Effect of electric diesel particulate trap on particulate emission characteristics of light-duty diesel engine

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Abstract. Based on the principle of corona discharge and electrostatic adsorption, an electric diesel particulate trap (EDPT) with high-voltage negative corona electrode structure was designed. The effect of EDPT on particulate emission characteristics of light-duty diesel engine was investigated based on engine bench test platform. The results show that at the external characteristics operating point of the engine, the trapping efficiency of EDPT for particulate number (PN) is 98.4%, and the trapping efficiency for particulate mass (PM) is 95.0%. With the increasing of exhaust flow, the trapping efficiency of EDPT for PN and PM both decreases slightly. At the load characteristics when engine speed is 1800 r·min⁻¹, the trapping efficiency of PN and PM by EDPT are 98.9% and 95.1%, and the trapping efficiency does not change significantly with the increase of load and temperature. The effects of EDPT and DOC (Diesel oxidation catalyst)+diesel particulate filter (DPF) device on engine backpressure and particulate trapping efficiency are compared. The results show that the effect of using EDPT on engine exhaust back-pressure is much lower than DOC+DPF, and the trapping efficiency for PN and PM is lower than that of DOC+DPF. From the perspective of trapping efficiency and device size, EDPT is more suitable for the exhaust gas treatment of construction machinery, agricultural machinery and factory fixed source diesel engines.

1. Introduction
Increasingly stringent emission regulations require diesel engines to be equipped with external particulate removal devices[1]. Diesel particulate filter (DPF) is currently the most effective particulate aftertreatment device[2,3], which could capture more than 90% of particulate matter in the exhaust. However, due to wall-flow structural reasons, the installation of DPF will increase the exhaust back-pressure of the engine. Besides, soot and ash will gradually deposit in the DPF trapping channels[4,5,6], which will further increase the engine backpressure, and will cause the engine's power to drop and its economy to deteriorate. Although the DPF can be regenerated periodically[7,8], the impact of the DPF on the engine in the non-regeneration phase is still can’t be ignored.

Electrostatic dedusting is a common method for gas dedusting[9,10,11], which has been developed
for many years. It was initially used for industrial dedusting. Later, with the advancement of technology, electrostatic dedusting technology has also been gradually applied in indoor dedusting. Therefore, in order to avoid the congenital deficiency of the wall-flow structure of traditional DPF, and inspired by electrostatic precipitator technology, based on the principle of corona discharge and electrostatic adsorption, an electric diesel particulate trap (EDPT) with high-voltage negative corona electrode structure was designed.

Based on a light-duty diesel engine bench test, the trapping characteristics of particulates by EDPT were explored. This study aims to provide new ideas for diesel particulate emission control technology.

2. Design of EDPT

EDPT is based on the principle of corona discharge. A high voltage is applied to an electrode with a small radius of curvature, which causes a strong electric field around the electrode. Free electrons in the electric field will collide with gas molecules under the action of the strong electric field, thereby generating more free electrons and positive ions, and continue to propagate outward in the form of "electron avalanche", generating a great number of free electrons and positive ions. Corona discharge is accompanied by light blue glow and noisy current sound.

Electrons or positive ions are attached to particles passing through the electric field area, and are moved to the electrode by the electric field force, thereby being trapped. Because the negative corona has a lower corona voltage and a higher breakdown voltage than the positive corona, a negative corona discharge is used in this design. Figure 1 shows the schematic diagram of the negative electrode corona discharge.

Equation (1) shows the trapping efficiency of the electrostatic adsorption device, which is called Deutsch Anderson formula. It can be known from the formula that when the area of the dust collecting plate is infinite, or the driving speed is infinite, or the gas flow is close to 0, the trapping efficiency is closed to 100%. In this device, a cylindrical "U" structure is used, and the corona electrode is designed as a sharp maple leaf structure, and a voltage boosting circuit is used to make the electrode voltage reach 12000 volts. The internal structure of EDPT is shown in Figure 2. The structural parameters are shown in Table 1.

\[
\eta = 1 - e^{-\frac{A}{D}}
\]  

(1)

Where the \( \eta \) represents the collection efficiency, \( A \) represents the area of the dust collecting plate,
\( w_r \) represents the driving speed of the particles moving toward the electrode in the electric field, and \( Q \) is the gas flow in the electric field.

![Figure 2. EDPT internal structure](image)

### Table 1. Main parameters of EDPT

| Parameters                          | Value               |
|-------------------------------------|---------------------|
| Carrier Length×diameter of cylinder (mm×mm) | 1200×200            |
| Number of cylinder                  | 2                   |
| Structure                           | Wire mesh structure |
| Shell Material                      | Steel (409L)        |
| Cushion Material                    | Foam nickel         |
| Cushion Thickness (mm)              | 20                  |

### 3. Test equipment and method

In this study, a bench test was conducted to explore the particulate emissions characteristics of a light-duty diesel engines before and after the installation of EDPT. The main parameters of the test diesel engine are shown in Table 2. The test equipment includes: electric dynamometer, fuel consumption meter and auxiliary equipment (cooling water temperature adjustment system, oil thermostat, engine data acquisition box, air filter, etc.); the main test equipment of exhaust includes: EEPS-3090 particle size tester and DEKATI-2000 two-stage dilution jet diluter, pressure sensor, and temperature sensor.

During the test, the engine particulate matter emission characteristics, exhaust temperature, and backpressure parameters were measured before and after the installation of EDPT. The test point include external characteristics operating point of the engine and load characteristics at engine speed of 1800 r·min\(^{-1}\) and 2400 r·min\(^{-1}\).

### Table 2. Main parameters of test engine

| Parameters    | Value          |
|---------------|----------------|
| Displacement  | 3.5 L          |
| Rated power   | 65 kW          |
| Number of cylinders | 4           |
| Fuel supply system | High pressure common rail |

### 4. Test results

#### 4.1. Trapping efficiency for particulate number (PN) and particulate mass (PM)

Figure 3 and Figure 4 show the trapping efficiency for PN and PM by EDPT at the external characteristics operating point of the engine and load characteristics operating point at engine speed of 1800 r·min\(^{-1}\).

It is known from Figure 3 that EDPT has a good trapping effect on particulate at each operating point. At the external characteristics operating point, the average trapping efficiency for PN is 98.4%,
and the trapping efficiency decreases slightly with the increase of the rotation speed, which is because the exhaust flow increased and the particles in the EDPT move quickly, and they became more hard to absorb the free electrons in the electric field and be trapped by electrode. At the load characteristics when engine speed is 1800 r·min⁻¹, the average trapping efficiency for PN is 98.9%. The overall trapping efficiency is high, and with the increase of load and exhaust temperature, the trapping efficiency remained almost unchanged.

At the external characteristics operating point of the engine and the load characteristics operating point at engine speed of 1800 r·min⁻¹, the trapping efficiency of PM is 95.0% and 95.1%, and meanwhile, the trapping efficiency decrease slightly with the increase of the rotation speed of the engine. The trapping efficiency does not change significantly with the increase of load and temperature.

4.2. Particles size distribution characteristics
EEPS3090 can measure particles with particle size range from 5.6nm to 560 nm. Figure 5 and Figure 6 show the particle size distribution before and after the installation of EDPT.

It can be known from Figure 5 that the EDPT has a high trapping efficiency for particles with different particle diameters. As the speed increases, the device's efficiency in trapping particulates
gradually decreases. In addition, with the 50 nm particle size as the boundary, the trapping efficiency of nuclear mode particles is higher than that of accumulated particles. The reason for the high trapping efficiency of nuclear mode particles is that the particles are small in size and light in weight, and are more easily affected by electric field forces.

Figure 5. Effect of EDPT on particles size distribution at external characteristics operating point
Figure 6 shows the particle size distribution at load characteristic when test engine speed is 1800 \( r\cdot\text{min}^{-1} \). It can be seen from the figure that when the load increases, there is no significant change in the trapping efficiency for particulates by EDPT, and the trapping efficiency of nuclear mode particulates is also higher than that of accumulation mode particulates.

5. Comparative test of EDPT and DOC+DPF

In order to compare the performance of EDPT and DPF, an additional set of DOC (Diesel oxidation catalyst)+DPF aftertreatment device emission reduction test was performed in the bench test. The parameters of the aftertreatment device are shown in Table 3. The test working conditions of the engine are 10\%, 50\%, 75\%, and 100\% load at engine speed of 2400 \( r\cdot\text{min}^{-1} \). The effects of this aftertreatment device on particulate emissions and engine backpressure are measured, and the data is compared with the EDPT.

| Parameters          | Value       | DOC  | DPF |
|---------------------|-------------|------|-----|
| Diameter (mm)       | 203         | 190.5|     |
| Length (mm)         | 90          | 203.2|     |
| Material            | FeCrAl      | Cordierite |     |
| Mesh (cpsia)        | 300         | 200  |     |
| PGM\(^{b}\) (g \cdot ft\(^{-3}\)) | 55          | 35   |     |

\(^{a}\) cpsi-cells per square inch
\(^{b}\) PGM-platinum group metal

Figure 7 shows the comparison of engine backpressure after the installation of EDPT and DOC+DPF devices. Compared with DOC+DPF devices, EDPT is more conducive to gas flow, making the engine exhaust backpressure smaller and closer to the original engine backpressure. This is a major advantage of EDPT.

Figure 8 compares the particulate emission characteristics of test engine installing with DOC+DPF devices and EDPT. It can be seen from the Figure 8 that DOC+DPF has a better trapping effect on PN at low and medium load, but when the engine load reaches 100\%, its trapping efficiency is lower than EDPT, which is mainly caused by the high exhaust flow and high temperature, which make part of
particles trapped by DPF being blown out. Without considering the full load work condition, the average trapping efficiency for PN by EDPT and DOC+DPF is 97.2% and 99.6%. In the four operating conditions, the trapping efficiency for PM by EDPT is lower than that of DOC+DPF, and the average trapping efficiency is 91.9% and 99.1%.

In order to better compare the difference between EDPT and DOC+DPF in the trapping effect of particles, the escape rate $\delta$ of particles passing through the particle trapping devices is defined as:

$$\delta = 1 - \eta$$

(2)

Without considering the full load work condition, the escape rate of PN by EDPT and DOC+DPF is 2.8% and 0.4%. The average trapping efficiency of PM by EDPT and DOC+DPF is 8.1% and 0.9%.

![Figure 7. Comparison of engine backpressure after the installation of EDPT and DOC+DPF devices at engine speed of 2400 r·min$^{-1}$](image)

![Figure 8. Effect of installing EDPT and DOC+DPF devices on engine particulates emission at engine speed of 2400 r·min$^{-1}$](image)

6. Conclusions

Based on the principle of corona discharge and electrostatic adsorption, an electrostatic diesel particulate trap with high-voltage negative corona electrode structure was designed.

Based on the bench test, the trapping effect of EDPT on the particulates was tested. The result
shows that at the external characteristics operating points, the trapping efficiency for PN and PM by EDPT are 98.4% and 95.0%; at the load characteristics when engine speed is 1800 r·min⁻¹, the trapping efficiency for PN and PM by EDPT are 98.9% and 95.1%. The EDPT has a good trapping effect on the particulates in the range of the measured particle size, and the trapping efficiency for the nuclear mode particulates is greater than the accumulated mode particulates. EDPT’s trapping efficiency decreases with the increase of exhaust flow.

The effects of EDPT and DOC+DPF devices on engine backpressure and particulate trapping efficiency are compared. The results show that installing EDPT has almost no effect on engine backpressure, while installing DOC+DPF will increase engine exhaust backpressure a lot. The trapping efficiency of EDPT for PN and PM is slightly lower than that of DOC+DPF. From the perspective of trapping efficiency and device size, EDPT is more suitable for the exhaust gas treatment of construction machinery, agricultural machinery and factory fixed source diesel engines.

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References
[1] Johnson T and Joshi A 2017 Review of vehicle engine efficiency and emissions SAE Paper 2017-01-0907.
[2] Khair M 2003 A review of diesel particulate filter technologies SAE Paper 2003-01-2303.
[3] Wei Q, Ziegler F and Winkler W 2010 PM emissions from light-duty diesel vehicles retrofitted with diesel particulate filters SAE Paper 2010-01-0788.
[4] Sappok A, Santiago M, Vianna T and Wong V 2009 Characteristics and effects of ash accumulation on diesel particulate filter performance: Rapidly aged and field aged results SAE Paper 2009-01-1086.
[5] Liu Y, Su C, Clerc J, Harinath A and Rogoski L 2015 Experimental and modeling study of ash impact on DPF backpressure and regeneration behaviors SAE Int. J. Engines 8 1313-21.
[6] Voutsi O, Tsinoglou D, Karamitros D and Koltsakis G 2019 Pressure drop of particulate filters and correlation with the deposited soot for heavy-duty engines SAE Paper 2019-24-0151.
[7] Rothe D, Knauer M, Emmerling G, Deyerling D and Niessner R 2015 Emissions during active regeneration of a diesel particulate filter on a heavy duty diesel engine: Stationary tests J. Aerosol Sci. 90 14-25.
[8] Mamakos A, Martini G and Manfredi U 2013 Assessment of the legislated particle number measurement procedure for a Euro 5 and a Euro 6 compliant diesel passenger cars under regulated and unregulated conditions J. Aerosol Sci. 55 31-47.
[9] Morawska L, Agranovski V, Ristovski Z and Jamriska M 2002 Effect of face velocity and the nature of aerosol on the collection of submicrometer particles by electrostatic precipitator Indoor air 12 129-37.
[10] Grass N, Hartmann W and Klockner M 2004 Application of different types of high-voltage supplies on industrial electrostatic precipitators IEEE Trans. Ind. Appl. 40 1513-20.
[11] Jaworek A, Marchewicz A, Sobczyk A T, Krupa A and Czech T 2018 Two-stage electrostatic precipitators for the reduction of PM2.5 particle emission Prog. Energy Combust. Sci. 67 206-33.
[12] Chen M 2018 Experimental study on removal of fine particles and VOCS by electrostatic precipitator and catalysis (in Chinese). Master thesis. Zhejiang University, Hangzhou, Zhejiang, China.