

Experiments with a simple electrostatic precipitator.

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Abstract

Particulate pollution (dust, pollen) in indoor environments is a major cause of allergies and discomfort. By mildly ionising the air using a high-voltage source, dust particles passing through this ionised region acquire an electric charge and are attracted to an earthed plate. This is a very efficient way of trapping not only dust, but also microscopic particles like viruses, pollen and smoke. However, care must be taken to not produce unacceptable levels of ozone; a corrosive, irritating gas (a highly reactive allotropic form of oxygen). While commercial precipitators exist in the marketplace, it was desired to construct a simple demonstrator prototype for educational use. This document lays out some of the basic theory of operation, construction considerations and performance of a simple electrostatic dust precipitator based on an ignition-coil high-voltage generator.

1. Introduction

The removal of dust from gas streams using electrostatic precipitation has long been an important method for reducing particulate emissions in industrial applications. For example, coal-fired power plants regularly “scrub” their chimney exhaust using electrostatic methods to reduce dust emissions into the atmosphere[1]-[3]. Furthermore, pubs and bars often make use of small scale precipitators in an attempt to reduce levels of cigarette smoke in poorly ventilated rooms. Home precipitators also exist on the market for the purpose of removing potential allergens from the home atmosphere of those susceptible to asthma or dangerous allergies to normal house dust.

This project illustrates, for educational and personal use (i.e. **no claim is made here that this device is fit for anything other than for an educational demonstration**), the construction and testing of a simple precipitator built out of commonly available parts. We start off with an overall description of the theory of operation and main system components of the home-brew precipitator. Next the high-voltage supply receives some special attention for reasons of safety and reliability while the enclosure, ion-generator and precipitation plates are discussed in the context of finding a simple geometry where the airflow maximises the deposition of dust particles.

2. Overall description: how it works

Intuitively, the basis of the precipitator's operation is simple. A sharp metal point (shown schematically in Figure 1) is used to concentrate the electric field such that the air in the vicinity of the point “breaks down” weakly and becomes ionised. The ions are accelerated away from the point, towards the plate by the strong electric field. Meanwhile, the dusty room air is moved (via a small fan) past the ionisation region such that the dust particles present in the air become charged by collisions with the ionised (mostly nitrogen and oxygen) molecules. As the dust particles become charged, they are accelerated towards the grounded plate, where they stick until the

ion current is switched off.

The mechanics of this process are actually very complex and we shall not go into them here. However, a couple of important points which can enhance the dust collection ability are worth mentioning. Namely, it is important that the incoming “dusty” air become well ionised. This requires some a bit of thought on how to maximise the interaction of the incoming air with the “corona” region of the ion generator. Generally, the airspeed must not be too great in the precipitation region (we will use about 1-2m/s) and the ion current must be significant without generating excessive ozone.

On the subject of ozone, it is a special form of oxygen (O_3) which is created under certain conditions by ultraviolet light and electric discharges. Ozone has an important function in the stratosphere, where it filters harmful ultraviolet light from the Sun's rays, but at the surface of the Earth, it is an irritating, corrosive pollutant which attacks buildings, metal structures and lung tissue. It forms a component of smog in densely populated regions and can initiate asthma attacks in susceptible people [4]. Since our precipitator relies on a “weak” corona discharge to generate ions, there is the possibility to generate some unwanted ozone. Fortunately, ozone production can be minimised in a couple of ways. Most important, the sharp ion-generator electrode must be fixed at a positive potential. Air ionisation takes place at lower field levels in the presence a sharp object held at a positive potential than one at a negative potential [5], [6]. This allows us to use lower voltages to generate substantial ion currents without noticeable ozone being produced. Furthermore, the ion generator should have a substantial emission area so that reasonable ion currents are produced with the lowest voltage level. Remember, the higher the voltage, the more ozone! Generally, we found that no more than 30kV is necessary for well developed corona (a very dim purple glow-no streamers-around the sharp emitter points, seen in total darkness).

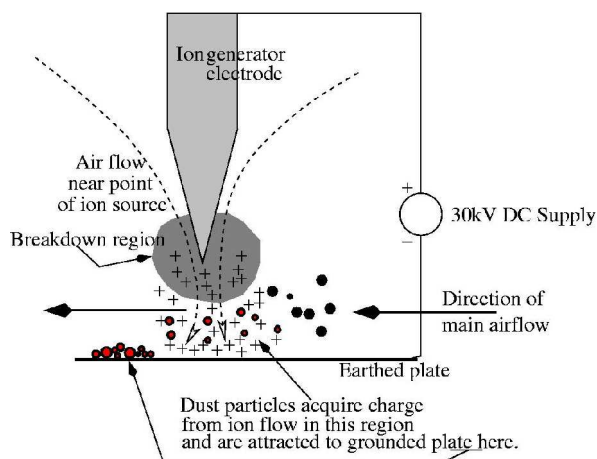


Figure 1 Illustration of ion generation and deposition of dust particles.

From the discussion so far, it can be seen that there three main components to our precipitator system: HV source, ion generator and deposition area (i.e. enclosure). Here, we come to the main part of our discussion.

3. The high-voltage source

Since this is supposed to be mainly an educational exercise, we wanted to avoid the need for expensive components while still maintaining reasonable performance. For this reason, we chose to use an automotive ignition coil to step a low-voltage up to 20-40kV DC. This does not mean that we should ignore basic high-voltage safety. This circuit can deliver blinding (and possible fatal) shocks. All exposed high-tension (HT) leads should be encapsulated or insulated with thick-walled plastic tubing (or both)! Do not come within several centimeters of bare HT conductors. At 30kV, sparks can jump unexpectedly from sharp points.

The HT generator circuit is simple, but powerful. A power MOSFET step-up converter is used and the schematic is shown in Figure 2.

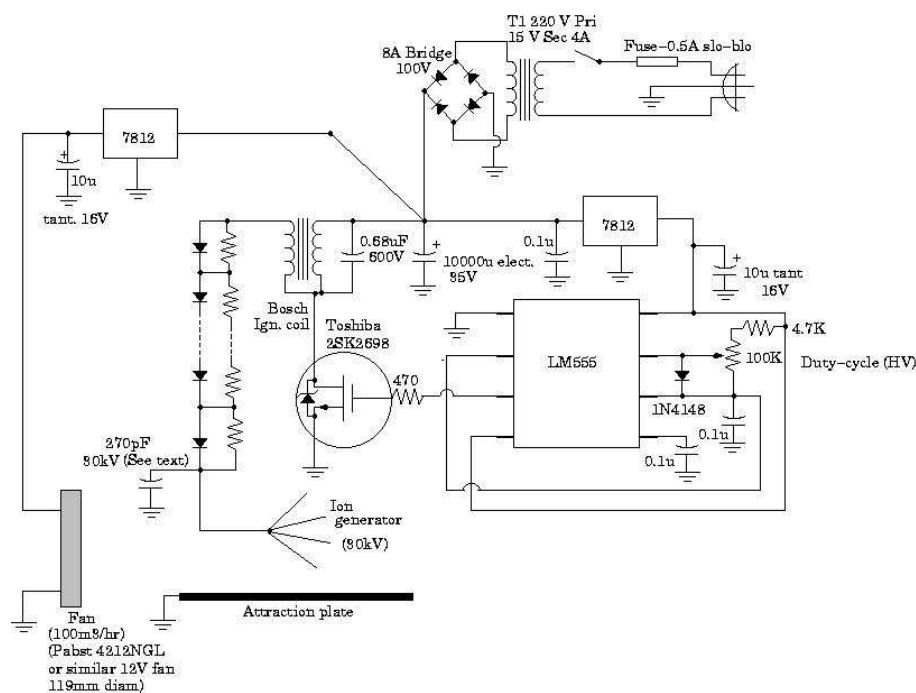


Figure 2 Schematic of the HV source and fan power supply for the electrostatic precipitator.

The driver oscillator is simply a 555 timer chip (the bipolar, not the CMOS variety) operating in an astable mode. As shown, the frequency of oscillation is about 100Hz. Of note is the 1N4148 diode connected across pins 6 and 7 of the 555. This allows a nearly constant-frequency adjustment of the duty cycle of the MOSFET drive pulse. This is how we adjust the output voltage.

The duty cycle can be varied from about 4% to nearly 100% by adjusting the 100K potentiometer (labeled duty-cycle HV on the schematic). In practice, no more than a 20-30% duty cycle is needed to produce 20-30kV depending on the type of ignition coil used in the circuit. Excessive duty cycle will cause excessive dissipation in the MOSFET snubber diode and possibly its destruction (as well as the destruction of the HV diode stack). Use of a 500V MOV can reduce the possibility of MOSFET destruction, but care should always be taken. Careful use of an HV voltmeter is

recommended for verification.

The resistors in the diode stack turned out not to be necessary because the avalanche characteristics of the HV rectifiers tend to equalise any voltage imbalances. For safety, we have included bleeder resistors in the HV capacitor stack (discussed below).

The Toshiba 2SK2698 withstands V_{ds} of 500V and continuous drain currents of 15A (pulses to 60A) and works very well in this application as long as the max V_{ds} is not exceeded. Since the turns-ratio of electronic-ignition coils is higher than the old style points ignition system, higher voltages can be produced for lower drain-source voltages (and thereby, less strain on the MOSFET) than with older ignition coils. It is recommended that a CDI coil from a recent model of car be used (wreckers are great for finding bucket-loads of these at good prices).

The ignition coil-0.68uF capacitor subcircuit form a resonant LC circuit. When the MOSFET is on, the coil “charges” up approximately according to the $L \cdot di/dt = V_{cc}$ (where L is the coil primary inductance....somewhere around 0.05H) rule from circuit theory. When the MOSFET switches off, the current in the coil primary cannot change as rapidly and proceeds to charge up the 0.68uF capacitor and reaches its peak at approximately (in the absence of the HV diode stack and capacitor)

$$t_p = \frac{\pi \sqrt{L_p C}}{2}$$

which, if the coil primary inductance is around 50mH, is in about 0.3msec. (Oscilloscope measurements bear this out.) This is the point when the maximum voltage is induced in the secondary. The HV diode stack, capacitor and load change this somewhat, but the timing under steady-state operation should not be too different. The unloaded HV output will be approximately given by

$$V_{HV} \approx \frac{V_{cc} T_{on}}{L_p} \sqrt{\frac{L_s}{C}}$$

where L_p is the primary coil inductance and L_s is the coil secondary inductance, C is the parallel capacitor value (0.68uF) and T_{on} is the duration of the MOSFET “on” time. V_{cc} is the supply voltage. Using an estimate of 500 H (a 100:1 turns ratio), we can estimate the open-circuit secondary voltage to be nearly 11kV for a 10% duty cycle (1msec MOSFET on time) and 33kV for a 30% duty cycle given a low-voltage supply level V_{cc} of 20V.

The resonant behaviour continues until the voltage across the coil/capacitor subsystem reverses polarity. When this happens, the snubber diode in the MOSFET begins to conduct, effectively pumping the excess coil energy back into the power-supply capacitor. Further resonant behaviour is effectively damped out until the MOSFET gate is triggered into conduction again and the whole process repeats again.

The diode stack- An attempt was made to operate the ion source without a rectifier,

but the efficiency appeared very low (ion current was barely detectable, less than $2\mu\text{A}$) and increasing voltage caused excessive ozone generation without any increase in ion current. Hence, a 40-50kV PRV diode is needed. A TV flyback stick rectifier works well, but these devices seem to be obsolete, so we wished to use a stack of 2 Philips BY8424. These are readily available in large quantities, but for the prototype we settled for the BY187/01 12kV diode (in a 4 unit stack, seen in Figure 3) which were available to us in small quantities. The entire array should be encapsulated (silicone works well) to prevent corona discharges from causing charge leakage which could unbalance the diodes (even though the avalanche characteristics would tend to prevent damage).



Figure 3 The four 12kV diodes, enclosed in PVC tubing to reduce unwanted corona discharge and enhance safety.

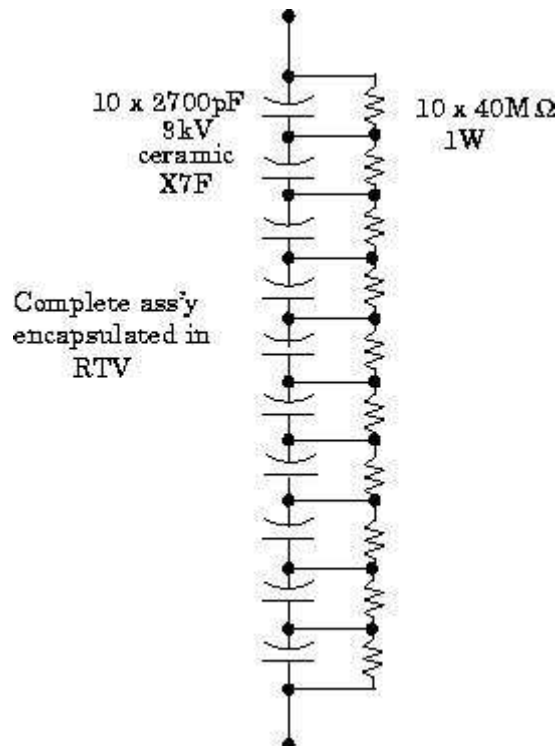
The inclusion of the HV rectifier (with the capacitor in the next section) caused the ion current to jump to $16\text{-}17\mu\text{A}$.

The capacitor stack - A HV capacitor is needed in order to provide the diode reverse recovery charge which is needed to switch the diodes off as well as provide as continuous as possible ion current and reduce any electromagnetic interference from the corona discharge.

The 270pF HV filter capacitor is constructed using a stack of 10 3kV 2700pF capacitors, each paralleled with a 40Mohm resistor (for bleeding residual charge as well as equalising leakage charge) as seen in the schematic in Figure 4. Like the diode array, the capacitor stack should be encapsulated in in some way (e.g. with silicone) to prevent unwanted corona discharge as well as enhance safety.

The time constant for this array is $RC=0.108$ sec., which means with about a 100 Hz driving signal, voltage ripple on the HV output should be less than 10% (not including the effects of ion-current loading). Although there is some leeway in the maximum

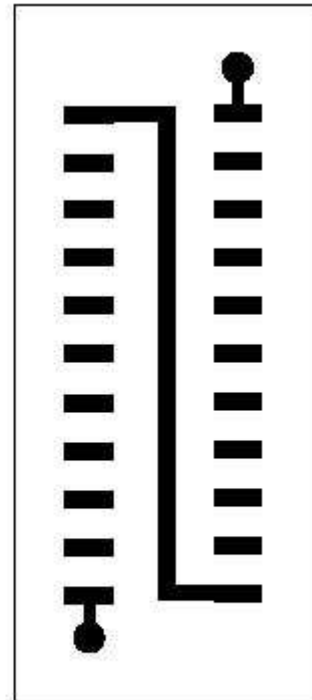
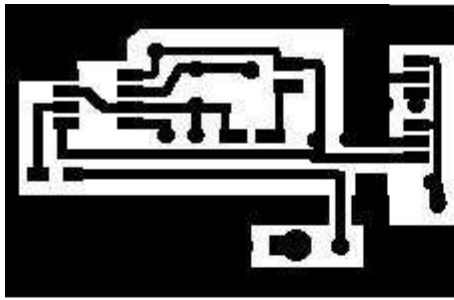
voltage that these capacitors can tolerate, try to keep the HV level below 30-35kV to prevent breakdown of the capacitor dielectric.



*Figure 4 - Schematic of HV filter capacitor stack.
Each capacitor is 2700pF, 3kV. Each resistor is
40 megohm, 1 watt. The whole assembly is
encapsulated in silicone.*

Printed circuit board layouts - For convenience, the 1:1 PCB layouts are given in Figure 5. The images are positives for use in “ugly” construction (component mounting is on the same side as the copper traces). Mirror images can be used if you want the trace plating on the opposite side of the PCB. Standard FR-4 type PCB material works well for this project.

Parts list- A more or less complete parts list is given in Table 1 (with prices at the time of construction). Depending on the choice of enclosure, there will be some variation in the mechanical components, but the electronic component list should be comprehensive.



Free Power Oscillator PCB (4.1)	
Version 0.1	2004-09-01
BOM Sheet	

Figure 5 PCB images, positive (black = copper), traces on component side.

Table 1 - Parts List

<i>How many</i>	<i>Part Ind #</i>	<i>Description</i>	<i>Supplier</i>	<i>Price (Euros)</i>
1	NE555	Timer 8-DIP pack.	Digikey #296-1411-5-ND	0.39
40		Rectifier (1kV PRV fast recovery)	Digikey #UF1007DICT-ND	0.39
1		100V/ 8A Bridge rectifier	Digikey #KBPC801-ND	1.64
3	0.1u/50V	Capacitor (price is for a lot of 10)	Digikey #P4525-ND	1.45
2	10u/16V tant	Capacitor	Digikey #399-1403-ND	0.57

<i>How many</i>	<i>Part Ind #</i>	<i>Description</i>	<i>Supplier</i>	<i>Price (Euros)</i>
1	0.22uF/600V	Capacitor	Digikey #EF6224-ND	0.85
2	6800uf/35V	Capacitor VZ series	Digikey #493-1090-ND	2.25
2	LM7812	Volt. Reg.	Digikey #497-1464-5-ND	0.47
1	4212NGN	Fan (Papst) 119mm 12VDC	Farnell Order# 315394	27.85
1	2SK2698	N-ch MOSFET 500V/10A	Digi-key	2.21
50	20Meg 1/2W	Resistors (in lots of 100)	Digikey #OF206J-ND	0.37
1	4.7K 1/4W	REsistor (SM, price is in lots of at least 10)	Digikey #311-4.70K-FCT-ND	0.71
1	470 1/4W	Resistor (SM, price is in lots of at least 10)	Digikey #311-470-FCT-ND	0.71
1	100K 1/8W	Potentiometer series 262	Digikey #U262R104B-ND	0.41
1	TI027260	15V/80VA Transformer	Farnell Order# 4335144	19.48
1		“Hot-shot” CDI style auto ignition coil		5
10	2200pF 3KVDC	Capacitor	Digikey Order# P4513A-ND	1.32
1		on/off switch	Digikey #EG1501-ND	1.43
1	0.5A/250V/3AG	Fuse-slo-blo (Price for lot of 5)	Digikey #F314-ND	0.76

<i>How many</i>	<i>Part Ind #</i>	<i>Description</i>	<i>Supplier</i>	<i>Price (Euros)</i>
1		Fuse holder	Digikey #F1497-ND	0.63
1		Power entry module	Digikey #486-1001-ND	0.99
1	141300	Photosensitive PCB S/S 160X100	Farnell #141300	5.71
1	1590WR1FLBK	Aluminium enclosure IP65 192X111X61	Farnell # 4437834	21.87
1		LED pilot light	Digikey #67-1150-ND	1.01
3		TO220 mounting kit	Farnell #522636	0.17
1		12mm dia, 1m len PVC tube - for HV insulation		
		Assorted wire, tape, glue, etc.		

4. The ion generator

The ion generator was fabricated out of short lengths of stiff copper wire (1.5mm²) assembled into a “christmas-tree” like strcture where the points are arranged as uniformly as possible. Two views are shown shown in Figure 6.



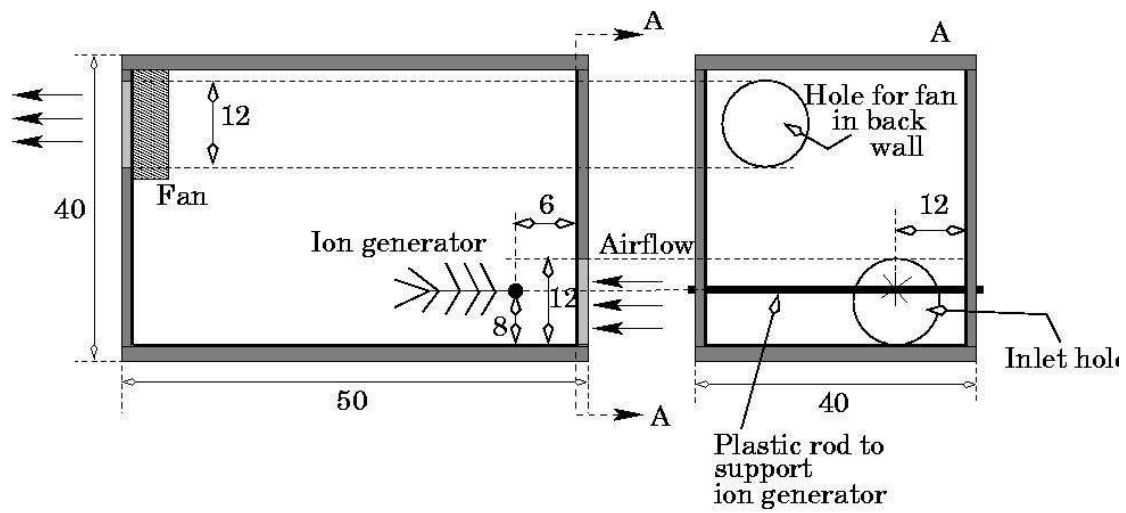
Figure 6 Two views of the ion generator "christmas tree." Note the positioning with respect to the air inlet.

The corona is generated near the points of the wire structure. In operation, we measured an ion current of 16 microamps at about 30kV. This indicates good emission and should yield good deposition of dust particles on the collection surface (the foil coated surfaces).

Future versions will test other ion generator geometries. For example, flat, sharp edges also seem to give large ion currents perhaps as a result of their large areas, which allow air movement to transport the ion space charge away from the emission area quickly. The air ionisation process becomes more efficient.

5. The dust collection area

As this is an experimental exercise, we did not want to chop up an expensive metal or plastic enclosure for the initial prototype, so a simple corrugated carton was used as the initial enclosure. The inside is lined with aluminium foil and holes cut for inlet and outlets. A 120cm muffin-fan is used to extract air from the box, thereby drawing dusty air into the box past the ion generator. Figure 7 shows a schematic drawing of the box Figures 8 shows the external view of the outlet. The mounting of the fan is shown in Figure 9.



All dimensions in cm.

Figure 7 A drawing of the precipitator enclosure.



Figure 8 External view of outlet port.

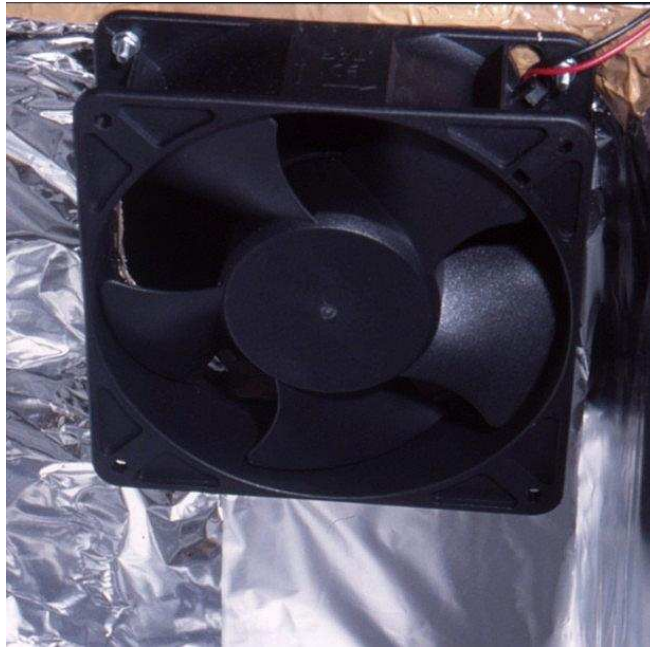


Figure 9 Depiction of the internally mounted 12V fan.

As the dust particles past the ioniser, they acquire a charge and are attracted to the aluminium coated walls of the box. Pay special attention to the airflow pattern. It is important that the incoming air be forced around some “bends” so that dust particle have a chance to stick to the walls. This design is obviously not optimal, but illustrates the operation reasonably well. It would be better to introduce a more “labrynthine” structure to the collection area so the air is forced around several bends. Moreover, a two-stage ionisation/collection system would be a great improvement and will be featured in a later experiment.

Adjusting and testing

After assembling all the components into the unit depicted in Figure 10, we carried out a couple of tests to check the functioning of our precipitator.

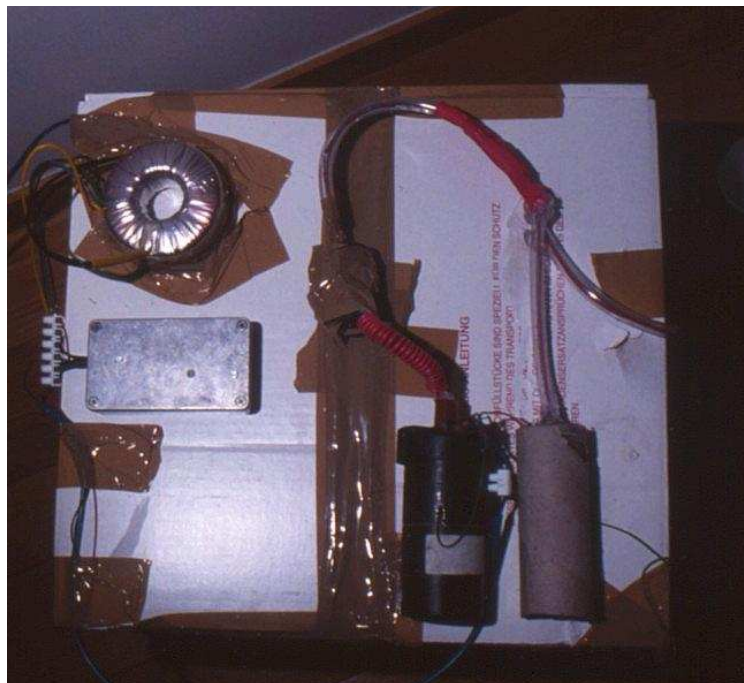


Figure 10 External view of the precipitator. The small aluminium box houses the ignition coil driver and voltage regulators. The ignition coil and power transformer are clearly seen. The diode stack and all HV wiring are enclosed in PVC tubing. The brown cylindrical object is the silicone encapsulated 270 pF 30kV capacitor stack.

The smoke test - For this test, we closed off all openings with clear plastic film and disconnected the fan. We introduced a piece of paper which had been allowed to burn for a moment and then blown out, so that it produced copious amounts of smoke. It was inserted in the box and the box allowed to fill with a dense cloud of smoke. From the fan opening, it was impossible to see the ion generator. The smoking paper was quickly withdrawn (without letting the smoke escape) and the HV switched on. With a strong light shining through the plastic-covered inlet opening and viewing through the fan opening, a significant amount of turbulent activity could be seen. Within a few seconds, the ion generator at the other end could be made out. With a further 20-30 seconds, the air within the box was completely clear. The smoke had been completely deposited on the interior aluminium foil surface.

Note that although the precipitator removed all the particulate matter from the atmosphere, the odour of smoke was still present. It took a few hours of operation to reduce the smoke odour to acceptable levels. The precipitator does not remove odours, in general. However, the ionising properties of the HV may gradually reduce them over *long* times.

The dust collection test - This was a simple test whereby the precipitator was allowed to run for several days. Over this period, it should extract a visible amount of dust from the atmosphere.

After cleaning the box and allowing the smoky smell to disappear after the first test, it was put in a corner of the office, near a bookshelf (we know how books usually collect dust) and switched on and left for several days. After this period, a clearly visible layer of dust was observed on the walls of the box next to and facing the inlet hole. Some of this dust was extremely fine and when touched, left a black greasy smear on the fingers (not unlike the dust one finds on television screens). This seems to indicate that even extremely fine dust particles are trapped using this method. Furthermore, the exhaust fan seems relatively clean, having no clear layer of dust attached to it. However, on close examination, it was found that there was a very small amount of the fine black dust present on the fan blades. Probably by forcing the air around sharper “bends” within the capture area would eliminate this. A two-stage precipitator would certainly eliminate this.

Forcing the air to do a U-turn - By inserting a baffle next to the outlet fan, thereby dividing the box into two regions and forcing the air to reverse direction (see Figure 11), we can improve the dust collection significantly.

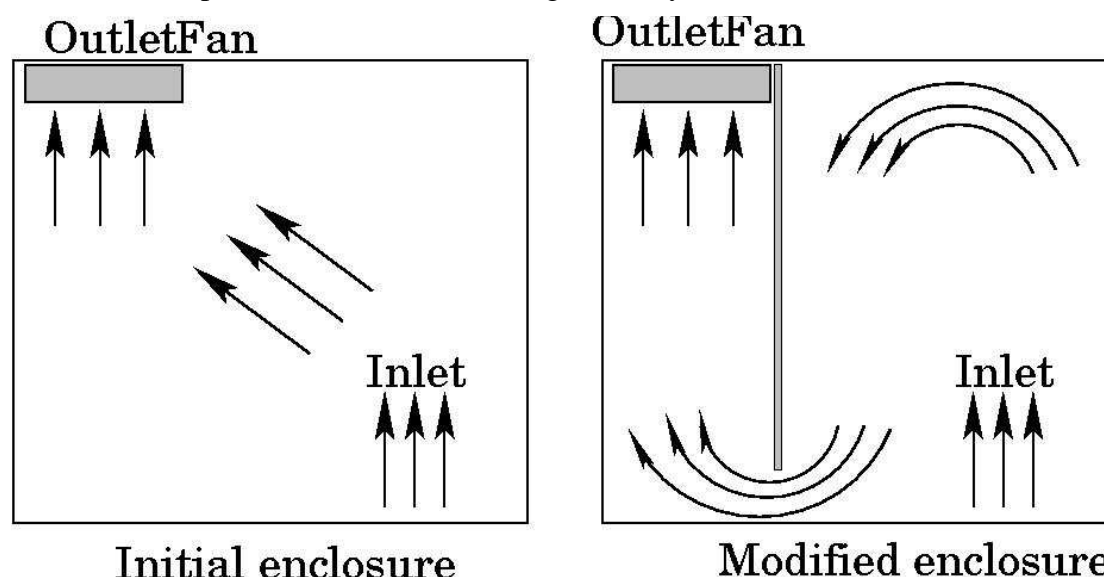


Figure 11 Schematic top view of the modifications to the enclosure to reduce the amount of particulate matter that “escapes.”

In the original box, the collection rate was good, but a piece of sticky tape near the outlet showed that significant dust passed through the box. Also, the blades of the fan became slightly dirty, indicating that some dust particles were passing through unscathed. This was despite the clear deposition of significant dust near the ioniser tree.

It was decided to make a simple modification to the enclosure, namely the addition of a foil-covered baffle placed as shown in Figure 11. By forcing the air to make two 180 degree turns, the pattern of dust deposition changed. More particles appeared on the back wall of the precipitator (where the air makes its first turn) as well as all along the bottom of the larger chamber. Also, the “sticky-tape” test revealed far fewer

escaping particles. We could probably reduce the number of escaping particles even further by adding a second ioniser at the entrance to the second chamber (in effect, making a 2 stage precipitator).

7. Conclusions

While we have successfully demonstrated the functioning of an electrostatic dust precipitator, there are improvements which could be incorporated. Namely, a labyrinthine collection structure (or multiplate structure) would ensure that nearly no particulate matter exits via the exhaust fan. Use of a dual-stage (ioniser-collector-ioniser-collector) structure may work even better.

It is important to keep the HV level high enough to generate sufficient ion current but low enough to prevent the production of ozone (which can be dangerous for people who suffer respiratory difficulties). The ion generator should be operated at a positive potential such that a weak corona is produced with a minimum of voltage.

When constructing the HV supply, keep in mind that it may be necessary to reverse the polarity of the primary to achieve a positive HV on the secondary. You will have to test for this.

Finally, be sure to enclose all high-voltage leads in PVC tubing to prevent accidental shocks. Remember that merely being too close to an exposed conductor under high tension is enough to receive a potentially dangerous shock. For 30kV, this means being at least 3-4 cm away for safety's sake.

The next step will be to build a more durable enclosure which has two or three precipitator stages. The one-stage device presented in this document exhibited good performance, but since multiple stages are no more difficult to construct, the resulting performance increase could be worth it.

8. References

- [1]Electrostatic Precipitators, Arizona State University School of Electrical Engineering, Document address:
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- [6]J. T. Kennedy, *Study of the Avalanche to Streamer Transition in Insulating Gases*, Doctoral Thesis, University of Eindhoven, The Netherlands, 1995, Document address: <http://alexandria.tue.nl/extra3/proefschrift/PRF11A/9511019.pdf>.