

Optical trapping of flow tracers for the characterization of thermo-osmotic slip flows around charged microparticles

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ABSTRACT

In this paper, we report a novel application of the optical trapping of tracers (e.g., micro- or nanoscale particles) to investigate experimentally a microscale fluid flow induced around a microparticle. In particular, we focus on the thermo-osmotic slip flows around a target microparticle fixed on a microchannel. The thermo-osmotic slip flows are creeping fluid flows near a solid surface induced by a temperature gradient of the fluid along the surfaces. By confining optically the tracer motions in a circular path around the circumference of a target microparticle immersed in a fluid with an inhomogeneous temperature field, we successfully visualize the flows induced around the target particle along its surface in a direction from the cold to the hot side. It is found that the magnitude of the observed creeping flow depends on the zeta potential of the target microparticles, i.e., the surface charge.

Keywords: Optical trapping, Thermo-osmotic slip flows, Charged surfaces, Flow tracers

1. INTRODUCTION

When investigating fluid flows experimentally, tracers are usually dispersed in a sample solution and the motion of the tracers is analyzed to characterize the flows. Here, the tracers should be much smaller than the characteristic length scales of the flow, that is, investigating the fluid flows of the order of several micrometers (or less) requires the tracers with the size of sub microscale to nanoscale. However, such tiny particles are inherently Brownian in usual conditions, e.g., a water at room temperature. Furthermore, the regions of interest (i.e., the test section) for the flow characterization in microfluidics and nanofluidics are often microscale and nanoscale, and the tracers tend to be scarce in such tiny regions. For instance, if one tries to visualize the flow in the near wall region a few micrometers away from its surface, it is necessary to wait for a tracer to come there accidentally [1].

In this paper, to increase the chance of finding tracers in the microscale test section and to reduce the effect of noise inherent to tracers' Brownian motion, we propose to use the optical trapping of tracers. To be more precise, we enforce tracers to be confined in the test section by the use of an optical force (Fig. 1(a)). Here, this method is applied to investigate a microscale flow around a target microparticle with a diameter of 7 μm , especially near the surface of the particle. Such a creeping flow near the surface can be driven by the temperature gradient of the fluid (Fig. 1(b)), known as thermo-osmotic slip (Fig. 1(c); see, Ref. [2] for a molecular simulation and Ref. [3] for an experiment). Flow tracers are optically trapped in a circular path around the circumference of the target particle by a scanning focused laser (Fig. 1(a)). The tracer motions of the trapped tracers are restricted in the radial direction but are free to move in the circular direction, and thus play a role to characterize the flow along the surface of the target particle. Based on our recent paper [4], we report the effect of the surface charge of target particles on the magnitude of thermo-osmotic slip flows.

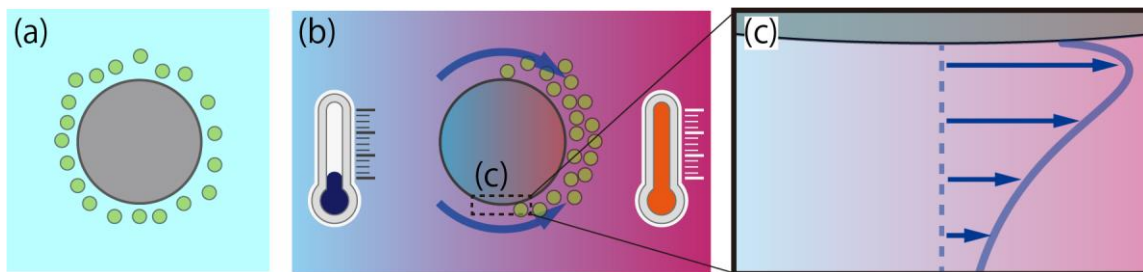


Figure 1. Concept of the experiment. (a) A target microparticle and smaller tracer particles that are optically confined in a circular path around a circumference of the target particle. (b) When the surrounding fluid attains an inhomogeneous temperature profile, the tracers move along the target particle's surface due to thermo-osmotic slip flows. (c) Schematic of thermo-osmotic slip flow.

2. EXPERIMENTAL SETUP

A polystyrene target particle with a diameter of $7\ \mu\text{m}$ and a sample solution (10 mM tris-HCl buffer) are confined in a microslit with a spacing of $17\ \mu\text{m}$, and observed from the bottom using an inverted microscope. The target particle is fixed to the ceiling of the microslit, and tracers with a diameter of $500\ \text{nm}$ are distributed in the sample solution. A focused laser with a wavelength of $1064\ \text{nm}$ is irradiated in the direction perpendicular to the slit. The focal spot is circularly scanned with a frequency of $200\ \text{Hz}$ around the target microparticle using a two-axis acousto-optic deflectors, realizing an optical trapping of tracers in the radial direction along a circular path. Images of the tracers are obtained through the same objective lens used for the laser irradiation and recorded to a sCMOS camera; therefore, after the trapping of the tracers, the obtained images can be schematically described as Fig. 1(a). Without heating, the tracer distribution is rather uniform in the circular direction.

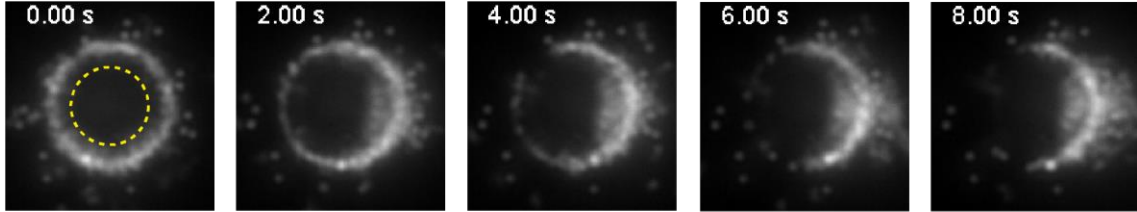
Another focused laser with a wavelength of $1480\ \text{nm}$, at which the absorption to the water is significant, is irradiated to a position at $18\ \mu\text{m}$ distant from the target particle to produce an inhomogeneous temperature field of the fluid. Then, the tracer motion takes places along the target particle's surface and thus the tracer distribution is biased, as schematically shown in Fig. 1(b). The spatial distribution is analyzed to estimate the magnitude of the thermo-osmotic slip flow. Thermo-osmotic slip is induced along the surface; it is expected from the theory of charged colloids that the surface charge affects the magnitude of the flow [5]. Therefore, we investigate two types of surface modifications of the target particle: (a) carboxylate-modified surface and (b) amine-modified surface. The zeta potentials of the carboxylate-modified and the amine-modified surfaces are measured as $-46\ \text{mV}$ and $-24\ \text{mV}$, respectively.

3. RESULTS AND DISCUSSION

Typical images obtained in the experiments are shown in Fig. 2 for (a) carboxylate-modified and (b) amine-modified surfaces. The heating laser is kept irradiated from a time $t = 0\ \text{s}$, and the figure shows snapshots at $t = 0\ \text{s}$, $2\ \text{s}$, $4\ \text{s}$, $6\ \text{s}$, and $8\ \text{s}$. The heating laser is irradiated at the right-hand side of the target particle in each image. In the panels of $t = 0\ \text{s}$, the dashed-circle indicates the positions (and the sizes) of the target particles ($7\text{-}\mu\text{m}$ diameter), and white speckles are the obtained images of fluorescent tracers. The radius of the circular path of the optical trapping of the tracers is $5.4\ \mu\text{m}$; it is seen from the figure that the tracers are distributed almost uniformly along the path at $t = 0\ \text{s}$.

It is clear that in the case of carboxylate-modified surface (Fig. 2(a)) that the numbers of tracers at the cold side on the left (or the hot side on the right) decrease (or increase) as time goes on. Since the tracer motion is restricted in the radial direction, this change of the tracer distribution indicates that the tracers start to migrate from the cold side to the hot side.

(a) carboxylate-modified



(b) amine-modified

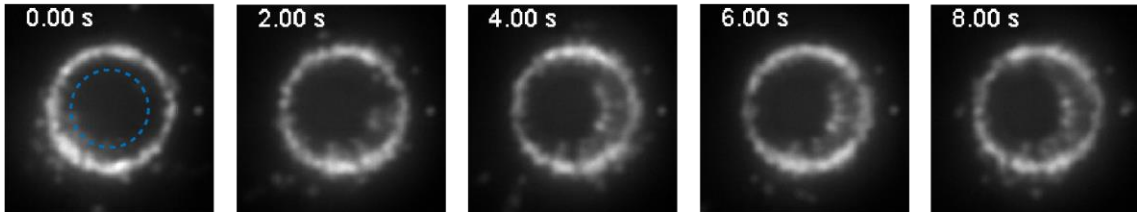


Figure 2. Snapshots of tracer motions confined in a circular path at instants $t = 0\ \text{s}$, $2\ \text{s}$, $4\ \text{s}$, $6\ \text{s}$, and $8\ \text{s}$ after the onset of the irradiation of the heating laser. The position of the heating laser is the right-hand side of the images, creating the temperature gradient in the rightward direction (see also the temperature profile schematically shown in Fig. 1(b)). Target particles (shown by dashed-circles) have either (a) a carboxylate-modified or (b) an amine-modified surface.

The magnitude of thermo-osmotic slip, v_{slip} , is empirically expressed as $v_{\text{slip}} = -K \nabla_t T$, where K is the slip coefficient and $\nabla_t T$ is the temperature gradient of the fluid along the surface of the target particle. The value of K is estimated as $K \approx -0.5 \text{ K } \mu\text{m}^2 \text{ s}^{-1} \text{ K}^{-1}$ using the analysis of the fluorescent intensity distribution. See Ref. [4] for more detailed procedure of the analysis.

On the other hand, the case of amine-modified surface (Fig. 2(b)) does not show significant tracer migration in the circular path. Because all other experimental settings are the same between Figs. 2(a) and 2(b), the difference should be caused by the surface modification. To be more specific, the flow magnitude is more significant for the larger value of the magnitude of the zeta-potential. This tendency is qualitatively consistent with the theory of charged colloids in Ref. [5]. Therefore, we consider that the motion of optically-trapped tracer enables the experimental characterization of thermo-osmotic slip flows along a charged microparticle.

4. CONCLUSION

In this report, we have proposed an application of the optical trapping of flow tracers to investigate a microflow along the surface of a microparticle induced by a temperature gradient of the fluid, namely, the thermo-osmotic slip flow. The time development of the spatial distribution of the trapped tracers indicates the onset of a thermo-osmotic flow and its magnitude around the microparticle. The analysis of not only the magnitude but also spatial profiles of the flow is also important and currently undergoing. Partial results will be presented in the presentation at the conference

REFERENCES

- [1] Bregulla, A. P. and Cichos, F., "Flow fields around pinned self-thermophoretic microswimmers under confinement," *J. Chem. Phys.* 151, 044706 (2019).
- [2] Ganti, R., Liu, Y. and Frenkel, D., "Molecular simulation of thermo-osmotic slip," *Phys. Rev. Lett.* 119, 038002 (2017).
- [3] Bregulla, A. P., Würger, A., Günther, K., Mertig, M. and Cichos, F., "Thermo-osmotic flow in thin films," *Phys. Rev. Lett.* 116, 188303 (2016).
- [4] Tsuji, T., Mei, S. and Taguchi, S. "Thermo-osmotic slip flows around a thermophoretic microparticle characterized by optical trapping of tracers," *Phys. Rev. Appl.* 20, 054061 (2023).
- [5] Fayolle, S., Bickel, T. and Würger, A., "Thermophoresis of charged colloidal particles," *Phys. Rev. E* 77, 041404 (2008).