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Controlling the Flow of Microscopic Particles—The Role of Beam Size

Jitendra Bhatt[1*], Ashok Kumar[2], Saiyed Nisar Ali Jaaffrey[1], Ravindra Pratap Singh[2]
[1]Department of Physics, University College of Science, Mohan Lal Sukhadia University, Udaipur, India
[2]Theoretical Physics Division, Physical Research Laboratory, Ahmedabad, India
Email: *jitendrabhattprl@gmail.com

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ABSTRACT

Flow of micro particles and fluids is important in many microscopic systems. Here we present details of our finding of a directional flow of micro particles due to a single beam optical trap. It was found that the directional flow depends upon the size of optical trap, the number density of particles in the solution and the time after the trap was created. We suggest controlling the motion of microscopic particles in a fluid by varying a simple parameter like beam size for microfluidics applications.

Keywords: Optical Manipulation; Optical Tweezers; Directional Flow

1. Introduction

Since the pioneering work done by Ashkin [1] on single beam gradient trap sometimes referred to as optical tweezers, optical trapping has found diverse applications in biophysical and colloidal studies as a tool for micromanipulation [2-7]. In most of the applications, microscopic objects like particles, colloids or biological cells moving around in a fluid are forced to remain confined in the trap volume. However, instead of restricting the movement, the optical trapping can also be used to facilitate the desired movement of the microscopic objects. In 1980s when researchers were still struggling for a 3D trap, Buican *et al.* [8] used properties of a 2D optical trap for transporting microspheres and biological cells to millimeter distances. Their automated optical manipulator used two orthogonal laser beams—propulsion beam and deflection beam for this purpose while a third beam was used as a probe beam to discriminate cells to be deflected. In their experiment the cells moved along with the beam trapped in two dimensions. In late 1980s invention of 3D optical traps popularly known as optical tweezers caught the fancy of biologists and the work shifted towards trapping and manipulating single biological cells. Here we point out our observations, which we believe are significant one, the role of a 2D trap in an inverted microscope configuration. In our experiment we have obtained a controlled flow of micro-particles and fluids using an optical trap. We have found that the trap is able to attract particles from substantially large distances, the distances being orders of magnitude more than the diameter of the beam or the particle itself. One can easily see that the directional movement in our experiment is very much different from the transportation achieved by Buican *et al.* [8]. Although light intensity of the trap has been used to control the flow of particles earlier [9], these methods relied on well established technique for optical trapping and used overfilling of the objective lens for their purpose.

The present experiment provides extra handle in the form of beam size to control the movement of microscopic particles in a standard 3D optical trap configuration that uses inverted microscope. However, it is very important that before making the observations, one takes care of certain practical considerations associated with the set up [2,10].

2. Experimental Setup

Our experimental setup shown in **Figure 1**, is typical of an inverted optical microscope based optical tweezers setup. It consists of a diode laser (785 nm, maximum power 46 mW) and inverted microscope from Nikon (TE-2000 U). The size of the beam entering the back aperture of the objective lens is 0.18 mm. It is a diverging beam with divergence of 0.02 radians at the back aperture of the objective lens. The laser beam is directed to the oil-immersion high numerical aperture (NA 1.40) 100X objective lens (Plan Apo vc 100X/1.40 oil, Nikon) using periscopic mirrors (M1, M2) and the dichroic mirror (DM). The refractive index of the immersion oil is 1.515. The particles used in this experiment are 0.99 μm

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[*]Corresponding author.

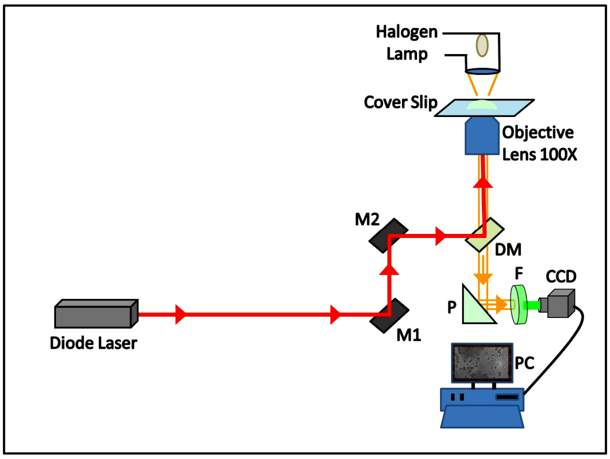


Figure 1. Experimental set up for directional flow of microscopic particles.

polystyrene latex beads (from Bang's Laboratory). These particles are spherical in shape and they were suspended in double distilled water. The specimen sample was illuminated by a halogen lamp assembly. The light from illuminated particles was sent to the cooled color CCD camera (Evolution VF, Q-Imaging) through the objective lens, dichroic mirror (DM) and a beam steering prism (*P*). The halogen lamp is used to illuminate the sample. The same objective lens is used for viewing and trapping of the particles. A color glass filter (*F*) is used before the CCD camera to block the laser for avoiding saturation of the camera. The stage movement with a knob was used to bring the trap at the different parts of the sample. Unlike the most optical trapping experiments which use a beam expanding device to fill the back aperture of the objective lens by the trapping beam, we do not use any beam expanding device.

3. Theoretical Background

Most of the theoretical work on optical tweezing or trapping of particles that involves calculation of optical gradient forces is applicable to either small particles (particle size $R \ll$ wavelength λ) or very large particles $(R \gg \lambda)$ [11,12]. The estimation of force for small particles requires electromagnetic (EM) theory where the EM field is computed by plane wave Fourier decomposition of the focused beam which is used to calculate the Maxwell stress tensor to find out the force on the particle. For very large particles the EM theory can be reduced to geometrical ray optics approximation and the force is calculated by vector summation of the contributions of single rays which are reflected and refracted by the particle. For $R \ll \lambda$, the EM approach reduces to a dipole approximation where the particle interacts with the field only as an electric dipole. However, for computing the force on a particle with size comparable to the wavelength, one needs to sum over the plane wave Fourier components for the entire volume of the particle. This makes the calculations very difficult. Moreover, due to interference effects between the plane waves, the calculated forces are found to be weaker than the experimental results [2]. To solve this problem, Tlusty, Meller and Bar-Ziv (TMB) [13] adapted a new approach for calculating the interaction of the dielectric particle with the focused beam of light. Instead of decomposing the fields into Fourier components they used the property of strong localization of the fields that makes the phase variation of the EM fields appreciably small over the diffraction limited spot of the beam. Therefore, the main contribution to the interaction arises from the steep variations in the amplitude of the fields and not from the interference effects. Thus, the relevant length scale for interaction becomes the spot size *w* and not *R* that makes this approach [13] applicable to particles of any size. In our experiment, the particle size *R* being comparable to the wavelength *λ*, and the experimental results depending on the beam spot, we find the TMB approach most suitable for our purpose of calculating the force on the particle. Since the interaction depends on the amplitude of the field only, one can deal with the observable quantity that is intensity of the light. In case of a diode laser, on focusing a laser beam through an objective lens, the spot formed is not exactly spherical; rather it is an ellipsoidal with the eccentricity *ε*. Considering the trap volume to have an axial symmetry, the localized electromagnetic fields near the focal point can be given by [13].

$$I(r,z) = I_0 \exp\left(-\frac{r^2}{2w^2} - \frac{z^2}{2w^2\varepsilon^2}\right) \qquad (1)$$

where I_0 is the energy density at the center of the trap, w and $w\varepsilon$ are the dimensions of the beam waist in transverse and axial dimensions respectively. The frame of reference is defined by the geometrical focus of the beam, $r = z = 0$. It is known that the optical trap formed by focusing of a laser beam through an objective lens is of the form of an Airy disc (first bright disc of the Airy pattern formed). Under Gaussian approximation its size *w* can be given by

$$w = 0.42\frac{\lambda f}{D} \qquad (2)$$

where λ is the wavelength of the light, f is the focal length of the lens, and *D* is diameter of the beam being focused.

The TMB approach makes the calculation of the force quite simple, knowing the intensity one can calculate the dipole interaction energy by a simple integral and taking the gradient of the dipole energy provides with the relevant central restoring force of the trap [13].

$$F(r) = \alpha I_0 w^2 A(\varepsilon)\, \mathrm{e}^{-(1/2)u^2} \sinh(a_c u) \qquad (3)$$

The anisotropy factors are embedded in the term $A(\varepsilon)$

$$A(\varepsilon) = 4\pi\varepsilon\, erf\left(\frac{b_c}{\sqrt{2}}\right) erf\left(\frac{b_c}{\sqrt{2\varepsilon}}\right) \mathrm{e}^{-(1/2)a_c^2} \sinh(a_c u).$$

In Equation (3), $\alpha = \alpha_p / \alpha_0 - 1$ is the relative difference of the dielectric constants of particle α_p and the surrounding medium α_0. The radius R of the particle being trapped is normalized as $\alpha = R/w$, while the distance of the particle from the trap centre r is the normalized to $u = r/w$ and $a_c = b_c = R/w(\pi/6)^{1/3}$.

Based on Equation (3) the central restoring forces have been plotted in **Figure 2**. The variation of central restoring force for trap size 0.96 μm has been shown in **Figure 2(a)** and for trap size 0.45 μm in **Figure 2(b)**.

These graphs convincingly suggest that for large trap sizes the range of trapping force is large while for small trap sizes the range is small.

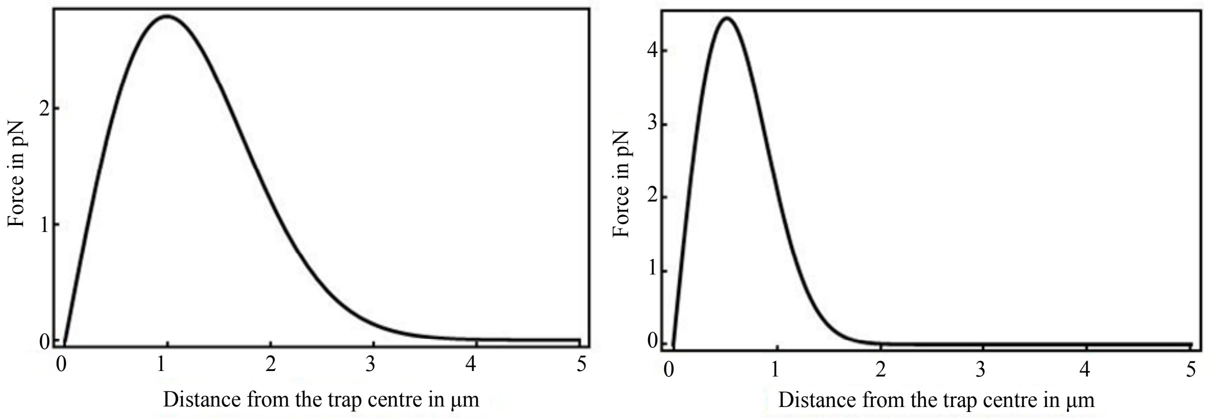
4. Results and Discussion

In our experiment, the size of the beam before entering the back aperture of the objective lens is 0.67 mm. The focal length of the objective lens is 2 mm that gives the spot size of the focused trapping beam as 0.99 μm; however, the experimentally measured spot size of the trap has come out to be 0.96 μm.

Figure 2 shows the variation of central restoring force with distance calculated from Equation (3). The restoring force for the particle size R = 0.99 μm and the trap size w = 0.96 μm are shown in **Figure 2(a)**, while **Figure 2(b)** shows the same for a reduced trap size of w = 0.45 μm. It becomes clear from these graphs that when the trap size is large, the range of force is large, thus the trap attracts the particles even from the large distances. While for small trap size, the value of maximum force is large but the range of the force is reduced, and the trap cannot attract particles from the large distances.

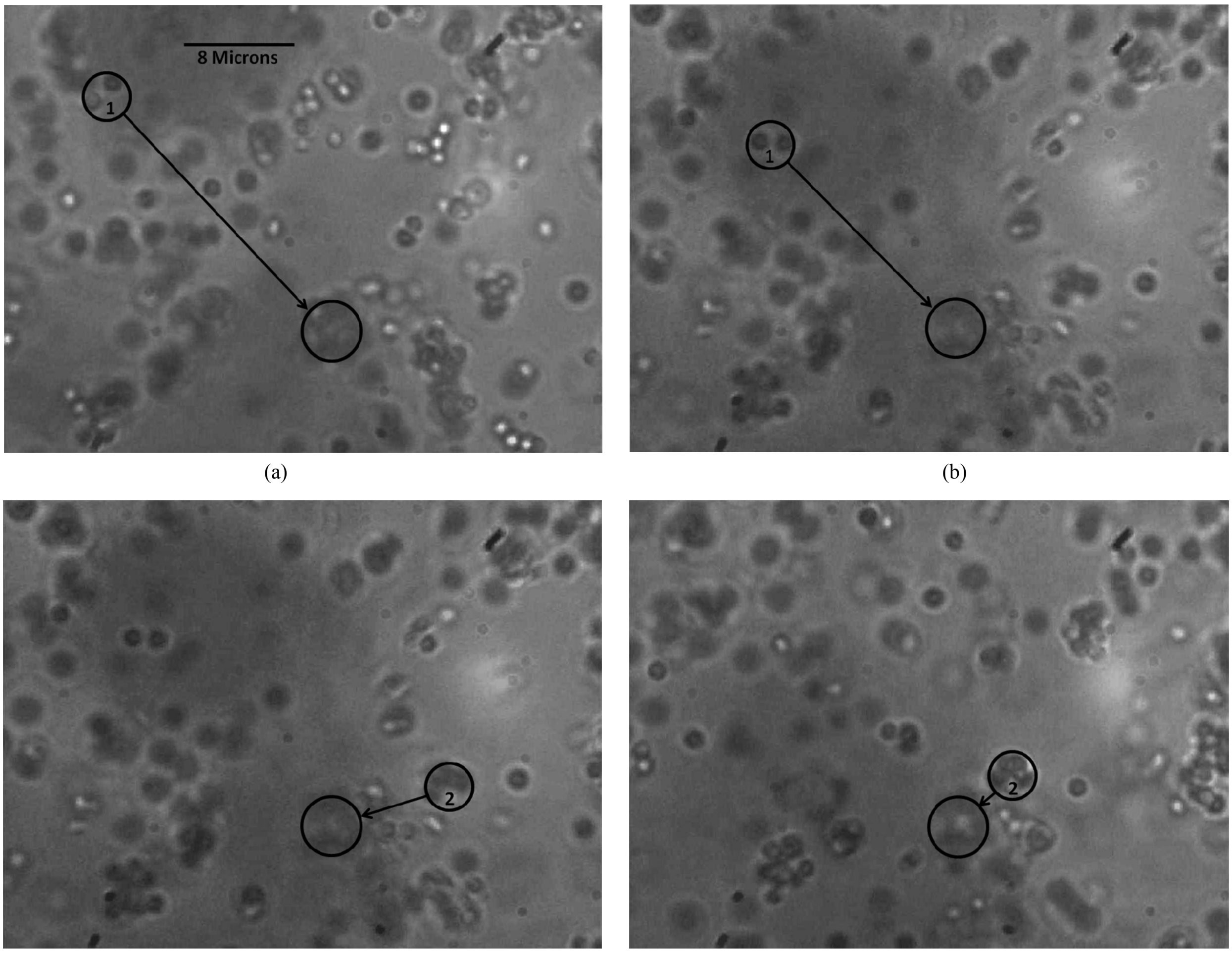
In our experiment, we observed that for the trap size 0.96 μm, obtained with a beam without any lens before the objective, there was a directional flow of particles from all parts of the sample towards the trap position. This flow was found to be dependent on the number density of the particles; it was observed that below a certain number density (~2 × 10^8 particles/ml) no significant directional flow could be observed. It was also observed that even for sufficient number density of particles, the establishment of directional flow takes some time to begin. It was found that the particles were coming to the trap and moving out of it. This phenomenon can be seen in the frames captured by the CCD camera (**Figure 3**). For the smaller trap size (0.45 μm), which could be achieved through filling the back aperture of the objective lens, no significant directional flow of particles could be observed, but the particles could be trapped stably at the trap position. It suggests that for larger trap size the range of trapping force in the X-Y plane is large, while the trap strength is low. However, for smaller trap sizes the range of trapping force in the X-Y plane has decreased although the trap strength has increased.

For calculating the velocity of particles under the influence of trapping force, we analyzed the frames captured with CCD camera. We obtained distances of different particles from the trap centre by measuring distances they moved between the two frames. We have taken 48 frames with a time interval of 0.1 seconds between two consecutive frames (frame rate of the CCD is 10 fps). This information was used to calculate the average velocity of the particles and the force acting on them at different distances from the trap centre. Following the



(a) (b)

Figure 2. Graphs showing theoretical variation (plot of Equation 3) of restoring trap force with distance from trap centre, (a) Represents the variation for the trap size 0.96 μm; (b) Represents the variation for the trap size 0.45 μm. For theoretical calculations we have taken α_p = 2.5, α_0 = 80.



(a) (b) (c) (d)

Figure 3. Frames showing the directional motion of polystyrene particles towards the trap position. The trap position has been shown by the circle towards which the arrows are pointing. The same numbers inside the circle represent the same particle at different positions. (a) and (b) show the movement of particle 1 in two successive frames; (c) and (d) show the movement of particle 2 in two successive frames.

calculated plot for the force (**Figure 4**), it is clear that with the distance from the trap, the average velocity first increases, reaches to the maximum and then decreases. As the particles approach the trap, they start hindering the motion of each other because of collisions, which is the reason for the average velocity to be maximum not at very near to the trap but slightly far from it. The positioning accuracy of the particle is fundamentally limited by the Brownian motion of the particle and the accuracy of vision sensing [14]; this led to the precision of ±0.5 μm/sec in determination of the velocity.

The range of central restoring force of optical trap of size 0.96 μm is about 4 μm; hence trap must attract particles from distances up to 4 μm only and bring them at the trap centre. However, because of Brownian motion of particles, another particle comes in the position of the previous particle and consequently gets attracted towards the trap. Such action sets the formation of a short lived channel (where these particles have to face less viscosity) for easy flow of other particles. This phenomena of channel formation draws similarity from the flow induced channel formation under pressure gradient forces [15]. Once the channels are formed, they lead to the attraction of particles towards the trap even from the distances several times the range of central restoring force of the trap. The higher number density of particles helps in the formation of these short lived channels, this leads to easier observation of directional flow in higher particle number density solutions. For smaller trap size (0.45 μm), the range of the central restoring force is about 2 μm. The smaller range of force results into attraction of less number of particles towards the trap centre. It causes decrease in formation of short lived channels and hence less significant directional flow. As the formation of short lived channels by movement of particles is important in this directional flow, therefore, it takes time for a

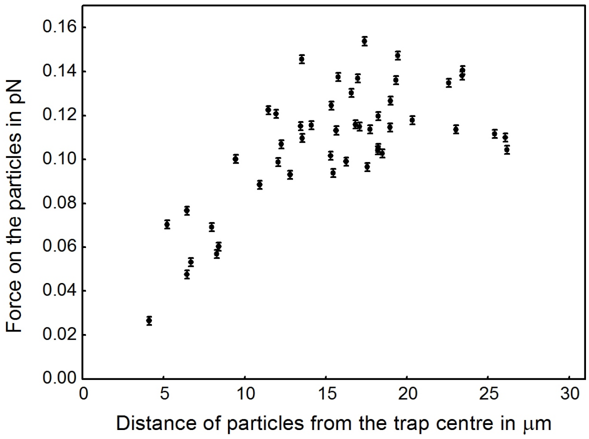


Figure 4. The experimental data showing variation of trapping force on the particles with distance from the trap centre. The size of the trap is 0.96 µm.

significant directional flow to take place since the trap is switched on.

We observe that the theoretical approach which takes spot size *w* as the relevant length scale of interaction and valid for all the particle sizes [13], should have given the correct range of forces to us. However, it is not very successful in the present case, although it provides us a qualitative explanation regarding range of forces for bigger and smaller trap sizes. We can say that the gradient forces alone cannot describe this kind of directional flow, one need to consider hydro-dynamical processes involved in the system.

We know that the spherical aberrations [16-18] which come into play because of refractive index mismatch in the glass-water boundary decrease the stability of the optical traps due to distorted focus. However, for a comparative study like ours, this does not affect the conclusions, the aberrations being same throughout the experiment.

5. Conclusion

In conclusion, we show an obvious but unexplored method to control the flow of particles that does not use micro-channels and may allow the possibility of an entirely fluidic process. Earlier studies used the light intensity of the trap to control the flow of particles and used the conventional method of overfilling the objective lens. In contrast, we show that it's not always required to overfill the objective; instead one can use the original beam and its different magnifications to control the flow of microscopic particles.

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