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A Self regenerating diesel emissions particulate trap using a non-thermal plasma

Bryce Rampersad

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ABSTRACT

There is great concern about the adverse effects associated with exposure to diesel exhaust. There is increasing evidence that diesel exhaust particulate matter (PM) is carcinogenic and may cause cancer. Non-cancerous lung damage and respiratory problems are also associated with exposure to diesel exhaust as well as acid rain and smog. Diesel exhaust PM is very easily respirable once emitted into the atmosphere and therefore poses a significant health problem.

A diesel engine emissions particle removal system which utilizes Electrostatic Precipitation (ESP) and Non Thermal Plasma (NTP) technologies was studied for trapping and oxidizing micron sized particles (0.01 to 10 microns) in the exhaust. Particles are first charged in a monopolar manner in a NTP in the diesel exhaust stream, and then collected on an electrically grounded precipitation surface. Gaseous radicals produced in the NTP oxidize the precipitated particles to provide a continuously regenerating system. This device is targeted to help meet recently instituted US Environmental Protection Agency (EPA) Tier II as well as upcoming European (Euro 4, 5) and Japanese diesel particulate emissions standards. This system can be coupled with a suitable catalyst or other emissions treatment technologies to produce a complete exhaust aftertreatment system.

Analytical and empirical methods were used to model the proposed Self Regenerating Diesel Emissions Particulate Trap. The analysis showed that a total particle precipitation efficiency of greater than 95% could be obtained using less than 0.5% of total engine energy output at a vehicle speed of 120 km/hr for a compact diesel powered vehicle. It was determined that the energy requirement for producing gaseous radicals in the exhaust stream is higher than is needed for particle charging and precipitation. It was also determined that the conversion of radicals can be accomplished using less than 2% of the total engine output. The results of the model developed shows that the proposed device would be effective reducing diesel PM emissions on a heavy-duty vehicle.
# Table of Contents

ABSTRACT ......................................................................................... 1

SYMBOL KEY .................................................................................... 3

LIST OF FIGURES ............................................................................... 5

LIST OF TABLES .............................................................................. 6

INTRODUCTION .................................................................................. 7

CHAPTER 1: THE PROBLEM (DIESEL PARTICULATE EMISSIONS) ........ 10

1.1 HEALTH AND ENVIRONMENTAL EFFECTS ............................................. 10

1.2 PARTICULATE EMISSIONS REGULATIONS ........................................... 17

1.3 CURRENT EMISSIONS TREATMENT TECHNOLOGY ................................ 19

1.3.1 Diesel oxidation catalysts (DOC) ......................................................... 20

1.3.2 Diesel particulate filters (DPF) ............................................................ 21

1.3.3 Selective Catalytic Reduction (SCR) ................................................... 22

1.3.4 Fuel-borne catalysts (FBC) in combination with filters and oxidation catalysts ......................................................... 23

1.3.5 Continuous Regenerating Trap (CRT) ................................................. 24

CHAPTER 2: CONCEPTUAL FRAMEWORK ........................................... 26

2.1 DESIGN OBJECTIVE ............................................................................ 26

2.2 SCOPE AND LIMITATIONS .................................................................. 28

2.3 PROPOSED SELF-REGENERATING DIESEL EMISSION PARTICULATE TRAP ....................................................................... 30

2.4 TARGET VEHICLE AND EMISSIONS CHARACTERISTICS .................. 33

CHAPTER 3: METHODOLOGY AND ANALYSIS FOR PARTICLE COLLECTION ........................................................................ 37

3.1 TECHNICAL APPROACH ...................................................................... 37

3.1.1 Technical Approach Summary ............................................................ 38

3.1.2 Initial Investigation of Device Requirements ....................................... 41

3.1.3 Determination of Corona Onset Voltage .............................................. 45

3.1.4 Determination of Electric Field Distribution ......................................... 48

3.1.5 Determination of Particle Charge by Field Charging ............................ 52

3.1.6 Determination of Particle Charge by Diffusion Charging ...................... 55

3.1.7 Determination of Total Particle Charge ................................................. 57

3.1.8 Determination of Particle Migration Velocity ....................................... 60

3.1.9 Determination of Total Precipitator Efficiency and Particle Output .......... 64

CHAPTER 4: RESULTS AND DISCUSSION .......................................... 66

4.1 DESCRIPTION OF FINDINGS ............................................................... 66

4.2 OXIDIZATION OF CARBONACEOUS PM ............................................. 76

4.3 DEVICE RECOMMENDATIONS ............................................................. 87

4.3.1 Discharge Electrode ............................................................................ 87

4.3.2 Supply Voltage ................................................................................... 89

4.3.3 Precipitation Section Gas Velocity ....................................................... 92

4.3.4 Precipitation Section Grounding ......................................................... 92

4.3.5 Hydrocarbon Additives .......................................................... 93

4.4 DEVICE SPECIFICATIONS, DIMENSIONS AND GEOMETRY .............. 95

4.5 CONCLUSION .................................................................................... 100

BIBLIOGRAPHY .................................................................................. 102

APPENDIX: SPREADSHEET CALCULATIONS ...................................... 107
## Symbol Key

### Input Values

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<thead>
<tr>
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<tr>
<td>(a_p)</td>
<td>Particle radius</td>
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<tr>
<td>(a_w)</td>
<td>Charging wire radius</td>
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<tr>
<td>(f)</td>
<td>Particle re-entrainment coefficient</td>
</tr>
<tr>
<td>(g_s)</td>
<td>Grid spacing</td>
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<tr>
<td>(\eta_d)</td>
<td>Desired collection efficiency</td>
</tr>
<tr>
<td>(i)</td>
<td>Input current</td>
</tr>
<tr>
<td>(L_c)</td>
<td>Actual charging length</td>
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<tr>
<td>(L_p)</td>
<td>Actual precipitation section length</td>
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<td>(m_r)</td>
<td>Wire roughness factor</td>
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<td>(r_c)</td>
<td>Radius of cylindrical electrode</td>
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<td>(V_d)</td>
<td>Desired average gas velocity through precipitator</td>
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<tr>
<td>(A_{cs})</td>
<td>Cross section area of precipitator</td>
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<tr>
<td>(C_u)</td>
<td>Cunningham correction factor</td>
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<td>Relative fluid density</td>
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<td>Electric field</td>
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<td>(E_{avg})</td>
<td>Charging section electric field</td>
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<tr>
<td>(E_c)</td>
<td>Corona initiating electric field</td>
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<td>(E_{col})</td>
<td>Precipitator section electric field at collection surface</td>
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<td>(E_{D})</td>
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<td>(\phi_t)</td>
<td>Townsend Variable</td>
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<td>(g)</td>
<td>Precipitator cross section dimension</td>
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<td>(N_\beta)</td>
<td>Dimensionless coefficient</td>
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<td>(N_{C})</td>
<td>Number of cells in precipitation section</td>
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### Constants

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<td>Boltzmann constant</td>
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<tr>
<td>d_o</td>
<td>Standard condition gas density</td>
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<tr>
<td>D_p</td>
<td>Particle diffusion coefficient</td>
</tr>
<tr>
<td>e</td>
<td>Electron charge</td>
</tr>
<tr>
<td>G</td>
<td>Ion diffusion constant</td>
</tr>
<tr>
<td>k</td>
<td>Relative Dielectric Constant of carbon</td>
</tr>
<tr>
<td>λ</td>
<td>mean free path of gas molecules</td>
</tr>
<tr>
<td>ν</td>
<td>Absolute Gas Viscosity</td>
</tr>
<tr>
<td>PD</td>
<td>Particle diffusion coefficient</td>
</tr>
<tr>
<td>PL</td>
<td>Particle loading</td>
</tr>
<tr>
<td>P_o</td>
<td>Standard atmospheric pressure</td>
</tr>
<tr>
<td>p_c</td>
<td>Density of carbon</td>
</tr>
<tr>
<td>T</td>
<td>Exhaust temperature</td>
</tr>
<tr>
<td>T_o</td>
<td>Standard atmospheric temperature</td>
</tr>
<tr>
<td>V_g</td>
<td>Exhaust volumetric flow rate</td>
</tr>
<tr>
<td>ξ_o</td>
<td>Permittivity of free space</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
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</tr>
<tr>
<td>Figure 1</td>
<td>Schematic of Diesel Particulate &amp; Vapor Phase Species</td>
</tr>
<tr>
<td>Figure 2</td>
<td>Average Source Contribution to Midtown Manhattan Site</td>
</tr>
<tr>
<td>Figure 3</td>
<td>Average Los Angeles Basin Cancer Risk Apportionment</td>
</tr>
<tr>
<td>Figure 4</td>
<td>Increase in Risk of Death vs. Ambient PM Levels</td>
</tr>
<tr>
<td>Figure 5</td>
<td>Percent Mortality Associated with a 100 μg/m³ Increase in Total Suspended Particulate</td>
</tr>
<tr>
<td>Figure 6</td>
<td>Past, Present and Projected Future Emission Levels from Heavy Duty Diesel Vehicles</td>
</tr>
<tr>
<td>Figure 7</td>
<td>Past and Present NOx and PM10 Emission Regulation for Diesel Vehicles in the US</td>
</tr>
<tr>
<td>Figure 8</td>
<td>Dominance of Heavy Duty Vehicles in the Total Emissions of NOx and PM10</td>
</tr>
<tr>
<td>Figure 9</td>
<td>Schematic and Operating Principle of a Diesel Oxidation Catalyst</td>
</tr>
<tr>
<td>Figure 10</td>
<td>Different Layouts and Types of Diesel Particulate Filters</td>
</tr>
<tr>
<td>Figure 11</td>
<td>Schematic of Selective Catalytic Reduction System</td>
</tr>
<tr>
<td>Figure 12</td>
<td>Schematic of Operating Principles of a Continuously Regenerating Trap</td>
</tr>
<tr>
<td>Figure 13</td>
<td>Device Cross Section Schematic</td>
</tr>
<tr>
<td>Figure 14</td>
<td>Lognormal Particle Distribution (Mass Fraction vs. Particle Diameter)</td>
</tr>
<tr>
<td>Figure 15</td>
<td>Typical Diesel Particulate Emissions Size Distribution by Mass</td>
</tr>
<tr>
<td>Figure 16</td>
<td>Discretised Particulate Size Distribution by Mass</td>
</tr>
<tr>
<td>Figure 17</td>
<td>Precipitation Section</td>
</tr>
<tr>
<td>Figure 18</td>
<td>Active and Passive Discharge Zones</td>
</tr>
<tr>
<td>Figure 19</td>
<td>Diagram Showing Dipoles of a Particle Subject to a Charge</td>
</tr>
<tr>
<td>Figure 20</td>
<td>Diesel Particulate Matter Simplified Free Body Diagram</td>
</tr>
<tr>
<td>Figure 21</td>
<td>Precipitation section shown divided into ten ‘slices’ for analytical work</td>
</tr>
<tr>
<td>Figure 22</td>
<td>Electric Field Strength vs. Radius in Charging Section</td>
</tr>
<tr>
<td>Figure 23</td>
<td>Particle Mass Removal for Precipitator Sections</td>
</tr>
<tr>
<td>Figure 24</td>
<td>Particle Mass Removal vs. Particle Radius</td>
</tr>
<tr>
<td>Figure 25</td>
<td>Effect of Hydrocarbon Additives on NO to NO₂ Conversion in an NTP</td>
</tr>
<tr>
<td>Figure 26</td>
<td>Energy Density Required for the conversion of NO to NO₂ in a NTP</td>
</tr>
<tr>
<td>Figure 27</td>
<td>Conversion of NO to NO₂ vs. Energy Density</td>
</tr>
</tbody>
</table>
List of Tables

Table 1: Tier II EPA Diesel PM Emissions Standards ................................................................. 18
Table 2: Emissions Data for VW Golf 1.9l Diesel Turbocharged Vehicle with EGR .................. 34
Table 3: Analytical Model Input Parameters ............................................................................... 66
INTRODUCTION

Diesel engines overwhelmingly dominate the bus and large truck markets and have been capturing a growing share of the light heavy-duty and passenger vehicle market over the last decade. The impact of diesel engines on air quality may grow even larger if automobile manufacturers carry out stated plans to increase sales of diesel powered light-duty trucks and cars over the next few years. Diesel engines are inherently more efficient than gasoline engines and they are very popular in foreign markets where fuel costs are high. In fact, in Europe, most vehicles are already diesel powered. The expansion of sales of non-commercial diesel vehicles is very apparent as automotive manufacturers are currently unveiling several diesel engines slated for light trucks, sport utility vehicles and passenger cars. The dominance of the diesel engine in the heavy-duty market is also unwavering.

There is great concern about the adverse effects associated with exposure to diesel exhaust. Exposure is wide spread, particularly in urban areas. There is increasing evidence that diesel exhaust PM is carcinogenic and may cause lung cancer. Non-cancerous lung damage and respiratory problems are associated with exposure to diesel exhaust PM. Acid rain and smog are also attributed to diesel exhaust PM. If a few contaminants in diesel exhaust can be controlled, diesel engines have the potential to be much cleaner than their gasoline counterparts.

Without significant new controls on motor vehicle emissions, millions of Americans will continue to breathe unhealthy air. Significant reductions in emissions of NOx, PM, NMHC (nonmethane hydrocarbons), carbon monoxide, sulfur dioxide and other toxins would result in substantial benefits to the public health and welfare. Several engine modifications and controls techniques have been tried to reduce harmful contaminants in diesel emissions. These techniques have had limited success. Many diesel engine manufacturers have recognized and stated that exhaust aftertreatment systems would be needed to meet emissions standards. Several aftertreatment technologies have also been tried with some success and several drawbacks. Many of these systems have one or a combination of the following drawbacks: high-pressure drop, high energy or fuel consumption, high maintenance requirements and catalyst fouling among others.
The Environmental Protection Agency (EPA) is the main federal institution for regulation of vehicle and other emissions. New stringent EPA standards have been recently instituted pertaining to emissions standards for heavy-duty vehicles. These new standards are referred to as Tier II and will be instituted in two distinct phases addressed in EPA regulatory announcements 420-F-00-022 (Ref. 54) published in May 2000 and 420-F-99-057 published in December 2000 (Ref. 53). Tier II diesel particulate emission standards take effect in 2007 while other emission regulations encompassed under the Tier II regulations begin as early as 2004. Diesel fuel sulfur content will be regulated as part of the Tier II emissions regulations. The reduction of sulfur levels in diesel fuel (to less than 15 PPM) would facilitate the increased use of catalyst technologies for diesel emissions. Diesel fuel sulfur regulations take effect in 2006.

Here are some quick facts about diesel-powered vehicles published by the EPA in May of 2000 (Ref. 58).

- In 2007 heavy-duty trucks and buses would contribute more than half of the NO and PM emissions from all highway vehicles.
- An older heavy-duty diesel vehicle can emit almost 8 tons of pollution per year. That amounts to 160 to 240 tons of pollution over the life of the diesel engine.
- Diesel engines are more durable and have better fuel economy than gasoline engines.
- Diesel engines will continue to dominate heavy duty vehicles and the diesel engine share of the light truck market is projected to grow 24% by 2015. The diesel engines share of the car market is projected to grow 9% by 2015.

Here are some of the anticipated benefits of the EPA’s Tier II Diesel Emissions Standards (Ref. 58).

- As a result of EPA’s proposal, each new truck and bus would be as much as 95 percent cleaner than today’s trucks and buses.
- Emissions of soot (PM) in the US would be reduced by 110,000 tons each year.
- Reducing harmful diesel exhaust contaminants will result in a significant reduction, almost 33,000 tons each year in the US, of toxic air pollutants (such as benzene), many of which are known human carcinogens.
The proposal is equivalent to removing the pollution created by 13 million of today’s trucks.

This proposed program would ensure that every American would breathe cleaner air. Many states will need to reduce smog causing and soot emissions, to attain national air quality standards by the required 2007 - 2010 timeframe. This proposal, in combination with other clean air programs, will ensure that a significant number of areas across the country, with a population of more than 120 million people, will be able to meet and maintain EPA’s national air quality standards.
Chapter 1: The Problem (Diesel Particulate Emissions)

1.1 Health and Environmental Effects

Diesel particulates are very small (generally less than 10 microns) and complex substances. Particulate consists of an uncombusted carbon core, adsorbed hydrocarbons from engine oil and fuel, adsorbed sulfates, water, and inorganic materials such as those produced by internal engine abrasion (Ref. 36, 40, 57). Diesel particles are generally spherical, but have the propensity to agglomerate and form chains or bundles of connected particles. Diesel particulate has raised a host of health and environmental issues considering their chemical composition and extremely small size. Several studies have shown that they contribute to or aggravate chronic lung diseases such as asthma, bronchitis and emphysema (Ref. 20). There is also growing evidence about the potential cancer risk from exposure to diesel particulate (Ref. 29, 30). These particles also impair visibility, soil buildings, contribute to structural damage through corrosion, and diesel exhaust gives off a pungent odor. Figure 1 shows a schematic of a diesel particulate chain (Ref. 64).

![Schematic of Diesel Particulate & Vapor Phase Species](Ref. 64)

The International Agency for Research on Cancer (IARC) carried out a comprehensive investigation of the health effect of Diesel Particulate in June 1988. This study concluded that diesel particulate is probably carcinogenic to humans meaning that it is capable of increasing the
incidence of malignant tumors. A 1993 EPA report entitled ‘Motor Vehicle-Related Air Toxics Study’ listed diesel particulate as one of the most serious hazardous pollutants emitted from mobile sources (Ref. 56). The California Environmental Air Resources Board (CARB) released a report in 1997 that concludes that diesel engine exhaust is hazardous to health (Ref. 57). Diesel PM was subsequently declared to be a toxic air pollutant in 1998 by CARB. The State and Territorial Air Pollution Program Administrators (STAPPA) and the Association of Local Air Pollution Control Officials (ALAPCO) published a study that attributes 125,000 additional cases of cancer in the US to Diesel exhaust (Ref. 61).

Several other studies have been carried out regarding the health effects of PM10 (PM smaller than 10 μm). Many of these studies do not attribute all adverse PM10 health effects to diesel particulate due to difficulties in isolating these particles for these studies. Other studies have however shown that diesel PM contributes anywhere from 17-71% of PM10 matter in urban areas. A comprehensive study in Manhattan showed a 52.5% contribution of Diesel Particulate to all PM10 matter as seen in Figure 2. A study on the contribution of different airborne contaminants to the increased risk of cancer in Los Angeles attributed diesel PM to 71% of all cancer occurrences caused by respirable airborne contaminants (Ref. 60). See Figure 3.

![Figure 2. Average Source Contribution to Midtown Manhattan Site](Ref. 60)
A PM10 study done in Europe and released in the Lancet Medical Journal done in 2000 attributes 6% of all deaths to PM10 amounting to 40000 deaths per year. This study also estimated that people that lived in cities would have a life expectancy of about 18 months less due to PM10 and that health cost due to traffic pollution was about 1.7% of the total GDP (Ref. 29). Another extensive 8 year study done by Pope and others (Ref. 30) in 1995 of more than half a million people in several US urban areas estimated that these residents lost about one to three years of life expectancy due to Diesel PM. A similar 15-year study conducted by Dockery and others of 8000 people living in areas of higher particulate pollution showed that these people had a 26% higher risk of early death (Ref. 31). McMurry complied the results of several PM studies (Ref. 20) for several US and international cites and some US states. Some of the results of his study are shown in Figure 4. These graphs show the increase in the risk of death with increasing Total Suspended Particulate Mass Concentration.
TSP: Total Suspended Particulate Mass Concentration

Figure 4. Increase in Risk of Death vs. Ambient PM Levels (Ref. 20)

McMurry also published the percentage increase in mortality for the cities included in his study as a function of increased exposure to PM (Ref. 20). Figure 5 shows a 4 to 8% increase in mortality rate corresponding to a 100 μg/m³ increase in the Total Suspended Particle Mass Concentration.
As can be seen from the studies listed above, there is overwhelming evidence that diesel PM and PM from other sources is detrimental to human health and the environment. It is also clear that diesel PM contributes a significant percent of the total ambient PM concentrations, particularly in urban areas. Ambient diesel particulate loading has actually decreased over the past ten years even though there has been a significant rise in the use of diesel engines over this time. Figure 6 shows the past decrease (and projected decrease) in heavy-duty diesel vehicle emissions, taking into account the mileage covered by vehicles. Figure 7 shows the trend in diesel PM emissions standards from 1988 to the upcoming Tier II emissions standards. These figures were published at the Better Air Quality Motor Vehicle Control & Technology Workshop, 2000 (Ref. 32).
VMT: Vehicle Miles Traveled

Figure 6. Past, Present and Projected Future Emission Levels from Heavy Duty Diesel Vehicles
(Ref. 32)

Figure 7. Past and Present NOx and PM10 Emission Regulation for Diesel Vehicles in the US
(Ref. 32)
These improvements in diesel emissions over the past 10 years can almost entirely be attributed to more stringent particulate emissions regulations for stationary and non-stationary sources as well as improved diesel engine and diesel emissions technology. Diesel engines continue to grow in popularity and usage due to a variety of factors including efficiency, durability and lower emissions of other harmful substances when compared to gasoline engines. If suitable technology can be developed to eliminate or significantly reduce diesel particulate emission as well as a few other toxins (such as Nitrous Oxides), diesel engine technology has the potential to be cleaner than gasoline engine technology. This technology would significantly improve adverse health effects due to these contaminants.
1.2 Particulate Emissions Regulations

The most widely recognized upcoming diesel emissions standards are the US EPA Tier II standards and the European ‘Euro’ standards. Many of these standards for mobile sources focus on trucks, buses and more recently, sport utility vehicles. This is because trucks and buses contribute most of the PM from all diesel mobile PM sources. Figure 8 shows the relative contributions from different classes of diesel vehicles (Ref. 32).

![Diagram showing relative contributions of different classes of diesel vehicles](image)

**Figure 8.** Dominance of Heavy Duty Vehicles in the Total Emissions of NOx and PM10 (Ref. 32)

New stringent EPA standards have been recently instituted pertaining to emissions standards for heavy-duty vehicles. These new standards are referred to as Tier II and will be instituted in two distinct phases addressed in EPA regulatory announcements 420-F-00-022 (Ref. 54) published in May 2000 and 420-F-99-057 published in December 2000 (Ref. 53). The first phase regulates NO and HC emissions for all vehicles with a gross weight rating of more than 8500 lbs. These new standards would take effect in 2004-2007. The second phase would begin with lower sulfur diesel standards (less than 15 PPM sulfur) by the middle of 2006. PM will also be regulated and will take full effect in 2007. NOx and NMHC (nonmethane hydrocarbons) will also be more stringently regulated than previous standards and would be fazed in between 2004 and 2007. The
new EPA Tier II diesel emissions PM standards that will be fully instituted by 2007 are as follows (Ref. 53, 54).

**Table 1: Tier II EPA Diesel PM Emissions Standards**

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<th>GVWR</th>
<th>PM</th>
<th>unit</th>
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<td>0.02</td>
<td>g/mi</td>
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<tr>
<td>10000-14000</td>
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<td>g/mi</td>
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<tr>
<td>&gt;14000</td>
<td>1.9-2.3</td>
<td>g/mi</td>
</tr>
<tr>
<td>HDE</td>
<td>0.01</td>
<td>g/bhp-hr</td>
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GVWR: Gross Vehicle Weight Rating  
HDE: Heavy Duty Engine

Several engine and emissions controls manufactures and the EPA have stated that diesel emissions aftertreatment devices would be needed to meet these standards as on board engine controls and technology would not be sufficient (Ref. 34, 55, 65).
1.3 Current Emissions Treatment Technology

The Manufacturers of Emissions Controls Association (MECA) has identified several current technologies regarding diesel emissions aftertreatment devices. These devices are listed in a report titled “Demonstration of Advanced Control Emissions Technologies Enabling Diesel-Powered Heavy-Duty Engines to Achieve Low Emissions” (Ref. 65). A brief evaluation of some of these devices, many of which have since been tested on trial fleets, is also discussed. This evaluation was done in conjunction with the Southwest Research Institute. Another valuable reference is an SAE paper entitled, ‘Diesel Emissions Control in Review’ published in 2001 by T. Johnson of Corning Inc (Ref. 40). This paper reviews many of the technologies being applied to the aftertreatment of diesel exhaust as well as the composition and hazards associated with different elements of raw diesel exhaust. The devices listed in The MECA report (Ref. 65) are as follows:

1. Diesel oxidation catalysts (DOC)
2. Diesel particulate filters (DPF)
3. Selective catalytic reduction (SCR)
4. Fuel-borne catalysts (FBC) in combination with filters and oxidation catalysts
5. Combinations of the above technologies

Another paper published by SAE and written at the Ford Research laboratory (Ref. 41) also gives a list of possible technologies or combinations of technologies that may be effective in controlling diesel particulate emissions. The paper also lists some of the drawbacks to these technologies. One of the recurring drawbacks to some of these technologies that include catalysts is the working temperature requirement for the catalysts. The optimum working temperature for many of the catalysts is outside of the normal operating exhaust temperature for most operating conditions. The list of possible solutions given in this paper (Ref. 41) is shown below.

1. Ceramic Wall Flow Filter (Filter with thermal regeneration at about 550 C. Heat is provided by engine.)
2. Catalyzed Filter (Filter with a catalyzed substrate; PM oxidation above 300 C)
3. Fuel Catalyzed Filter (Fuel borne catalyst combined with a filter)
4. Continuous Regenerating Filter (Combination of NO to NO₂ oxidation catalyst with wall flow filter for oxidation of particles by radicals; catalyst operates above 250 °C)

5. Plasma Regenerated Filter (Non Thermal Plasma conversion of NO to NO₂ with wall flow filter for oxidation of particles by radicals; not temperature dependant)

6. Additional Heat Regenerated Filter (Filter with external heat source for regeneration such as electrical, fuel combustion and microwave)

I will now discuss some of the current prevalent diesel exhaust PM control technologies.

**1.3.1 Diesel oxidation catalysts (DOC)**

Several exhaust aftertreatment devices include catalysts that are mainly intended for reducing harmful gaseous emissions from the diesel exhaust stream. A SAE paper presented by the Ford Research Laboratory confirms that stand-alone catalyst systems are primarily effective against NOₓ and other gaseous emissions (Ref. 41). The paper goes on to state that catalyst technologies would have to be combined with some sort of a filter to be effective against PM emissions.

Diesel oxidation catalysts have had some success, but this technology has had several problems related to fouling by diesel PM and sulfur compounds. Diesel oxidation catalysts are effective at removing the Soluble Organic Fraction (SOF) of diesel exhaust, which accounts for 25 to 30% of PM by mass (Ref. 40). They are however not very effective at removing nano-particles and carbonaceous PM from the exhaust stream (Ref. 40). MECA reports that they have achieved a total diesel oxidation catalyst particle removal efficiency of about 42% for a heavy duty Detroit Diesel engine (Ref. 65). Diesel oxidization catalysts require very low sulfur content for their operation (Ref. 40, 65). Sulfur will be a regulated diesel fuel contaminant in future (US). Problems related to sulfur fouling for the devices listed above could be significantly reduced by upcoming diesel fuel sulfur content regulations.

Catalyst technologies are temperature dependent; in fact, some of the catalysts in use require a higher operating temperature than is encountered in many standard-operating environments for optimum operation. There are also emissions problems at start-up when the catalyst is not yet up
to standard operating temperature. It seems that catalysts would have to be combined with some other type of technology to make them a viable option. It should be noted that several of the other technologies investigated include some type of catalyst integrated into the system (Ref. 65). The principle of a diesel oxidation catalyst is shown in the Figure 9 (Ref. 63).

![Figure 9. Schematic and Operating Principle of a Diesel Oxidation Catalyst (Ref. 63)](image)

1.3.2 Diesel particulate filters (DPF)

Compared to other technologies, diesel particulate filters have seen the most widespread use. This technology has shown some success in the control of diesel PM and several studies indicate that this technology would allow heavy-duty diesel engines and vehicles to meet new PM emission standards. This technology, however, has its problems. Filtration technologies present a backpressure problem for diesel engines and rob the engine of some operating efficiency. They can also become plugged after prolonged operation. This is expected considering the heavy particulate loading of raw diesel exhaust.

Some regeneration techniques have been looked at for diesel particulate filters. Most of these include heating to very high temperatures by burning diesel fuel or electrical heating. These regeneration methods decrease fuel economy, produce harmful emission of their own or decrease
the vehicle efficiency and performance. Non-regenerative systems require manual removal and proper disposal of the particulate filters and are thus a high maintenance item. Some of the filtration substrates that have been investigated are: ceramic, glass ceramic, silicone carbide, glass or metal fibers, knit fibers and sintered metal. Several of them have been treated with catalyst substances to assist in the reduction of particulate accumulation and the reduction of other harmful gaseous emissions. Figure 10 shows some typical configurations and types of DPFs (Ref. 52).

Figure 10. Different Layouts and Types of Diesel Particulate Filters (Ref. 52)

1.3.3 Selective Catalytic Reduction (SCR)

Selective Catalytic Reduction is a system of various catalysts designed to reduce selected substances in the exhaust stream. These have many of the same problems encountered by Diesel oxidation catalysts. SCR is primarily targeted to the reduction of NO\textsubscript{x} components of diesel exhaust. However, unlike oxidation catalysts, a reductant is added to the exhaust stream in order
to convert NO to nitrogen and oxygen in what would otherwise be an oxidizing environment (Ref. 63). The reductant that is added to the exhaust stream needs to be stored on board the car and have its own metering system. Ammonia and urea are typical additives (reductants) used for this purpose. The reductant also has to be replenished from time to time, which is undesirable. The reductant allows for efficient operation of the catalysts onboard the vehicle. SCR has generally not been shown to be effective for PM reduction. Figure 11 shows the general configuration of a SCR system (Ref. 66).

![Diagram of Selective Catalytic Reduction System](image)

Figure 11. Schematic of Selective Catalytic Reduction System (Ref. 66)

1.3.4 Fuel-borne catalysts (FBC) in combination with filters and oxidation catalysts

Fuel borne catalysts are almost always combined with another type of emission control technology to assist with the particle oxidation and reduction of other harmful gaseous emissions. These catalysts are injected into the fuel stream and alter the composition of diesel emissions. These catalysts therefore require replenishing after some period of operation and are
therefore unfavorable to several automotive manufacturers. Some of the fuel borne catalysts that are used for this purpose are cerium, iron/strontium and platinum/cerium (Ref. 40). One other restriction on some of these fuel borne catalysts is the cost associated with producing large quantities of these catalysts. Many catalysts are often composed of rare and expensive substances such as platinum. Urea injection has been found to improve the operation of selective reduction catalyst and hydrocarbon injection aids the oxidation of PM for other catalyzed surfaces. Fuel borne catalyst has had some success in reducing diesel PM (Ref. 40), however it is still a generally undesirable technology due to some of the drawbacks mentioned above.

1.3.5 Continuous Regenerating Trap (CRT)

A continuous regenerating trap utilizes a catalyst followed by a particulate filter. The function of the catalyst is to convert NO into NO₂ radicals. The NO₂ is then used to oxidize soot collected on the filter. These catalysts are typically very expensive and the most common catalyst coating that is used in CRTs is platinum or platinum mixes. There are some difficulties encountered when using this system. The catalyst only operates well above temperatures of about 300 °C (Ref. 64). PM is trapped in the filtration media until this temperature can be obtained though heating from the exhaust. If this temperature cannot be obtained by exhaust heating then the filter can become clogged, reducing the efficiency of the engine. The main drawback to this type of system is that it is extremely sensitive to exhaust sulfur contamination. Sulfur is a typical contaminant contained in diesel fuel, which manifests itself as sulfur oxides in the exhaust. Sulfur, even in small concentrations can cause fouling of the catalyst. Ultra low sulfur content fuel is therefore required for the use of a CRT (Ref. 64). A schematic of the operation of a CRT is shown in Figure 12 (Ref. 64). The NO to NO₂ conversion catalyst is shown on the left and the wall flow filter is shown on the right.
Figure 12. Schematic of Operating Principles of a Continuously Regenerating Trap (Ref. 64)

Several of these technologies stand to benefit if a separate system was designed to efficiently extract and oxidize PM to provide a continuously regenerating system with less power or fuel consumption than a regenerative system for a diesel particulate filter. A device that would have a very small pressure drop would be favorable, as it would maximize the efficiency of the engine. Such a device would need to perform two different functions. The first function would be to extract the particle matter in the exhaust stream without inhibiting or restricting the overall exhaust flow. The second function would be to oxidize the collected PM.
Chapter 2: Conceptual Framework

2.1 Design Objective

A diesel engine emissions particle removal system to trap and oxidize micron-sized particles (.01 to 10 Microns) in the exhaust stream is being developed. ESP technology and NTP regenerative methods are utilized.

The problems that were specifically addressed in the design are the appropriate electrode shape, electrical requirements, and geometrical configuration and packaging of the collection system. This device was designed and evaluated analytically using scientific as well as established empirical methods. When possible, more than one analytic or empirical approach was utilized to confirm the results obtained by different methods (formulae). This was done through correlation between similar results obtained for several calculations in the analysis. Since an analytic approach was taken in designing this device, several engineering assumptions are made. These assumptions are evaluated where possible. The efficiency and power usage of the device was evaluated. The conceptual design of this device as part of this thesis is complete enough to produce a prototype device that can be evaluated in a laboratory. Some minor additional work may be necessary such as the specification of insulation and other materials used in the construction of this device. Non-critical design details are also omitted and are left to the discretion of the person building this device. The analytical methods used in the design have been incorporated into a spreadsheet such that changes made to the operating conditions and design parameters can be evaluated.

A target ‘current technology’ diesel vehicle with defined emissions characteristics (data) was used as a basis for the design of this device. A smaller vehicle was targeted, as further development and construction of this device would be easier on a smaller scale. It is anticipated that the device designed as part of this thesis would be scaled and adapted for larger heavy-duty applications. The emissions characteristics obtained for the target vehicle were used as an input for the analysis. The output of the analysis can predict the combined operating characteristics of this device for any particular definable operating condition.
It is anticipated that the NTP produced for particle charging would also be used for the formation of radicals in the exhaust stream. These radicals have been investigated as a means to oxidize carbon based PM as it is precipitated out of the exhaust stream. An analytical analysis of the chemistry involved in this is beyond the scope of this thesis. The chemistry involved is very complex and dependant on changing operating conditions. Instead, an investigation was conducted into past work that has been completed in this area. These past works are correlated to the current work in this project to allow this device to complete its regenerative function. It is anticipated that the regenerative method sought for this device will be investigated experimentally. The technology developed in this thesis is targeted to address EPA Tier II diesel particulate emissions standards that take full effect in 2007.
2.2 Scope and Limitations

The objective of this thesis is to develop a design for a self regenerating diesel emissions particle trap that can be analytically shown to fulfill the requirements of capturing and oxidizing PM from a diesel exhaust stream. The proposed device is discussed in Section 2.3. The resulting design will be complete enough so that a prototype can be built. The science and physics of the processes involved in the operation of the device are also investigated. The science involved in designing and analyzing this device deals with electrical and microscopic phenomenon that may not be fully explained through pure analytical methods. Much of the analysis is therefore based on past empirical work or analytical methods that contain correction factors for predictable differences between scientific and experimental results.

The analysis done here is able to predict the particle removal spread by mass (vs. particle diameter) for any definable operating condition. The self regenerating diesel emissions particle trap will be built to create uniform flows with no significant velocity or pressure gradients. This will be accomplished through the use of flow straighteners and flow vanes. Further investigation will be required to evaluate the actual flows that result. Turbulence is assumed for all operating conditions due to the pressure pulsations (produced by the engine) in the exhaust stream. The specific energy requirements of this device are evaluated as part of the analysis. All attempts are made to minimize energy consumption. Every effort is also made to keep energy consumption of this device to a reasonable level (less than 2% of total engine energy output) while maximizing the efficiency of the device.

The results of the analytical and/or empirical work are correlated to past work done in this area. As mentioned previously, the regenerative function of this device will not be designed analytically due to the complexity, variability and lack of complete understanding of these chemical processes. Past works are investigated that indicate that exhaust stream radicals (such as NO₂, O, and OH) can be used to oxidized carbon based PM. The recommendations of these past works are used to adapt the device as best as possible to perform a self regenerating function.
The design and investigation of the electrical devices needed to supply the self regenerating diesel emissions particulate trap is outside the scope of this thesis. The analysis done in this thesis was done at a steady DC voltage. Recommendations are made based on past works that indicate that the use of DC high frequency waveforms can be used to improve the efficiency of the device while minimizing energy consumption and sparkover problems. It is anticipated that further experimental investigation into these waveforms will be done at a later date.
2.3 Proposed Self-Regenerating Diesel Emission Particulate Trap

The proposed self-regenerating diesel emission particulate trap combines a corona discharge device that will be placed in the untreated exhaust stream followed by a cellular collection surface in a separate section where particles are collected. The corona discharge device is intended to serve two functions. The first function is to charge particle matter by generating a NTP, the second function would be to create radicals in the exhaust stream as NO₂, O and OH through an ionization and disassociation process. The radicals that are created are intended to be oxidizing agents for the particles that are collected in the precipitation section of the device. This section of the thesis explains some of the conceptual design aspects. Detailed designs and construction information are given in Section 4.4. A cross section of the proposed device showing all of the major components is shown in Figure 13.

![Device Cross-Section Schematic](image.png)

Figure 13. Device Cross Section Schematic

A corona discharge device is placed in a short cylindrical section at the inlet of the self-regenerating diesel emission particulate trap. A fine metallic wire electrode is used for the discharge electrode. Since carbon particles present the greatest difficulty in the control of diesel exhaust particulate, the analysis is completed based on spherical carbon particles in various sizes
as the primary particulate contained in the exhaust. This assumption is made to facilitate the analytical investigation. Due to the physical properties of carbon, the material is very easy to charge and requires a very short charging residence time (on the order of milliseconds). The device can therefore afford a very short charging length even at very high aerosol velocities. The discharge electrode is suspended in a larger cylindrical (or receiving) electrode. All of the gas passes between the cylindrical and the discharge electrodes. An adapter (diffuser) section may be needed at the inlet of the device to connect the exhaust pipe diameter to the cylindrical electrode diameter. The dimensions of all components in the charging section are vital to the operation of the device and are therefore closely controlled.

The charging section of this device is connected to a precipitation section (See Figure 19 and 33). These two sections are attached using a diffuser/adapter with flow vanes to ensure uniform flow into the precipitation section. The precipitation section consists of an array of square cells that the exhaust flows through. This array serves two purposes. The first purpose is to provide a precipitation surface that the charged particles would be electrostatically attracted to and eventually adhere to. The cellular array provides a short distance for a particle to travel before it encounters a precipitation wall. The second function of the cellular array is to laminarise the flow of exhaust to some extent. Several sources have indicated that laminar flow is favorable for precipitation of particles (Ref. 2, 8).

The precipitation of particle matter out of the exhaust stream serves to increase the time that radicals formed in the charging section have to oxidize the PM in the precipitation section. This precipitation and oxidization processes are meant to occur simultaneously so as to have a system that continuously regenerates itself without becoming plugged with PM. This device can also be combined with other exhaust aftertreatment devices such as catalysts not previously compatible with particulate laden exhaust. This device is unique because it employs a straight flow through particle precipitation system for removing particles from the exhaust stream which departs significantly from prior art which utilizes filtration and catalyst technologies. Particles are then continuously oxidized using radicals produced in the NTP. The combination of these two functions and the methods and configuration described in this thesis have not been previously attempted. This is according to the research done during the development of this thesis.
Part of this thesis encompasses the analytical investigation of the design and performance characteristics of this device. Due to the types of technology used such as corona discharges, the dimensions of this device are critical. A great portion of the work is therefore targeted towards defining and optimizing these dimensions (trial and error using spreadsheet model). The electrical input is also considered in the theoretical treatment. A good balance is desired for the power consumption of this device considering, particle collection, radical formation and sparkovers. Methods and recommendations for minimizing undesired sparkovers are discussed later in Section 4.3.2. Every stage of analysis and design in this thesis is done considering the restrictions associated with an automotive application.
2.4 Target Vehicle and Emissions Characteristics

To simplify the analysis in this thesis, a target vehicle was chosen with known exhaust and operating characteristics. This would allow specific exhaust characteristics to be analyzed using the theoretical approach. A smaller vehicle was also chosen as this target vehicle even though most upcoming diesel emission standards are targeted towards heavy duty vehicles. This was done because of the ease and economy of further development of this device with a smaller engine in mind. The vehicle that was chosen was a 1999 Volkswagen Golf equipped with a 1.9L diesel turbocharged engine with exhaust gas recirculation (EGR). There is an abundance of emissions and operating data available for this particular vehicle as it is a popular research vehicle (due to size, cost, availability etc.) for many experimental programs (Ref. 12). There is also data available for the predecessor of this vehicle in the Volkswagen line, the Rabbit.

The primary source of emissions data for the target vehicle was obtained from an AEAT paper (Ref. 12). This paper targeted measurement and instrumentation methods for emissions particulate measurement. During some of AEAT’s evaluations, detailed emissions characteristics were obtained for several vehicles including the Volkswagen Golf. Several of these tests were done using recognized and mandated drive cycles for the US and Europe. The analysis shown in this thesis was done using data for emissions during 120Km/hr driving. This condition was the highest speed available and presented the ‘worst’ operating condition for particle loading and exhaust velocities for the device proposed. The specific data used is shown in the Table 2.

Reference 12 provides a lot of useful information about the composition of diesel emissions exhaust for the Volkswagen Golf as well as several other vehicles. Another important set of information that was needed was the particle size composition in the diesel exhaust. This information was not available in the AEAT report. No information could be found that specifically addressed the particle size distribution in a diesel Volkswagen Golf. Sources were found however that did have experimental data on typical particle size distributions for diesel emissions (Ref. 36, 40, 41). A typical particle size distribution for diesel emissions was published by Kittelson at the University of Minnesota (Ref. 23). A reproduced graph of this distribution is shown in Figure 14.
Table 2: Emissions Data for VW Golf 1.9l Diesel Turbocharged Vehicle with EGR

Vehicle: VW Golf 1.9l diesel turbocharged with EGR
Mileage: 6400 Km
Max Horsepower: 110 HP 82060 Watts

Hot Steady State Exhaust Analysis

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Unit</th>
<th>Speed Idle</th>
<th>Speed 50 Km/h</th>
<th>Speed 75 m/h</th>
<th>Speed 120 Km/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>g/min</td>
<td>21.36</td>
<td>59</td>
<td>329</td>
<td>12</td>
</tr>
<tr>
<td>CO</td>
<td>g/min</td>
<td>0.055</td>
<td>0.007</td>
<td>0.09</td>
<td>0.013</td>
</tr>
<tr>
<td>THC</td>
<td>g/min</td>
<td>0.026</td>
<td>0.028</td>
<td>0.033</td>
<td>0.005</td>
</tr>
<tr>
<td>NOx</td>
<td>g/min</td>
<td>0.212</td>
<td>0.17</td>
<td>0.18</td>
<td>0.09</td>
</tr>
<tr>
<td>Smoke K</td>
<td>m⁻¹</td>
<td>0.0012</td>
<td>0.041</td>
<td>0.075</td>
<td>0.01</td>
</tr>
<tr>
<td>Particulate</td>
<td>Kg/s</td>
<td>0.000001</td>
<td>0.00000000</td>
<td>4.30556E-07</td>
<td>2.77778E-08</td>
</tr>
<tr>
<td>Particulate</td>
<td>mg/Km</td>
<td>6.3 mg/min</td>
<td>31</td>
<td>108</td>
<td>21</td>
</tr>
<tr>
<td>Exhaust Flow</td>
<td>l/min</td>
<td>400</td>
<td>570</td>
<td>2000</td>
<td></td>
</tr>
<tr>
<td>Temp</td>
<td>deg C</td>
<td>132</td>
<td>199</td>
<td>415</td>
<td>7</td>
</tr>
</tbody>
</table>

Figure 14. Lognormal Particle Distribution (Mass Fraction vs. Particle Diameter)
(Ref. 23)
The particle size distribution shown in Figure 15 (Ref. 36) was adapted for the analysis done in this project since exhaust particle size distribution was not readily available for the target vehicle. This distribution was separated (discretised) into several different size ranges and was used in the determination of the overall particle removal for the proposed device.

\[
W_p = \text{Particle mass by size; } W_t = \text{Total particle mass of all sizes}
\]

S2000 and S500 represent different grades of diesel fuel

**Figure 15. Typical Diesel Particulate Emissions Size Distribution by Mass** (Ref. 36)

The particle size distribution that was adapted as an input for the analysis done in this thesis is shown in Figure 16. The cumulative mass for all particle sizes for the distribution shown in Figure 16 is approximately equal to the total particle mass output for the target vehicle. It can be noted visually that there are differences between the particle size distributions shown in Figures 14 and 15. Particle size distributions such as the ones shown in Figures 14 and 15 will generally change somewhat depending on the particular engine, the operating conditions (speed and load) and the experimental equipment used to collect the data. Any definable particle size distribution can be used as an input to the analytical model developed in this thesis.
Figure 16. Discretised Particulate Size Distribution by Mass
Chapter 3: Methodology and Analysis for Particle Collection

3.1 Technical Approach

The analysis of the design concept discussed previously was done in several discrete steps. As mentioned earlier, a 1.8L Diesel Volkswagen Golf was chosen to base the calculations on. This vehicle provides the basic exhaust and emissions information that the analysis is based on. There are several different parameters that arise as part of the analysis. These parameters have been put into three categories. The three categories are:

1. Calculated values (Light brown cells in spreadsheet analysis)
2. Given values (Light green cells in spreadsheet analysis)
3. Assumed values (Light blue cells in spreadsheet analysis)

Assumed values are “design parameters” that can be changed to alter the operation of the device for example, the collection section grid cell size ($g_s$). Given values are “constants” that arise from the physical conditions such as material properties or an operating temperature, for example, the relative dielectric constant of carbon ($k$). Calculated values are intermediate or final results of some of the calculations, for example, the corona initiation field strength ($E_c$). Some of the calculations have been done by more than one method to verify (cross-reference) the results. All of the initial calculations are done using a single particle radius. The analysis is then extended to include the entire particle size spectrum encountered in typical diesel emissions. The analysis has been put into a spreadsheet where all of the steps are linked. This allows the design changes to be quickly evaluated and intermediate results can be monitored.
3.1.1 Technical Approach Summary

The analysis of the self-regenerating diesel emission particulate trap follows the steps shown below which are detailed in the following sub-sections.

1. Initial investigation of device requirements
2. Determination of corona onset voltage
3. Determination of electric field distribution
4. Determination of particle charge by field charging
5. Determination of particle charge by diffusion charging
6. Determination of total particle charge
7. Determination of particle migration velocity
8. Determination of total precipitator efficiency and particle output

The first steps to this approach include some basic estimation of the operating parameters that are desired for this device. The first of these operating parameters is the cross sectional area that would provide the desired gas flow rates for different sections of the proposed device. The desired gas flow rate was then estimated based on the recommendations from two different sources (Ref. 2, 3). These recommendations are discussed later in Section 4.3.3. The second major operating parameter that was determined is the desired particle migration velocity that allows the proposed device to operate at specified target particle removal efficiency. These estimations are a guide for the analysis that follows.

The next step is to determine the corona discharge onset voltage. This gives the minimum electrode voltage that will produce a corona for the charging section and electrode geometry. The charging section and electrode geometry fall into the ‘assumed values’ category and are ‘design parameters’ that can be changed. The corona discharge onset electrical field at the discharge electrode is also determined as part of this step. The corona onset voltage and the onset electric field are partially dependent on operating pressure, temperature and gas density. This is because these factors affect the electron mobilities. These factors are all accounted for in this section.
The electric field based on an input current for the charging section of the device is then determined. This input current is an ‘assumed’ or input value. An operating input voltage is determined which is a function of the input current. The electric field is a significant factor in the level of charging that is acquired by particles passing through the charging section. Two methods are used to calculate this electric field. These two methods are described in detail in Section 3.4. The results of the two methods used match very closely. The lowest value of this calculated electric field is used for most of the following calculations. This gives a worst-case scenario of the operation of this device. Similar assumptions based on the worst-case scenario are used at several other points in the analysis. The power consumed by this device is also calculated in this section. The ratio of power usage to total engine power output is given as a percentage. A steady DC input to this device is used for the analysis for reasons of simplicity. Experimental investigations of this device should however be extended to include DC waveforms. DC waveforms have been shown to have several benefits (Ref. 2, 39, 49), but this topic is be addressed later in Section 4.3.2.

The acquired particle charge is then determined. There are two main methods for particle charging. The first method is diffusion charging and the second method is field charging. One of these two methods is usually the dominant charging mechanism depending on the particle size and other factors. The spectrum of particle sizes encountered in diesel exhaust requires that both of the charging methods be considered to significantly affect the total particle charge. The specific mechanisms of particle charging are discussed in detail in Sections 3.5 through 3.7. Field charging attains a limit after a specific time where no more charge is acquired for a given electric field. The device charging section length is determined based on the time needed to acquire the field charging saturation charge and the average gas velocity. The charging section is discussed in detail with drawings in Section 4.4. Diffusion charging attains no saturation point. Diffusion charging is therefore determined for the same conditions as was determined for field charging. These two charging effects are added to produce the total particle charge.

The particle migration velocity is then determined. These calculations involve the mechanics of the particle. Electrostatic, drag and accelerating forces are all accounted for in this section. This
section includes the first consideration of the precipitation section of this device. The precipitation section is described in detail with drawings in Section 4.4. The grid provides two main functions. The first function is to laminarise the flow (reduce turbulence) and the second function is to provide a very short distance between a particle and the collection surface (the grid). The close proximity of particles possessing a similar charge causes a repulsive force inside each grid that pushes the particles towards the grounded grid surface. When a particle touches a collection surface, it should be held there for some period of time by the electrostatic force as its charge is slowly dissipated through the grid. The collected particles are then oxidized by mechanisms discussed in the Section 4.2.

Particle collection efficiency is then determined based on the preceding calculations. It is anticipated that some of the precipitated particle matter will not remain attached to the wall, but will be re-entrained in the flow. A factor for particle re-entrainment is therefore considered. The exact value for this re-entrainment is difficult to model. A value is therefore assumed which can be changed based on experimental investigation into the operation of this device. The last step is to extend the analysis for a complete particle size spectrum that accounts for changes in the precipitation section space charge along the length of the precipitator.

The precipitation section was divided into ten sections (slices) perpendicular to the flow. This is described in detail in Section 3.1.8 (see Figure 19). The division of the precipitation section allows for the consideration of each section accounting for the change in the electric field in the precipitation section as charged particles are removed. The particle density at the inlet of the precipitator is much higher than at the outlet of the precipitator. This density gradient is what causes the change in the electrical field in this section. The particle output for any section would be the particle input into the following section. This analysis allows for the determination of the specific particle removal from each of the ten sections by particle size. A total device particle removal efficiency was then determined. An important result of this analysis is that it shows the particle removal of the entire system (by mass) further broken down by particle size.
3.1.2 Initial Investigation of Device Requirements

The first step in the design of the proposed device was to determine some basic parameters for the operation of the device. The worst-case conditions are considered for all of the analysis done. Several works discuss the desired gas velocities for effective ESP of PM (Ref. 2, 3). The recommended aerosol velocity in the collection section of the precipitator is less than 2 m/s (Ref. 2). A desired gas velocity of 1 m/s was chosen for the analysis. This value can be changed, as it is an input variable for the analytical model. The geometry of the device would have to be designed to produce this aerosol flow rate with the given volume flow rate. This device was designed around the diesel Volkswagen Golf described earlier operating at a speed of 120 Km/h (Ref. 12). The volume flow rate for this speed was found to be 0.0333 m$^3$/s. This operating speed corresponds to the highest particle density and flow rate in the exhaust. It was therefore selected to evaluate the performance of the proposed device at one of the harshest operating conditions that this device will see. A square cross sectioned precipitation section was selected in the basic design as shown in Figure 17. Further investigations and experiments can be conducted with different geometry cross sections with different types of polygonal collection grids. The cross sectional area was determined using Equation 1.

\[
A_{cs} = \frac{V_g}{V_d}
\]

(1)

Where $A_{cs}$ = cross sectional area of precipitator; $V_g$ = exhaust volumetric flow rate; $V_d$ = desired precipitation section gas velocity

From the required precipitation section cross sectional area determined, dimensions were found that would accommodate this area for a square section. This dimension (g) was found to be 0.211 m as shown in Figure 17.
Figure 17. Precipitation Section

These calculations are set out in the spreadsheet such that the desired gas velocity is an input (can be changed) and the volume flow rate is a constant. The collection area dimension is the output. The Deutsch-Anderson equation enables the determination of the collection efficiency given the collection area geometry, the gas flow conditions and the individual particle velocities. This equation was developed in the early 1920’s and is now a standard in many texts (Ref. 1, 2, 6). This equation was developed based on the following assumptions:

1. Particles are fully charged at inlet to collection area
2. Particles are distributed uniformly in collection area
3. Gas velocity does not affect particle migration velocity
4. The particle moves with its electrical terminal velocity
5. Particle on particle repulsion can be neglected
6. There are no additional disturbing effects such as re-entrainment and uneven gas flow

The Deutsch-Anderson equation is developed as follows. The theoretical particle migration velocity, \( W \) is given by (Ref. 2):
\[
W = \frac{q_p E_{\text{col}}}{6\pi \eta a_p} C_u
\]  

Where \( q_p \) = total particle charge; \( E_{\text{col}} \) = precipitator section electric field strength; \( C_u \) = Cunningham correction factor; \( \eta \) = gas viscosity; \( a_p \) = particle radius

The Cunningham correction factor is required when the particle size is small enough that it loses its continuum characteristic. It is generally required for particles smaller than 10 \( \mu \)m in diameter (Ref.2). The Cunningham correction factor is given by (Ref. 2):

\[
C_u = 1 + 2.46 \frac{\lambda}{a_p} + 0.42 \frac{\lambda}{a_p} \exp\left(-0.87 \frac{\lambda}{a_p}\right)
\]

Where \( \lambda \) = mean free path of molecules

Equation 2 uses the forces generated on a charged particle and the frictional or drag forces acting on the particle to obtain the particle migration velocity. An alternate derivation for the theoretical particle migration velocity is given by Oglesby (Ref. 1) which accounts for the Newtonian acceleration force is given by:

\[
W = \frac{q_p E_{\text{col}}}{6\pi \eta a_p \nu} \left[1 - \exp\left(\frac{6\pi a_p \nu t}{m_p}\right)\right] C_u
\]

Here the term \( \left(\frac{6\pi a_p \nu t}{m_p}\right) \) is the inverse of the time constant governing the length of time needed for the particle to acquire its terminal velocity. A terminal velocity is reached in about five of these time constants (Ref. 1). This time constant is very small for particles below 10 \( \mu \)m in diameter (less than .025 ms) (Ref. 1). The accelerative forces can therefore be neglected for the particle size range dealt with in this thesis. Results from Equation 2 are therefore almost identical to the results from Equation 3 regardless of the input condition used. The result from Equation 2 was therefore used for all analysis that follows.

Particle mobility, \( b_p \) is given by (Ref. 2):

\[
b_p = \frac{q_p}{(6\pi \eta a_p \nu)}
\]

The Coulomb-Stokes value of the particle migration velocity, \( W_e \) is then given by substituting 4 into 2 as follows:
\[ W_e = b_p E_{col} \]

The Deutsch number is then found by:
\[ D = \left( \frac{A W_e}{V_g} \right) \]

where \( A \) = collection area of precipitator.

The collection efficiency is then determined using the Deutsch-Anderson equation shown below:
\[ \eta = 1 - e^{\left( -\frac{A W_e}{V_g} \right)} \]

A modification of this formula is also investigated in the analysis. This modification is based on the work of Cooperman (Ref. 1) and is meant to include diffusion effects along a precipitator. These effects are caused by the decrease in particle concentration along the length of the precipitator. This modification is given in Equation 8.
\[ \eta = 1 - e^{\left( \left( 1 - f \right) \frac{1}{2} \frac{A W_e}{V_g} \right)} \]

where \( f \) = particle re-entrainment coefficient; \( \alpha = \left( \frac{g V_g}{4D_*} \right) \); \( D_* \) = particle diffusion coefficient; \( g \) = precipitation cell dimension.

\( D_* \) is the particle diffusion coefficient that is typically determined experimentally but a typical value is given by Withers (Ref. 4) as 1E-10 m\(^2\)/s. Zhuang (Ref. 27) gives a correlation that allows for the analytical determination of \( D_* \). This correlation was used in this analysis and is given as follows:
\[ D_* = \frac{Cu BT}{6 \pi \nu a_p} \]

where \( B \) = Boltzmann constant; \( T \) = exhaust temperature.

The value determined for the diffusion coefficient from the equation shown above was found to be comparable to the typical value recommended by Withers (Ref. 4). The product of this analysis is to determine the rough dimensions of the precipitation section and the required particle migration velocity needed to attain a desired particle removal efficiency.
3.1.3 Determination of Corona Onset Voltage

A corona discharge is an electrical phenomenon that allows for the creation of ions and the charging of particles in a gas stream. The discharge system always consists of a discharge electrode with very small radii or sharp points and an oppositely charged 'receiving' electrode with comparatively large radius. The discharge electrode is usually contained in or between the receiving electrodes. These electrodes are held at a very high electrical potential difference. The geometry of the discharge electrode causes a concentration of charge at small radii points. Once the potential difference exceeds a certain value, a current can be measured between the discharge and the receiving electrodes. This potential difference and the corresponding field strength are called the corona initiation voltage and field strength respectively. The current measured in such a configuration indicates that a corona discharge has been initiated. If the voltage between the electrodes is increased, a point is reached where there is a complete electrical break down of the gas. At this point a spark over occurs.

The high voltage of the discharge electrode causes the dissociation of electrons. These electrons are accelerated to very high velocities away from the discharge electrode. There are two zones associated with a corona discharge. There is an active zone, which is in the immediate vicinity of the discharge electrode. There is also a much larger passive zone. In the active zone the discharged electron collides with neutral molecules. This collision causes further disassociation of electrons from this neutral molecule. The product of this is two or more electrons and a positive ion. These electrons are now available for further collisions with other neutral molecules. This process causes an avalanche effect in areas where the electrical field strength is high enough to bring electrons to ionization energy levels. The electrons lose momentum with each additional collision and there comes a point where the electrons no longer have enough energy to cause ionization by disassociation. This point marks the extent of the active region.

The positive ions created in the active region are attracted to the negative discharge electrode and are neutralized and reprocessed. The electrons that escape the active region enter the passive region. In this region, molecules are ionized by electron attachment instead of disassociation. The passive zone therefore contains negative ions. The active zone is only a few percent of the
passive zone and as a result the gas is negatively ionized. There are two very distinct electric field regions. The active zone is marked by very high electric field strength that quickly decays as you move away from the discharge electrode. The passive zone is a lower but fairly constant electric field strength region that occupies most of the space between the electrodes. Particle charging primarily occurs in the passive zone by the same electrons that cause ionization of the gas. The active and passive regions can be seen in Figure 18 which shows the electric field strength vs. radius for the entire charging section. No analytic method was found that gives the thickness of the active zone. An assumption was made for a derivation given in Reference 1 that the thickness of the active zone was approximately the thickness of the discharge electrode. Electric field strength plots done as part of the analysis in this thesis indicate that the thickness of the active zone was generally less than 5 mm.

![Diagram showing active and passive discharge zones](image)

**Figure 18. Active and Passive Discharge Zones**

The corona onset voltage was then determined by Equation 9 based on the work of Peek (Ref. 1).

\[ V_c = E_c a_w \ln \left( \frac{r_c}{a_w} \right) \]

where \( E_c \) = corona initiation field strength; \( a_w \) = discharge wire radius; \( r_c \) = receiving electrode radius.

It can be seen from this formula that the corona initiation voltage and field strength are primarily dependant in the geometry of the electrode system. The corona initiation field strength is given by (Ref. 1):
E_c = 3 \times 10^6 \delta m_r (1 + 0.03 \sqrt{\frac{\delta}{a_w}})

where \( \delta = \text{relative air density} = \frac{T_o}{T} \frac{P}{P_o} \); \( m_r = \text{discharge electrode wire roughness factor} \); \( T = \text{temperature} \); \( P = \text{pressure} \). The subscript 'o' indicates ambient conditions.

The formula used for the relative density (\( \delta \)) shown above was suggested based on the work of Oglesby (Ref. 1). This formula assumes that the ambient air and the exhaust gas both have the same gas constant (\( R \)) and constant pressure to constant volume specific heat capacity ratio (\( \gamma \)). Values for diesel exhaust gas could not be found for \( R \) and \( \gamma \). The gas constant for air is 287 J/KgK and gamma is 1.398. The gas constant for all of the major gaseous constituents of diesel exhaust, such as \( \text{CO}_2 \), \( \text{N}_2 \) and \( \text{CO} \), all fall between 189 and 297 J/KgK at the exhaust gas temperature (388K). Similarly, the gamma values for these same gasses fall between 1.288 and 1.372. The similarity between the \( R \) and \( \gamma \) values for air at standard conditions and major diesel exhaust gaseous components at operating temperatures indicated that a reasonable value for \( \delta \) could be obtained without ant modification to the formula above. The discharge electrode wire roughness factor is typically between 0.7 and 0.9 (Ref. 1). Equation 10 has been determined empirically. The relationship indicates that the onset voltage increases as the diameter of the wire increases.
3.1.4 Determination of Electric Field Distribution

The current supplied to the discharge electrode is used as the input for the calculations. The electric field is heavily dependant on the geometry and configuration of the charging section. The voltage needed to supply the input current is also determined. The charging section as motioned previously is composed of a wire discharge electrode enclosed in a cylindrical receiving electrode or anode. The length of this charging section is determined later based upon the length of time needed to charge the particles as well as the aerosol velocity. The exhaust passes through this cylindrical section before entering a diffuser to the precipitation section. The calculations of the electric field, voltage and power requirements are done by two different methods. These methods are then checked for agreement.

The axial symmetry in the charging section allows the problem to be simplified from a two dimensional to a one-dimensional problem. The standard equation for the electric field strength, E at a radius r inside a cylinder with no current flow is given by (Ref. 1):

\[ E = \frac{V}{r \ln(r_c/a_w)} \]  

where \( V \) = applied voltage; \( r_c \) = receiving electrode radius; \( a_w \) = discharge wire radius.

The presence of electrons, ions and charged particles as is the case for a corona discharge causes a transmission of current from the discharge to the receiving electrode. Equation 11 therefore no longer holds. The electric field becomes dependant on the space charge density. This can be found by solving the following Poisson’s equation given in cylindrical coordinates (Ref. 1):

\[ \frac{d^2V}{dr^2} + \frac{1}{r} \frac{dV}{dr} + \frac{\rho}{\varepsilon_0} = 0 \]  

where \( \rho \) = space charge density; \( \varepsilon_0 \) = permittivity of free space.

The current density in any region of space in the charging section can also be given by:

\[ j = \frac{i}{2\pi L_c} \]  

where \( i \) = applied current; \( L_c \) = length of charging section.
The space charge density, \( \rho \), can also be given as a function of the current.

\[
\rho = \frac{j}{bE}
\]

The electric field strength in the space between the electrodes is found by:

\[
E = -\frac{dV}{dr}
\]

Substituting the Equations 13, 14 and 15 into the Poisson’s equation (Equation 12) gives the following:

\[
rE \frac{dE}{dr} + E^2 + \frac{i}{2 \pi \varepsilon_0 b} = 0
\]

where \( b = \) mobility of gaseous current carrier.

Equation 16 is then integrated and solved for the electric field in the inter-electrode space. This integration requires a boundary condition for the solution. The boundary condition is that the electric field strength at the surface of the corona glow region is equal to the corona onset field strength. The corona glow radius is taken to be approximately equal to the discharge wire radius, which is much smaller than the receiving electrode radius. The integration of the Equation 16 with the appropriate boundary condition gives the following form (Ref. 1):

\[
E = \left[ \left( \frac{a_w E_c}{r} \right)^2 + \frac{i/L_c}{2 \pi \varepsilon_0 b} \left( 1 - \frac{a_w^2}{r^2} \right) \right]^\frac{1}{2}
\]

The required boundary condition to find the integral given by Equation 17 is that the value of the electric field at the surface of the corona glow region (active zone) is equal to the corona field initiating strength, \( E_c \) (given by Equation 10) of the gaseous medium at the prevailing pressure and temperature (Ref. 1)

Once the electric field distribution is determined, the required voltage can then be determined. The voltage is determined using the following formula (Ref. 1):

\[
V = \int_{r=a_w}^{r=r_e} E(r)dr
\]
Substituting Equation 17 into Equation 18 and taking the integral gives the following equation where the corona onset voltage was used as before as a boundary condition (Ref. 1):

\[
V = V_c - \frac{V_c}{\ln \frac{r_c}{a_w}} \left[ 1 - \exp \left( \frac{r_c}{a_w} \frac{i/L_c}{2\pi \epsilon_b} \right) \right] + \ln \frac{1}{2} \left[ 1 + \left( \frac{r_c}{E_c a_w} \frac{i/L_c}{2\pi \epsilon_b} \right)^2 \right]^{1/2}
\]

Katz (Ref. 3) gives an alternate method for determining the electric field properties and the required supply voltage. His formulae are based on the work of Townsend and Robinson. The electric field is determined using the following formula:

\[
E = \sqrt{\frac{r_c j_c}{\epsilon_o b} + \frac{a_w}{r} \left[ E_c^2 - \frac{r_c j_c}{\epsilon_o b} \right]}
\]

The determination of the voltage required to drive the given electric field given by Katz (Ref. 3) uses a parameter substitution method to simplify the overall formula and the determination of the operating voltage. The two parameters that are required for the determination of the operating voltage are given below.

\[
\Phi_t = \left( \frac{r_c}{E_c a_w} \right)^2 \frac{r_c j_c}{\epsilon_o b}
\]

\[
\Psi_t = \sqrt{1 + \Phi_t} - 1 - \ln \left( \frac{1 + \sqrt{1 + \Phi_t}}{2} \right)
\]

where \( j_c \) = current density at the surface of the receiving electrode.

\( j_c \) is obtained by using Equation 13 and substituting the discharge electrode radius, \( r_c \) for the general radius, \( r \) in Equation 13 as is shown below:

\[
j_c = \frac{i}{2\pi r_c L_c}
\]
Once the parameters ($\Phi_t$ and $\Psi_t$) in Equations 21 and 22 are determined and the current density at the surface of the receiving electrode has been found, the supply voltage is then determined using the following formula (Ref. 3):

$$V = V_c + V_c \frac{\Psi_t}{\ln\left(\frac{r_c}{a_w}\right)}$$

This method is shown to provide very similar results to the previous method described (Equation 19) as is shown later in the results of this analysis (Section 4.1).
3.1.5 Determination of Particle Charge by Field Charging

Field charging is caused by the collisions of ions under the influence of an electric field with particles suspended in the gas stream. These ions travel along the electric field lines. Once the ion is retained by the particle, the particle becomes charged. Field charging typically dominates for particles with a radius larger than 0.5μm in diameter. Diffusion charging dominates the charging process for particles smaller than 0.2μm in diameter (Ref. 1). In the intermediate range, both mechanisms play a significant role. Field charging is shown to be the dominant particle charging method considering the particle size range and the operating conditions of the proposed device, however, diffusion charging is not considered to be insignificant and is therefore considered and accounted for in the analysis. The determination of particle charging dominance is explained in Section 3.1.7 and the results of this method are described in Section 4.1.

Some of the assumptions are made prior to the determination of a particle charge by field charging. These assumptions are: The particles are considered to be spherical, a particle's field does not interact with any other particle's field and the particles and ion are suspended in a region with a constant electric field. As an ion approaches an uncharged particle in the aerosol stream, an induced dipole is created in the particle through a re-arrangement of electrons in the particle. This can be seen in the Figure 19.

![Figure 19](image.png)

**Figure 19.** Diagram Showing Dipoles of a Particle Subject to a Charge

This induced dipole causes an attraction between the ion and the particle. The ion is then absorbed into the particle and the particle therefore becomes charged. Charge continues to accumulate on the particle in this manner until a sufficient electrostatic field is created around the particle to prevent additional ions from being attracted to the particle. Once this happens, the particle is said to have achieved its saturation charge. This is the point where the particle
accumulates no more charge by field charging for the given ion distribution and the electric field present.

The rate of change of the accumulation of charge on a particle with respect to time is given by (Ref. 1):

\[
\frac{dq}{dt} = \int_{\theta_0}^{\theta_e} (N_o e b E) dA = N_o e b E \left[ 3E_c \cos \theta - \frac{q}{4\pi \varepsilon_o \alpha_p^2} \right] dA
\]

Where \( j \) = current density; \( N_o \) = average ion density; \( e \) = charge of an electron; \( b \) = mobility of gaseous current carrier; \( E \) = electric field strength; \( E_c \) = corona initiation electric field strength; \( a_p \) = particle radius; \( \varepsilon_o \) = permittivity of free space.

In Equation 25, \( \theta \) is the angle between a point on the sphere and the electric field lines. \( \theta_o \) is the limiting angle for charge flow to the particle. \( dA \) is an element of area \( 2\pi a_p^2 \sin \theta d\theta \). When the particle saturation charge is achieved, the electric field in the vicinity of the particle goes to zero as the charges from ions and the particle cancel. The saturation charge therefore occurs when \( \theta \) approaches zero or when \( \cos(\theta) = 1 \). The formula for the saturation charge of a particle is given by (Ref. 1):

\[
q_s = 12 \pi \varepsilon_o a_p^2 E_{min}
\]

where \( E_{min} \) = minimum electric field strength in the charging section.

Substituting Equation 26 into Equation 25 and expanding gives (Ref. 1):

\[
\frac{dq}{dt} = 6\pi a_p^2 E_c N_o e b \left[ \int_{\theta_0}^{\theta_e} \cos \theta \sin \theta d\theta - \frac{q}{12\pi \varepsilon_o a_p^2 \varepsilon_o E_c} \int_{\theta_0}^{\theta_e} \sin \theta d\theta \right]
\]

Taking the integrals in Equation 27 and simplifying gives:

\[
\frac{dq}{dt} = 3\pi \alpha_p^2 E_c N_o e b \left( 1 - \frac{q}{q_s} \right)^2
\]

Integrating this equation gives:

\[
\frac{q^2}{q_s - q} = 3\pi \alpha_p^2 E_c N_o e b t + K
\]
where $K$ is the integration constant.

Applying the initial condition of zero charge gives $K = q_s$. Rearranging Equation 29 gives:

$$q = \frac{t}{t + \frac{4\varepsilon_0}{N_0eb}}$$  

If we designate $\tau$ to be a time constant given by:

$$\tau = \frac{4\varepsilon_0}{N_0eb}$$  

then an expression for particle charge as a function of time can be given by:

$$q(t) = q_s \frac{1}{1 + \tau/t}$$  

Sources (Ref. 1, 2) indicate that a particle reaches its saturation charge in a time that is less than 10 time constants or $10\tau$. A correction factor should be applied to $q_s$ to account for the resistivity of the particles. This factor is of the form:

$$\frac{k}{k + 2}$$

where $k = $ particle dielectric constant.

Since one of the assumptions made in this thesis was that the particles were made of carbonaceous material, a particle dielectric constant, $k$ for carbon of 2.75 was used throughout the analysis. The actual particle dielectric constant for diesel particulate was not known and could not be found in reference materials. Substituting the correction factor given above into Equation 26 gives the equation shown below.

$$q_s = 12 \frac{k}{k + 2} \pi \varepsilon_r a_p^2 E_{\text{min}}$$  

The result for the particle saturation charge given in Equation 34 was used for all the analysis that follows since it gives the more accurate result when compared to Equation 26.
3.1.6 Determination of Particle Charge by Diffusion Charging

The process that causes diffusional charging is very similar to the field charging process. The primary difference is that the ion particle collisions that cause diffusional charging occur due to random thermal ion motion. Diffusional charging requires no electric field. As mentioned before, diffusional charging predominates for particles smaller than 0.2μm (Ref. 1, 2). The molecular density of a gas in a potential filed can be given by (Ref. 1):

\[ N = N_0 \exp \left( \frac{q_p e}{dBT} \right) \]  

where \( N_0 \) = average ion density; \( q_p \) = particle charge; \( e \) = electron charge; \( d \) = distance from particle to position in space; \( B \) = Boltzmann’s constant; \( T \) = absolute temperature.

If then a single particle is considered, then the density of ions becomes (Ref. 1):

\[ N = N_n \exp \left( \frac{q_p e}{a_p BT} \right) \]  

The number of ions that collide with the particle per second then becomes (Ref. 1):

\[ \pi a_p^2 N v_i \]  

where \( v_i \) is the thermal velocity of the ions which is given by (Ref. 1):

\[ v_i = \sqrt{\frac{8BT}{\pi m_p}} \]  

and \( m_p \) is the mass of the particle.

If every ion that collides with a particle is retained, the rate of change of charge (ion-current) is given by (Ref. 1):

\[ \frac{dq}{dt} = \pi a_p^2 e v_i N_0 \exp \left( -\frac{q_p e}{a_p BT} \right) \]  

where \( a_p \) = particle radius; \( q_p \) = particle charge.

Integration of this with respect to time gives the particle charge as a function of time (Ref. 1).
\[ q_p = \frac{a_p B T}{e} \ln \left( 1 + \frac{\pi a_p \sqrt{8 B T \pi n_p e^2 N_o t}}{B T} \right) \]

where \( t = \) charging time.

This gives the total charge by diffusion acquired by a particle.

An alternate method based on the work of White (Ref. 4) was also investigated for determination of the particle charge by diffusion charging. The formula proposed by White is of the form:

\[ q_p = 4 \pi \epsilon_o a_p \frac{B T}{e} \ln \left( 1 + \frac{a_p \sqrt{8 B T \pi n_p e^2 N_o t}}{4 \epsilon_o B T} \right) \]

where \( \epsilon_o = \) permittivity of free space.

Equation 41 provided very similar results when compared to Equation 40. The particle charge by diffusion charging obtained from Equation 40 was used in the calculations that follow.
3.1.7 Determination of Total Particle Charge

Once the particle charge by methods of field and diffusion charging are determined, the total particle charge can be found. There is generally a small particle size range where the overlapping effect of field and diffusion charging is significant. Several sources (Ref. 1, 2) indicate that this range is from 0.2 to 0.4 μm in particle diameter. There is a small variation in this range depending on the source of information. Some sources (Ref. 2, 8, 11) have found it acceptable to either consider only the dominant particle charging method or to add the effects of both particle-charging methods. This method is shown in equation form below:

\[ q_p = q_{pf} + q_{pd} \]

where \( q_p \) = total particle charge; \( q_{pf} \) = particle charge by field charging; \( q_{pd} \) = particle charge by diffusion charging.

Other works (Ref. 1, 4) indicate that the overlapping effects should be accounted for. This can be done by adding the rate of change of particle charge for the two charging methods and then taking an integral of the term obtained to find the total particle charge (Ref. 1, 4, 18). This process requires very complex numerical solutions.

The process used as part of this analysis first utilized simple methods to determine the dominant particle charging method. Field charging was found to be dominant for most of the particle size range. This step was primarily for informational value and for making assessments of the model later. The particle charge obtained by field and diffusion charging were then added together to give the total particle charge. The dominant method of charging was found by the following equations (Ref. 4):

\[ \frac{3a_p E_{avg} ebV}{B\varepsilon_o V} \gg 1 \text{ For field dominated charging} \]

\[ \frac{3a_p E_{avg} ebV}{B\varepsilon_o V} \ll 1 \text{ For diffusion dominated charging} \]

where \( a_p \) = particle diameter, \( E_{min} \) = minimum electric field strength; \( e \) = electron charge; \( b \) = ion mobility; \( B \) = Boltzman constant; \( \varepsilon_o \) = permittivity of free space; \( V \) = applied voltage.
An alternate method of finding the total particle charge was also investigated. This method first requires the determination of several dimensionless parameters. This method is based on the work of Kreamer and Ranz (Ref. 5). The formulae for these parameters are shown below:

\[ N_\gamma = \frac{4}{12} \frac{G \, \nu}{Cu \, E_{\text{min}}^2 a_p^2} \quad N_\beta = \frac{b \, E_{\text{min}} L_c}{4r_c V_{gc}} \]

\[ N_\lambda = \frac{G \, L_c}{6\pi V_{gc} a_p r_c} \quad N_\phi = \frac{\pi \, \nu \, b}{12 \, Cu \, E_{\text{min}}^2 a_p^2} \]

where \( G \) = ion diffusion constant; \( Cu \) = Cunningham correction factor; \( L_c \) = charging length; \( V_{gc} \) = charging section gas velocity; \( r_c \) = charging section radius; \( b \) = ion mobility.

Once these dimensionless parameters are determined, the total particle charge by both charging methods is then found by (Ref. 5):

\[ q_p = \left( \frac{3\pi b a_p}{2 \, Cu \, N_\phi} \right) \exp \left[ \frac{N_\lambda - 32/105}{N_\beta} \right] \]

This formula is semi-empirical in nature. The values of the dimensionless parameters can also indicate if a spark over condition would exist in the charging section. Sparking is not desired because there are high currents associated with sparking causing a large power draw. Sparking also fouls the discharge electrode and compromises the particle charging process. To prevent spark over, the following inequalities must be met:

\[ N_\phi > 30 \quad \text{and} \quad N_\gamma > .5 \]

A third method was investigated for finding the particle saturation charge is given by Cochet as (Ref. 3):

\[ q_s = \left( 1 + \frac{\lambda/a_p}{k-1} \right) \left( 1 + \frac{\lambda/a_p}{k+2} \right) \pi e_o a_p^2 E_{\text{min}} \]

where \( k \) = relative dielectric constant of carbon; \( \lambda \) = mean free path of molecules.

This method adjusts the particle saturation charge obtained by field charging for diffusion charging effects. Once this modified saturation charge is determined, the total particle charge can be calculated using Equation 32 with this modified saturation charge. The first method of adding the charge obtained by field and diffusion charging provided a more conservative (lower) result.
for the total particle charge. The result of the first method (superimposing charge obtained by both field and diffusion charging) is therefore used in all following calculations including the determination of the particle migration velocity, particle collection efficiency and the determination of the overall system efficiency.
3.1.8 Determination of Particle Migration Velocity

To determine the velocity that a charged particle moves with towards a precipitating surface, a force analysis has to be completed for a particle. There are four main forces that act on the charged particle. These forces are: Momentum Force, Electrostatic Force, Drag Force and the Gravitational Force (Ref. 1). The momentum force can be represented by Newton’s Law as follows:

\[
\overline{F}_m = m_p \overline{a}
\]

where \( m_p \) = mass of particle; \( \overline{a} \) = acceleration.

The electrostatic force can be represented by the following.

\[
\overline{F}_{el} = q_p \overline{E}
\]

where \( q_p \) = particle charge; \( \overline{E} \) = electric field vector.

The Drag force can be represented by Stoke’s Law as:

\[
\overline{F}_d = 6\pi \nu a_p |\overline{V}_{rel}| \left( \frac{1}{Cu} \right)
\]

where \( \nu \) = gas viscosity; \( |\overline{V}_{rel}| \) = particle/ gas relative velocity; \( Cu \) = Cunningham correction factor.

If the particle size is small enough that the particle is of comparable size to the gas molecules, the fluid is said to have lost its continuum characteristic. This continuum characteristic is a requirement for many different methods of flow analysis including Stoke’s law. To correct this problem, a correction factor is included in Equation 48. This correction factor will be seen in other equations that follow. The correction factor is called the Cunningham correction factor (\( Cu \)). It is a function of the mean free path of the molecules and the diameter of the particle. This correction factor is given by the following (Ref. 2):

\[
Cu = 1 + 1.246 \frac{\lambda}{a_p} + 0.42 \frac{\lambda}{a_p} \exp \left( -0.087 \frac{a_p}{\lambda} \right)
\]

where \( a_p \) = particle radius; \( \lambda \) = mean free path of molecules.
Gravity can generally be neglected for the size of particles encountered in diesel exhaust (Ref. 1). There are of course other non-ideal forces that act on the particles. These other effects are primarily due to turbulence and secondary flows in the exhaust stream. The particle is therefore not expected to have a predictable path towards the collecting surface. The particles, however, have an average velocity that will cause it to move towards the collection surface. The sum of the forces acting on the particle sums to zero by Newton’s laws. This can be shown as (Ref 1):

\[ \vec{F}_{el} + \vec{F}_d + \vec{F}_m = 0 \]

where \( F_m \) = inertial force, \( F_d \) = drag force; \( F_{el} \) = electrical force.

A Free body diagram of a single diesel exhaust particle in the precipitation section is shown in Figure 20.

![Diesel PM Free Body Diagram](image)

**Figure 20. Diesel Particulate Matter Simplified Free Body Diagram**

The components of these forces perpendicular to the collecting surface were then summed. Expanding Equation 50 term by term with the appropriate force formulae gives:

\[ q \varepsilon E - 6 \pi \nu a_p W \left( \frac{1}{Cu} \right) - m_p \frac{dW}{dt} = 0 \]

where \( W \) = migration velocity in the direction of the collection surface.

Rearranging this gives:
\[
\frac{dW}{dt} + \frac{6\pi \nu a_p W}{m} \left( \frac{1}{C_U} \right) = \frac{q_p E}{m}
\]

Integrating this equation to solve for the particle migration velocity, \( W \) using the initial condition of zero particle velocity gives:

\[
W = \frac{q_p E_{col}}{6\pi \nu a_p} \left[ 1 - \exp\left( \frac{6\pi \nu a_p v t}{m} \right) \right] C_U
\]

where \( E_{col} = \) average precipitation section cell electric field.

This equation can be further simplified if the transient terms are neglected. This effectively means that the particle is assumed to travel at its terminal velocity. This simplification is shown below:

\[
W = \frac{q_p E_{col}}{6\pi \nu a_p} C_U
\]

The results from Equations 53 and 54 were very similar for most particle sizes. This indicated that the particle reaches its terminal velocity in a negligible time period. The average precipitation section cell electric field strength, \( E_{col} \) has to be determined before the precipitation section electric field strength can be determined. This is the electric field strength that exists in each cell in the precipitation section due to the charges of the gaseous ions and the PM. In order to determine the precipitation section cell electric field strength, the average charge in each precipitation cell, \( q_{col} \) had to be determined. The average charge in each precipitation cell is found by summing the charge due to ions and charged PM in a precipitation cell. This is given in the formula below:

\[
q_{col} = N_0 (g_s^2 L_p) e + \frac{NP}{V_g} (g_s^2 L_p) q_p
\]

where \( N_0 = \) average ion density; \( g_s = \) cell cross sectional dimension; \( L_p = \) length of precipitation section; \( NP = \) number of particles per second; \( NC = \) number of cells in precipitation section.

Here the terms on the left of Equation 55 represents the charge due to the gaseous ions and the terms on the right represent the charge due to PM.
The electric field strength in each cell in the precipitation section was then found by using Gauss’s law. The control volume for the application of this law was taken to be the dimensions of a single cell in the precipitation section. An assumption was made that the lines of flux in the cells intersect the wall of the cell at a right angle (perpendicular) even though the cells have a square cross section. This assumption simplified the application of Gauss’s law and is justifiable since the frontal area of each cell in the collection section is small (4 to 10 mm$^2$). This simplification of Gauss’s law is shown in Equation below.

$$E_{col} \approx \frac{q_{col}}{4 \pi L_c \varepsilon_0}$$
3.1.9 Determination of Total Precipitator Efficiency and Particle Output

The particle collection efficiency is found by the Cooperman modified Deutch-Anderson equation discussed earlier in Section 3.2. This formula is shown below.

\[
\eta = 1 - e^{-\left(\frac{1-fK}{2\alpha^2} \frac{AW}{V_g}\right)}
\]

where \( W \) = particle migration velocity; \( V_g \) = exhaust volumetric flow rate; \( A \) = collection area of precipitator; \( f \) = particle re-entrainment coefficient; \( \alpha = (g V_g)/(4D) \); \( D \) = particle diffusion coefficient; \( g \) = precipitation cell dimension.

This equation accounts for diffusional effects along the precipitator as well as re-entrainment effects. This modified equation was used to determine the particle collection efficiency since it provided the most conservative estimate of efficiency.

All of the analysis up to this point disregarded the contributions of a combined range of particle sizes as well as changes in the collection section of the device due to changing particle concentrations. The final part of this analysis seeks to extend the theories and the approaches described in the previous sections to account for these factors. The first step taken was to approximately determine the particle size spectrum based on previous published works. See the ‘Target Vehicle’ section of chapter two for details. This spectrum was discretised into several particle size ranges. The number of particles in each range was then determined such that the adapted distribution closely matched the published distribution and that the total particle output matched the total reported target vehicle output. The particles were in the size range of 0.01\( \mu \)m to 5\( \mu \)m in radius. Twelve discrete particle sizes, each with the appropriate mass loading were used. Once this was done the total particle charge for each discretised particle size was determined.

The second step that was taken was to discretise the collection section in several smaller parts perpendicular to the flow of exhaust. The changing electric field in the precipitation section due to changing charged particle density could therefore be accounted for. The collection section was split into ten discrete equal geometry parts. The collection efficiency for the first collection
section was then determined for all particle sizes. The number of particles exiting this section for each particle size was then determined based on the collection efficiency. These remaining particles were then used as the input particles going into the subsequent collection section. The collection field was recalculated in every section based on the particle loading in that section. This process was repeated for all the remaining sections. The total particle mass removal for each section was determined as well as the total particle removal of the entire device. The percentage removal of each discrete particle size was also determined. A bar graph was then plotted that shows the mass of particles entering the device and the mass of particles exiting the device for each discretised particle size. The sectioning of the precipitation section for analytical purposes is shown in the Figure 21.

![Figure 21. Precipitation section shown divided into ten 'slices' for analytical work](image)

This step completes the analysis of the particle charging and precipitation of the device. This analysis was done in an Excel spreadsheet so that the 'input' or design parameters could be easily changed and evaluated. Several combinations of reasonable input values were tried so that the operation of the device could be investigated. That is, that values were used that would be acceptable for an automotive application, particularly for a small automobile like the target vehicle. The size and geometry of the device as well as the power and voltage requirements were most heavily considered. This spreadsheet analysis is flexible enough so that design changes can be evaluated once one of these devices is built and tested. The result of this analysis is sufficient to provide design guidelines for the construction of the first prototype device proposed as part of this thesis. The specifics of the design and construction of this device is addressed in Section 4.4.
Chapter 4: Results and Discussion

4.1 Description of Findings

The analysis discussed in detail in Chapter 3 can be used as a design ‘tool’ for any given engine or operating condition provided that the exhaust characteristics (flow rate, particle loading etc.) are known and used as inputs for the analysis. The analysis in Chapter 3 was put into a spreadsheet format for ease of use. Several ‘input’ or design variables can be changed that can alter the operation of this device. The findings discussed in this section are therefore general and are subject to change based on the specific ‘input’ parameters used. A list of a typical set of ‘input’ variables is shown in Table 3. These input parameters are used for all of the discussions in this chapter.

Table 3: Analytical Model Input Parameters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Input</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_p )</td>
<td>0.0000001 m</td>
<td></td>
<td>Particle Radius</td>
</tr>
<tr>
<td>( a_w )</td>
<td>0.00025 m</td>
<td></td>
<td>Charging wire radius</td>
</tr>
<tr>
<td>( f )</td>
<td>0.3</td>
<td></td>
<td>Particle re-entrainment coefficient</td>
</tr>
<tr>
<td>( g_s )</td>
<td>0.25 cm</td>
<td></td>
<td>Grid Spacing</td>
</tr>
<tr>
<td>( \eta_d )</td>
<td>0.95</td>
<td></td>
<td>Desired collection efficiency</td>
</tr>
<tr>
<td>( I )</td>
<td>0.002 A</td>
<td></td>
<td>Input Current</td>
</tr>
<tr>
<td>( L_c )</td>
<td>0.04 m</td>
<td></td>
<td>Actual charging length</td>
</tr>
<tr>
<td>( L_p )</td>
<td>75 cm</td>
<td></td>
<td>Actual Precipitation section length</td>
</tr>
<tr>
<td>( m_r )</td>
<td>0.9</td>
<td></td>
<td>Wire roughness factor</td>
</tr>
<tr>
<td>( r_c )</td>
<td>0.04 m</td>
<td></td>
<td>Radius of cylindrical electrode</td>
</tr>
<tr>
<td>( V_d )</td>
<td>1 m/s</td>
<td></td>
<td>Desired Average gas velocity through collector</td>
</tr>
</tbody>
</table>

The typical average gas velocity for a plate type electrostatic precipitator should be less than 2m/s (Ref. 2). A lower gas velocity is expected to yield a device that is more efficient in extracting particles in the exhaust stream. This is because each particle has more time to migrate towards a collection surface. The gas velocity is a function of the operating conditions and the cross-sectional area of the precipitation section. The operating condition was fixed for the analysis. This operating condition was chosen such that the particle loading and the gas volume flow rate would be high. An operating condition of 120Km/hr was therefore chosen for the target vehicle. Since the gas velocity in the precipitation section was determined to be a critical value (primarily dependant on the device geometry), it was chosen as an ‘input’ variable. From this
input and the given volume flow rate of exhaust gas; the square cross sectional area (as shown in Figure 33) for the precipitation section was determined. For example, for the desired collection section gas velocity of 1 m/s in the precipitator shown in Table 3 and the target vehicle operating condition of 120 Km/hr (exhaust gas flow rate of 0.0333 m³/s) yields a cross-sectional area of 18.26cm.

This average gas velocity should not be confused with the space velocity which is commonly referred to in the exhaust aftertreatment field. The space velocity is the number of times that the exhaust is replaced in any given section of an exhaust aftertreatment system in a given time. Space velocity is measured in units of inverse time. For the Self Regenerating Diesel Emissions Particulate Trap discussed in this thesis, the space velocity can be found using the average gas velocity and the length of any given section of the device. The gas velocity in the precipitation section is very important as it affects the efficiency of particle collection. The space velocity can therefore be found using the following formula.

\[
SpaceVelocity = \frac{Average \ Exhaust \ Velocity}{Length \ of \ Section}
\]

Taking the information from Table Three, and using the formula above the space velocity in the precipitation section is 4800 hr⁻¹.

The next major variables that were determined were the corona onset voltage and the corona starting electric field. The radius of the cylindrical (receiving or outer) electrode and the radius of the discharge wire electrode are 'input' values to this analysis. Other factors that affect the corona starting voltage and the corona initiating field strength are gas density, pressure and temperature as well as discharge electrode roughness (through the electrode roughness factor, mᵣ). For the discharge electrode radius (2.5x10⁻⁴m) and the cylindrical 'receiving' electrode radius (0.04m) shown in Table 3, a corona initiating voltage of 5702 V was found. This voltage corresponds to an initiating electric field of 4.49x10⁶ V/m. It should be noted that the gas composition was assumed to be Carbon Dioxide (CO₂) for the analytical modeling in this project. Critical properties of other gasses typically found in diesel exhaust closely match that of carbon dioxide. CO₂ also accounts for a large percentage of the composition of typical diesel exhaust gas.
The selection of the electrode dimensions is critical to the operation of this device. The required corona onset voltage increases with increasing discharge wire radius. For a smaller discharge electrode radius, the electric field decays more rapidly in the active corona zone, which produces a lower electric field strength in the passive zone. A larger diameter discharge electrode causes a higher corona starting voltage, but the electric field in the active zone decays less rapidly producing a higher electric field strength in the passive zone. This relationship is reported by Oglesby and Sabert (Ref. 1). A trial and error optimization of the discharge electrode radius may be conducted using the spreadsheet program developed as part of this thesis. In general, the system will operate better with a smaller radii discharge electrode. The robustness of the discharge electrode in its operating environment also has to be a concern and will limit how small this radius can be made.

Once the corona starting conditions are determined, the complete electric field characteristics are determined. The electric field in the charging region is a function of radius in the charging region (distance from inner to outer electrode). The only new input value needed to determine the electrical field characteristics is the supply current. During these calculations, the accompanying input voltage can be determined. Both methods used to find the electric field matched very closely. For a discharge electrode input current of 2mA, as in Table 3, the required supply voltage was found to be about 91 KV (using the other variables listed in the Table 3).

The characteristic of the electric field generated by a corona discharge is a high field that rapidly decays in the corona discharge region otherwise known as the active region. This region does not extend very far away from the surface of the discharge electrode. The region that extends to the ‘receiving’ electrode is called the passive region. In this region the electric field maintains a fairly constant value, only decaying by a very small amount throughout the region. These two discharge regions are shown conceptually in Figure 18. Most of the particle charging and gas ionization occurs in the passive region. The electric field strength determined for the input variables listed in Table 3 versus the charging section radius is shown in Figure 22.
This is the expected form of the electric field distribution and the electric field in both the active and the passive regions can be seen. A similar non-dimensional electric field distribution for a coaxial cylinder electrode set up is published by Parker (Ref. 2). The close correspondence between the two methods used to determine the electric field distribution can also be seen from
this Figure. Since the electric field in the passive charging region is fairly constant, the minimum value of the electric field was used for all calculations that follow. In the passive region, particle and gas charging occurs by electron-molecule and electron-particle attachment.

Once the characteristics of the electric field were determined, then the particle charge was found. As mentioned earlier, there are two charging mechanisms that contribute to particle charging. These two mechanisms are Field and Diffusion Charging. Several methods were used to find these individual as well as the combined charging from the two methods. Field charging reaches a saturation point after a particular period of time after which no additional field charging occurs. Diffusion charging does not reach a saturation value, but becomes exponentially less with time almost to the point of a horizontal asymptote. A criterion for charging mechanism dominance is published by Lloyd (Ref. 4) and is described in Section 3.1.6. Conditions for this study indicate that the dominant particle charging method, for the particle size range and the device configuration given, is field charging. Even though field charging is dominant, diffusion charging was determined not to be small enough to neglect.

The first particle charge characteristic that was determined was the saturation charge by field charging. The time taken to acquire this field saturation charge was also very important. The particle saturation charge for the input values shown in Table 3 for a particle of radius 1x10^{-7} m was found to be 4.46x10^{-18} C. A time constant for this charge was also determined, which for this particular case is 4.11x10^{-4}s. Katz reports that a particle acquires most of its charge by all charging methods in less than 10 of these time constants (Ref. 3). It was therefore determined that the particle would acquire most of its charge in 4x10^{-3}s.

The PM was modeled as carbon for this analysis since not enough data was available for diesel PM. The particle dielectric constant affects the saturation charge that a particle is able to acquire. The particles were modeled entirely as carbon black. Carbon black was the closest material to diesel PM that could be found that dielectric constant and other data was available for. Carbon black is produced during the partial combustion of hydrocarbons which makes it essentially a type of soot. The reported dielectric constant for Carbon Black is between 2.5 and 3 depending on the conditions under which the carbon black was made. The dielectric constant of carbon was
therefore taken as 2.75 (average of reported values) for the entire analysis. Carbon black has a relatively low resistivity by ESP standards and the particles are therefore easily charged. It is however more difficult to precipitate out of the exhaust stream.

Since the dominant method of charging was shown to be field charging, the charging time constant determined was a critical factor in determining the charging section length. The charging section was designed such that the length would be longer than that needed to acquire the saturation charge for a conservative design. The charging section length determined from the time need to acquire most of the particle charge (10 time constants) was found to be 0.027m based on the volume flow rate of the exhaust. The charging section and the discharge electrode was therefore designed to be at least this length. A charging length as shown in Table 3 of 0.04m is used in the rest of this discussion. This length represents a 33% increase over the ideal analytical charging length. The charging length used here is an ‘input’ variable and can be changed as part of the design. The total particle charge obtained by field charging for the parameters shown in Table 3 was found to be \(4.18 \times 10^{18}\)C. It is expected that this charge varies only slightly from the particle saturation charge as a result of the design of this device.

Two methods were used to determine the total particle charge by diffusion charging. Both of the methods described in Chapter 3 yield very similar results. It was found that for the majority of the particle size regime encountered in diesel exhaust, the particle charge obtained by diffusion charging, was always at least one order of magnitude less than the total charge obtained by field charging. The total particle charge obtained from diffusion charging for the parameters listed in Table 3 is \(4.7 \times 10^{21}\)C. This dominance by the field charging method is supported by Withers (Ref. 4) for this particular application. Withers suggested a method, which indicates the dominant particle charging method. The formula used in this method is explained in Section 3.1.6 and is given here again for simplicity:

\[
\frac{3a_p E_{\text{min}} e b v}{B \varepsilon_\text{o} V} \gg 1 \quad \text{For field dominated charging}
\]

\[
\frac{3a_p E_{\text{min}} e b v}{B \varepsilon_\text{o} V} \ll 1 \quad \text{For diffusion dominated charging}
\]
For the input value given in Table 3, the constant obtained from this formula is 85. If the particle size in increased from 0.1µm as shown in Table 3 to 1µm in diameter, this constant jumps to 850. This indicates that field charging is dominant.

Even though it was determined that field charging is dominant, the particle charge obtained by both charging methods was determined individually to evaluate if the contribution of diffusion charging was insignificant. The particle charge obtained by diffusion charging determined for the input values given in Table 3 using Equation 40 is 4.816x10^{-21} C. The particle charge obtained by field charging determined for the input values given in Table 3 using Equation 34 is 4.119x10^{-18} C. These calculations indicate that field charging contributes about 99.9% of the charge to the particles. This percentage increases even higher for larger particle sizes. The approach of adding the particle charge obtained by both field and diffusion charging yielded a total particle charge of 4.124x10^{-18} C. An alternate method given by Kraemer and Ranz (Ref. 5) in Equation 44 which accounts for both charging methods simultaneously yielded a total particle charge of 8.270x10^{-18} C which is about twice as much found using the previous method. The method of adding the charge obtained by field and diffusion charging produces the most conservative result for the total particle charge. The value obtained by this method (4.124x10^{-18} C) is therefore used in all the analysis that follows.

Once the total particle charge is found, the particle migration velocity can be determined. Two similar methods were used to determine the particle migration velocity. One of these methods included a term that accounted for the acceleration of the particle while the other assumed that the particle always moved with its terminal velocity. Both of these methods yielded very similar results, indicating that the inertial effect of the particles in the exhaust stream were negligible. In order to determine the particle migration velocity, the electric field in the precipitation section had to be determined. The electric field in the precipitation section was caused by two main contributing factors. The first is the ionic space charge resulting from the gas ions created in the exhaust gas by the NTP. This ionic space charge remains fairly constant along the length of the precipitator. The second contributing factor is the space charge due to the charged particles in the exhaust. This charge decays along the length of the precipitator as particles are removed from the exhaust stream. The effect of the particle space charge is much less then the ionic space charge
as can be seen in the analysis. The particle space charge is sometimes neglected because of this fact for many particle loading applications for electrostatic precipitators. The particle space charge was however taken into account in this analysis. The total space charge for the input variables given in the Table 3 is 2.32x10^9 C per precipitation cell (Shown in Figure 36). There are 5329 precipitation cells in the precipitation section for the input variables given.

The electric field conditions only needed to be determined for a single cell in the precipitation section to be able to determine the particle migration velocity. This particle migration velocity is then applied to all the cells as they all act in a similar manner once a uniform well-distributed flow is achieved. It is expected that the entire flow is turbulent even though the flow is split into many smaller cells thus lowering the Reynolds number. This is because the diesel engine causes pulsations in the exhaust stream that manifest themselves as pressure waves. For the input variables listed in Table 3, the particle migration velocity was found to be 0.003 m/s. The migration velocities determined for several particle sizes fall within the expected range based on a similar analysis published by Parker (Ref. 2). Once the particle migration velocities are determined, the particle collection efficiency can be found. The particle collection efficiency for the input variables listed in Table 3 was found to be 97.1%. This value is an ideal value that does not account for re-entrainment. For the assumed re-entrainment ratio of 0.3 listed in Table 3, a collection efficiency could be found. This collection efficiency was determined to be 91.6% using the Cooperman modified Deutch Equation (Equation 8, Section 3.1.2). This is a more conservative result and thus the Cooperman's method for determining the particle collection efficiency was used in the comprehensive model that accounts for the particle removal from the entire spectrum of particle sizes.

Once all of the preceding basic analysis has been completed, the next step is to create a comprehensive system model. This model accounts for the entire diesel emissions particulate size range. It also accounts for the small changes in total space charge along the length of the precipitator. The methodology involved in this comprehensive model was discussed in Section 3.9. Figure 23 shows the percentage of particle mass removal in each section of the precipitator. This percentage is based on the total mass of particles entering each individual section, not the total mass entering the precipitator.
Figure 23. Particle Mass Removal for Precipitator Sections

The overall precipitator efficiency by mass accounting for the entire particle size spectrum was found to be 87.4% based on the input variables given in Table 3. The particle removal by mass for particles larger than 0.2\(\mu\)m in diameter was found to be 96.9%. It was found that the particles with a diameter larger than 0.5\(\mu\)m (radius) can usually be precipitated to the cellular collection surface at an efficiency approaching 100%. The removal efficiency falls for particles smaller than 0.1\(\mu\)m (radius) in size as shown in Figure 23. This result is expected, as the mechanisms of ESP do not work as well for particles in the sub-micron size range. The smallest particle size range for the model used was 0.01\(\mu\)m radius. This particle size range yielded a total precipitation efficiency by mass of 80.2% for the input variables listed in Table 3. The main factor affecting these collection efficiencies is the charge that the particle is able to obtain due to the particle size. The particle removal by mass for the entire particle size range used in the comprehensive model is shown in Figure 24.
Figure 24. **Particle Mass Removal vs. Particle Radius**

This type of particle output from the device is what can typically be expected over a range of input values. The EPA Tier II regulations focus on PM2.5 and PM10 PM. This device would be well suited for these particle size ranges. The total mass and number of particles emitted in the Sub-micron PM range (particles less than 1μm in diameter) exceeds that of the larger size ranges (above 1μm in diameter) for typical diesel exhaust. It is expected that more emphasis will be placed on the sub-micron particles in diesel exhaust in the future.
4.2 Oxidization of Carbonaceous PM

Traditional methods of oxidizing carbonaceous PM precipitated (generally by filtration) from diesel exhaust require that the filtration media be raised to very high temperatures in excess of 500°C for an extended period to effectively ‘burn’ the carbon. This heating is generally achieved by either electrical means or by the burning of additional fuel. This process is undesirable for automotive applications. It requires significant energy and fuel usage and it causes deterioration of the filtration media. This type of carbon oxidation is not used in the proposed device. A description of the proposed oxidation process follows.

Precipitated carbonaceous PM in the precipitation section of the proposed device will be oxidized by a chemical reaction between the particles and gaseous radicals produced in the NTP. The specific chemistry and science associated with these reactions is beyond the scope of this thesis, however, several references (Ref. 14, 15, 16, 33, 34, 35, 41) demonstrate that these types of oxidizing reactions are possible. These references indicate that:

Gaseous radicals such as NO₂, OH, O can be produced from naturally occurring species such as NO, O₂ and hydrocarbons in a diesel exhaust by NTP.

Radicals such as NO₂, OH, O are oxidizing agents for the oxidation of carbonaceous PM.

The preceding points are listed in the order that they occur in the proposed device. I will discuss the findings of several of these papers that directly relate to the production of gaseous radicals to the oxidation of carbonaceous PM. References that address just the production of radicals in the exhaust stream are then addressed. There has been significant research into NTP for the purpose of producing radicals in the exhaust stream solely for improving the efficiency of catalysts in removing NOₓ species from diesel exhaust. While NOₓ reduction is not the primary objective of this thesis, the methods of producing these radicals are similar to the methods proposed for NOₓ remediation. Radicals in the exhaust stream are typically produced by the following reactions (Ref. 34):

1. \( O_2 + e \rightarrow O + O + e \)
2. \( NO + O + M \rightarrow NO_2 + M \)
3. \( NO + O_2 \rightarrow NO_2 + O \)
4. \[ \text{H}_2\text{O} + e \rightarrow \text{OH} + \text{H} + e \]

5. \[ \text{HNO}_3 + \text{M} \rightarrow \text{NO}_2 + \text{OH} + \text{M} \]

Where \(\text{NO}_2\) radicals are produced in reactions 2, 3 and 5 and \(\text{OH}\) radicals are produced in reactions 4 and 5. Reaction 1 shows the formation of \(\text{O}\) directly through disassociation by an electron produced in the NTP.

Penetrante and others of Lawrence Livermore National Laboratory have published an SAE paper entitled, “Feasibility of Plasma Aftertreatment for Simultaneous control of \(\text{NO}_x\) and Particulates” (Ref. 33). This paper specifically addresses the formation of \(\text{O}\), \(\text{OH}\) and \(\text{NO}_2\) radicals in diesel exhaust by a NTP. \(\text{O}\) and \(\text{OH}\) radicals are reported to be formed by electron impact dissociation of oxygen and water molecules. The paper also states that \(\text{O}\) radical can further oxidize \(\text{NO}\) species to \(\text{NO}_2\). This process therefore creates species that are reported to oxidize carbonaceous PM. The products of this particle oxidation process are stated to be primarily \(\text{CO}\) and \(\text{CO}_2\). It is also reported that the presence or introduction of a hydrocarbon species (propene) into the exhaust stream in the NTP can significantly improve the efficiency of radical formation in the exhaust stream. Other sources that are discussed later describe injections of different types and amounts of hydrocarbons for this purpose. It is however stated in this reference that the soluble organic fraction (SOF) absorbed into the surface of PM may be utilized for this purpose without introducing additional hydrocarbons into the exhaust stream.

Penetrante used a simulated exhaust which was composed of 10% \(\text{O}_2\), 10% \(\text{CO}_2\), 5% \(\text{H}_2\text{O}\) and the balance was \(\text{N}_2\) (Ref. 33). The absorbed hydrocarbons on the simulated diesel soot (carbon, carbon black, graphite etc.) are not always representative of actual diesel exhaust PM. Diesel exhaust usually has more absorbed hydrocarbons than commercial carbon produced for laboratories. Penetrante then goes into a more detailed experimental analysis of the conversion of \(\text{NO}\) to \(\text{NO}_2\). The independent variable in these tests is the input electrical energy density, generally measured in \(\text{J/L}\). The dependant variable is the conversion of \(\text{NO}\) to \(\text{NO}_2\), which is stated as a percent. These tests are repeated for several hydrocarbon to \(\text{NO}_x\) ratios from 0 to 10 (based on a PPM ratio). The hydrocarbon used in these experiments was propene. Carbon pellets were used in Penetrante’s experiments to simulate diesel exhaust PM. In general, up to a 90%
conversion efficiency could be realized by having a hydrocarbon to NO\textsubscript{x} ratio of 10. These results can be seen in Figure 25 (Ref. 33).

Reference 33 also investigates the effects of different NO input concentrations from 100 to 600 PPM of exhaust as shown in Figure 25. The authors found that there was generally a linear increase in required energy density with increasing NO concentration to achieve the maximum conversion efficiency. A result of this experiment for a condition of Hydrocarbon (propene) to NO\textsubscript{x} concentration of 6 is shown in Figure 26 for different NO input conditions (Ref. 33).

Reference 33 gives a required energy density for efficient conversion (70 to 80\%) of NO to NO\textsubscript{2} of 5 to 25 J/L. This reference, however, does not give specific data on particle oxidation efficiencies. The reference also states, however, that the process of oxidizing carbonaceous PM causes the back-conversion of NO\textsubscript{2} back to NO. This may pose a problem for NO\textsubscript{x} catalysts that may follow the proposed device, but it is anticipated that this problem would be easily handled.
through the combination of catalysts that could first convert NO to NO₂ then to N₂ and O₂ before exiting the exhaust system.

![Graph](image)

**Figure 26. Energy Density Required for the conversion of NO to NO₂ in a NTP** (Ref. 33)

Thomas and others of AEAT Inc. have published an SAE paper entitled ‘Non Thermal Plasma Aftertreatment of Particulates’ (Ref. 34). This paper focuses on the conversion of NO to NO₂ for the oxidization of carbonaceous PM. Two types of plasma reactors were investigated in this paper. The first type of reactor is the traditional empty anode-cathode reactor. The second reactor that was tested was packed with dielectric beads. The authors claim that this packing may improve the particle collection of the device without significantly increasing the system pressure drop. Since the proposed device in this thesis does not have any such packing, the focus shall be on the unpacked plasma results. The paper also discusses the importance of having hydrocarbon species present for the improved conversion of NO to NO₂. A hydrocarbon (propene) to NOₓ
ratio of 3 (PPM ratio) was used throughout this work. NO to NO$_2$ conversion in the plasma for the unpacked reactor is shown in Figure 27 (Ref. 34). The NO$_x$ concentrations are shown as a function of the input energy density.

![Graph showing NO and NO$_2$ concentrations](image)

**Figure 27. Conversion of NO to NO2 vs. Energy Density**

(Ref. 34)

Figure 26 shows a maximum NO to NO$_2$ conversion at an energy density of 40 J/L (Ref. 34). No data was provided for the particulate removal in an unpacked reactor. A synthetic exhaust stream with a carbon black pre-coated reactor beads was used to demonstrate that the radicals produced could oxidize the carbon black on the reactor beads. The operation of the device was observed indirectly by monitoring the CO and the CO$_2$ concentration in the outlet exhaust stream, as these species are the by-products of carbon oxidation by radicals. The packing beads were then observed after prolonged operation to show that the carbon was oxidized. The duration of this experiment was not given. A picture of these packing beads is shown in Figure 28 with no NTP and NTP respectively (Ref. 34). The authors claim very high particle removal efficiencies with the packed reactor system. One of the reasons why this type of a system was not investigated as part of this thesis is because the packed reactor requires at least twice as much energy density for comparable radical conversion in the exhaust stream. This increased power consumption was deemed unacceptable for the proposed device at this initial stage of work.
Figure 28. Depiction of Diesel PM Oxidation as a Result of NTP in a Packed Bead Reactor (Ref. 34)

Grothaus and others of Southwest Research Institute have published an IEEE paper entitled, "Investigation of Pulsed Corona Reactor for Heavy-duty Diesel Engine Emissions Reduction" (Ref. 14). This paper is very interesting as it relates very closely to some of the aspects proposed in the present device. This system uses a corona discharge system with a concentric cylinder electrode, which is very similar to the charging section of the proposed device. These concentric cylinder electrodes are stacked into an array to accept the diesel exhaust as shown in Figure 29.

Figure 29. High Voltage Power Supply System with High Frequency DC Waveform Capability (Ref. 14)
High voltage, high frequency (50 ns pulse width) DC pulses were used as the input voltage into the reactors. The benefits of a pulsed voltage supply are discussed in Section 4.3.2. This system did not have any specific architecture for the precipitation of particles. Particles were oxidized as they moved through the reactor system. These particles have a very short residence time in the reactor system during this oxidation process. The authors, in fact, specifically state the particles were not collected in the reactor system. Particle removal efficiencies of 30 to 100% were observed for different engine operating conditions. Their particle removal efficiencies are shown in Figure 30 (Ref. 14).

![Figure 30. Particle Removal as a Function of Specific Energy Density (Ref. 14)](image)

Note: The percentage torque shown in Figure 29 is the torque resistance applied to the engine as a percentage of the total available torque at the operating RPM.

Energy densities of 10 to 250 J/L were used in this investigation. One of the goals of this thesis is to design a device with minimal energy consumption for automotive applications. An energy density usage below 20 J/L would be acceptable, as this would typically represent only a few percent of the total available energy from engine output. Producing an energy density of 250 J/L as investigated by the authors of this paper would require a significant portion of the total engine energy output. In a follow up paper to the present work discussed entitled, ‘A synergistic
Approach for the Removal of NO\textsubscript{x} and PM from Diesel Engine Exhaust' (Ref. 15). The authors recognize that, while the chemical species produced in diesel exhaust by NTP facilitate the removal of PM and other pollutants, the electrical and chemical efficiency is inadequate for a mobile platform. The authors also indicate that their device cannot meet a relative level of energy consumption that would be acceptable for an automotive application. The implementation of a precipitation device in this study significantly increases the residence time that particles are exposed to oxidizing gas species, thereby reducing the required energy input required and the amount oxidizing species necessary to achieve significant oxidation levels.

Fleck of The Technical University of Vienna has published a paper entitled, 'A compact Soot Burning Electrostatic Particulate Filter without Additives' (Ref. 13). The author describes in this paper a two stage particle charging and precipitation device. Charging is accomplished in a concentric annulus electrode system. There are several annulus discharge electrodes suspended in a cylindrical receiving electrode. The exhaust flows through this charging section and then flows through a monolithic core. This monolithic core is composed of an array of ceramic honeycomb shaped cells. Fleck's proposed device is shown in the Figure 31 (Ref. 13).

![Figure 31. Diesel PM Removal System Using an NTP Reactor and a Monolithic Core Filter (Ref. 13)](image)

Fleck claims that the soot is trapped in a monolithic core and that corona discharge would produce negative O\textsubscript{2} ions, which in the correct quantities could oxidize most of the PM. The author also investigated a Fe\textsubscript{2}O\textsubscript{3} catalyst coating on the monolithic core, which he demonstrated
to cause a particle oxidation improvement in the monolithic core of about 50%. The results of his experimentation of the device are shown in Figure 32 for different operating temperatures. Particle removal efficiencies of 85 to 95% are achieved with this device according to Fleck (Ref. 13).

An article entitled 'Reduction of NOx and Smoke in Diesel Exhaust Gas by DC Corona' by Morimune addresses the reduction of smoke from a diesel exhaust source as a result of NTP treatment (Ref 9). Smoke is a visual manifestation of diesel emissions of PM. A charging section similar to one proposed in this thesis was used. The NTP unit consisted of a thin discharge wire (1.6mm diameter) and a cylindrical receiving electrode (54mm inner diameter). A 6 KW Mitsubishi single cylinder diesel engine was used for the testing. The experimental apparatus is shown in Figure 33 (Ref. 9). Experimentation of the NTP device in Figure 31 showed a 70 to 90% reduction in exhaust smoke from the test engine. This measurement was done with a Bosch Smoke Meter which operated based on the opacity of the diesel exhaust. It should be noted that the power input to the NTP reactor was less than 100W. Other references that address the oxidation of carbonaceous PM by gaseous radicals can be found in references 7, 24 and 25.
There are several published papers (Ref. 37, 38, 39, 43, 45) that address the formation of radicals in a diesel exhaust stream. As mentioned before many of these papers investigate the use of NTP in diesel exhaust for the purpose of creating gaseous chemical species that allow NO\textsubscript{x} removal catalysts to operate more efficiently. Many different types of discharge configurations have been investigated. Some of these discharge systems utilize a dielectric coating on the electrodes to provide a more uniform electric field distribution. Two important factors can be determined from these papers. The first is that production of the radicals needed in the exhaust stream for the oxidation of PM is indeed feasible with NTP. The second factor is the energy density that is required for optimal creation of these radicals. This may change slightly depending on the specific configuration and the volumetric flow rate. These sources however, generally indicate that 10 to 100 J/L is required for optimum creation of these radicals once the appropriate hydrocarbon species and concentrations are contained or injected into the exhaust stream.

Now that several references addressing the oxidation of diesel exhaust PM, particularly carbonaceous PM have been discussed, the regeneration process to be utilized in the proposed device will be described. The energy density needed for the generation of oxidizing radicals is a very important indication of the energy consumption of this device. There are two main
considerations. The first is the required energy density needed for efficient particle charging and precipitation. The second consideration is the required energy density needed for efficient creation of radicals in the exhaust stream. An operating energy density has to be chosen for the proposed device that is a good compromise between these two values. It has been found through the analysis of the particle charging and precipitating mechanisms of the proposed device (results discussed in the previous section) that an energy density of 10 J/L can give an overall particle precipitation efficiency of about 95%. It is therefore apparent that the generation of oxidizing radicals dictates the maximum required power needed to operate the proposed device.

Each 10 J/L of energy density that is added to the system accounts for about 0.5% of the total engine output for the target vehicle specified (assuming 100% electrical production efficiency). It is anticipated that the minimum energy densities described in some of the previous works would be used. This is estimated to be about 20 J/L for the proposed device or twice the energy required for 95% efficient particulate precipitation. This energy input and the effect on radical generation have to be experimentally evaluated. The increased residence time of the PM in the precipitation section as compared to non-precipitating current art devices allows for a more efficient particulate oxidation process. This would mean that less oxidizing radicals and therefore less energy would be needed to achieve equal precipitation and particle oxidization rates. The particle precipitation process is therefore one of the significant improvements over previous work done. This improvement helps to overcome the excessive power requirement problems encountered by Grothaus (Ref. 15) and other researchers. In order for this device to be continuously regenerating, the rate of particle oxidation must at least equal the rate of particle precipitation. If for example the particle precipitation rate exceeded the particle oxidation rate, then the proposed device would either become clogged or intermittently emit PM that has built up on the precipitation surface.
4.3 Device Recommendations

Several recommendations can be made for the design of the proposed device based on the research done in this thesis. Some of these recommendations could not be modeled in the analysis due to the complexity. Many of the recommendations are based on the experience of the authors of related published works. These recommendations are broken down into the following specific categories.

1. Discharge Electrode
2. Supply Voltage
3. Precipitation Section Gas Velocity
4. Precipitation Section Grounding
5. Hydrocarbon Additives

4.3.1 Discharge Electrode

The discharge electrode is one of the most important if not the most important component of the proposed device. The shape of the discharge electrode allows the concentration of charge at certain points, which then leads to a corona discharge. Charge accumulates naturally at sharp points or areas of very small radii on the discharge electrode (Ref. 2, 6, 8). The electrode that was modeled as part of this thesis was a plain wire. Several sources indicate that barbed or surrogated electrodes can produce a more efficient discharge, leading to lower power consumption. These electrodes are very difficult to model by traditional methods due the complexity and the non-symmetry of the field produced. It is also recognized here that the discharge electrode is in a hostile environment with high temperatures, significant amounts of vibration and oxidizing gasses. A thin suspended wire electrode is not very well suited to such an environment, especially when considering the structural integrity of the electrode.

A corona discharge itself is an unpredictable phenomenon, which is generally analyzed by using more predictable averages. The discharge itself for example usually occurs in tufts or streamers which dance or change position on the discharge electrode. These localized changes occur due to
localized gas breakdowns, which can be better explained statistically than scientifically. Areas on
the discharge electrode that are not producing an actual discharge at any point in time are subject
to particle fouling. This fouling causes the surface of the discharge electrode to deteriorate and it
hinders the efficient operation of the device. The variations in the corona discharge regions
would eventually cause the entire electrode to become fouled. This occurs very commonly in
industrial electrostatic precipitator applications. Standard maintenance schedules for industrial
equipment easily address these problems. This type of maintenance would not be desirable or
plausible for automotive applications. A discharge electrode therefore has to be designed that can
stand up to the hostile environment and is resistant to particle fouling.

One method that is used for resistance to fouling is to have many points where small radii are
located on the discharge electrode rather than having a constant small radius, as is the case with a
wire discharge electrode. These points cause the charge concentrations to be focused at the
points. This confines the discharge to these points and significantly reduces the discharge
‘dancing’ along the electrode. This in turn, significantly reduces the fouling at the discharge
points. The discharge points should be polished, as roughness reduces the discharge efficiency.
The smaller the radius of the discharge point, the lower the initiating corona voltage and current.
The proposed conceptual design of discharge electrode provides more structural integrity as well
as focuses the discharge to a smaller area to reduce fouling and required maintenance. I refer to
this design as a ‘Dual Cone’ design that may be used to replace the wire discharge electrode used
in the analysis. The effects of this type of an electrode are not completely understood and have to
be experimentally determined. This concept electrode can be seen in the Figure 34.
The 'Dual Cone' discharge electrode would provide better structural integrity due to its bulkier center section. The corona discharge is concentrated at the opposing cone pinnacles, thereby reducing electrode fouling. The symmetry of the discharge characteristics should also be retained for simplicity of evaluation. The analytical model constructed as part of this thesis assumed a wire discharge electrode with a discharge over the entire length of the electrode. This 'Dual Cone' concept limits the discharge to the ends of the electrode. The effects of a shorter discharge length will have to be investigated experimentally to gain a complete understanding of its operation. This is by no means a finalized design and it is suggested as a possible improvement over the wire discharge electrode that was modeled in the analysis.

4.3.2 Supply Voltage

The recommendations for a supply voltage are split into two main topics. The first topic is discharge polarity and the second topic is discharge voltage waveforms. A corona discharge can be produced with either a positive or negative discharge electrode. The physics governing a positive corona discharge are similar, but different from that of a negative corona discharge. A negative corona discharge is more difficult to control in terms of stability and potential for sparkover. A negative discharge is used as part of this device because negative corona discharges have been reported to produce more gaseous radicals than a similar positive discharge corona.
Household electrostatic air cleaners utilize a positive corona discharge because the production of gaseous radicals indoors is not desirable for health reasons. Ozone for example is a poisonous gas if inhaled. The production of radicals is however desired for this particular application for the oxidization of carbon.

Production of radicals is vital to the successful operation and regeneration of this device. Radicals are essentially chemically unstable and highly reactive molecules of gas. Radicals are often reverted to their previous state as a result of the particle oxidation process. In general, it is not desired that radical be emitted to the atmosphere as a result of the operation of this device. A balance therefore has to be maintained between the amounts of radicals being produced in the NTP and the amounts of radicals being consumed by particle oxidation. Catalysts can be used to remove any remaining radical species as is typically done in NOx reducing diesel exhaust aftertreatment systems.

Several sources (Ref. 14, 45) and investigators have also used DC voltage waveforms as the input to electrostatic precipitators. This has been done for several reasons. A very high frequency DC waveform can breakup any sparking formed in an electrostatic precipitator, thereby reducing the power draw and electrode fouling due to arcing. The use of wave DC waveforms also allows the use of a higher energy density than would be possible without sparkovers occurring for a constant DC input. Higher operation efficiencies have also been reported for similar actual power consumptions for a DC waveform input as opposed to a DC constant voltage input. Sparkovers occur when the discharge electrode voltage increases past the point where the air surrounding the discharge electrode breaks down electrically and allows a thermal discharge or spark to travel between the discharge and receiving electrodes. Prolonged sparkovers are generally undesirable because they carry significantly more current that a non thermal discharge. Significantly more energy is therefore consumed. Sparkovers can also cause damage to the electrodes.

There are some drawbacks to these techniques that arise from shortcomings in the available technology for producing these waveforms. The devices and circuits that are currently available for the production of very high voltage, high frequency waveforms are typically inefficient. Much of the operating efficiency is lost in the creation of the waveform. It is recommended that a waveform input be investigated as part of the experimentation of this device. Some of the
concerns about the efficiency of producing these waveforms have to be addressed for an automotive application. Waveforms from several hundreds to several thousands of Hertz have been investigated in different studies. It is recommended that the effects of different DC waveform inputs on the operation of the proposed device be investigated experimentally.

One novel high voltage, high frequency DC power supply system that was discovered during research included a capacitor for power storage between waveform pulses and a self-breaking hydrogen spark gap switch. This system has several apparent benefits over other methods of producing a high voltage waveform. It stores energy between pulses instead of discarding (dissipating) this energy as some devices do. It eliminates the need for an expensive, complicated and inefficient function generator. The waveform is instead created with the solid-state spark gap switch. A readily available high voltage power supply is also used as part of this system. This device was found in the work of Grothaus and others (Ref. 14). A published diagram of this power supply and waveform generation device is shown in the Figure 35.

![Diagram of high voltage power supply system](image)

Figure 35. High Voltage Power Supply System with High Frequency DC Waveform Capability (Ref. 14)
4.3.3 Precipitation Section Gas Velocity

The gas velocity in the precipitation section of the proposed device significantly affects the number of particles collected in that section. The number of particles that are re-entrained into the exhaust stream also increase with increasing exhaust velocity and turbulence. In general, the slower the exhaust velocity in the precipitation section, the more efficient the particle precipitation will be. The volumetric flow rate of the exhaust is a function of the engine operating condition. The geometry of the device therefore has to be designed so that the desired gas velocity can be obtained for the maximum volumetric flow rate supplied by the engine. Several sources (Ref. 2, 8) indicate that for a plate type precipitator, the gas velocity should be less than 2m/s. Gas velocities exceeding this value would significantly decrease particle precipitation under most conditions. The design gas velocity in the precipitation section of the proposed device is 1m/s. This is an input variable and can be changed in the spreadsheet analysis of this device. The cross sectional area of the precipitation section was therefore designed for this 1 m/s target velocity at an engine operating speed of 120 Km/hr. Alterations to the cross sectional area of the precipitation section should only be done after careful consideration of the effects on the gas velocity in that section.

4.3.4 Precipitation Section Grounding

Carbon has a relatively low resistivity for typical PM encountered in typical electrostatic precipitator applications. This can be seen for the low relative dielectric constant of 2.75 for carbonaceous material. The PM in the analysis was modeled as carbon or ‘lamp black’. Other domestic names exist for laboratory grade carbon PM used to simulate diesel exhaust PM. The low resistivity of carbon means that the particles are very easy to charge, but they are more difficult to precipitate because the carbonaceous PM would have a tendency to immediately give up all of its charge once precipitated. This would leave no electrostatic holding force to keep the particle adhered to the precipitation surface. The only force that would tend to hold the carbon to the precipitation surface is the ‘stickiness’ of the particles. A method that is regularly practiced in industry to improve the stickiness of particles is to introduce moisture into the precipitators. This is typically done by spraying a fine mist of water over the exhaust stream. This technique may not be desirable for automotive applications because of the need for a stored liquid source and
additional injecting equipment. There are also forces from the gas stream that tend to erode these particles from the precipitation surface. This causes particle re-entrainment.

There are two plausible solutions to this problem. The first is to construct the precipitation surface out of a material with a higher electrical resistance than a standard metal surface. This would slow the transfer of charge and keep the carbon particles adhered to the precipitation surface. The second option would be to construct the precipitation surface using metal, but ground the collection section through a rheostat. This would also slow the transfer of charge and keep the particles adhered to the precipitation surface until they can be completely oxidized. This second option allows more control and fine-tuning of the operation of the device as the rheostat can be easily adjusted. The resistance cannot be made too high so that the force on the particles due to the particle charge diminishes significantly. Again, this is a suggestion that should be investigated experimentally once the device is built. Other methods that have been applied in industrial applications to combat these types of problems include chemical additives and chemical conditioning of particles prior to entering the precipitator (Ref. 2, 8). These are not feasible solutions for an automotive application because of the need for a chemical reservoir onboard the vehicle that requires replenishing.

**4.3.5 Hydrocarbon Additives**

Several sources that address the formation of radicals in an exhaust stream for the oxidation of PM or for the improved efficiency of NOx catalysts suggest that the introduction of trace amounts of additional hydrocarbons into the diesel exhaust stream prior to NTP processing significantly increases the production of radicals in the exhaust stream (Ref. 33, 34). This increase in production of radicals leads to a lower required power consumption by the NTP unit. Under such conditions, the production of radicals of over 50% has been observed. Minimal power consumption is one of the major targets of this project. It has already been established in the previous section that the production of radicals would consume more power than that which is needed for 95% efficient particle precipitation.

Quantities of hydrocarbons introduced for these applications are typically in the PPM range compared to the exhaust stream. The addition of hydrocarbons is generally not desirable for
automotive applications due to the necessity for the storage, dispensing and refilling of the hydrocarbon species aboard the vehicle. There is also the issue of higher hydrocarbon emissions resulting from this practice. Diesel fuel contains several complex chains of hydrocarbons and would be an easy source to tap off for the purpose of hydrocarbon additives. Some manufacturers have developed systems that would introduce diesel fuel hydrocarbons into the combustion chamber during normal operation, completely eliminating the need for additional hydrocarbon injection equipment.

Many investigations have been done with simulated PM that does not contain as many absorbed hydrocarbon species as real diesel exhaust PM. It is anticipated that the hydrocarbon species naturally occurring in diesel PM would reduce or eliminate the need for additional hydrocarbons. It is however recommended that the effect of introducing hydrocarbon species into the exhaust stream be investigated as part of the laboratory experimentation on the proposed device once it is built. Obviously the preferred hydrocarbon source for this application would be diesel fuel as it would be readily available on a diesel vehicle. Other hydrocarbons may also have to be investigated for this application. There are advantages and disadvantages to the addition of hydrocarbons. The pros and cons of this practice have to be weighed to assess the feasibility of this practice once the resulting improvements in radical production and reduced power consumption can be quantified.
4.4 Device Specifications, Dimensions and Geometry

A conceptual drawing of the proposed device is shown in Figure 36. This drawing shows the exterior of the proposed device. The charging section and the precipitation section can be seen. The diffuser that connects the charging section to the precipitation section is also shown.

**Figure 36.** Self Regenerating Diesel Emissions Particulate Trap Using Non-Thermal Plasma

The details needed for construction of the proposed device are described and shown in detail in this section. An important consideration in the construction and the operation of this device is the insulating materials used. Two main areas require electrical insulation. Electrical insulation is required on the high voltage lead passing through in the charging section. The precipitation section should also be electrically isolated from the charging section and the exhaust system. It should be grounded to the vehicle chassis though an appropriate rheostat. The voltages used in this device are prohibitive for several standard electrical insulating materials. Ceramic and
polymer materials are usually used for applications with such high voltages. Materials will however have to be chosen that can not only withstand the high voltages, but the exhaust temperatures and system vibrations. Some of these materials would also be required to provide a reasonable seal between different sections. The overall cross section of the device is shown in the Figure 13.

The charging section is shown with the discharge electrode. The discharge electrode that is investigated in the theoretical analysis of this device is a plain wire electrode as shown in Figure 13. The discharge electrode is rigidly suspended in the center of the charging section with insulating materials. The high voltage lead powering the discharge electrode will be passed though the charging section through another insulator. The diffuser between the charging and the precipitation section is also shown. This diffuser slows the exhaust gas to the desired velocity for the precipitation section. The flow vanes are important to the operation of this device also. Their purpose is to create a uniform velocity profile leading to the precipitation section. This is important so that significant velocity variations do not occur the collection cells. This helps to maintain a uniform particle loading in all of the collection cells. The flow vanes have to be rigidly suspended in this diffuser. Flow testing may be necessary to evaluate and optimize the performance of this diffuser. CFD may also be employed, but electro-hydrodynamic flows have to be accounted for which present significant difficulties for CFD methods.
The precipitation section is simply an array of square cells that the exhaust passes through for the precipitation and oxidation of particles. This section should be electrically isolated from the rest of the exhaust system including the charging section. It will be grounded through the rheostat as mentioned previously. The outer shell of the precipitator can be made from stainless steel plates. The thickness of these plates is not critical, however, there should be a good electrical connection between the conducting precipitation grid and the precipitator shell. An alternative to this is to build the collection grid from a material with more resistance to transfer of charge than would be encountered with a typical metal. Both of these options can be explored, but the addition of the rheostat allows for greater control of the operation of the device. The rheostat was not accounted for in the theoretical model. It was derived from a suggestion made in the Section 4.3.4 of this thesis. The effects of using the rheostat and different resistance settings should be investigated experimentally to validate its usage. The precipitation section ends in a nozzle that feeds into the exhaust pipe. The charging section is detailed in the Figure 35. This drawing is shown with the ‘double cone’ concept discharge electrode.

Figure 37 shows the cylindrical charging section. The dimensions shown (See Table 3 for values) are dimensions that have been determined for the theoretical model. Recommended charging section dimensions that correspond to the dimensional callouts in Figure 37 are given in Table 3 in Section 4.1. Figure 37 shows discharge electrode rigidly supported at the center of the charging section. These supports will be made of an insulating material. Figure 37 also shows the pass through for the high voltage lead supplying the discharge electrode. Stainless steel can be used for both the discharge and the receiving electrodes. A thickness specification for the cylindrical electrode has not been given since it is not critical to the operation of the device. A wire discharge electrode as shown in Figure 37 is used in the configuration of the theoretical model. The discharge electrode wire radius of would be used would be \( a_w \) obtained from the analytical model. Table 3 is shown again below for ease of reference to dimensions.
Figure 37. Charging Section and Wire Discharge Electrode

The precipitation section of this device is shown in the Figure 17. Dimensional callouts are made.

Figure 17. Precipitation Section
Table 3: Analytical Model Input Parameters

<table>
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<th>Symbol</th>
<th>Input</th>
<th>Unit</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>$a_p$</td>
<td>0.0000001 m</td>
<td>m</td>
<td>Particle Radius</td>
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<tr>
<td>$a_w$</td>
<td>0.00025 m</td>
<td>m</td>
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<td>$f$</td>
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<td>$g_s$</td>
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<td>$\eta_d$</td>
<td>0.95</td>
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<td>Desired collection efficiency</td>
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<tr>
<td>$I$</td>
<td>0.002 A</td>
<td></td>
<td>Input Current</td>
</tr>
<tr>
<td>$L_C$</td>
<td>0.04 m</td>
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<td>Actual charging length</td>
</tr>
<tr>
<td>$L_p$</td>
<td>75 cm</td>
<td></td>
<td>Actual Precipitation section length</td>
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<tr>
<td>$m_r$</td>
<td>0.9</td>
<td></td>
<td>Wire roughness factor</td>
</tr>
<tr>
<td>$r_c$</td>
<td>0.04 m</td>
<td></td>
<td>Radius of cylindrical electrode</td>
</tr>
<tr>
<td>$V_d$</td>
<td>1 m/s</td>
<td></td>
<td>Desired Average gas velocity through collector</td>
</tr>
</tbody>
</table>

The overall dimensions of the precipitation section are shown. These dimensions are determined from the theoretical model. The array of cells in this section forms a square grid. The thickness of the material used to construct the cells has not been taken into account in the dimensioning or in the analysis. This is because an investigation of available grids for emissions and other applications has not yet been completed. It is anticipated that this grid should be as unobtrusive to flow as possible. This would mean that the grid would be made from very thin materials. Of course, corrosion and structural integrity should be considered when specifying these grids for the prototype device. Critical dimensions are given here and accommodations for material thickness can be easily accounted for later. Recommended precipitation section dimensions that correspond to the dimensional callouts in Figure 37 are given in Table 3 in Section 4.1.

Many compromises can be made in the construction of this device. It is however, important to adhere to the critical dimensions given. The electrical operation of this device can be significantly affected by changing any of these dimensions. Electrical connections and insulators should also be carefully selected and installed. Different construction materials can also be investigated to determine their effect on the operation of this device. The use of improper or poor insulating materials can create hazardous conditions for operating this device due to the high voltages (up to 100 KV) used. The environment that the insulating materials are exposed to is also very important. The surface of the insulating material should not be porous so that there would be no moisture absorbed. The insulating materials used should also be able to withstand the operating temperatures, gaseous species and vibrations that are encountered in this application.
4.5 Conclusion

Diesel emissions PM have been shown to cause significant adverse health effects and higher mortality rates and they have also been shown to cause or contribute to other detrimental environmental problems. The effects of diesel particulate emissions are significant and widespread and diesel engine technology is becoming more popular due to increased engine efficiency over gasoline powered vehicles and higher durability. Diesel engines also dominate the heavy-duty automotive markets. NTP technology shows significant promise for the reduction of harmful diesel emissions, particularly PM. The analysis provided in this thesis on what is referred to as the proposed device gives indications that it is feasible to use ESP and NTP technology for automotive diesel applications. The major conclusions are:

1. The production of NTP in a diesel exhaust stream was shown analytically to be possible with energy consumption of less than a few percent of total engine energy output.
2. The analysis shows that a total particle precipitation efficiency greater than 95% can be obtained using less than 0.5% of total engine energy output at an operating condition of 120 Km/hr on the target vehicle.
3. For these operating conditions, the particulate precipitation efficiency for particles above 0.1 μm in diameter is greater than 99%. Particle removal efficiencies at this level would allow a heavy-duty vehicle to meet EPA Tier II particle emission standards.
4. Evidence given shows that radicals (NO₂, O, OH) could be created in the exhaust stream by the use of NTP. These radicals that are produced in the exhaust stream as a result of the NTP were shown to be oxidizing agents for diesel PM, particularly carbonaceous diesel PM.
5. The energy requirement for the production of these radicals is higher than the energy input needed for particle precipitation.
6. Prior work has shown that reasonable radical production efficiencies are attainable without exceeding the maximum desired energy requirement (less than 2% of total engine energy output) for the proposed device.
7. The PM has a significantly longer exposure time to the oxidizing radicals in the exhaust stream as a result of particle precipitation out of the exhaust stream in the proposed device. This should allow for the production of less radicals and lower energy consumption required.
to oxidize particles. This feature constitutes a significant difference to technologies that are currently available or in preliminary development.

8. Catalyst technologies could be combined with the proposed device to create a complete diesel exhaust aftertreatment system. There is significant confidence that the proposed device would provide a viable solution to the problem of diesel particulate emissions from mobile sources with significant benefits over other technologies.

9. Experimental investigations of the Self Regenerating Diesel Emissions Particulate Trap proposed in this thesis will be completed at Rochester Institute of Technology (RIT) in the future to confirm the analytical and empirical methods utilized in this thesis. An emissions laboratory is also being developed at RIT to facilitate ongoing work in the area of diesel emissions.
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<td>Ozone oxidation of graphite powder for electrochemical applications</td>
<td>24th Conference on Carbon</td>
<td>OCLC 3744519</td>
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<td>26</td>
<td>B. Liu, H. Yeh</td>
<td>On the theory of charging of aerosol particles in an electric field</td>
<td>Journal of Applied Physics, Vol.39 #3 pg 1396-1402</td>
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<td>28</td>
<td>H. Schmid, E. Schmidt</td>
<td>Investigations on local mass flux of dust to be precipitated at the collecting electrode</td>
<td>Proc. 6th Int. Conf. on Electrostatic Precipitation</td>
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<td>31</td>
<td>Douglas W. Dockery, Joel Schwartz, John D. Spengler</td>
<td>Air Pollution and Daily Mortality: Associations with Particulates and Acid Aerosols</td>
<td>Environmental research. 59, no. 2, pg 362-373</td>
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<td>33</td>
<td>Penetrante, Brusasco, Merritt</td>
<td>Feasibility of Plasma Aftertreatment for Simultaneous Control of NOx and Particulates</td>
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<td>36</td>
<td>Tanaka, Shimizu</td>
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<td>Abdul-Khalek, Kittelson, Brear</td>
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<td>Slone, Ramavajjala, Palekar</td>
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<td>Toxic Air Contaminant Identification - Diesel Exhaust</td>
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<td>U.S. Environmental Protection Agency Proposal for Cleaner Heavy-Duty Trucks and Buses and Cleaner Diesel Fuel Fact Sheet</td>
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<td><a href="http://www.epa.gov/otaq/regs/fuels/diesel/factsheet.pdf">http://www.epa.gov/otaq/regs/fuels/diesel/factsheet.pdf</a></td>
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<td>Walsh Carlines</td>
<td>Current and Future Technology For Controlling Technology For Controlling Diesel Exhaust</td>
<td>Understanding Urban Air Pollution and the Role of Diesel and the Role of Diesel Exhaust</td>
<td><a href="http://www.walshcarlines.com/pdf/delhi">http://www.walshcarlines.com/pdf/delhi</a> Diesel 1100.p df</td>
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<td>64</td>
<td>Marty Lassen</td>
<td>CRT Particulate Filter Particulate Filter for On-Road Applications</td>
<td>Johnson Matthey</td>
<td><a href="http://www.deq.state.or.us/aq/diesel/Johnson_Matthey.pdf">http://www.deq.state.or.us/aq/diesel/Johnson_Matthey.pdf</a></td>
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Appendix: Spreadsheet Calculations
### Step 1: Determination of dimensions for desired gas velocity in collection section of precipitator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross Section Area</td>
<td>333,333 cm²</td>
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<tr>
<td>Effective Volume Flow Rate</td>
<td>0.033333 m³/s</td>
</tr>
<tr>
<td>Desired Average Gas Velocity</td>
<td>1.0 m/s</td>
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</table>

### Step 2: Estimation of particle migration velocity needed for device

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Predictive Dimension (square section)</td>
<td>182.57418 m</td>
</tr>
<tr>
<td>Predictive Dimension (square section)</td>
<td>0.033333 m</td>
</tr>
<tr>
<td>Predictive Dimension (square section)</td>
<td>182.57418 cm²</td>
</tr>
<tr>
<td>Predictive Dimension (square section)</td>
<td>0.033333 m²</td>
</tr>
</tbody>
</table>

### Particle Migration Velocity

- **Max Required Particle Migration Velocity**
  
  \[\vartheta = \left( \frac{A}{M} \right) \left( \frac{1}{V} \right) \left( \frac{1}{f} \right) \]

- **Eqn. 9**
  
  \[\vartheta = \left( \frac{A}{M} \right) \left( \frac{1}{V} \right) \left( \frac{1}{f} \right) \]

### Collection Efficiency

- **Required Migration Velocity**
  
  \[\vartheta = \left( \frac{A}{M} \right) \left( \frac{1}{V} \right) \left( \frac{1}{f} \right) \]

### Desired Gas Velocity

- **Eqn. 10**
  
  \[\vartheta = \left( \frac{A}{M} \right) \left( \frac{1}{V} \right) \left( \frac{1}{f} \right) \]

### Collection Area of Precipitator

- **Eqn. 11**
  
  \[\vartheta = \left( \frac{A}{M} \right) \left( \frac{1}{V} \right) \left( \frac{1}{f} \right) \]

### Key to Calculations

- **Key:**
  - Given Value
  - Calculated Value
  - Assumed Value
  - Value used for further calculations when multiple methods used

### Spreadsheet Calculations
<table>
<thead>
<tr>
<th>Date</th>
<th>Total Particle Mass Removal (%) for Section</th>
<th>%</th>
<th></th>
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<tbody>
<tr>
<td>10/07/2019</td>
<td></td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>10/08/2019</td>
<td></td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>10/09/2019</td>
<td></td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>10/10/2019</td>
<td></td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>10/11/2019</td>
<td></td>
<td>%</td>
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</tr>
<tr>
<td>10/12/2019</td>
<td></td>
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<td>10/15/2019</td>
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<td>10/30/2019</td>
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<tr>
<td>10/31/2019</td>
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<td>%</td>
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This table represents the total particle mass removal data for a specific section over a series of dates, with each date indicating the percentage of mass removal.
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<th>Total Particle Mass (%) for Section</th>
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<td>1.01873E+08</td>
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## VW Golf Exhaust Characteristics

**Vehicle:** VW Golf 1.9l diesel turbocharged with EGR  
**Milage:** 6400 Km  
**Max Horsepower:** 110 HP  
**82060 Watts**

### Hot Steady State Exhaust Analysis

<table>
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<tr>
<th>Constituent</th>
<th>Unit</th>
<th>Idle</th>
<th>50 Km/h</th>
<th>120 Km/h</th>
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<tr>
<td></td>
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<td>+/-</td>
<td>+/-</td>
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<tr>
<td></td>
<td>g/min</td>
<td>21.36</td>
<td>59</td>
<td>3</td>
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<tr>
<td>CO2</td>
<td>g/min</td>
<td>0.055</td>
<td>0.029</td>
<td>0.007</td>
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<tr>
<td>CO</td>
<td>g/min</td>
<td>0.026</td>
<td>0.006</td>
<td>0.028</td>
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<tr>
<td>THC</td>
<td>g/min</td>
<td>0.212</td>
<td>0.01</td>
<td>0.17</td>
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<tr>
<td>Nox</td>
<td>g/min</td>
<td>0.012</td>
<td>0.0016</td>
<td>0.041</td>
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<tr>
<td>Smoke K</td>
<td>m^-1</td>
<td>0.00000001</td>
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<td>2.778E-08</td>
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<tr>
<td>Particulate</td>
<td>Kg/s</td>
<td>6.3 mg/min</td>
<td>0.9</td>
<td>31</td>
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<tr>
<td>Exhaust Flow</td>
<td>l/min</td>
<td>400</td>
<td>570</td>
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| Temp | deg C | 132 | 6 | 199 | 4 | 415 | 7 |
Particle Size Distributions
Typical Diesel Emissions Particulate Size (Mass Fraction)

Adapted from SAE paper 1999-01-3487 (SP-1484)

<table>
<thead>
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<th>a_p (μm)</th>
<th>Wp/Wt (%)</th>
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<td>0.015</td>
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</tr>
<tr>
<td>0.05</td>
<td>15</td>
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<td>0.5</td>
<td>5</td>
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<tr>
<td>1.5</td>
<td>3</td>
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<tr>
<td>5</td>
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\[ y = 3.8198x^{-0.4403} \]

\[ R^2 = 0.9974 \]

Wp/Wt (%) Vs. a_p

\[ \text{Wp/Wt} (\%) \text{ and Power (Wp/Wt (\%))} \]