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Radiometric Levitation of Opaque Particles in a Laser Beam

Capstone Project

Abstract

We investigate the trapping of opaque microscopic particles in mid air by a laser beam. Radiometric interactions with ambient gas molecules suspend and hold the particles in place. Tungsten, charcoal, and black liquor particles are observed. A microscope and CCD camera are used to image the particles and to capture video footage of particle jitter motion while trapped. A shutter controller is used to determine particle jitter speeds, which typically range from 1.5 x10 $^{-3}$ m/s to 4.8 x10 $^{-3}$ m/s. Particle sizes up to 14 microns are observed with various shapes and jitter. The on-axis jitter motion has a typical range of excursion of 30 to 60 microns. Many particles can simultaneously be trapped near the focus. Particles separated by less than 15 microns often exhibit synchronized coupled motion.

CHAPTER 1 BACKGROUND

1.1 Overview

Shortly after the development of lasers, Eric G. Rawson and A. D. May observed particles moving in a laser beam. Particles moving parallel to the beam axis they called runners, and particles moving perpendicular to the beam axis they called bouncers [1]. Since then, many people have researched particles in a laser beam. Arthur Ashkin devolped a 3 dimensional trap for transparent particles, otherwise known as optical tweezers. Optical tweezers require a sharp focus. It operates through the transfer of light momentum. Transparent particles with a higher index of refraction than the surrounding medium remain in the focus. If the particle begins to move out of the focus, the beam is bent and a restoring force results from the change in light momentum. Ashkin's work was experimentally verified by observing the opposite result of air bubbles in water. Because air has a lower index of refraction than water, the bubbles were repeatedly pushed out of the beam. [2]

The laser group at BYU headed by Dr. Peatross in the Physics Department has sought to understand the 3 dimensional trapping mechanism for opaque particles. The laser group found that opaque particles can be trapped in 3 dimensions in a laser focus. Orientation of the trap does not seem to be important. Transparent trapping in a focus is possible due to the redirection of photon momentum. This explanation is insufficient however for opaque particles because photon momentum would tend to push opaque particles out of the focus.

Since the transfer of photon momentum does not seem to adequately explain the trapping of opaque particles an explanation on trapping is sought. Dr. Baxter from the BYU Chemical Engineering department joined the investigation and suggested that buoyancy forces from convection currents may be responsible for the trapping mechanism.

1.2 Free Fall

In order to investigate Dr. Baxter's hypothesis, a free fall experiment was designed to test if particles can remain trapped in a zero gravity environment. By removing the gravitational force, the balance of convection from rising air would be elliminated. During the summer of 2004, John Painter and I conducted free-fall tests, which demonstrated that gravity is not critical to the trapping phenomenon. The conclusion is that convection currents are not primarily responsible for particle trapping.

For the free fall experiment conducted last year, a chamber was designed to slide on a rail attached to a wall. The chamber was allowed to fall approximately 1.6 meters providing half a second of free fall. A laser beam from the ceiling was aligned parallel to the rail. A motor controlled mirror was attached to the side of the chamber to direct the laser into the chamber's lens. The mirror rotated during free fall to help confirm that particles were really trapped and not accidentally remaining in the beam path

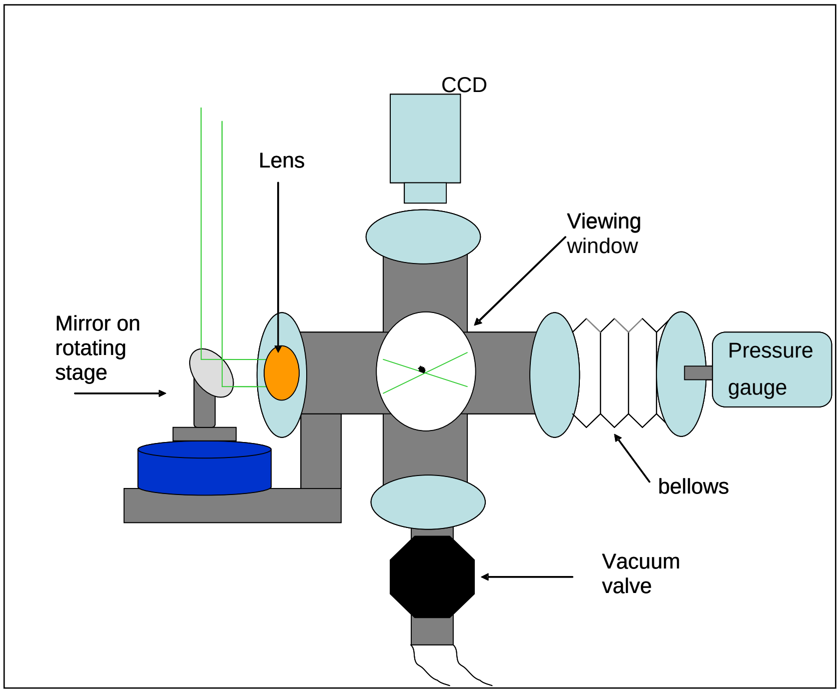


Figure 1.1 Free Fall setup [3]

Our results showed that the particles remained in the beam throughout freefall. As a result of scanning the motorized mirror, the particles moved about 2mm during freefall. We checked that this amount is expected by comparing with images of the scanning beam taken when the chamber is at rest. Given air friction for a moving particle, the small beam diameter near the focus, and the curved path that particles take when the mirror scans, it seems unlikely that the particles accidentally followed the beam for 2 mm during freefall if they were not trapped.

Occasionally particles would fall out immediately at the beginning of freefall, but we found this was caused by a jolt when the chamber was released from rest at the beginning of the drop. Typically, if the particle remained trapped through the first two or three frames (each 1/15 second) of freefall it stayed trapped the entire drop.

Compelling evidence has been presented that the trapping mechanism still works in the absence of gravity. This suggests that convection (hot air rises) is not the primary trapping mechanism; it should be possible to trap opaque particles in a laser onboard the Space Shuttle. [3]

1.3 Particle Shape

An electron scanning microscope has been used to image samples used in the trapping experiments. Figures 1.2 – 1.6 were taken with an electron scanning microscope and show that a variety shapes and sizes exist. However, since the particles that trap in the laser are self selected as many particles are spinkled into the focus, it is unclear which of the many particle shapes seen in the electron-microscope images might be preferred. To further investigate the behavior of opaque particle traps I imaged particles while they were trapped using an optical 40X microscope. By optically imaging trapped particles and uncovering their behavior, we may better understand the mechanisms and forces that govern opaque particle traps.

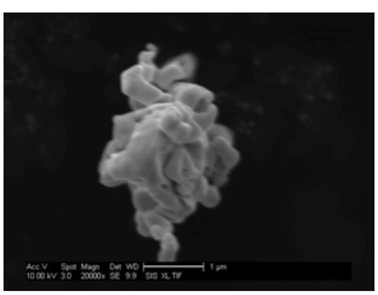


Fig. 1.2 Tungsten, 1-5μm [3]

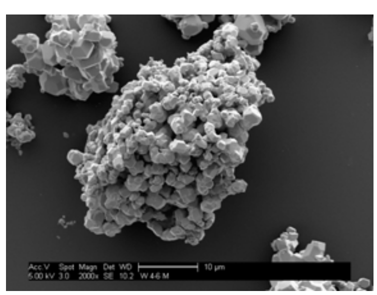


Fig. 1.3 Tungsten, 4-6μm [3]

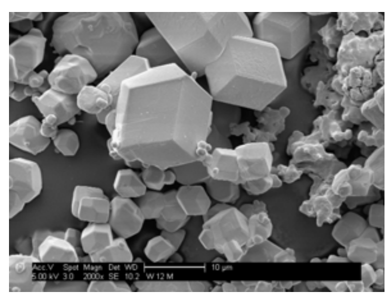


Fig. 1.4 Tungsten, 12μm [3]

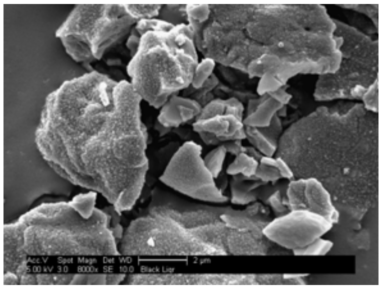


Fig 1.5 Black Liquor, unknown size[3]

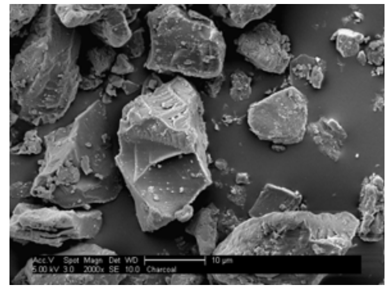


Fig 1.6 Charcoal, unknown size [3]

1.4 Photophoresis & Thermal Creep

There have been several proposed mechanisms for the levitation of opaque particles. Photophoresis and thermal creep are often suggested to be involved in papers on the subject. [4,5]

Photophoresis occurs when there is a temperature difference between a gas and a particle. Air molecules that come in contact with a particle are heated and increase in kinetic energy. Rebounding gas molecules then exit at a speed much greater than incoming molecules. A particle that is uniformly heated and has a uniform surface temperature would experience forces which are equivalent in all directions. However, if a temperature gradient existed across the particle, then gas molecules wouldn't rebound uniformly across the particle's surface. The particle would experience a net force aligned with the temperature gradient.

Thermal creep (a type of thermophoresis) occurs when a temperature gradient exists within the neighboring gas. Thermal creep is responsible for how a Crooke's Radiometer works. A Crooke's Radiometer works by creating a temperature difference on a vane inside a glass container filled with low pressure. One side of the vane is black and acts as a light absorber while the other side is white. As light falls onto the vane, a temperature gradient is created between the black and white portions along the edges of the vane. Air molecules flow around the edges of the vane from the colder side to the warmer side creating a pressure difference. Typically this would not be possible with macroscopic air flow. However, air viscosity drops when the characteristic length of an object approaches the mean free path of a fluid. The drop in viscosity is often referred to as "slip" and the motion of cold molecules towards increasing temperature is referred to as "thermal creep". "Equilibrium is reached when the ratio of pressures on either side is the square root of the ratio of absolute temperatures."[6] The pressure difference from edge effects (thermal creep and slip) on the cold side of the vane is what causes the radiometer to turn.

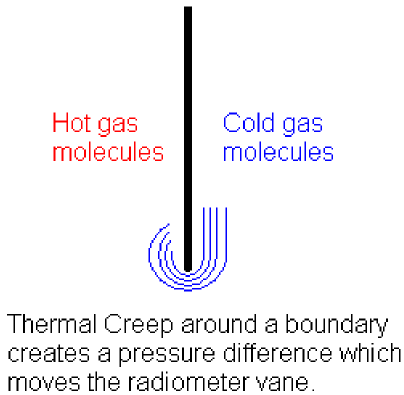


Fig. 1.7 A Crooke's Radiometer enclosed in an evacuated bulb. Light creates a thermal gradient across the vane. The effects of thermal creep then create a pressure difference which in turn, moves the vane away from the hot gas.

These same thermal creep flows that cause a Crooke's Radiometer to turn, would also exist around a particle with a temperature gradient. If there is a temperature gradient across trapped particles, then thermal creep will be involved and may be part of an overall theory on the trapping mechanism and the behavior of trapped particles.

CHAPTER 2 EXPERIMENTAL SETUP

2.1 General Setup

For my trapping experiments, I used a 5-watt laser with wavelength of 532 nm (Coherent Verdi). I would typically set the laser power at 4.50 watts when trapping tungsten and at about half that when trapping charcoal or black liquor particles. Before the experimental setup, the initial laser beam diameter is ~ 3mm. Experience has shown that a low f-number focus makes it easier to trap particles in a focus. To accomplish this, I expanded the beam in a Keplarian telescope (magnification 5) to get a collimated beam with diameter ~17 mm. The beam was sent through an iris and finally through a 10-cm focal-length lens.

Experiments were conducted at atmospheric pressure in air. A box was placed around the microscope and laser focus to minimize air currents in the lab that may knock out trapped particles. A vacuum setup which encases the entire CCD camera and beam focus is also available for future imaging experiments. Particles are loaded into the trap by dipping the head of a needle into a sample and either quickly dragging the needle down the beam near the focus, or by shaking it above the focus.

2.2 Microscope Setup

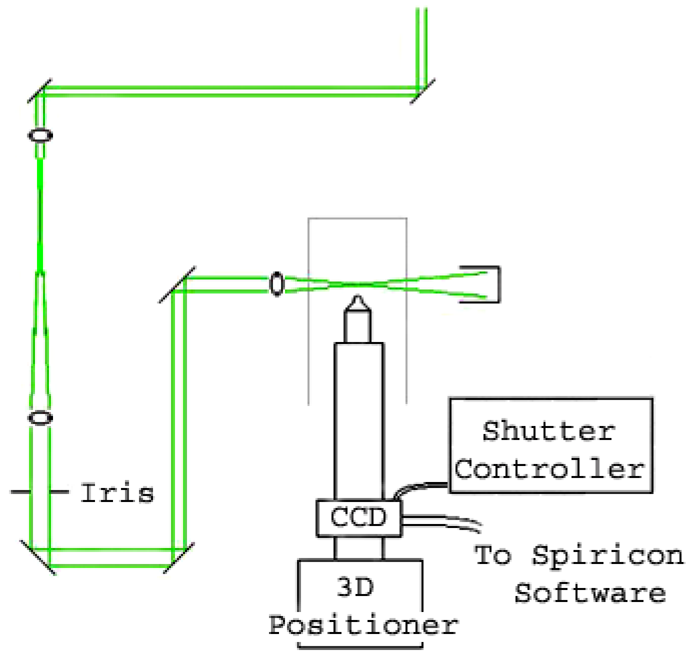


Figure 2.1 Experimental Setup

A microscope objective (40x) was setup to view the focus, which was perpendicular to the beam path. The microscope imaged the particles onto a CCD camera (Pulnix, TM-7CN). Because the working distance of the microscope was only a few millimeters, the camera setup was attached to a 3D positioner. A Pulnix shutter controller was attached to the camera to control shutter speed. The shutter controller could keep the shutter open or flash the shutter as fast as 1/10,000 seconds. The shutter controller also acted as a filter to reduce saturation on the CCD. The data was sent to a computer and viewed with Spiricon imaging software (LBA-PC version 3.31). The laser enters from the left for all images.

During the imaging process, the 3D positioner was used to move the microscope objective closer or further away from a trapped particle. As the objective was brought in, the particle image became smaller until it was in focus. If the microscope objective was brought in too close then the particle image began to increase in size indicating that the particle was out of focus.

2.3 Camera

The camera interlaced image data at a rate of 60 Hertz. For every complete image the shutter opened twice, once for the first half of the interlaced image and then again for the second half. For the first half of an image, the camera shutter opened for 1/10,000 seconds. This data is displayed on every other horizontal line in a complete image. 1/60 seconds later, the camera shutter opened again for another 1/10,000 seconds to take the second half of the image. The two images are interlaced to create a full image representing 1/30 seconds. Fig. 2.2 represents the process.

Figure 2.2 Two halves of an image are interlaced to produce a complete image.

The camera interlacing process was useful because it allows the speeds of moving particles to be measured. Particle speed was measured by measuring the distance a particle moved and dividing it by 1/60 seconds.

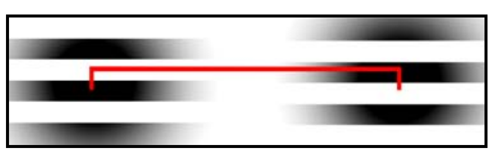


Figure 2.3 The particle moves a certain distance in 1/60 seconds, providing a way to measure the average speed of a particle.

Because camera vibrations and resolution were of concern, I imaged a razor blade near the focus of the laser. Using a 40X microscope I observed a resolution of one micron or 4 pixels. The vibration amplitude during the interlacing time was under 1.5 microns. The table and camera vibrations did not cause the image to drift with time. Vibrations within the experimental setup were not significant.

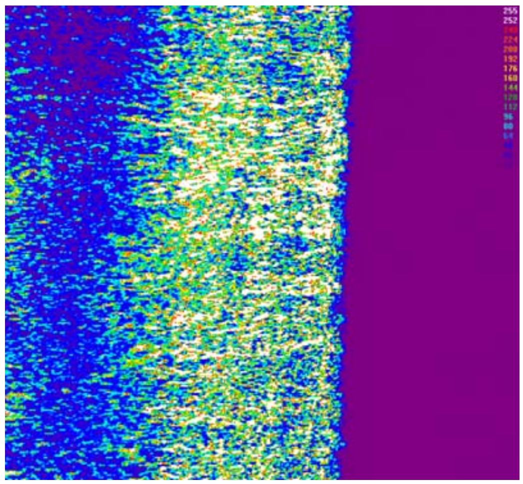


Figure 2.4 Edge of razor blade, 125x117μ window

CHAPTER 3 MICROSCOPE OBSERVATIONS

3.1 General Observations

I found a number of general attributes that were common among all of the trapped particles I observed. Since I focused on trapping in atmospheric pressure, I trapped black liquor, charcoal, and some tungsten. My field of view was limited to125 microns along the beam path and 117 microns perpendicular to the beam. All particles I observed jittered or oscillated parallel to the beam. Most stable particles oscillated in an individual "well" that varied between 15 and 60 microns.

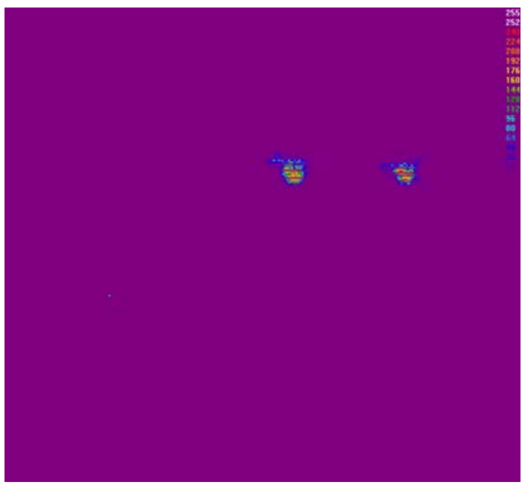


Figure 3.1 6μ size Tungsten particle in 4.5 Watt laser beam
The particle moves 27μ in 1/60 seconds with an
average speed of 1.6 x10^{-3} m/s, 125x117μ window

Using the camera's interlacing frequency of 60 Hertz; most stable particles had a measured speed between 1 x10^{-3} m/s and 2 x10^{-3} m/s which often depended on the well size. Larger wells often tended to have faster moving particles.

3.2 Particle Drift & Jitter

The position of particle wells drift with time. In most cases I observed particles drift less than 80 microns. The orientation of the drift was greatest along the beam axis. Most often, the well would drift back to its original position within a minute. Often if a particle does drift, the neighboring particles drift as well. On a few rare occasions I observed a single particle drifting with respect to the neighboring particles. Particle drift seems to indicate that all potential wells are being displaced by a common force, such as slowly changing ambient air currents, or perhaps changes in the laser beam mode. All of the trapped particles I observed jitter along the beam axis around a general location. Larger particles tended to have correspondingly larger well.

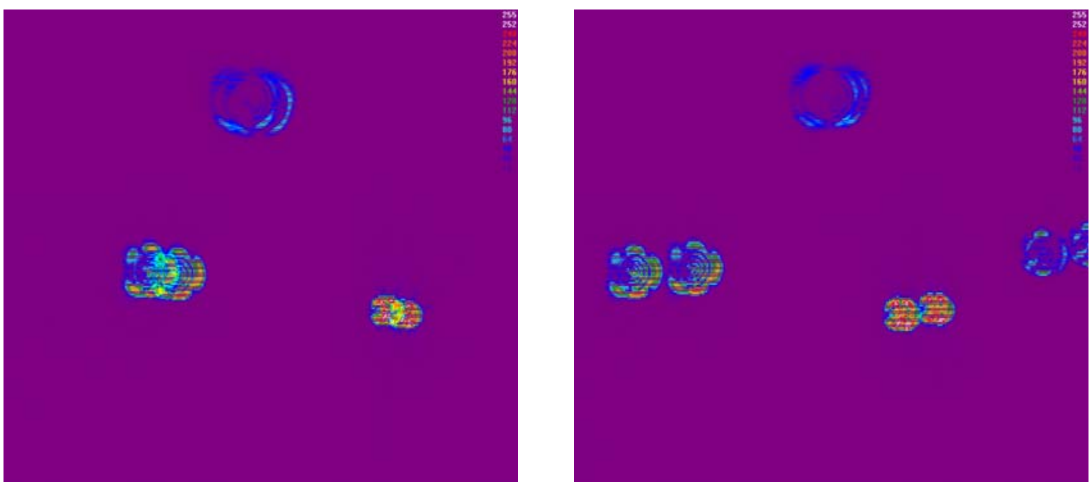


Figure 3.2 & 3.3 Black Liquor particles drifting with time (20+ seconds).
Only the bottom "red" particle is in focus in figure 3.2, 125x117μ window size

3.3 Particle Shapes & Sizes

The smallest particle that I observed was 1 micron in diameter and had a well size of under 10 micron. The largest particle I observed was 14 microns in diameter.

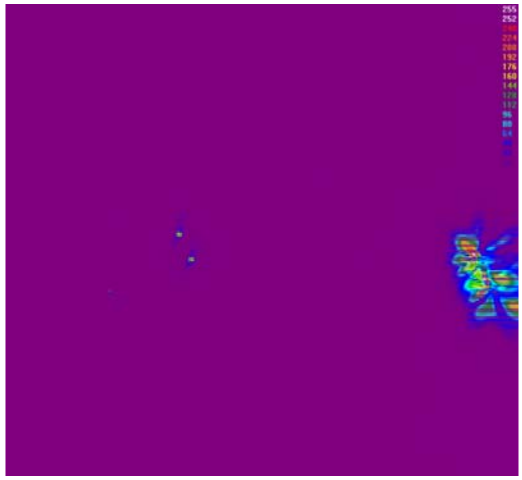


Figure 3.4 1μ size Black Liquor particle in a 2.22 watt laser beam. The particle moves 7μ in 1/60 seconds with an average speed of 0.4×10^{-3} m/s. The particle's well size is unusually small (under 10μ). The particle on the right is out of focus. 125x117μ window size

The particle shapes most commonly observed were spherical. A few oblong and nonsymmetrical shapes were also observed. Of particular interest was a fish or boomerang shaped particle shown below. Keep in mind that what looks like a pair of identical particles is actually the interlacing effect, the same particle viewed 1/60 second in sequence.

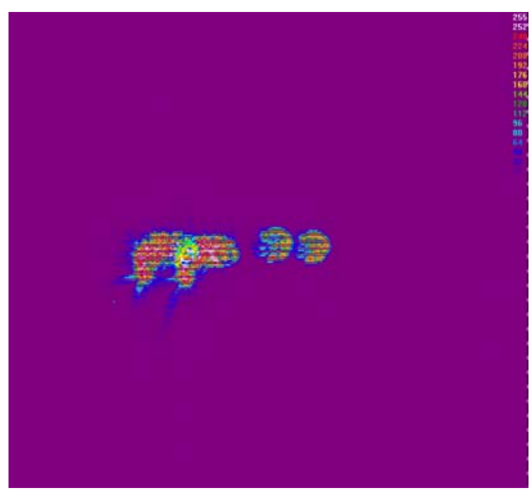
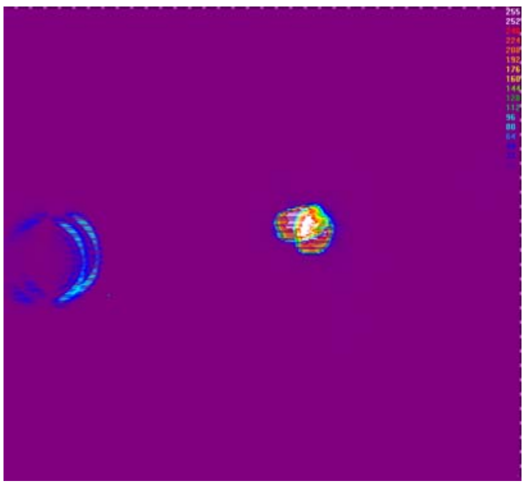


Figure 3.5 & 3.6 Charcoal particle(s) in a 4.5 watt laser beam. Figure 3.5 shows the particle moving 15μ in 1/60 seconds with an average speed of 0.9×10^{-3} m/s. Several minutes later the original particle becomes coupled with a 10μ size particle as seen in Figure 3.12. 125x117μ window size

The fish shaped particle was interesting because it held its shape and orientation within the well. Because of its unique shape any rotation would be observed. This clearly shows that some particles do not rotate or spin in the trap. This led me to investigate the spinning of spherically shaped particles. The particles that I worked with are not exactly spherical but have distinct features such as notches, bright spots, etc. By focusing on a feature I observed that nearly all spherically shaped particles do not spin in the trap. Below are two rare exceptions.



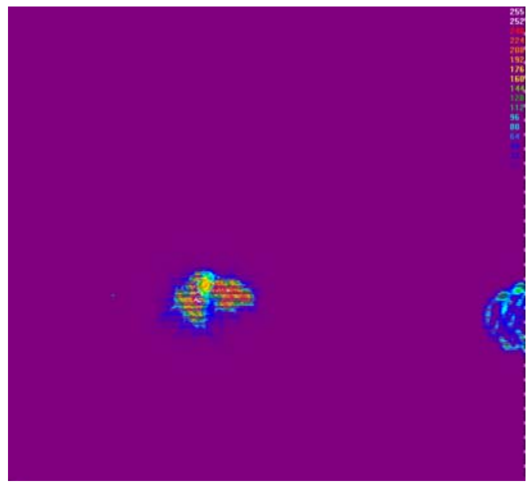


Figure 3.7 & 3.8 Figure 3.7 shows an oblong shaped black liquor particle spinning while Figure 3.8 shows a triangular shaped charcoal particle. Frequency of spin is not constant. 125x117µ window size

Oscillations and jitters transverse to the beam path were rare for most spherical particles. Exceptions occurred most frequently with odd shaped or exceptionally bright particles. When transverse oscillations occurred, the transverse amplitude was typically less than the oscillation amplitude in the axial direction.

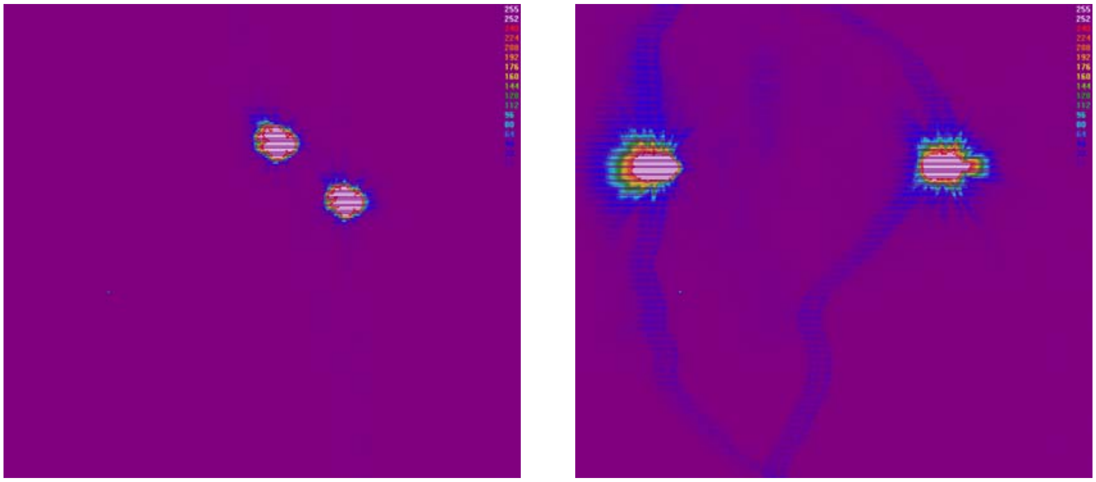


Figure 3.9 & 3.10 Because these images are saturated, particle dimensions are unknown. Figure 3.9 is a Black Liquor particle in a 4.5 watt laser beam. Figure 3.10 is a Black Liquor particle in a 2.22 watt laser beam. The blue trails are camera effects due to image bleeding from saturation. 125x117µ window size

Exceptionally bright particles like that in Figure 3.10 typically had normal oscillation amplitudes, but were prone to have a sudden burst in oscillation amplitude as seen in figure 3.10. Oscillation bursts tended to be larger than 70 microns. The burst seen in figure 3.10 is 71 microns. The oscillation would immediately return to a normal 30-60 µ amplitude after such a burst.

3.4 Coupled Particles

Sometimes particles would interact with one another. When this happened, it was possible for the particle motions to become coupled. Coupled particles have wells that overlap and usually exhibited synchronized rather than asynchronous motion. With few exceptions both particles in a couple were nearly the same size. I observed that coupled particles always aligned themselves strictly in the axial direction and were typically separated by less than 10 microns. At no time did I observe a non-axial aligned coupled pair. It is interesting that the fish shaped particle in figures 3.5 & 3.6 was also aligned in the axial direction.

This alignment is strikingly similar to the findings of Gauthier et al. in 1999. Gauthier et al. conducted particle trapping experiments on micrometer sized cylindrical shaped particles. The particles were immersed in distilled water and manipulated within a 2-D trap. It was shown that an aligning force exists on cylinder shaped particles. This force tends to align a particle's longest dimension with the beam axis in a 2-D trap. [7]

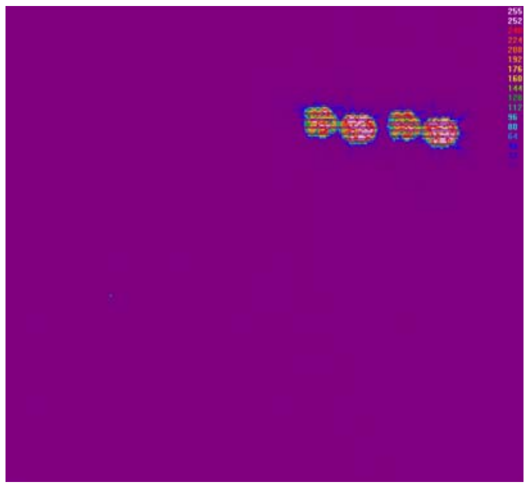
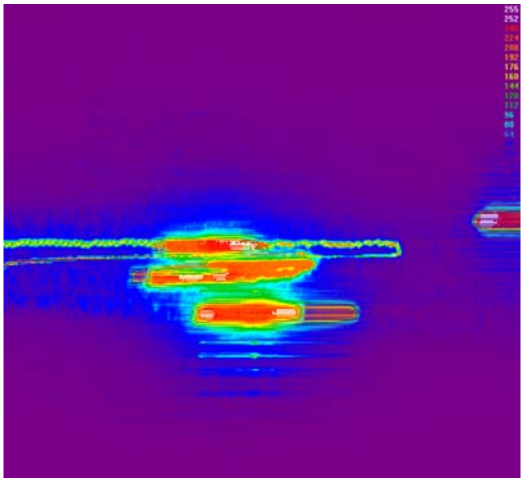


Figure 3.11 Two 9µ sized Black Liquor particles move 20µ (1.2 x10^{-3} m/s) in synchronous motion in a 2.22 watt laser beam. Coupled particles often briefly "kiss" as shown in the figure. 125x117µ window size

3.5 Runners

Runners are particles that zip up and down the beam path. They sometimes seem to bump into other particles, making abrupt turns at the well boundaries of other particles. Since runners travel further than can be observed in my viewing range, I have not been able to obtain an estimate for their average speed. It seems most runners have an average speed that is greater than 1 x10^{-2} m/s which is an order of magnitude greater than the average speed of stable particles.



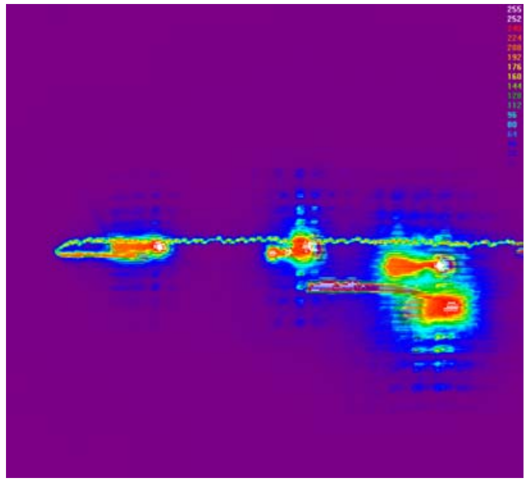


Figure 3.12 & 3.13 Runners zip up and down the beam path. The shutter speed controller that normally takes half of the 60 Hz interlaced image in 1/10,000 seconds was turned off so as to show the path taken by runners during the entire 1/30 seconds. Notice the sharp turn and small zigzag bumps in the path.

Runners are much more common when many particles are trapped simultaneously, in which case even stable particles seem to move around more than usual. Runners travel in fairly straight lines showing hardly any transverse motion, and then only a little at the turn-around point. A runner's path does not widen or narrow as it travels, suggesting that runners do not move in and out of focus. The runner paths recorded on the CCD are often jagged with small zigzag bumps. It is unknown if runners spin as they zip along the beam axis. If they do spin, it may explain the small zigzags recorded on the CCD. The particle dimensions of runners are unknown, but appear to be less than the dimensions of stable particles.

3.6 Future Work

Radiometric interactions with ambient gas molecules may explain how opaque particles are suspended and held in place in a laser focus. Thermal creep or photophoresis effects (which are types of radiometric interactions) may be at work. Since thermal creep flows require a thermal gradient, removing thermal gradients may be one way to verify or discredit whether thermal creep effects are involved. Increasing the air pressure in a vacuum effectively reduces the thermal gradient across a particle. Future work may include slowly increasing the air pressure in a vacuum until particles fall out of a trap and are no longer trappable. Other work might involve experimentally finding the thermal gradient across a particle, if one exists at all.

References

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[2] A. Ashkin, "Acceleration and trapping of particles by radiation pressure," Phys. Rev. Lett. **24**, 156-159 (1970).

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[7] R. C. Gauthier, M. Ashman, and C. P. Grover, "Experimental confirmation of the optical-trapping properties of cylindrical objects," Appl. Opt, **38**, 4861-4869 (1999).