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An abstract of
a thesis submitted to the Faculty of Emory College of Arts and Sciences
of Emory University in partial fulfillment
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Abstract

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This study investigates electrostatic charging mechanisms of insulating particles in humid environments. These mechanisms are relevant to known electrostatic effects in mesoscale organisms, such as insects. While electrostatics are crucial in the world of these organisms, the specific charging mechanisms remain largely a mystery. Previous research indicates that ticks and nematodes, which inhabit high humidity environments, behave as electrical conductors when ambushing prey. This paper explores whether humidity enhances the charging capabilities of these organisms. We hypothesize that a water coating improves the conductive properties of insulators by allowing freely moving ions on the surface, thus enabling ticks and nematodes to exhibit conductive behavior.

To test this hypothesis, a theoretical model was designed involving a charged copper sphere suspended above a spherical glass grain on a grounded plate. The sphere was lowered until the grain was lofted or "jumped" toward the copper. Initial tests on silver-coated spheres showed slight discrepancies between experimental and predicted values, attributed to the approximation of the copper sphere as a point charge. Subsequent experiments on spherical glass grains, with varying humidity levels, revealed no clear humidity dependence on "jump height." These experiments also prove that polarization force is an insufficient explanation as to why the grains are lofted. Trials taken at constant voltage and humidity showed variability in "jump height" indicating the presence of static electricity.

Final experimentation proves the grains are capable of being lofted at both positive and negative polarities, proving that static electricity alone cannot account for the observed behavior. The findings suggest that at greater distances, static electricity dominates, while at closer distances, an induced polarization force influences the grains' charge.

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A profound thank you to Dr. Burton for his professional guidance, patience, and support throughout this project. My time in Burton Lab has been so valuable to my academic growth. I would like express my appreciation to Schuyler Arn for assisting with the experimental set-up and being so adept at handling technical problems. A sincere thank you to Ran Ranjiangshang for doing the research that motivated this project and for his leadership in the lab. I have immense gratitude for Dr. Brody and Dr. Berland for contributing to my passion for physics through incredible instruction and mentorship.

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Chapter 1

Introduction

1.1 Prominence of Electrostatics in Nature

For large animals, nature's static electricity is negligible. However, electrostatics is a powerful force influencing the way small creatures infest other living bodies, migrate, and obtain food. For example, Victor Ortega-Jimenez observed how spiders attract their prey electrostatically. A spider's web reacts instantly by deforming toward a charged fly, aphid, honey bee, and water droplet. This mechanism assists spiders catching charged insects [4, 5, 6].

Insects like bees are so in tune with electrostatic forces that bees can sense the negative charge of a flower recently visited by a positively charged bee. Researcher Daniel Robert explored the effects of electrostatics on pollination and found that bees can collect pollen without making contact [7]. When a bee flies through the air, its body is charged due to frictional electricity, also known as flow electrification. In turn, as a bee drinks a flower's nectar, negatively charged pollen flies directly to its body. This new finding explains a process called plant-pollinator mutualism, where a bee feeds on a flower, and in the process, gathers pollen to feed larvae as well as distributes the pollen among other flowers to promote reproduction [7].

Sam England sought to discover if Lepidoptera, an order of winged insects, were able to build up enough static during flight to collect pollen the same way bees do. He did so by taking these insects on a "walk" by tying "little lassos around their waists" [8]. The insects flew around the cage for 30 seconds to accumulate charge. He then led them through a metal loop to determine their charge. He conducted this experiment on 11 species of which all accumulated charge during their flight. A number of species created an electric field strong enough to attract pollen from 6 millimeters away [8].

Further, an experiment conducted by George E. Bucker and Hugh C. Crenshaw explores the electrostatic charge on pollen grains for seven species of wind pollination plants. Researchers connected pollen-saturated branches to a grounded plate. The branches were suspended horizontally above a set of vertical aluminum plates connected to a $1200V$ DC power supply as seen in Figure 1.1. When switched on, the power supply generated a horizontal electric field of 6.34×10^4 Vm^{-1} between the plates. Researchers tapped the branch to release the pollen. Once the setting pollen reached the field view of the vertical aluminum plates, the electric field was turned on for only 1 second. In the presence of the electric field the charged grains migrated toward either the positive or negative plate. The pollen accelerated horizontally until the electrostatic force and the drag force were equal, and the pollen reached a constant horizontal velocity (U_X). The velocity of the pollen was tracked and used to solve for the pollen's charge by setting the electrostatic force $F = qE$, where q is the charge on the pollen and E is the electric field, to the drag force [1]. They found:

$$q = \frac{6\pi\mu U_x a}{E}, \tag{1.1}$$

with μ being the dynamic viscosity of air, and a being the radius of the grain. Results of the experiment show that most of the pollen grains carried a measurable amount of charge.

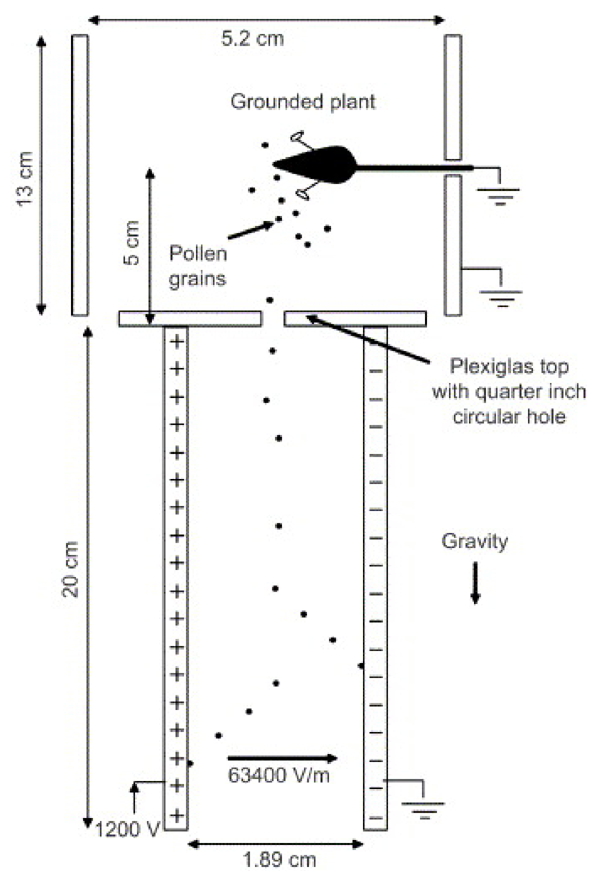

Figure 1.1: Pollen Charge Measurement Experimental Set-Up [1]

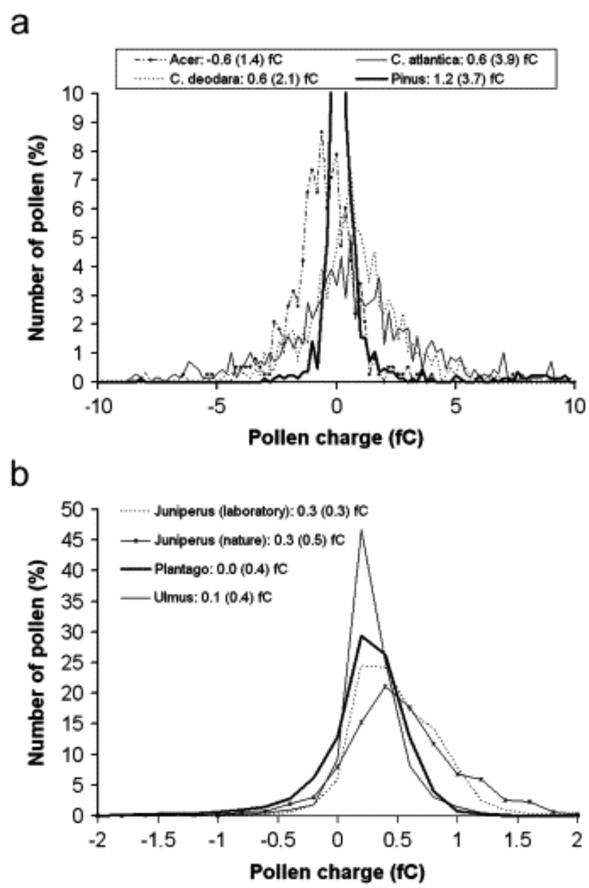

Figure 1.2: Pollen grain frequency distribution as a function of pollen charge [1]

The average pollen grain carried a charge of 0.32 fc [1]. The frequency distribution as a function of charge for the different pollen species is shown in Figure 1.2. Although there was a popular charge for each species, the charge on each grain varies significantly. The experimentalists hypothesize that the charging on the pollen grains is due to either the tribo-electric effect, the process in which two bodies exchange charges when coming into contact with each other [9], or an effect of fair weather electric field. However, the question has yet to be answered [1].

A significant amount of work has been done to understand how electrostatics influence nature, playing a significant role in the lives of small organisms. Still, research lacks in what charging mechanism allow nature to behave this way. This paper aims to explore this gap in knowledge.

1.2 Significance of studies on Ticks and Nematodes

More specifically, this paper will explore this how mesoscale organism such as ticks and nematodes respond to electrostatic forces. Tick-borne diseases such as Lyme disease cause over 500,000 diagnoses in the United States yearly. The incidence of Lyme disease has been increasing drastically over the past few decades. This is reflected in both a rise in cases in endemic areas, and geographic spread from the Northeastern and Midwestern regions [10]. With a rise in cases, prevention methods are necessary. Ticks not only impact humans by spreading diseases, but they also threaten food security around the word through the infestation of livestock [11].

Tick-transmitted pathogens affect 80% of the world's cattle [11, 12]. In fact, the estimated annual cost associated with disease spread via ticks in cattle in the United States amounts to between 13.9 billion and 18.7 billion [12, 11]. In Columbia, these costs can reach $168 million USD. Brazil can lose up to $3.24 billion USD in infestation and in Mexico losses can amount to $573.61 million due to the loss of meat and milk.

To limit the presence of ticks on cattle, acaricides can be used but are limited due to their harm on the environment, carcinogenic effects on humans and animals, and increased resistance. Unfortunately, ticks are not the only parasites that threaten the lives of humans and our food sources .

Like ticks, Nematode parasites pose widespread and dangerous health risks. About one billion people globally are affected by at least one nematode infection, with the majority of cases occurring in low-income tropical and subtropical regions [13]. Parasite nematode contagions can cause ”gastrointestinal distress, anorexia, anemia, and stunted physical and cognitive development in children” [13]. Some nematode species can even cause disfigurement, blindness and can be lethal to infants and the immunocompromised. Further, prevention and control methods for non-human animals such as commercial livestock and household pests cause billions of dollars annually [13]. However, not all nematodes are disruptive. Entomopathogenic Nematodes (EPNs) are known as beneficial nematodes because they infect and kill a wide variety of pets and disease carrying insects [14]. EPNs are not only useful for bio-control but for understanding human-infecting parasites. Understanding how ticks and nematodes ambush their hosts is essential to designing preventative measures for human- and livestock-infesting parasites and ticks.

1.3 Electrostatics in the Lives of Ticks

Electrostatics play a significant role in the lives of ticks. Victor Jimenez, Allison M. Gardner, and Justin C. Burton explained how despite having limited locomotion, ticks can be successful in ambushing their hosts via electrostatics [15]. Ticks are millimeter-sized parasites that latch to hosts by exerting minimal energy. Ticks await their prey on top of vegetation, remaining stationary with their hind legs extended [15]. Previously it was assumed that ticks required physical contact to fasten themselves to their prey [16]. However, a 2023 study conducted by Sam England proves that Ixodes ricinus, a species of tick, can ”close the gap” to their hosts using electric fields [17]. To gain insight into this tick to host attraction England sought out to understand how the electric field is distributed along the host body. England charted the electric field along the body of a 3D cow positioned on a ground surface with an electric potential of approximately 0.8 kV [17]. The locations with the highest field strength, including the head, chest, tail, feet, and inguinal region, coincide with the attachment preferences of tick on cattle [17, 15]. The experiments also demonstrate the electrostatic interaction between the ticks and their host is independent of the polarity of the electric field, suggesting that the mechanism of attraction is induction of an electric polarization within the tick [7]. Significantly, ticks thrive in high humidity environments [18, 11]. Jimenez, Burton, and Gardner hypothesize the humid environment in which ticks live influences their conductivity for reasons discussed later.

1.4 Electrostatics in the Lives of Nematodes

A similar mystery is observed in previous research conducted in the Burton lab. The researchers proved that electrostatic pulling increases the likelihood of a parasitic jumping worm (nematode) making physical contact and attaching to its host. More than that, the study establishes that nematodes behave like conductors in the presence of the electric field generated by their prey. The study was done on Entomopathogenic Nematodes (EPNs), roundworms with the ability to parasitize and kill insect hosts using symbiotic bacteria [2]. Some EPNs such as Steinernema Carpocapsae can catapult themselves into the air to latch onto insects, an operation which is crucial to the life of these parasites because failure to land on their prey could result in predation or desiccation. Scientists have learned the most effective method of travel for these parasites is via electrostatics. The physicists at Burton Lab were able to test this theory and develop quantifiable results by observing the trajectories of these flying nematodes using high speed video analysis. The results of their study prove that the capability of these parasites to travel through the air and attach to insects is significantly improved by a difference of a few hundred volts, a charge common among flying insects. The physicists conducted their experiments on Steinernema Carpocapsae. The nematodes were placed on wet paper towels on a grounded plate. Hanging above them were dead fruit flies on a wire connected to a power supply. Due to the tribo-electric effect, bumblebees, honeybees and other flying insects commonly accumulate a charge of 10-200 pC correlating to 50-1000 V [19]. The team applied a voltage of 100-700 V to the flies. The experimenters placed the nematodes at two different heights: 5.1 mm and 6.2 mm below the flies. As shown in Figure 1.3 despite the nematodes initially advancing in the wrong direction, the parasites were pulled toward the fruit flies via electrostatics. Without the presence of electrostatics the nematodes were much less likely to be successful in their jump toward the fruit flies as evidenced in Figure 1.4. In fact, only 1 out of 20 parasites reached the insect host successfully without the aid on an electric force. This attraction is explained in three stages: polarization, grounding, and detachment. When a charged fly nears a nematode, the mobile charges in the nematode separate. This is the polarization portion of the process. Grounding occurs when the mobile positive charges move onto the grounded plate. Finally, the negatively charged parasite is lifted off the grounded plate and lands on the host [2].

As a theoretical representation of the nematode's behavior, the authors of the study modeled a fruit fly as a sphere with uniform positive charge above a smaller sphere with negative charge, representing the nematode. According to Maxwell, the charge on a conductive sphere with radius r in contact with a conductive plane with surface charge density σ is:

$$\frac{2}{3}\pi^3 r^2 \sigma = \frac{2}{3}\pi^3 r^2 \epsilon_0 E, \tag{1.2}$$

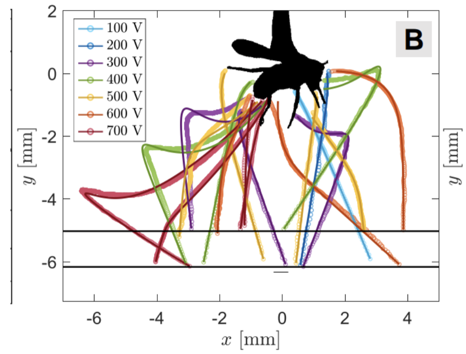

Figure 1.3: Trajectory of Nematode to fruit flies using electrostatics [2].

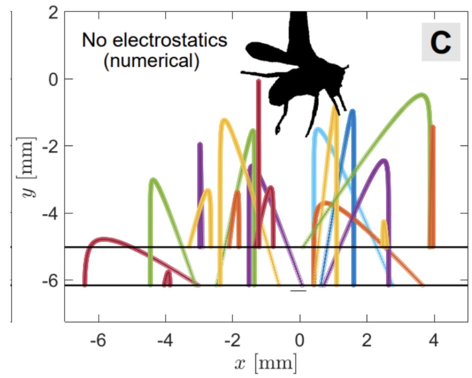

Figure 1.4: Trajectory of Nematode to fruit flies without electrostatics [2].

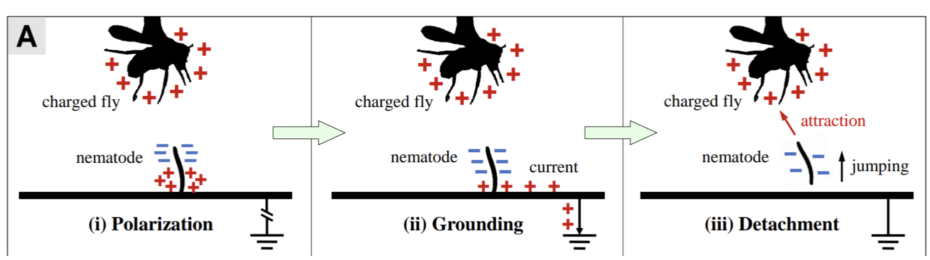

Figure 1.5: Attraction of a Nematode to its prey [2].

where E is the electric field [20, 2].

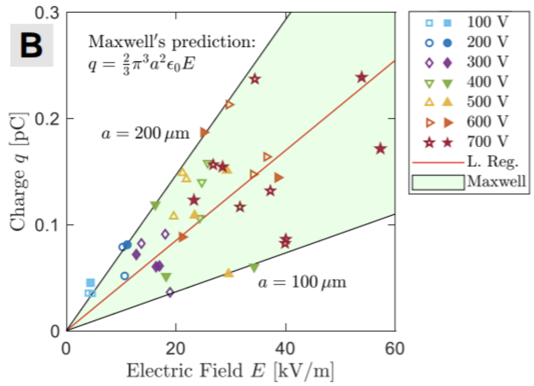

Figure 1.6: Inferred charge on a jumping nematode predicted by trajectory fitting as a function of electric field. The shaded region represents Maxwell's prediction as stated by Equation 1.2

All data collected by Burton Lab on the charge of the nematodes aligned with Maxwell's prediction as shown in Figure 1.6. This data demonstrates the parasite behaves as a conductor, and disproves that static electricity is the main factor in facilitating this "jumping". However, the scientists were left unsure as to why the nematodes are able to behave as conductors.

Like the experiments conducted by Sam England on ticks, a plausible catalyst for the charging behavior of nematodes and other mesoscale organisms is water. Not only do nematodes contain water in their bodies, [21] but Nematodes need to be kept at high humidity to remain hydrated, so the experiments by the authors were conducted at humidity levels around 80-90% RH [2]. This paper hypothesizes that the high humidity environments in which ticks and nematodes live is essential to their behavior as conductors.

1.5 Humidity and Electrostatics

This paper will explore the question: Do high humidity levels allow small insulators to behave as conductors? If so, then a plausible reason ticks and nematodes are able

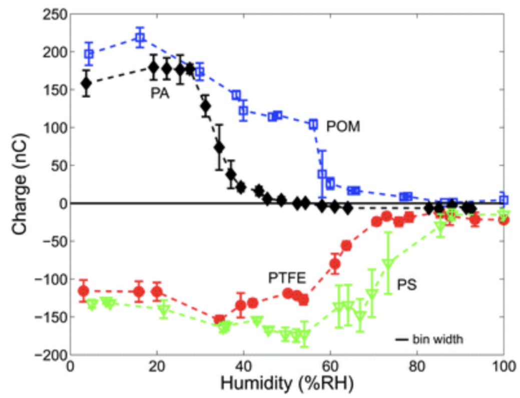

Figure 1.7: Impact of humidity levels on tribo-electric charging of polymer spheres [3]

to behave as conductors is because of the water coating their bodies in the humid environments in which they live.

This investigation tests this theory on spherical glass grains with a radius of 97 microns. Research on granular material has been conducted in the past to understand how humidity effects tribo-electric charging. In a paper titled *Influence of humidity on tribo-electric charging and segregation in shaken granular media*, André Schella, Stephan Herminghaus, and Matthias Schröter discuss how humidity influences the charge accumulation of polymer granulates when they are shaken vertically in a stainless steel container. There results are presented in Figure 1.7. What they found after testing over 2,000 polymer sphere samples is, the spheres become extremely charged at low humidity levels due to tribo-electric charging but acquire little to no charge at humidity levels above 80% RH [22], as shown in Figure 1.7. Humidity strongly alters the amount of charge generated via tribo-electric charging [23, 24] because higher humidity increases the air conductivity, and as a result enhances the number of charges that leak from the surface into the ambient air [25, 26, 14, 27]. Similarly, in the paper *Polymer Tribo-Electric Charging: dependence on thermodynamic surface properties and relative humidity*, the scientists conclude that charge transfer mechanisms are governed by electrons at low humidity. Additionally, they found that at higher humidity, adhered water facilitates electrostatic charging for polymer particles [3]. When the humidity increases, water either forms thin layers on the surface of the polymer or causes the polymer to swell. The introduced water layers present ions and allow electrical charges to move more freely across the surface, increasing the surface's ability to conduct electricity [3]. The hypothesis this paper aims to test is that at low humidity, electrostatic charging is governed by static. However, at high humidity, water coating the surface of insulators improve a materials conductive properties. The work done by Nomura and Schella described above serves as motivation to discover whether a thin layer of water coating allows these organisms to behave as conductors and improve our understanding of how mesoscale biological organism, such as ticks and nematodes, are capable of behaving like conductors when ambushing charged hosts.

Chapter 2

Approach

The goal of the experiment is to assess whether humid environments enable mesoscale organism such as ticks and nematodes to behave as electric conductors. In order to explore the relationship between electrostatics and mesoscale biological organism, a theoretical model was utilized. A 2mm copper ball is soldered to a wire connected to a high-power voltage supply. A singular spherical grain of sand is placed on a grounded metal plate directly below the copper ball. The experiments are conducted by applying a voltage to the copper ball and then lowering the copper vertically toward the grain of sand until the sand "jumps" up the ball. As depicted in Figure 2.1, the "jump height" (h) is measured from the center of the sand grain to the center of the copper ball.

To understand the forces on the sand grain, we must first know the size of the sand grain. Using a digital microscope, images of 9 sand grains were taken and then their diameters were measured using ImageJ software. The average diameter of one grain of sand was 199.35 microns or $1.9935 \times 10^{-}4m$. We then calculate the mass using $Mass = Density \times Volume$ to get

$$m = \frac{4}{3}\pi a^3 \rho, \tag{2.1}$$

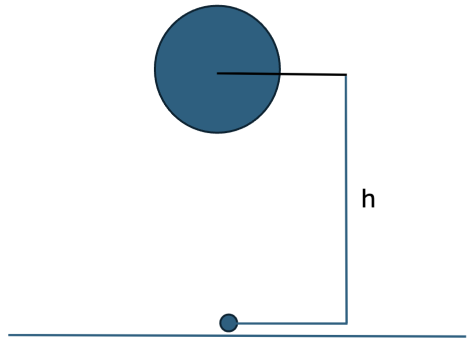

Figure 2.1: Value h as represented from the center of the grain to the center of the sphere

where the density of glass (ρ) is $2,500$ kgm^{-3} and a represents the radius of the grain. This results in a mass of 1.04×10^{-8} kg.

2.1 Image Charge Approach

Next, we must understand the forces on the grain of sand. We can do so using the Image Charge Approach. As described by Maxwell, an electrical image is "an electrified point or system of points on one side of a surface which would produce on the other side of that surface the same electrical action which the actual electrification of that surface really does produce" [20]. According to this approach, we place a symmetrical picture of our charges below the grounded plate. The electric field experienced by the sand grain from the "real" copper ball when the copper sphere is estimated to be a point charge is described by:

$$\vec{E} = \frac{-kQ}{h^2}\hat{z}. \tag{2.2}$$

For Equation 2.2, Q represents the charge on the copper sphere,

$$\hat{Q} = \frac{VR}{k}, \tag{2.3}$$

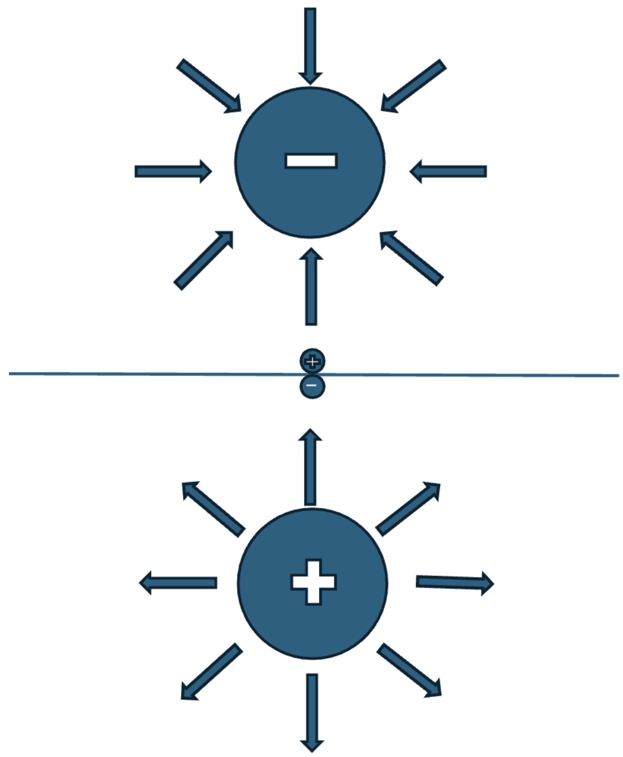

Figure 2.2: Image Charge Approach Diagram

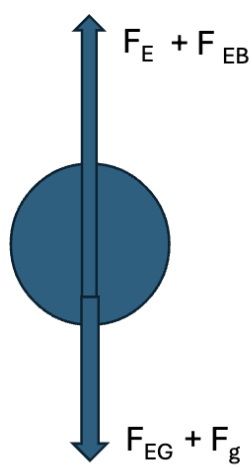

Figure 2.3: Force diagram for the sand grain

V is the voltage applied to the sphere, R is the radius of the sphere ($.001m$), and k is coulombs constant. The electric field due to the copper sphere with charge Q points upward at the location of the sand grain as illustrated in Figure 2.2. The electric field due to the image of the copper sphere with charge Q_B is described by:

$$\vec{E_B} = \frac{-kQ_B}{h^2}\hat{z}. \tag{2.4}$$

As represented by Figure 2.2, the electric field due to Q_B also points in the positive z-direction. Following, we must take into consideration the electric field produced by the image charge of the sand grain which we describe using

$$\vec{E_G} = \frac{-kq_G}{4a^2}\hat{z}, \tag{2.5}$$

where q is unknown the charge on the sand grain and a is the radius of the grain. We then use $F = qE$ to calculate the force on the grain of sand. Just before the grain jumps, the system is in equilibrium and can be described using the equation

$$q\left(\frac{-2kQ}{h^2} - \frac{kq_G}{4a^2}\right) - mg = 0. \tag{2.6}$$

2.2 Calculating Jump Height (h_c) for a Conductive Sphere

The hypothesis this paper aims to test is that insulating spheres will behave like conductors at higher humidity levels. In order to test this theory, we must have an understanding of at what height, h, a pure conductive sphere and dialectic sphere would "jump" to the copper ball. First, we calculate this height for a pure conductor. As stated in Equation 2.6 the force balance equation for the sand grain just before the grain "jumps" is:

$$q\left(\frac{-2kQ}{h^2}-\frac{kq_G}{4a^2}\right)-mg=0. \tag{2.7}$$

Maxwell's prediction for the charge on a conductive sphere lying on a conductive plane is described by: [20, 2]

$$q=\frac{2}{3}\pi^3a^2\epsilon_0E. \tag{2.8}$$

By plugging Equations 2.8, 2.1, 2.3, and 2.4 into 2.7 and solving for the height we determine:

$$h_c=\frac{\sqrt{\pi}}{2}\left(8-\frac{\pi^2}{2}\right)^{\frac{1}{4}}\left(\frac{R^2V^2\epsilon_0}{ag\rho}\right)^{\frac{1}{4}} \tag{2.9}$$

2.3 Calculating Jump Height (h_p) for a Dielectric Sphere

Next, we discuss the case in which the grain of sand is a pure insulator. For these calculations we will consider the image charge of the grain negligible because the force contribution is small compared to the force from E and E_B. As the copper ball nears the sand grain, the grain begins to polarize until enough negative charges gather at the top of the grain and the grain "jumps" onto the positively charged copper ball. The force on a dielectric sphere is

$$\vec{F}=\alpha(\vec{E}\cdot\nabla)\vec{E}. \tag{2.10}$$

Plugging in E, as calculated in Equation 2.10, and plugging in the gradient of E, the equation becomes:

$$\vec{F}=\alpha\frac{-2kQ}{h^2}\left(\frac{-4kQ}{h^3}\right). \tag{2.11}$$

Then by plugging in $k = \frac{1}{4\pi\epsilon_0}$ and $Q = \frac{VR}{k}$ the result is:

$$\frac{8V^2R^2}{h^5}\alpha. \tag{2.12}$$

Finally, we can plug in α:

$$\alpha = \frac{3V_{volume}}{4\pi}(\frac{\epsilon_r - 1}{\epsilon_r + 1})\epsilon_0, \tag{2.13}$$

where we estimate $\epsilon_r = 5$ to get

$$\vec{F} = \frac{16V^2a^3R^2\epsilon_0}{3h^5}. \tag{2.14}$$

Because we are calculating the force at the moment just before the sand jumps we also know that $F = mg$. So,

$$\frac{16V^2a^3R^2\epsilon_0}{3h^5} = mg. \tag{2.15}$$

Solving for the height at which the grain jumps we see that

$$h_p = \sqrt[5]{\frac{16V^2a^3R^2\epsilon_0}{3mg}}. \tag{2.16}$$

Now, we have all the theoretical tools necessary to analyze our experiments.

Chapter 3

Experiments

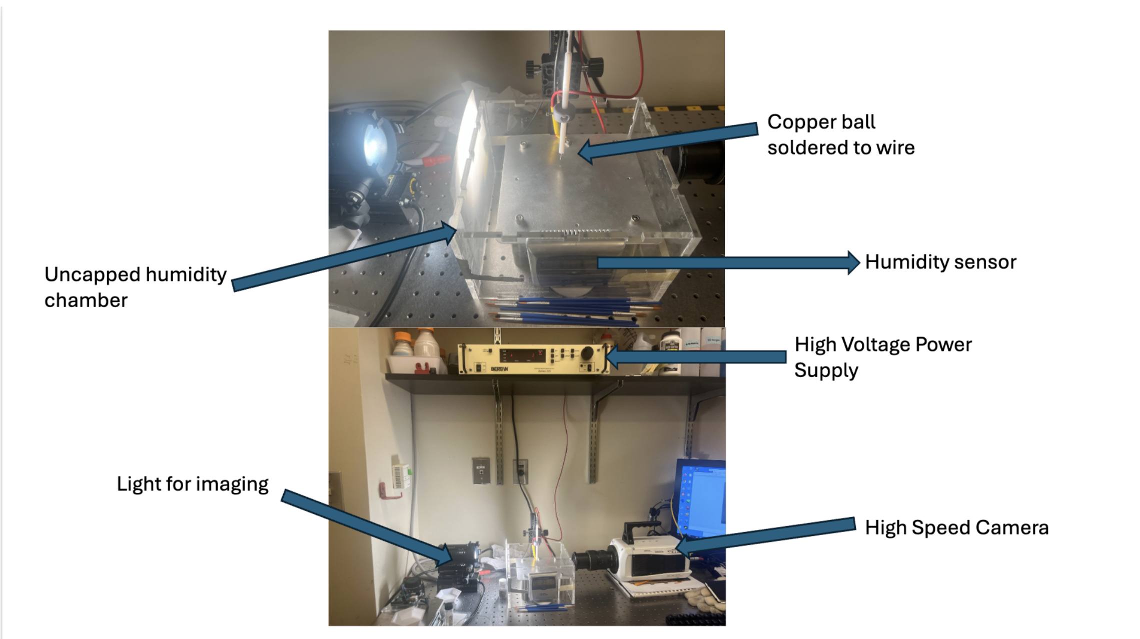

Figure 3.1: Experimental set-up

The theoretical model consists of a charged copper sphere hanging vertically above a grain lying on a conductive plate. Figure 3.1 demonstrates the experimental set-up. To charge the copper ball, the sphere is soldered to a wire and connected to a high voltage power supply. Directly under the copper ball, lying on the grounded plate, is one singular grain of sand displayed in Figure 3.2. This grain is brushed onto the

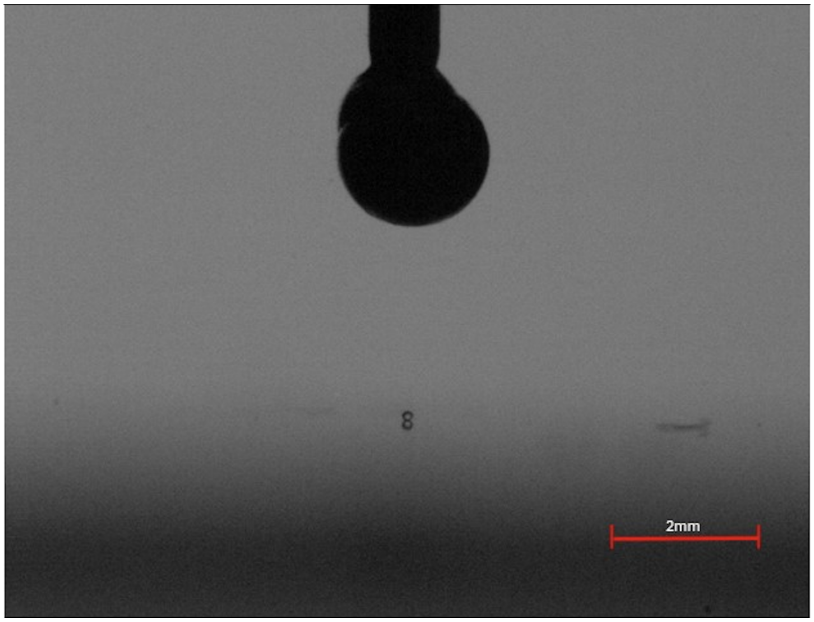

Figure 3.2: Grain under the copper sphere shown using the high speed camera

plate using a paint brush. The brushing mechanism transfers charges to the grain that will be reflected in the results [21]. The high-speed camera is placed next to the experimental set-up and used to verify the grain lies directly under the center of the copper sphere and record the "jumping" motion of the grain. Once the grain is placed on the plate, the copper ball is charged and lowered toward the plate until the grain of sand "jumps" onto the copper ball. The height at which the spherical grain jumps is later measured using Image J, where the grain of sand is measured to be 96 pixels. Before data were collected, evaluations were performed to understand which voltage range would be the most effective for experimentation. Below 2,000 volts, at low humidity, the grains did not "jump" toward the copper sphere. Above 5,000 volts, we commonly observed static discharge between the copper sphere and the conductive plate [25]. Given these parameters, the experiments were carried out for 6 voltages ranging from $2,000V - 5,000V$, incrementing by $500V$ each trial.

The focus of each experiment is to assess how the "jump height" of the spherical grain varies in different humidity levels to evaluate how closely the insulating sphere behaves as a conductor when placed in a high humidity environment. As verification for Equation 2.9, the first experiments performed used a conductive silver coated micro-spheres roughly the same size as the sand grains instead of the insulating glass grains. The silver-coated spheres were brushed directly under the copper sphere. The copper is charged and lowered toward the sand grain until the grain "jumped" onto the copper sphere. This was done for 6 voltages ranging from 2,000 to 5,000 in intervals of 500 volts. The height at which the grain jumped was recorded for each trial. Next, the experiments were performed using the sand grains, this time altering the humidity levels. An acrylic box was designed and constructed to trap humidity around the grounded plate. The box was first designed using Inkscape software. Notches were added around the edges of each side of the box for maximum stability and ease of connection. Then, the pieces were cut using a laser cutter and ethylene dichloride was used to meld the acrylic together. A hole was placed at the center of the lid in order for the copper ball to enter the chamber while being lowered toward the plate. To measure humidity levels, a humidity sensor was placed in the box. In order to create a humid environment, a beaker of warm water was placed in the chamber under the grounded plate. Because humidity was controlled using a beaker of warm water, it was difficult to obtain consistent humidity values for each trial. Like in the first tests, the copper sphere was charged and lowered toward the grain until the grain "jumped" onto the sphere. The copper spheres were charged to six different voltages. For each voltage, tests were conducted at three or four different humidity levels. Finally, two error tests were conducted. For these tests, the voltage and humidity were kept constant to check if the grain would "jump" at the same height, h, for each trial.

Chapter 4

Results and Discussion

4.1 Charging Mechanisms to Consider

After experimentation, it was clear that the manner in which the glass grains charged did not follow just one regimen. We will outline four different charging mechanism that will be used to analyze the results.

1. **Induction through surface-absorbed ions in water:**

Induction Through Surface-Absorbed Ions in Water

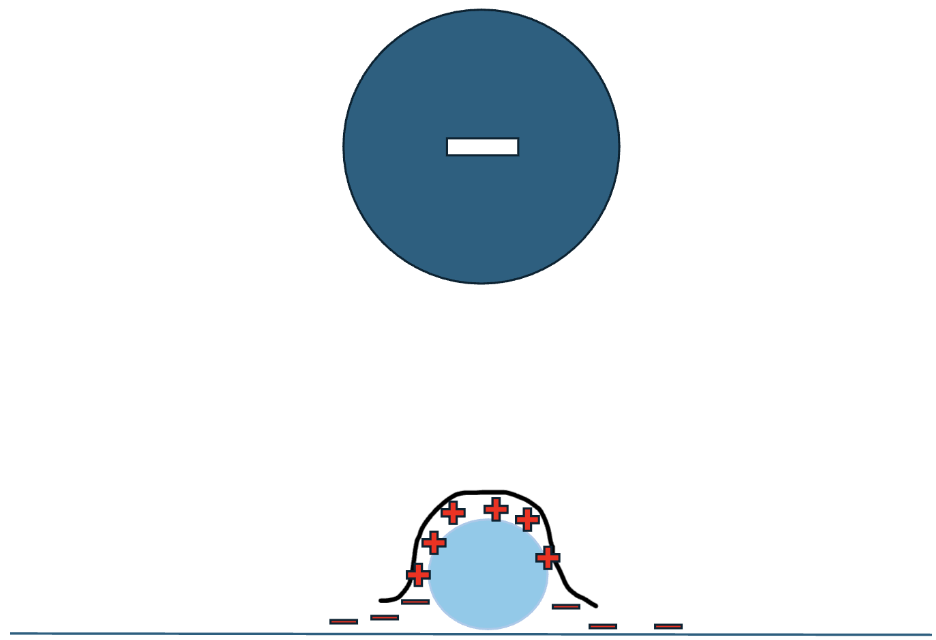

Figure 4.1: Induction via free moving ions in water on the surface of the grain

When water coats the surface of the sand grain, the water layer introduces ions and permits the movement of electrical charges along the surface of the grain [3]. A drawing of this theory is presented in Figure 4.1. When the negatively charged copper sphere approaches the grain in a humid environment, the electric field produced by the copper sphere induces a current on the water coating the surface of the sphere. In turn, the negative charges advance toward the top of the sphere, and the positive charges move to the grounded plate. When the grain is lifted, it carries the negative charges.

2. **Induction of ions through the air:**

   An electric current can be induced in the air because of the charge on the copper sphere, and cause charge transfer from the air to the grain. This charging method is increasingly successful as humidity increases because humid air is more effective in ion capture [28].

3. **Static electricity generated by the placement of brushing of the particle:**

   When the brush is used to place the sand grains on the grounded plate and center the grain under the copper sphere, charges transfer from the brush to the sand.

4. **Polarization force induced on the dielectric sphere due to a gradient in the electric field:**

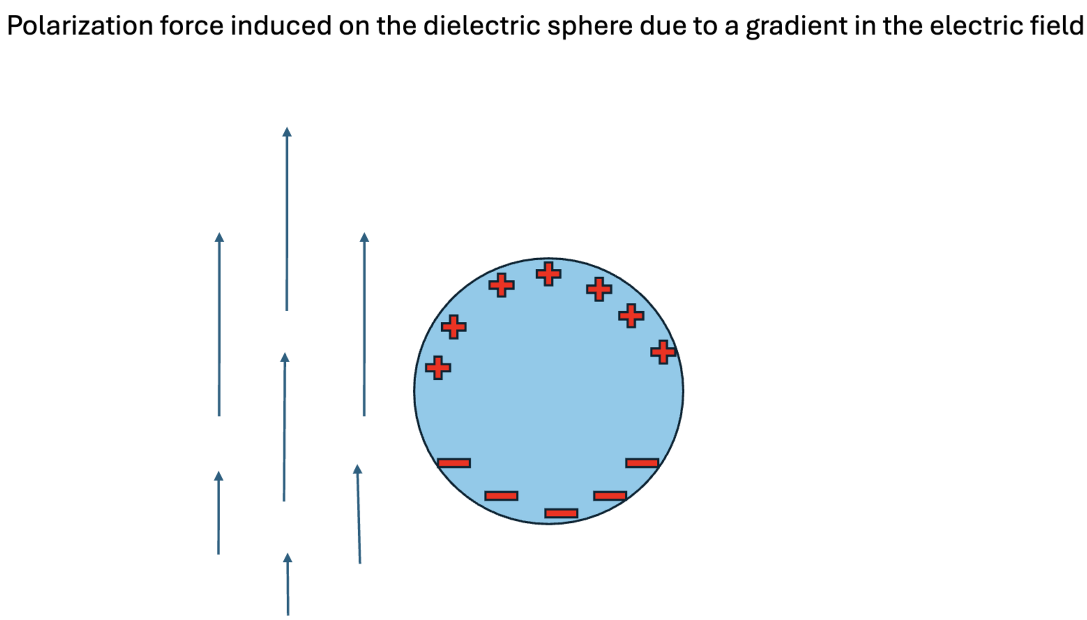

Figure 4.2: Induced polarization force on the sand grain due to an electric field gradient

When the copper ball approaches the sand grain closely, it generates a gradient in the electric field at the location of the grain. The electric field is stronger at the top of the grain and weaker at the bottom, inducing a polarization force.

4.2 Experiments Performed on Conductive Spheres

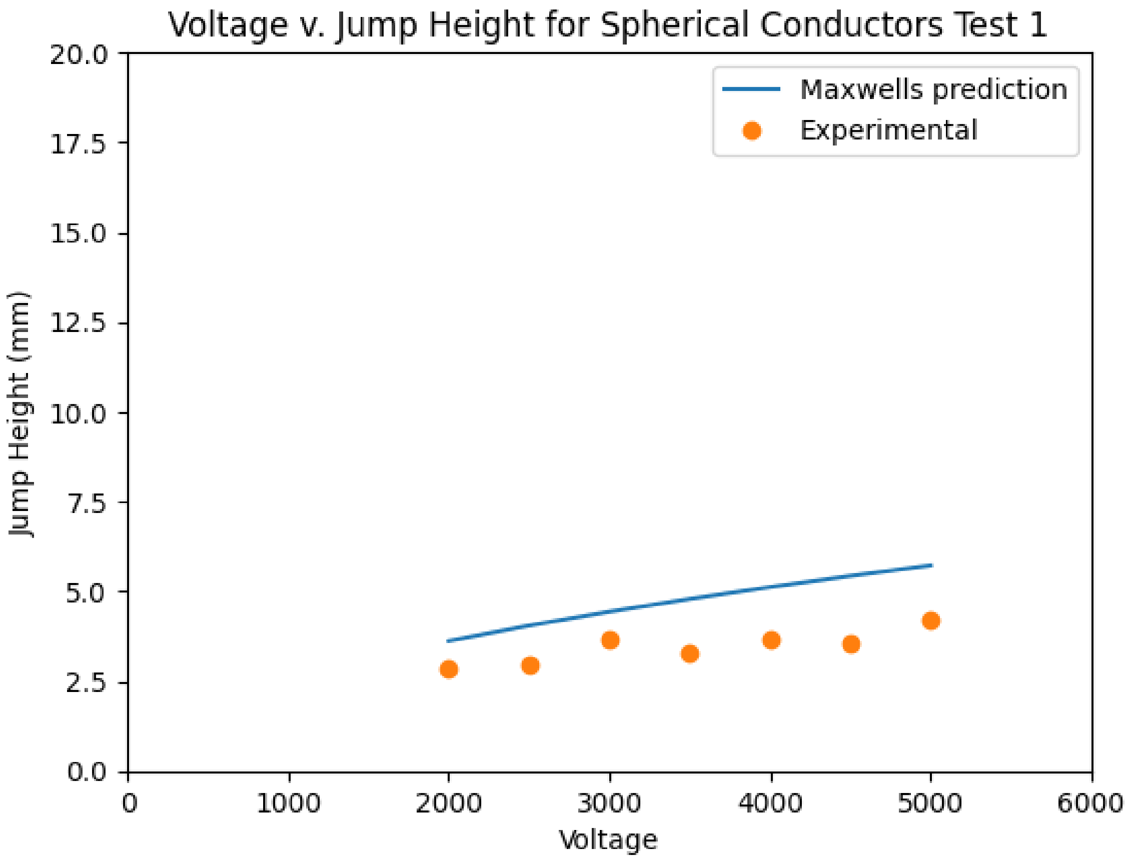

Figure 4.3: Jump Height (h) v. Voltage for silver coated grains test 1

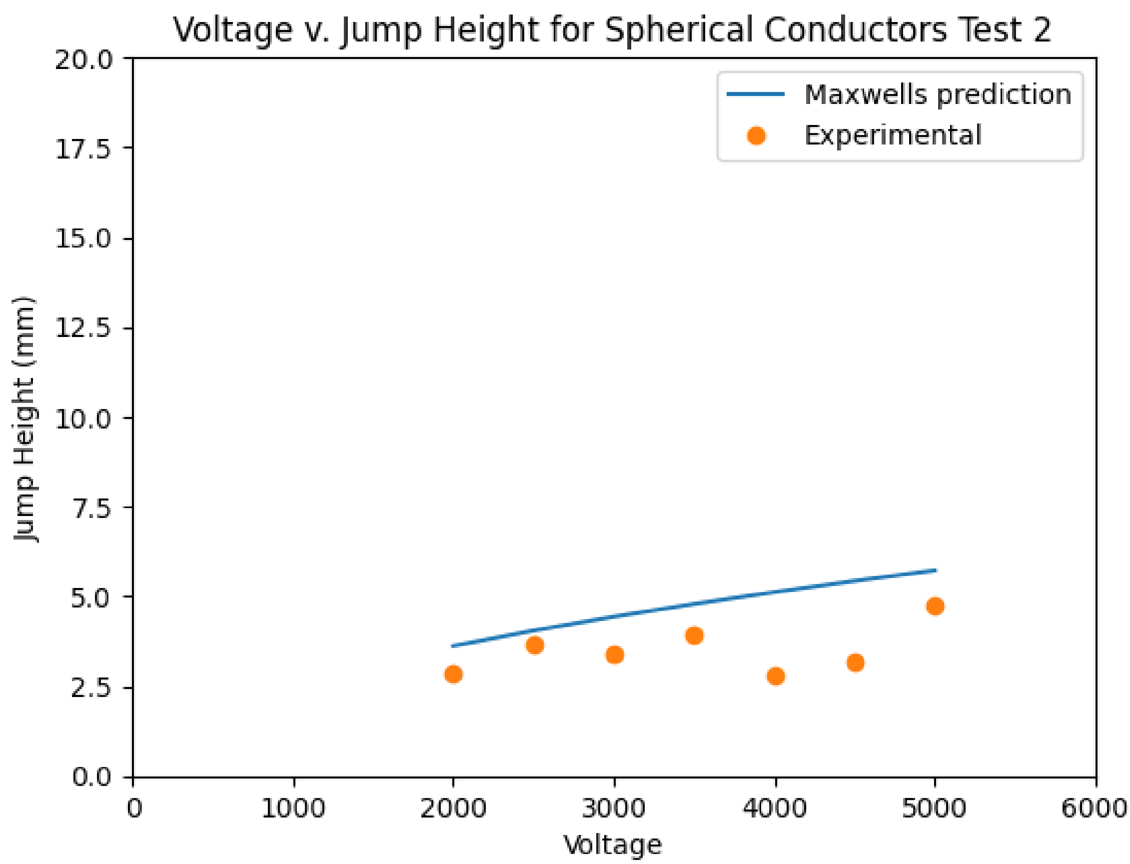

Figure 4.4: Jump Height (h) v. Voltage for silver coated grains test 2

As quality assurance, the first data collected used silver coated soda lime glass spheres with a radius of 98 microns, about the same size as the sand grains. The "jump height" as a function of voltage compared to Maxwell's prediction for the "jump height" as a function of voltage (Equation 2.9) is plotted in Figure 4.3 and Figure 4.4. If the experiments were perfect, the data would exactly match Maxwell's prediction for how a conductive sphere should behave on a conductive grounded plate. However, in Figures 4.3 and 4.4, we notice a slight discrepancy between the prediction and experimental values. This difference is most likely due to the assumption that the copper sphere is a point charge. When the copper sphere approaches the grain very closely, there is a redistribution of charge on the copper due to its proximity to the image charge. Moreover, at such close proximity, the copper sphere may no longer appear spherical to the grain. The exact electric field would need to be calculated using an infinite sum of image charges. These calculations are beyond the scope of this paper. The theoretical equation allows an accurate approximation of how these grains react to electrostatic forces in different humidity conditions.

4.3 Impact of Humidity Variations on Jump Height (h) of Glass Grains at Different Voltages: Data Collection as Compared to h_c Found Using Maxwell's Prediction for a Conductive Sphere on a Conductive Plate

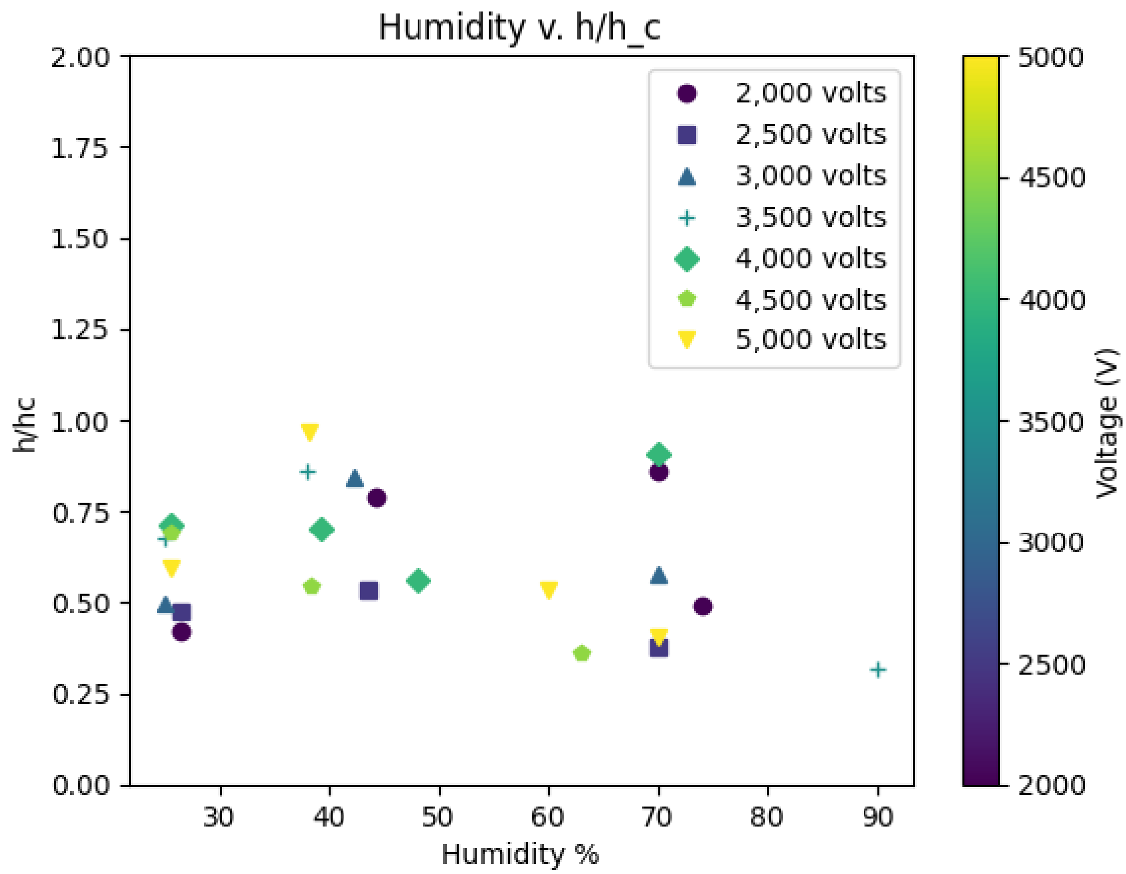

Figure 4.5: h/h_c v. Humidity

Figure 4.5 displays the data collected in an effort to understand if the sand grains will behave as conductors when exposed to higher humidity environments. We divide our initiation height by h_c calculated in Equation 2.9, the theoretical jump height for a conductive sphere on a grounded plate [20]. Figure 4.5 reveals that if the grains were conductors the experimental initiation height would have been greater at all humidity levels. Further, there is no significant trend in Figure 4.5 that proves the grains behave as better conductors at higher humidity levels. When 2,000 volts are applied, the grains' behavior becomes more conductive as humidity increases from 26.5% RH to 44.2% RH, peaking at 70% RH with a ratio of 0.85, but drops to 0.49 at 74% RH. At 2,500 volts, the ratio remains around 0.5 up to 43.5% RH, then decreases to 0.37 at 70% RH. At 3,000 volts, the ratio increases from 0.5 to 0.84 between 25% RH and 42.3% RH, but drops to 0.57 at 70% RH. Following, the data taken at 3,500 volts again exhibits an increase in the ratio h/h_c between 25% RH where the ratio is about .67 and at 37.9% RH where the ratio is .86. Above 70% RH the ratio decreases dramatically with a ratio of .32 at 90% RH. It is worth mentioning that one reason why the jump height (h) might not be larger at higher humidity, for example at 3,500 volts and 90% RH when the ratio decreases to .28, is capillary action. Albeit, there is no specific humidity we can pinpoint for this data where capillary action dominates. At 4,000 and 4,500 volts the trends are even more variable. At 4,000 volts, the ratio decreases from 0.71 to 0.7 between 25.5% RH and 39.2% RH, but increases to almost 0.9 at 70% RH. Finally, at 5,000 volts, the ratio increases from 0.59 to 0.97 between 25.5% RH and 38.2% RH, but drops significantly to 0.4 at 70% RH. Overall, through Figure 4.5, we see there is no clear trend in the grains' behavior in response to humidity.

Because of the lack of reliance on humidity, this data does not defend the induction through surfaced absorbed ions referenced in Section 4.1 Item 1. It appears a governing mechanism influencing the charge on the grain is static electricity, as referred to in Section 4.1 Item 3. In this case, the leakage of charge from the surface of the grain to the ambient air would make the grains less conductive [24, 29, 9, 26]. Yet, this is not always the case at higher humidity. The behavior of the grain in Figure 4.5 at 2,000 and 4,000 volts at 70%RH is very close to that of a conductor. More so, regardless of humidity levels, the grains are still always attracted to the copper ball. Further investigation is necessary to determine the leading charging mechanism on the grain.

4.4 Error Test Data Collection: Multiple Trials with Constant Humidity and Voltage

Due to the irregularity in the data presented in Section 4.3, an error test was conducted to determine if the "jump height" (h) would be the same for multiple trials conducted at the same voltage and humidity. The data is presented in 4.6 and 4.7.

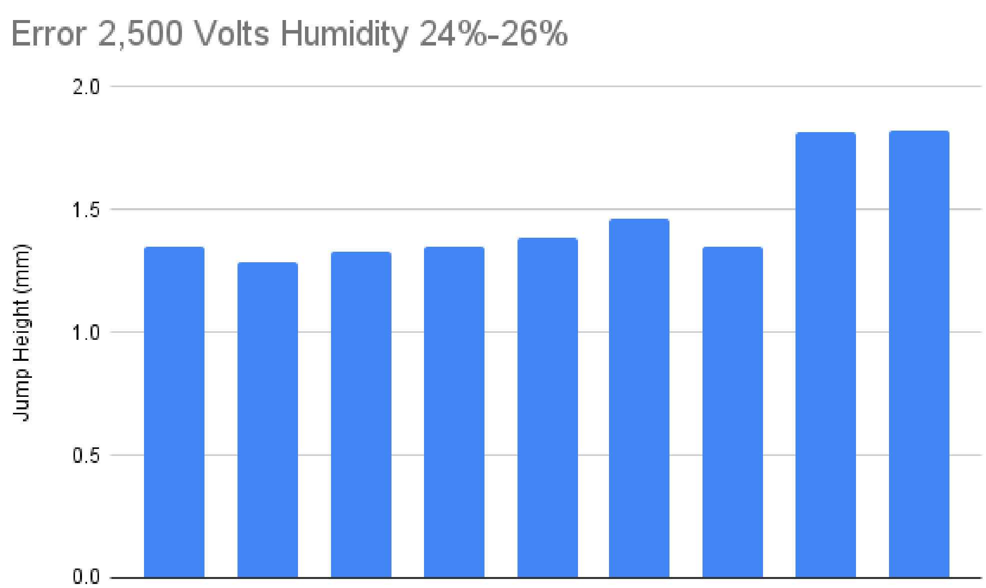

Figure 4.6: Multiple trials at 2,500 volts

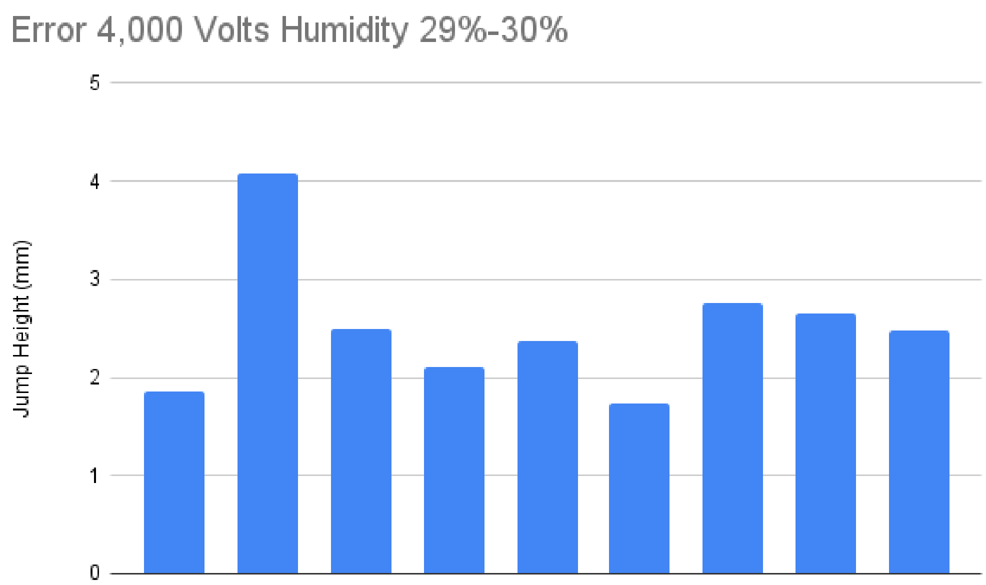

Figure 4.7: Multiple trials at 4,000 volts

For the data collected in Figure 4.6 the copper ball was charged at 2,500 volts and experiments were conducted sequentially at room humidity. For each trial, there is some variation, the largest difference being .532mm between the second and last trials. The standard deviation for the results is .2 mm. In Figure 4.7 the same error test was executed, this time at 4,000 volts. Here we see even more variation with a standard deviation of .69 mm. This error data confirms the presence of static electricity as a prevailing force in the initiation jump of the grains. For each test, the grains are brushed onto the plate and placed directly below the copper ball. Because the experiment is carried out manually, it takes a different amount of brushes each test to position the sphere perfectly. Each grain has a different amount of charge due to the static generated by the brushing of the grain onto the plate.

4.5 Impact of Humidity Variations on Jump Height (h) of Glass Grains at Different Voltages: Data Collection as Compared to Jump Height (h_p) of a Dielectric Sphere

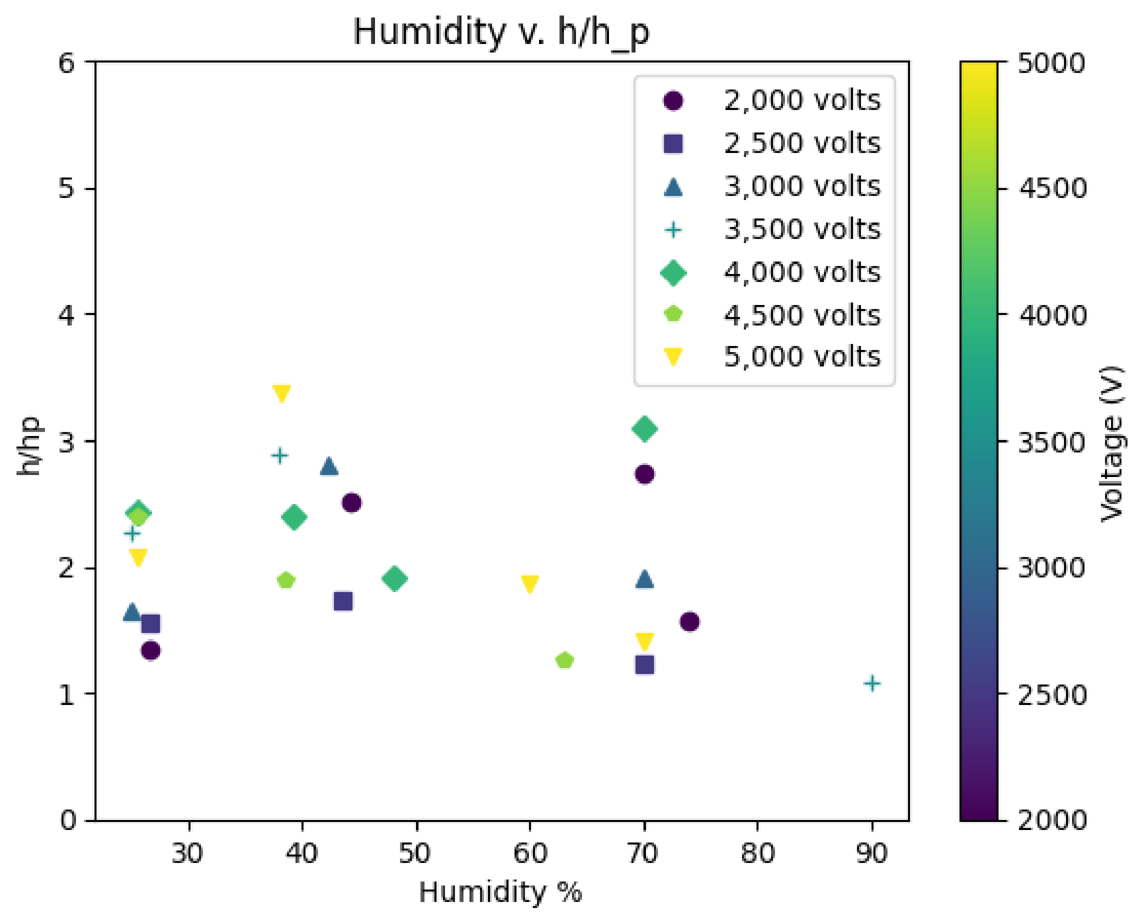

Figure 4.8: h/h_p v. Humidity

Since the data in Figure 4.5 reveals the grains do not behave as pure conductors at higher humidity levels, we will compare their behavior to that of pure insulators. In Figure 4.8 we divide the "initiation height" of the ball by the theoretical initiation height for a dialectic sphere (h_p) calculated using Equation 2.16. If the grains behaved as pure insulators, the h/h_p would be 1. However, in Figure 4.1, the data rests at values above 1. Ratios closest to 1 include the trial taken at 2,500 volts at 70% RH where the ratio reaches 1.22, and the trial run at 3,500 volts at 90% RH where the ratio is 1.08. Still some grains behave much more closely to conductors, for example at 5,000 volts and 40% RH the ratio becomes 3.37 and at 4,000 volts and 70% RH the ratio is high as well at 3.1. This data indicates, if the grains behaved as pure insulators, the copper ball would have to approach the grains more closely for the grains to have "jumped". From this result, we determine that the induced polarization force due to a gradient in the electric field described in 4.1 Item 4 is not the dominating charging mechanism. If this were the case, the grains would behave like pure insulators.

4.6 Influence of Polarity on Jump Height (h) of Glass Grains

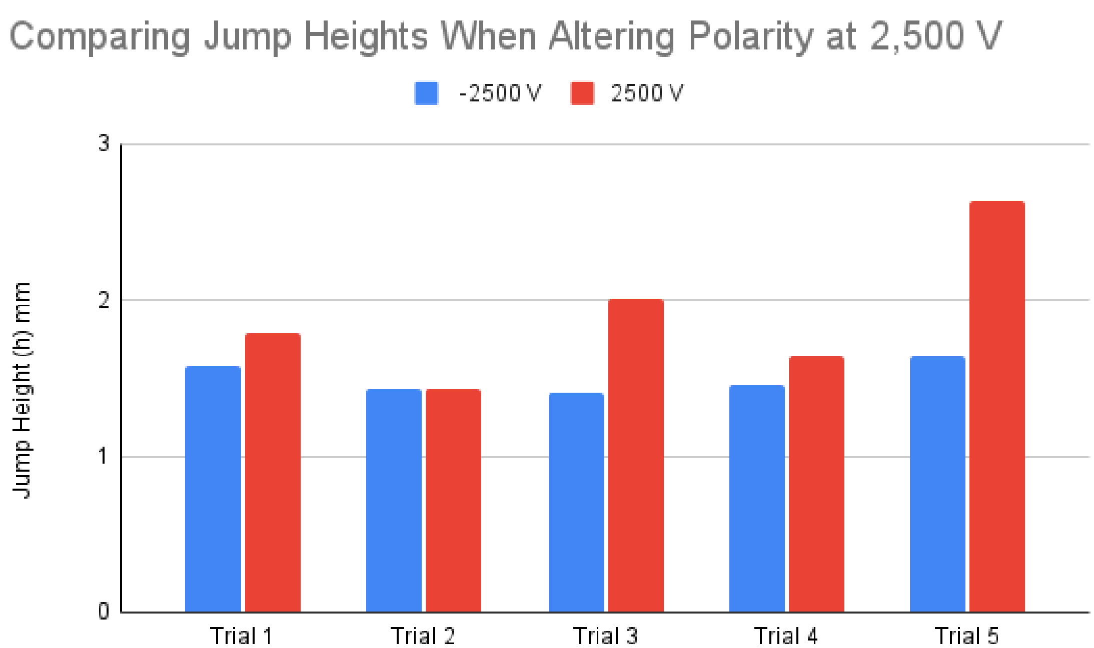

Figure 4.9: Modifying polarity at 2,500 V to determine the effect on jump height (h)

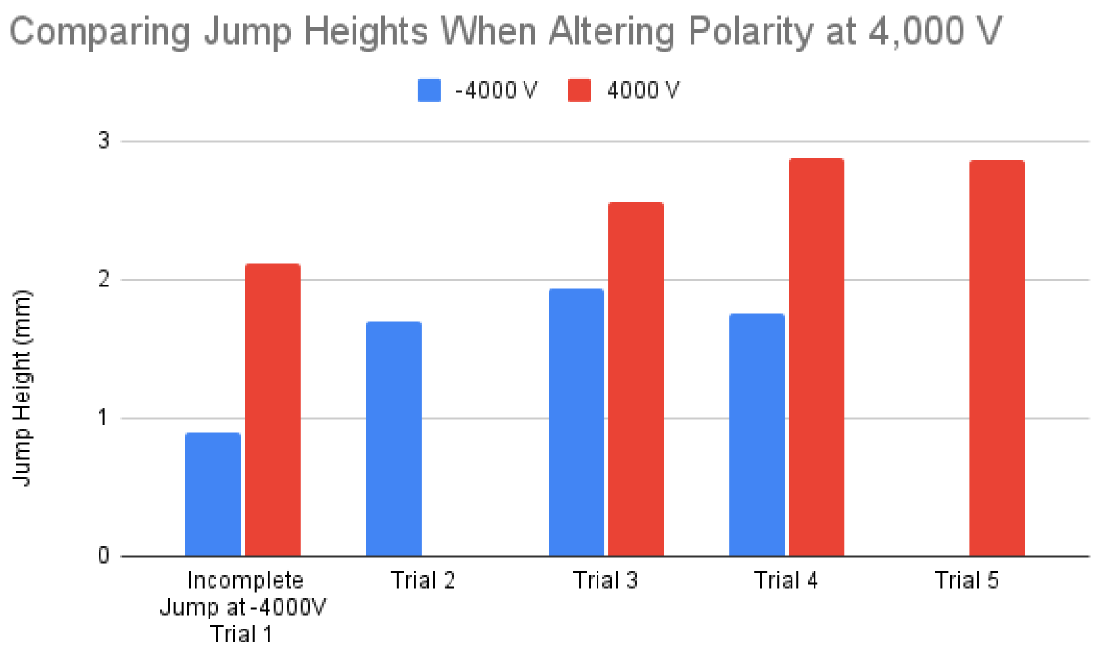

Figure 4.10: Modifying polarity at 4,000 V to determine the effect on jump height (h): Note that missing bins indicate the grain did not ”jump”

Considering that most of the data indicates that static electricity is the dominant force in the jump height (h) of the sand grains, regardless of humidity, one more experiment was administered. For these trials, the polarity on the copper sphere was flipped to see if the change would result in different charging behavior. The first 5 trials were conducted at -2,500 V and the subsequent 5 were performed at +2,500 V as represented in Figure 4.9. The mean value for the ”jump heights” determined when applying -2,500 V to the copper sphere is 1.5012 mm. The mean value for ”jump heights” when the +2,500 V were supplied to the sphere is higher, at 1.8982 mm. To verify this result, another set of data was collected, this time varying the polarity at 4,000 volts as depicted in Figure 4.10. These results vary from the data conducted at 2,500 volts because for trials 1 and 5 at -4,000 volts, and trial 2 at 4000 volts, the grain was not attracted to the ball, and was instead repelled. For trial 1, the grain was initially attracted to the ball but failed to fully reach the copper sphere. We denote this behavior by "Incomplete Jump" in Figure 4.10. These results verify that when a positive polarity is applied to the sphere, the "jump height" is larger. The mean "jump height" when -4,000 V are supplied to the copper ball is 1.576 mm, while the mean value is 2.60275 mm when +4,000 volts are imposed on the copper sphere. These experiments are telling, and require a review of Section 4.1. If the jumping on the grains were completely facilitated by static, the grains would not jump when the polarity was switched. This is not the case because the grains are capable of jumping at both positive and negative polarity. Therefore, static electricity cannot be the only charging mechanism. Induction through the air does allow "jumping" at both positive and negative polarity, however Figure 4.5 did not prove charging via airborne induction is amplified by an increase in humidity. A possible explanation is, when the copper sphere is further from the sand grain, static electricity dominates. This is why we see larger h values at positive polarity. However, at closer distances, induction assumes control and alters the charge on the grain of sand, explaining why the copper sphere needs to come closer to the grain when a negative voltage is applied.

Chapter 5

Conclusion

This paper aims to investigate how mesoscale organisms respond to electrostatic forces. While electrostatics play a crucial role in the world of these organisms, the specific charging mechanisms involved remain largely unknown. Previous research on ticks and nematodes proves that these organisms behave as electrical conductors when ambushing their prey [2, 15]. Notably, ticks and nematodes both live in high humidity environments [18, 21]. The question this paper aims to analyze is whether humidity could be the reason these organism have strong charging capabilities. This paper hypothesizes that water coating could improve the conductive properties of insulator due to freely moving ions on the surface of the insulator, and therefore allow ticks and nematodes to posses the electrical properties of a conductor.

To test this hypothesis a theoretical model was designed. A charged copper sphere was suspended above a spherical glass grain lying on a grounded plate. The copper sphere was lowered toward the grain until the grain "jumped" toward the sphere. The data collected reveals that at high humidity, micro-spherical glass grains do not behave as conductors. The first tests conducted were performed on silver coated spheres with radii of 98μm, to assess whether Equation 2.9 aligns with the behavior of a conductor for the given experimental framework. There was a slight discrepancy between the experimental and predicted values as demonstrated in Figures 4.3 and 4.4. This error is due to the fact that the copper sphere was estimated to be a point charge when implementing the image charge approach. For an exact calculation an infinite sum of image charges would be required. Nonetheless, Equation 2.9 is a great approximation for the behavior of a conductor.

Subsequently, experiments were conducted on spherical glass grains with radii of 97μm, varying the humidity three to four times per voltage. The data does not indicate a humidity dependence on "jump height" (h) and therefore does not defend induction through free ions in water on the grain surface as a dominant charging mechanism. A suspected significant influence is static electricity. When the grains are brushed onto the plate there is a transfer of charges from the brush to the grain. This lends to unpredictability in the data.

To confirm the prominence of static electricity a third set of data was taken. Nine trials were performed sequentially at room humidity and at the same voltage. The data is displayed in Figures 4.6 and 4.7. Because of the significant amount of variability in h between each trial, the results verify the strong presence of static electricity due to electron transfer from the brush to the grains.

Because not all the trials demonstrated similar behavior to that of conductors, we compared the data to Equation 2.16 to see how similar the grains behaved to conductors. The grains behaved much more closely to conductors than insulators indicating that induced polarization force is not the primary charging technique. The grains behavior is most likely dominated by the presence of static electricity.

A final set of data was taken to further investigate the charging mechanism dominating the charging of the sand grain. For these trials, the polarity on the copper sphere was altered. The data in 4.9 and 4.10 proves that the jump height on the grain (h) is higher when the polarity is positive. This difference in the jump height for positive and negative polarity is significant. If the grains' jumping were entirely due to static electricity, they likely would not be lofted at both polarities. This indicates that static electricity isn't the sole mechanism. The polarization force alone is also inadequate, as demonstrated in Figure 4.8, because the force is too weak to cause jumping and doesn't explain the higher jump heights at positive polarity. Induction through the air allows the grains to jump at both polarities, but Figure 4.5 didn't show increased charging with higher humidity. One possibility is that when the copper sphere is farther from the sand grain, static electricity is dominant. Electrons on the glass grain's surface facilitate attraction between the positive copper ball and the grain. However, at closer distances, induction may take over, altering the sand grain's charge due to the electric field gradient.

This study reveals that humidity does not enable an insulating sphere to behave as a conductor, insinuating that the reason ticks and nematodes are able to behave as conductors is not water coating on their surfaces. Because of the intricacies in determining the charging procedures on the grain, next steps include resolving the discrepancy seen in Figures 4.3 and 4.4 by modeling the exact electric field near the grain of sand and calculating the true behavior of a conductor using a sum on infinite image charges.

5.1 Future Work

Despite the results of this study being humidity independent, the answer could still lie in water. Victor Jimenez proposed that the reason ticks behave as conductors could likely be due to the liquid inside the ticks bodies [15]. A paper titled *Interpretation of Electrical Properties for Humid and Saturated Hematitic Sandstone Sample* discusses the effects of humid, partially, and saturated porous hematitic sandstone samples [14]. A small quantity of water located in the pore space of the sample induces polarization and improves charge transport [14].

Moreover, a study conducted on the electrical resistivity of polyester proves that resistivity in the material decreases when relative humidity increases because water absorbed into the material contributes free charge carriers. Electrical conduction in the material only occurs after a certain amount of water has been absorbed. The research suggests that in order to create polymeric materials with high electrical insulation properties, materials need to be deigned so that water does not percolate due to absorption [30].

Likewise, the conductive ability of ticks and nematodes may be attributed to the liquids within their bodies. Future work should aim to consider the conductive properties of water permeated insulators when assessing the charging capabilities of ticks and nematodes.

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