Carbon nanotubes for "Ionic Wind" Craft or "Ionocraft"

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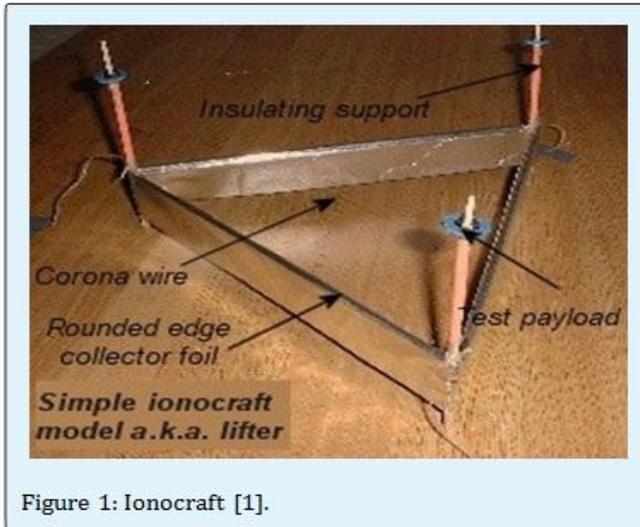
Abstract

Peter Thiel of the Founders Fund once famously said, "We wanted flying cars, and we got 140 characters."But nanotechnology now does make possible the long desired flying cars. It's a different propulsion method though than propellers or jets however. It's propulsion by electric fields known as electrohydrodynamic propulsion (EHD). It works by ionizing air then using electric fields to propel the charged air molecules rearward, thus producing thrust. It's quite analogous to the famous space ion drive of NASA. EHD has been known at least since the sixties. Its problem is, as with ion drive, the thrust is so low. So far the EHD craft have not been able to lift both themselves and their power supplies. The ones made so far leave the power supply on the ground and connect to the craft through power cables. But the equations of EHD suggest the thrust for the power required gets larger for thinner ionizing wires. In fact if the wires are at the nanoscale then this important thrust-to-power ratio can be a hundred times higher than for the craft constructed so far. This would be enough to lift the craft and the power supply. This research is to prove what the mathematics suggests. Note that if it works then all propeller and rotor driven craft become obsolete. Also, intermediate range automobile travel would be taken over by the EHD craft, so a large proportion of carbon-emissions would be eliminated, replaced by this zero-emission travel method. In regards to space propulsion, since EHD is so similar to ion drive, using components at the nanoscale may also work to improve the thrust of ion drive. This would be important to shortening the flight times of spacecraft using such drives. This is important not just for robotic spacecraft but also satellites that use such ion drives to reach their final GEO destinations. As it is now, the ion drives used have such low thrust it takes months for such satellites to reach GEO, resulting in millions of dollars of lost revenue to the satellite companies. Being able to increase the thrust of these drives would reduce the flight time, and therefore reduce this lost revenue.

Keywords: Electrohydrodynamic propulsion; Carbon nanotubes; Nanowires; Ionic wind; Ionocraft; Plasma drive

Introduction

Long has it been dreamed about a personal "aircar" or "flying car" that could be privately owned and takeoff from and land at the family garage. Carbon nanotubes now make that possible. About the last decade or so there was much research among amateur experimenters about "ionocraft", commonly called "lifters":

Figure 1: Ionocraft [1].

They work on the principle of electrohydrodynamic (EHD) [2] propulsion: electrical power is used to ionize the air which is then directed by electric fields.

The problem with the lifters has been though the power requirements are so high they could not produce enough thrust to lift their own independent power supply. The lifters that have been produced so far work by having a power supply on the ground and connecting the power supply to the lifter through cables. But there is an interesting aspect of the equations describing the thrust produced by the lifters. The thrust increases as the diameter of the wires producing the ionization, called the "corona wires", decreases. The wires used for the lifters so far have been a few hundred microns wide, a few widths of a human hair. However, the nanotubes have widths at the nanoscale. Calculations show the thrust then produced should be enough to lift the lifters and their power supply.

Calculations

Theoretical discussion of the inverse dependence of the thrust on the corona wire radius by Evgenij Barsoukov here:
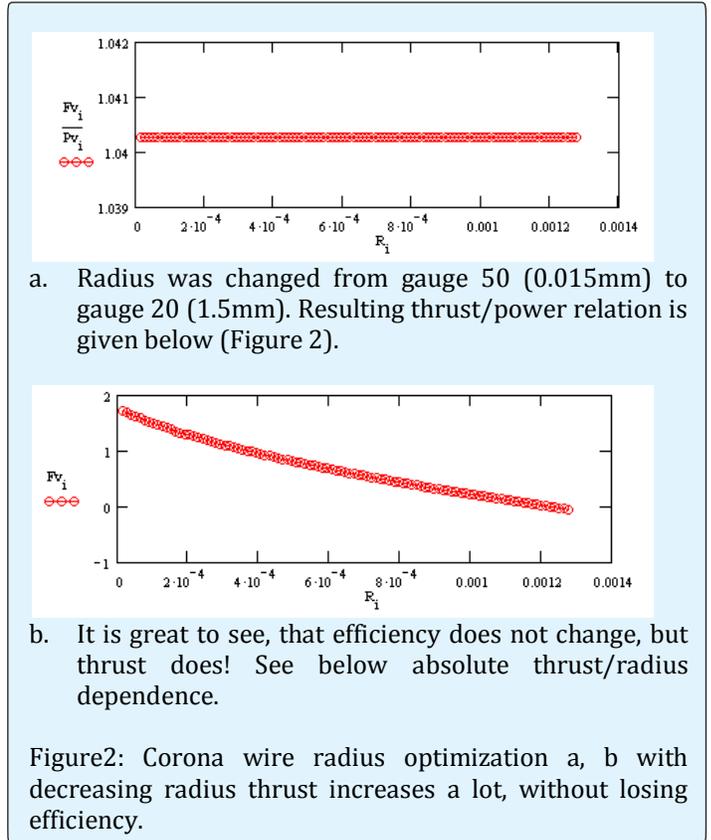
Lifter theory

Force/Power optimization
Thrust/current:

$$F = i \cdot \frac{d}{k}$$

Current/voltage

$$i = 2 \cdot \pi \cdot e0 \cdot V \cdot k \cdot L \cdot \frac{\left[V - 30 \cdot 10^3 \cdot volt \cdot delta \cdot \left(1 + 0.301 \cdot \sqrt{\frac{delta}{r \cdot cm^{-1}}} \right) \cdot r \cdot cm^{-1} \cdot \ln\left(\frac{d}{r}\right) \right]}{\left(d^2 \cdot \ln\left(\frac{f\_geo2(d)}{r}\right) \right)}$$

Corona wire radius optimization

a. Radius was changed from gauge 50 (0.015mm) to gauge 20 (1.5mm). Resulting thrust/power relation is given below (Figure 2).

b. It is great to see, that efficiency does not change, but thrust does! See below absolute thrust/radius dependence.

Figure2: Corona wire radius optimization a, b with decreasing radius thrust increases a lot, without losing efficiency.

Conclusion

- Increasing the wire/collector distance by simultaneous increase of wire/collector length can allow to achieve thrust/power ratios up to 40g/W.
- Decreasing wire radius increases thrust without degrading thrust/power ratio [3].

We can give a heuristic argument for why very small diameter wires might be effective. You need high ionization of the air to get high thrust, though below the breakdown voltage. Sharp points are known to more easily create corona discharge, i.e., at a lower voltage and also more intense ones for the same voltage: Corona discharge [4].

When the potential gradient (electric field) is large enough at a point in the fluid, the fluid at that point ionizes and it becomes conductive. If a charged object has a sharp point, the electric field strength around that point will be much higher than elsewhere. Air near the electrode can become ionized (partially conductive), while regions more distant do not. When the air near the point becomes conductive, it has the effect of increasing the apparent size of the conductor. Since the new conductive region is less sharp, the ionization may not extend past this local region. Outside this region of ionization and conductivity, the charged particles slowly find their way to an oppositely charged object and are neutralized (Figure 3).
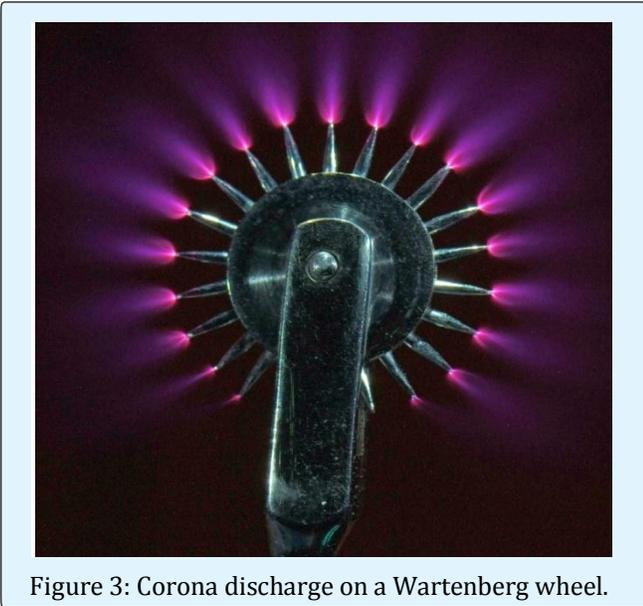

Figure 3: Corona discharge on a Wartenberg wheel.

The same is also true for very thin wires, a fact well-known to electrical engineers by Peek's Law [5]. Then for very small diameter wires you might need much smaller voltage to get the air ionization effect. In fact, it might only be in the hundreds of volts range, instead of tens of thousands volts as used now. You could then also have a shorter gap between the emitter and collector, resulting in a smaller craft. And not needing such high voltage would result in a smaller, simpler, lighter power supply. Indeed the largest weight for the ionocraft made so far is the weight of the iron-cored transformers needed in the power supply to increase the voltage to the 20,000 to 40,000 volt range. It would therefore result in a great reduction in the total weight if there were no transformer needed at all. So for ultra thin wires such as nanotubes would the same thing be true? A key fact is it has already been confirmed for nanotubes used as field-emitters in regards to their sharp points, [6]. Some researchers in

experiments with electrohydrodynamic devices have also taken to using sharp pins as the emitter instead of a long wire (discussed below).

But the fact that the intense ionization effect has been confirmed for the nanotube sharp points strongly implies this will also be true in regards to ultra thin wires such as nanotubes. From that, you draw the conclusion the force produced using nanowires, i.e., wires at the nanoscale, would be enough to lift the raise the lifters and their power supplies. For the equation showing the thrust for the lifters is simply:

$$F = i*d/k, [2,7] \qquad \text{Equation 1}$$

i the current, d the distance between the emitter and collector, and k constant for air known as ion mobility, $k=2*10^{-4}$ m^2/(volt*sec) at STP, with all variables in MKS units.

Therefore the thrust to electrical power ratio is $F/P = F/(i*V) = d/(k*V)$ Equation 2

So you see if you can get V small, you can get high thrust to power ratio. Then since the lifter itself consists of thin wires and lightweight foil, the power supply is the primary weight of the system, and we can consider the voltage required to be a proxy for the weight of the power supply.

You can't just arbitrarily set V small though. V has to be of a size to initiate corona discharge, i.e., ionization, around the wire. Then that's the key point: with wires at the nanoscale Peek's law suggests, and experiments with nanotube sharp point emitters imply, that you can get ionization at just a few hundred volts, a hundred times smaller than with the voltages used now, which thus would correspond to thrust/power ratio's a hundred times higher than those attained now.

But that's not the entire story. It turns out the maximum thrust for a given wire radius is dependent on the distance d. If we kept the distance d the same when we switched to nanoscale wires as for the current lifters of a few centimeters part, then the thrust would be reduced greatly. Quite likely we could get sufficient thrust for a practical vehicle by using billions of the nanowires, but we would want to avoid that if possible for simplicity and cost. Also we would want to especially avoid that if we are just in the testing phase to validate theory. So we'll take a look at the actual formula for the thrust to see how

we can optimize the distance d for thrust for the nanoscale wires.

We'll use the formula in [8] as it is somewhat simpler than the above Evgenij Barsoukov formula:

$$F = 4.792\pi\epsilon_0 l \frac{V_0}{b} \left(\frac{V_0}{1.011 \ln(b/a) + 1.3035} - 3 \times 10^6 \left(a + .03\sqrt{a} \right) \right)$$

where ϵ_0 is the permittivity of the vacuum $8.85*10^{-12}$ F/m, b is used here for the distance between the emitter and collector, V is voltage, l is the length, and a is the wire radius.

We did some estimates on the thrust using an online graphing program, https://www.desmos.com/calculator. This is useful since it allows you to vary some parameters while graphing in terms of another variable. So we used the distance b and the voltage V as the varying parameters and graphed thrust in terms of the radius r, keeping the length l fixed at 1 meter (Figure 4).
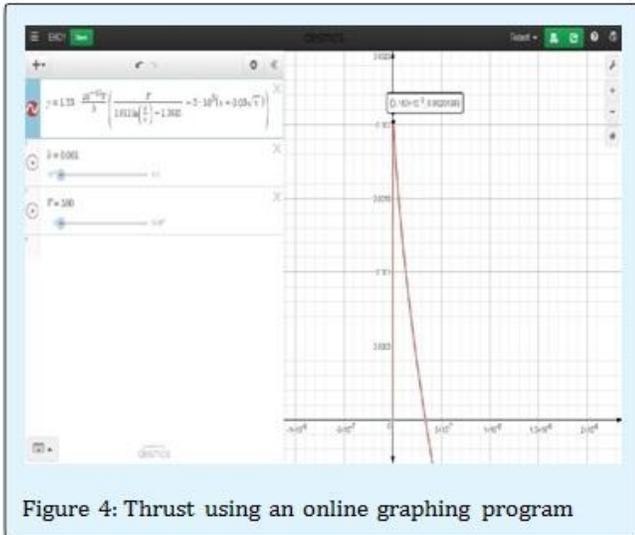

Figure 4: Thrust using an online graphing program

We found when we used the distance b in the range of millimeters and V in the hundreds of volts range, we got thrust in the millinewton range, with power usage at tenths of a watt. This thrust is small but because the thrust/power ratio is still good, you could add together several of these lifters to get significant lift capacity, while still not using very high power. Note because the size of the radius r and distance b are so small very many of these lifters could be added together and while still having a manageable size.

Reducing the distance between emitter and collector to the millimeter range from the centimeter range used now means the improvement in the thrust/power ratio would only be by a factor of 10 instead of a factor of 100, as is apparent from the formula for thrust/power in eq. 2. However, not needing the high voltage power supply requiring a heavy iron-cored transformer, means there would be a great reduction in the weight of the total system, making it much easier to get an independently flying vehicle. To get an idea how much the weight of the high voltage power supply adds to the total system weight, see here (Figures 5 & 6).

Figure 5: The Lifter is able to have a stable hovering with only +23 KV DC and 288uA (6.6 Watts) [9].
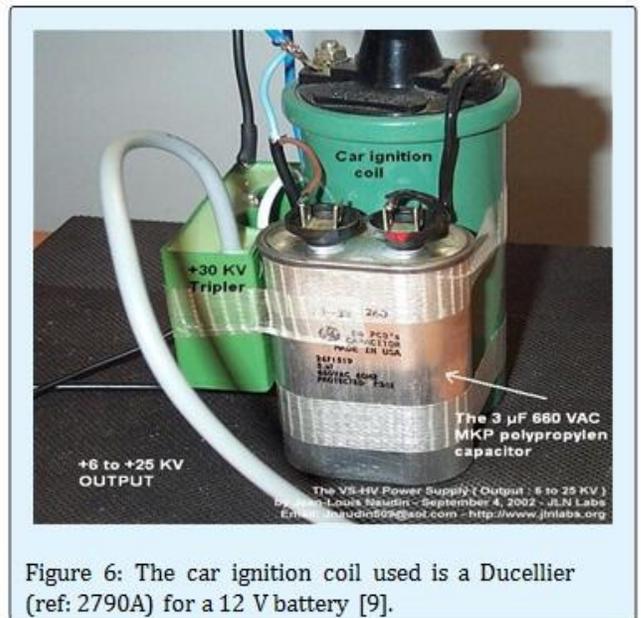

Figure 6: The car ignition coil used is a Ducellier (ref: 2790A) for a 12 V battery [9].

It's apparent the power supply weighs significantly more than the lifter itself which might only be a few grams in this case. Another interesting thing we discovered from the graph is at one place it blows up to infinity. This occurs where the denominator becomes 0. This was puzzling at first but noticeably it's where the distance b is comparable in size to the wire radius b, whereas normally b is hundreds of times larger.

So likely this is reflecting the fact that there is an ionization region around the wire and if the collector is too close to the wire it is essentially in this ionization region, i.e., the corona, and it is like the air has undergone breakdown. But even though the equations say you have infinite current and thrust there, actually, like breakdown, you get very high current flow but actually the thrust disappears.

An interesting question though of what happens when b gets close to this distance but not actually in the area of the corona? Would the thrust get very high there? This should be something that can be tested with the current lifters without having nanowires.

Producing Long Nanotubes

So the question becomes can we make nanotubes of arbitrarily long lengths? Note it has already been proven by Rice University researchers the nanotubes when tied together can conduct electricity better than the metal wires now in use [10,11] (Figure 7).
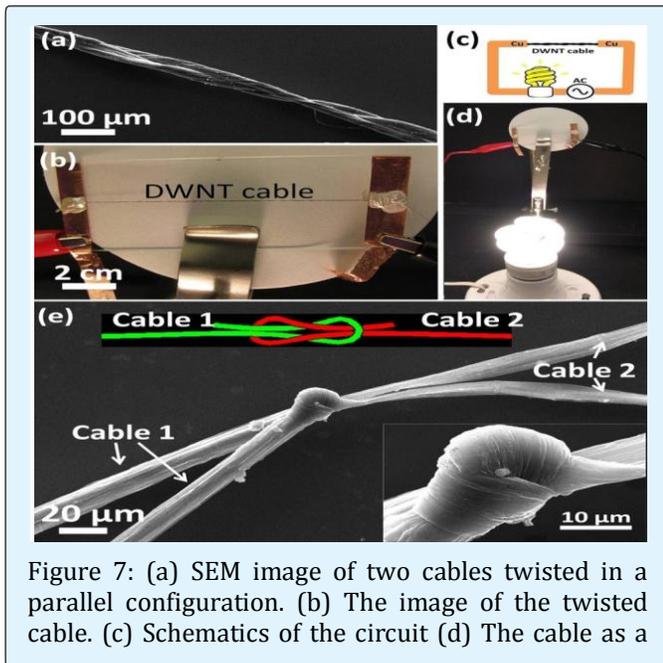

Figure 7: (a) SEM image of two cables twisted in a parallel configuration. (b) The image of the twisted cable. (c) Schematics of the circuit (d) The cable as a

segment of conductive media connected with the household power supply and loaded with a light bulb (9 watts, 0.15 A, 120 V). (e) SEM images shows that cable 1 and 2 can be knotted and joined. Inset is a higher magnification SEM image of the tie [11].

The article describes research by scientists at Rice University who created lightweight electrical cables by mechanically tying together nanotubes. In their research the Rice scientists also tested the strength of these tied together nanotubes and found them to be of comparable strength to the aluminum or copper wires now used but at lighter weight.

Then the only thing needed now is to confirm experimentally the validity of the modeled thrust of the lifters that nanoscale wires can produce EHD thrust sufficient to lift the craft and its power supply.

The Nanomanipulator™ that can manipulate objects at the nanoscale will be used to produce an ionocraft with wires consisting of nanotubes tied together (Figure 8).

Figure 8: The Nanomanipulator™.

Actually you don't need nanotubes to confirm the theory. It can be confirmed by using any nanowires, such as used in microelectronics for example. Carbon

nanotubes are lighter and can carry more current, but so far as confirming the theory it likely could be confirmed by metal nanowires.

Note that using nanotubes for the wires would be trebly more efficient than the thicker metal wires currently used. First, their extremely small diameters should significantly increase the thrust. Second, their small weight compared to metal wires should greatly reduce the weight and third, their increased conductivity, i.e., reduced resistance, means less power would be required to achieve the same result which means a smaller, lighter power supply, further reducing the weight of the craft.

Putting these factors together means there's a very good chance we can finally get an independently flying lifter able to carry its own power supply. Note this would also work to get a real, i.e., hovering, hover board (Back to the Future II would only have been off by 1 year, [12] and personal jetpacks. Note also it makes the U.S. Army's billion dollar V-22 Osprey, [13] obsolete before being fully deployed.

The equations though show the higher thrust should arise for any wires at the nanoscale not just for carbon nanotubes, though the carbon nanotubes may be able to carry more current. Note also this can be used with nanowires or nanotubes in other applications to increase the thrust or force produced by ionic wind flow, such as proposed for use on aircraft to improve laminar air flow or electrophoresis or dielectrophoresis devices for particle or molecule separation.

Increased Air Pressure Increases Thrust

The equations for the ionic wind thrust also show that the thrust should be higher at higher pressures, which has been confirmed experimentally. However, not only that but in fact the thrust to power efficiency also increases at higher pressures. This should not be surprising since that is also the case for example with jet engine propulsion, which is why compressors are used after the intakes of jet engines. In fact typically 2/3rds of the power generated by a jet engine goes just to run the compressors.

What is a Gas Turbine Engine and How Does it Work? The turbine drives the compressor via a fixed shaft, and the cycle is complete and self sustaining. The cycle that governs the operation of a gas turbine engine is referred to as the Brayton constant pressure cycle. The engine compressor typically requires about 2/3 of the usable

heat energy produced in the burner to turn at maximum speed; the remaining energy can then be used to produce thrust or mechanical power, or a combination of the two[14].

Remarkably a recent analysis found that actually the thrust to power ratio for the ionocraft is higher than for jet engines [15,16]. This is surprising considering the low thrust of the ionocraft.

MIT researchers study electro-hydrodynamic thrust. In the '60s, the ionocraft seemed like a revolution in aviation. There was talk about them being used in all sorts of small aircraft, and the military were interested because ionocraft give off no heat, so there's no infrared signature. Ionocraft were seen as replacing helicopters, as silent commuter ferries, as craft capable of operating at the edge of space, as traffic monitors or anti-missile platforms. The problem was, the technology didn't scale very well. What worked for a small model that was built like a kite didn't do at all well as the ionocraft got bigger. It couldn't even carry its own power supply, so it wasn't long before ionic thrusters became the denizens of science fairs and the obsession of anti-gravity cultists.

Where MIT came in was at the point that the researchers realized that very few rigorous studies of ionic wind as a viable propulsion system had ever been carried out, and exactly what the ionic thruster is capable of hadn't been measured. So, they devised a test where an ionocraft was hung under a digital scale and tens of thousands of volts with enough amperage to run a light bulb were run through the craft.

The results were surprising. The team discovered that the ionic thruster turned out to be remarkably efficient compared to, for example, jet engines. Where a jet produces two newtons of thrust per kilowatt, the ionic thruster punched out 110 newtons per kilowatt. Furthermore, the thruster was most efficient at low thrust, which meant that power wasn't being wasted. [15] Then increasing the pressure of the air before applying the ionic wind thruster *should* improve this thrust/power even further.

However, the calculations that say thrust to power for the lifters should improve at high pressure are simply taking the air as already pressurized when presented to the lifter. That is, none of the power is being used to drive compressors. More careful analysis that considers the power requirements needed to pressurize the air needs to be made before it can be said this offers an improvement on the performance. Still, because the lifters are 50 times

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better than jet engines without even being pressurized, it is likely pressurization will help to provide sufficient thrust for liftoff while still remaining better than jet engines in thrust to power ratio.

So additionally this proposal will cover methods suggested here of producing high pressures with the ionic wind propulsion. A problem with the jet engine compressors is their high weight which severely reduces a jet engines thrust/weight ratio, compared to rocket engines for example. But the weight issue is an even more important problem for ionic wind devices. One suggested method to get the compression at lightweight would be to use for example carbon fiber piston within a carbon fiber cylinder.

Other possibilities in keeping with nanotechnology would be to use recently discovered carbon nanotube "rubber". This is stretchable yet has high strength and temperature resistance.

Still another possibility would also be in keeping with the nanotechnology theme. The compression due to centrifugal compressors is due to air being forced against the wall due to the acceleration measured by a = v^2/r. Normally, the high acceleration comes from high velocity. But it can also come from the radius r being at the microscale or nanoscale even using low velocities, v.

Then another proposal here would be use multiple microscale or nanoscale cylinders with the air being circulated within them by the ionic wind devices. This creates high pressure on exit. Then use ionic wind devices *again* on this high pressure air, resulting in increased speed, once more. Then this process can be repeated in stages at each time increasing the pressure and therefore the speed and thrust.

Single Electrode Operation

The classical lifter design uses an emitter wire and a collector plate. However, it has been known for many years you can get thrust using an emitter only known as a "corona wheel" or "corona pinwheel" (Figure 9).
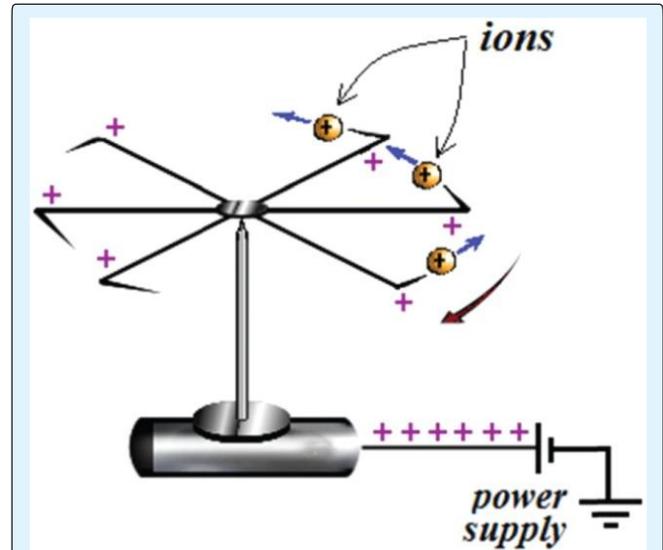

Figure 9: The electrostatic pinwheel rotates as result of the ions created by the corona effects being repelled away from the needle-like points [17].
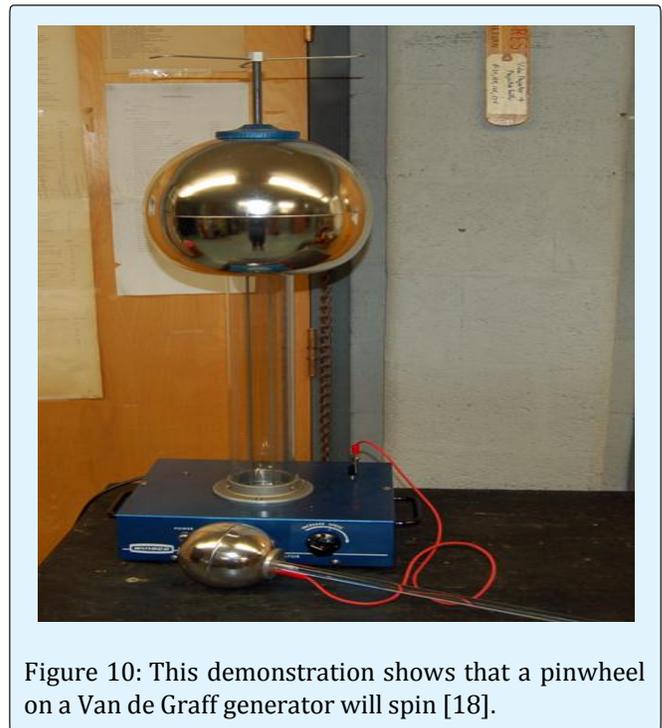
5B30.50: Electrostatic pinwheel (Figure 10).

Figure 10: This demonstration shows that a pinwheel on a Van de Graff generator will spin [18].

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It is also known you can get an intense corona discharge around sharp points. This report compared the thrust between this single electrode approach and the dual electrode approach and found for low voltages the thrust is comparable, at least for AC, though the dual electrode approach has the significant advantage for high voltage:

ON THE THRUST OF A SINGLE ELECTRODE ELECTROHYDRODYNAMIC THRUSTER [19] (Figure 11).
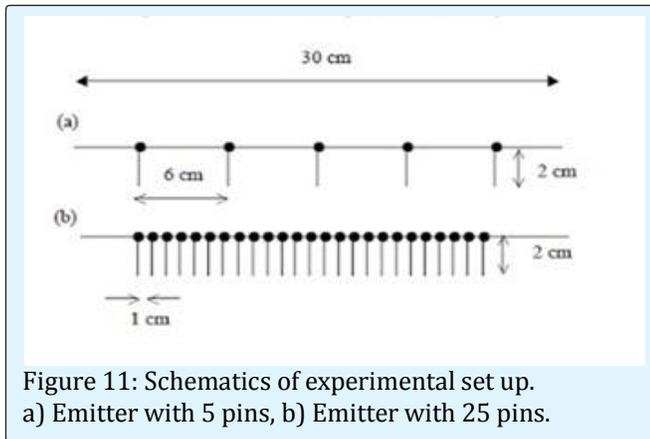

Figure 11: Schematics of experimental set up.
a) Emitter with 5 pins, b) Emitter with 25 pins.

The idea of using sharp points for the emitter might be especially useful for carbon nanotubes used as the emitter. Then since the flat collector plate makes up the majority of the weight for the lifter, removing that and using the emitter only would save significantly on the weight. This becomes especially important with the nanotubes used as the emitters because of their ultra low weight. Another report was able to increase the thrust using solid plates rather than aluminum for the collector [20].

The researchers noticed the there was vibration with the aluminum foil lifters. They reasoned this may detract from the thrust since some of the energy of the moving air molecules would go to causing the collector vibration rather providing thrust.

They were able to get higher thrust using the solid plates. However, the plates were so heavy the lifter could not then liftoff. To get lightweight but stiff plates perhaps we could use graphene as the collector material. Presumably as with nanotubes there would be versions of the graphene that is conducting.

Graphene would have usefulness besides just the collector plates however. Graphene is composed of strings of individual carbon atoms, and just as with nanotubes it has been shown to have large current carrying capacity. In relation to this application though they have been shown to also create ionization through much lower voltages. Since the graphene would also have very many nanowires, which would be needed to produce thrust at practical levels, they would also have this automatically as an advantage for demonstrating the principle for a practical sized craft [21].

Space Applications

A non-propellant method of satellite station-keeping being investigated now is the "electrodynamic tether". One version uses a conducting tether and produces thrust by acting against the planets magnetic field. However, another version acts in an analogous process to the ionic wind devices. The advantage of the space version though is that it is operating through already ionized air. So the amount of power that is needed to ionize the air is eliminated. For this version as well using carbon nanotubes for the tether can significantly improve the thrust. Ion drive and plasma drive thrusters also work on a similar principle to the ionic wind devices. Then they also should have improved thrust using carbon nanotubes for their ion inducing wires. Then this could improve the thrust/weight ratio for these thrusters given better performance both for unmanned and manned space drives.

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