A COMPACT CORONA DISCHARGE DEVICE (CDD™) FOR NON-THERMAL PLASMA GENERATION IN GASOLINE OR DIESEL ENGINE EXHAUST

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INTRODUCTION

Higher fuel economy targets and hybrid vehicles are increasing the marketability of diesel engines. But in order to implement the growth of diesels to achieve the fuel economy benefits, all emission regulation issues must be met. To do this traps and catalysts are being utilized. One of the main problems is finding a technology that enables the exhaust emission system to not only meet the emission requirements when new, but also to meet them at the regulated intermediate and full life requirements. Work is being done that enables catalysts to remain highly efficient throughout their full life. It is done by using a corona discharge device (CDD™) that introduces non-thermal plasma into the exhaust ahead of the converter. This low power device creates radicals that alter the chemistry of the exhaust so as to limit the poisoning of the catalyst. This can be done without so called 'purge' cycles that lower fuel economy and degrade catalyst long-term durability. This device has been developed, not as a laboratory tool, but as a production ready product and is the first of its kind that is commercially available for testing. It is this product, the Corona Discharge Device, CDD™, which will be described.

In this paper, we describe a compact and robust production-intent corona discharge device that can survive the extremely harsh environment of an automotive exhaust. The device is part of a corona generation system that includes a high voltage, high frequency power supply run off an engine's electrical system, a high voltage shielded cable to transmit the power to the device, and a particular CDD™. This paper is concerned only with the details of a particular CDD™. Details of work done by Litex in the gasoline emissions area can be found in other published papers, see reference [1] and [10]. Litex and others are also doing work in lean gas and diesel applications [2, 3, 4].

In this paper, the design theory of the CDD™ will be presented, including design geometries, material properties, thermal challenges, electromagnetic compatibility issues and verification test procedures.

CORONA DISCHARGE DEVICE, (CDD™)

The Corona Discharge Device, called the CDD™, was developed to increase the in-use efficiency of the exhaust gas aftertreatment system by mitigating the negative effects of undesirable material in the exhaust gas of the engine.

By undesirable, we mean any material that can reduce the efficiency of the catalyst. The most notable harmful material is sulfur, but it could also be phosphorus, carbon, etc. The CDD™ permits the vehicle's catalyst to remain highly efficient during the full life of the vehicle. This allows the vehicle to meet in-use compliance regulations both during any emission test and also, during it's actual on-road use with a minimum of precious metals in the catalyst. This is important as both precious metal prices continue to rise annually and emission regulations become more stringent.

The CDD™ System is a low power, about 25 watts per exhaust system, low cost exhaust aftertreatment device.

Figure 1. Prototype CDD™ System

The system shown in Figure 1 is a Research and Development CDD™ Prototype. It is made up of a power module, a cable and the CDD™ actuator. Figure 2 shows the low volume production intent model for a V-Engine, which requires 1 CDD™ in each exhaust pipe. Note that because it is low power, it cannot replace the catalyst, but it works in conjunction with the catalyst to keep the catalyst highly efficient throughout its life.

Figure 2. Low volume production intent CDD™ System for V-Engine application

The CDD™ System:

1. Converts low voltage direct current battery power to a high voltage high frequency supply. This is done in the power module.

2. The high voltage high frequency supply is delivered through the cable to an electrode of a barrier discharge device, which will be later described in detail.

3. The corona generated through the dielectric by means of this barrier discharge creates a non-thermal plasma in the exhaust gas. This takes place in the CDD™ itself, as seen in Figure 3. The corona is found in the gap between the dielectric material and the ground.

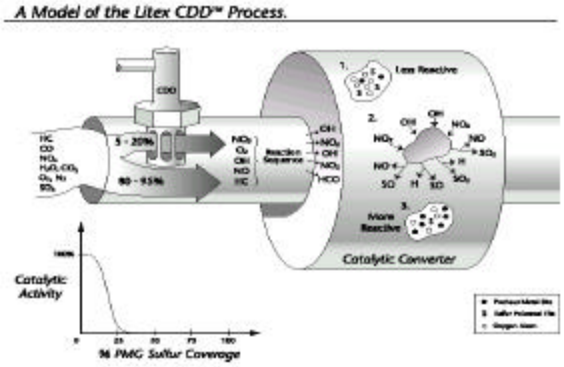

Figure 3. Exhaust flow and process model through the CDD™

4. The exhaust gas is directed, at a significant space velocity, through the corona so as to alter the exhaust gas constituent chemistry, creating radicals.

5. The radicals continue to be generated in a continuation reaction sequence that combine with and prevent material, such as sulfur, from contaminating the precious metal in the catalyst, keeping the catalyst more highly efficient.

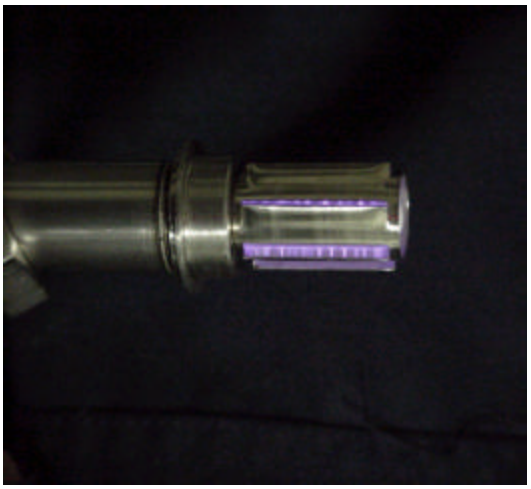

Figure 4. CDD™ Actuator

The actual CDD™ is shown in Figure 4. This CDD™ is operating. The corona can be seen in the gap area, which is where the non-thermal plasma is generated. The area of the CDD that will be discussed is the portion that is directly inserted into the exhaust pipe ahead of the catalyst.

In cross section, the barrier discharge device portion is shown in Figure 5 and Figure 6. Figure 5 is the scientific diagram. Figure 6 is the cross section of the corona portion of the CDD™. The CDD™ has a;

- Power Electrode
- Ceramic Dielectric ($\varepsilon 1$ and $\varepsilon 3$)
- Air Gap ($\varepsilon 2$)
- Ground Electrode

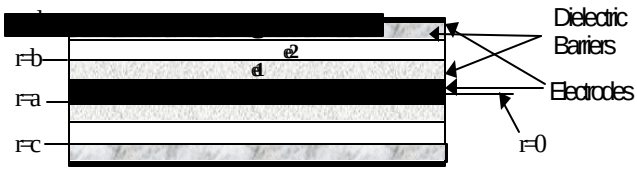

Figure 5. Cross section of barrier discharge device

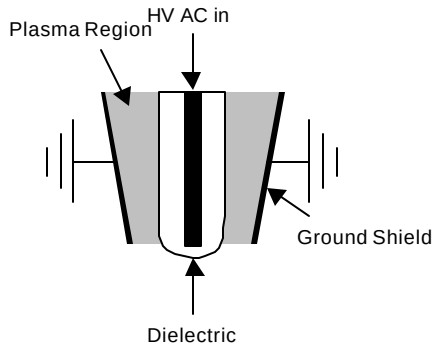

Figure 6. CDD™ Cross Section.

Barrier discharge devices like the CDD™ can have a dual barrier as shown above. For ease of fabrication, the CDD™ was designed and built as a single barrier device.

POWER OF THE CORONA

Figure 7 shows typical plasma power vs. temperature curves for barrier discharge devices of varying gaps [7]. Although the curves are quite different, they all exhibit the characteristic peak power followed by the power drop-off as the temperature continues to rise.

Corona power is important in optimizing the creation of the radicals needed for the CDD™ effect in improving emissions, demonstrating the importance of the proper gap selection in obtaining the optimum power curve.

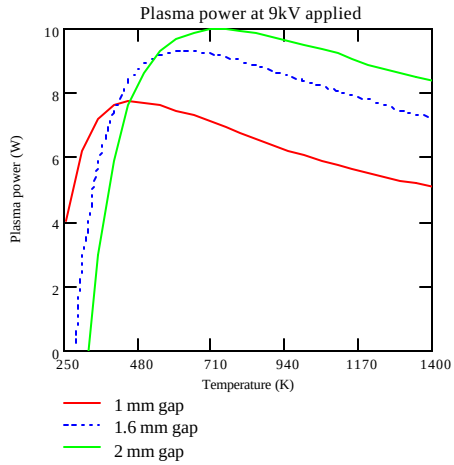

Figure 7. Plasma power vs. temperature

Work has begun to model as many of the important parameters as possible. This makes the development of the CDD™ easier and faster. As an example, it is important to know the breakdown voltage over temperature so that the corona power is known at any engine-out condition.

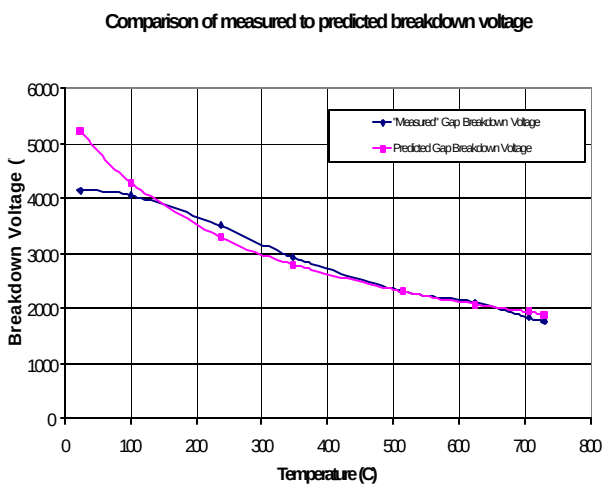

Figure 8. Comparison of measured breakdown voltage to predicted breakdown voltage for a particular CDD™

Figure 8 shows the comparison of measured to predicted breakdown voltage. Work will continue to perfect the model as much as possible. The effect of temperature on the breakdown voltage is also illustrated, reiterating the care needed in design to insure proper operation over a wide temperature range.

DIELECTRIC

The selection of the proper dielectric material and design is important to the optimization of the operation of the CDD™. One of the first considerations is the Dielectric Breakdown Strength. There is an electric field that is built up across the dielectric. If this breakdown field is exceeded, catastrophic failure may occur. This failure is irrepairable and irreversable. Particular note must be taken since the breakdown strength of the dielectric changes over temperature.

Figure 9 shows the field strength vs. temperature. The applied voltage was adjusted to give 15W corona power. Three CDD's™ of varied gaps (1.0mm, 1.5mm and 2.0mm) were measured. The smaller gaps have higher field strengths; and the field strength increases with temperature.

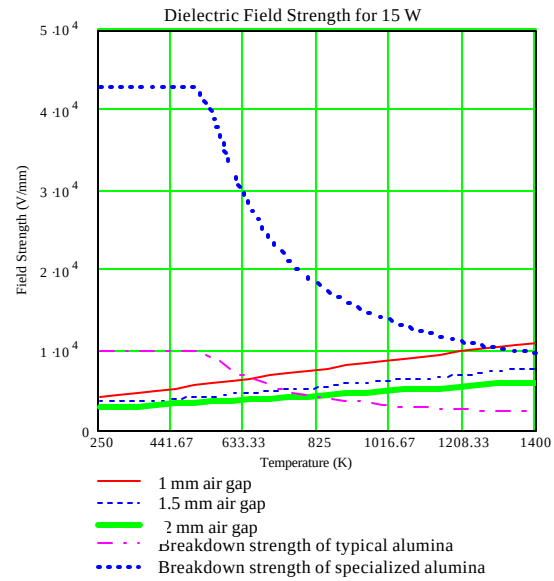

Figure 9. Electric field strength across dielectric for a constant power

The dielectric property, as can be seen, is important. The "typical alumina" has a breakdown strength that is below the field strength of the device in the 650°K to 800°K range. The specialized alumina clearly can tolerate higher exhaust gas temperatures. The temperature dependence is estimated from the curves in reference [8].

Dielectric loss is also a problem. There is an increased resistive loss in the dielectric as the exhaust gas temperature increases. The resistance decreases with increasing temperature. This will cause the device to draw more current and further heat the dielectric. Further heating decreases the resistance. A thermal runaway can occur until the current exceeds that rated for various components, causing failure. The appropriate ceramic material with the proper resistance vs. temperature characteristics therefore needs to be selected for any given exhaust temperature.

EMI

The CDD™ System is fully shielded and the cable used is fully integrated. Non-thermal discharges result in short bursts, in the sub nano second range, of high current that can cause considerable noise [9]. Without shielding, the noise will be induced on any nearby metallic surfaces.

The results of the EMI development are summarized in Figure 10. This is a graph of the radiated EMI plotted against the General Motors 9100 specification for radiated emissions.

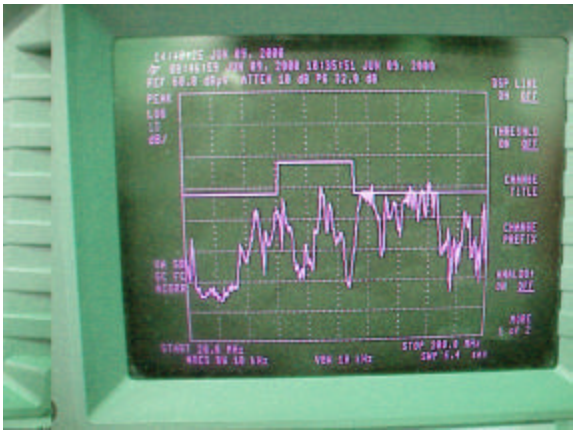

Figure 10. CDD™ EMI development

As you can see, the CDD™ System meets the specification except for a brief point or two. Additional filtering will bring this into full compliance with the specifications. This is true even in the 80 – 100 megahertz range, which is the frequency of the arcing in the discharge. In summary, even though this is an "arcs and sparks" device which typically has inherent difficult EMI problems, the CDD™ can be designed so as to meet EMC specifications.

THERMAL CONSIDERATIONS

Since ambient temperatures range from -40°C to exhaust gas temperatures as high as 1100°C, thermal design considerations are also important. One of the most important considerations is keeping the heat in the exhaust stream and away from the electrical connection of the cable to the CDD™.

Figure 11 shows the CDD™ in its application. Of course the heat is inside the pipe. It is desirable to keep the heat away from the electrical connection and the cable, avoiding two concerns. One concern is that the coefficient of thermal conductivity is very high for both stainless steel and ceramic (the two major components of the CDD™). The second concern is that there are little or no air gaps in the CDD™. Air gaps are good for insulation, but permit stray coronas which are not desirable.

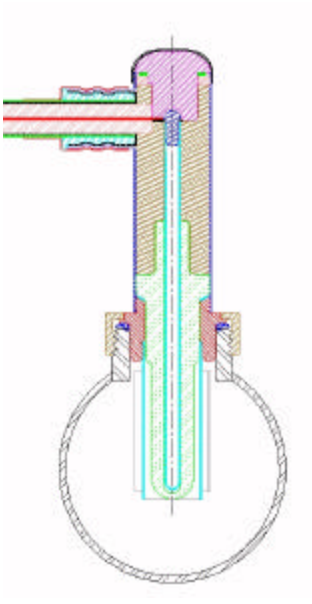

Figure 11. Cross section of cable and CDD™ interface, inserted into an exhaust pipe

Some of the problems are higher system current draw, resulting in lower system efficiency and the degradation of non-metallic components. The solution is the use of different ceramics. As shown in Figure 10, there is a proper dielectric, high thermal conductivity ceramic in the exhaust pipe portion of the CDD™ and a poor dielectric but low thermal conductivity ceramic in the upper section. Additional design features, such as the hollow electrode, lower the heat transfer to the cable connection. This can be accomplished since both sides of the tube are at the same potential, making it impossible to develop a discharge inside the tube.

GAS EXCHANGE

Gas exchange is also an important design issue when considering the CDD™ effect on the after-treatment system.

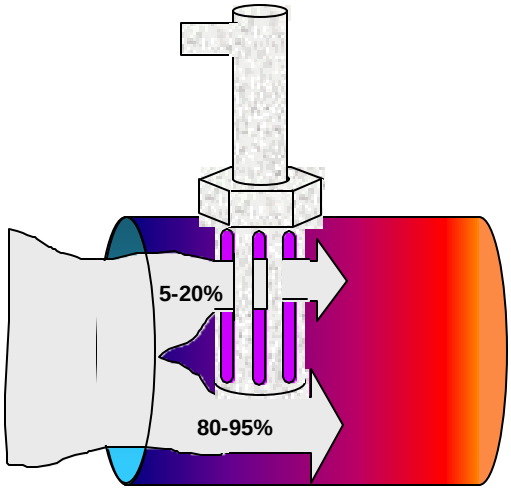

Figure 12. Gas flow through the CDD™

Figure 12 shows that only a small percentage, roughly 5 – 20 %, of the gas flow is actually treated by the CDD™, producing radicals. The radicals produced in the device are then "pushed" into the exhaust stream. It is desirable that the CDD™ not be placed in a stagnant flow area. The vehicle maker must be involved in this optimization. This type of barrier discharge device is a "transverse" type, looking very similar to an oxygen sensor. A "planar" type design can be visualized by two flat planes with the exhaust gas being directed between the plates. The reason the transverse geometry was chosen is because the transverse type described here is much easier to install.

To enhance the gas exchange for this transverse type corona generator, several design activities were taken:

First, a study was performed to optimize the slot design. The tradeoff here is that large slots are needed for better gas exchange. However, less slot area and more ground surface is necessary to form as much corona as possible. Complicating the study was the effect of the gap, which was referenced previously. Gap changes, by themselves, directly affect corona power. The study resulted in the slot configuration that is used today, as illustrated in Figure 4.

Second, to improve gas exchange, an additional design effort was performed to study the effects of adding louvers to the slots. This increases the frontal area of the CDD™ in the exhaust flow, creating a larger gas exchange corona area resulting in larger radical introduction into the exhaust, thereby increasing the CDD™ effect.

Since it cannot be easily tested in production with exhaust gas, a surrogate measurement is needed to quickly check the radical producing capability of the CDD™. It has been determined that the radical production could be quantified by measuring the effectiveness of the CDD™ as an ozone generator [5, 6]. A test stand was developed using dried air as the medium.

The test stand consists of an air flow source with a sufficient dryer to achieve dew points less than -40°C, piping the same size as the automotive exhaust pipe, an air flow sensor, a CDD™ installation point, an ozone analyzer and finally an ozone destroyer (catalyst). When the air is flowed through the CDD™ at various flow rates, measured by a calibrated airflow sensor, it's ozone output is measured downstream by a calibrated ozone analyzer. The ozone is then measured in PPM. Because of the self-heating of the device and the sensitivity of the device to temperature, care was taken in proper test methodology.

SUMMARY

In summary, a compact and robust barrier discharge device called a corona discharge device (CDD™), has been presented. It has been designed to operate in the exhaust stream. Its corona generates a non-thermal plasma which introduces radicals into the exhaust. These radicals, through a chemical reaction, mitigate aftertreatment system poisoning such as sulfur, even at 30 PPM sulfur fuel. The device has been designed to meet the life requirements of a SULEV vehicle. It is durable in the high temperature environment of the vehicle exhaust. It has been designed to meet the durability sections of the oxygen sensor specifications. It only requires a few amps to

operate. The CDD™ will not adversely affect other vehicle components or systems.

The Litex CDD™ has been designed to provide 15W of corona power in the non-thermal plasma region of 600°C exhaust gas temperature. Thermal, plasma power, and gas exchange data were generated and presented in this paper. The design is adaptable to different temperature ranges, size, or power requirements.

A special note of thanks to our development partners at Saturn Electronics and Engineering of Auburn Hills, Michigan, for their dedication to the development of the hardware and the production design of the CDD™.

REFERENCES

1. Caren, Ekchian, Roth, Cowart, Noordzij, "Reduction of exhaust emission from a stoichiometric engine using non-thermal plasma generated by a corona discharge device", SAE # 1999-01-3636.
2. Penetrante, Brusasco, Merritt, Pitz, Vogtlin, Kung, Kung, H.H., Wan, C.Z., and Voss, K.E., "Plasma-assisted catalytic reduction of NO_x", SAE #982508.
3. Hammer, Broer, "Plasma-enhanced selective catalytic reduction of NO_x for diesel cars", SAE #982428.
4. Hemingway, Goulette, Ripley, Thoreson, Kupe, Herling, Baskaran, Smith, Lessor, Virden, "Evaluation of a non-thermal plasma system for remediation of NO_x in diesel exhaust", SAE # 1999-01-3639.
5. Carlins, J.J., "Engineering Aspects of Ozone Generation", Env. Prog. 1, 113 (1982).
6. U. Kogelschatz, "Advanced Ozone Generation" in Process Technologies for Water Treatment, S. Stucki, Ed. New York & London: Plenum, 1988. Pp-87-120.
7. Meek and Craggs, Electrical breakdown in gases, John Wiley & Sons, New York, 1978.
8. Rosebury, Handbook of Vacuum Techniques, Springer-Verlag, 1993.
9. Khan, A.A.,"Studies on the inhomogeneous nature of the silent discharge reactor part 1. Experimental Investigations", Can. Jour. Chem. Eng. 67, 102 (1989).
10. Ekchian, Balles, Christeller, Cowart, Fuller, "Use of non-thermal plasma generated by corona discharge device (CDD) to improve the efficiency of a 3-way catalyst" Global Powertrain Congress 1