

Optical guiding of aerosol droplets

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Abstract: We characterize the ability of Gaussian and Bessel beams to guide water, ethanol and dodecane aerosol droplets. Droplets produced from a nebuliser source are trapped using radiation pressure and then by varying the beam power are controllably guided in a vertical direction. The use of a zeroth-order Bessel beam, which has a non-diffracting thin core, is shown to improve guiding distances over a comparable Gaussian beam by more than three times with guiding distances of up to 2.75mm for dodecane droplets. We discuss the applications for this work in the context of tools for optically manipulating airborne particles.

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1. Introduction

Optical manipulation of microscopic particles was first demonstrated by Ashkin and colleagues in the 1970s [1]. This ground breaking work, which would pave the way for atomic

cooling [2] and optical tweezers [3], initially concentrated on understanding the radiation pressure of light by which light exerts a force on particles in the direction of propagation. While Ashkin's original work studied the acceleration of particles in the horizontal direction, subsequent work would involve optical levitation of both particles and droplets, balancing the gravitational force with the scattering force [4-6]. This work was the forerunner of what are now termed *optical tweezers*, which rely on the optical dipole force rather than radiation pressure to trap particles (the dipole trapping of airborne particles has only been more recently demonstrated [7-10]). Optical tweezers confine particles in three-dimensions by use of optical forces near the focus of a tightly focussed laser beam. The dipole force confining the particle to the focal region overcomes the radiation pressure pushing the particle in the beam propagation direction. With a weaker focus (typically NAs less than 0.9), a particle can be held in the transverse plane of the beam and levitated or guided along the direction of propagation. It is the guiding of particles, and specifically liquid droplets, that is the focus of this paper.

For particle guiding applications, Bessel beams [11, 12] offer advantages over Gaussian laser modes. This stems from the pseudo-nondiffracting nature of the central maximum of the profile. The distance over which the beam is considered non-diffracting is termed the propagation distance in our experiment. This can be as great as a hundred times the Rayleigh range of a Gaussian beam with a beam diameter equivalent to the Bessel beam core size. The 'advantages' of the Bessel beam always come at a price, however. For a given core size the beam propagation distance is a function of the Gaussian beam waist used to create the beam. However for a long propagation distance the number of rings in the Bessel beam increases and as such the power is distributed across the entire beam profile. Therefore a balance must be found between propagation distance and the fraction of the overall power present in the core.

While Ashkin and Dziedzic examined optical guiding of particles immersed in fluid, and we have studied Bessel beam levitation in fluid [14] carrying out guiding experiments in air is more challenging than in liquid, and as such has not been considered before. Our work is motivated by applications in aerosol chemistry and dynamics [13] and the attraction of optical manipulation of particles in this way is that it offers potentially greater control over aerosol sample collection and analysis.

2. Experiment

A single vertical Bessel beam was used to levitate and guide droplets over millimeter distances, balanced against gravity and an opposing air flow. The guiding properties of the trap were tested and compared for droplets of dodecane, ethanol and water. Guiding in the Bessel beam was also compared to that achieved with a Gaussian beam for the same liquids.

Previous work has utilized the optical levitation of a variety of liquid droplets (see overview in [8]). In order to capture and guide droplets, a standard laser levitation scheme was used. A 2W CW ytterbium fibre laser at 1064 nm was used to provide a satisfactory range of levitating intensities for particle guiding. For the Gaussian beam experiment the beam is collimated with an appropriate beam waist so as to form the desired spot size after being focused with a final $f=25\text{mm}$ lens. The Bessel beam is made using an axicon with an opening angle of 1.5 degrees in a double telescope arrangement [15] resulting in a beam with ten rings and a core intensity of approximately one-tenth of a Gaussian beam. The first telescope expands the beam to allow adjustment of the propagation distance of the beam, while the second telescope is used to adjust the central core size of the beam (to match the spot size of the Gaussian beam). The experimental arrangement is shown in Fig. 1 for the Bessel beam.

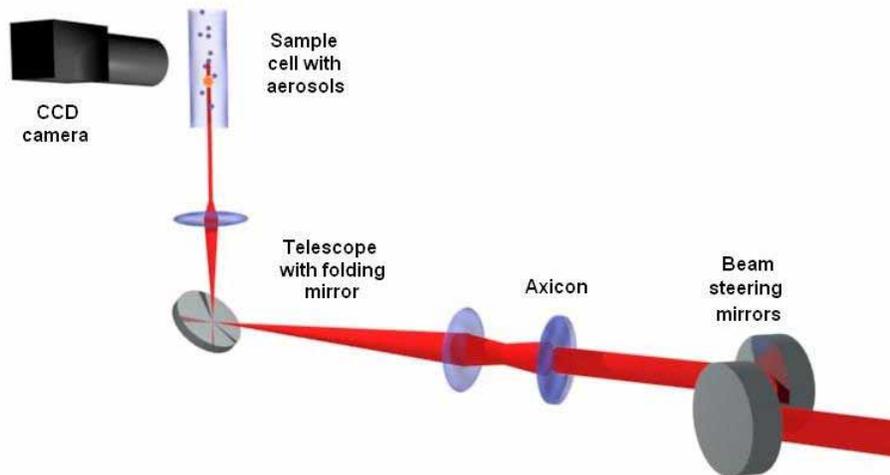


Fig. 1. Experimental setup for optical levitation using a Bessel beam.

The droplets were generated using a pneumatic nebuliser, filled with a liquid sample driven by a pressurised nitrogen flow. The magnitude of the flow was regulated using a combined flow controller and meter (Omega FMA 5400 Flow Controller) and could be adjusted from 0-2000 cm³ per minute of gas flow. The trapped droplets had diameters of 7+/-2µm. The resulting aerosol was passed into the top of an open-ended glass cell, where in then fell into the guiding laser beam. A CCD camera with a long working distance 10X microscope objective lens was used to image the droplets through a flat window in the cell. The camera was mounted to an xyz translation stage to allow the droplets to be observed along their entire guiding distances.

Ambient conditions in the laboratory and near the cell were also an important factor in the success rate of the experiment. The temperature was regulated at 22°C, and the humidity in the cell was kept as high as possible by placing a water reservoir in the cell. Care was also taken to minimize air currents around the cell, and the optical bench was floated to prevent any mechanical vibration in the cell. We successfully levitated droplets at 100mW for upwards of 20 minutes with this apparatus.

To test the guiding properties of both the Gaussian and Bessel aerosol trap, the balance point of a single droplet against the upward scattering force due to the levitating beam was found for a range of laser powers. In addition to the gravitational force acting on the droplets, there was also a down-force due to the airflow which was required to drive the nebuliser generating the droplets. It was found that the precise flow required to generate droplets depended both on the viscosity of the liquid as well as the angle of inclination of the nebuliser. So despite trapping powers of less than 10mW being recorded in Ashkin's previous droplet levitation experiments [6], a much greater power was required initially to offset the nitrogen flow and successfully trap the droplets. The flow could then be reduced in tandem with the laser power to a minimum value for each experiment. Thus although this experimental set-up allows for the short-range guiding of droplets, it is more complicated to operate than standard single-beam optical gradient traps which are capable of z-trapping [3].

The equilibrium positions were measured for single droplets at a constant flow rate. This was repeated for both the Gaussian beam and the Bessel beam profiles and for samples of three different liquids (water, ethanol and dodecane – an outline of liquid properties is shown in table 1). Direct imaging of trapped droplets confirms that the droplet sizes for each of the liquids were roughly the same, although there was no means of accurate particle sizing for each individual droplet in the guiding case.

Table 1. Properties of the liquids used in the droplet manipulation studies

Chemical Name	Refractive Index	Density (kg/m ³)	Viscosity (cP)
Water	1.33	998.2	1.02
Ethanol	1.36	789.2	1.26
Dodecane	1.42	754.6	1.38

The Gaussian beam had a diameter of 12 μm at the focus. The beam diameter expanded to $\sim 25 \mu\text{m}$ after 500 μm along the direction of propagation. To test the guiding properties of the beam, droplets were generated at a constant flow rate for each of the three test liquids. Care was taken to ensure that only one droplet was trapped in the beam at any one time. Too great a flow of droplets resulted in up to three droplets being trapped before merging to become larger droplets than originally intended. The optical levitation of multiple droplets, we believe, is evidence of optically bound arrays [16] and will be explored in more detail in the future. An indication of the type of effect that is observed is illustrated in Fig. 2. The video shows an array of three water droplets being trapped. The upper two droplets merge with each other and then the new coagulated drop is too heavy for the beam to support and falls out of the beam. The merged droplet does not fall directly down to hit the lower droplet, as a result of air currents in the sample chamber.

We compared the Gaussian beam guiding with a Bessel beam with a minimum core diameter of 4 μm and a propagation distance (the distance over which it can be considered non-diffracting) of 4mm. In choosing this core diameter we note that with 1W of power in each of the beams this leads to a near equal intensity in the core of the Bessel beam and at the focus of the Gaussian, as our Bessel beam contains 10 rings with the power evenly distributed between them. A detailed profile was made of the beam along its direction of propagation at 250nm intervals. The core was found to expand to 25 μm at the end of the 4mm propagation distance, at which the 2nd ring became indistinct and the central spot became irregular.

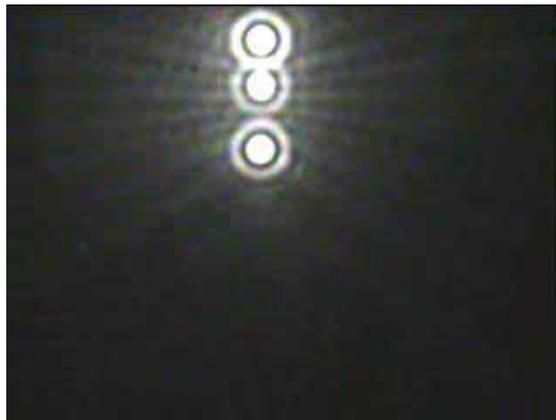


Fig. 2. Video of water droplets merging in a Gaussian beam

3. Results

Using the Gaussian beam both water and ethanol behaved in a stable manner and could be made to move up and down with adjustment of the output power. Although dodecane droplets were trapped at lower intensities than water and ethanol, they were found to be less stable in the beam, as result of the higher refractive index and hence scattering of the

dodecane. Despite the increase in vibrational motion observed, the maximum guiding distance was found to be significantly greater for dodecane, consistent with an increased scattering force. The maximum guiding distances were found to be 250 μm for water (Fig. 3), 275 μm for ethanol (Fig. 4).

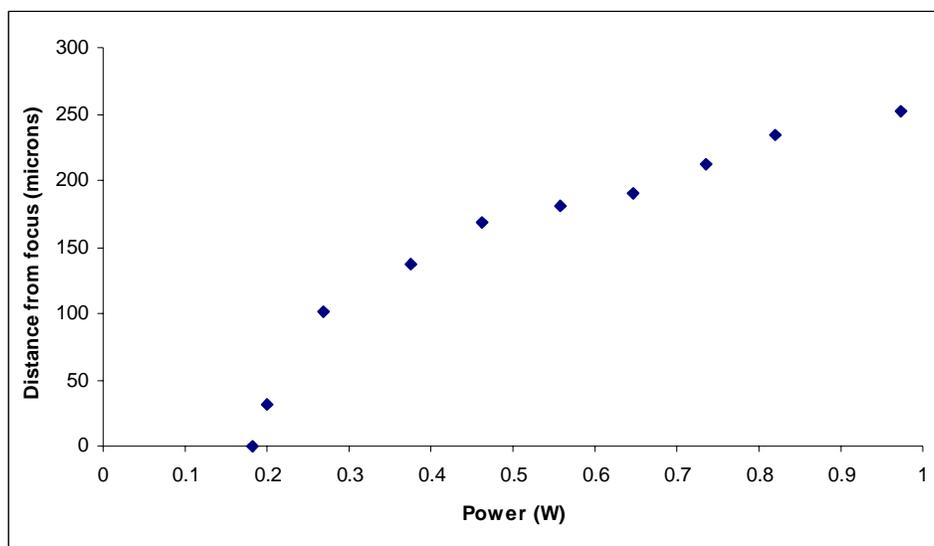


Fig. 3. Water droplet height against laser power (W) for water for a constant flow rate of 0.58 litres/min levitated in a Gaussian laser beam.

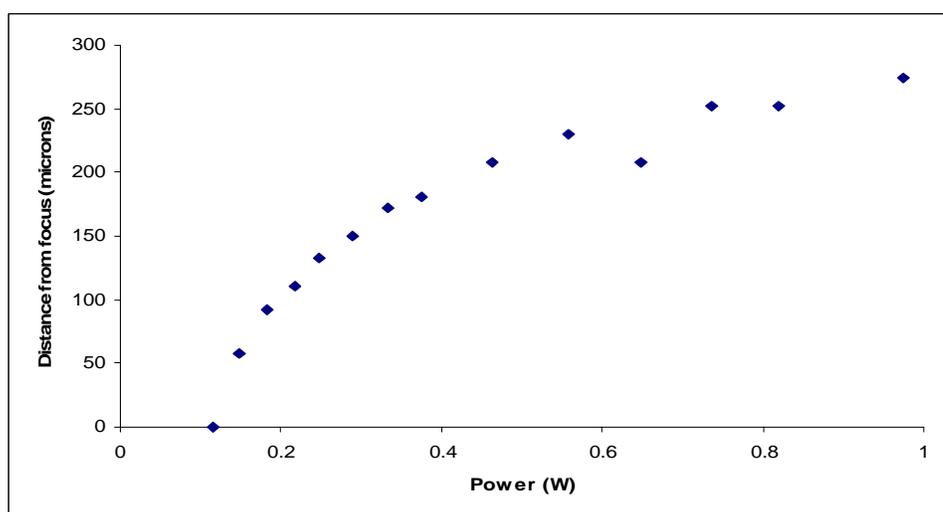


Fig. 4. Particle height against laser power (W) for ethanol for a constant flow rate of 0.5 litres/min levitated in a Gaussian laser beam.

We could not consistently repeat the guiding for dodecane, although a maximum distance of 800 μm was observed in a single, but uncontrolled, experimental run. This non-repeatability is due to a combination of instability once trapped and the increased chance of additional droplets entering the trap during the course of each run of the experiment. However, the total guiding distance can be found easily by rapidly adjusting the power, and

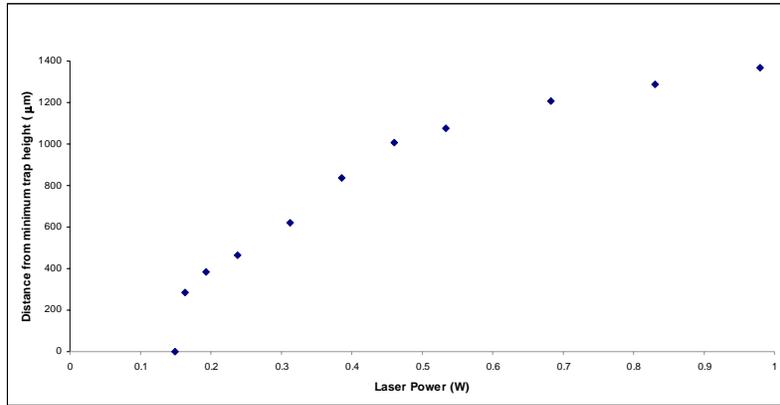
the increased guiding distance compared with water and ethanol is consistent with an increased scattering force

We then performed similar experiments with the Bessel beam. As with the Gaussian beam experiments, dodecane was found to be more easily guided than the other sample liquids. In addition, the problem of trapping multiple droplets was a greater issue for the Bessel beam trap. Isolating single droplets was particularly difficult and the flow rate had to be carefully selected to avoid trapping multiple droplets. In some cases, droplets were trapped over a significant portion of the beam, forming extended arrays of particles. This was possible due to the relatively large vertical trapping region presented by the core over the large propagation distance. Another factor may have been the documented self-healing effect of Bessel beams which we have shown to form similar arrays in colloidal solutions [14].

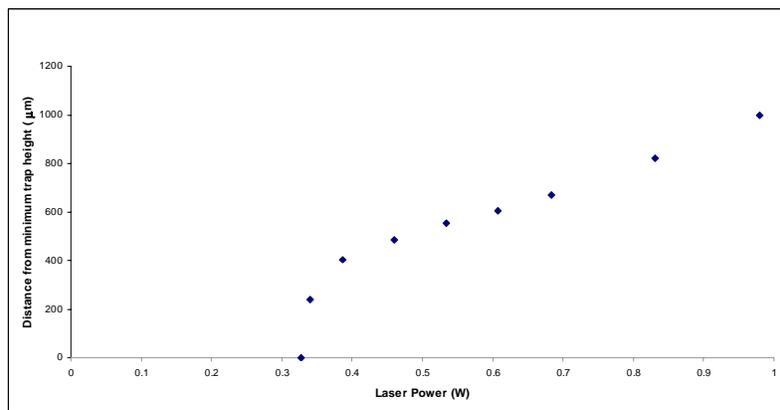
For water droplets, the Bessel beam allowed guiding to occur over 1.2 mm. This is approximately five times the distance achieved in the Gaussian beam. There was less improvement in the ethanol case, with only an approximate fourfold increase observed. Similar improvements were evident in the case of dodecane, where we observed maximum guiding distances of approximately 2.75mm, ~3 times the distance achieved with the Gaussian beam trap. A video of the vertical guiding of dodecane in a Bessel beam is shown in Fig. 5. The guiding results are illustrated in Fig. 6. In addition, the guiding was more controllable in the Bessel case, due to the smaller changes in intensity as the particle moved in the beam, and the increased stability allowed more precise measurements to be made. We note that the increases in guiding distances are in accordance with the relative refractive indexes of the liquids which is proportional to the scattering force. We also note that while we have restricted the comparison in this paper to powers of 1W, the maximum guiding distances observed in the Bessel beam were 2mm for water, 1mm for ethanol and 3.5mm for dodecane using 2.25W of power in the beam.



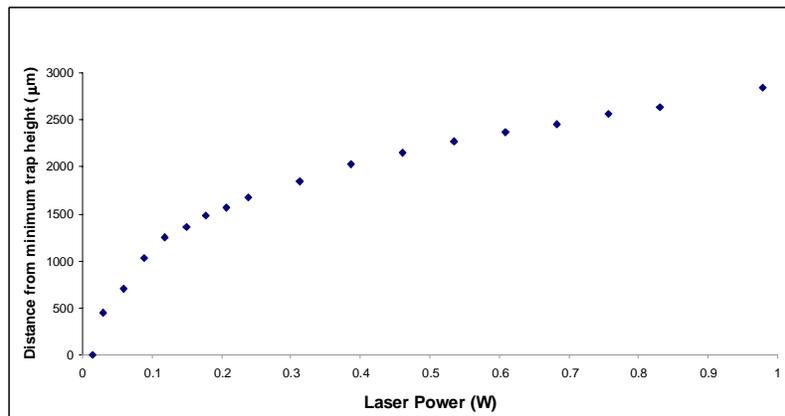
Fig. 5. Video of dodecane droplet guiding with a Bessel beam The maximum guiding distance shown is 800 μ m.



(a)



(b)



(c)

Fig. 6. Particle height against laser power (W) for (a) water, (b) ethanol and (c) dodecane at a constant flow rate in a Bessel beam. The particle displacement is relative to the displacement for the minimum trapping power.

4. Discussion and conclusions

The guiding of the droplets is a simple consequence of radiation pressure and the ability of the Bessel beam to guide further than the Gaussian, for a similar beam core size similar to the Gaussian beam diameter, is due to the quasi-non-diffracting nature of such beams which results in an effective larger depth of focus than a Gaussian beam, and hence a less rapidly diverging intensity profile than a tightly focused Gaussian.

In this comparison we must of course choose some sort of basis on which to compare. For this work we have chosen the beam intensity at the focus as the constant. Other parameters such as the power in the part of the beam doing the guiding or in the depth of focus of the Gaussian or the beam sizes at the focus could have been used and could be deemed fairer. However for a given power and intensity we have shown that the Bessel beam outperforms the Gaussian and offers practical advantages for the type of work we in which we envisage using such beams.

We note that the increased guiding distances achieved by the Bessel beam are a result of the non-ideal nature of our experimental beam. For the case of an ideal beam we would not be able to guide by adjusting the power, as provided we could find a power which resulted in an equilibrium position, every point in the beam core would be an equilibrium point. Any increase in power would result in an increase in power along the whole of the beam, and no point in the beam would now be an equilibrium point. We make use of the fact that our quasi-Bessel beam has a varying intensity profile along the beam propagation distance.

In conclusion we have demonstrated the successful levitation and guiding of aerosol droplets of water, ethanol and dodecane in vertical optical radiation pressure traps. The guiding characteristics of both Gaussian and Bessel beam geometries were compared. For a minimum core diameter of $4\mu\text{m}$, droplets were captured and guided up to 2.75mm in the Bessel beam using adjustments in the output power only. For a comparable Gaussian beam we achieve guiding distances of $800\mu\text{m}$.

This shows potential for applications in "lab-in-a-box" concepts. The ability to capture aerosol samples and guide them through a number of sensors would appear to be particularly feasible using a Bessel beam for droplet guiding and this is the intended future direction of this work - to improve single droplet sampling and detection techniques. Future work will also concentrate on horizontal guiding and the manipulation of droplets from single droplet sources.

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