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Thermophoresis-assisted micro-scale magnus effect in optical traps

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Here we report on the experimental evidence of the lift force acting on the optically trapped magnetic microparticle rotating in a liquid flow. The lift force grows with the increase of local microparticle temperature, which is controlled by the trapping laser power. The correlation between the lift force and the heating of the microparticle in an optical trap indicates that the observed effect appears due to the thermophoretic forces that act on the heated microparticle rotated in the liquid flow. Using numerical simulations we have shown that the heated microparticle rotating in the flow creates a temperature gradient around itself. The appearance of the temperature gradient can be explained by the displacement of the particle from the center of the optical trap during particle motion. The microparticle under the thermophoretic force moves in the direction opposite to the temperature gradient; therefore the force has a component perpendicular to the flow. This is what constitutes the thermophoresis-assisted micro-scale Magnus effect.

In our experiments, the magnetic microparticle rotated at a rate up to 100 Hz. The trap position oscillated with an amplitude of up to 500 nm along the Ox-axis, with a frequency range of 2 to 20 Hz, causing linear particle motion with velocity that did not exceed 60 μm/s. For technical details of the experimental setup see [1, 2]. The Reynolds number is

$$Re = \rho U a/\eta, \tag{1}$$

where a is the radius of a particle, ρ is the density, and η is the viscosity of the fluid. For translational motion U is the particle velocity, and for rotational motion $U = 2\pi\Omega a$, where Ω is the frequency of particle rotation. Thereby, in our study, the translational Reynolds number is 10^{-4} and the rotational Reynolds number is 10^{-3} orders of magnitude. This is the case of ultra-low Reynolds numbers [3, 4].

The absorption of laser radiation leads to heating of the trapped microparticles. The dependence of the transversal force on the laser light power inside the trap is shown in Fig. 1a. As the laser power increases the force

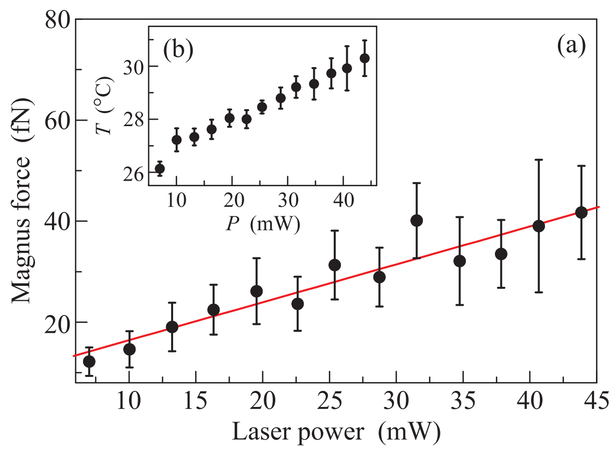

Fig. 1. (Color online) (a) – The thermophoresis-assisted Magnus force dependence on the laser power in the optical trap. The oscillation frequency $f = 9$ Hz, the amplitude of the trap oscillation $A = 200$ nm, and the microparticle rotation rate $\Omega = 50$ Hz. (b) – The effective temperature of the microparticle's surface as a function of the trapping laser power

grows significantly, allowing one to suggest that heating plays an important role in the effect. The effective temperature of the liquid around the trapped magnetic microparticle grows linearly along with the light power inside the trap (see Fig. 1b). The studied effect could arise from the local non-uniform heating and the appearance of temperature difference on the opposite sides of a trapped microparticle. The observed high values of the Magnus force can account for thermophoresis, also called thermal diffusion, that moves microscopic particles along temperature gradients [5–7].

Thus, the thermophoresis-assisted Magnus force is caused by temperature difference on opposite sides of the microparticle. The difference appears due to the displacement of the absorbing microparticle from the center of the optical trap during its motion in the liquid flow. The temperature distribution around the optically

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trapped microparticle rotating in the liquid flow was obtained by numerical solutions of the heat equation, solved using the finite element method. To illustrate the key processes of the studied phenomena, we calculated the temperature distribution. For the particle rotation rate of 50 Hz and the liquid flow speed of 25 μm/s, the temperature difference is $\Delta T = 0.12\,^{\circ}$C, which corresponds to the gradient of $0.04\,^{\circ}\mathrm{C}/\mu$m.

The calculated dependence of ΔT on the microparticle's rotation rate is shown in Fig. 2a. The dependence of

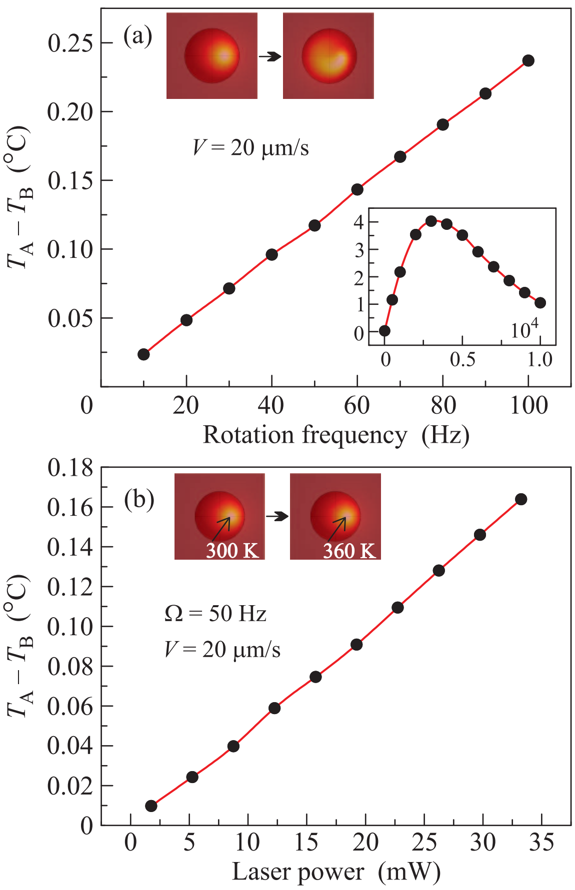

Fig. 2. (Color online) The temperature difference between the left and the right sides of the particle, obtained using numerical simulation: (a) is the dependence on the frequency of microparticle rotation, inset is the case of high values of rotation frequency; (b) – is the dependence on laser power

ΔT on the microparticle rotation rate grew linearly from 0 to 10^3 Hz, which includes the experimentally studied values of microparticle rotation rates. At the frequencies above $3{\cdot}10^4$ Hz, ΔT decreases because the speed of microparticle rotation becomes higher than the speed of heat transfer to liquid. The dependence on the laser power also grew linearly (Fig. 2b) in accordance with the data for the experimentally measured force (Fig. 1a).

The coupling coefficient S_M between the temperature distribution and the force acting on the particle can be estimated using the closest analogue – the equation for the thermophoretic force in the case of a uniform temperature gradient:

$$\mathbf{F}_{\text{thermo}} = -k_{\text{B}} T S_T \nabla T, \tag{2}$$

where k_{B} is the Boltzmann constant, T is the temperature of the liquid, and S_T is the is the Soret coefficient.

We estimated the value of S_M from Eq. (2), substituting it with S_T and using the experimental data for $\mathbf{F}_{\text{thermo}} = 25\,\text{fN}$ (see Fig. 1a), calculated the value of $\nabla T = 0.04\,^{\circ}\mathrm{C}/\mu$m (see Fig. 2b) and obtained the value of $S_M \approx 150\,\mathrm{K}^{-1}$. While in the case with a uniform gradient, the coefficient $S_T \approx 18\,\mathrm{K}^{-1}$ for a similar system [8].

There is no generally accepted theoretical framework for the Soret coefficient [9], but it is known that S_T strongly depends on the particle-solvent interface, and therefore has a highly specific surface chemistry, such as the degree of surface ionization, or the amount of residual surfactant used in emulsion. Moreover, it strongly depends on temperature [8]. In the case scrutinized here, the temperature distribution on the surface of the particle is strongly non-uniform, and the temperature inside the particle is much higher than it is on the surface, which can significantly affect the charge of the particle and the degree of surface ionization.

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