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Development of an Electromagnetic Pump: Putting Ideas into Motion

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by

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Abstract

In this project, we set out to design a pump using electromagnetic forces instead of mechanical ones. After testing several different models, we arrived at one that worked for pumping oil and other non-polar liquids. This report goes over the experimental procedure of how even with little resources and funding, scientists are able to overcome obstacles and contribute to knowledge in some meaningful way. The pressure head developed by our pump peaked at 0.162 kPa.

Acknowledgements

This project would not have been possible without the assistance and support of many people on campus. First and foremost, we'd like to thank Professor Burnham, who allowed us to experiment in her lab and use much of her available resources and Professor Steele, who allowed us to borrow many of the parts required to create our pump. We would also like to thank the people in the Biology Department and WPI Facilities, who provided us with some of the tubing and electrical equipment. Finally, we would like to thank our advisor, Carolann Koleci, for guiding us and believing in us every step of the way.

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1 Introduction

Ever since the classical era, humans have used pumps to move or compress fluids. What started out as a simple spiral pump has turned into a diverse field using varying types of forces to accomplish its mission. Many pumps utilize mechanical forces to move fluids, with pistons or spirals applying direct pressure to the liquid. Some utilize centripetal forces to accelerate fluids outwards. Finally, there are pumps which use electromagnetic forces to increase the pressure within fluid.[1]

Most of these electromagnetic pumps require the fluid to have a special property, whether it requires conductivity (useful for liquid metals) or a high enough permittivity constant (which is typical of nonconductive materials). Additionally, the actual parts of making the pump can be quite complicated, requiring finely machined parts to put out their pressure, which can drastically increase the cost required to make them. The major advantage of these pumps is there is little to know movement, so there is no mechanical wear unless the pump reacts with the fluid.

The goal of our project was to design an electromagnetic pump that didn't require the delicate parts of some pumps, but still had a respectable amount of pressure. Ideally, we were designing our pump to move water, which is only slightly conductive and has a fairly low permittivity constant. Our pump works well with oils, which are liquid at low temperatures but still retain a high permittivity constant. Given a proper voltage source, our pump can produce pressure with minimal parts, the actual pumping mechanism consisting of

[1] http://www.pumpindustry.com/Pump-History.aspx

nothing more complicated than a needle. We also tried a variety of other prototypes of pumps, but none worked as effectively, if at all. We used these failed attempts to discern some of the ways in which water behaves, which helped us design our later version of the pump.

2 Background

Pumps have existed for thousands of years, the first ones being designed in order to relocate water from low places, such as groundwater wells or springs, to higher places, the villages where the people had need of the water. Later, they were used in applications in plumbing, still moving primarily water. In recent times, however, pumps are used in everything from automobiles to vacuum chambers. Most of these pumps fall into one of two categories, the positive displacement pump and the velocity pump.

A positive displacement pump is designed to take an amount of fluid, and then apply pressure to it in order to make it leave the chamber and apply pressure to the system.[2] This can happen in a variety of ways. Some of these pumps are piston driven; some are spiral driven, forcing water up along a spiral path. In general, however, these pumps are designed to apply pressure to the system by directly applying pressure to the water via mechanical means.

A velocity pump is designed to take some fluid and provide kinetic energy to the fluid by use of some force acting on the water, often the centripetal force of a rotating blade.[3] This often takes the form of a quickly rotating fan that takes water in, and then forces it out along the outside, while applying rotational forces to the fluid, which provides it with additional velocity upon leaving the pump chamber. This velocity translates into greater water pressure as explained by Bernoulli's principle.

[2] http://www.engineeringtoolbox.com/positive-displacement-pumps-d_414.html
[3] http://www.engineeringtoolbox.com/centrifugal-pumps-d_54.html

2.1 Early Pumps

One of the oldest known pumps is the Archimedean Screw Pump, invented by the Greek scientist Archimedes in the third century BC. This pump was essentially a large screw inside a tight fitting tube, so that the water was forced to move in the grooves, which was turned in order to bring water up.[4] A contemporary to this was invented in Egypt, by Ctesibus, also in the third century BC. Also used to pump water, this pump utilized a double-piston approach that is similar to the piston used in modern engines, and is now classified a reciprocating pump. Both of these early pumps would be classified as positive displacement pumps.[5]

Few other significant advances in pump technology were made until the Renaissance, when many pumps were designed in a variety of styles (many of them were likely only designed, and not actually used). Sometime in the early nineteenth century, the first centripetal pumps were developed, and instead of pumping fixed amounts of water, they were actually for use on continuous streams, unlike the positive displacement pumps which move discrete quantities of water at a time.[6]

Both of these families of pumps have their own diverse uses, but all fall prey to one major weakness: they are based around the physical movement of some or all of their components. This movement makes them targets for failure, as friction will eventually lead to physical breakdown of the system, most likely at seals or at joints. The obvious solution to this is to remove moving parts from the pump.

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[4] http://www.pumpindustry.com/Pump-History.aspx
[5] http://www.smithsonianmag.com/science-nature/ancient_calendar.html
[6] http://www.pumpindustry.com/Pump-History.aspx

2.2 Electromagnetic Pumps

In recent years, electromagnetic forces have been used in increasing regularity to power pumps. In the later 1990s, the Lorenz force pump was first patented, using a magnetic field and a DC current to apply pressure to a conductive liquid.[7] These pumps are often used to pump molten metals. After the turn of the century, other types of pumps started to be explored. Using electromagnetic forces to move a variety of fluids, of both conducting and non-conducting natures, these pumps are often used as micro pumps to move very small quantities of fluids, where the physical limitations would prevent other pumps from being able to function. These pumps often require finely machined parts to operate at their maximum efficiency.

2.3 Chemicals

In the process of testing our pump designs, multiple chemicals were used, with different properties making one or more appropriate to any given design. The chemicals were water, canola oil, nonane, and heptadecane. The following is a brief summary of the applicable properties of each.

2.3.1 Water

Water (H_2O) is one of the most abundant liquids on the planet. Its chemical structure makes it highly polar, and is therefore able to dissolve many other molecules, giving it the name the “universal solvent.” Water has an dielectric constant of about 80, which makes it a fairly good dielectric when pure, but water has a tendency to dissociate, which means that

[7] http://www.freepatentsonline.com/5763951.html

free ions are floating around, allowing for much better current flow.[8] The density of water is 1 g/mL.

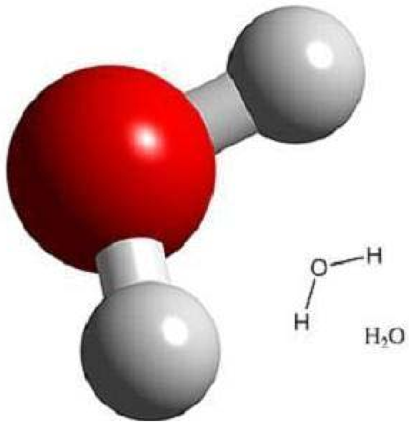

Figure 1: Diagram of Water Molecule (*taken from http://www.3dchem.com/imagesofmolecules/water.jpg*)

2.3.2 Canola Oil

Rapeseed Oil, more commonly known as Canola Oil, is a product of the seed of the canola plant, a relative of the mustard plant. The oil is primarily composed of two types of fatty acids, 61% Linoleic Acid ($C_{18}H_{32}O_2$) and 21% Oleic Acid ($C_{18}H_{34}O_2$). These two molecules have very similar properties electromagnetically, both with dielectric constants between 2.5 and 3.[9] Oil is also slightly less dense than water, being only .92 g/mL,[10] meaning that any pressure buildup will correspond to a larger increase in vertical displacement. Being both molecules are also fairly long chains of carbon and hydrogen atoms, with an oxygen cluster on one end. They are mostly nonpolar, with small polar sections on the oxygenated end.

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[8] http://physics.info/dielectrics/
[9] http://www.clippercontrols.com/info/dielectric_constants.html
[10] http://www.engineersedge.com/fluid_flow/fluid_data.htm

Linoleic Acid

Figure 2: Diagram of Linoleic Acid (*taken from http://en.wikipedia.org/wiki/File:Nonane-3D-balls-B.png*)

Oleic Acid

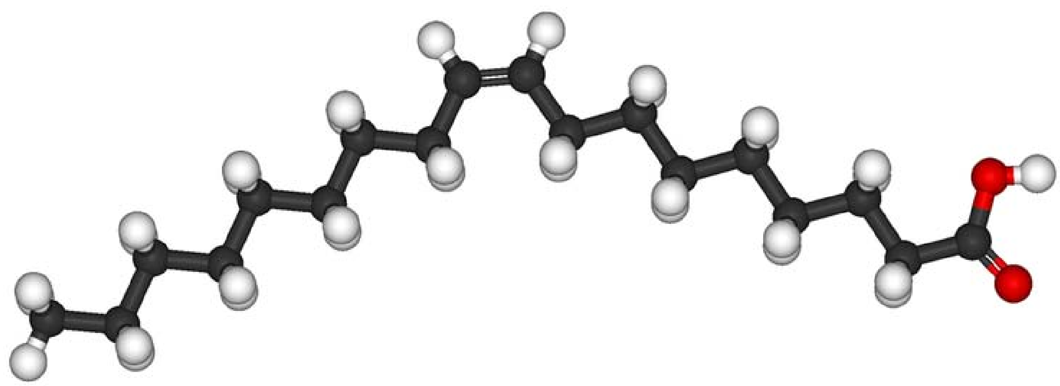

Figure 3: Diagram of Oleic Acid (*taken from http://commons.wikimedia.org/wiki/File:Oleic-acid-3D-ball-&-stick.png)*

2.3.3 Nonane

Nonane (C_9H_{20}) is a small chain of carbon with attached hydrogen atoms. Its primary use in our experiment was to see if length of the carbon chain had an effect on the pump's effectiveness. Nonane was chosen at the expense of some shorter molecules due to its high flash point, meaning it was relatively safe to work with even with electric currents nearby, due to a low risk of combustion. Its dielectric constant is 2.0, which is significantly lower than that of rapeseed oil. [11] The density of nonane is also significantly lower, being only .71 - .72 g/mL.[12]

Figure 4: Diagram of Nonane (*taken from http://en.wikipedia.org/wiki/File:Nonane-3D-balls-B.png)*

2.3.4 Heptadecane

Heptadecane ($C_{17}H_{36}$) is a fairly long chain of carbon with attached hydrogen atoms. Again, its use in our experiments was to test if length of the carbon chain had any effect on the pump's effectiveness. Heptadecane was chosen because it was the longest simple carbon chain that remained liquid at room temperature, which meant we did not need to alter the temperature of our equipment to test them. The dielectric constant of liquid heptadecane 2.05, [13] and the density is .778 g/mL.[14]

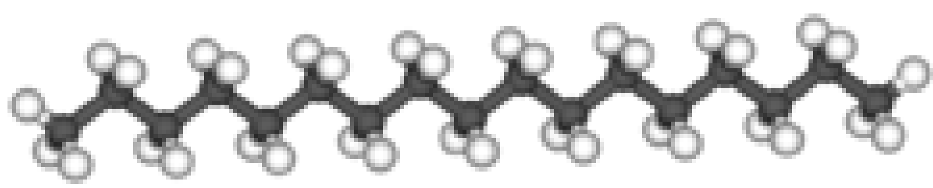

Figure 5: Diagram of Heptadecane (*taken from http://en.wikipedia.org/wiki/File:Heptadecane_3D.png*)

[11] http://www.clippercontrols.com/info/dielectric_constants.html
[12] http://www.engineersedge.com/fluid_flow/fluid_data.htm
[13] "Relative Dielectric Constant εr (dk Value) of Liquids and Solid Materials."
[14] http://www.chemexper.com/cheminfo/servlet/org

3 Physics Primer

3.1 Basic Laws of Electrostatics

When doing anything with electricity or magnetism, it is the movement and storage of charge that governs the motion of the system. The most basic law is Coulomb's Law in a vacuum (Equation 1), which governs the force between two charged particles.[15]

$$F = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2} \quad (1)$$

F = Force

q_n = Charge of point "n"
r = Distance between the charges
ε_0 = Permittivity of free space

The permittivity of free space changes to "ε" if the force is acting through matter, where a larger "ε" blocks out more of the force.

The next most important concept is that of potential, which when multiplied by a particular charge gives the potential energy at that point. This potential is also known as the voltage, and is governed by Equation 2, where q_2 is the voltage source and you are measuring at distance r away.[16]

$$V_{21} = \frac{1}{4\pi\varepsilon_0}\frac{q_2}{r} \quad (2)$$

V_{21} = Voltage of charge 2 at charge 1

ε_0 = Permittivity of free space
q_2 = Charge of point 2
r = Distance from point 2

Both the Coulomb's Law and the corresponding voltage law need to be integrated over space to get the forces associated with any real objects, but this gives a fundamental understanding of the forces, and can always be used to approximate the force if it is sufficiently large. With

[15] Halliday, **Fundamentals of Physics**, p. 566
[16] Halliday, p. 635

these two laws, a strong basis of electrostatics can be made, but once charges start in motion, these laws are no longer sufficient to explain what is going on.

3.2 Basic Laws of Magnetism

Once charges start moving, it is often easier to think of them not as individual charges moving, but as a line with charge moving through it. This motion of charge is known as current, and is dependent on the movement of charge. Ohm's Law (Equation 3) governs the current, voltage, and resistance interactions in matter.[17]

$$V = IR \qquad (3)$$

V = Voltage drop
I = Current
R = Resistance

V is the electrostatic voltage drop through a particular stretch of matter, and R is the resistance associated with that stretch (resistance is determined both by the physical dimensions of the resistor but also the properties of the material).

A moving charge also produces a magnetic field in the surrounding space, governed by the Biot-Savart Law (Equation 4). In this law, d**l** is a particular line element, I is the current through that element, and **r** is the separation between the line element and the point at which you are calculating field B.[18]

$$\vec{B} = \frac{\mu_0 I}{4\pi} \oint \frac{d\vec{\ell} \times \hat{r}}{r^2} \qquad (4)$$

B = Magnetic Field
μ_0 = Permeability of free space
I = Current through a line element
dℓ = Particular line element
r = Separation between point and line element

[17] Halliday, p. 692
[18] Halliday, p. 765

This field is a vector quantity that can be used to calculate the force on any moving charged particle, as governed by the Lorenz Force Law, Equation 5 for the force on a wire of length L in a magnetic field[19] and Equation 6 for a moving particle of charge q.[20]

$$F = L\vec{I} \times \vec{B} \quad (5)$$

$$F = q(\vec{v} \times \vec{B}) \quad (6)$$

F = Force

L = Length of wire
I = Current
B= Magnetic Field
q = Point charge
v = Velocity of point charge

These laws are equivalent, the only difference being whether acting on a current or on a single point charge. In both cases, the field B acts on the charge(s) by applying a force on them perpendicular to their velocity (or the current flow direction) and the magnetic field itself.

3.3 Basic Laws of Circuits

In a circuit, there is motion of charge around a closed loop, usually starting and ending at a power source. Some other elements contained in a circuit can be the following, complete with the basic rules governing their function and their effect on current flow.

Resistors are built to increase voltage drop over a section of the circuit, or often is the working mechanism in the system. This is simply a part of the wire with a higher resistance than usual, no matter whether that resistance is being used to move a load or simply to lower the voltage of the wire

[19] Halliday, p. 737
[20] Halliday, p. 751

Capacitors are built to store charge in the circuit, up to a maximum charge equal to the capacitance of the unit multiplied by the voltage. These have the property of having a strong magnetic field inside the capacitor. For a basic plate capacitor the physical capacitance of the element is governed by its geometry and the matter between the two plates, if any.

$$C = \varepsilon_r \varepsilon_0 \frac{A}{d} \qquad (7)$$

C = Capacitance

A = Area of the plates
d = Separation of plates
ε_0 = Permittivity of free space
ε_r = Relative static permittivity of material

Equation 7 calculates the capacitance (C) for two parallel plates[21]. "ε_r" is the relative static permittivity of the material, which is equal to "ε", the material permittivity, when multiplied by the permittivity of free space, "ε_0". As the charge stored in the capacitor is minimal, it has no impact on the flow of charge, but as it approaches maximum capacity, it makes a near total block of current.

Inductors are built to induce a magnetic field by looping wire as governed by the Biot-Savart Law. This element approaches its value asymptotically from zero, with its resistance on the circuit being greatest at the start but lessens as it approaches its maximum value.

These are the basic circuit elements, which can be combined in parallel or in series to make many electronic devices you see today.

3.4 Basic Laws of Polarization

[21] Halliday, p. 669

When working with non-conductive materials in an electric field, the electric field changes slightly inside the material. This is because the material polarizes itself to block out some of the field inside it by developing a surface charge. The magnitude of this "polarization" is given by Equation 8.[22]

$$\vec{P} = (\varepsilon_r - 1)\varepsilon_0 \vec{E} \qquad (8)$$

P = Polarization
ε_0 = Permittivity of free space
ε_r = Relative static permittivity of material
E = Electric field

E is the outside electric field, and ε_0 and ε_r are the permittivity of free space and the relative permittivity of the material. P in this case is equal to the density of dipole moments in the material. It is this induced dipole that created the field counter to the original field that lessens its effect inside the nonconductor.

A common way of measuring the electric permittivity a material is through the dimensionless constant k, a ratio of the capacitance of a capacitor with the given material as the medium compared to the capacitance with a vacuum as the medium. This value is the dielectric constant. By definition, it is equal to one for a vacuum. This constant is also a convenient way of measuring the polarity of substances, with nonpolar substances having low dielectric constants, and highly polar substances having much larger dielectric constants.

3.5 Basic Laws of Pumps

In general, fluids are moved by one thing, pressure. Pumps are a way of creating pressure to go against the static pressure on a fluid. The static pressure on a fluid can be complex depending on how tall the fluid column is and whether or not it is compressible.

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[22] Griffiths, **Introduction to Electrodynamics**, p. 174

For most purposes, a constant gravitational force approximation and a non-compressible view of fluids will suffice.

The static pressure on a fluid is given by Equation 9.

$$P_s = \rho g h \qquad (9)$$

P_s = Static Pressure
g = Acceleration due to gravity
h = Height of fluid

In this type of pressure comes from the weight of a column of fluid pushing down to whatever depth you are measuring at, represented by h. ρ is the density of the fluid, and g is the acceleration due to gravity (approximated at 9.8 m/s^2 for most applications). If the fluid column is compressible, such as atmospheric pressure, Equation 9 no longer applies, needing more complex calculations to compute pressure. These can still be calculated, however, using such fields as thermodynamics and statistical physics.

Pressure is technically the force per unit area on a material, and that works both in calculating the force exerted by the pressure but also in calculating the pressure generated by inducing a force on the fluid by any means.

3.6 Real World Application 1: Lorenz Force Pump

Many of the current strategies in motionless pumps make use of the conductive properties of some liquids. A magnetic field and a current across the liquid combine to make a force on the liquid. Since the primary forces in this system are not mechanical but electromagnetic, there is no friction among the parts of the pump, which greatly increases longevity. In addition, the lack of moving parts means that the energy requirements can be very low.

The driving force of this pump is predicted by the Lorenz Force law (Equation 5), where the force (F) on a current is given by the cross product of the current (I), multiplied by the length (L) over which the current is acting, with the magnetic field (B).[23]

The field is traditionally produced by a pair of wire coils, forming a strong, unidirectional magnetic field between them; an alternative to wire coils is a permanent magnet. This gives a lower energy requirement, but provides the operator with slightly less control over the system, since once a permanent magnet is installed it is difficult to change its magnetization. Meanwhile, a pair of electrodes on the edges of the pipe cause an electric voltage differential across the liquid, which will actually conduct a current if the liquid is the proper type.

This force is then transmitted through the local fluid as an increase in pressure, which can be used to either accelerate the fluid or raise it up, fighting against the static fluid pressure. This general principle is the same for all pumps, using mechanical (or electrical) forces to apply pressure to fluid, and then use that pressure to overcome static pressure.

3.7 Real World Application 2: Ion Drag Pump

Another popularized version of an electric based pump is an ion drag pump. This class of pump used an electrode to ionize the fluid molecules, than accelerate them towards an oppositely charged electrode to de-ionize the molecules, but continue them at approximately the same velocity, creating pressure. A common application of this is the Ion Breeze, which uses two electrically charged plates to accelerate air.[24]

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[23] http://www.freepatentsonline.com/5763951.html
[24] http://ionicbreezeairpurifiers.com/

Many versions of this have also been experimented with for liquids, to some success. Very easy to scale down to smaller sizes than most mechanical pumps, ion drag pumps often find places as micropumps.[25] Using Equation 1, it is plain to see that a force would be generated if we were to insert a charged particle between two oppositely charged plates by integrating the force over a line or a plane. Since the liquid is not a vacuum, some of the field would be mitigated by a field generated by the polarization of the fluid, governed by Equation 8. An approximation of the maximum possible pressure obtainable with an ion drag pump was computed by Darabi et al (Equation 10).[26] In this equation, the maximum pressure is proportional to the dielectric constant, and the square of the potential difference divided by the square of the separation of the electrodes, squared.

$$P_{\max} \propto \varepsilon \left(\frac{V}{d} \right)^2 \qquad (10)$$

P_{max} = Maximum pressure

ε = Dielectric constant (permittivity of material)
V = Voltage difference between electrodes
d = Separation of electrodes

This relationship has been confirmed theoretically, deriving it from the laws mentioned previously in this section. It has also been confirmed experimentally that real tests are in agreement with theory.

3.8 Prototype 1

The first of our designs involves the polarity of the water molecule. The incoming water travels through a horizontal tube toward the pump. The tube enters a copper pipe at the midpoint of the pipe and exits the pipe at the top. The driving force on the water molecules is due to the electric charge on the copper pipe.

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[25] Darabi et al., "Design, Fabrication, and Testing of an Electrohydrodynamic Ion-Drag Micropump"
[26] Darabi et al

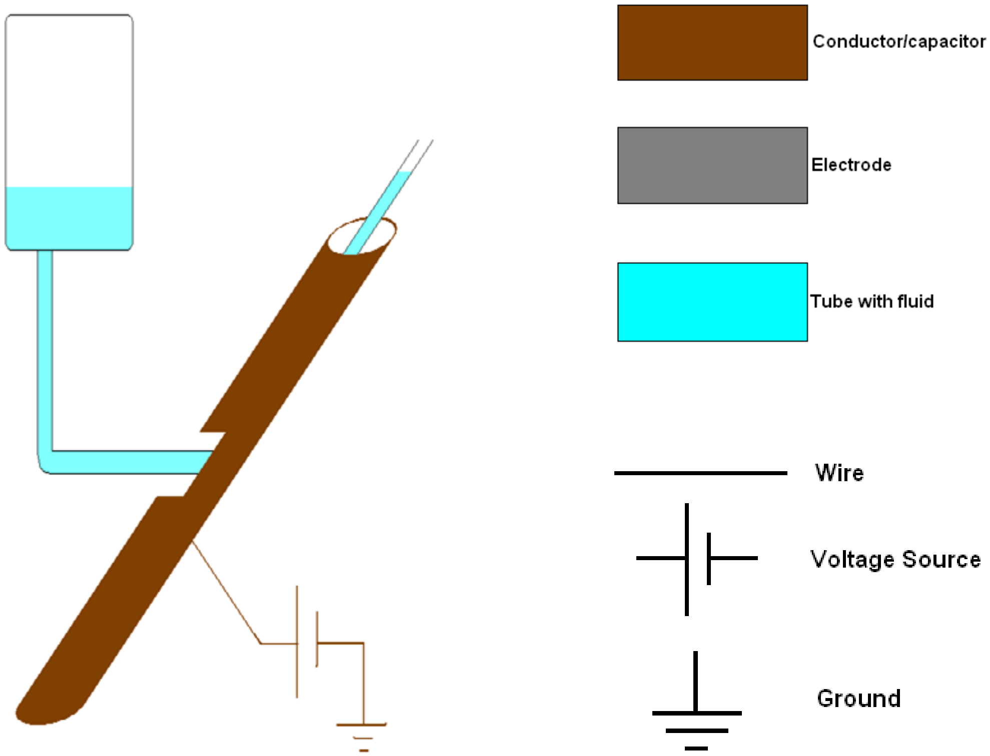


Figure 6: Diagram of Prototype 1

To understand why a copper pipe was chosen you have to look at the electric fields produced by different sources. A capacitor made of two infinite parallel plates produces a uniform electric field in between the plates. The force on either side of the dipole is of equal magnitude and of opposite direction resulting in no net force. The electric field produced by a single infinite sheet of copper is also uniform and will not produce a force on the dipole for the same reason. An infinite line of charge produces an electric field that varies with the distance from the line; given by Equation 1. When this field interacts with a dipole aligned with the electric field it produces a force that varies as an inverse square; given by Equation 2. The electric field produced by a point charge varies with distance as an inverse square, and the force on a dipole in this field varies as an inverse cube with distance.

$$E = \frac{\lambda}{2\pi\varepsilon_0 r} \qquad (11)$$

$$F \approx \frac{p\lambda}{2\pi\varepsilon_0 r^2} \qquad (12)$$

E= Electric Field

λ= Linear Charge Density

ε_0= Permittivity of Free Space
r= Perpendicular Distance from Line of Charge
F= Force
p=Dipole Moment

The advantage to charging a copper pipe to simulate the infinite line of charge is that inside the pipe there is little to no electrical field. This is because copper is a conductor of electricity and there is no charge on the inside of a conductor. This is appropriate because the copper pipe is sufficiently long.

Disadvantages to this design include the fact that ions of one same charge as the pipe will be repelled by the charge on the pipe. Likewise any non-conductive materials, once close enough to pick up the charge of the pipe will be repelled. Because the pipe cannot possibly be infinite there will be some electrical field inside the pipe due to the edge effects. It is also disadvantageous that in order to get the maximum force on the dipole, the molecule must be aligned with the electric field and therefore must overcome the natural Brownian motion that liquids exhibit.

One of the major advantages to this design is that the force attempting to move the water acts on the water molecule itself.

3.9 Prototype 2

The second prototype that we will test also relies on the polarity of the water molecule. This prototype will simulate a large pulse of current that slowly travels along a pipe in the output direction. This would ideally be achieved by a pulse generator and some conductive material, or by a cascade of stationary charges. This can be easily simulated by a large charged item that is moved along the path during the test.

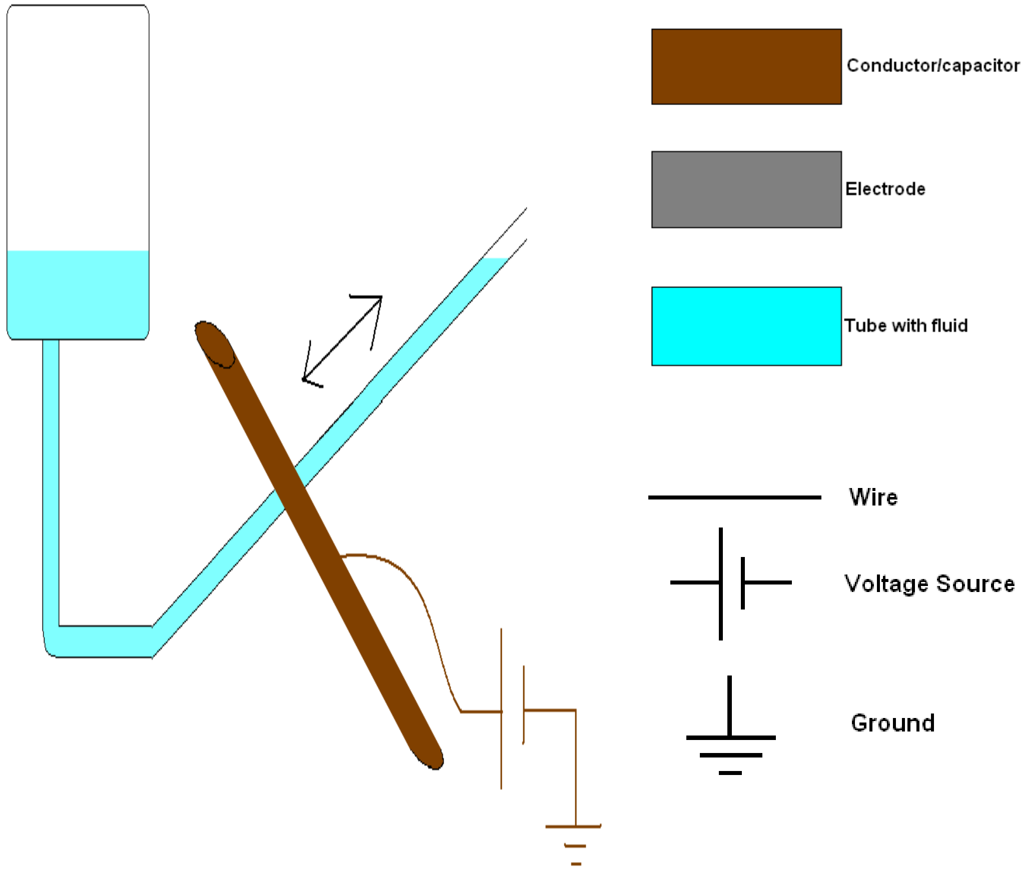


Figure 7: Diagram of Prototype 2

The idea is that the water molecules will be pulled toward the charged ring and therefore the inside wall of the pipe. When the charge is moved the attraction of the molecules closest to the charge is strong enough to support the movement of the molecules ahead of the charge. Effectively the molecules will form a sort of block in the pipe then slide with the movement of the charge.

A disadvantage to this design is that if the attraction is not sufficiently strong the molecules ahead of the charge will simply align to the field of the charge rather than be pushed by the block. This scenario would have a wave of aligned and misaligned molecules that follow the charge.

Non-conductive materials in front of the ring will help the pumping action. As the charge moves closer to non-conductive items they will be repelled in the direction of desired flow. Non-conductive materials on the other side of the ring will not help, but their effect will be reduced. The charge will all ready be moving away from any materials close enough to pick up the charge.

Ions of the same charge as the rod will be repelled upwards, and will help push along the surrounding water. Ions of the opposite charge of the large charge will act against the pumping action when in front of the charge. But when those ions are behind the charge they will be attracted toward following the charge.

3.10 Prototype 3

In this prototype the water molecule is not of concern, but rather the non-conductive contaminates in the water. The vast majority of water sources do not provide pure water. The water enters in a tube between two large charged copper plates acting as a capacitor. The tube makes several turns of a spiral then exits the area between the copper plates.

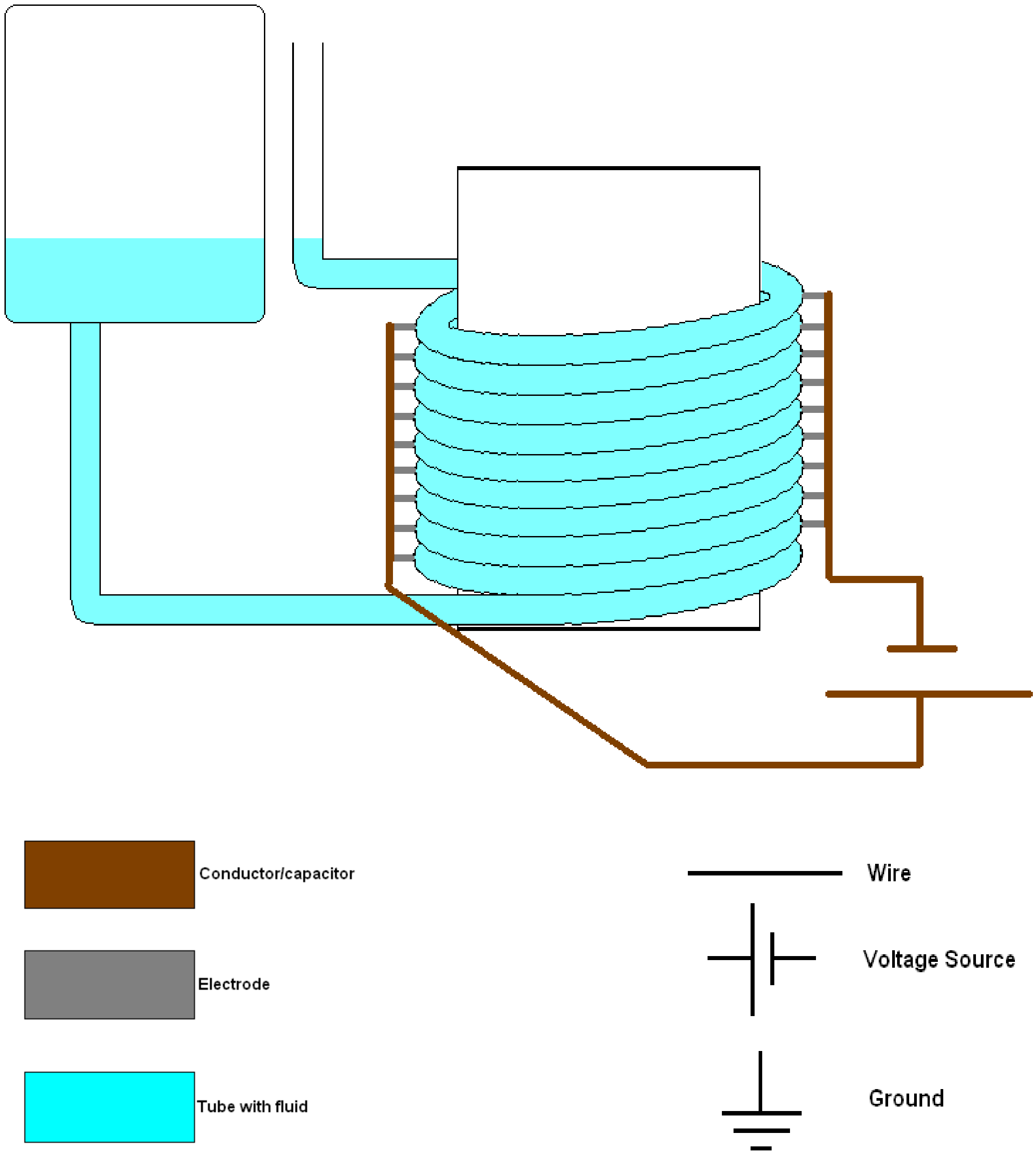


Figure 8: Diagram of Prototype 3

The idea is that the non-conductive materials pick up the charge of the nearest copper plate. Then those materials are forced to the other side of the capacitor where they then pick up the charge of that plate and are forced to the other side of the capacitor again. The spiral tube allows this to occur while increasing the elevation.

The first pitfall is that normal tap water might not have enough non-conductive materials. Any ions that are in the water might tend to accumulate near the plates they are attracted to. Polar molecules, including the water molecule, will not be affected in the uniform electric field between the plates.

Another pitfall is that in the absence of a check valve the fluid might tend to travel the spiral in the downward direction. This tendency will be combated by inertia of the fluid. If the fluid is already moving in the upward direction of the spiral it is not as likely that the flow will change direction.

4 Methods

Before the testing of the prototypes began, the output voltages of the power sources were measured. The first power source used claimed a voltage of 7.5kV. Initially the voltage from this power source was measured by a spark gap due to the availability of resistors for a voltage splitter. The distance between the ends of two wires were measured with a ruler. The distance was decreased to a gap of 2mm where a spark was observed. Using formula 4.1 the voltage was determined to be 7.35kV.

$$V = 30\left\{\frac{kV}{cm}\right\}d + 1.35\{kV\} \qquad (13)$$

V= Voltage (in kV)

d= spark distance (in cm)

Note "{}" indicate units

When a 100MΩ resistor was obtained the voltage was measured with a voltage splitter. The 100MΩ resistor was connected in series with a 1MΩ resistor and connected to the power source. A voltage drop of 73.1V was measured across the 1MΩ resistor with a multimeter. Using formula 4.2 the voltage of the power source was determined to be 7.38kV.

$$V_{Source} = \frac{R_2}{R_1 + R_2} V_2 \qquad (14)$$

V_{Source}= Output voltage of the power source

R_1= Resistance of resistor 1 (100MΩ)

R_2= Resistance of resistor 2 (1MΩ)

V_2= Voltage across resistor 2

A Van de Graaff generator was later used as a power source. The voltage was measured using the spark gap method. The gap was measured between the two identical spheres of the generator by measuring the distance between the centers of the spheres and subtracting twice the radius. The radius of the spheres were each 13cm and the total distance measured where a spark was observed was 33cm leaving a gap of 7cm. Using formula 4.1 the output voltage of the generator was determined to be 211kV.

Note that during the testing of the prototypes all of the linear measurements were taken with a ruler. The value of the measurement was estimated to within half of the smallest division of the ruler. Therefore, it must be noted that the uncertainty of each of the linear measurements is ±0.5mm unless otherwise stated. In the case of converting a length along a path to a vertical height the uncertainty will propagate as in the following example.

$$f(x) = \sin(\theta)x \quad (15)$$

$$\sigma_{f(x)} = \sqrt{(\sin(\theta)\sigma_x)^2 + (x\cos(\theta)\sigma_\theta)^2} \quad (16)$$

f(x)= Height as a function of length along path

θ= Angle above horizontal of the path
x= length along the path
$\sigma_{f(x)}$= Uncertainty in f(x)
σ_x= Uncertainty in x
σ_θ= Uncertainty in θ

Note that the uncertainty in "θ" is estimated to within a tenth of the smallest marking, which is 0.1 degrees or 0.002 radians (the uncertainty value must be in radians in the equations shown). Also note that when the average of a value is reported the standard deviation is used as the uncertainty.

4.1 Prototype 1

Using a pitcher as a reservoir, Prototype 1 was set up as shown in Figure 6. The valve on the pitcher is opened and the pipe is rotated about the midpoint until the top of the pipe matches the water level in the pitcher. The pipe is held up by ring stands and electrically isolated from those ring stands by electrical tape.

The copper pipe was connected to the positive terminal of the 7.4kV power source. There was no response from the water level. Using negative pressure on the end of the tube, to allow the water to be flowing in the direction it was being acted upon. This also yielded no response as the water level returned to that of the pitcher.

The setup of the experiment was changed to allow a second copper pipe. A tee pipe fitting was used to connect the tubes to the pitcher as well as through both copper pipes. The second copper pipe was set in a plane parallel to the first copper pipe with a distance of 60.5cm. It was rotated about its midpoint until the top of the pipe matched the water level in the pitcher. This pipe was rotated in the opposite direction of the first pipe so as to form an “X” if viewed from the side. A tube of outside diameter 1.7cm and wall thickness of 0.2cm was used so that the tee fitting could be used.

The first pipe was again connected to the positive terminal and the second to the negative terminal. The static and dynamic water levels were again tested, both showing no measurable response to the voltage. However while testing the static water level a small discharge sound was heard and the minuscule vibration on the surface of the water in the tube was observed to coincide with the sound. The discharge sound was traced to a pipe discharging to a ring stand due to a hole in the electrical tape. This was repaired and the tests were repeated yielding no measurable response.

The distance between the pipes was changed to the closer distance of 47cm. This did not yield a response from the water.

One liter saturated solution of sodium chloride was prepared in the pitcher of water. The valve was opened and the tubes were filled with this solution. When the pipes were connected to the power source initially water began flowing out of the tubes. However this result was not repeatable and most likely caused by air bubbles in the system. Both the static and dynamic water levels were tested yielding no response.

The tubes were switched to the large tubes used with the single pipe test as this tube did not form air bubbles as easily. However both tests yielded no response.

The salt water solution was diluted by adding 1 liter of tap water to the pitcher. Again both tests did not affect the water level.

All parts and tubes that came in contact with the salt water solution were rinsed thoroughly with tap water. Three liters of de-ionized water were obtained and poured into the pitcher. When this was let into the tubes and tested, both tests did not affect the water level.

The fact that the salt water did not respond to the two pipes showed that the second pipe was not necessary. A small tube with an outside diameter of 0.8cm and a wall thickness of 0.1cm and held to a ring stand. The tube turned horizontally into the hole in the side of the copper pipe and exited the top the pipe. The pipe remained tilted at the angle from the previous set up. The de-ionized water was poured directly into the open end of the tube. The pipe was connected to a Van de Graaff generator to increase the charge on the pipe. However both tests yielded no response from the water level.

4.2 Prototype 2

The setup of this prototype consisted of a tube that dropped from 90cm to 5cm above the table and is consistent with Figure 7. The tube is a straight line from the bottom corner to a point that is 100cm away horizontally and 80cm above the table in the case of the tube that has a 1.8cm outside diameter and a wall thickness of 0.2cm. In the case of the tube that has a 0.8 outside diameter and wall thickness of 0.1cm the point is 90cm away and 65cm above the table.

The larger tube was tested first. Distilled water was used in this test. The copper pipe from the previous experiment was moved slowly along both the angled and vertical sections of the tube with no reaction from the water.

The smaller tube was then tested with distilled water. There was no reaction from the water surface in either of the two tests.

A saturated solution of potassium iodide was tested in the smaller tube. This was tested with the copper pipe as before and again with a probe of four steel bars 9.5cm long and 1.5cm wide separated by 1cm. There was no reaction in either test with either probe.

4.3 Prototype 3

For this prototype there were many different experiments with many different configurations. The following sub sections explain each configuration and the corresponding experiments.

4.3.1 Spiral Configuration

As in Figure 9, this configuration consisted of a rubber tube wrapped around a glass cylinder for 10 turns. The tube had an outside diameter of 8mm and a wall thickness of 1mm. The outside diameter of the spiral was 4.5cm and had a length of 8.1cm along the glass cylinder. Two 1 ft^2 copper plates were placed on ether side of the spiral, held in place by ring stands electrically isolated by electrical tape. The 7.5kV power source was connected to copper plates.

The tube was filled with tap water and the power source turned on. This yielded no reaction. The experiment was attempted again with salt water and yielded the original result.

The tube was switched to a tube with an outside diameter of 1cm and a wall thickness of 3mm. This tube was again wrapped 10 times around the glass cylinder. This tube was pierced with nine metal pins on each side of the spiral, so as to put the working fluid in direct contact with the power source.

This configuration was tested with out the plates for distilled water and again with salt water with the 7.5kV power source, both yielding no reaction. Plates were then added with a separation of 8.5cm, again yielding no reaction for both experiments.

The power source was switched to the Van de Graaff generator and the configuration was tested with tap water. This yielded no reaction, but it was noticed that no significant charge was building up. The copper plates were removed from the setup as a possible source for the electrical short. Both tap water and salt water yielded no reaction and neither had a significant charge build up.

Canola oil was tested to see if the generator was shorting though the water that was tested previously. Canola oil was used in this test as it is a known insulator and readily available in the lab. The generator did build up a charge and the oil level rose 10.0mm along the path of the tube, a vertical rise of approximately 8.0mm. This result was duplicated several times, however after a period of about 24 hours it was noticed that this configuration had developed leaks and was no longer usable. This configuration with the oil as the working fluid proved that it is possible to pump a fluid using only electrostatic forces.

4.3.2 Two Needles Configuration

In an attempt to more clearly observe the processes a simpler configuration was used. This configuration consisted of two dissection needles inserted through the wall of the tube directed toward each other. The tube had an outside diameter of 10 mm and an inside diameter of 5 mm, leaving a wall thickness of 2.5 mm, and was in the shape of a “U”. The tips of the needles were separated by 1cm and the points of insertion into the tube were separated by 3cm with the center between the needles at the base of the “U”.

This configuration was first tested with the Van de Graaff generator with water and showed no reaction. Oil was then tested. This resulted in a very slight change in height. It was noticed that bubbles had formed at the tips of the needles and were observed traveling between the needles suggesting convection currents.

The configuration was changed so that the needles were pointed in roughly the same direction. The tips of the needles were separated by 1cm and the points of insertion were separated by 2cm.

Oil was tested with this configuration and was observed to rise along the path of the tube 3.0mm. At that point on the tube the path was at a 15 degree angle to the horizontal, making the change in height 0.8±0.3mm.

At this point a third configuration was designed in an attempt to have a configuration with a higher pressure. This attempt was not successful and a full description is available in Appendix B. The two needles configuration was slightly modified in that the “U” shape was changed. The end sections of the new shape are linear at 30 degrees to horizontal. The middle section is horizontal and holds the needles. Brass washers with the outside diameter of 40 mm and inside diameter of 20 mm were placed at the points where the needles intersected the tube and electrically connected to the nearest needle. To keep from arcing, the washers were wrapped in electrical tape.

Different liquids were tested in this pump and the resulting pressures compared. Canola oil traveled 5.0mm, a 2.5±0.5mm change in height. The oil was also tested with the 7.5kV source and resulted in no height change; however sparks were noticed in the oil connecting the terminals. Water was known to show no reaction from previous tests, and was not tested here. A saturated solution of sugar water was tested and showed no reaction. A saturated solution of sugar in canola oil was tested and gave a change in height of 1mm. Nonane and heptadecane were chosen for the next set of tests as they are isolative (non-conducting) liquids with similar dielectric constants and have similar molecular structures that differ only in size. In a fume hood nonane was tested and showed no reaction. Heptadecane was also tested in the fume hood. However the heptadecane was heated in a bath to 22 degrees Celsius so that the sample was completely melted. The heptadecane pumped 3.0mm along the path, a change in height of 1.5±0.5mm. The heptadecane also displayed a pulsing behavior. The liquid level would pump up and settle on a specific height and stay for only a moment, then settle on a lower level for a moment before returning to the higher level.

From this configuration it was shown that the pump worked by injecting a charge into the working fluid forcing it to travel to the other terminal. Adding an external capacitor, in the form of two parallel washers, around the pump did improve the performance. And finally by comparing nonane to heptadecane, which should have similar results according to the previous research, it was shown that there are more factors to consider.

4.3.2 Needle and Grid Configuration

A third configuration was constructed based on research of previous groups. This configuration used the same tube of as the two needle configuration with the two ends at a 30 degree angle to the horizontal. The pump consisted of a needle emitter and a 2 needle by 3 needle grid as the collector. The normal polarity was chosen arbitrarily to be a negative emitter and a positive collector. Note that in the following five figures the uncertainty of each individual height can be calculated in accordance to the example given and are displayed on graph in the form of error bars. However, the standard deviation is used as the uncertainty in the average value reported.

The first set of tests performed was a series of seven on/off pumping cycles. The pumping height is shown in the following figure. A significant hysteresis, where relaxed conditions are affected by previous actions, was observed. The oil level did not return to the starting position during the relax part of the cycle when the pump was turned off. In fact the relaxed position rose with every cycle.

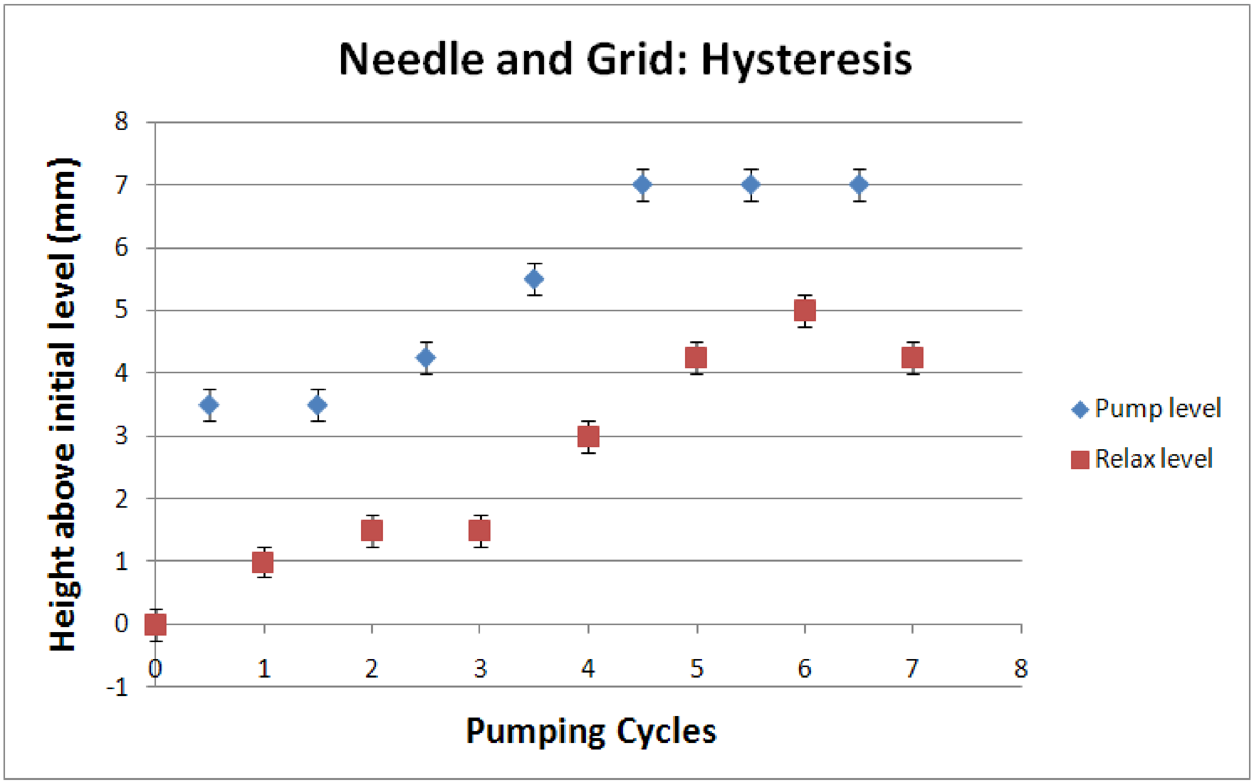


Figure 9: Graph #1 of Performance for Needle and Grid Configuration

One possible explanation for the hysteresis is that the oil was draining back along the sides of the tube from the filling process. In order to test this, the pump was allowed to sit for a full two days before the next set of tests. When the pump was again tested the oil level did return to the starting position in the relax part of the cycle. This is shown in the following figure. The average pump height for this set of test was 2.7mm with a standard deviation of 0.9mm.

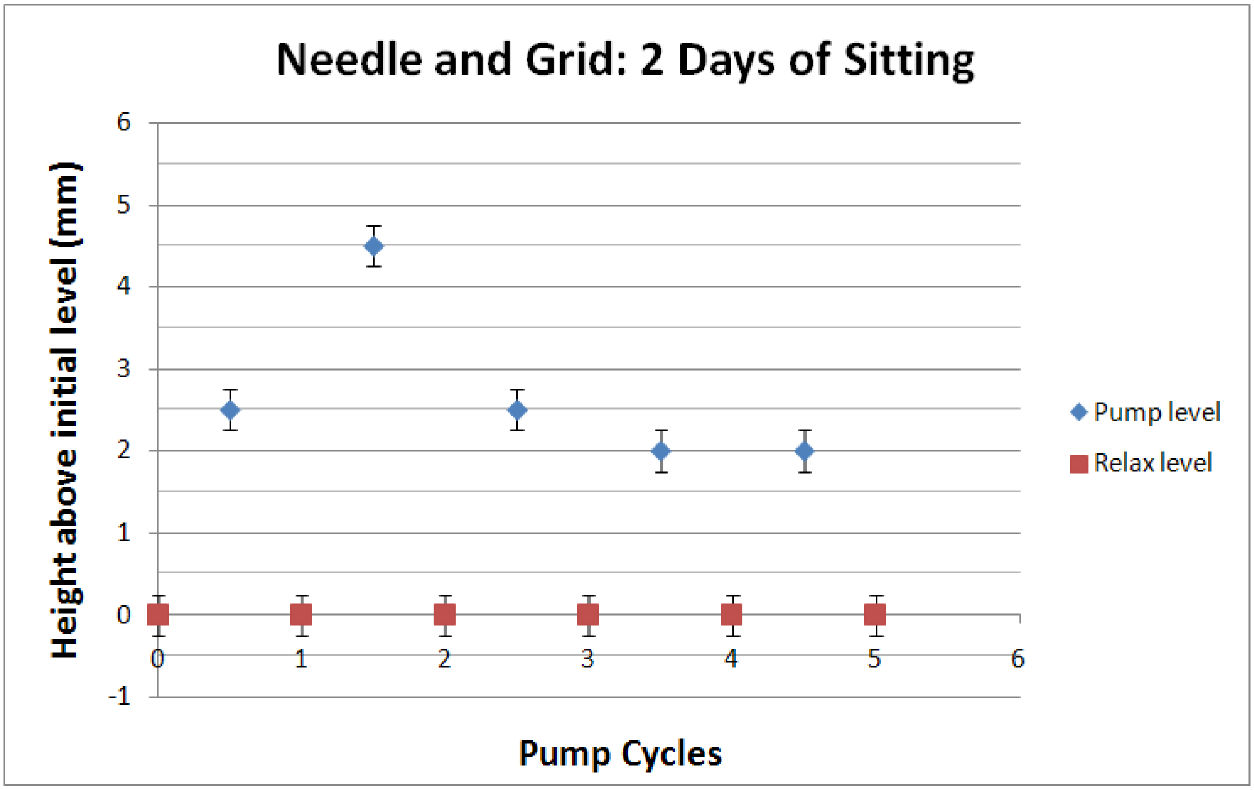


Figure 10: Graph #2 of Performance for Needle and Grid Configuration

The polarity of the pump was reversed in order to compare the performance between the two scenarios. This resulted in much the same performance as the normal polarity over several cycles. One of the pumping cycles is reported at a height of zero; note that at this point in the testing an electrode disconnection was noticed. Upon repairing the connection the testing resumed. The results of this set of tests are shown in the following figure. If the pump cycle with a height of zero can be disregarded on the basis that there was an electrode disconnection, the average height would then be 2.4 mm. The standard deviation of this was calculated to be 0.2mm. By comparing this set of tests to the previous set, it can be seen that this average height is within two standard deviations of the average height from the previous set of tests.

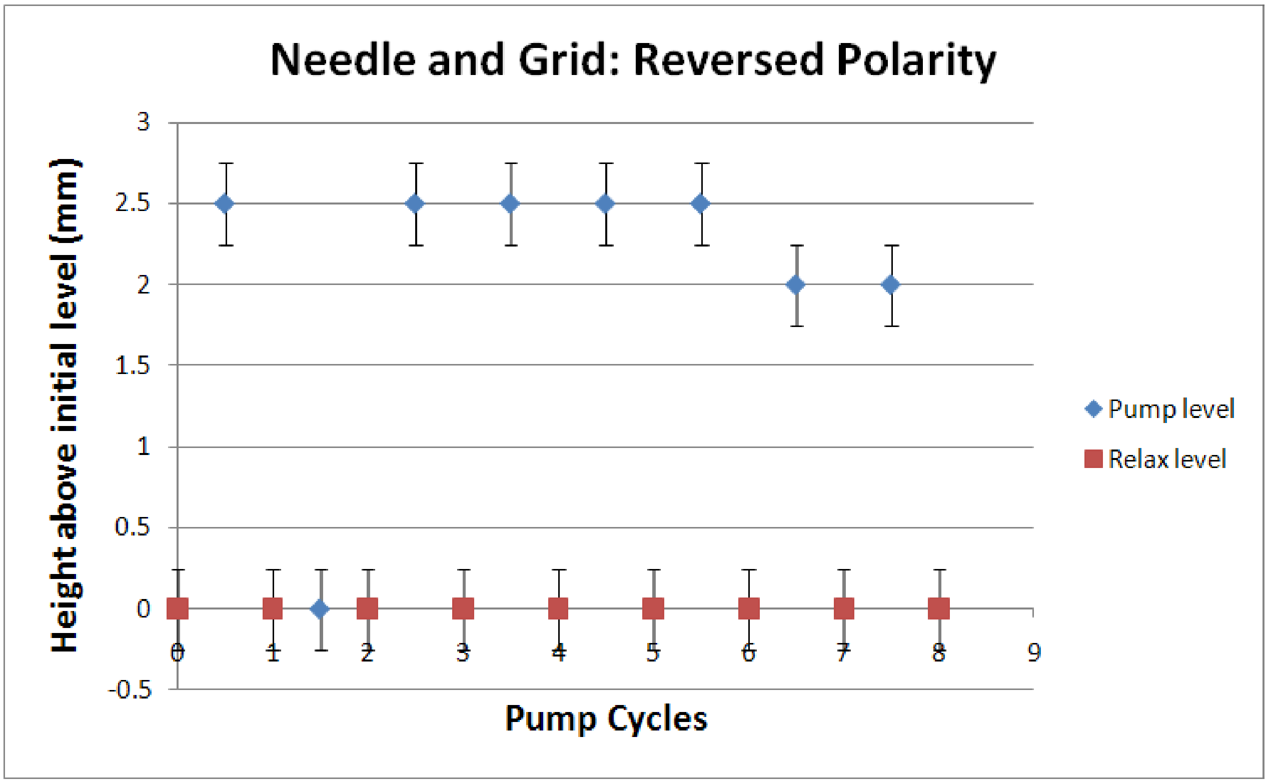


Figure 11: Graph #3 of Performance for Needle and Grid Configuration

The washers that were used in the previous configuration were added to this configuration as well. The polarization was left reversed from the previous experiment. The performance was noticeably improved and shown in the following figure. The average height of this set is 4.2mm with a standard deviation of 0.4mm.

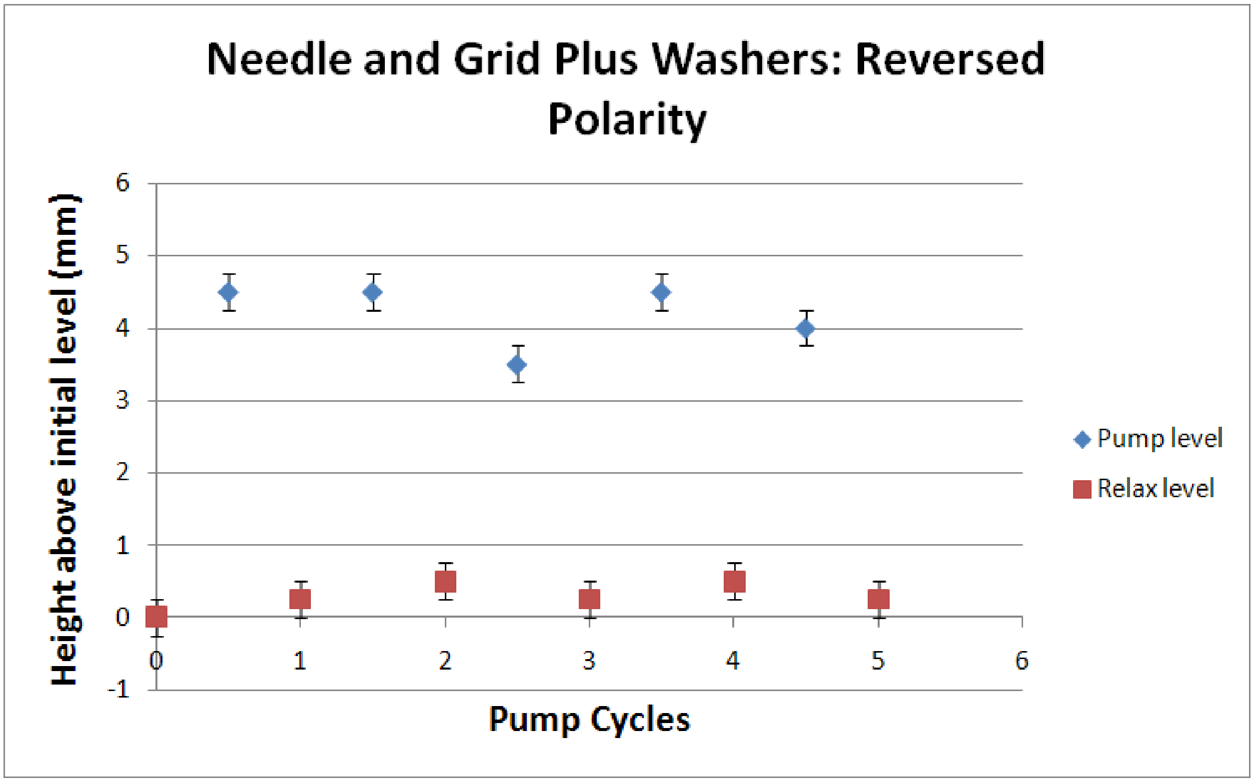


Figure 12: Graph #4 of Performance for Needle and Grid Configuration

The polarity was changed back to the normal position. After two pumping cycles the performance was drastically improved. One possible explanation is that the washers were not properly connected for the previous test as well as the first two cycles. The performance is shown in the following figure. The average height of this set of tests is 11mm with a standard deviation of 7mm.

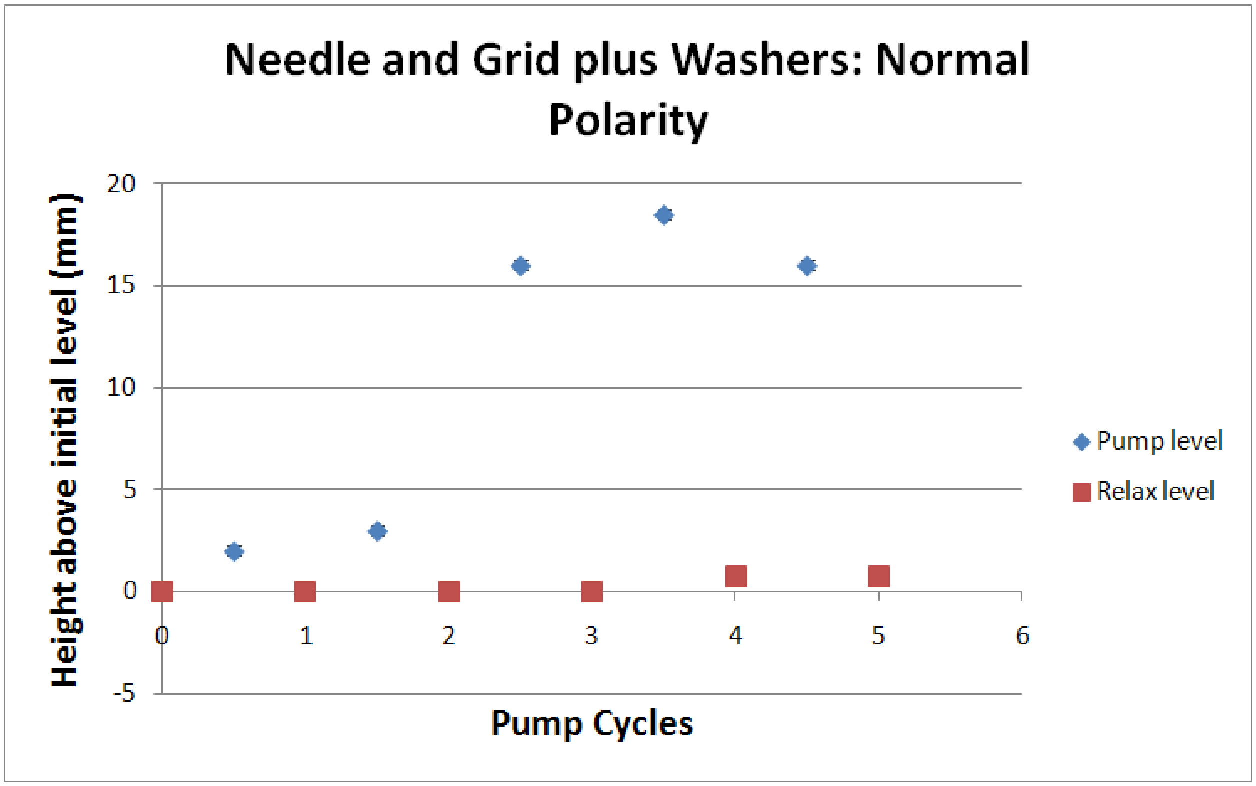


Figure 13: Graph #5 of Performance for Needle and Grid Configuration. Note: the error bars are barely visible due to the scale of the graph.

A video* of the performance of the pump was taken during a cycle where the pump height was approximately 16mm. From this video the volume flow rate was analyzed. The distance along the path of the oil level was recorded at one second intervals from the video. The approximate slope was calculated about each point according to the following example.

$$s_2 = \frac{d_3 - d_1}{t_3 - t_1} \qquad (17)$$

s_2= Slope at point 2

d_n= Distance along the path at point n
t_n = Time at point n

The slope that was calculated is the velocity of the oil level in mm/second. By multiplying the velocity of the oil level by the cross-sectional area of the tube the flow rate is calculated. The uncertainty in the slope was calculated using the quadrature rule using ±0.5mm as the uncertainty in the distance and ±0.1s as the uncertainty in the time. This is shown in the following example. Note that to calculate the uncertainty of flow rate from the uncertainty in the velocity a simple multiplication by the cross-sectional area is used as this area is a constant.

$$\sigma_{v2} = \sqrt{\left(\frac{\sigma_{d3}}{t_3 - t_1}\right)^2 + \left(\frac{\sigma_{d1}}{t_3 - t_1}\right)^2 + \left(\frac{-(d_3 - d_1)\sigma_{t3}}{(t_3 - t_1)^2}\right)^2 + \left(\frac{(d_3 - d_1)\sigma_{t1}}{(t_3 - t_1)^2}\right)^2} \qquad (18)$$

σ_{v2}= Uncertainty in the velocity at point 2
σ_{d3}=σ_{d1}=σ_{dn}=Uncertainty in the distance at point n =0.5mm
σ_{t3}=σ_{t1}= σ_{tn}= Uncertainty in the time at point n =0.1s
t_n= Time at point n
d_n= Distance at point n

The following graph displays the flow rate of the pump over time during the pump part of the pumping cycle. The maximum flow rate observed is 350±30 mm^3/s.

* Video is attached in the online copy

Note that the time starts at time 2 as there is no velocity measurement for time 1 due to the way that the velocity was calculated; likewise for time 17.

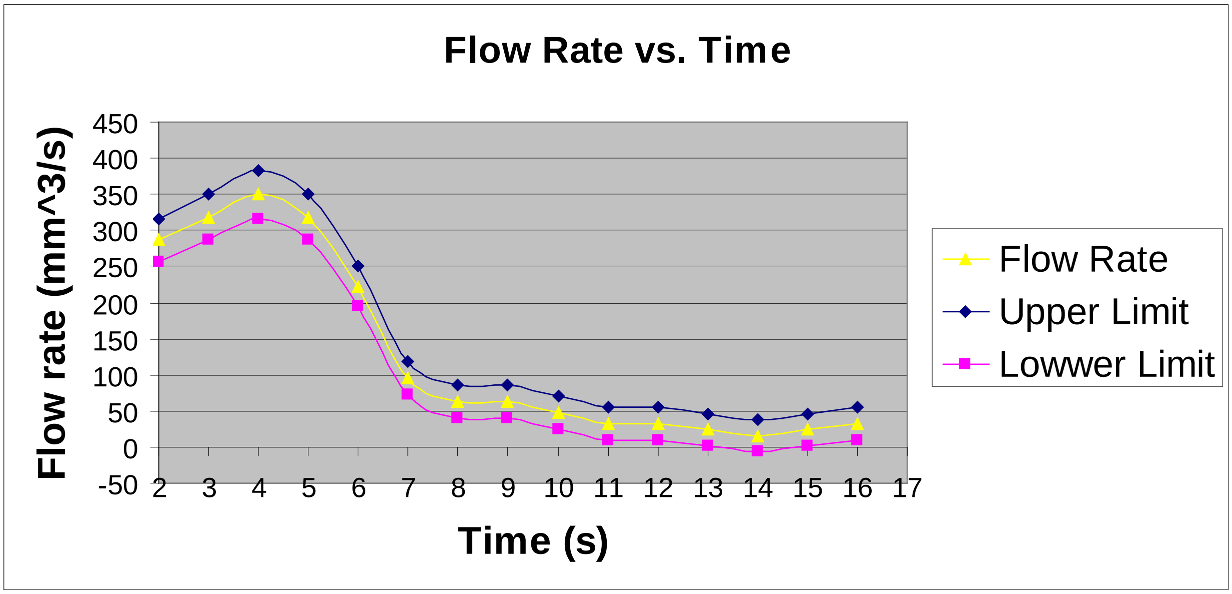


Figure 14: Graph of Flow Rate vs. Time for the pumping portion of the pump cycle

The setup was drained and stored for 4 weeks over the holiday break. Upon returning it was noticed that the belt for the Van de Graaff generator had broken. The belt was repaired and fresh oil was put into the pump. However when the pump was turned on there was no reaction from the oil level. The combs of the Van de Graaff generator were adjusted to achieve the maximum output. However, when the generator was connected to the pump there was no reaction from the oil level. By attempting to adjust the position of the emitter needle it was noticed that this needle was stuck and could not be moved by hand. A second emitter needle was then inserted through the wall of the tube. The first emitter needle was disconnected and the second needle was connected to the generator. When the generator was turned on the pump moved the oil level several millimeters.

This experience served as inspiration for testing how the needle separation from the grid affects the performance of the pump. The original emitter needle was adjusted carefully with pliers so that needle tip was flush with the inside of the tube. This needle was not completely removed as that would have allowed the tube to leak. The second emitter needle (which is connected to the Van de Graaff generator) was tested at six distances to the grid collector electrode. Each distance was tested four times and the average of these four results is shown in the following figure. Note that there is one exception; the performance of the pump on the fourth test at a separation of 2mm was interesting so two more test cycles were performed. The standard deviation of each point is represented by the error bars.

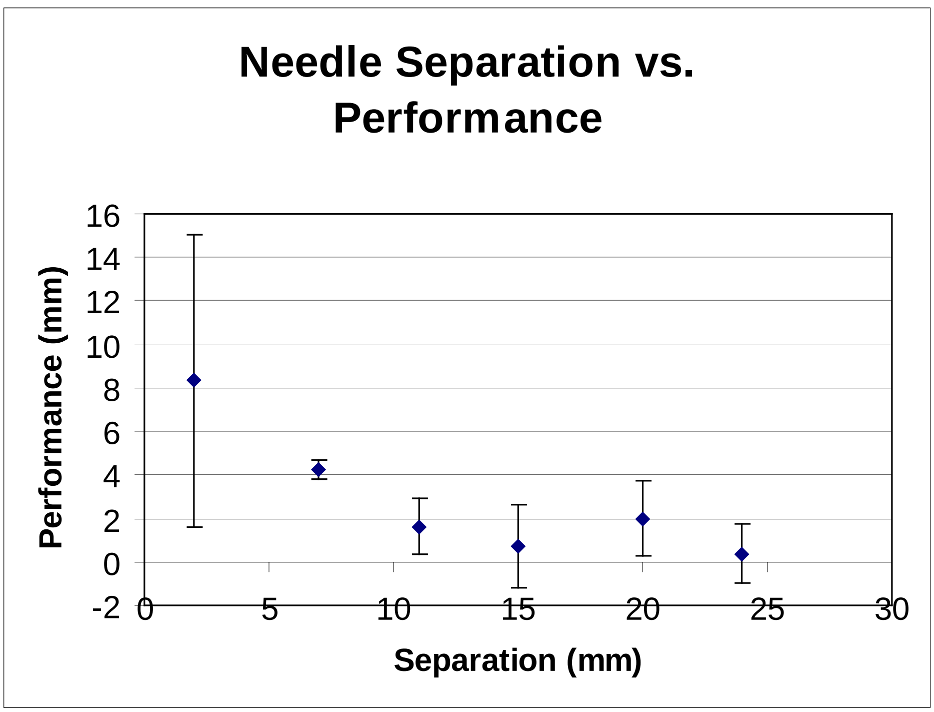


Figure 15: Graph of the Needle Separation vs. the Performance for the Needle and Grid Configuration

Note the large error bars for the separation distance of 2mm. This is due to the fourth test cycle at this distance. The performance for this distance was recorded as follows: 5mm, 5mm, 4mm, 26mm, 5mm, 5mm.

This irregular jump in performance was interesting and was the inspiration for the remaining tests. It was thought that the amount of time between cycles might affect the performance. The pump was tested at several different lengths of time of the relax portion of the cycle; 15s, 3min, and 15min. However in each of these tests the pump would move the oil level approximately 5mm and remain there.

Another possibility that was tested was that the length of time of the pumping cycle could affect the performance. For this test the pump was turned on and left on for a length of time while the oil level was monitored. Two tests 20min in length were performed as well as one test 40min in length. However, during each test the oil level was moved approximately 5mm and remained there for the rest of the test.

5 Analysis

In the following sections the results of the experiments discussed in chapter 4 are analyzed.

5.1 Prototype 1

Recall that the idea behind this prototype is to use the interaction between the dipole of the water molecule and a line of charge. When the single charged pipe did not yield a response to the water, it was thought that ionic impurities in the water were affecting the force on the bulk water. To reduce this effect a second pipe of opposite charge was added. After this configuration did not yield any motion for the water it was decided that theory behind adding the second pipe should be tested. This was tested by using a salt water solution, as it has many ions. From this test it was shown that the second pipe at the very least did not help. A possible reason for the second pipe to not help is that if the ions travel to the pipes they were attracted to a large force, due to this separation, would cause them to recombine. As the second pipe was not needed it was eliminated. A smaller tube was used so that the pump would be acting on a smaller mass of water. De-ionized water was used so that there would be as little ions as possible. Finally, the pipe was connected to a Van de Graaff generator with a much larger voltage than the other source. The higher voltage would lead to a higher charge on the pipe and therefore a higher force on the water molecules. This did not yield a response from the water level and it can then be concluded that the interaction between dipoles in water and a line of charge are too weak to be a significant pump.

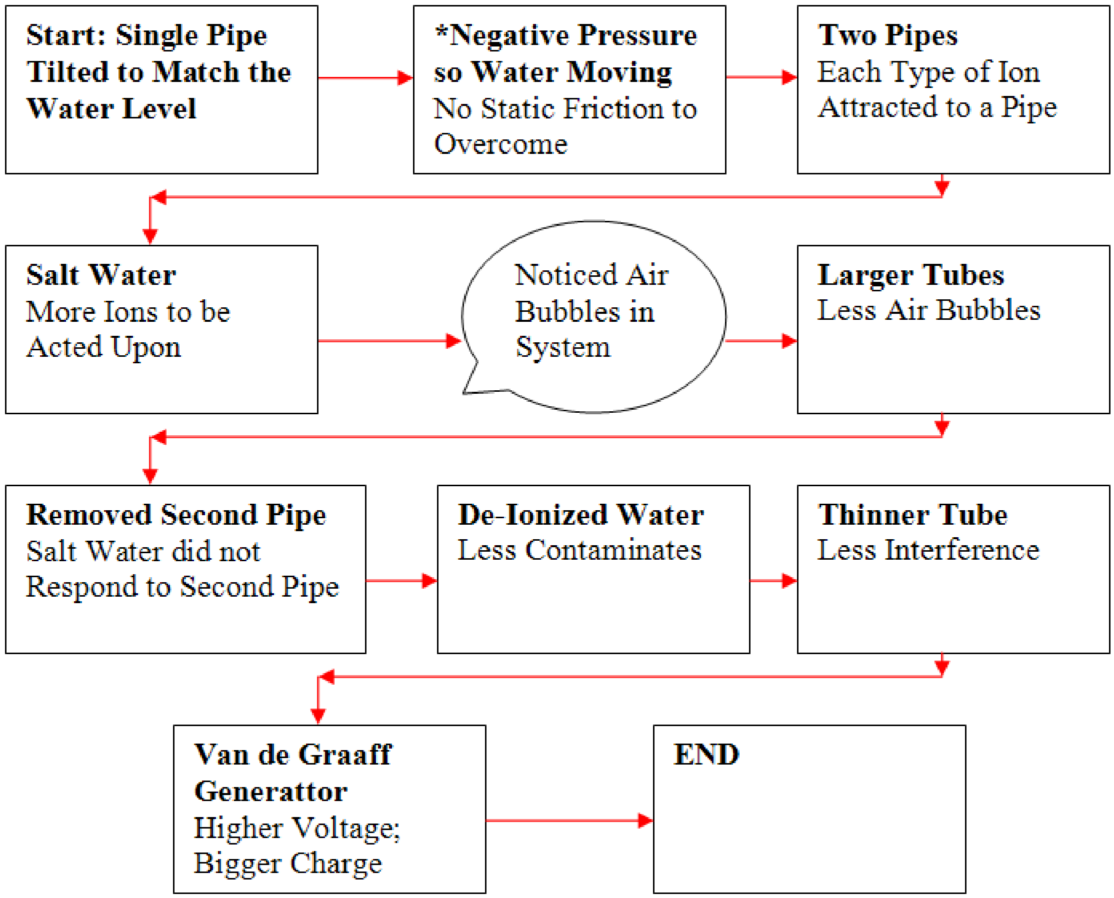


Figure 16: Flow chart explaining testing process of Prototype 1. Key: Bold text = Action, Normal text = Reason, Green arrows = Pump worked, Red arrows = Pump didn't work.

5.2 Prototype 2

The idea behind this prototype is that if the interaction between the dipole and the line of charge is not strong enough to pump the water on its own right, it may be strong enough to hold a small amount of it in place with respect to the line of charge while the line moves on the path. When the first test did not work a smaller tube was tested as this would require a smaller mass to be moved. Salt water was then tested to determine if having more ions in the fluid would strengthen this interaction. When this did not move the water level a four pronged probe was used to determine if bands of ionic species would form to help move the water level. This did not work and it can then be concluded that the interaction is ether too weak for large scale or too weak to overcome the separation due to the plastic of the tube.

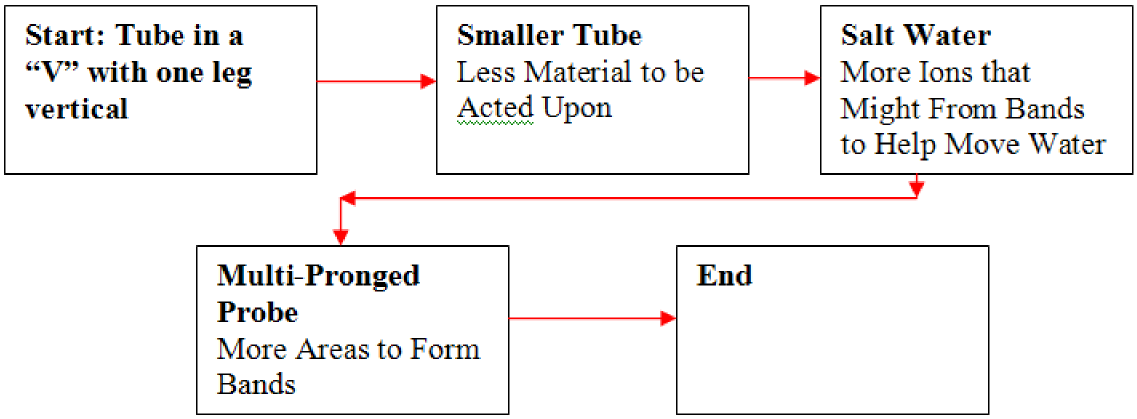


Figure 17: Flow chart explaining testing process of Prototype 2. Key: Bold text = Action, Normal text = Reason, Green arrows = Pump worked, Red arrows = Pump didn't work.

5.3 Prototype 3

The idea behind this prototype is that the impurities in the water would pick up a charge when close to one side of a charged capacitor then travel to the other side, where it would pick up that charge and repeat the process. Putting a spiral between the two plates would convert the back and forth cycles into an increase in height. When the first test did not move the water it was thought that the water was not close enough to the charge to cause a significant effect. The walls of the tube were pierced with metal pins to put the fluid in direct contact with the water. After that test showed no change in the water level, it was thought that a higher voltage would yield a stronger response, so a Van de Graaff generator was used. The Van de Graaff generator did not build up a significant charge and, finding no electrical short outside of the pump, it was thought that the generator was conducting though the water. Canola oil was then tested to see if a more insulating fluid would work better. From this, it was shown that Canola oil could be pumped directly using electrostatic forces only. However, due to the pins, leaks developed and a new configuration was needed.

To test if the pins were simply injecting the charge into the fluid, the Two Needle Configuration was built. Initially the two needles were arranged toward each other. When this yielded a very slight reaction and evidence of convection currents, the arrangement of the needles was changed so that the needles faced in the same direction. The idea here is that charge is more concentrated at the tip of the needles and that facing the needles in the same direction makes it so that the high concentration of charge at the tip of the second needle is not working against the tip of the first needle. This did work to improve the performance. To see if the performance could be further improved with the application of an external electric field, washers were added as a parallel plate capacitor. This also worked to improve the performance of the pump.

Different liquids were then tested. Canola oil was tested as before and shown to have a significant reaction. Sugar was dissolved into water to determine if non-polar molecules would help move the water, but this was shown to have no reaction. Nonane and heptadecane were tested to see if liquids with the similar dielectric constants but different molecule sizes would have similar results. It was shown that while heptadecane responded, nonane did not. From this configuration and the test performed on it, it can be concluded that ion drag pumps do work by injecting a charge into the fluid. It is also a conclusion that the size of the molecule must be considered, rather than just the dielectric constant.

The needle and grid configuration of this prototype was constructed because this setup yields a greater electric field density, which suggests that this type of configuration will markedly improve performance. When the hysteresis of the relax level was observed it was thought that oil was draining along the side of the tube from filling. To test this, the pump was allowed to rest for approximately two days then tested again. After this second testing it was confirmed that the oil was in fact draining along the side of the tube. For the third set of testing the polarity of the pump was reversed to determine if that had an effect on the performance. The average of the third set, which has the most closely clustered data points, was within two standard deviations of the average of the second set of tests. From this it can be concluded that there was not a significant difference between the two sets of tests. Washers were again added to determine if the performance could be further improved by the application of external electric field. The average of this fourth set of tests was more than two standard deviations away from the average of both the third and second set of tests, confirming that the performance was improved. When the polarity was switched and the widely varying data points were observed it was thought that there was a loose electrical connection jostled when the polarity was switched. However it can be concluded that the performance of the pump has the potential to be vastly improved.

When the pump was disassembled and then later restored, the irregular behavior of the pump was even more evident. During the testing of the needle separation against the performance this behavior was displayed. In one of those tests the performance increased by a factor of 5; changing from about 5mm to 26mm. In the next pump cycle however, the pump returned to the regular performance of 5mm. The pump was then tested to determine if the length of the relax portion of the pump cycle affected the performance. From our results, it can be concluded that this is most likely not a factor.

The pump was then tested to determine if the length of the pump portion of the pump cycle affected the performance. By conducting long run-time tests lasting up to 40min, it can be concluded that running the pump for longer periods of time does not affect the performance.

This pump, although it was able to pump oil, has been consistently inconsistent. That is, the pump consistently displays irregular behavior. There were instances where the pump did not work (i.e. after returning from the holiday break) and instances where the performance increased by factors of 5 or greater (i.e. during the test of needle separation against the performance) that we are at a loss to explain.

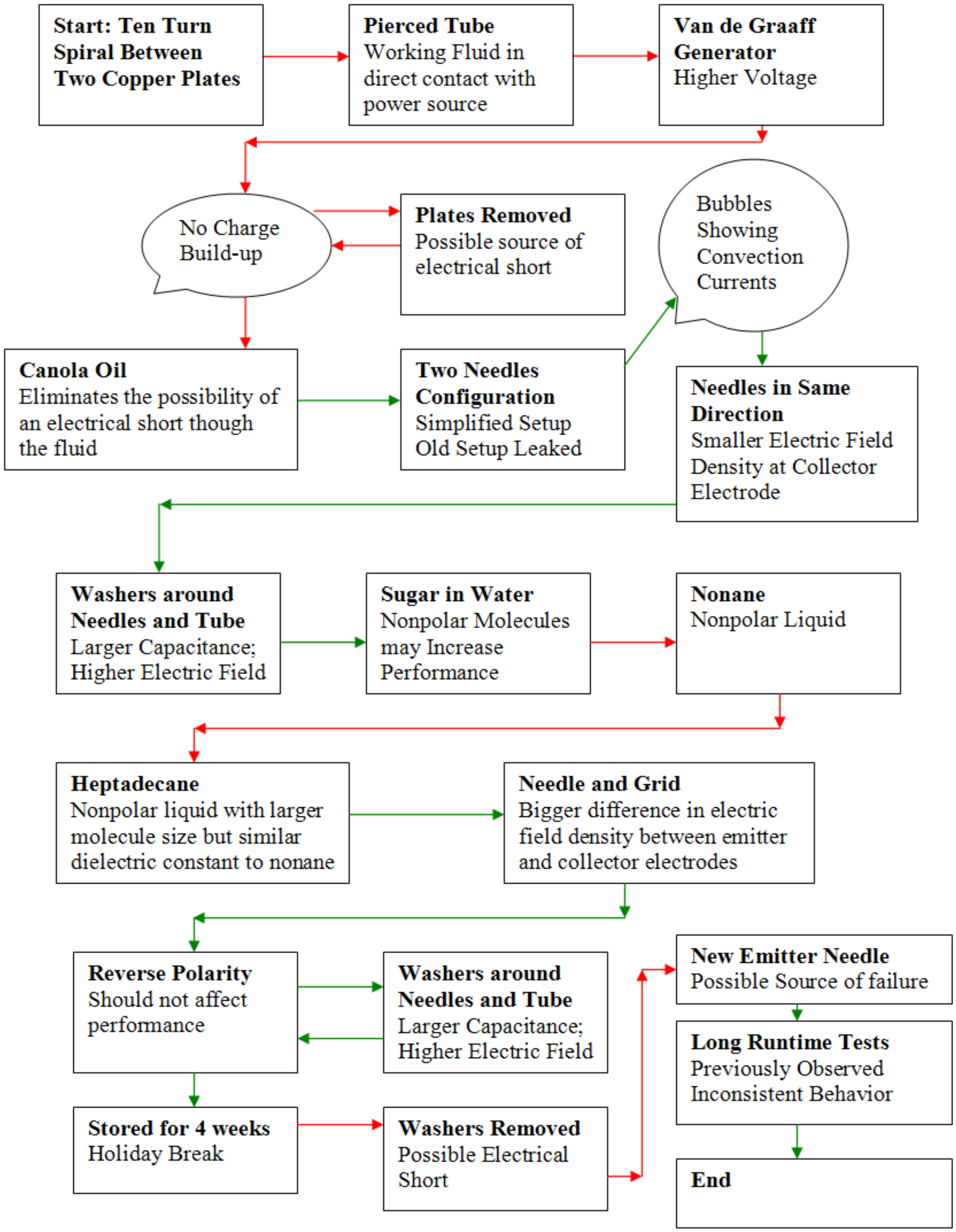


Figure 18: Flow chart explaining testing process of Prototype 3. Key: Bold text = Action, Normal text = Reason, Green arrows = Pump worked, Red arrows = Pump didn't work.

6 Conclusions

In this project several designs for an electrostatic water pump were tested. After seeing no reaction from water in these pumps it was concluded that these designs were unlikely to work and if they did work they would most likely be improbable for any application. However one of these designs was shown to be able to pump oil. This pump was a version of a pump known as an ion-drag pump. It was shown that these pumps do work by injecting a charge into the working fluid. It was also shown that size of the molecule is a factor that affects the performance of these pumps. By applying an external electric field the performance of the pump was drastically improved. The performance of the pump could be further improved by exaggerating the difference in the electric field intensity between the emitter and collector electrodes.

During the testing of our ion-drag pump, we were able to show that that our pump regularly displayed irregular behavior. On several occasions the performance of the pump drastically increased for reasons we could not determine, an example being in the second pump cycle after reversing the polarity with the washers added. Again the jump in performance occurred during the fourth pump cycle after adjusting the needle separation. There were also several occasions where the pump did not work without a solid explanation. An example of this is when the pump was tested after a 4 week break. Changing the emitter needle allowed the pump to work, but we found no reason for the original emitter needle to not work.

We set out to find a way to pump water with electrostatic forces. We ended up finding three ways to not pump water and one way to pump oil. Although this ion-drag pump was not exactly novel, we were able to investigate how these pumps work. Testing this pump put our experiment design and other laboratory skills to the test. We were able to experience the lows and highs of experimentation; when for reasons you cannot explain the test doesn't work the way you think it should, and against all odds your test does exactly what you thought it would.

Appendix

A. Dipole and Infinite Line of Charge

p= Dipole Moment

q= Charge

d= Length of the Dipole

E= Electric Field

λ= Linear Charge Density

ε_0= Permittivity of Free Space

r= Distance from Line of Charge

F= Force

$p \equiv qd$ -- Definition of Dipole Moment

$E = \frac{\lambda}{2\pi\varepsilon_0 r}$ -- Electric Field of Infinite Line of Charge

By using the relation F= qE, and breaking up the dipole into two charges. In this case we will calculate the force when the dipole is aligned to the field (i.e. perpendicular to the line). This means that one charge (the one attracted to the line) is d/2 closer to the line and the other charge is d/2 further away.

$$F = \frac{q\lambda}{2\pi\varepsilon_0}\left(\frac{1}{r-d/2} - \frac{1}{r+d/2}\right)$$ --- Combined force on both charges of the dipole

$$F = \frac{q\lambda}{2\pi\varepsilon_0}\left(\frac{(r+d/2)-(r-d/2)}{r^2-d^2/4}\right)$$ --- Common denominator

--- Combining like terms

$$F = \frac{q\lambda}{2\pi\varepsilon_0}\left(\frac{d}{r^2-d^2/4}\right)$$ --- Using the definition of dipole moment

--- Using the approximation "d" is small

$$F = \frac{p\lambda}{2\pi\varepsilon_0 (r^2-d^2/4)}$$

$$F = \frac{p\lambda}{2\pi\varepsilon_0 r^2}$$

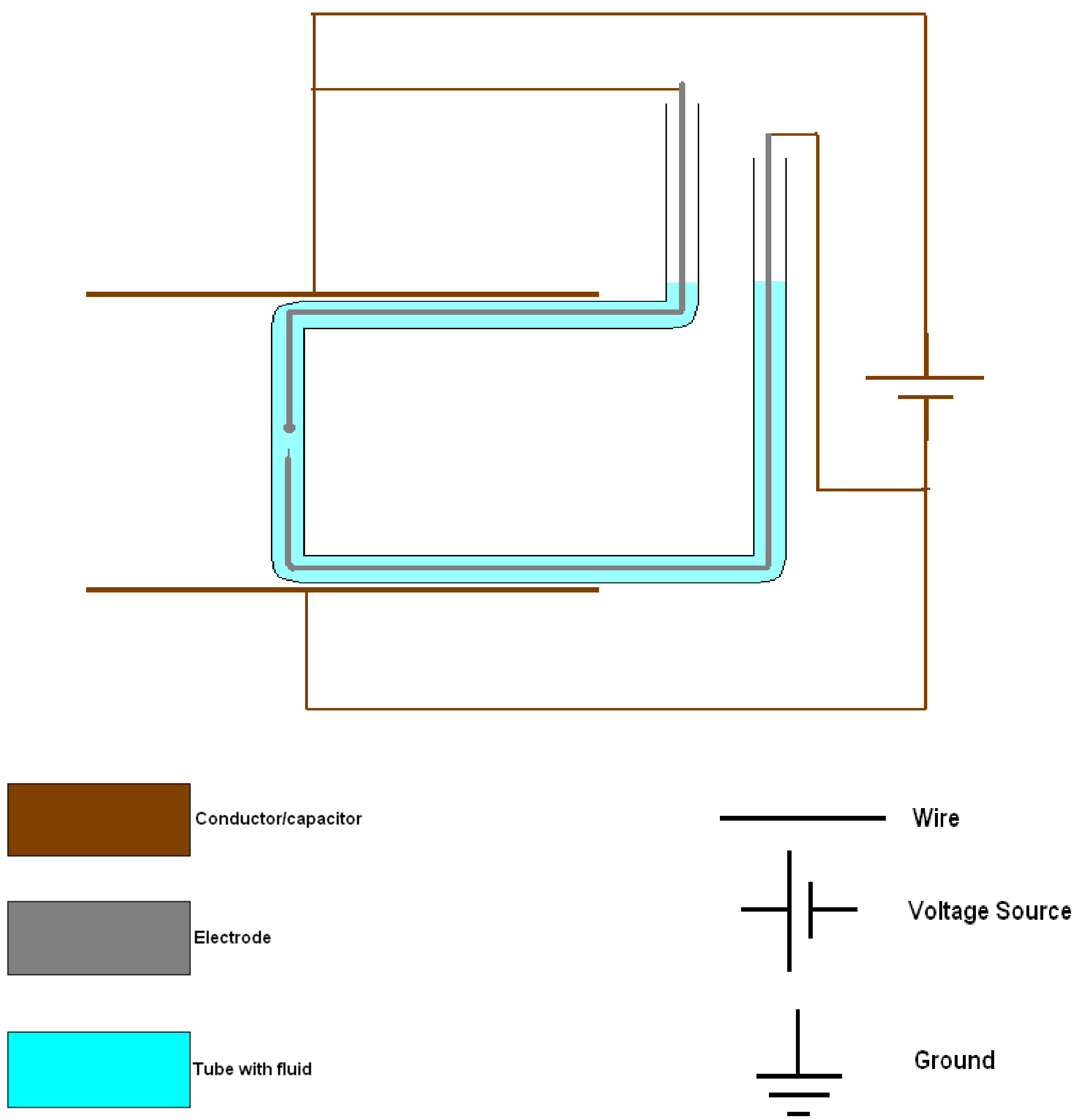
Capacitance of a finite cylinder, provided height above the earth is much greater than both the radius and the length and the radius is much smaller than the length. [A]

[A] D. F. LEACH, "Design of a single electrode capacitor for use with moisture meters and similar apparatus."

$$C = \frac{11 \cdot \varepsilon_0 l}{2\ln(l/r)}$$

B. Configuration of Prototype 3 Not Used

This configuration was not used as it was not able to move the oil. This is due to an electrical short that could not be fixed. This configuration attempted to use the electric field produced by two horizontal one foot square copper plates. One plate was placed on the table. The second plate was place on top of cement bricks that were on top of the first copper plate. Cement bricks were placed on top of the second plate to keep it from curving. A tube was placed between the plates such that the tube went vertically down from the stand, horizontally to the center of the bottom plate, vertically up to the center of the top plate, then horizontally out from the area between the plates then finally vertically up to a second stand. A copper wire was inserted from each end of the tube so that there was a small separation between the wires in the middle of the plates. One of the wires was had a bulbous blob of solder on the end of the wire to smooth out any sharp features. The other wire had a blob of solder that was drawn out to a spike on the end of the wire to make a sharp feature. Canola oil was then poured into the tube.



The bottom plate and the bottom wire were connected to the negative terminal of the Van de Graaff generator. The top plate and top wire were connected to the positive terminal of the generator. Upon turning the generator on there was no reaction of the oil level. It was noticed that the generator was not building up a charge, suggesting an electrical short. After not finding any electrical short it was thought that the cement bricks might be causing the short.

The negative terminal of the Van de Graaff generator was unplugged and removed. A tower of four cement bricks was built. A bare wire was connected to the negative terminal and between the bottom two bricks. If the bricks were nonconductive a spark would be expected to travel vertically between the bare wire and the positive terminal of the generator. However, when the generator was turned on the spark traveled horizontally between the surface of the top brick and the positive terminal of the generator. This suggests that the bricks were conductive.

No material could be found that was sufficiently nonconductive to allow for the separation of the copper plates. This being the case, this configuration was disregarded.

C. Comprehensive List of Tests Done

Liquid	Design	Result
Water	Prototype 1	NR
Salt Water	Prototype 1	NR
De-ionized water	Prototype 1	NR
Water	Prototype 2	NR
Salt Water	Prototype 2	NR
De-ionized water	Prototype 2	NR
Water	Prototype 3: Spiral	NR
Salt Water	Prototype 3: Spiral	NR
Canola Oil	Prototype 3: Spiral	8 mm
Canola Oil	Prototype 3: 2 Needles Towards Each Other	Slight
Canola Oil	Prototype 3: 2 Needles in Same Direction	0.8 mm
Canola Oil	Prototype 3: 2 Needles in Same Direction with Washers	2.5 mm
Sugar Water	Prototype 3: 2 Needles in Same Direction with Washers	NR
Sugar Oil	Prototype 3: 2 Needles in Same Direction with Washers	1 mm
Nonane	Prototype 3: 2 Needles in Same Direction with Washers	NR
Heptadecane	Prototype 3: 2 Needles in Same Direction with Washers	1.5 mm
Canola Oil	Prototype 3: Needle and Grid	2 mm – 4.5 mm
Canola Oil	Prototype 3: Needle and Grid with Washers	2 mm – 18 mm

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