Ion Discharge Cooling Device

by

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Abstract

This paper discusses ion wind based on corona discharge. Ion wind generated by corona discharge voltage and an electric field can be used as a cooling device to replace a ventilation fan. Like some prior works done by others, the device is mainly composed of thin wires and blunt brass bars. The wind velocity can reach a value of 1 m/s under 3000 volts. In this report, the relationships between velocity and many parameters have been determined.

Keywords: Corona discharge, ion wind, electric field, negative discharge

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Introduction:

The energy consumption of electronic devices such as laptops is mostly transferred as heat, requiring cooling systems to ensure their normal operation. Fans are the most popular method of generating air-flow. This method is efficient and cheap. However, using fans has many disadvantages, such as noise, and their large sizes. The noise can be up to 55 dB. In addition, a whole device may vibrate because of the rotations of a fan's blades. These disadvantages can be eliminated by applying the ion discharge cooling device.

The ion discharge cooling device is based on the principle of corona discharge into air. Many studies have been conducted to prove this concept is valid. There are two main types of structural design. One is a pin-to-plates design, which means a device is combined with a sharp pin as a corona electrode and two blunt plates as collecting electrodes [2]. The ion wind is generated between the two electrodes and flows through the space between the two plates. The other is a wires-to-bars design [1], which means a device is combined with several thin wires as corona electrodes and several contoured metal bars as collecting electrodes. The ion wind is generated between the wires and contoured metal bars, and it flows across the gaps between each metal bar.

Theoretical background:

1. Corona discharge

Corona discharge is a part of the Townsend dark discharge. As the voltage increases in an insulated system, molecules in the gas can be ionized in the region of a high electric field around sharp points, edges or wires where the electrical field strength is higher than other areas and more charges are generated. Corona discharge is invisible at first. When the voltage reaches the breakdown voltage, the current starts to increase dramatically with the increase of voltage. Then, corona discharge becomes visible to the eye.

2. Ion wind generating process

When a continuously increasing voltage beginning from 0V is applied between two electrodes, the current at low voltage can hardly be detected by a current meter with a resolution of 0.01 μA. As the voltage becomes high enough to reach the threshold voltage, molecules are ionized around the sharp point of an anode, and the positive ions are accelerated by the electric field formed across the anode and cathode. The reason why ionization happens around a sharp point is that the electric field strength is much higher there than other parts of the anode. The corona discharge occurs when the potential gradient is high enough for a certain structure and environment. Therefore, the anodes used for corona discharges are usually sharp tips or thin wires. In the process of ion

transportation, the moving ions and neutral molecules collide with each other, causing a momentum exchange. Meanwhile, some of the molecules are also ionized by these fast moving electrons to form new ions and electrons. The phenomenon of thousands of collisions between electrons and molecules is like an avalanche. In addition, the rapid ion movement from anodes to cathodes results in low pressure, which causes ambient air-flow.
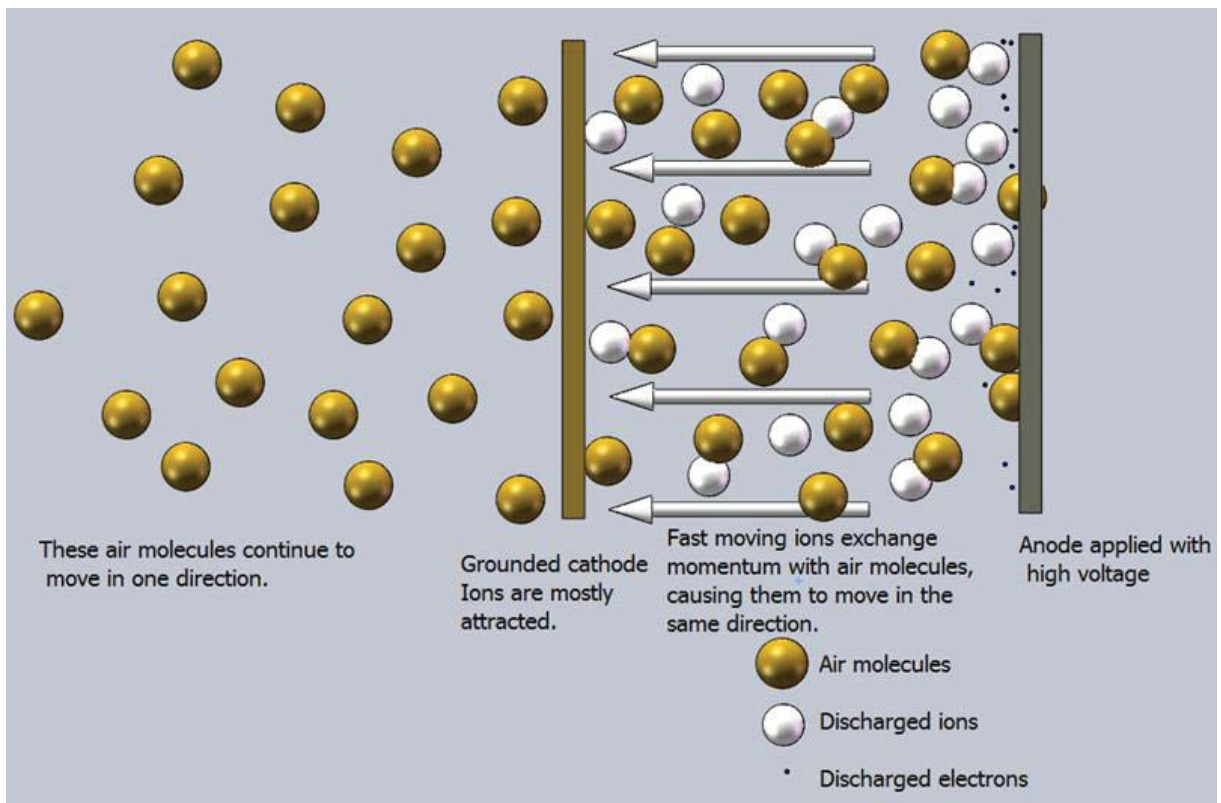

Figure 1. The theoretical ion wind generating process.

Several parameters are involved in corona discharge. The first one is onset voltage. The equation of onset corona discharge voltage for a wire-to-cylinder structure is described as Peek's Law which states:

$$V_c = m_v g_0 \delta r (1 + \frac{c}{\sqrt{\delta r}}) \ln(\frac{d}{r}),$$

where m_v is an irregularity factor to account for the condition of a wire surface, g_0 is the disruptive electric field, δ is the air density factor with respect to standard conditions for pressure and temperature, r is the radius of the anode wire, and d is the distance between the anode and the cathode. This equation suggests that a larger distance between electrodes requires higher voltage to operate corona discharge.

Another parameter is the ratio of wire radius and distance between electrodes. In a conventional corona wind system, the ratio is required to be less than 1:6 [3][6]. If the system operation is taken into consideration, the ratio needs to be decreased as the gap decreases.

3. Ion wind generator structure

In order to enhance the efficiency of ion discharge, a semi-cylindrical structure is used. As shown in Figure 2, the area of wires to cathode bars is maximized by this structure. The air molecules around the wires are discharged to form ions and electrons. Between the wires and cathodes, a strong electrical field causes the acceleration of ions. When the ions are propelled by the electrical field, there is a momentum component in the direction

of X axis. However, these will cancel each other out, which makes the main direction of air-flow in the negative Y axis.
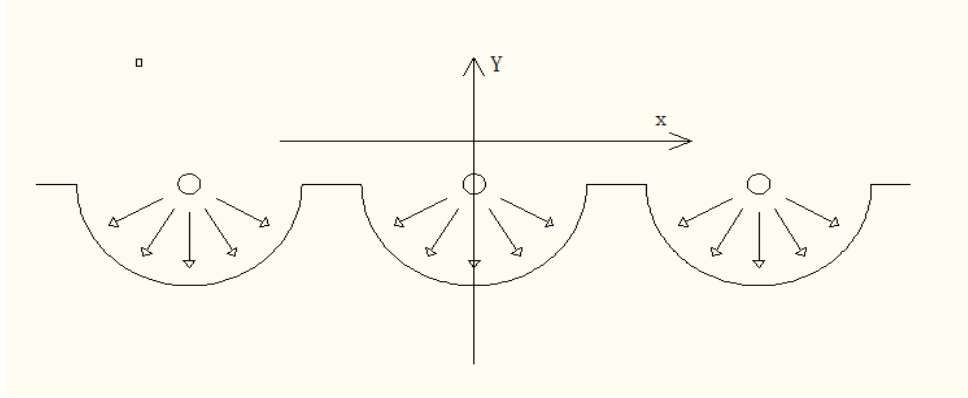

Figure 2. Sectional view of semi-circle cathodes and tungsten wire anodes.

4. Metal Oxidization

In the process of corona discharge, high voltage is applied on an anode, which means an anode is easily oxidized, especially in cases where electrode is exposed to air. Therefore, the material chosen for an anode should be unreactive. Platinum, gold and tungsten are suitable candidate materials.

Experimental design and setup:

In this study, the wires-to-bars structure was selected. To ensure that the cathodes are large enough to collect the ions, and the moving air molecules can pass by the cathodes

after the collisions with ions, the size of grounded cathodes needs to be taken in-to consideration. The following figure shows the size of the brass bars chosen in case 1.
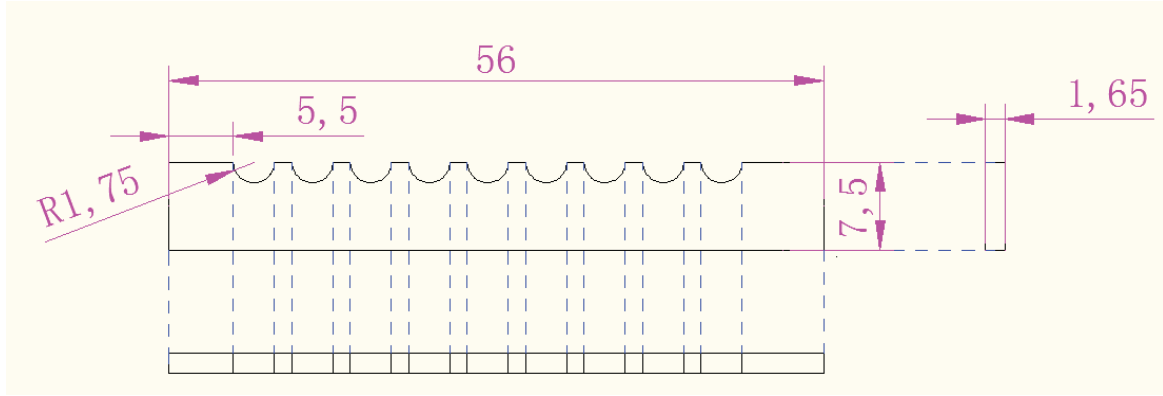

Figure 3. Design drawing of the cathodes for case 1 (units in mm).

Seven brass bars were machined from raw materials. They were inserted in a yellow plastic set made by a 3D printer, with all the corresponding centers of the circles in the same lines. In this study, 50 um diameter tungsten wires were chosen to be the anodes. Two PCB boards were cut to the size such that one row of pinholes was 7.5 mm from the bottom so that the tungsten wires were aligned at the center of the semi-cylindrical cathodes. The following figure shows the 3D model of the device, but with the circuit not included.
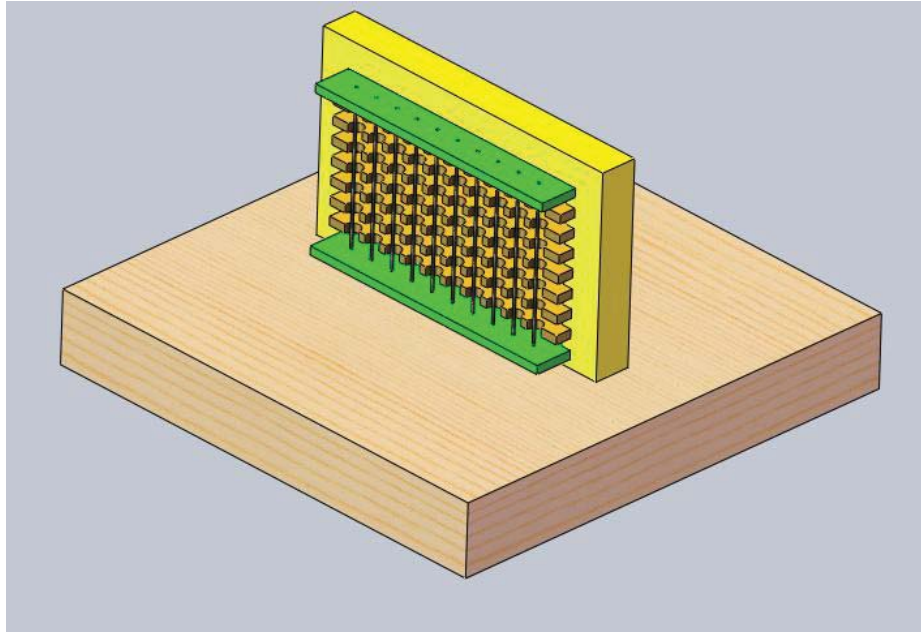
Figure 4. Design drawing of the assembly device.

Although theoretically the diameters of each tungsten wire are all the same, in reality they cannot be exactly the same because of the surface and tightness. In addition, the brass bars were not exactly the same, and the wires were not aligned exactly at the center of the corresponding semi-circles after assembly. All these factors caused different onsets of corona voltages of each wire. When one of the tungsten wires reached the onset voltage, the discharge current in this branch would increase dramatically, producing a large voltage drop across the resistors in the front of this circuit, which lowered the voltage applied to the other tungsten wire and stopped them from reaching their onset voltage.

To prevent this phenomenon, parallel resistors (10 M ohm) were connected to the tungsten wires. In this case, when a wire started a discharge and the voltage kept increasing, most of the increased voltage would be added on the resistor in this branch so that all the branches would not affect each other. The resistors also play an important role in protecting the closed circuit.
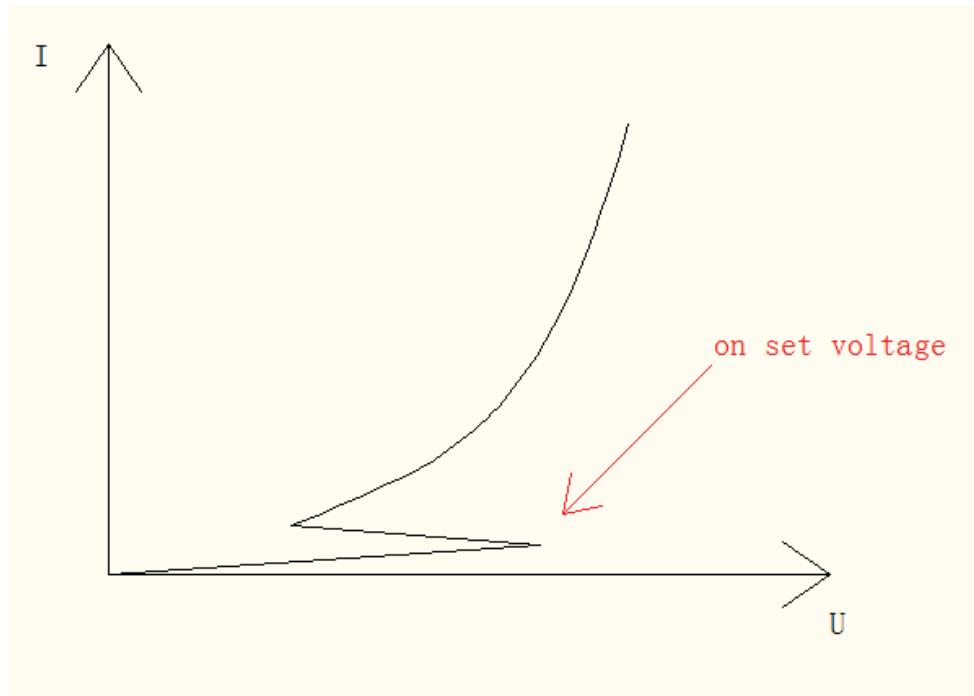

Figure 5. I-V curve of corona discharge.

In positive discharge, while the wires were applied with DC positive, the brass bars were always grounded. The current value was monitored by a multimeter(Tektronix TX1). The air-flow speed was measured by a Hot Wire Anemometer (GM8903), the sensor of which

was placed 3 cm away from the ion discharge cooling device. A lighted candle, at a distance of 3 cm away from the device, was also used to show the existence of the wind. The surrounding temperature was 25 degrees centigrade, and the air pressure was 760 torr.
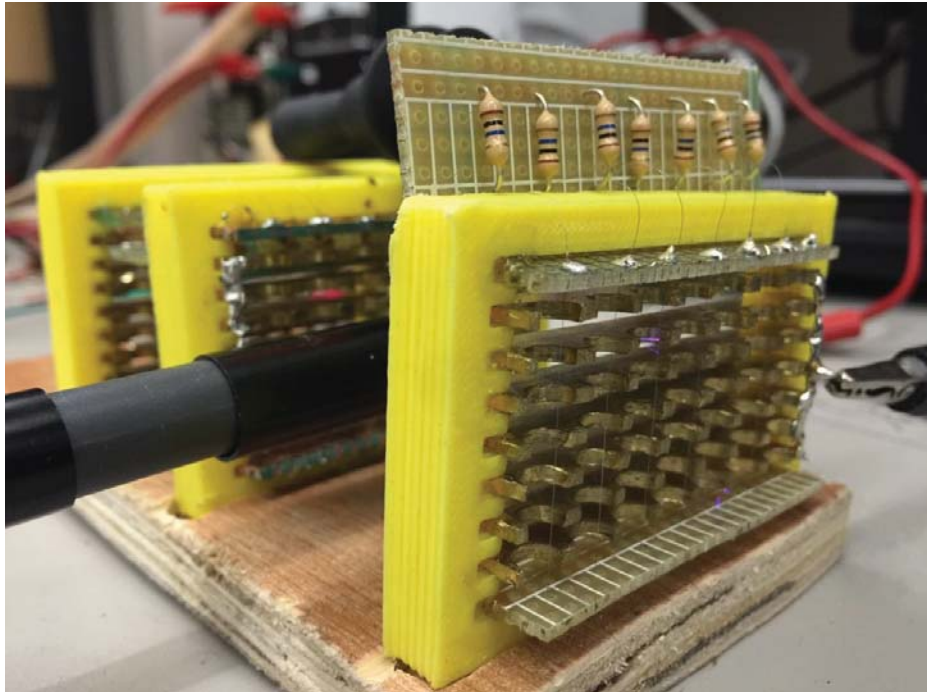

Figure 6. The real setup of the experiment in this study.

Results and Analysis:

Case 1,

The positive voltage applied on tungsten wires increased from 0 to 3.5 kV with a step of 0.2 kV. Seven wires in the middle were used in this case because in cases 2 and 3 the

number of tungsten wires that could be arranged was up to 7. The relationship between the voltage and the current for a single wire discharge is shown in Figure 7. As is shown in the graph, the onset discharge voltage was around 2.7 kV. When the voltage was lower than 2.7 kV, the current going through the circuit was negligible. When the voltage was continually increased after 2.7 kV was reached, the current started to increase dramatically. The current value became unstable (fluctuating between hundreds of μA and several mA) when the voltage was higher than 3.6 kV. Purple corona discharge glow could be seen between the electrodes. The smell of ozone was obvious. There were also some faint sounds when the voltage went even higher.
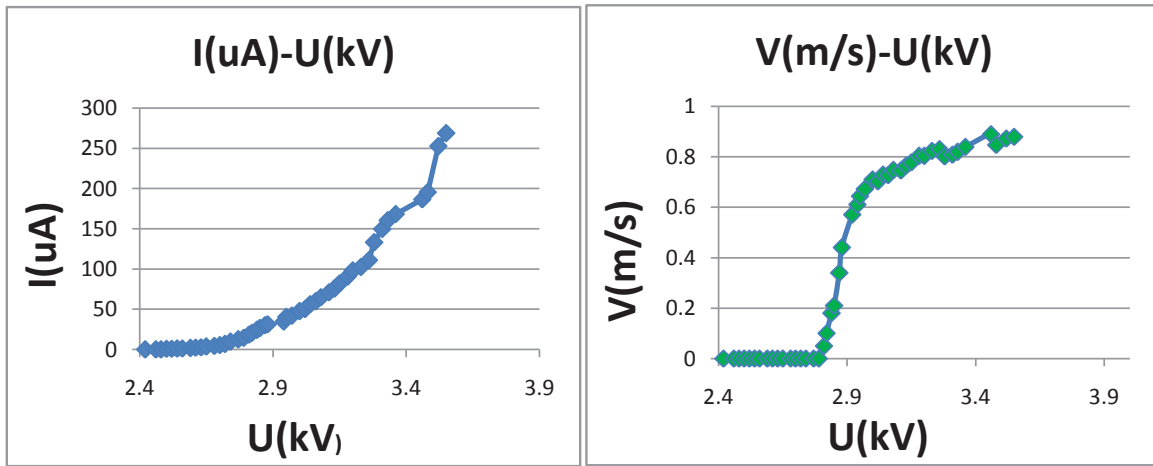

Figure 7. Graph of I-U curve for case 1 (left). Graph of V-U cruve for case 1.

According to Figure 7 that shows the relationships between wind velocity and voltage, and current and voltage, the velocity of ion wind starts to increase after the voltage became higher than onset voltage. In Figure 7, as the voltage increased from onset

voltage to about 3.0 kV, the velocity increased dramatically, but when the voltage became higher than 3.0 kV, the increase of velocity leveled off to a value of 0.9 m/s. The wind velocity could not go even higher than 0.9 m/s, even if the voltage continued to increase. Figure 8 shows that the velocity increased from 0 to 0.7 m/s when the current increased from 0 to 50μA. The curve is very steep. When the current was higher than 50 μA, the curve leveled off to almost a horizontal line. Figure 8 indicates that V-P velocity increased from 0 to 0.7m/s as the power changed from 0 to 0.15 W, but the velocity only changed from 0.7 m/s to 0.87 m/s when the power continued to be increased by 0.8 W.

Therefore, the performance of the ion wind discharge cooling device can be divided into three regions: the first region is the quiet region from 0 volt to 2.7 kV. In this region, the current is negligible and the velocity is too small to be detected. The second region is the high efficiency region from 2.7 kV to 3.0 kV. As the name implies, the current increases very fast as the voltage increases. "High efficiency" indicates that the rate of velocity increase to power is the highest among the three regions. The last region is the leveling off region from 3.0 kV to infinity. In this region, the slope of I-V gets smaller and smaller. The power efficiency becomes lower, which means the percentage of energy consumption that transfers to kinetic energy becomes smaller. The last region shows that there is a limitation for this ion discharge cooling device. The velocity cannot surpass 0.9 m/s. This could be due to the size of the device, in particular the distance between the

electrodes. When in the level off region, the current was increased as shown in Figure 8, which means more ions were generated and transferred from anode to cathode. Meanwhile, the ions could obtain more kinetic energy because of the increasing electric field. However, the gas between the wires and brass bars is limited. In this case, when the voltage was 3.6 kV, most of the molecules around the wires might be ionized and the avalanche effect reached its maximum level. In another word, the ion wind from this device reached a saturation point. Additionally, there was some energy waste caused by friction, because the ion wind had to pass between the brass bars.
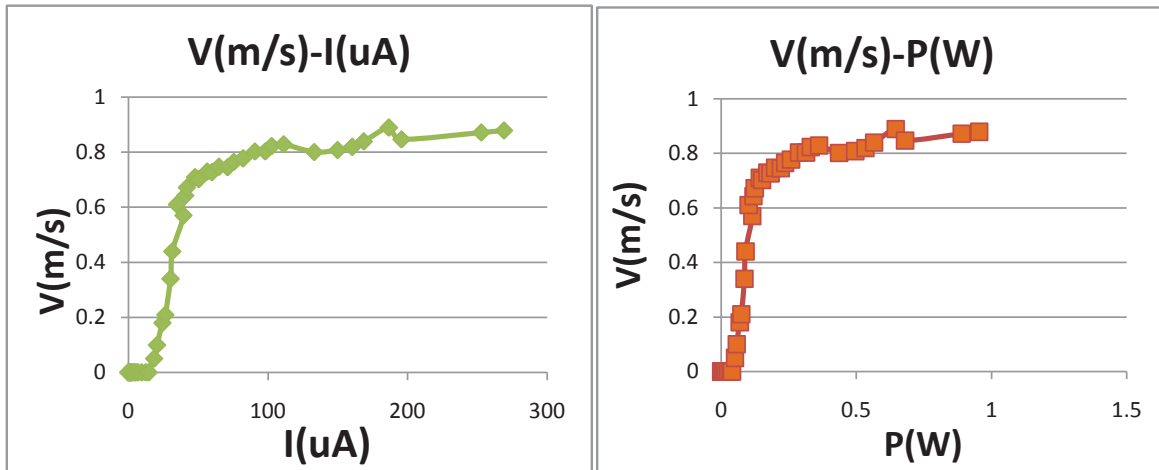

Figure 8. Graph of V-I curve for case 1(left). Graph of V-P curve for case 1.

Hypothesis:

If the distance between wires and brass bars becomes larger, the maximum wind velocity will be larger. Larger distance allows more gas molecules to be accelerated by discharged ions so that the avalanche can be more violent. Meanwhile, the onset voltage of corona

discharge is higher than it would be in a device with a smaller wire-to-bar gap due to the

Peek's Law equation.

Cases 2 and 3,

To prove the hypothesis, two other experiments were set up. The main difference was the

size of the semi-circle on the brass bars, 4.76 mm and 5.6 mm in diameter respectively.

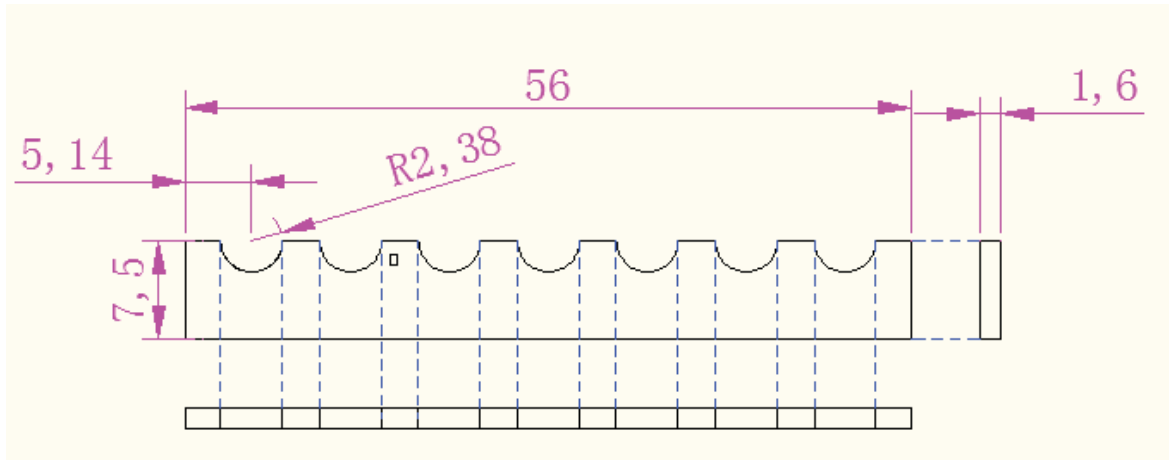The following were the part drawings

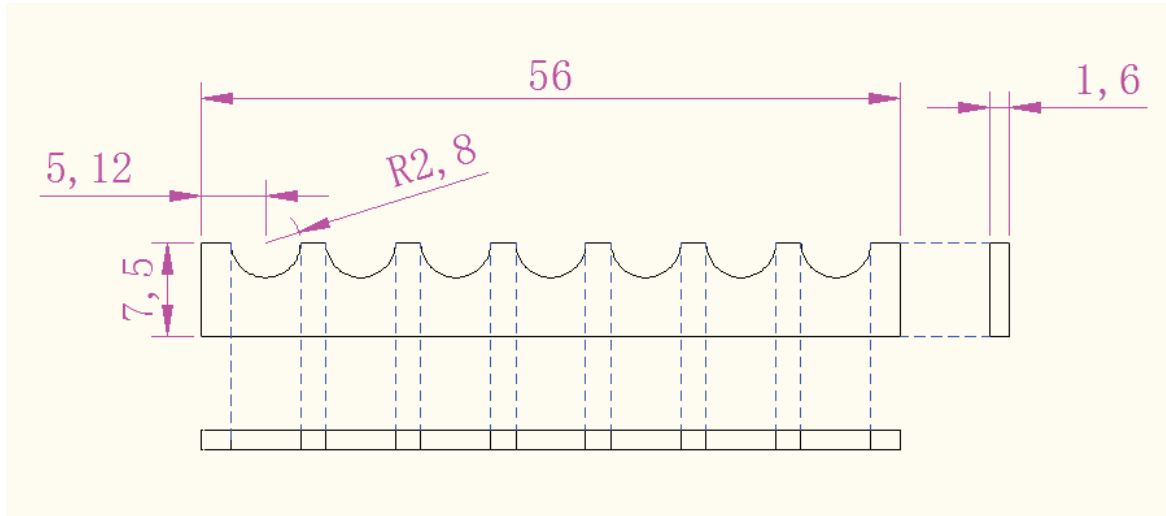Figure 9. Design drawing of the cathodes for case 2 (units in mm).

Figure 10. Design drawing of the cathodes for case 3 (units in mm).

Due to the limitation of existing materials, there were only 7 tungsten wires in these two devices. The resistors, diameter of tungsten wire and the outside structure were the same as the previous device.

To test their performances, positive voltage was applied on the anodes and increased from 0 to 3.8kV and 4.5 kV, respectively. The onset voltages for the 4.76mm device and for the 5.6mm device were 2.6 kV and 3 kV, respectively. It is hard to conclude that the onset voltage of an anode wire with a certain radius increases with the distance between electrodes. Theoretically, the onset voltage in case 2 should be between 2.7 kV and 3 kV. However, because of the inevitable inaccuracy from machining and assembly, there were some sharp points on the semi-circle cathodes, which sometimes caused sparks. Moreover, the tungsten wire cannot be aligned right at the center of each semi-circle.

Some tungsten wires in cases 2 and 3 may have been closer to the cathodes than those in
case 1. These might be the reasons for the unexpected result of the onset voltage in case 2.
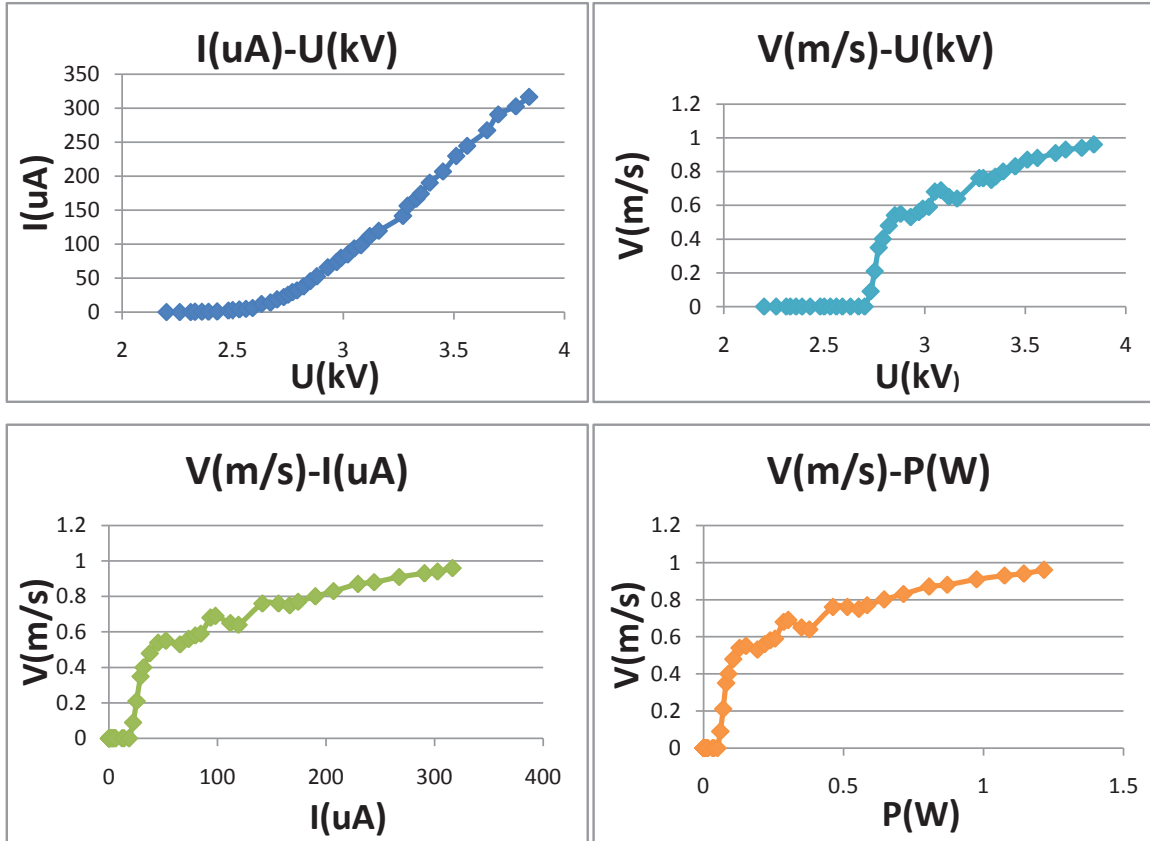Figure 11 and Figure 12 summarize the results.

Figure 11. Graph of I-U curve for case 2 (upper left). Graph of V-U curve for case 2 (upper right). Graph of V-I curve
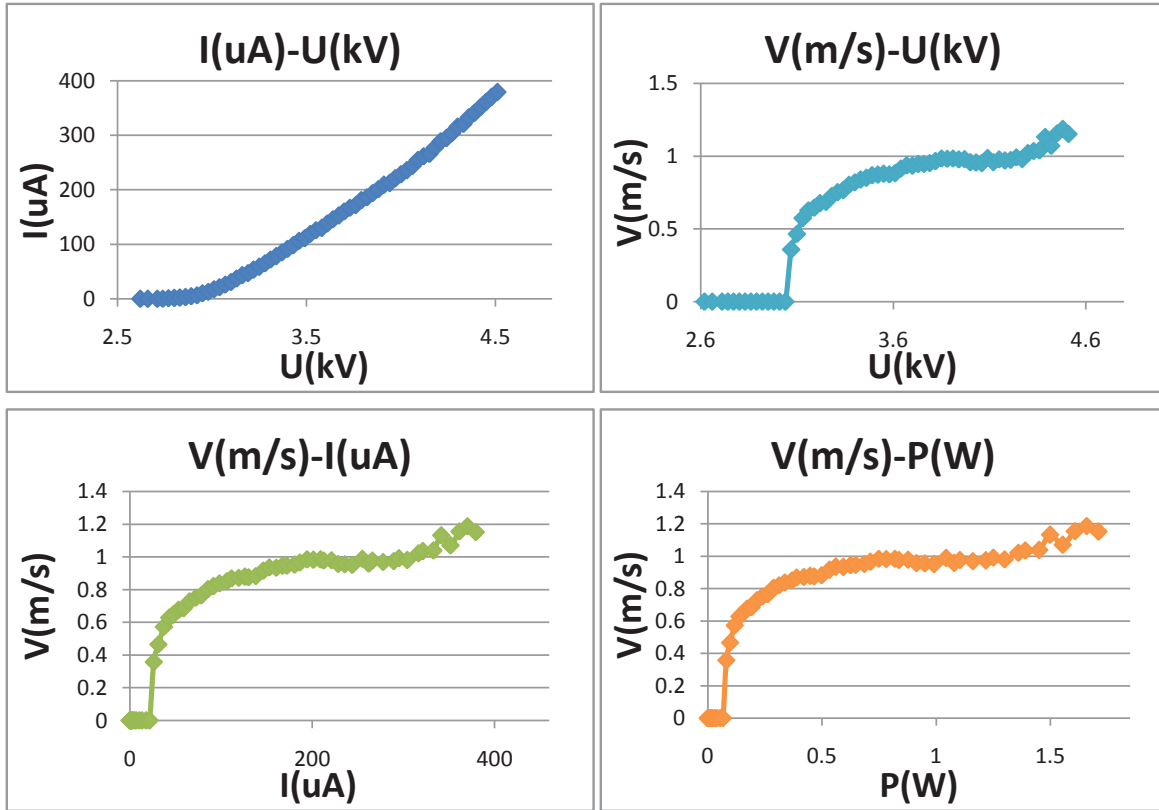for case 2 (down left). Graph of V-P curve for case 2 (down right).

Figure 12. Graph of I-U curve for case 3 (upper left). Graph of V-U curve for case 3 (upper right). Graph of V-I curve for case 3 (down left). Graph of V-P curve for case 3 (down right).

Being the same as the phenomenon in case 1, the ion wind was detected right after the voltage was higher than the onset voltage and the velocity increased dramatically at the beginning. The slope flattened out as the voltage kept increasing. The device that was 4.76 mm in diameter could reach a maximum velocity of 0.96 m/s, while the device that was 5.6 mm in diameter could reach a maximum velocity of 1.2 m/s. The radii in case 2 and case 3 were 36% and 59% larger than the radii in case 1, respectively, which means

the air volume was 84% and 152% larger, respectively, for a semi-cylinder. However, the air-flow speed was not proportional to the air volume.

Case 4. Negative discharge:

In this experiment, the wires were grounded, while the brass bars were applied with positive voltage increasing from 0 to around 2.8 kV, in which the relative wire-to-bar voltage was negative. The device was the same as the one in case 1. The following figures are the results.
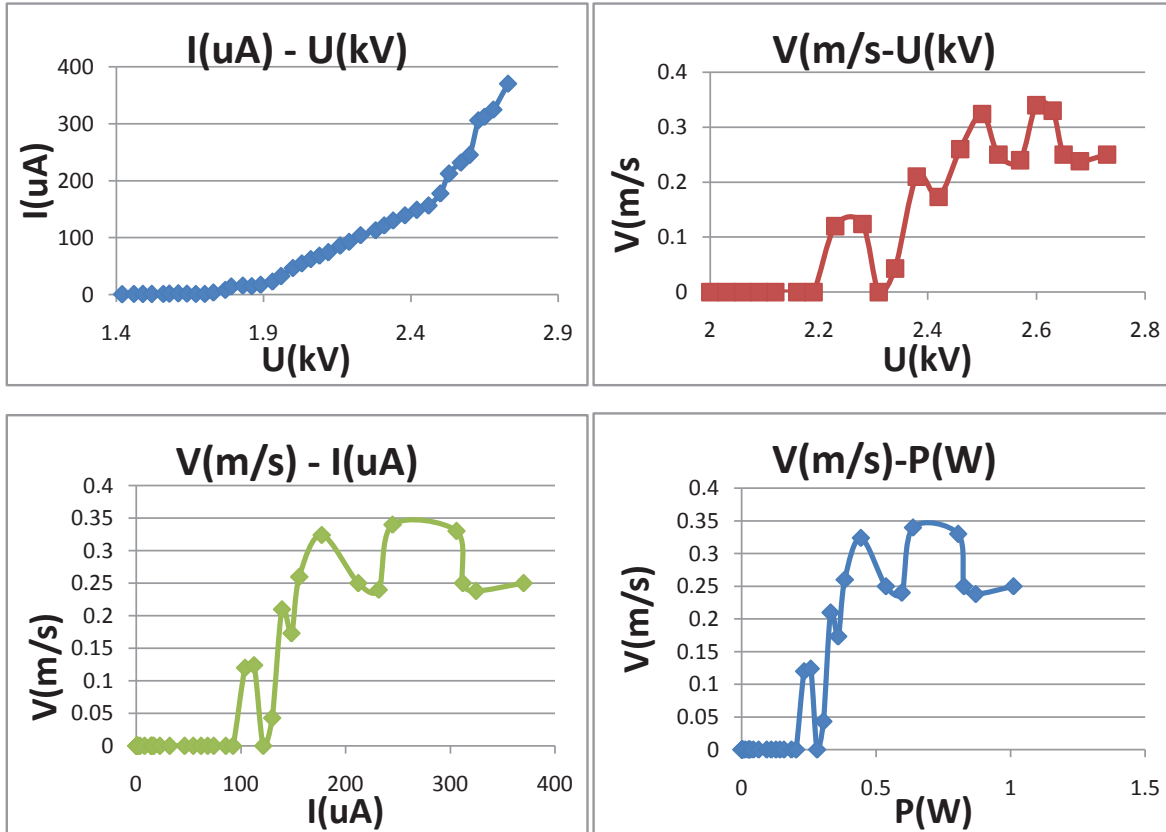

Figure 13. Graph of I-U curve for case 4 (upper left). Graph of V-U curve for case 4 (upper right). Graph of V-I curve for case 4 (down left). Graph of V-P curve for case 4 (down right).

According to Figure 13, the onset voltage was about 1.8 kV. This was 900 V lower than the positive discharge. When the current was 370 µA, the voltage was 2.7 kV. While in case 1, the corresponding voltage was 3.6 kV. The maximum wind velocity in this case was less than 0.35 m/s, which is less than half of the positive case.

Case 5,

This experiment aimed to show the effect of diameter of anodes on onset voltage and ion wind velocity. Due to the limitation of existing materials, 150 um in diameter brass wire was used as anodes. To control for variables, the brass bars used in case 2 were chosen to be the cathodes.

Figure 14 shows the maximum wind velocity in this case was also about 1 m/s. The onset voltage was about 3.7 kV, 1.1 kV higher than the onset voltage in case 2. Compared with the distance between electrodes (2.38 mm), the difference in radius (25 µA – 75 µA) is negligible, which means the distances between the electrodes in case 2 and case 5 can be considered to be the same. Anodes with smaller curvature seem to have higher onset voltage.
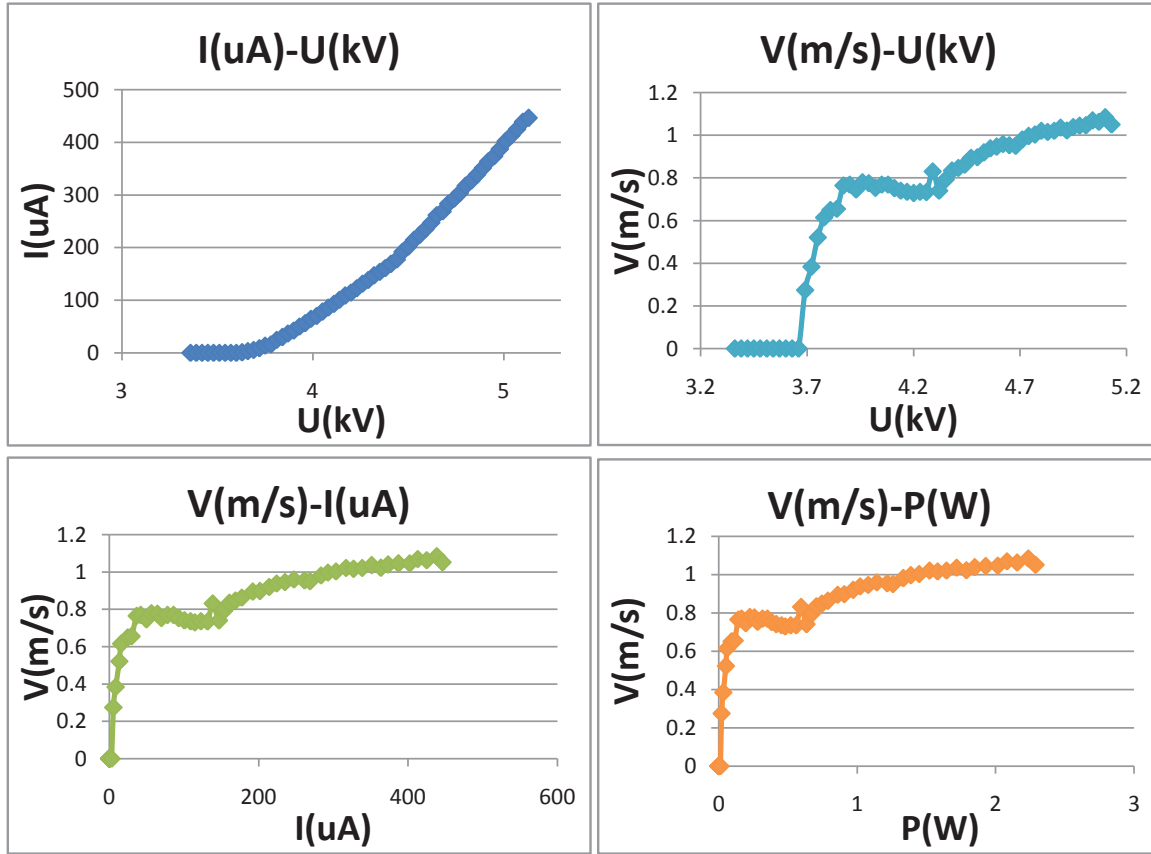
Figure 14. Graph of I-U curve for case 5 (upper left). Graph of V-U curve for case 5 (upper right). Graph of V-I curve for case 5 (down left). Graph of V-P curve for case 5 (down right).

Efficiency:

To optimize the performance and study the efficiency of the ion discharge cooling device, the parameter V*Area/Power is an important index. This parameter defines the air-flow volume per second in unit power. In this study, V*Area/Power is equal to the average wind velocity multiplied by the inner area of the yellow frame and divided by the corresponding power.
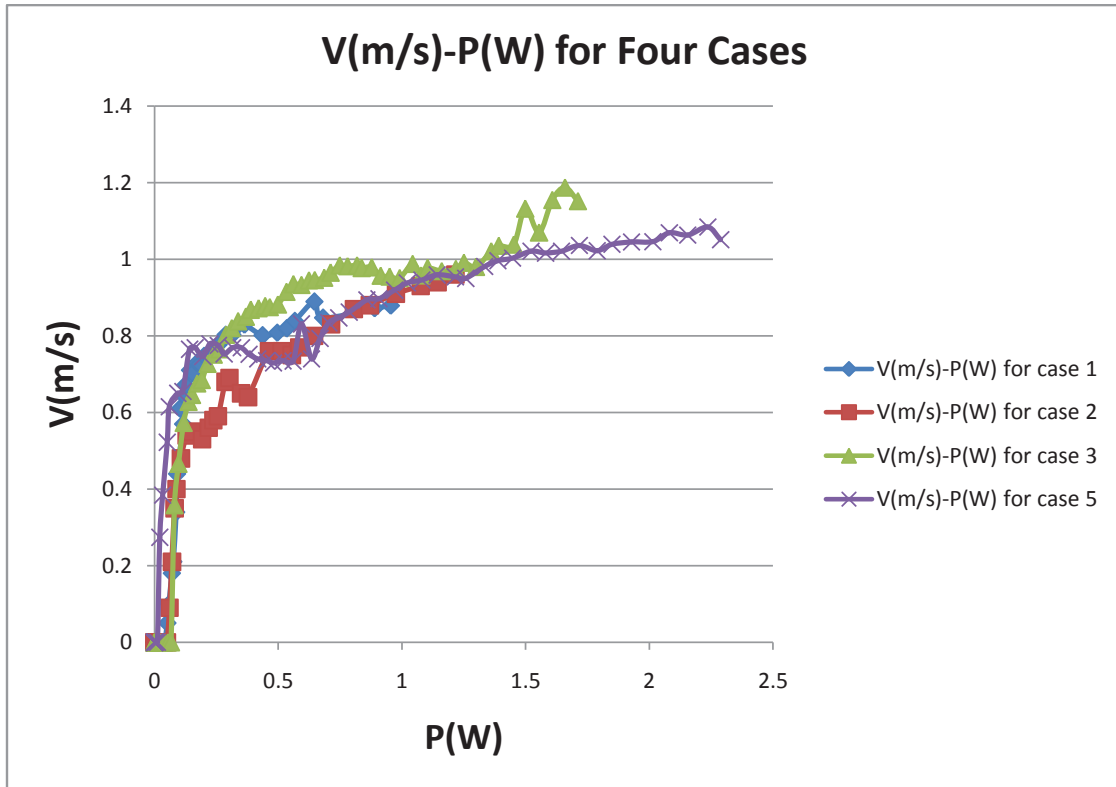
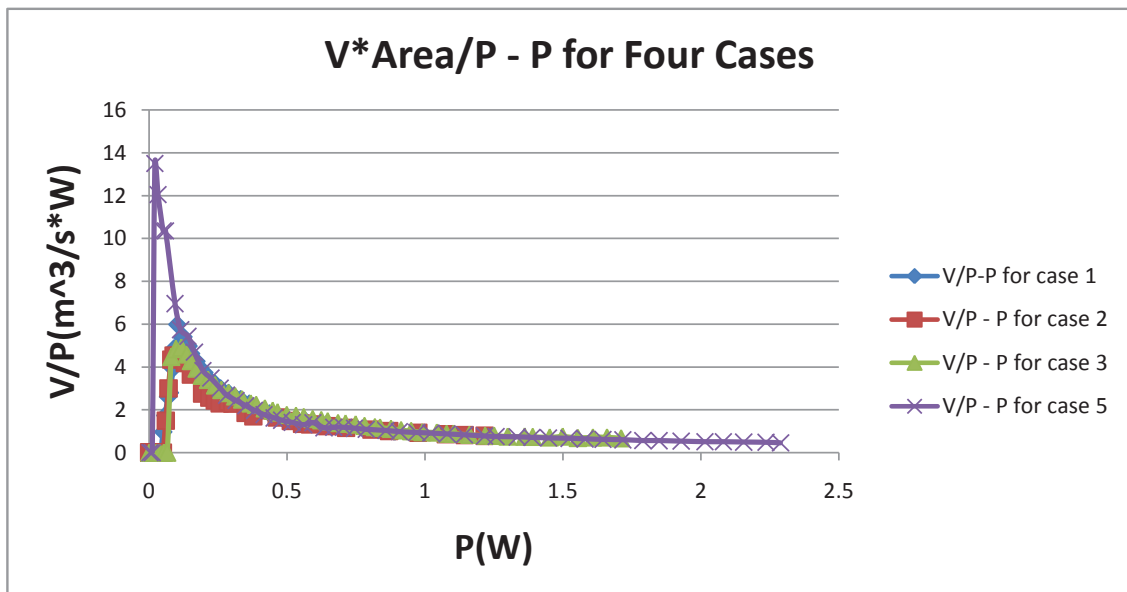Figure 15. Graph of V-P curve for four cases.

Figure 16. Graph of V*Area/P-P.

Figure 15 and Figure 16 show that the efficiency of an ion wind cooling device only increases at the very beginning and continues to decrease as the power supply continues to increase for all the cases (different cathodes and different anodes). Therefore, for an energy-saving ion wind cooling device in this study, the suggested power should be controlled between 0.1 to 0.3W.

Discussion:

Since the experiments in cases 1, 2 and 3 cannot explain why the wind velocity hardly increases in the level off region, there are three probable guesses for the "velocity saturation."

1. In fluid dynamics, there is a phenomenon called "choked flow," [7] which means the air-flow will reach a maximum velocity when the velocity is extremely high. In this case, the ions and neutral molecules between the electrodes had probably reached the extremely high velocity so that the molecules behind the device pushed by the neutral molecules could not be accelerated any more.

2. The drift velocity of atomic ions is proportional to the square root of E/p in a high electrical field [8], where E is the electrical field and p is the air pressure. The

electrical field between the electrodes of the device was over 1,000,000 V/m. Therefore, the ion velocity may have had a slower growth.

3. During the process of wind generation, the electric energy was transferred into different forms of energy, such as kinetic energy, heat and light. When the voltage continued to increase, more and more electric energy may have been converted into heat and light instead of the kinetic energy of wind.

Conclusion:

In this study, experiments using an ion discharge cooling device based on both negative and positive corona discharges were carried out with various dimensions of cathodes and anodes. The velocity of wind can reach up to 1.2 m/s. In all the cases, with the voltage supply increased continuously, the wind velocity hardly went up. To prove the hypothesis that the velocity was limited by the air volume between electrodes, cases 2 and 3 were carried out to compare results with case 1. In cases 1, 2, and 3, faster wind speeds were generated in the device with larger cathodes. However, the differences were not large enough to support the hypothesis. In response to this aspect, three probable explanations have been given in the discussion section, such as "choked flow" of ions, origin of moving air, and drift velocity vs. E/p curve. Case 4 involved negative corona discharge. The onset voltage was much lower than positive discharge on the same device and the

velocity was about 0.35 m/s when its growth was leveling off. Case 5 showed that the onset voltage was higher when the curvature of anodes was smaller. The velocity in case 5 reached up to 1.05 m/s. The most efficient power range of an ion discharge cooling device in this study was defined between 0.1W to 0.3W.

In future studies, the machining of cathodes can be improved to reduce the effect of sharp points. A wider array of differently sized cathodes needs to be tested in order to study the reason for "velocity saturation." To apply this device in an electron device cooling role, the high operating voltage and ozone release should also be taken into consideration.

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