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Investigation on the photophoretic lift force acting upon particles under light irradiation

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ABSTRACT

Considering the characteristics of photophoresis in the actual process, the viewpoint that particles in fluids will experience photophoretic lift force is proposed. The force is related to the particle motion with photophoresis but different from the traditional photophoretic force. Analysis shows that there are mainly two factors contributing to the lift force, one stems from the variation in the distribution of light intensity, the other originates from the rotational motion of particles in a direction which is perpendicular to the optical axis. The expression of the photophoretic lift force has been given in the study. The impacts of the force have been analyzed and validated by comparing with previous experimental results.

1. Introduction

There are mainly two efficient ways to control the motion of absorbing particles, which are respectively based on the photophoretic force and radiation pressure. In general, the ratio of the former to the latter is about $c/3v$, where c represents the light speed and v is the characteristic molecular velocity. Therefore, the photophoretic force can be 5 orders of magnitude greater than radiation pressure force. Illuminated particles in fluids will move along or against the direction of incident light, which is called positive or negative photophoresis. The optical capture and manipulation of particles can be achieved by using photophoresis (Brzobohaty et al., 2013; Sukhov, Kajorndejnukul, Naraghi, & Dogariu, 2015; Wurm & Krauss, 2006). For instance, the movement of particles can be controlled in the direction of the optical axis by using two beams propagating in opposite directions.

Based on photophoresis, gold-coated hollow glass spheres have been transported over tens of centimeters along the tunable optical beam in ambient air by Shvedov, Davoyan, Hnatovsky, Engheta, & Krolikowski (2014). The manipulation technique based on photophoresis has vital application in greenhouse and space science. The photophoretic force exerted on particles is mainly comprised of two parts. One is that the temperature increases and its uneven distribution on the surface of illuminated particles (Shvedov, Hnatovsky, Shostka, Rode, & Krolikowski, 2012; Soong, Li, Liu, & Tzeng, 2010), the other part is the variation of the accommodation factors on particle surface. If the particle is isotropic, the temperature difference plays a main role.

Most previous studies considered longitudinal photophoretic motion, which was only aligined to the incident light beam and the longitudinal photophoretic force acted in the same way, which does not fully satisfy the actual situation. As the actual distribution of light intensity is inhomogeneous and the particle motion is relatively complex, the effect of photophoresis should not exhibit a single behavior. Generally, light intensity varies around the relatively larger particles and the particle rotates occasionally in a direction perpendicular to the optical axis. Based on the above considerations, the viewpoint that particles will experience photophoretic lift force is proposed and its effects have been analyzed. The word lift is used here, as it is only one kind of lift force, which is different from that against gravity force.

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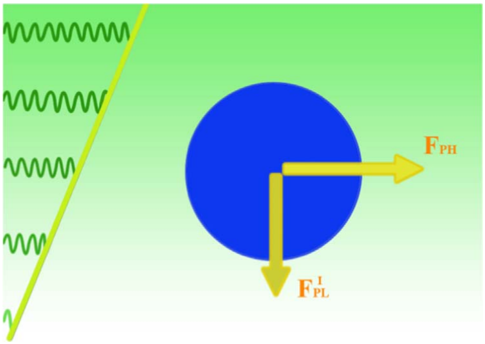

Fig. 1. Spherical particle in the fluid under light irradiation with nonuniform intensity. Particle is heated warmer on the side facing the light, where F_{ph} represents the traditional photophoretic force and F_{pl}^{I} is the photophoretic lift force caused by variation in intensity.

2. Effect of variation in light intensity

In the process of optical manipulation, particles will move from the side to the center of the light beam, and then they will be constrained in the area with weaker light intensity. For the particles near the stable position, the force which points to the center of light beam will act on the particles. The variation of light intensity distribution will produce a force that is perpendicular to the optical axial direction, and it is different from traditional photophoretic force parallel to the irradiation direction and is extracted as the first type of photophoretic lift force. As shown in Fig. 1, the light intensity varies spatially and the line length of the wave in the left part represents the intensity. The longitudinal photophoretic force F_{ph} is caused by the averaged light irradiation and the photophoretic lift force F_{pl}^{I} originates from the variation in intensity.

2.1. Expression of the first type of lift force

The expression of photophoretic lift force can be obtained by solving equations according to conventional approach. In general, the temperature fields of the gas and the particle satisfy the steady temperature distribution equation with and without heat source respectively. The velocity of gas around the particles satisfies the Stokes equation. The steady equation of temperature and the Stokes equation can be solved jointly to calculate the photophoretic lift force. It should be noted that the heat source term in the particles temperature equation is not caused by the uniform light intensity, but by the light intensity change in spatial distribution. When solving the temperature by the Laplace equation, the boundary conditions for temperature containing both the terms sine and cosine, which is different from the case heated by light with uniform intensity. The distribution function of the velocity is also different near the wall boundary.

In consideration of the complexity to solve these equations mentioned above, an analogy based approach is adopted here to obtain the expressions for photophoretic lift force. For obtaining the photophoretic force, the equation for temperature distribution needs to be solved first, then the velocity equation. The wall velocity boundary conditions depend on the solution of the temperature distribution. After deriving the velocity distribution and integrating the stress, the expression for photophoretic force can be obtained. The above process is equivalent to the determination of the drag force impacting on a particle when velocity boundary condition at wall for the Stokes equation is taken as photophoretic velocity.

When calculating Saffman lift force, the boundary of velocity consists of two components of uniform and shear rate varied translation. The two fluid induced forces are orthogonal to each other. For the photophoretic lift force, the far field velocity boundary consists of two parts, one is induced by temperature gradient heated with uniform light intensity and the other is contributed by the temperature component with shear rate varied intensity. The temperature contribution can be replaced with the photophoretic velocity. The photophoretic lift force can be obtained with the translational and shear rate velocity boundary components. It is consistent with the equations and boundary conditions for deriving the Saffman lift force, therefore this analogy approach is effective with rigorous derivation and can be performed. In other words, under uniform irradiation intensity, the photophoretic force particles experience in fluid can be regarded as the drag force when particles move in a uniform flow. For a particle illuminated by light with shearing intensity, the photophoretic lift force on it in fluid is equivalent to Saffman lift force the particle suffered in shear flows.

Incorporating thermal radiation, temperature dependent heat conductivity and viscosity of gas as well as particle conductivity, the photophoretic force can be generally calculated by Loesche and Husmann (2016)

$$F_{ph} = -\frac{4\pi c_s a\mu^2 I J_1}{\rho_f T_0(k_p + 2k_f + 4a\sigma_{SB}\varepsilon T_{bb}^3)} \tag{1}$$

where a is known as the radius of a particle, c_s is called the thermal slip coefficient, μ represents the dynamic viscosity of the fluid, I denotes incident light intensity, J_1 is the symmetry factor for absorption of light (Mackowski, 1989; Yalamov, Kutukov, & Shchukin, 1976), ρ_f represents the density of fluid, T_0 denotes the initial temperature of the fluid, k_p and k_f represent the thermal conductivity of particle and the fluid respectively, σ_{SB} denotes the Stefan-Boltzmann constant, ε represents the surface emissivity, T_{bb} is the black body