RADIOMETRIC PARTICLE LEVITATION IN A LASER BEAM AT HIGH AMBIENT GAS PRESSURE

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ABSTRACT

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We observe the stability of fine graphite particles (diameter 1-10 microns) suspended radiometrically in a laser beam, as the ambient gas pressure increases from 1 atm to 10 atm. Particles are self-selectively captured near the focus of a 2.5 W CW 532 nm beam, by sprinkling graphite powder above the beam. After a particle becomes trapped in the beam, the ambient pressure of nitrogen gas is gradually increased until the particle is observed to 'fall out' of the laser. Results show that 90% of the graphite particles do not remain trapped in the beam past an ambient pressure of 4 atm. The mean 'fall-out' pressure is about 2 atm. Only 2% of the particles remained trapped in the laser above 8 atm. No particle in our 40-particle sample group remained trapped at 10 atm. Qualitatively, we observed that smaller particles (i.e., particles that scatter less light) tend to survive to higher pressures.

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Chapter 1

Introduction

1.1 Background Material

In the 1960's Eric G. Rawson and A. D. May observed particles in their laser cavity that were propelled with unusual motion. The dust particles traveled both parallel, 'runners', and perpendicular, 'bouncers', to the laser beam. [1] They proposed that this motion was due to photophoresis. 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. The 'photo' prefix implies that the temperature gradient is due to absorbed radiation." [2]

In the 1970's Arthur Ashkin [3] hypothesized that radiation pressure could be used to trap transparent micron sized particle in the laser's focus in the absence of heating or an interaction with surrounding gas or liquid. Ashkin's technique, known as optical tweezers, relies on a sharp focus and wide divergence to the laser beam. Optical tweezers work only for transparent spheres which act as lenses through which the laser beam is focused. When the transparent particle moves away from the focus it deflects the light, redirecting the photon's momentum, thereby transferring opposite

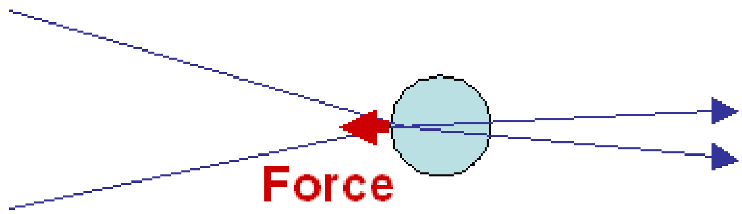

Figure 1.1 Transparent particle being forced back into the focus, known as optical tweezers.

momentum to the particle, pushing it back towards the focus. (see Fig. 1.1)

In the 1980's Lewittes showed that it is also possible to trap opaque particles in the laser's focus,using a dyed glycerol sphere. Lewittes hypothesized the existence of a laser intensity minima in the laser beam and suggested radiometric recoil (i.e., heated molecules recoiling from the particle with extra momentum) as the primary mechanism for trapping the particle. He also thought it was necessary for the laser beam to be directed vertically in order for the radiometric force to cancel out gravity. [4]

Antonino Pluchino subsequently reported successfully trapping multiple particles both above and below the laser focus. He also was able to trap particles with the beam path directed either vertically or horizontally (counter to Lewittes hypothesis). He states, "It seems, therefore, that gravity and convection are not necessary influences for the levitation of particles. The mechanism is entirely particle, laser beam, and surrounding gas molecules dependent." [5] He states that the particle levitation is "due to these regions of higher energy density and swirling energy flow." [5]

In his BYU senior thesis, John Painter notes that "[Pluchino] believed that the Poynting vector, adjacent to the down-stream side of these pockets, was directed against the propagation of the main beam." [6] In other words, Pluchino imagines that more energy from the light is deposited on the 'shady' side of the particle.

1.2 Basic Forces Involved

Optical tweezers require the particle to be transparent so it can bend the light. This same explanation doesn't work for opaque particles. That is, the levitation of opaque particles relies on heating and a subsequent interaction with surrounding air molecules. This can produces forces far in excess of the light radiation pressure and gravity. Uneven heating of the particle allows gas molecules on one side of the particle to rebound faster than from others. Many of the explanations cited have suggested the need for local minima in the laser beam to provide pockets in which the particle can trap.

1.3 Effects of Low Pressure

Experiments involving trapping the particles at low pressure were conducted by Cody Bliss. [7] Various materials and sizes of particles were trapped in the laser beam. His data showed that the ability of the particle to be trapped in the laser beam was affected by the size of the particle and the ambient pressure, although he only looked at pressure below an atmosphere. Smaller particles tended to trap more consistently in the laser, and remained in the beam longer. The trapping stability improved down to an ambient pressure of 200 torr, depending on the material. As pressure further decreased, the tendency of the particles to trap also decreased. Lower pressures also increased the tendency of the particle to bounce back and forth in the beam, and their tendency to drop out of the trap. Increasing the laser intensity improved the trapping ability, yet results showed that at least a few torr of air was needed for the particle to remain trapped. This contrasts with optical tweezers which can work even in vacuum, although the forces are much weaker, since optical tweezers work by redirecting the photon's momentum.

1.4 Effects of Gravity

The possibility of convection currents from the surrounding air molecules being explaining particle levitation has also been explored. Convection currents work through gravity, allowing the hot air to rise, thereby creating a buoyant force to hold the particle. John Painter conducted an experiment in which the particle was trapped in a chamber that was then released and allowed to free-fall for 0.6 s. The mirror that directed that laser beam into the chamber was rotated through an angle of six degrees during the fall to check that the particle followed the beam. "The nanorotator confirms that the particles are indeed trapped in the beam during free fall (i.e. not just accidentally staying in the focus)." [6]

Further experiments concerning gravity were conducted by Matthew Turner and Nathan Powers aboard NASA's 'Vomit Comet.' The airplane allowed the experiment to be conducted in a zero-gravity environment for up to 30 seconds. The particles trapped in the laser remained in the beam throughout the free-fall, showing no irregular tendencies during the experiment. Results clearly showed that gravity and therefore convection currents do not play a role in trapping and levitating the particle. For his BYU senior thesis, Adam Hendrickson, observed the motion of trapped particles using a microscope. Particles would exhibit sudden bursts of speed over large distances, then return to normal. Hendrickson observed particles moving with accelerations exceeding 10 g's, thereby demonstrating forces large compared to g. He noted, "Most stable particles oscillated in an individual 'well' that varied between

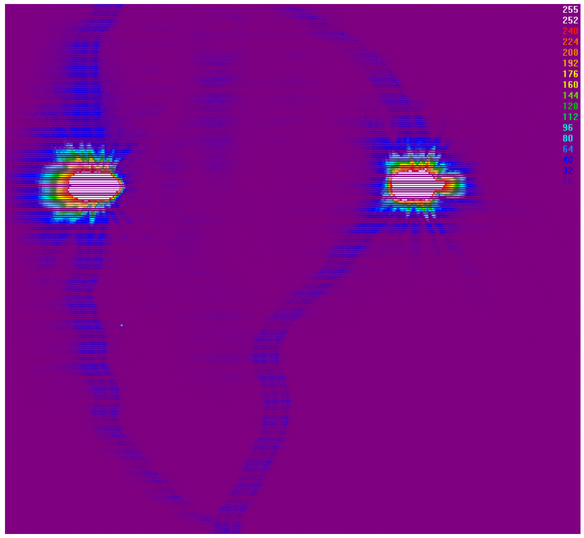

Figure 1.2 Jitter motion of 71 microns observed by Adam Hendrickson [8]. Camera interlacing shows the particl in two position 1/30 second apart

15 and 60 microns...Most stable particles had a measured speed between 1x10^{-3} m/s and 2x10^{-3} m/s, which often depended on the well size [8](see Fig. 1.2)."

1.5 Laser-Intensity Profile

It has been speculated, as noted above, that the structure of the laser beam is responsible for the trapping phenomenon, due to maxima and minima in the intensity profile. Experiments by John Painter [6], and Mindi Martin [9] showed no evidence for these variations in the laser profile. Research by Mindi Martin indicates, "the laser beam effectively traps opaque particles without the presence of any intensity pockets detectable at a 1 micron resolution. Thus, even though intensity pockets can be used to trap opaque particles, they are not the main explanation for particle levitation, since it can be accomplished in a comparatively smooth laser beam." [9] It has also been observed that particles will trap both in the upper and lower portions of a horizontally directed beam as well as upstream and downstream from the focus,

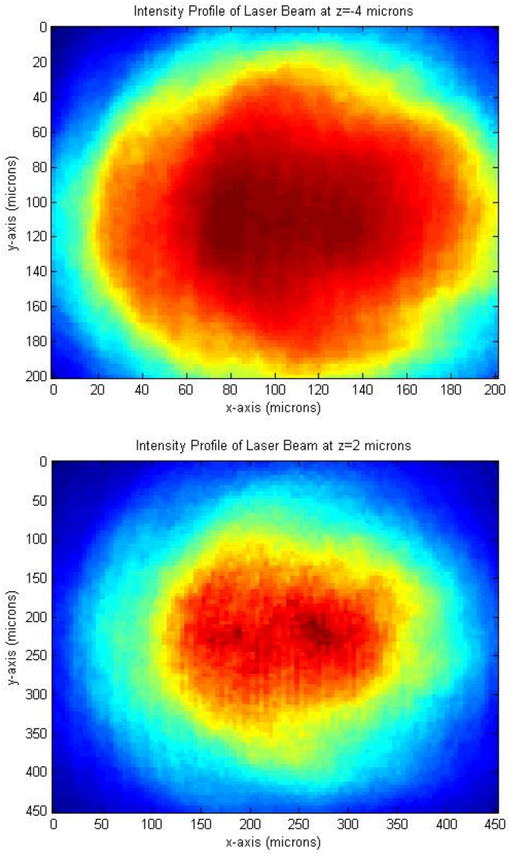

Figure 1.3 Cross-sectional picture of the laser beam intensity recorded by Mindi Martin [9].

which is inconsistent with the low intensity theory of pockets in the laser. Obviously, there must be some structure in the laser beam for a particle to prefer one location over another, but it appears that the required variation is subtle.

Referring to Fig. 1.3 Mindi notes, "Clearly, the laser beam is relatively smooth. There do not appear to be any significant intensity pockets that could accommodate the trapping of a particle that flees high intensity. Even though distortions in the beam do appear to help particles trap more easily, intensity pockets appear to be ruled out as the main cause of opaque particle levitation." [9]

1.6 Particle Shape and Size

Previous experiments at BYU were conducted by Adam Hendrickson and others to determine if the particles that became trapped showed any general consistency in size or shape. They tested several different materials and found no consistent shape or size among the various powders that they were able to trap. Adam Hendrickson notes, "The smallest particle that I observed was 1 micron in diameter...The largest particle I observed was 14 microns in diameter. The particle shapes most commonly observed were spherical. A few oblong and non-symmetrical shapes were also observed." [8] Hendrickson also observed the particles motion and rotation. He states, "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." [8] He reported that most of the spherical particles did not spin. However, there were exceptions. Particles trapped close together also could become coupled and exhibit synchronized motion.

1.7 Thermal Creep

E. Huisken recently suggested that thermal creep may play a role in the particle's levitation. [10] Thermal creep, a type of photophoresis, occurs when the mean-free-path of the molecules is longer than characteristic temperature gradients in the gas surrounding objects. For example, Crook's radiometer, a common science demo that uses white-and-black-sided veins in a incompletely evacuated glass bulb, relies on thermal creep to make the veins rotate when warmed by absoption of light. This suggests a molecular mean-free path that is on the scale of or larger than the particle. For air at atmospheric pressure, the mean-free path is approximately 7 microns. This is on the same scale as the particles observed in the trap.

If thermal creep is involved in the process, then a shorter mean-free path should affect the particle's ability to trap. By increasing pressure, the mean-free path of the air molecules is lowered, and the effect of thermal creep ought to be reduced. Rhett Lindsey, also at BYU, performed experiments testing the particles ability to trap at different pressures. However his results were inconclusive, as he was unable to test at pressures above 2 atm. [11]

My experiment involved trapping particles in the laser beam and observing them as the air-pressure was raised from 1 to 10 atm. Chapter 2 describes the apparatus I developed for my experiments. I learned that the trapping mechanism clearly deteriorates at higher pressure; it does not seem possible to trap above 10 atm. These results are outlined in Chapter 3. This suggests that the molecular mean free path of the surrounding gas plays a role in the ability of the particle to trap.

Chapter 2

Experimental Setup and Procedures

2.1 Trapping Chamber

A small vacuum chamber was purchased for this experiment. The chamber in the pressure experiment has five ports (see Fig. 2.1). Each port has a diameter of 5 cm, using a Kwik-Flange clamp with O-rings to seal the chamber. I made custom retaining rings, which were placed outside the O-rings to prevent them from moving outward under pressure and breaking the pressure seal. A 10 cm lens is positioned next to the chamber to focus the laser into the middle of the chamber through a window. Other ports accommodate a window, a pressure gauge and a leak valve. A safety relief valve was attached to a gas-filling tube, which would release the pressure if the chamber became dangerously over-pressurized. A nitrogen tank was connected to the chamber through a leak valve, allowing the flow rate of gas into the chamber to be controlled to mitigate unwanted air currents. The leak valve was set such that the pressure increased to 9 atm in about 20 minutes. The maximum pressure reached

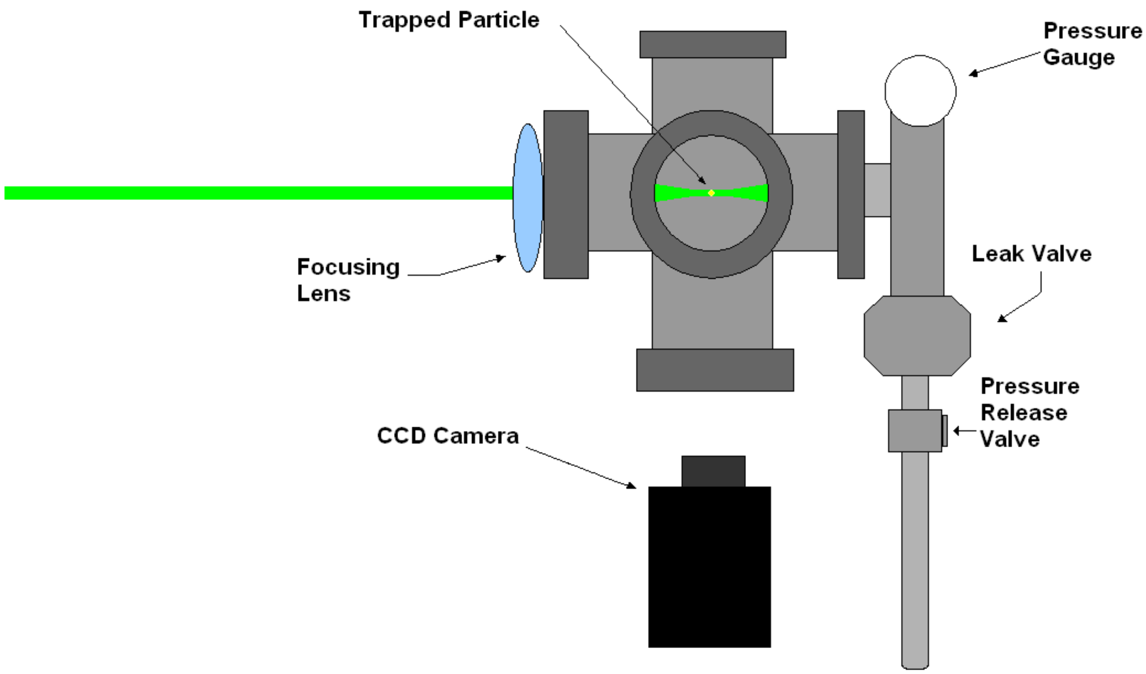

Figure 2.1 Schematic of chamber used for pressure experiments.

in the chamber was limited to about 10 atm. A viewing window allowed the particle to be observed as the pressure increased.

The particles were sprinkled in through the temporarily open top port at an atmosphere. The particles were allowed to fall into the beam path and self selectively become trapped. We used fine charcoal powder for these experiments.

2.2 Laser Setup

The trapping apparatus utilizes a 2.5 W CW 532 nm laser with an initial beam diameter of 3 mm. The beam is sent through a series of mirrors that directs the beam into the chamber. A 10 cm-focal length lens focuses the beam to the center of the chamber. The laser beam was first expanded so that its diameter filled the 20 mm focusing lens.

2.3 Particle Trapping Duration

Particles were sprinkled over the focus and self selectively trapped by the laser beam. Particles that became trapped varied in their behavior, with some dropping out quickly, some lasting a few minutes, and others remaining trapped in the laser indefinitely. Particles also exhibited a wide range of motion with some remaining confined to a fairly small area, and others rapidly jumping back and forth. Due to the tendency of particles to fall out on their own randomly, the duration time of the particles in the laser beam was characterized. This benchmark is important to distinguish the effects of pressure from random events, since it takes time to introduce pressure in the chamber in a gradual manner. After the individual particles were trapped in the laser, they were observed under atmospheric pressure until they dropped out of the laser beam, and the time the particle spent trapped was recorded.

As can be seen from Fig. 2.2 the duration tests showed that most particles dropped out in the first 5-6 minutes. Of the particles that remained in the chamber over 10 minutes, the average time spent trapped was approximately 23 minutes. Particles trapped longer than 30 minutes were intentionally discarded by interrupting the beam, and a new particle was then trapped. The 30 minute limit was used because during the pressure tests, the chamber would reach its maximum pressure of 10 atm in 20 minutes.

2.4 Impact of Air Current

The air current flowing into the chamber to raise the pressure presented another possible reason the particles might drop out from the laser. A constant setting was used on the leak valve. This meant that at higher pressure, the rate of increase was slower, and therefore the current flowing into the chamber was less. However, it also

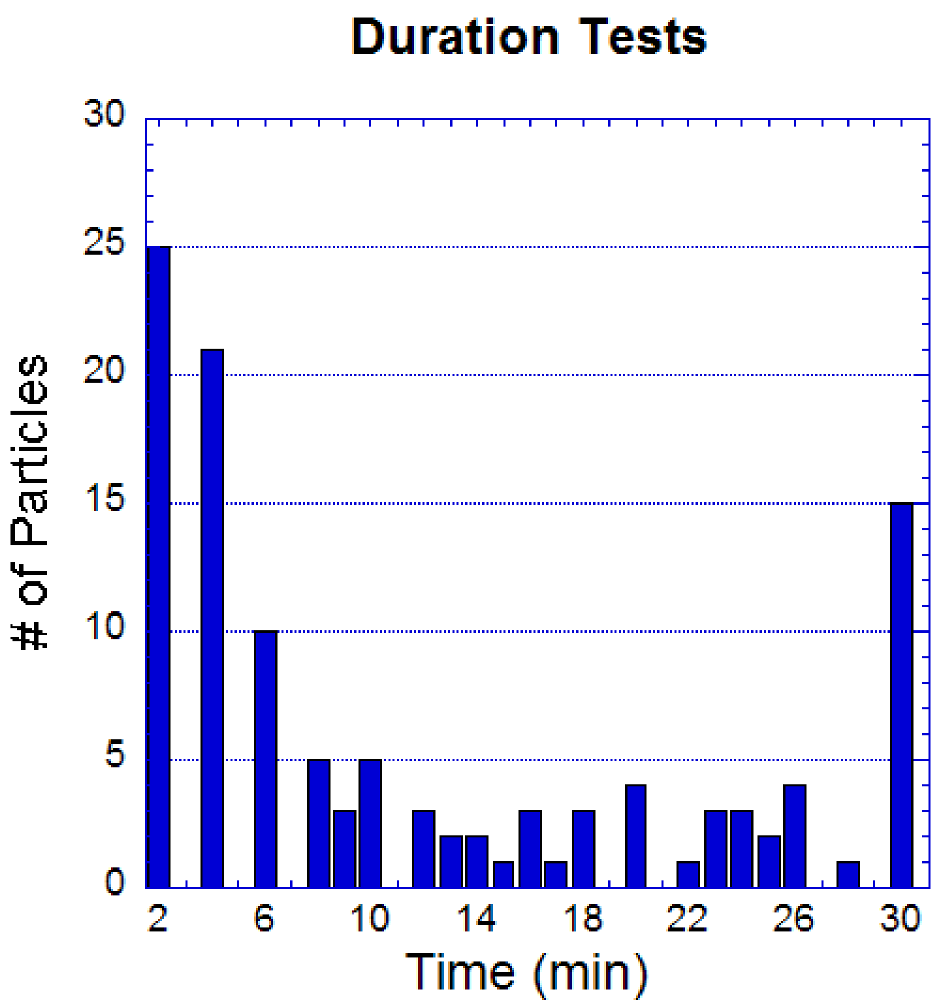

Figure 2.2 Duration test results. The drop-out rate is roughly consistent from the 8 minute mark to the time limit of 30 minutes.

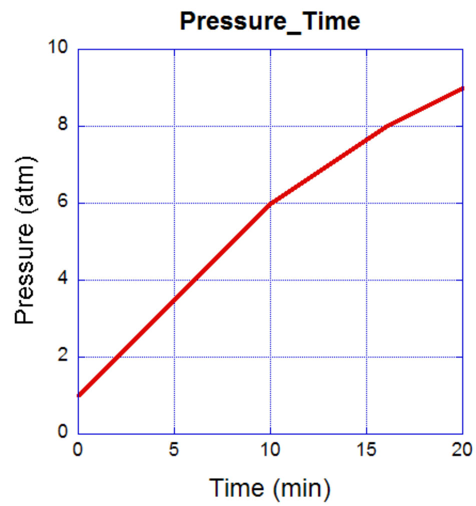

Figure 2.3 Graph of pressure as a function of time. A fairly consistent pressure increase can be seen for the time interval.

meant that as the pressure increased, it was less likely that the particle was blown out of the focus by air currents. In any case, a graph of pressure vs time Fig. 2.3 shows that the pressure rises at a reasonably consistent rate throughout the time interval.

The leak valve was left open during the duration tests, so that the particle would experience the same air current, whether it was part of the benchmark or pressure study.

Though the air current in the chamber did make it slightly more difficult for the particles to become trapped, after a particle was trapped, the flow of air did not seem to have an effect. The duration tests also showed that the time required for the ambient pressure to rise to its maximum was less than than the time required for the average particle to 'fall-out' of the beam focus.

2.5 Pressure Tests

After a particle was successfully trapped in the chamber, it was allowed to sit for 10 minutes. During this time the leak valve remained open. The 10 minute waiting period allowed time for particles with a tendency to drop out quickly to be eliminated from the study, helping to ensure that particles that dropped out during an increase in pressure, did not do so because of general instability. After 10 minutes, the top port was sealed, thereby allowing the chamber to rise in pressure. The pressure at which the particles dropped out from the laser was then recorded, and the experiment repeated.

Chapter 3

Results and Conclusion

3.1 Pressure Data

As was explained in section 2, after the 6-8 minute mark the drop out rate settles down to a roughly consistent relatively low rate. Pressure data tests were conducted after exceeding this high drop-out time window, with the particle being subject to increased pressure after the 10 minute mark We used the duration tests as a benchmark for comparison with the pressure tests.

Pressure vs Duration data in Fig. 3.1 shows that although the duration tests vary from one minute to the next, the overall pattern is fairly consistent, especially the time interval from 10 to 30 minutes. The spike at 30 minutes represents the particles that lasted 30 minutes or longer. For our experiment a duration of 30 minutes was sufficient.

The red column represents the duration of the particles undergoing the pressure tests. As time progresses, the pressure rises according to Fig. 2.3. Most particles in the pressure test dropped out within the first 5 minutes, and only a few sporadic ones remained longer than that.

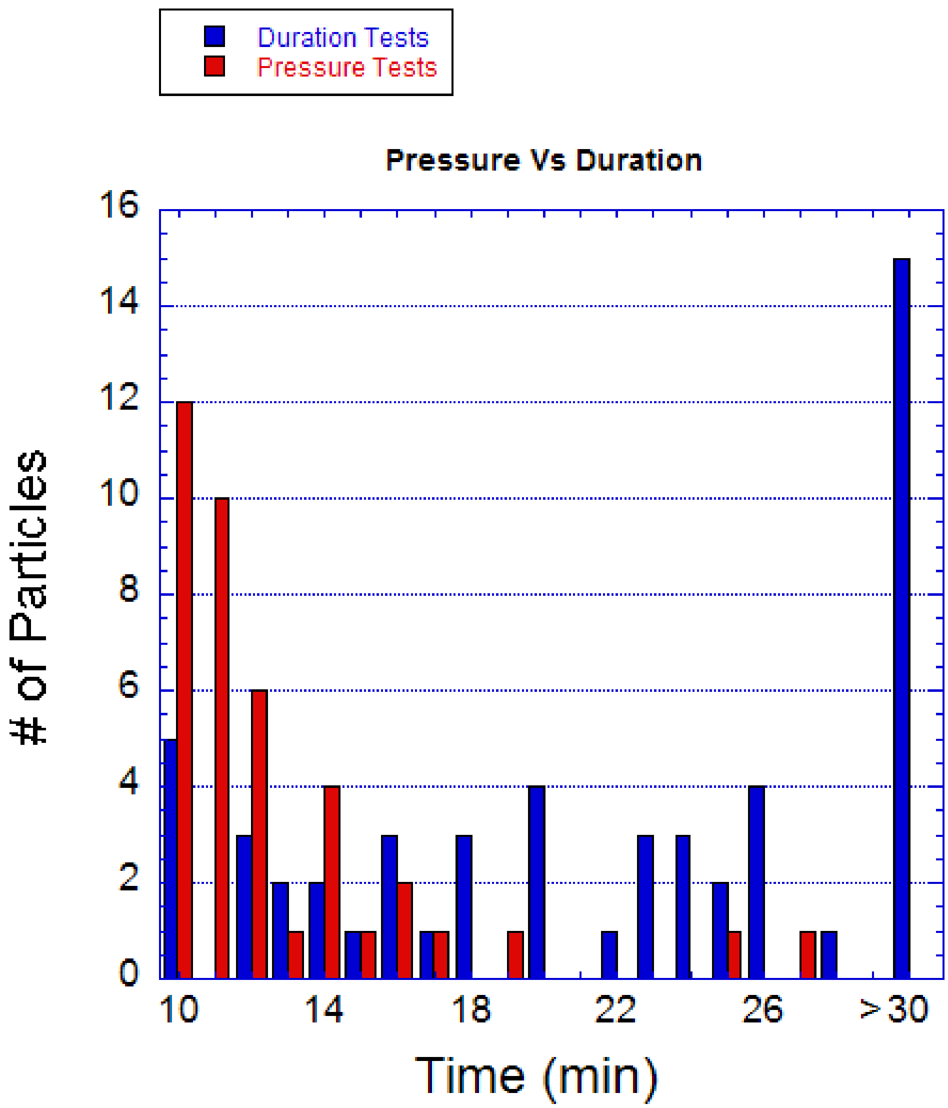

Figure 3.1 Comparison of Pressure Tests vs Duration Tests as a function of time. Pressure is rising at the rate given in fig 2.3

The two graphs have little resemblance as the duration tests are spread out over the whole 20 minute window, while the pressure drop out times are clumped together near the beginning. Referring to Fig. 3.2, which is comparing directly to pressure, we see the same basic features.

Only four particles out of 40 made it past 4 atm. More than half the particles fell out with the pressure being raised to only 2 atm. Some of the tendency of particles to drop out can be attributed to duration, instead of to the rise in pressure. However, comparing the benchmark duration tests with the pressure tests as a function of time, it is apparent that the rise in pressure has a major impact on the particle's ability to stay trapped in the laser beam. From Fig. 3.2 it can be seen that only 1 particle out of 40 remained at an ambient pressure over 8 atm. No particle in the sample remained trapped in the beam at 10 atm.

3.2 Discussion

Qualitative observations of the particles trapped in the laser beam indicated that smaller particles, (i.e. particles that scatter less light) tend to survive to higher pressures. The tendency of the particle to exhibit jittery motion bouncing back and forth also increased at higher pressures. These jittery particles were much more likely to suddenly fall-out of the trap than those particles that remained relatively motionless in the beam.

One might expect the particles to be expelled out of the beam if the side facing the laser absorbs the most light and heats up. Air molecules would rebound from this hotter side with more momentum and therefore push the particle away from the focus. Thermal creep would suggest that air molecules from the colder side would flow around towards increasing temperature, thereby increasing pressure on the hot

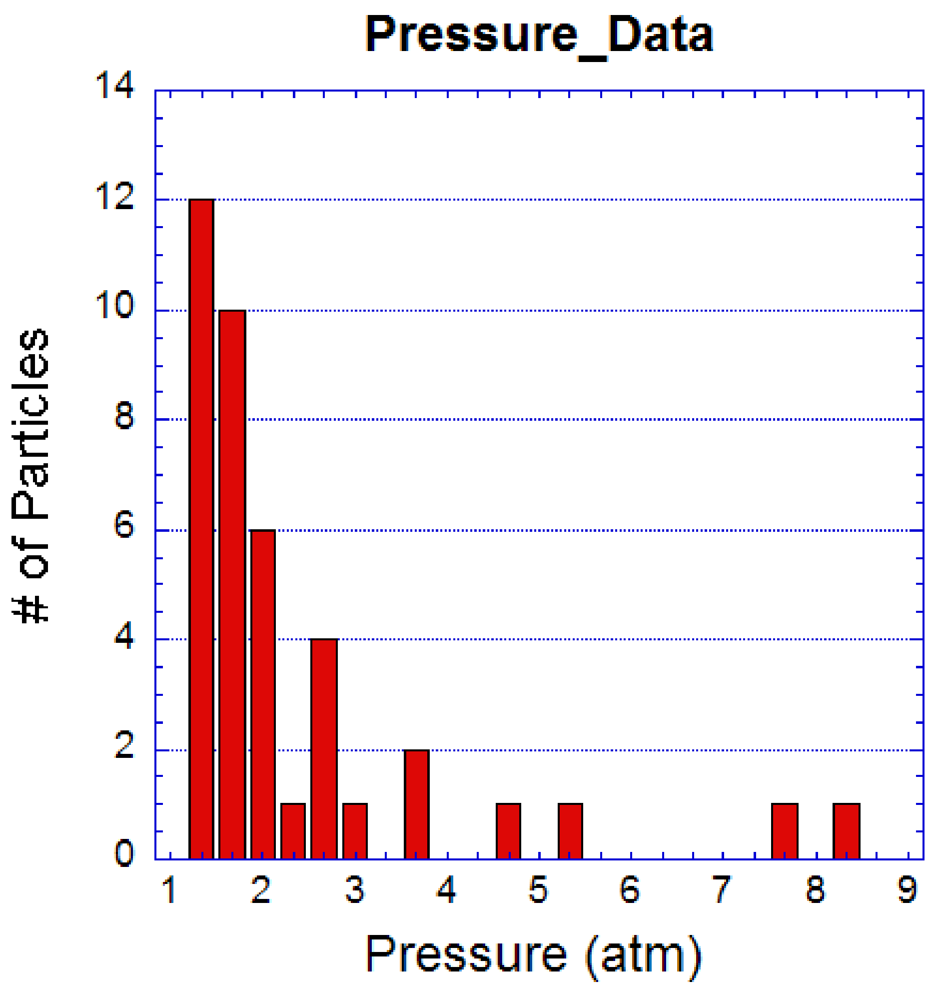

Figure 3.2 Pressure Test results. Only four particles remain past 4 atm. No particle survived to 9 atm.

side. This pressure difference would also tend to push the particle out of the beam. However, the effect of pressure lends support to the mean-free-path affecting the particles ability to remain trapped. The affect of the mean-free-path upon the particle may provide a clue as to how particles remain stable in the trap. Our observations are consistent with the hypothesis Sec. 1.7 that thermal creep plays an important role.

Bibliography

[1] E. G. Rawson and A. May, "Propulsion and Angular Stabilization of Dust Particles in a Laser Cavity," Appl. Phys. Lett. **8,** 93–95 (1966).

[2] E. G. Rawson and A. May, "Propulsion and Angular Stabilization of Dust Particles in a Laser Cavity. II," Appl. Phys. Lett. **38,** 206–209 (1966).

[3] A. Ashkin and J. Dziedzic, "Optical levitation by radiation pressure," Appl. Phys. Lett. **19,** 283–285 (1970).

[4] M. Lewittes, S. Arnold, and G. Oster, "Radiometric levitation of micron sized particles," Appl. Phys. Lett. **40,** 455–456 (1982).

[5] A. B. Pluchino, "Radiometric levitation of spherical carbon aerosol particles using a Nd:YAG laser," Applied Optics **22,** 1861–1866 (1983).

[6] J. Painter, "Optical Levitation of Opaque Particles in a Single Gaussian Laser Beam: Zero Gravity Experiment," Senior Thesis (Brigham Young University, Provo, UT) (2004).

[7] C. Bliss, "Optical Levitation of Intensity-Fleeing Particles in a Single-Beam Laser Trap," Senior Thesis (Brigham Young University, Provo, UT) (2002).

[8] A. Hendrickson, "Radiometric Levitation of Opaque Particles in a Laser Beam," Capstone Project (Brigham Young University, Provo, UT) (2005).

[9] M. Martin, "High-Resolution Imaging of a Laser Beam Used to Levitate Opaque Microscopic Particles," Capstone Project (Brigham Young University, Provo, UT) (2007).

[10] E. S. J. Huisken, "Optical levitation of absorbing particles with a nominally Gaussian laser beam," Optics Letters **27,** 1223–1225 (2002).

[11] R. Lindsey, "Optical Levitation of Opaque Particles in a Laser Beam at High and Low Pressures," Senior Thesis (Brigham Young University, Provo, UT) (2005).