OPTICAL LEVITATION OF OPAQUE PARTICLES IN A LASER BEAM AT HIGH AND LOW PRESSURES

by

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Abstract

We investigate the trapping of opaque microscopic particles at 2 atm and at about 7 torr. A microscope and CCD camera are used to observe the shape, size, and velocity of trapped particles. Particles are found to trap more easily and abundantly at low pressures than at 2 atm. However, particles trapped at 2 atm typically remain trapped for longer periods. Particles at low pressures tended to trap in the laser beam upstream from the focus, while particles at 2 atm tended to trap at the focus. The hypotheses of thermal creep and convection currents for explaining the levitation phenomenon are considered. The evidence presented does not seem to support either hypothesis.

Acknowledgements

I would like to thank Dr. Justin Peatross, my advisor and friend, for spending countless hours advising and helping me on this project. I would also like to thank John Painter, Robert Petersen and Chris Young for their unselfish sacrifice when it came to helping me with this project, even when it required them to come in at all hours of the morning and night. I would like to thank my wife Traci, for supporting my efforts to become educated in physics and for loving me even when I didn't always deserve it. I would also like to thank my parents, Ellis and Connie Lindsey, for teaching me that dreams really do come true. Finally, I would like to acknowledge my son Bennett and daughter Jordan for the joy they bring to my life.

CONTENTS

LIST OF FIGURES

List of Tables

CHAPTER 1. BACKGROUND

1.1 Early History of Particle Levitation

A few years after lasers became widely used, E. Rawson and A. May observed dust particles executing intriguing motions in a laser beam.[1] "Dust Particles have been observed in an He-Ne laser cavity which travel at constant velocities in one of three preferred directions and which exhibit remarkable stability of orientation."[1] Particles moved either transversely or longitudinally in the beam path. Transversely moving particles were called bouncers, while longitudinally moving particles were called runners (see Figs. 1.1 and 1.2).

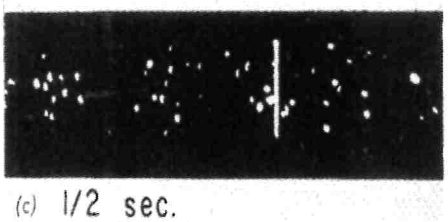

Fig. 1.1 Particles moving transversally, "bouncers." Reproduced from [1].

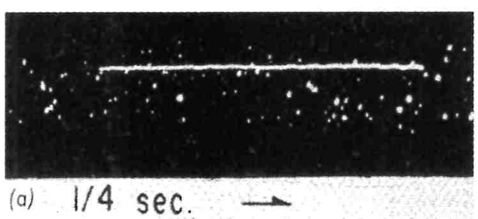

Fig. 1.2 Particles moving longitudinally, "runners." Reproduced from [1].

In their first paper, Rawson and May speculated that light pressure was the main cause for the motion of bouncers and runners. In their second paper [2], they shifted their explanation to photophoresis. "In this communication, we present additional observations and some order of magnitude calculations which show that photophoresis is the probable source of the driving force and stabilizing torque."[2]

Photophoresis is "the net transfer of momentum to a particle due to gas molecules rebounding from the hotter surface with greater momentum than from the cooler surface."[2] In this way, Rawson and May theorized that dust particles respond to energy deposited by the He-Ne laser, which was the agent for heating the particles.

The phenomenon observed by Rawson and May is distinct from optical tweezers, later developed for transparent particles by A. Ashkin.[3] Using a sharply focused laser beam, Ashkin specifically relied on radiation pressure to trap transparent particles. Radiation pressure is the force due to the change in momentum of deflected light. In this case, the trapped particle acts as a tiny lens that deflects the laser beam. This deflection pushes the particle back to the laser beam's focus if it tries to leave. Interestingly, optical tweezers work in a liquid, whereas the phenomenon studied by Rawson and May requires an ambient gas.

1.2 Trapping of Opaque Particles

For over a decade, the work of Rawson and May lay forgotten. In the early 1980's, Lewittes et al. [4] observed opaque particles becoming trapped in a laser beam's focus. Since radiation pressure could not explain the effect, Lewittes proposed that opaque particles were trapped by an alternative two-pronged phenomenon. The first ingredient is a radiometric force. "Radiometric levitation, unlike levitation by light pressure, utilizes the recoil of molecules from a heated surface to provide the force which balances gravity." [4] This explanation is the same one offered by Rawson and May (photophoresis). Apparently, Lewittes was unaware of the earlier work done by Rawson and May. However, Lewittes was the first to observe particles becoming trapped as opposed to runners and bouncers.

The second part of Lewittes' two-pronged phenomenon was the use of a laser beam with a donut mode (TEM_{01}). As seen in Fig. 1.3, Lewittes used a laser beam with a minimum in the center. He explained, "The need for an intensity minimum for forward radiometric levitation is easily understood. If the particle moves laterally from the intensity minimum it will experience increased heating on the side to which it moves. The corresponding increase in radiometric pressure on this side will drive the particle back toward the intensity minimum." [4] Thus, Lewittes believed that the radiometric force and the donut mode (laser oriented vertically) work together to produce an overall trapping effect.

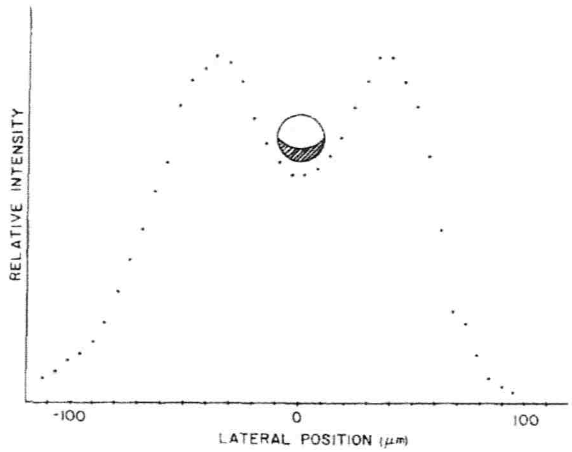

Fig. 1.3 Laser profile with an intensity minimum.[4]

Although this explanation sounds convincing, it is not a universal explanation as shown by A. Pluchino [5] a year later and more recently by J. Huisken and E. Stelzer. [6] They showed that an intensity minimum in the center of the laser beam is not needed and, in fact, the beam can be oriented in any direction. Huisken and Stelzer refined their explanation for why particles trap. Their new explanation included a process called "thermal creep."

Thermal creep occurs when there exists a temperature gradient along a solid surface surrounded by a rarified gas where the molecular mean-free path is on the scale of the thermal gradient. Molecules move from the cold region to the warm region without encountering other molecules en route. The idea is that a trapped particle would be unevenly heated by the laser beam, causing a temperature gradient along the particle, and allowing for the forces of thermal creep to somehow constrain the particle from fleeing the beam. Thermal creep governs the popular science novelty called a Crooke's radiometer.

Huisken and Stelzer incorrectly imply that thermal creep is fundamentally different from photophoresis. Actually, thermal creep is a sub-class of photophoresis. The process of photophoresis simply means that particles gain kinetic energy via light heating. This of course happens for thermal creep with the added caveat that hot and cold gas molecules inter-diffuse with a mean-free path greater than the dimension of the particle.

Huisken and Stelzer used a beam vertically directed towards the ceiling to counteract the force of gravity. They did not use other beam orientations. On the other hand, Pluchino did point his beam downwards and sideways, but resorted to an implausible argument about the Poynting vector of light to explain why particles trap.[5] Our group recently also examined different beam orientations for trapping particles.[7,8] Particles trapped even when the beam was directed vertically downward. Therefore, a balance between the force of gravity and heating of the underside of the particle cannot be the explanation for why particles trap.

1.3 Work Done at BYU

C. Bliss and B. Bellville, both BYU undergraduates, were the first to study particle levitation in our group.[8] C. Bliss trapped various types of materials at various pressures (7 torr through 760 torr). The types of particles that he trapped are listed in Table 1.1. The particles typically ranged from 2-10 microns in diameter. C. Bliss speculated that optical trapping is due to dark pockets in the beam resulting from Fresnel diffraction from the hard aperture of the laser cavity.[8] Since then, John Painter, an undergraduate student at BYU whose work will be discussed later in this section, checked to see if the laser beam used for trapping particles contained diffraction pockets. "I have extensively checked the laser beams used in trapping for evidence of diffraction or intensity pockets. No pockets were seen in our beam."[7] Therefore, intensity minima (at least observable ones) does not explain why particles trap.

Particle	Size	Trapped	Unable to Trap
Silver	1.3 - 2.3 μm	X	
Tungsten	1 - 5 μm	X	
Tungsten	4 - 6 μm	X	
Tungsten	12 μm		X
Aluminum	10 - 14 μm	X	
Aluminum	17 - 30 μm		X
Nickel	7 - 9 μm	X	
Iron	162 mesh	X	
Magnesium Oxide	100 mesh	X	
Charcoal	unknown	X	
Graphite	325 mesh	X	
Black Liquor	unknown	X	
Polystyrene spheres	3 μm	X	

Table 1.1 Particles trapped by C. Bliss at pressures ranging from 7-760 torr.[8]

Photophoresis (thermal creep), however, is in our opinion the leading candidate for explaining the phenomena of particle levitation. However, this hypothesis is not without its problems. It would appear that particles should flee from the intense regions of the laser beam. After all, a Crooke's radiometer turns away from the warmer side of the veins, which are heated by light.

An alternative idea that might account for the trapping phenomenon, is the possibility of convection currents established in the air surrounding the particles. Dr. Larry Baxter's group in the Chemical Engineering Department at BYU, developed a computer simulation showing that convection forces can balance gravitational forces.[9] In this picture, gravity is an active ingredient in the formation and orientation of the convection current. The appeal of this model is that it does not depend on the orientation of the beam. Although this explanation is tenable, research done by John Painter and Adam Hendrickson of our group contradicts this explanation.

Since convection depends on gravity (hot air rises), our group constructed an apparatus that allowed the observation of a trapped particle during free fall. The system effectively eliminated the force due to gravity, which in turn should eliminate convection too. Their experimental setup consisted of a metal chamber attached to a slide rail secured to the wall. The laser remained aligned with the chamber as it slid along the rail. After several observations which included active side-to-side scanning of the laser beam, it was concluded that particles stay trapped even during free fall. "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 on the Space Shuttle."[7]

The zero-gravity results renewed interest in the hypothesis of thermal creep as the primary agent for particle trapping. J. Painter also studied the performance of a Crooke's radiometer under different pressures. He found that there is a range of pressures in which the radiometer works; both an upper limit and lower limit. The upper limit was at a few torr. The speculation is that the trapping phenomenon might also have an upper limit. A lower limit in pressure was observed by our group to be a few torr, but a higher limit in pressure has not yet been tested.

1.4 Overview

For my thesis, I set out to test if there is a higher limit in pressure beyond which particles no longer trap in the laser beam. If a higher limit is found, this would endorse that thermal creep somehow plays a role in particle levitation. We constructed a chamber that allows us to control ambient pressure while trapping particles in the laser. Low pressures were achieved by using a roughing pump, whereas high pressures were achieved by leaking in nitrogen gas. We trapped a variety of particles with pressures ranging from a few torr to two atmospheres. We used a CCD camera imaging system to observe trapped particles.

This work may be considered an extension of Adam Hendrickson's thesis, wherein he obtained close-up images of trapped particles. However, all of his work was done at atmospheric pressure. His results showed that smaller particles are more likely to trap than larger ones. All of the particles were found to jitter over a distance of tens of microns. He found that trapped particles that are asymmetric typically do not rotate within the beam.

Chapter 2 of this thesis gives details of the vacuum apparatus used for my experiments. Also, the camera and laser setup are explained in detail. Chapter 3 presents observations of trapped particles under low (~7 torr) and high pressure (2 atm). We found that particles trap at both pressures, but more easily at low pressure.

CHAPTER 2. EXPERIMENTAL SETUP FOR TRAPPING AT HIGH AND LOW PRESSURES.

2.1 Chamber for Particle Levitation

As mentioned in chapter 1, we built a special chamber to control pressure for particle-trapping experiments. A photograph of the chamber is shown in Fig. 2.1. Fig. 2.2 shows a schematic of the same.

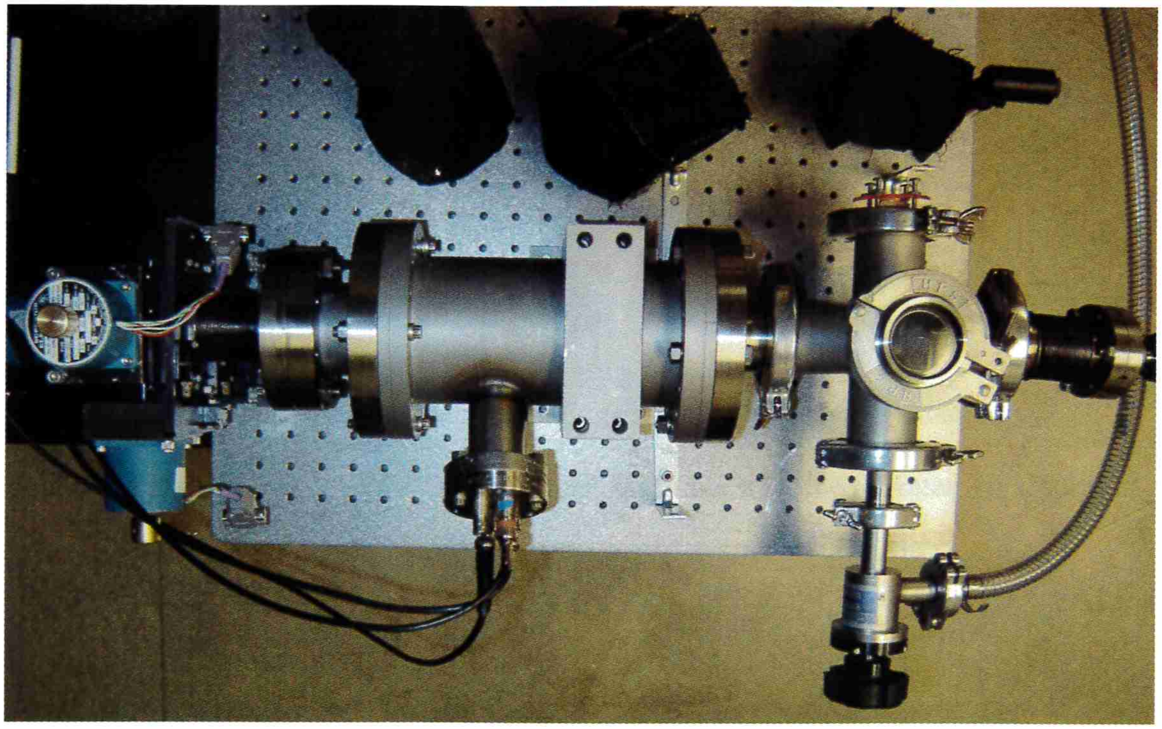

Fig. 2.1 Picture of trapping apparatus taken from overhead.

A key part of the chamber is the cross-shaped portion on the right, which includes a window on top for viewing trapped particles. Attached to the cross apparatus is a gauge tube (Sentorr, Varian) for reading the pressure inside the chamber. A bellows is attached to an internal armature, which can be manipulated from outside the chamber. On the end of the armature is a sewing needle for dipping into substances such as black liquor or silver particles. A 10-cm focal-length lens is placed in another arm of the cross, which focuses the laser to the center of the cross, below the viewing port. Finally, a valve is attached to the side of the cross apparatus (opposite the lens) for evacuating or filling the chamber with air (refer to Fig. 2.2).

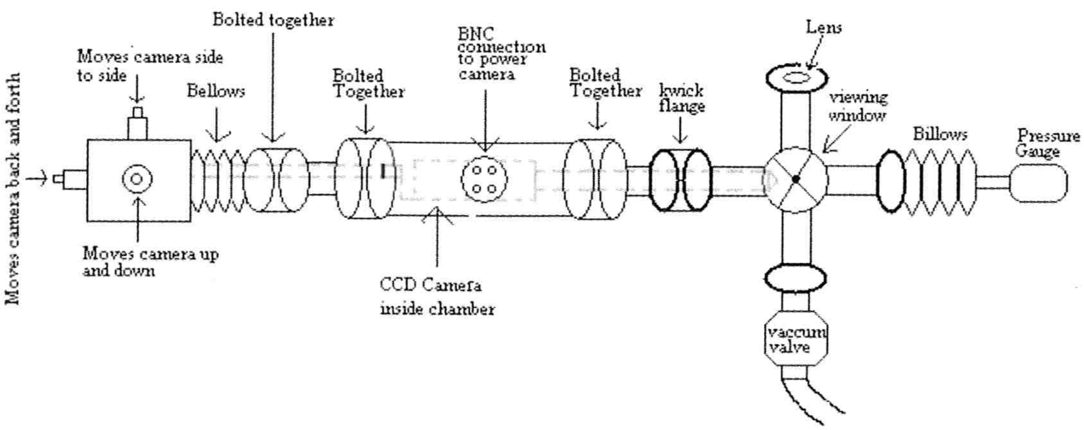

Fig. 2.2 Schematic of the chamber (top view).

To the left of the cross apparatus, a large metal tube is connected to an xyz translation stage that holds a CCD camera inside. In this way, the operator has control of camera movement even while the chamber is sealed. Electrical feed-throughs are connected to the camera (one for ground, one for power, and one for signal).

The full range of motion for the camera within the chamber is only about 10mm side-to-side. Since particles are trapped near the laser focus, it is important that the focal length of the laser lens be appropriate to place the focus at the center of the cross. Otherwise, the camera would be unable to view the particle if it is trapped too far to the right or left of the focus.

For safety reasons we were limited to pressures lower than two atmospheres inside our chamber (primarily due to the bellows). For an extra precaution, a blast shield was made from Plexiglas that was placed over the top of the chamber's viewing window.

2.2 Laser Setup

For our trapping experiments, we used a 5-watt laser with wavelength 532 nm (Coherent Verdi). Most of the experiments were performed at 4 watts. The initial laser beam diameter near our setup was 3 mm. We found that particles were more easily trapped if the laser beam fills the focusing lens at the chamber entrance. To accomplish this, we placed a 15-cm-focal-length lens 1m before the chamber. This caused the diameter of the beam at the chamber entrance to be 9 mm.

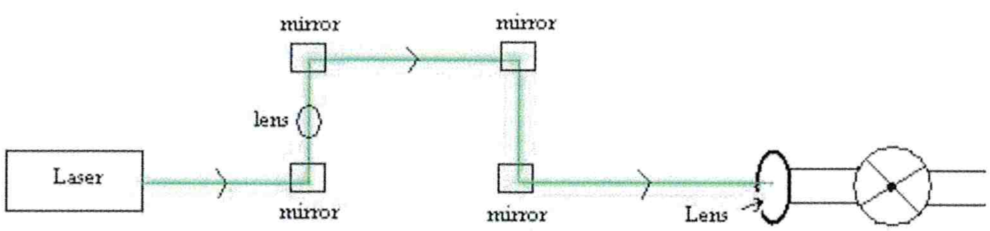

Fig 2.3 Laser setup.

A diagram of the laser path is shown in Fig. 2.3. The beam initially strikes a mirror, passes through the 15 cm lens and then strikes three more positioning mirrors before arriving to the cross apparatus for a total traveled length of 1.5 meters. The purpose of the long meandering path is to allow enough distance for the beam's diameter to expand.

2.3 Camera

For our work, we used the same camera as described in A. Hendrickson's thesis.[10] A 20x microscope objective was mounted on a 16cm tube attached to the camera. Our CCD camera interlaces two images taken 1/30 of a second apart. This remains true even when the shutter opens for only 1/10,000 of a second for each image. The first image displays data on every other horizontal line. The second image displays data on the remaining lines (see Fig. 2.4). When the CCD camera images a single trapped particle, this interlacing effect makes it look as though there are two particles because the particle typically move during a thirtieth of a second. The displacement between the two images allows the viewer to measure the speed of the trapped particle. The speed is simply the distance moved divided by 1/30 s.

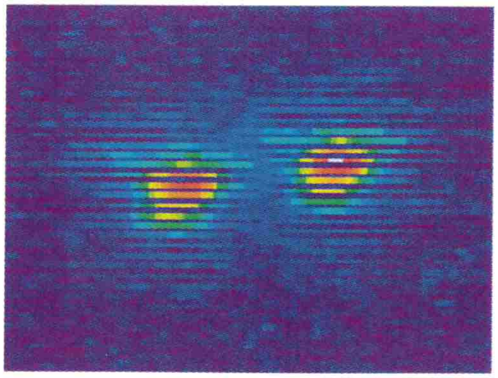

Fig. 2.4 A single trapped particle observed 1/30 s apart due to the camera interlacing effect.

Because camera vibrations might be confused for particle motion, it was necessary for us to ensure that camera vibrations are below an acceptable limit. This was accomplished by imaging the edge of a razor blade. We determined that the effects of camera/table vibrations are small compared to the particle motion observed.

CHAPTER 3. RESULTS

3.1 Trapping at Low Pressure

We studied the trapping of particles at ~7 torr. We were able to easily trap nickel (7-9 μm), silver (4 μm), and black liquor (~20 μm) particles. In general, we noticed that, at least for denser materials, smaller particles were easier to trap than larger ones. However, black liquor, which is often up to 20 μm in size, violates this general rule. This may be due to black liquor's low density. We were unable to trap tungsten at low pressure, although others in our group previously trapped tungsten at atmosphere and at pressures as low as 50torr.[8] Fig. 3.1 shows a tungsten particle trapped in a laser's focus at 50 torr. To the eye, trapped particles made of any material look about the same as in this picture.

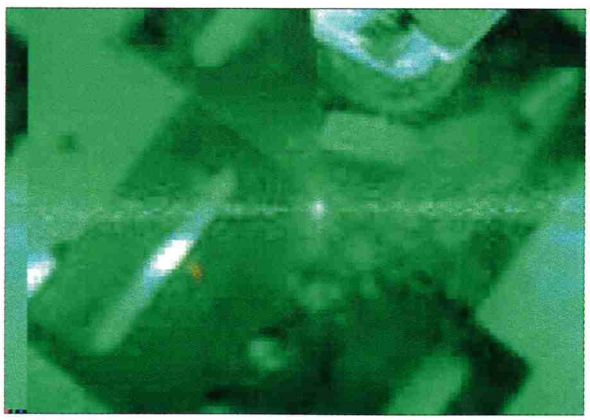

Fig. 3.1 A tungsten particle trapped in the focus of a laser beam at 50 torr.

We observed that particles under low pressure generally prefer to trap in the beam several millimeters upstream from the focus. This is different from what is seen at atmospheric pressure, where particles tend to trap at the focus. With our microscope imaging system, we also noted that at low pressure most of the trapped particles are roughly spherical in shape (as opposed to trapped particles at high pressure, which often exhibited unusual shapes). An example of a spherical particle is shown in Fig. 3.2.

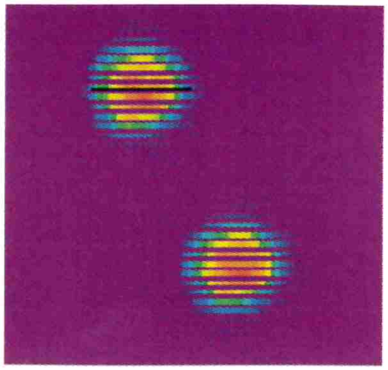

Fig. 3.2 Black liquor particle trapped at 11 torr with 4 watts. The frame is 65μm × 62μm and the particle diameter ~18μm. The same particle is viewed twice 1/30 s apart.

At low pressure, we found that many particles often trap simultaneously. These large groups of particles tend to cluster together until unknown forces cause a majority of the particles to become runners, bouncers, or fallen particles, while just a few remain trapped.

Figs. 3.3-3.4 show pictures of a trapped black liquor particle, again under low pressure (~7 torr). This particle is somewhat atypical in that it is not as spherical as most particles trapped at low pressure. The particle dimension is approximately 23μm by 15μm. One notices immediately upon observation that the particle does not rotate. In fact, after observing a number of particles with unique shape, we conclude that in general particles do not spin while trapped under vacuum. This agrees with observations of particles trapped at atmosphere by A. Hendrickson.[10]

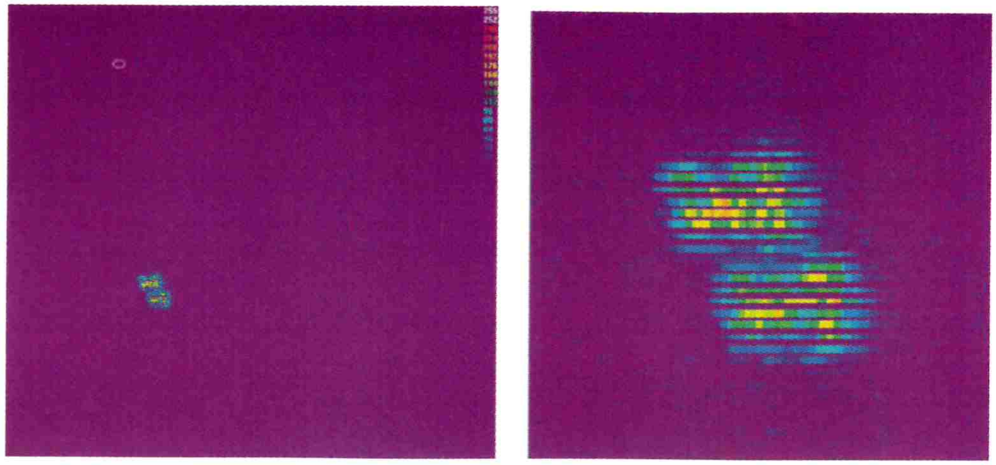

Fig. 3.3 Black liquor particle trapped at 7 torr with 4 watts of laser power. The frame on the left is 250μm × 235μm. The zoomed frame on the right is 70μm × 65μm. The same particle is viewed twice 1/30 s apart.

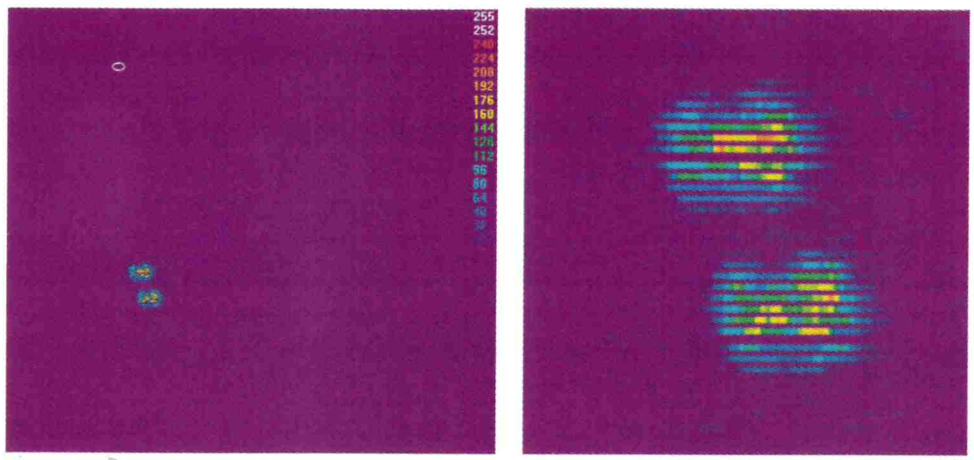

Fig. 3.4 Same particle as seen in Fig. 3.3. The picture is taken a half second later.

Again, the appearance of two particles in Figs. 3.2 and 3.3 is due to the camera interlacing, as explained in chapter 2. The particle seen in the figures moved in a periodic orbit with a speed of approximately 30μm in 1/30 s. This corresponds to a velocity of approximately 1 mm/s, which was one of the faster velocities observed. We measured the velocities of a number of other particles and found that the average was in the neighborhood of 0.5 mm/s. A notable exception to this rule is the particle seen in Fig. 3.1.

3.2 Trapping at Two Atmospheres

For comparison with our low-pressure work, we also studied the trapping of particles of the same material at 2 atm. We speculated that fewer types of materials would trap at the higher pressure because thermal creep should depend on the mean-free path of ambient molecules. The mean-free path at two atmospheres is two orders of magnitude shorter than that at low pressures. Thus, at this higher pressure, the ambient gas molecules cannot inter-diffuse as easily between hotter and colder sides of the particle. However, we were able to trap all of the same types of particles at high pressure as well as low.

As mentioned in the previous section, particles trapped at low pressure prefer to trap upstream in the laser. At two atmospheres, however, particles prefer to trap near the focus. Also, at high pressure, particles do not trap as easily or as abundantly as they do at low pressures. Thus, particle clustering is not observed. The particles that become trapped at two atmospheres are more stable than those trapped at low pressures, in the sense that they seldom fall out of the trap.

The average velocity of a particle trapped at two atmospheres was seen to be approximately twice that observed at low pressures. This may be due to the fact that at two atmospheres trapped particles experience more interaction with air molecules than at low pressures.

A. Hendrickson discussed a trapped tungsten particle that he called "boomerang shaped."[10] His boomerang-shaped particle demonstrated that particles that are trapped at atmosphere do not rotate. We also observed many different "boomerang shaped"

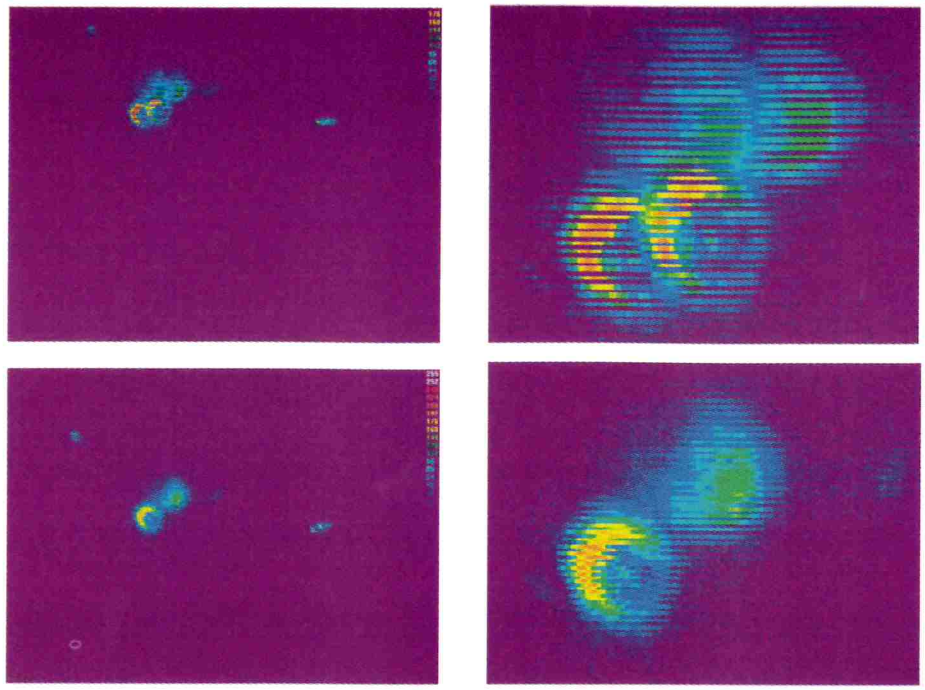

Fig. 3.5 Black liquor particles trapped at 2 atm with 4 watts of laser power. The frames on the left are 250μm × 235μm and taken a half second apart. The zoomed frames on the right are 70μm × 65μm. In each frame, a pair of particles is viewed twice 1/30 s apart.

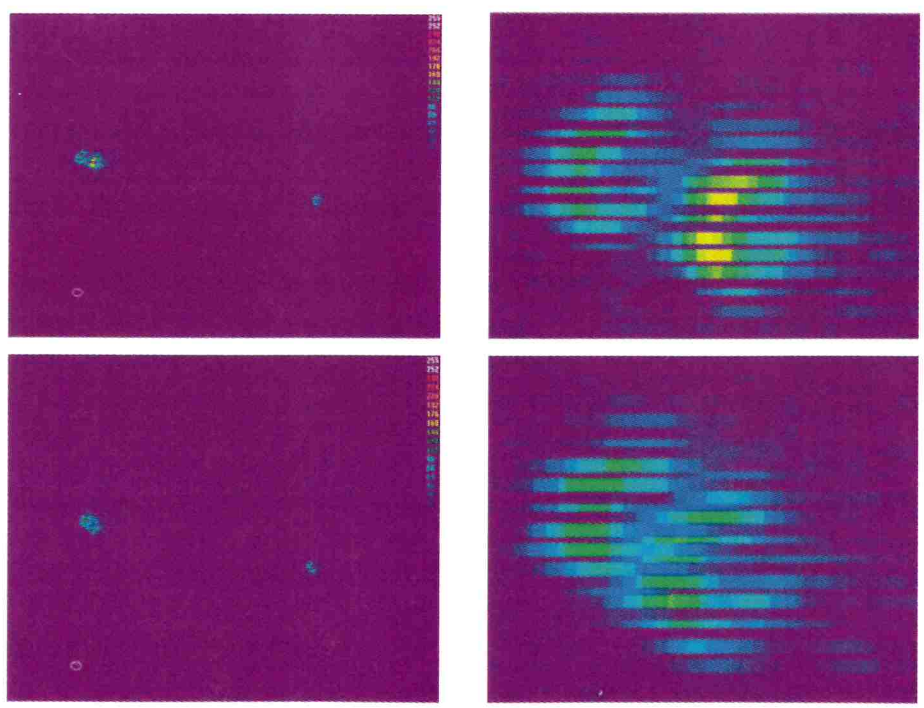

Fig. 3.6 Nickel particle trapped at 2 atm with 4 watts of laser power. The frames on the left are 250μm × 235μm and taken a half second apart. The zoomed frames on the right are 70μm × 65μm. In each frame, a pair of particles is viewed twice 1/30 s apart. The particle is 6μm × 11μm.

particles at 2 atm (see Figs. 3.5-3.6). Rarely did we observe any that rotated. Unlike at low pressures, most of our trapped particles at 2 atm were not spherical.

3.3 Curiosities

An interesting observation we made was that trapped particles were influenced by the motions of the camera and the sewing needle (used to introduce particles into the trap). For example, if the camera or the needle moved to the right, the trapped particle also moved to the right. This effect may be caused by a buildup of electrostatic charge on the camera and the needle. Evidence supporting this hypothesis comes from the observation of black liquor particles "jumping" away from the needle as though charged. On the other hand, if the needle is electrostatically charged, the trapped particles should be influenced less when the needle is moved further away. This did not seem to be the case.

At two atmospheres, the needle and camera had little effect on trapped particles. However, while working in Dr. Baxter's lab under atmospheric pressure, we noticed that black liquor particles jump from the needle towards the laser beam, similar to we observed at low pressure. We sometimes found that the metal of our apparatus became electrically charged (giving us occasional electrostatic shocks).

Some unusual particles can be seen in Figs. 3.6 and 3.7. These black-liquor particles are worth mentioning not only because they do not rotate, but also because they have unusual shapes (see Fig. 3.6).

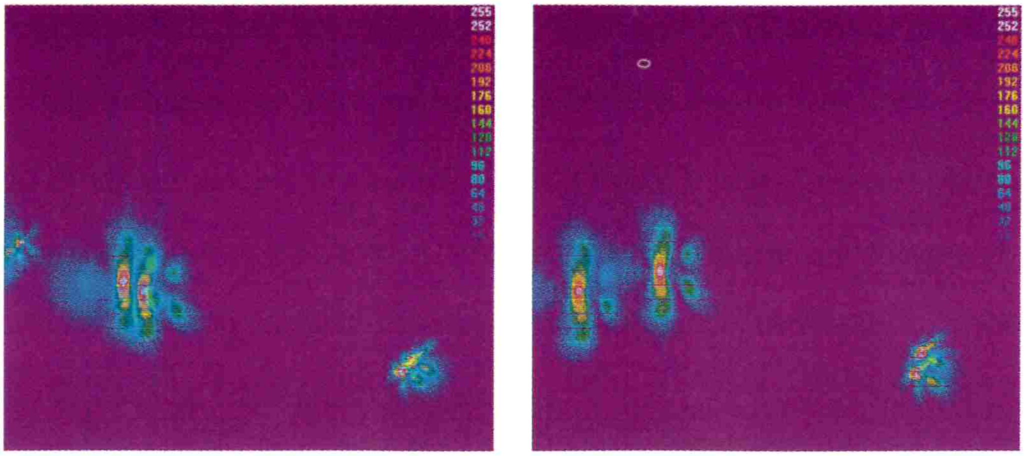

Fig. 3.7 Black liquor particles trapped at 2 atm with 4 watts of laser power. The frames are 250μm × 235μm and taken a half second apart. In each frame, a pair of particles is viewed twice 1/30 s apart. The tall elongated particle is 10μm × 75μm.

3.4 Conclusion

In summary, we have studied and observed how trapped particles behave in low and high-pressure environments. The main difference we observed between these two pressures was the location at which particles trapped. At low pressure, particles usually trap upstream millimeters before the focus, while at higher pressure the particles trap near the focus. Many particles become trapped simultaneously at low pressures, but they tended to be less stable than the fewer particles that become trapped at high pressures. At high pressure, particles typically move twice as fast as particles at low pressure. Another interesting difference is the fact that the particles trapped at low pressure tend to be more spherical. (Note that trapped particles are self selected as many particles are sprinkled over the laser.) In spite of these differences, we were able to trap the same materials at both pressures.

It appears that both the hypothesis of thermal creep and that of convection currents are in doubt as a result of our observations. If thermal creep is responsible for particle levitation, the phenomenon might be expected to fail at the higher pressure. The reason for this is that the mean-free path at low pressures is two orders of magnitude larger than the mean-free path at two atmospheres. Perhaps it is necessary to go to even higher pressure to see this failure. Since fewer particles become trapped at higher pressure, this may indicate a trend. One should keep in mind that at higher pressure, many more molecules are involved in supporting the particle, which may help to mitigate a possible decrease in a thermal creep effects.

The hypothesis of convection is also in doubt according to what we observed. One might expect it to be easier to trap at two atmospheres rather than at low pressures because the air is more fluid-like and there is more of it. However, as was mentioned, we found that particles become trapped more readily at low pressures.

3.5 Future Work

Our research was limited by the fact that, due to safety concerns, we were only able to reach two atmospheres. In the future, we would like to build a chamber rated for pressures up to 10 atmospheres. If photophoresis (thermal creep) is the correct explanation for particle trapping, we will have a better chance of seeing the point at which particles are no longer able to trap (just as a Crooke's radiometer will not work if the pressure is too high).

The appendix discusses the possibility of measuring a particle's temperature while trapped in a beam. Although it is concluded that an expensive camera may be required to observe blackbody radiation from particles, it might aid in determining whether particles are trapped by photophoresis (thermal creep) or convection. Other research might include a systematic approach of testing whether or not electrostatic forces play a role.

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APPENDIX

In earlier work, I attempted (with Dr. Larry Baxter's group in Chemical Engineering at BYU) to measure blackbody radiation emitted from trapped black-liquor particles. We attempted to make the observation using a CCD camera and narrowband filters. The hope was to calculate the temperature of particles from their radiation at visible wavelengths. A filter was used to block the wavelength of the laser light so that only thermal emission would be seen (ignoring the possibility of fluorescence). Different band-pass filters could be placed in front of the camera to measure the brightness of different wavelength intervals and match it to a blackbody radiation curve. The response of the filter/camera system could calibrated by observing a known blackbody radiator such as the Sun.

Unfortunately, we were never able to detect a sufficient amount of light emitted from the particles to make a measurement. This prompted an analysis to determine what camera sensitivity is needed to be able see the blackbody radiation for expected temperatures.

The intensity per wavelength λ given off by a perfect blackbody radiator is

$$I(\lambda)=\frac{2\pi hc^2}{\lambda^5\left(e^{hc/(\lambda kT)}-1\right)}. \qquad (1)$$

Here, $h=6.63\times10^{-34}\,J\cdot s$ is Planck's constant, $k=1.38\times10^{-23}\,J/K$ is Boltzman's constant, and $c=3.00\times10^{8}\,m/s$ is the speed of light. The intensity of light with wavelength lying between λ_1 and λ_2 is given by

$$I_{\lambda_1,\lambda_2} = \int_{\lambda_1}^{\lambda_2} I(\lambda)\,d\lambda = \int_{\lambda_1}^{\lambda_2} \frac{2\pi hc^2}{\lambda^5\left(e^{hc/(\lambda kT)}-1\right)}\,d\lambda. \qquad (2)$$

Suppose that a particle trapped in the laser beam reaches $T = 800\mathrm{K}$. If we observe the narrow wavelength range from $\lambda_1 = 630\mathrm{nm}$ to $\lambda_2 = 640\mathrm{nm}$, Eq. (2) yields the following approximate intensity:

$$I_{630\mathrm{nm},640\mathrm{nm}} \cong \frac{2\pi hc^2}{\lambda^5\left(e^{hc/(\lambda kT)}-1\right)}\Delta\lambda \cong 1.5\times10^{-5}\frac{W}{m^2} \qquad (3)$$

If we now consider a black-liquor particle such as discussed in this thesis, say $A \cong 20\mu m \times 20\mu m \cong 4\times10^{-10}m^2$, we can calculate the power radiated from the particle within the wavelength interval, which turns out to be

$$P = IA = \left(1.5\times10^{-5}\frac{W}{m^2}\right)\left(4\times10^{-10}m^2\right) = 6\times10^{-15}W. \qquad (4)$$

This corresponds to about 10^4 photons per second.

We used a He-Ne laser beam attenuated by filters to characterize the faintest possible signal that could be detected with our CCD camera (Pulnix TM-7). We placed a Schott NG10, and two NG4 (3mm thick) in the beam for a total attenuation of $\sim10^{-10}$. We also focused the beam down to a spot on the camera that covered approximately $12\times12 = 144$ pixels. This means that if we were to concentrate the light onto just one pixel, we could detect light 144 times dimmer. The He-Ne produces approximately 5×10^{-3} W, leading to a minimum detection threshold of

$$P \cong \frac{\left(.005W\times10^{-10}\right)}{\left(144\,pixels\right)} \cong 3\times10^{-15}\,W/pixel. \qquad (5)$$

Thus, it would seem that our camera has a chance of detecting the indicated wavelength range from a black liquor particle. However, this is only true if the imaging is good enough to put the light onto just one pixel. It also assumes that it is possible to capture all of the light emitted from the particle into a hemisphere. We are able to do neither. In particular, our optics are only likely to collect about a tenth of the available light. If the light ends up distributed over, say, 10 pixels, then we would be at least two orders of magnitude below the detection threshold. Also, the particle might not reach temperatures as high as 800K. If so, this also hurts the overall chance of imaging a particle with a CCD camera such as ours.

A possible solution is to buy a camera with higher sensitivity and lower background noise such that the image can be integrated for many seconds to accumulate enough signal. Another possible solution is to use a photomultiplier tube, which would mean that the particle could not be imaged.