Function of an electrostatic precipitator using bipolar corona discharges

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Abstract—The discharge spikes in the ionizer of the ESP (electrostatic precipitator) with bipolar corona-discharge are arranged not only in the energized-plates but also in the grounded-plates. The discharge from the spikes in the grounded-plates generates ions of opposite polarity to those from the energized-plates. A two-stage-type ESP with bipolar-corona discharge is composed of the ionizer and a collector to which DC high voltage is applied. In the previous test, this bipolar collection method, using positive and negative discharges simultaneously, proved that the particles were enough collected. In this report, discharge-current-density and attached-particles on the ionizer-plates have been discussed in order to clarify the charging-mechanism in the bipolar discharge.

Keywords—Electrostatic precipitator, DC corona, positive discharge, negative discharge, spike, bipolar

I. Introduction

Two-stage-type ESPs (electrostatic precipitators) are composed of both ionizers and collectors to which DC high voltages are applied. Since these ESPs can collect particles under the condition of relatively high wind-velocity such as 9 m/s, they are widely adopted for purifying tunnel-exhaust from motor-vehicles in which the concentration of diesel-particles is high [1].

In order to decrease the phenomenon of abnormal re-entrainment from the ESPs, the authors have been studied the two-stage-type ESP with "bipolar corona discharge" in which both positive corona and negative corona are simultaneously generated. In the front-stage ionizer, particles are charged positively and/or negatively, and in the rear-stage collector, charged particles are collected [2-5].

The principle is shown in Fig. 1. Each double-circle in the ionizer represents the part of spike-tip at which corona-discharge is taking place. The image is shown that particles are charged in bipolarity at the ionizer and they are caught not only on the grounded-plate but also on the energized-plate.

The authors' studies [2-4] have reported that the case of the positive corona at windward and the negative corona at leeward realizes higher collection-efficiency η than the opposite case with the negative corona at windward and the positive corona at leeward. In case of the discharge-gap of 15 mm and power consumption of 2.8 W in the ionizer, for example, the efficiency η in case of the positive corona at windward is approx. 80% whereas approx. 70% of η in case of the negative corona at windward.

In a comparison between a bipolar discharge ESP and a mono-polar discharge ESP, the study reports that some of the data have shown that the bipolar ESP realizes higher efficiency η than the mono-polar ESP [4]. In case of 15 mm (gap) and 2.8 W in the ionizer, for example, the efficiency η of mono-polar ESP with positive discharge is approx. 75%. There is also another study by the authors which reports that diesel-particles can be caught on the energized-plates as much as on the grounded-plates in the collectors of bipolar ESPs.

The purpose of this study is to clarify the mechanism of particle-charging in bipolar corona-discharge by measuring discharge current-density and observing vestiges of soot-particles attached on both electrode-plates in the bipolar ionizer.

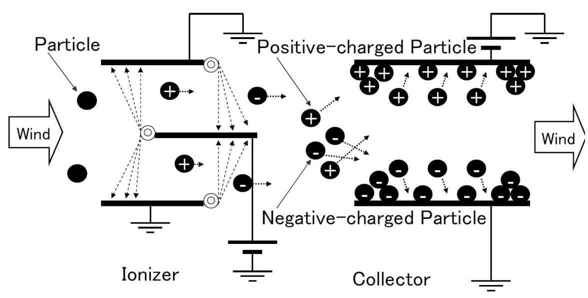

Fig. 1. Principle of ESP with bipolar corona discharge.

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II. METHODOLOGY

The shape of the electrode plates in the ionizer for bipolar discharge is shown in Fig. 2. Ten spikes for discharge are located on the edge of one side of a stainless steel plate.

Fig. 3 shows the test system. The ionizer generates bipolar discharge under the condition of ventilating the air with diesel-particles.

Table I shows the specifications of the test equipment.

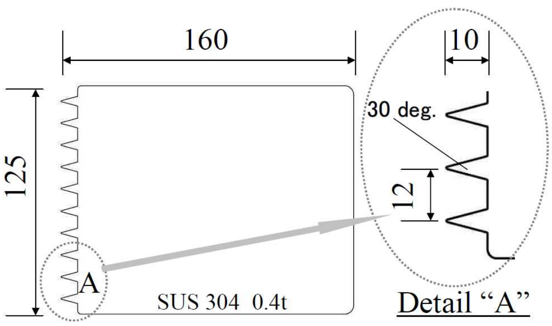

Fig. 2. Ionizer-plate with spikes for bipolar discharge.

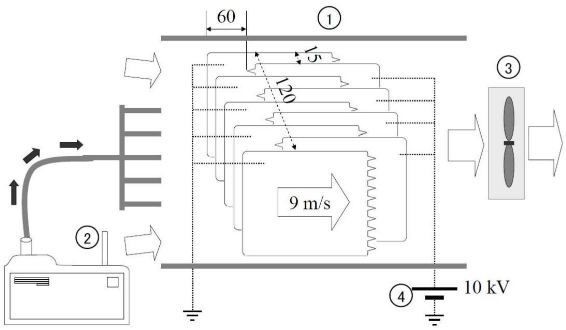

Fig. 3. Test system of the bipolar ionizer.

The nine ionizer-plates, which are shown in Fig. 2, are arranged in an ionizer-duct #1. The spike-tips of four plates, to which DC +10 kV from a dc high voltage power supply #4 is applied, are pointing to the windward. The spike-tips of five plates, which are connected to the ground, are pointing to the leeward. The plates of tip-to-windward and the plates of tip-to-leeward are alternately allocated in parallel with the gap of 15 mm. The distance between each spike-tip and the nearest edge of the adjoining plate on the projected plane is approximately 60 mm. This arrangement of the ionizer-plates produces positive corona from the spikes of tip-to-windward and negative corona from the spikes of tip-to-leeward.

Soot-particles generated from a diesel engine #2 are supplied via nozzles to the windward of the ionizer-duct #1. A fan #3 is for ventilation. Air velocity of "primary wind" in the ionizer-duct #1 is 9 m/s. The output of the diesel engine #2 is adjusted in order to keep the concentration 0.5 mg/m^3 of soot-particles. After the operation of 16 h under these conditions, the ionizer-plates are taken out and observed.

Both positive corona and negative corona are simultaneously generated in the bipolar corona discharge. Both coronas are accompanied with ionic wind as "secondary wind". Since it has been known that the strength of ionic wind is proportion to the root of current density [6], current density of the positive corona and the negative corona were measured in order to evaluate the interrelation between ionic wind and attached soot particles on the ionizer-plates.

A set of electrode plates for measuring current density is shown in Fig. 4 and 5. Fig. 4 is for a spike-plate made of stainless steel to which dc high voltage of positive or negative is applied. Fig. 5 shows the grounded-plate on which aluminum tapes are separately mounted to measure the current distribution. Nine aluminum tapes of 10 mm (W), 108 mm (L) and 0.05 mm (t) are parallel put on a dielectric plate keeping the distance of 2 mm between adjoining tapes, which makes *Area 1* to *Area 9*.

The test equipment for measuring current density is shown in Fig. 6. The arrangement of these two plates is that all the spikes are projected on the *Area 5* on the grounded-plate. The gap distance is 15 mm between the two plates. The current of each part from *Area 1* to *Area 9* was measured with applying positive or negative dc 10 kV to the spike-plate.

The current density is obtained by dividing the measured current by the aluminum tape area of 1,080 mm^2. As shown in Fig. 6, a current meter is connected to *Area 2* whereas other eight areas are directly connected to the ground. The current at the other areas can be measured by switching the meter circuit. This test was done under the condition of "no wind".

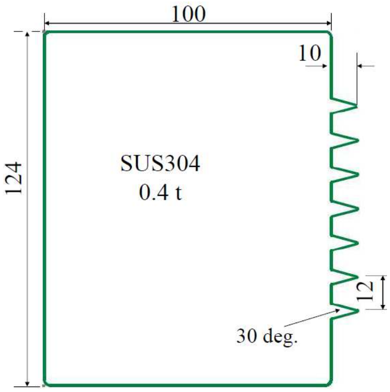

Fig. 4. Spike-plate for measuring current-density.

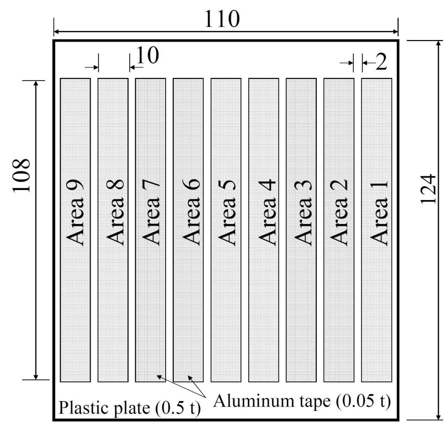

Fig.5. Grounded-plate for measuring current-density.

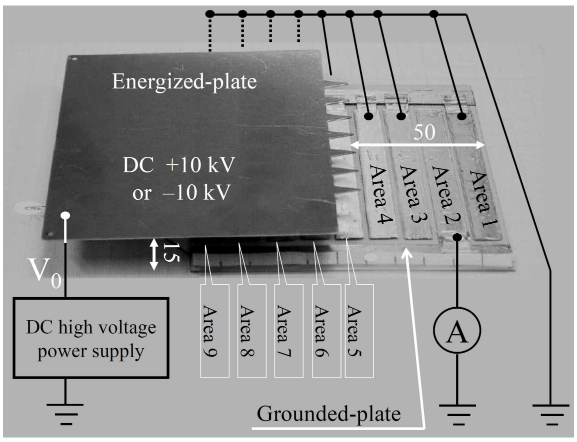

Fig. 6. Test system for measuring current-density.

TABLE I
TEST EQIPMENT

Items	Details
Ionizer duct (#1)	W 121, H 140, L 600 [mm] (Inside)
Diesel engine (#2)	ISUZU 4BD1-1, 1200 rpm, fuel: diesel oil
Fan (#3)	MU1238A-11B (Oriental Motor Co.,Ltd.) Quantity ; 2 (tandem coupled) With a variable frequency controller
High voltage power supply (#4)	Tunnel-ESP power supply (Origin Electric) Max. output ; DC +13 kV , 150 mA and Ripple; 5 % or less
Wind velocity meter	Climomaster MODEL6531 (Kanomax) Mode;1 sec. measuring & 10 times ave.
Voltage meter and probe	Digital multi meter type73303 (Yokogawa) Ratio;1/1000 (FLUKE), For high voltage
Current meter	Type 201133 (Yokogawa) Range; 0.1, 0.3, 1, 3 mA
High voltage power supply	Model-502 (Pulse Electric Engineering) Max. output ; DC+25kV , 25mA Stability 0.01%
High voltage power supply	MODEL-600F (Pulse Electric Engineering) Max. output ; DC-15kV , 30mA Stability 0.005%
Microscope (Optical)	Digital microscope VHX-100F (KEYENCE) Lens; VH-Z25 (25-175 times)

III. RESULTS AND DISCUSSION

Fig. 7 shows the vestiges which are obtained after 16 h operation of the bipolar ionizer with the air containing diesel particles. It seems that all the vestiges of attached particles are not the same but depending on locations on both plates of the energized-plate and the grounded-plate.

The distribution of current density in the nine areas on the grounded-plate is shown in Fig. 8. The case of applying negative voltage to the spike-plate generally indicates larger current-density than the case of positive voltage.

The area, where the current-density was the maximum, was *Area 4* which was adjacent to the spike-tips in both positive case and negative case. The current-density at *Area 5*, which is the closest to the spike-tips, was not the largest. It has been reported in the reference [7] that the direction of ionic wind is equal to the direction to which the spike-tips are pointing in both cases of positive and negative voltage. Consequently the area of maximum current-density might not be *Area 5* but be just neighboring *Area 4*.

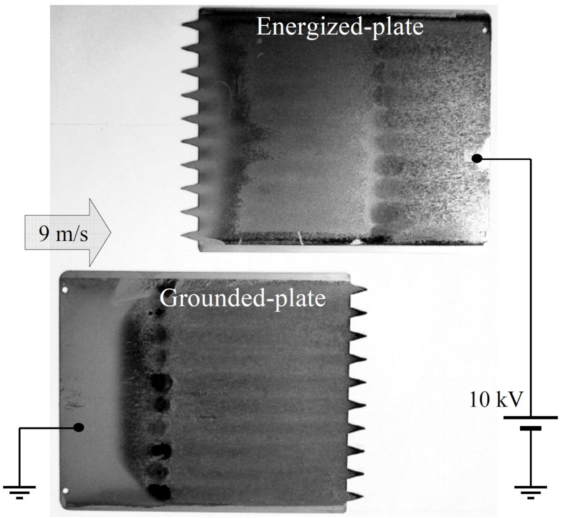

Fig. 7. Vestiges of ionizer-plates after 16 h operation.

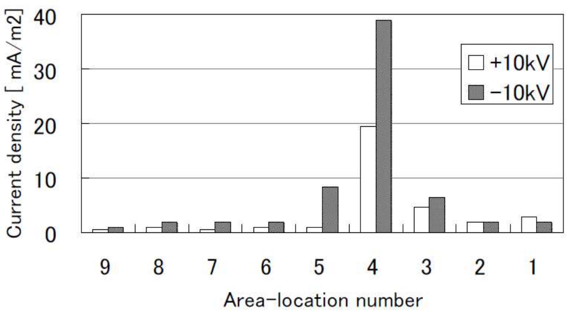

Fig. 8. Current density distribution in the ionizer.

In order to observe the ionizer-plates after 16 h operation more carefully, the characteristics of current density distribution in Fig. 8 are superposed on both ionizer-plates in Fig. 7. These are shown in Fig. 9 of the grounded-plate and Fig. 10 of the energized-plate. The locations of the nine areas and the adjacent spikes are marked in white-color on both plates in these two figures.

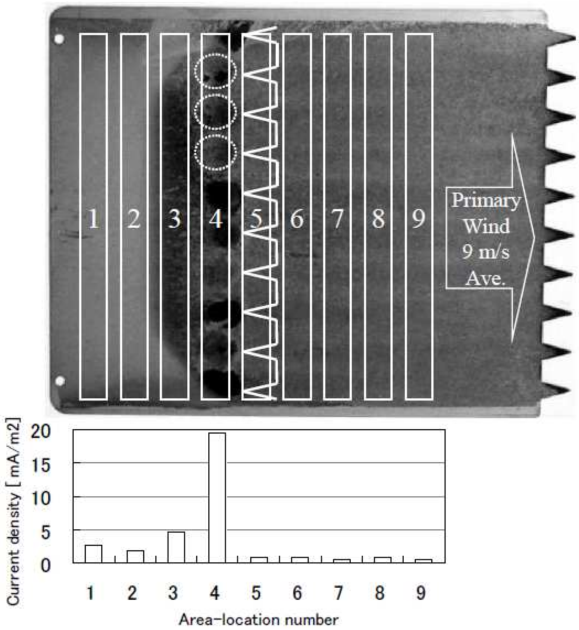

Fig. 9. Positive current density on the grounded-plate.

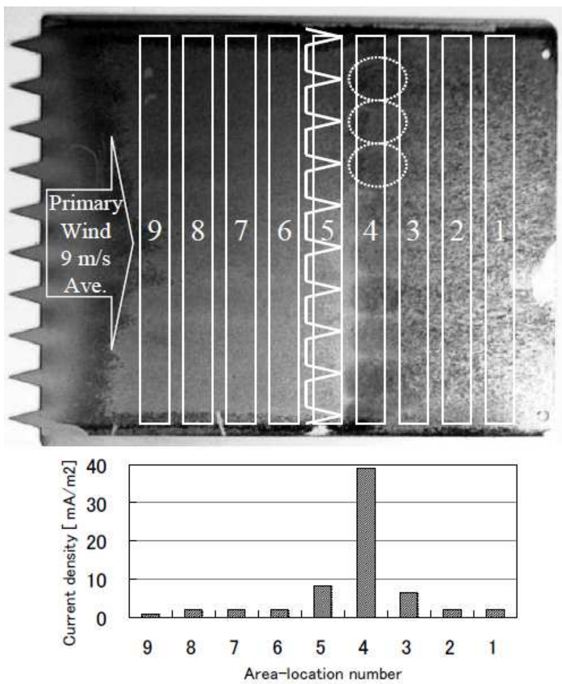

Fig. 10. Negative current density on the energized-plate.

As the current density of *Area 4* on the grounded-plate in Fig. 9 is the largest, deep-black vestiges, which are marked as ellipses of broken-lines, are left on the plate by the secondary wind (ionic wind) by positive discharge from the adjacent spike-tips. The current density of *Area 4* on the energized-plate in Fig. 10 is also the largest. There are black (but non-deep-black) vestiges (marked by ellipses of broken-lines on the plate) caused by the secondary wind of negative discharge from the adjacent spike-tips.

In the comparison between *Area 4* in Fig. 9 and *Area 4* in Fig. 10, the vestiges by positive discharge in Fig. 9 are smaller but darker than the vestiges by negative discharge in Fig. 10. The reason of the smaller-ellipse vestiges in case of positive discharge in *Area 4* is explained as the current density of positive discharge is smaller than that of negative discharge.

In order to clarify why the vestiges by positive discharge are darker than those of negative discharge, the image of modes of particles in the bipolar-ionizer is indicated in Fig. 11. Double-circle represents spike-tip of the energized-plate and the grounded-plate.

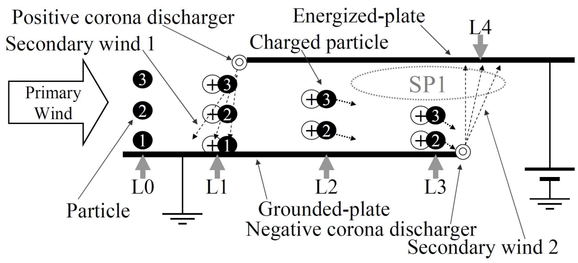

Fig. 11. Modes of particles in the bipolar-ionizer.

At first, *Particle 1*, *Particle 2* and *Particle 3*, which are illustrated in black circles, reach to *L0* point at the inlet position of ionizer with ventilated primary-wind. These three particles shortly arrive to *L1* point, which is in the discharge space of positive corona, and the three are charged in positive. At this time, *Particle 1*, which is located at the closest position to the grounded-plate, is moved toward the grounded-plate by *Secondary wind 1* (positive ionic wind) and the Coulomb force to be caught on the grounded-plate. Although *Particle 2* and *Particle 3* fly to the leeward, they are also moved towards the grounded-plate by the Coulomb force in due course of passing *L2* point.

Particle 2 and *Particle 3* fly to *L3* point which is close to the spike of negative discharge, and almost all the charged particles are positioned in the closest space to the grounded-plate. This means that the concentration of particles is high in this space. In other words, the particle-concentration is low in the space of *SP1* which is close to *L4* point on the energized-plate to which *Secondary wind 2* by negative discharge hits. As the concentration of particles which were caught on the energized-plate was low, therefore the vestiges of collected soot by negative discharge were not so dark.

Fig. 12 shows three binarized-images which are made from the microscope photos of *Part A*, *Part B* and *Part C* on the grounded-plate. The photo of bottom-left in Fig. 12 indicates the locations.

The binalization software of “Photo Filter” is used and the obtained microscope-photos are converted into black-and-white images. The threshold level of black or white is *Level 60* in total 256 levels. Black parts in the binalized-images represent the caught diesel-particles on the plate.

The image of *Part C* in Fig. 12 describes the part on which secondary wind (ionic wind) by positive discharge hits directly. It seems that many large and small spots densely gather to become dark in the whole area. On the other hand, the vestiges of *Part A* near to the center axis are located on the position of approximate 15 mm windward from *Part C* toward primary wind. “Black streaks” with taper-shape are pointing to windward. *Part B* shows the image of a place between *Part C* and *Part A*. At the center area of *Part B*, relatively fewer particles are caught, which might mean the boundary between *Part C* and *A*.

In order to discuss the streak-vestige of *Part A*, Fig. 13 is introduced. Although both *Part D* and *E* in Fig. 13 are also located in *Area 3*, same as *Part A*, these two parts are apart from the center axis indicated in a dashed line.

Although both *Part D* and *E* also reflect the streak-vestige like *Part A*, there is a big difference between them. Whereas the streaks of *Part A* are pointing to the just reverse direction to primary wind, the streaks of *Part D* and *E* are pointing to the direction having the angle of approximate 30 deg. to primary wind. As the pointing directions of streaks in *Part A*, *D* and *E* are different, it is concluded that the streak-vestiges are formed not by the primary wind but by the secondary wind. The mechanism of forming the streak-vestige in *Part A* might be explained as the secondary wind hits the surface of the grounded-plate in *Area 4* and bends along the surface with charging particles which have flowed from windward along the surface-space on the grounded-plate.

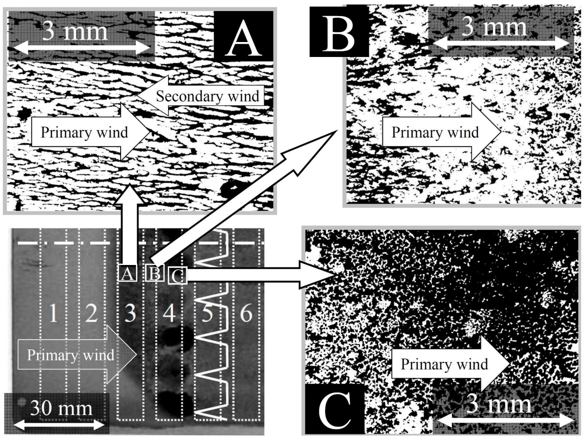

Fig. 12. Observation of *Part A*, *B* and *C* on the grounded-plate.

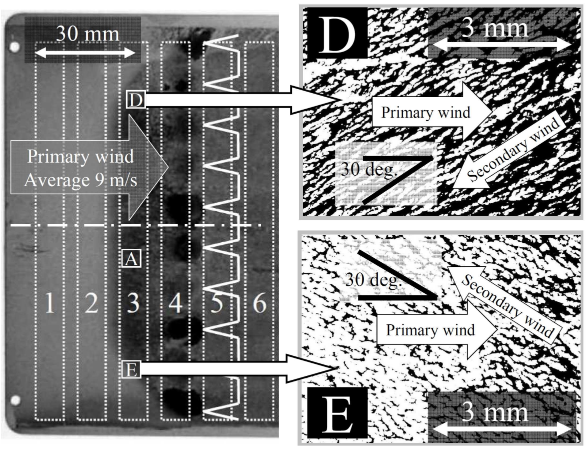

Fig. 13. Observation of *Part D* and *E* on the grounded-plate.

Part F, *G* and *H* in Fig. 14 are also binalized-images on the grounded-plate. The spot-vestiges are relatively not so crowded on *Part F* and most part of *G*. As *Part F* corresponds to *L2* point in Fig. 11, some particles such as *Particle 2* which makes itself approach the grounded-plate might be caught on the grounded-plate. *Part H* in Fig. 14 indicates a spike for negative discharge on the grounded-plate. Many particles stick to the spike whose color has turned into deep-black. As the electric field around negative spikes is strong, it seems that positive charged particles are apt to be attached.

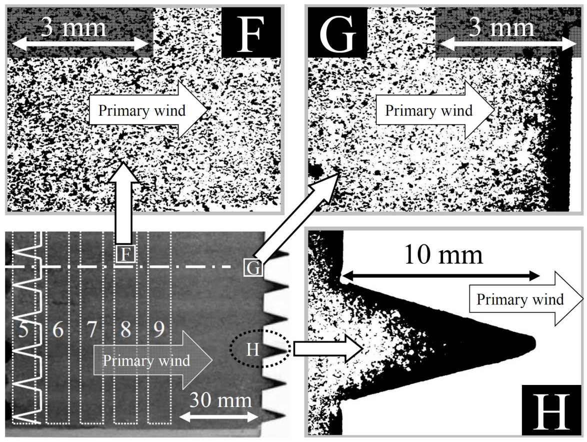

Fig. 14. Observation of *Part F*, *G* and *H* on the grounded-plate.

Fig. 15 shows three magnified pictures of *Part J*, *K* and *L* on the energized-plate, although only *Part J* is not binalized due to easier understanding.

Part J exhibits a spike for positive discharge. As the surface of stainless-steel plate of *Part J* is clearly seen without stuck particles, soot-particles are rarely caught on the discharge-spikes located at windward. The stuck particles on *Part K* are very few and those of *Part L* are relatively few. A few re-entrained particles from the grounded-plate might be attached on both parts. At this moment, it should be noted that there is a deep-black area between *Part K* and *L*. This area, called *Part M* later, is discussed by using Fig. 16.

The reason for the deep-black part including *Part M* in Fig. 16 might be due to the intense re-entrainment from the grounded-plate. When the total area of this deep-black part is surrounded by a white broken-line, the zone exhibits “Arch shape” whose reason should be further discussed. Although the velocity of primary wind is 9 m/s average, there is a velocity distribution of maximum speed 11 m/s at center axis and minimum speed 8 m/s at edge as shown in Fig. 16. It is also noticed that there is differential distance of 10 mm between the start point of deep-black vestiges on the center axis and the start point on the edge area due to the differential wind-velocity 3 m/s between maximum speed and minimum speed. Taking account of the gap distance 15 mm between the energized-plate and the grounded-plate, the information such as the speed of re-entrained particles can be obtained by using mathematical calculation. The results of this calculation are as follows.

1) Flying velocity of re-entrained particles (perpendicular vector to the plate); 4.5 m/s approx.
2) Time between the start of re-entrainment and the end in catch on the opposite side; 1/300 s approx.
3) Generation point of re-entrainment on the grounded-plate; *Area 4* including *Part C* in Fig. 12.

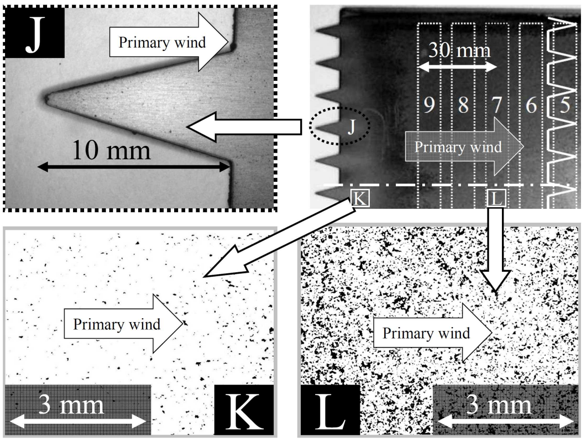

Fig. 15. Observation of *Part J*, *K* and *L* on the energized-plate.

Fig. 17 indicates three magnified binalized-images of *Part N*, *P* and *R* on the voltage-applied plate. *Part N* in *Area 4* is the part to which secondary wind by negative corona from a spike on the grounded-plate directly hits. As described in the explanation of particle-modes in Fig. 11, particle-concentration around the "surface space" of *Part N*, which corresponds to *L4 point*, is low and therefore there are no deep-black vestiges relatively. On the other hand, it is observed that fairly-black vestiges of *Part P* in *Area 2* last to *Part R* as expressing many large banks. Whereas the *Area 2* is approximately one twentieth the current-density of *Area 4* with Fig. 10, the vestiges of *Part P* show the more black aspect than those of *Part N*. The reason is considered to be an abnormal re-entrainment of agglomerated particles on the negative spikes of *Part H* of the grounded-plate in Fig. 14. That is; the accumulated particles on the negative spikes become larger and larger, then finally re-entrainment takes place, and this process is repeated. Some of the re-entrained particles, which are charged negatively, might be collected on the energized-plate, as indicated in the vestiges of *Part P*. The vestiges at the windward position in *Part R* are darker than those at the leeward. The reason for this fact is that the electric field from the negative-spikes is stronger at windward.

Although it is natural that the spikes located at the leeward have the function of collisional electrification, the test results imply that the spikes at the leeward also have the function of electrifying the re-entrained particles.

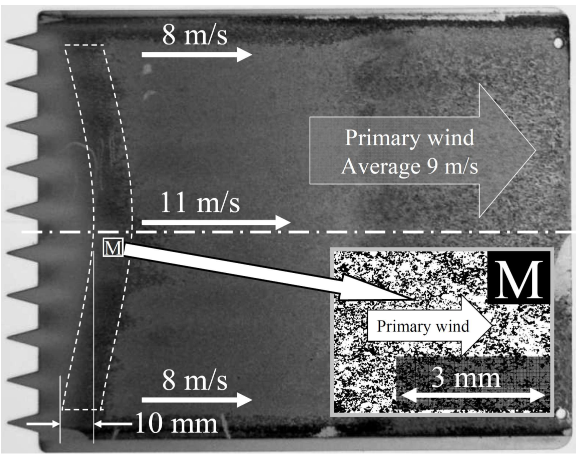

Fig. 16. Observation of "Arch shape" area including *Part M* on the energized-plate.

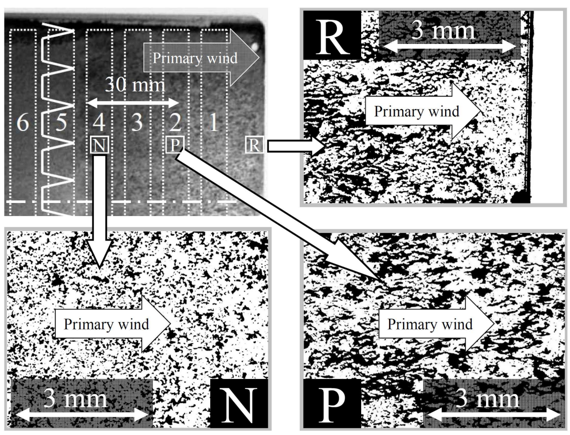

Fig. 17. Observation of *Part N*, *P* and *R* on the energized-plate.

IV. CONCLUSION

After 16 h of operation of the ionizer with bipolar corona discharge (gap 15 mm and dc +10 kV) with ventilating the air with diesel particles, pattern of the collected soot particles on the electrode plates of the ionizer were observed, together with the current distribution of the grounded-electrode. From the test results, following conclusions are obtained.

(1) The current density distribution shows the maximum value at the area 10 mm far from the spike-tips on the adjacent projected plane.
(2) When the secondary wind (ionic wind) from discharge-spikes reaches the adjacent plate, the secondary wind is hardly affected by the primary wind.
(3) Some particles which are charged by positive corona discharge from the spikes at windward accumulate on the spikes of negative corona discharge at leeward.
(4) The distribution of particle-concentration exists in the inner-space of ionizer.
(5) Flying velocity of re-entrained particles (perpendicular vector to the plate) is 4.5 m/s approx.
(6) The accumulated particles on the negative spikes at leeward become larger to re-entrain finally and repeat this process.
(7) The spikes at the leeward have the function of electrifying the re-entrained particles.

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