Electrostatic Precipitator Utilizing Gradient-force

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***Abstract*— ESPs (electrostatic precipitators) charge particles which are passing through corona-discharge space and collect them by Coulomb's force. The purpose of this study is to charge particles without using corona-discharge and collect them. *i.e.* Due to Gradient force, the particles which enter the non-uniform electric-field attach onto the parts of electrodes whose electric field is stronger. This study clarifies that the attached particles possess electric-charge after re-entrainment. This means that particles can be collected by Coulomb's force, utilizing at first "temporary collection by Gradient force", and then, "re-entrainment" even under the condition without corona-discharge current. The possibility of drastic reduction of the power consumption in ESPs has been found.**

Keywords—Electrostatic precipitator, Gradient force, Re-entrainment, Non-uniform electric-field, Uniform electric-field

I. INTRODUCTION

Two-stage ESPs (electrostatic precipitators) are composed of both ionizers and collectors. 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 concentration of diesel-particles is high [1].

Although particles have conventionally been charged by using corona-discharge, the authors consider that the power consumption of ESPs might be decreased if particles could be charged without corona-discharge. The reasons of the idea depend on the following.

The reference [2] shows that gradient-force has an influence on particles in non-uniform electric field with corona-discharge and the particles are attached to discharge-poles whose electric field is stronger, and the attachment causes reduction of the discharge-current and decrease in collection-efficiency.

The reference [3] describes that re-entrained particles will be charged with the opposite polarity to the polarity of corona-discharge when the attached particles on pole-plates are re-entrained. It is also pointed that the re-entrainment causes degradation of collection-efficiency.

Although gradient-force and re-entrainment has been thought as negative factors which cause decrease of collection-efficiency in the above two references, the reference [4] describes, on the other hand, that re-entrained particles will be attached to the opposite pole-plates.

All the above-mentioned references have helped the authors reach the idea of an ESP without using corona discharge, as shown in Fig. 1.

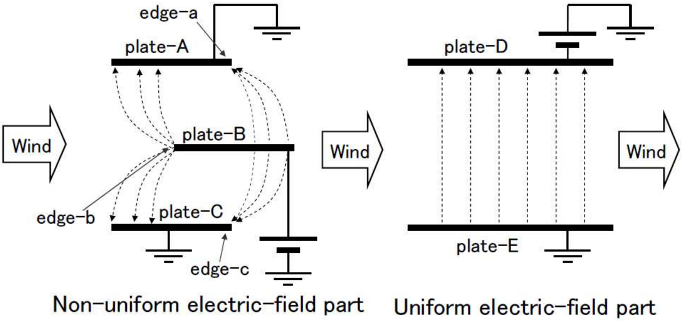

Fig. 1. Concept of particle collection system.

The ventilation-wind of the ESP in Fig. 1 blows from the left to the right. It is composed of a non-uniform electric-field part at windward position and a uniform electric-field part at leeward position. The flat-plate A, B and C without spikes at the non-uniform electric-field part are staggered in its location. The plate B is connected to the dc high-voltage power-source and the plate A and C are grounded.

The lines of electric force shown as broken lines in Fig. 1 are concentrated at the edge “a”, “b” and “c” in the plates where the electric field becomes stronger. At first, inflow-particles are temporarily attached to the edges of “a”, “b” and “c” with Gradient-force but without corona-discharge under the condition of the applied voltage to the plate B.

The uniform electric-field part is composed of the plate D, to which dc high-voltage is applied, and the grounded plate E.

If the attached particles on the edges of “a”, “b” and “c” in the non-uniform electric-field would be re-entrained with electric charge, the re-entrained particles might be collected by Coulomb’s force in the uniform electric-field.

The purpose of this study is to verify whether or not the re-entrained particles in the space of the first-stage with Gradient-force but without corona-discharge are charged by induction-charging enough to be collected in the rear stage.

II. METHODOLOGY

The size of pole-plates in this test is shown in Fig. 2. The plates of Type-1 and Type-2 were used for the non-uniform electric-field part. The location of these plates, whose arrangement is in parallel but staggered, is shown in Fig. 3. The plates of Type-2 were connected to the power-source of dc +8 kV whereas the plates of Type-1 were grounded. The plates of Type-3, whose location is shown in Fig. 4, were used for the uniform electric-field part. The plates of Type-3, which are located in parallel without staggering, were used for both applying dc -9 kV and grounding.

The test equipment is depicted in Fig. 5. And the specifications for the test equipment are shown in TABLE 1.

The particles to be removed in this study were those in the air in the laboratory room. Although components of particles in the air are not clear, the resistivity of particles might not become higher than the level of provoking back-corona discharge. In such case, the time constant of induction-charging, which might appear after particles attached to pole-plates, would relatively be small.

The inlet duct, the connection duct and the housing-duct of the non-uniform electric-field part are shown as #1, #2 and #3 in Fig. 5. The connection duct #4, the housing-duct #5 of uniform electric-field part, the connection duct #6, the outlet duct #7 and the fan #8 with variable speed-control composed a duct system which was able to ventilate the air containing the particles in the laboratory room.

The dc high-voltage power supplies of #9 and #10 were connected to the housing-ducts of the non-uniform electric-field part and the uniform electric-field part. The high-voltages and the currents of both circuits were measured by the voltage meters of #13 and the current meters of #14.

By measuring the wind velocity with the wind velocity meter #12 at the inlet of the inlet duct, the wind velocity in the non-uniform and uniform electric-field parts was adjusted with a fan-speed-controller in order to attain the wind speed of 9 m/s in both parts.

The concentration (count-concentration) of particles in the air was measured by the particle counter of #11, whose two sampling tubes for the inlet-duct and the outlet-duct were alternately switched.

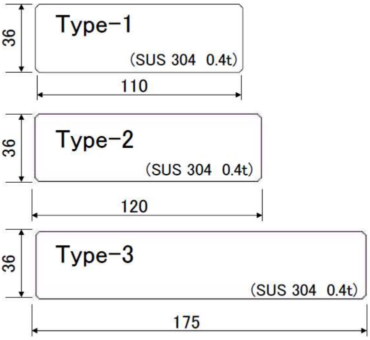

Fig. 2. Three types of electrode-plates.

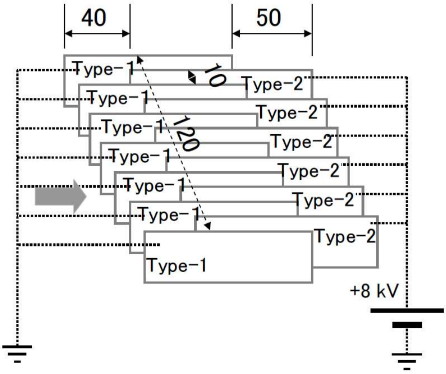

Fig. 3. Plates arrangement of non-uniform electric field part.

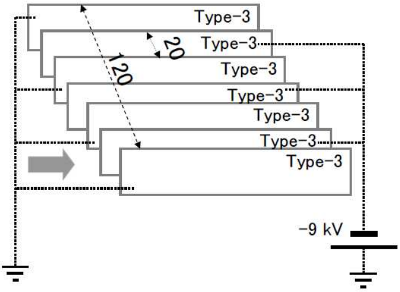

Fig. 4. Plates arrangement of uniform electric field part.

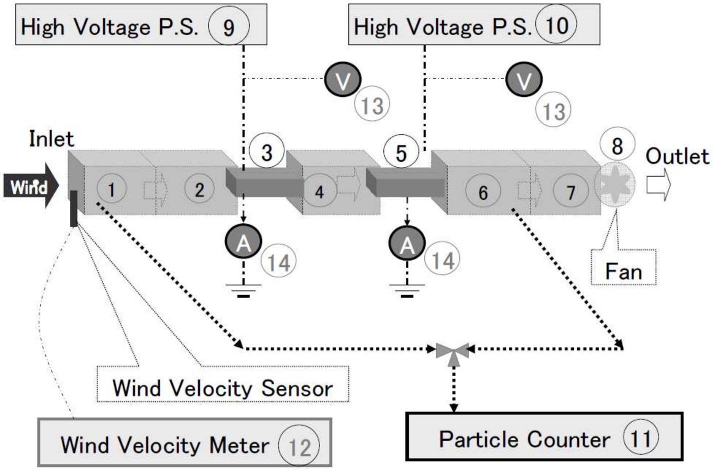

Fig. 5. Schematic diagram of test equipment.

TABLE 1: SPECIFICATION OF TEST EQUIPMENT

Items	Details
Duct(#1,2,4,6,7)	W 121, H 140, L 200 mm (Inside)
Non-uniform electric field part(#3)	Duct ; W 121, H 32, L 180 mm (Inside) Gap between adjoining plates ; 10 mm 6 energized-plates & 7 grounded-plates.
Uniform electric field part (#5)	Duct ; W 121, H 32, L 180 mm (Inside) Gap between adjoining plates ; 20 mm 3 energized-plates & 4 grounded-plates.
Fan (#8)	MU1238A-11B (Oriental Motor Co., Ltd.) Quantity ; 2 (tandem coupled) With a variable frequency controller
High voltage power supply (#9)	Model-502 (Pulse Electric Engineering) Max. output ; DC +25 kV , 25 mA Stability 0.01%
High voltage power supply (#10)	MODEL-600F (Pulse Electric Engineering) Max. output ; DC -15 kV , 30 mA Stability 0.005%
Particle counter (#11)	KC-01C (RION), Light scattering method Range ; 0.3, 0.5, 1, 2, 5 over µm Sampling volume ; 0.01 CF (per 34 s)
Wind velocity Meter (#12)	Climomaster MODEL6531 (Kanomax) Mode;1 s measuring & 10 times ave.
Voltage meter & Probe (#13)	Digital multi meter type73303 (Yokogawa) Ratio;1/1000 (FLUKE), For high voltage
Current meter (#14)	Type 201133 (Yokogawa) Range; 0.1, 0.3, 1, 3 mA

Three test cases as follows were evaluated.

Case 1; whereas pole-plates are installed in the housing-duct of non-uniform electric-field part, there are no pole-plates in the housing of the uniform electric-field part.

Case 2; whereas there are no pole-plates in the housing duct of non-uniform electric-field part, pole-plates are installed in the housing of the uniform electric-field part.

Case 3; pole-plates are installed in both housing-ducts.

The performance of removing particles was evaluated with collection-efficiency which was calculated and averaged by measuring the inlet/ outlet concentration seven times for each case.

III. RESULTS AND DISCUSSION

A. Test Case 1

In *Case 1* (installed plates in the housing of the non-uniform electric-field and no plates in the housing of the uniform electric-field), the collection-efficiency was measured under the condition of using the non-uniform electric-field part only. The result is shown in TABLE 2. The counted particle-numbers are described per each range of particle-sizes in TABLE 2. There are ranges of “0.3 to 0.5 μm”, “0.5 to 1.0 μm”, “1.0 to 2.0 μm”, “2.0 to 5.0 μm”, “5.0 μm over” and “all counted number” in order from top of Table 2. The counted numbers in each row are the summed numbers after seven-time measurement.

Although the particle counter indicated the counted numbers in 0.01 cubic foot of air volume, these numbers were converted into the numbers of 1 m^3 as shown in TABLE 2. The collection efficiency “η” [%] for each range was defined as follows.

$$\eta = [1-(\text{inlet number}) / (\text{outlet number})] \times 100 \qquad (1)$$

The particles in the air in the laboratory room had the characteristics as follows.

(1) The smaller size, the more particles.
(2) Particles over 5.0 μm were not counted due to the fewer particles according to shifting to the larger size.
(3) In the minimum range of “0.3 to 0.5 μm”, the collection-efficiency was 2.2% when the inlet-counted number was relatively large as approx. 5.3×10^8.
(4) On the other hand, in the maximum range, which was able to sense particles, of “2.0 to 5.0 μm”, when the inlet-counted number was as approx. 1.6×10^5, the collection-efficiency was -15.2%, which means the increase of particle-numbers in this range.

As to the above-mentioned results, it is assumed that the effect of electrostatic agglomeration in the non-uniform electric-field part might convert small particles into larger particles.

Although the collection-efficiency based on counted numbers has been highlighted so far, the collection-efficiency by “mass” can be treated as follows.

1) Assuming that each particle is in spherical shape and that the representative-particle-diameters of the ranges are 0.4, 0.75, 1.5 and 3.5 μm in order.
2) Then, the "total mass" on both the inlet and the outlet can be calculated. i.e. This means "mass-collection-efficiency".

The mass-collection-efficiency was described at the bottom row of TABLE 2. As the mass-collection-efficiency was -0.1 % (nearly zero), it is concluded that the non-uniform electrostatic-field part might not have the function of collection but have the performance for small particles to be converted into the larger particles.

TABLE 2 : PARTICLE-SIZE DISTRIBUTION, COLLECTION EFFICIENCY FOR EACH & ALL RANGE AND "MASS COLLECTION EFFICIENCY" ABOUT NON-UNIFORM ELECTRIC FIELD PART

Size of particle [μm]	Counted number per m^3		Collection efficiency [%]
	Inlet of "non-uniform"	Outlet of "non-uniform"	
0.3 to 0.5	528,367,449	517,013,784	2.2
0.5 to 1.0	33,591,311	33,623,094	-0.1
1.0 to 2.0	1,620,943	1,529,125	5.7
2.0 to 5.0	162,447	187,168	-15.2
5.0 over	0	0	?
All	563,742,150	552,353,171	2.0
"Mass collection efficiency" by representative particle-diameters per each range			-0.1

B. *Test Case 2*

In *Case 2* (no plates in the housing of the non-uniform electric-field and the installed-plates in the housing of the uniform electric-field), the collection-efficiency was examined under the condition of using the uniform electric-field part only. The result was shown in TABLE 3.

Whereas the collection-efficiency in the range of "1.0 to 2.0 μm" was a negative value around zero, the collection-efficiency of positive values was observed in the other ranges. The highest collection-efficiency of 10.5% was indicated in the range of "2.0 to 5.0 μm". The mass-collection- efficiency was 3.3%. The reason of the positive mass-efficiency in the uniform electric-field part only is in the possibility that particles might be collected by Gradient force at plate-edges of both windward and leeward.

TABLE 3: PARTICLE-SIZE DISTRIBUTION, COLLECTION EFFICIENCY FOR EACH & ALL RANGE AND "MASS COLLECTION EFFICIENCY" ABOUT UNIFORM ELECTRIC FIELD PART

Size of particle [μm]	Counted number per m^3		Collection efficiency [%]
	Inlet of "uniform"	Outlet of "uniform"	
0.3 to 0.5	497,004,494	483,517,822	2.7
0.5 to 1.0	31,147,536	30,660,194	1.6
1.0 to 2.0	1,529,125	1,543,251	-0.9
2.0 to 5.0	201,294	180,105	10.5
5.0 over	0	0	?
All	529,882,449	515,901,372	2.6
"Mass collection efficiency" by representative particle-diameters per each range			3.3

C. *Test Case 3*

In *Case 3* (Pole-plates are installed in both housing-ducts of the non-uniform electric-field and the uniform electric-field), the collection-efficiency is shown in TABLE 4. In each range of particle-sizes, the collection-efficiency by counted number was indicated as positive value. The collection-efficiency of "2.0 to 5.0 μm" was the highest of 35.6%. On the other hand, the mass-collection-efficiency was 10%.

TABLE 4 : PARTICLE-SIZE DISTRIBUTION, COLLECTION EFFICIENCY FOR EACH & ALL RANGE AND "MASS COLLECTION EFFICIENCY" ABOUT BOTH ELECTRIC FIELD PARTS

Size of particle [μm]	Counted number per m^3		Collection efficiency [%]
	Inlet of "non-uniform"	Outlet of "uniform"	
0.3 to 0.5	562,407,256	533,488,076	5.1
0.5 to 1.0	36,995,645	34,671,940	6.3
1.0 to 2.0	1,910,523	1,553,845	18.7
2.0 to 5.0	158,916	102,413	35.6
5.0 over	0	0	?
All	601,472,340	569,816,274	5.3
"Mass collection efficiency" by representative particle-diameters per each range			10.0

D. Collection Efficiency by Calculation

As the collection-efficiency of both parts was separately obtained in *Case 1* and *Case 2*, the "combined" collection-efficiency of both parts can be calculated. The measured collection-efficiency in *Case 3* and the calculated collection-efficiency with *Case 1* and *Case 2* are shown in Fig. 6 in which "black bars" indicate the measured collection-efficiency against "the horizontal-striped bars" by the calculated collection-efficiency. In the comparison of all the particle-size-ranges and the converted mass, Fig. 6 shows that the measured collection-efficiency is greater than the calculated collection-efficiency. This means that agglomerated particles by passing through the non-uniform electric-field might be continuously charged and, as a result, charged particles be collected by Coulomb's force in the uniform electric-field. The reason of generated charged-particles after passing through the non-uniform space is in the possibility that the re-entrained particles from plate-edges will have electric-charge when the collected particles on plate-edges by Gradient force are re-entrained with dielectric polarization.

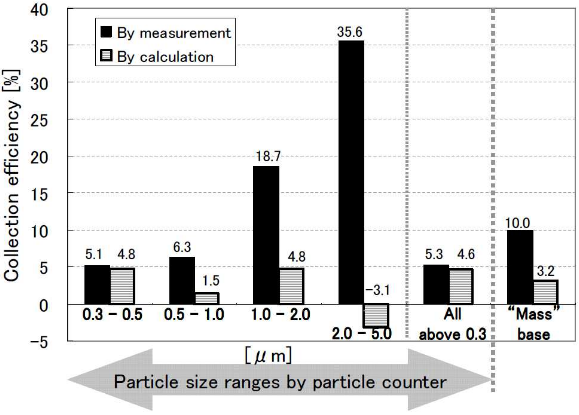

Fig. 6. Comparison on collection efficiencies between measurement and calculation.

Finally is there the fact that the discharge currents were not sensed when the high-voltages were applied to both the non-uniform part and the uniform part. (Remark; corona-discharge-ionizers whose bulks are almost the same as those of the non-uniform and/or uniform electric-field parts used in this study would have the discharge-current from approx. 100 to 250 μA. When the currents of both the non-uniform part and the uniform part were measured by using current meters with 100 μA full range, each finger of the meters pointed to 0 μA.)

E. Additional Test (Operation for 12.5 h)

As an additional test, the test equipment of *Case 3* was operated for 12.5 h and the transition of collection efficiency was observed. The inlet and outlet concentrations were measured ten times respectively for averaging from the time-point of just after the start of operation in order to obtain the collection efficiency for the particle diameters. It took 0.5 h for the ten-time measurement. The collection efficiency obtained from the first averaged values means the efficiency at 0.5 h passed from the start-point. The collection efficiency was measured per every 2 h. The last collection efficiency was measured at the operation point of 12 h and the test equipment was shut down at 12.5 h point.

The transitions of the collection efficiency based on counted number of the four ranges of “0.3 to 0.5 μm”, “0.5 to 1.0 μm”, “all counted number over 0.3 μm” and “mass base” are shown in Fig. 7. The transitions of the three ranges of “1.0 to 2.0 μm”, “2.0 to 5.0 μm” and “5.0 μm over” are shown in Fig. 8.

The “inlet particle-mass distribution [%]”, which is obtained from converting the inlet counted number of each range into “mass”, is shown in TABLE 5 where the mass distribution in *Test Case 3* is also indicated for the better comparison.

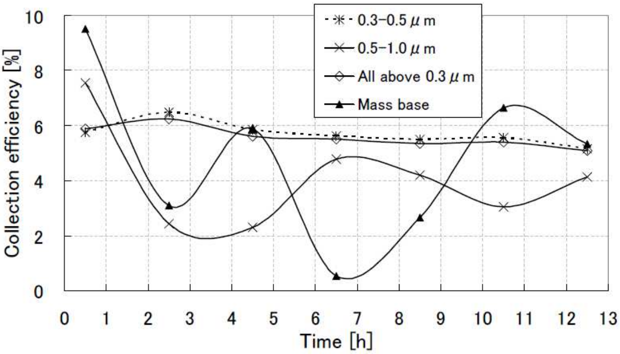

Fig. 7. Collection efficiencies for 12.5 h operation. (Small diameters and mass base)

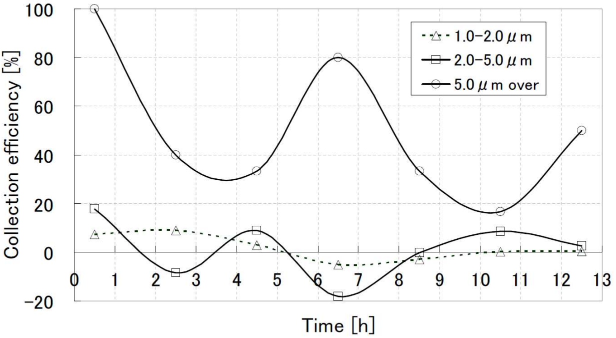

Fig. 8 Collection efficiencies for 12.5 h operation. (Large diameters)

TABLE 5 : COMPARISON OF "INLET PARTICLE-MASS" DISTRIBUTION [%] BETWEEN CASE 3 AND ADDITIONAL TEST

Size of particle [μm]	Inlet mass [%] of "Case 3" (approx. 0.5 h operation in January 2013)	Inlet mass [%] of "Additional Test" (12.5 h operation in March 2013)
0.3 to 0.5	55.5	39.2
0.5 to 1.0	24.1	16.0
1.0 to 2.0	9.9	12.1
2.0 to 5.0	10.5	30.1
5.0 over	0	2.6
All	100.0	100.0

In TABLE 5, the distribution of "5.0 μm over" range in *Additional Test* occupied 2.6%, although the particles of the same range in *Test Case 3* had not been sensed. Whereas the mass-distribution of "2.0 to 5.0 μm" range in *Case 3* gave 10.5%, the distribution of the same range in *Additional Test* showed the three-time greater value of 30.1% approximately.

On the other hand, the mass-distribution value of "0.3 to 0.5 μm" and "0.5 to 1.0 μm" range in *Additional Test* decreased. This means that the inlet mass-distribution of *Additional Test* would have been shifted to the larger particle-diameters comparing to *Test Case 3* on the whole. As one of the reasons, it will be raised that the time-point of the two tests was different. Whereas *Case 3* was tested on the beginning of January 2013, *Additional Test* was executed on the middle of March 2013. The mass media in Japan reported that the visibility in the atmosphere had been degraded everywhere in the country due to a large amount of the flying "Asian Dust" ("Yellow Sand") from some deserts in the China continent since the beginning of March 2013 [5]. Therefore, one of the reasons of the shifted particle-diameters would be attributed to the difference between *Additional Test* with much Asian Dust and *Case 3* with less Asian Dust.

In order to understand Fig. 7 and Fig. 8 more simply, the initial value of collection efficiency and the averaged value of collection efficiency during 12.5 h in *Additional Test* are shown in TABLE 6 comparing to the collection efficiency of *Case 3*.

TABLE 6 : COMPARISON OF COLLECTION EFFICIENCY [%] BETWEEN CASE 3 AND ADDITIONAL TEST

Particle size [μm]	Case 3 (Jan. 2013) [%]	Additional Test (Mar. 2013)	
		Initial [%]	Average of 12.5 h [%]
0.3 to 0.5	5.1	5.8	5.6
0.5 to 1.0	6.3	7.6	4.2
1.0 to 2.0	18.7	7.4	0.7
2.0 to 5.0	35.6	17.7	2.0
5.0 over	?	100.0	40.0
All	5.3	5.9	5.5
"Mass"	10.0	9.5	4.6

The collection efficiency of “0.3 to 0.5 μm” range in Fig. 7 is almost constant and around 6% with no relation to time-transition. TABLE 6 depicts that the initial value and the averaged value of the efficiency in *Additional Test* do not differ from the value in *Case 3* so much. And the collection efficiency of all counted number of “0.3 μm over” has also almost the same characteristic because the most part (more than 90%) of the counted number of “0.3 μm over” lies in “0.3 to 0.5 μm” range.

The collection efficiency of “0.5 to 1.0 μm” range in Fig. 7 and in TABLE 6 shows that the collection-efficiency characteristic varies from around 2% to around 8% with time-transition, although the initial value of 7.6% does not differ from the value of 6.3% in *Case 3* so much. The averaged collection efficiency during 12.5 h operation was 4.2%. The mass collection efficiency indicates the same tendency with the variation from around 0% to around 10% (initial value). The averaged collection efficiency during 12.5 h was 4.6%.

The collection efficiency of “1.0 to 2.0 μm” range in Fig. 8 and in TABLE 6 depicts that the initial value of 7.4% is less than the half value of 18.7% in *Case 3*. And the collection efficiency varies from around positive 10% to around negative 5% with time-transition and the averaged collection efficiency during 12.5 h operation was almost 0%. The collection efficiency of “2.0 to 5.0 μm” range indicates the same tendency with the variation from around positive 20% to around negative 20% and with the average value of 2.0%. The collection efficiency of “5.0 μm over” was 100% as initial value and 40% as averaged value with the fluctuation between around 100% and 20%. The variation of the collection efficiency of “5.0 μm over” range was the largest of all the ranges. One of the reasons of this would be pointed out as the counted number of “5.0 μm over” during 12.5 h measurement was extremely small and only 0.003% of the all the inlet-counted-number of approximate 4.5×10^9 particles. Therefore the collection efficiency of “5.0 μm over” might have uncertainty not a little.

The result of this *Additional Test* has clarified that the smallest diameter range of “0.3 to 0.5 μm” and the range of “0.3 μm over”, which is almost occupied by the particles of the smallest diameter range, have stable characteristic of the collection efficiency during 12.5 h operation. However the collection efficiency fluctuated in cases of the other ranges of larger diameters and the mass-base. Although this means that abnormal re-entrainment has a great influence on the collection efficiency in case of the larger particle size, the occurrence part of the re-entrainment is unclear now and will be investigated with further study. (The part is in non-uniform electric-field, in uniform electric-field or in both?)

IV. CONCLUSION

The system in which dc high-voltages was able to be separately applied to both the non-uniform electric-field part and the uniform part was prepared. The function of the non-uniform electric-field part was such that there was an electric field without corona-discharge but with Gradient-force. The collection efficiency of each part and the combined parts was evaluated. The following items were highlighted.

1. Small particles were changed into larger particles by the effect of electrostatic agglomeration in the non-uniform electric-field part. And the mass collection-efficiency of the part was almost 0%.
2. The mass collection-efficiency of the uniform electric-field part was approx. 3% by the effect of Gradient force at the edges of electrode-plates.
3. In case of using both of the non-uniform electric-field part and the uniform electric-field part, the mass collection-efficiency by measuring altogether was 10%, whereas the mass collection-efficiency by calculation of both parts altogether was around 3%. The reason of the higher collection-efficiency by real measurement comparing to calculation is that particles might not only be collected by the Gradient force but also charged by re-entrainment and collected by Coulomb's force in the uniform electric-field part.
4. The reason for generation of charged-particles in the uniform electric-field part is due to induction charging of re-entrainment particles that have been collected by gradient force. This induction charging takes place continuously in the non-uniform electric-field part.
5. As the result of operating both the non-uniform electric-field part and the uniform electric-field part for 12.5 h, the smallest diameter range of "0.3 to 0.5 μm" has shown the constant collection-efficiency as a whole. The collection-efficiency in case of the other ranges has fluctuated more or less because the abnormal re-entrainment would be easy to occur in case of larger particle.

The further study for improving higher collection-efficiency will be investigated with the clarification of the items as follows.

(1) The relation between geometrical layout of electrodes, voltage and efficiency.
(2) The relation between particle-diameter distribution of inlet and efficiency.
(3) To confirm the part of particle collection and re-entrainment on electrode plates.
(4) To confirm the collection efficiency of other kind of particles than "room dust".

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