diagnose a range of diseases based on MEMS and NEMS [9]. Compared to traditional methods, these new methods display a fast-reliable analysis. In addition, the final size of these systems is comparatively very small since the most common fundamental building blocks of these systems are microscale structures [10-22] and nanoscale structures [23-29]. Due to their small size, they can be utilized everywhere regardless of lab equipment and facilities [30]. Microfluidics-based technology has been shown to be very promising for many applications in the field of microtechnology including water purification, drug delivery, virus detection and cell separation [31]. For instance, Shafiee et al. [32] invented a microfluidics-based microscale sensor, which is able to detect human immunodeficiency virus (HIV) in blood samples. This sensor is small, light and unexpansive, which make it an ideal candidate for HIV screening in areas in which there is no access to advanced hospital equipment and trained technicians. Microfluidics-based devices are divided into different groups according to their size, applications and governing forces. One widespread categorization of these ultra-small devices is based on governing forces. According to this categorization, there are two types of microfluidics-based devices:

- a. Active, and
- b. Passive.

If there are external forces, which act on the particles and fluids inside the microfluidics-based device, it belongs to the active group. By contrast, if the particles and fluids are subject to intrinsic forces such as drag, inertial and wall-induced forces, the microscale device is considered as passive. Each group of microfluidics-based devices is also divided to several sub-groups. One of significant sub-groups of passive microfluidics-based technology is inertial microfluidics, which is focused in this paper. Inertial microfluidics has shown a promising potential in various biomedical applications such as the separation of rare ultra-small biological objects and the preparation of biological samples. In these applications, when an ultra-small object moves in a flowing fluid, various forces including Magnus, Saffman and drag forces act on the object, and significantly affect its motion. In this work, the drag force, as

an important intrinsic force in a microfluidic channel, as well as the drag coefficient are analytically examined. Explicit expressions are

given for this important force. Moreover, the influences of particle diameter on the drag force and coefficient are analyzed.

Drag Force and Coefficient

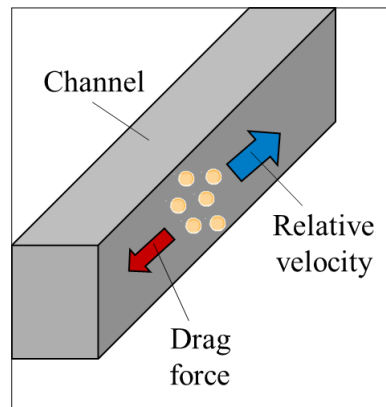


Figure 1: Schematic representation of drag force due to the mainstream flow in an inertial microfluidic channel.

When an ultra-small object travels in an inertial microfluidic channel, due to the need for carrying away other ultra-small objects such as fluid molecules, a load, which is called drag force, is exerted on the ultra-small object (Figure 1). Assuming that this object has a spherical shape. In addition, the deformation of the ultra-small object itself is neglected. The relative velocity between the object and fluid is indicated by U_r . The drag force is obtained as [33]

$$F_{drag} = c_{drag} A_{obj} = \frac{1}{4} \pi d_{obj}^2 c_{drag} \quad (1)$$

in which c_{drag} , A_{obj} , and d_{obj} are, respectively, drag coefficient, the area of the object cross-section and object diameter. The drag coefficient and consequently the drag force are a function of object Reynolds number Re_{obj} that is given as

$$Re_{obj} = \frac{d_{obj} U_r \rho}{\mu} \quad (2)$$

In Eq. (2), and as well as U_r indicate the fluid viscosity and density as well as relative speed, respectively. It is worth stating that size effects are ignored in these relations. Size effects are commonly incorporated for analyzing the dynamics of nonstructural components [29,34-36]. It is assumed that $0.2 < Re_P < 500$ 1000. For this range of Reynolds number, the drag coefficient and force are [33,37]

$$c_{drag} = \frac{12 \mu U_r}{d_{obj}} \left(0.15 (Re_{obj})^{0.687} + 1 \right) \quad (3)$$

and

$$F_{drag} = 3 \pi \mu d_{obj} \left(0.15 (Re_{obj})^{0.687} + 1 \right) U_r \quad (4)$$

More information and assumptions about the derivation procedure of Eqs. (3) and (4) are given in Refs. [33,37]. In inertial microfluidics, the drag force is generated in two main cases:

- A. In the mainstream, and
- B. In the secondary flow.

The first one exists along the axial axis of the microfluidic channel whereas the second one is in the cross-section of the microfluidic channel. Equations (3) and (4) are valid for the mainstream flow

in inertial microfluidics provided that the object Reynolds number does not exceed the above-mentioned range. Inertial microfluidic systems usually work in an intermediate Reynolds number, which belongs to a smaller range inside the above-mentioned range. From Eq. (3), it can be concluded that if the diameter of the ultra-small object increases, the drag coefficient decreases. Nonetheless, the object diameter has an increasing effect on the drag force, as seen from Eq. (4). In addition, other parameters such as fluid viscosity, the relative velocity of particles with respect to fluid and Reynolds number have important effects on the drag force inside an inertial microfluidics-based device. For instance, if the relative velocity diminishes, the drag coefficient decreases due to two main reasons. First of all, as can be concluded from Eq. (3), the reduction in relative velocity directly results in lower drag forces. Secondly, when particles travel with a lower relative velocity, Reynolds number decreases according to Eq. (2), and this leads to a reduction in the drag force as well. In a similar way, when the relative velocity is reduced, the drag force is also noticeably reduced, as can be seen from Eq. (4). This analysis and formulation would help researchers with the analysis of small-scale systems used to convey fluid [38-44] and a mixture of particles and fluid [37,45,46].

Conclusion

The drag force and coefficient have been analyzed in inertial microfluidic channels. Analytical expressions were given for both drag force and coefficient in an appropriate range of object Reynolds numbers for spherical rigid ultra-small objects. It was found that the drag coefficient, which affects the motion of ultra-small objects in a microfluidic channel, decreases with increasing the object diameter whereas the drag force substantially increases when the diameter of the object grows.

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