Reduction of NOx Generation from Electrostatic Precipitators

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Abstract—Electrostatic Precipitators (ESPs) have recently been applied in environmental air purification for congested car roads. When ESPs are used to remove suspended particles, corona discharges generate NOx (=NO + NO_2), or oxidize NO in contaminated environmental air into more toxic NO_2. This drawback of ESPs should be improved for more wide use of ESPs as a tool for environmental air purification. In this study, effectiveness has been evaluated of the non-woven sheet made of activated carbon fiber (ACF) attached on collection electrodes of an ESP. The experimental results show that this method can not only minimize NOx generation from ESPs but also improve collection efficiency of suspended particles.

Keywords—Electrostatic precipitator, NOx generation, ozone generation, corona discharge, positive discharge, negative discharge

I. Introduction

Over past two decades, due to increasing environmental concerns, technologies for removing SPM (Suspended Particulate Matter), NOx (nitrogen oxides) as a sum of NO_2 (nitrogen dioxide) and NO (nitrogen mono-oxide), along congested car roads in metropolises have been studied intensively [1-6]. Background of these studies implies the fact that the regulation of the environmental air quality, day average of SPM; 0.1 mg/m^3 or less, and NO_2; not greater a zone between 0.04 and 0.06 ppm, has seldom been attained in inhabitant areas with congested roads [4, 6, 7]. In general, the "ppm ratio" of NO_2 to NOx in the atmosphere along congested roads is between 20 and 50 percent (the rest is NO), according to the field data reported [8] by ERCA (Environmental Restoration and Conservation Agency, Japan). Another report [9] from ERCA suggests the following features for ESPs used along congested roads.

1) ESPs can be used as separations for walk ways from main roads and/or at the center of roads. For this purpose and to save energy, natural ventilation method is recommended utilizing natural wind and/or wind generated by running cars.
2) One-stage ESP with parallel corona electrodes is preferable to reduce the size and the pressure loss.
3) For safety, distributed high voltage supply shall be used. Maximum current of each high voltage generator must be small, preferably less than the maximum of 10 mA.

Those features can be achieved technically, however, there is another important problem to be solved. Corona discharges in ESPs undesirably generate NOx and ozone, and this must be minimized.

Characteristics of NOx generation in ESPs used are as follows [10, 11, 18-20].

1) Positive discharges usually generate more NOx than negative discharge.
2) Most part of NOx generated by dc corona is NO_2.
3) Higher humidity enhances the NOx generation.

Ozone generated in corona discharge [12, 13] is consumed for oxidation of NO from exhaust of vehicles to NO_2 which is more harmful to human bodies [9, 14]. Ozone from ESPs can be detected when NO is completely oxidized to NO_2.

The above mentioned background requires that ESPs for removing SPM in the atmosphere along roads should be operated safely using limited current power supply for corona discharge, and should minimize NOx and ozone generation. In order to meet these requirements, non-woven filters made of activated carbon fiber (ACF sheet) could be used to reduce NOx and ozone generation in ESPs [15]. In this study, evaluation of de-NOx performance of the ACF sheet attached on the collecting (earth) electrode of the test ESP has been made.

II. Methodology

A one-stage type ESP, as shown in Fig. 1, was used to evaluate the collection efficiency of SPM and generation of NOx and ozone vs. the discharge power. Target value of the collection efficiency of SPM was 80 percent.

Fig. 2 shows the electrodes. The discharge electrode is saw-tooth with the discharge poles on both sides. Angle of the discharge pole, "Angle", is 30 degrees, "Height" of the pole is 10 mm, and "Pitch" between the adjacent two poles is 16 mm. The electrode is made of stainless steel 304 with 0.6 mm thickness. This figure also shows conventional flat earth-plates (SUS304) used for comparison with the other electrode attaching the ACF sheet on the plate. Characteristics of the ACF is as follows; Manufacturer: OSAKA GAS Co., product number: FN-150-P20, category: "Pitch" from coal tar, thickness: approx. 3 mm, specific surface area: approx. 500 m^2/g, fiber diameter: approx. 18 μm, average diameter of porous thin holes for adsorption of gas

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Received; September 24, 2009

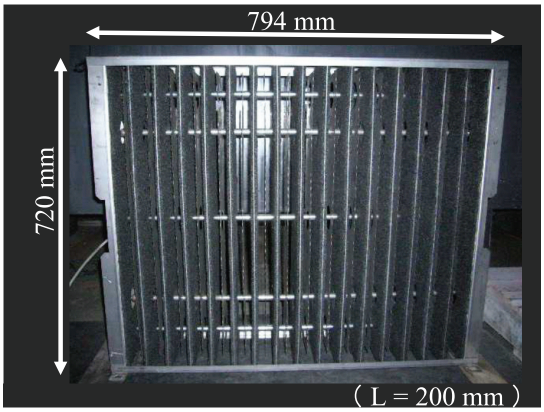

Fig. 1. Appearance of the ESP.

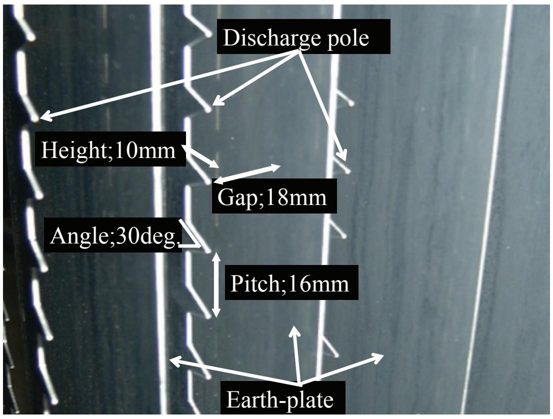

Fig. 2. Structure of the electrodes.

molecules: approx. 15 x 10^{-7} mm, ratio of contained metal: between 0.01 and 5 wt%.

The spacing between the discharge and the earth-plate, designated as "Gap", is 18 mm for both cases with or without the ACF on the earth-plates.

The test equipment and their specifications are shown in Fig. 3 and Table I. The duct system with a fan was used in the experiment to measure the performance at gas velocity of 0.5 m/s. Positive or negative dc high voltage was applied to the ESP. The sampling nozzles for measuring NOx, ozone and SPM were set at 2 m windward and 3 m leeward from the ESP. To generate SPM, exhaust from the diesel engine was used and the inlet SPM concentration was regulated to be approx. 0.5 mg/m^3. For NOx (NO_2 and NO) and ozone measurement, room air without exhaust was supplied (without the diesel engine operation) with the same gas velocity of 0.5 m/s. The increased amount of NOx and ozone was determined.

After confirming that the engine operation did not affect the discharge current of the ESP, the following four cases were tested. Relative humidity during the test was between 35 and 45 Rh%. The gas temperature was almost constant between 35 and 40 degrees.

Case 1 "Positive": Positive discharge without ACF

Case 2 "Negative": Negative discharge without ACF

Case 3 "Positive ACF": Positive discharge with ACF on the earth-plate

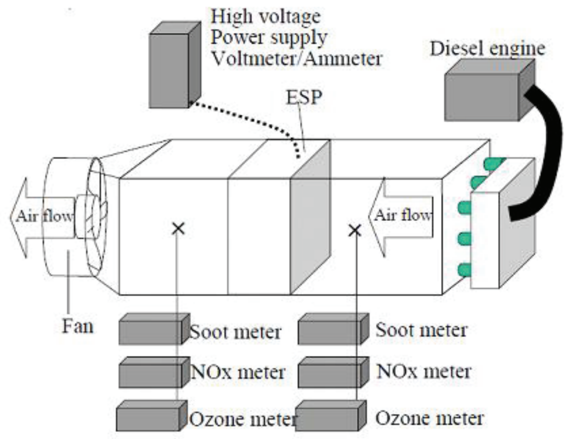

Fig. 3. Experimental setup and measuring equipment.

TABLE I
EXPERIMENTAL CONDITION AND SPECIFICATIONS

Items	Details
Duct	W;940mm , H;780mm , L;12,500mm
Flow rate	0.23 m^3/s (0.5m/s of line velocity in front of ESP)
ESP without ACF	W;775mm , H;720mm , L;200mm Number of spike plate lanes ; 19
ESP with ACF	W;794mm , H;720mm , L;200mm Number of spike plate lanes ; 16
Meters	For soot concentration ; AP632T type (SHIBATA, light scattering) For NOx concentration ; APNA-370type (HORIBA, chemi-luminescence) For ozone ; APOA360 type (HORIBA, ultraviolet absorption)
Diesel engine	Type: 4BD1-T (ISUZU) Displacement volume:4000cc
Concentration	0.5 mg/m^3 on SPM at windward of ESP
High voltage power supply	Controlled phase by thyristor and duplicated voltage type (Origin Electric) Max. rate DC±12kV,150mA Ripple ; ±3% or less

Case 4 "Negative ACF": Negative discharge with ACF on the earth-plate

III. RESULTS AND DISCUSSION

Characteristics of the applied voltage vs. discharge current for Case 1 to Case 4 are shown in Fig. 4. Each case indicates the discharge current increases with the rise in the applied voltage. Finally spark takes place at V_s.

V_s in Case 1 and Case 2 are ± 12 kV. When the absolute value of the voltage is the same, negative corona gives larger discharge current than positive corona.

V_s for "Positive ACF" is 7.5 kV, whereas that of "Negative ACF" is 6.5 kV. When the ACF is used, the current increases more rapidly in both polarities. "Negative ACF" shows, on the contrary to the Case 1 and 2, less discharge current than "Positive ACF" at the same absolute value of the voltage.

Mode of the corona discharge in "Positive" is shown in Fig. 5. With increasing applied voltage, brush corona (b) appears at first. With further increase in the voltage, streamer corona (c) appears. Streamers are expanding and extending in the full discharge gap. This change from

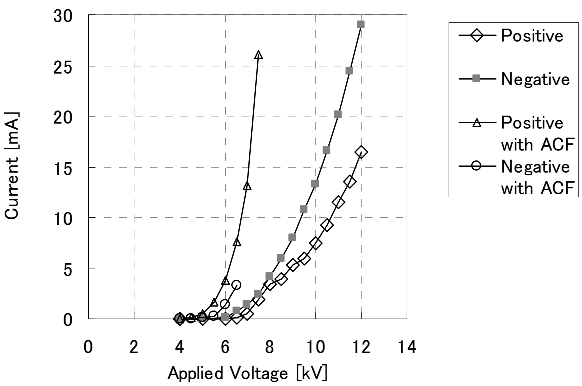

Fig. 4. Applied voltage – Current characteristics.

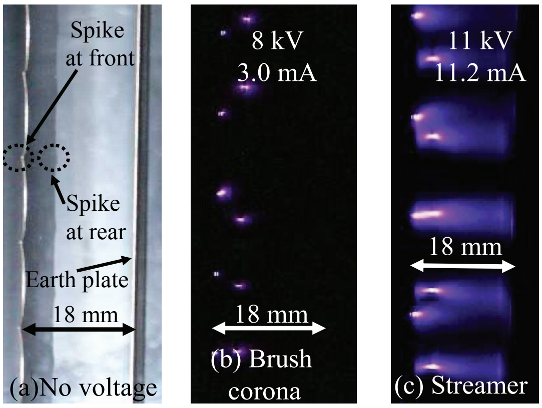

Fig. 5. CASE 1 Positive discharge without ACF.

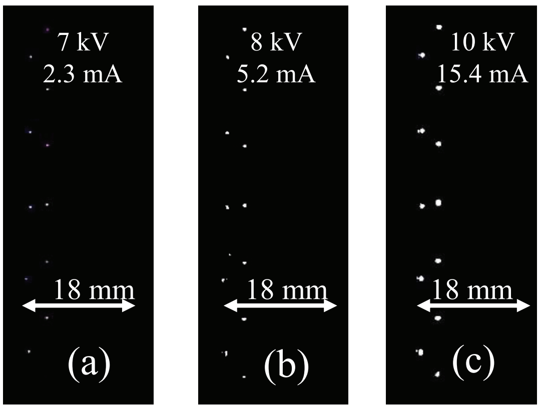

Fig. 6. CASE 2 Negative discharge without ACF.

brush to streamer is affected by the shape of the discharge electrode, especially radius of curvature of the corona tip [14]. Both brush and streamer corona in "Positive" radiates lunar-colored light.

The discharge mode of "Negative" is shown in Fig. 6. With increasing applied voltage, the luminosity at the poles becomes intense with the order of (a), (b) and (c).

Mode of the discharge of "Positive ACF" is shown in Fig. 7. With increase in the applied voltage, fibers of the ACF are pulled upward by the electric field as shown in "A" of photo (a). As this picture was taken under the condition of no ventilation, this aspect of fuzzing might be slightly changed with the gas flow on the surface. The

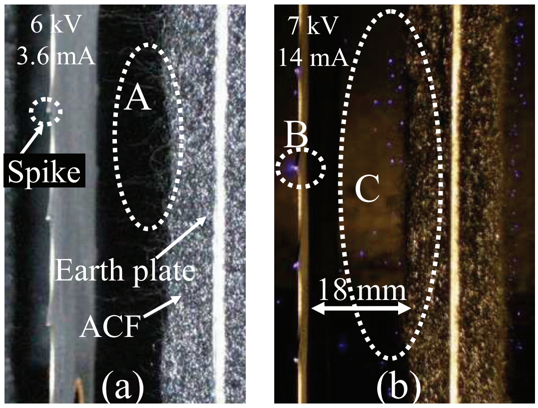

Fig. 7. CASE 3 Positive discharge with ACF.

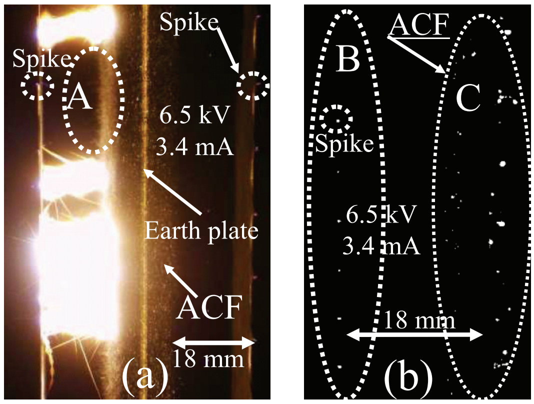

Fig. 8. CASE 4 Negative discharge with ACF.

poles discharge in "B" of photo (b). In addition, tips of lifted ACF are also discharging in "C". Positive corona is taking place at the poles and negative corona discharge is taking place from tips of fuzzing ACF, forming bi-polar ionic field. The lifted ACF fibers cause the Gap shorter, resulting in lower sparking voltage of 7.5 kV.

Mode of the discharge in case of "Negative ACF" is shown in Fig. 8. The photo (a) shows a sparking. The surface of ACF with fuzz indicated as "A" of photo (a) is almost the same as the case of "Positive ACF". The photo (b) is taken during no spark. The poles of the electrode glow as dots, indicated as "B". From the tips of the lifted fibers of ACF, light emission associated with streamers and glow coronas are seen, indicated as "C". With the increasing voltage, more points of the lifted fibers are generating streamers, resulting in lower spark voltage of 6.5 kV.

The characteristics of the collection efficiency η vs. power consumption in each Case are shown in Fig. 9. In each case, η increases with the power consumption. The power consumption for the targeted η of 80 % for each case is as follows.

Case 1 "Positive" : 40 W (9.0 kV, 4.4 mA)
Case 2 "Negative" : 42 W (8.0 kV, 5.2 mA)
Case 3 "Positive ACF" : 49 W (6.5 kV, 7.6 mA)
Case 4 "Negative ACF" : 22 W (6.5 kV, 3.4 mA)

The characteristics of η in case of "Positive" and "Negative" are almost the same. The η of 80 % can be achieved with approximately 40 watts.

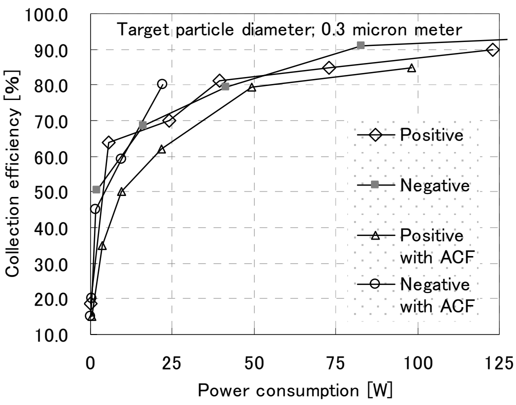

Fig. 9. Collection efficiency vs. Power consumption

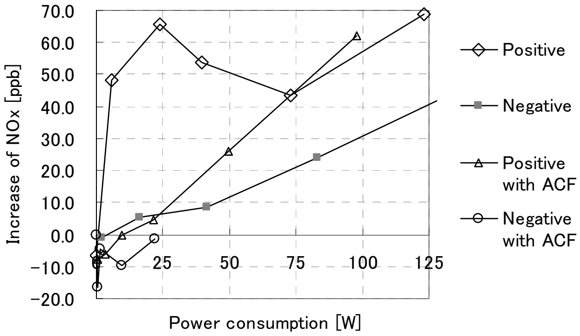

Fig. 10. Generated NOx in the ESP.

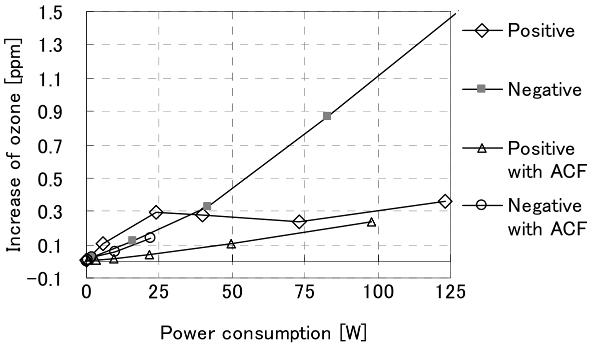

Fig. 11. Generated ozone in the ESP.

The power consumption of “Positive ACF” for η = 80 % is about 20 % larger than that of “Positive”. In “Positive ACF”, both positive and negative coronas exist. In this case, significantly larger current compare to “Positive” is observed, indicating the formation of bi-polar ionic field. For instance, at 6.5 kV, the current is 0.5 mA in “Positive” and 7.6 mA in “Positive ACF”.

In “Negative ACF”, the spark voltage decreased significantly, therefore, the applied voltage should be kept lower than “Negative”. At 6.5 kV, the current is 1.5 mA in “Negative” and 3.4 mA in “Negative ACF”. Bi-polar field is also formed in “Negative ACF”. Compare to positive polarity, increase in the current with ACF is smaller in negative polarity, or ratio of corona current with and without ACF is 7.6/0.5 = 15.2 in positive polarity, and 3.4/1.5 = 2.2 in negative polarity.

B. Sung *et al.* reported that the synergetic effect of ionic wind for particle transport can be used if the ionic wind is decelerated near the collection electrode to avoid carrying back the particles near the collection electrode to the space. They verified using the flocking electrode [17, 21]. In “Negative ACF”, the higher measured η at lower power consumption can be achieved even bi-polar ionic field is formed. This could be due to the same synergetic effect as in the case of flocking electrode. And the report from B. Sung *et al.* also concluded that the ESP with the flocking electrode would cause better characteristics of soot collection efficiency on the following points.

1) The re-entrainment was not easy to occur because the stronger gradient force at the tip of the flocking fiber in the electric field captured particles.

2) The structure with the flocking fiber increased the collection area.

Although the discharge from the tip of ACF was similar to the phenomenon of back corona in Fig. 7 and/or Fig. 8, the two points above mentioned might keep the collection efficiency still high. And the another reason that the discharge from the tip of ACF occurred not at all over the surface of ACF but at spot points is conceivable.

The generated NOx vs. power consumption is shown in Fig. 10. The NOx generated by ESPs is NO_2 only in all test cases, and NO is not detected. The generated ozone vs. power consumption is shown in Fig. 11.

The test results in each case can be summarized as follows:

“Positive”: With increasing power consumption, ozone increases at first then decreases above 20 watts and increases again above 70 watts. The same tendency of the ozone generation in ESPs was reported previously [14]. The reason is the transition of the discharge mode from brush corona via glow to streamer corona. The NOx generation depends on the discharge mode, similar to the ozone generation characteristics.

“Negative”: With increasing power consumption in “Negative”, both NOx and ozone increase almost linearly. “Negative” generates less NOx than “Positive” and generates more ozone than “Positive”, as described previously [10, 11, 13, 16]. The result of this test corresponds to them.

“Positive ACF”: With increasing power consumption, NOx in “Positive ACF” increases almost linearly like “Negative”. Ozone in this case also increases almost linearly. The generated ozone is the least of all four cases. In this case, ozone is generated by negative corona at the tip of ACF fibers, and generated ozone might be deoxidized with the ACF effectively.

“Negative ACF”: The smallest increase of NOx was observed in the four cases. Ozone generation in this case is almost the same as that of “Negative”.

“Positive ACF” and “Negative ACF” common: Negative values of indicating decreased NOx were observed in a range of a horizontal axis in Fig. 10. “Positive ACF” showed the decrease of NOx in less than 10 watts and “Negative ACF” showed the decrease in less than 25 watts. The reason is that the ACF can absorb NOx. (especially NO_2)

IV. Conclusion

In order to minimize generation of NOx and ozone and to improve collection efficiency of particles with reduced operating power of ESPs for air cleaning along roads, non-woven cloth made of activated charcoal has been attached on earth-plates of the ESP, and the performance has been experimentally measured. The use of ACF has been proved to be effective for the purpose, and further studies including durability tests are necessary towards practical use. Followings are the results obtained in this study.

1) In case of "Positive corona with ACF on earth-plates", positive corona from the discharge electrode, and negative corona from tips of lifted ACF fibers coexists. Discharge current increases up to approx. 15 times larger than that of "Positive without ACF".

2) In case of "Negative corona with ACF on earth-plates", negative corona from the discharge electrode and positive corona from tips of lifted ACF fibers coexists. In this case, the discharge current increases up to approx. 2 times larger than that of "Negative corona without ACF". With the ACF, the power consumption for attaining the collection efficiency of 80 % is almost a half of the other cases tested in this study. In this case, the lowest NOx generation has been confirmed in the all cases tested.

3) In all test cases, NOx generated by ESPs is NO_2 and NO is not detected.

4) Generation of NOx and ozone in "Positive corona without ACF" is depending on the discharge mode, and similar tendency can be observed.

5) In case of "Positive corona with ACF", the least ozone generation is observed among the tested cases.

Acknowledgment

The authors are grateful for the discussions given to this work by Prof. Kitabayashi of Kogakuin University, Prof. Daisho of Waseda University, Prof. Matsushita and associate professor Amagai of University of Shizuoka, Prof. Mochida of Kyusyu University, Dr. Moriguchi of National Institute for Environmental Studies, and Environmental Restoration and Conservation Agency Japan for the financial support.

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