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Deflective Behavior of Charged Particles in a Two-Stage Electrostatic Precipitator

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Abstract

Even if smoke, fumes, mist or dust particles are removed by electrostatic precipitators (ESPs), the occurrence of ozone, which is harmful to human body, has to be severely restricted in the indoor environments of hospitals, offices, and workshops. Therefore, the two-stage ESP generating positive corona at the ionizer is typically used because it creates less ozone than the two-stage ESP generating negative corona at the ionizer.

In order to predict the collection performance and the optimal design of the two-stage ESP applied to positive high-voltage, particle concentration is experimentally investigated in this paper. In addition, particle motion within the collector section is also numerically analyzed.

The positive corona discharge current of the ionizer is found to be affected by the applied voltage in the collector section but less so by the particle concentration. Particle concentration shows a minimum near the high voltage electrode of the collector section. The minimum value of the collection efficiency is almost proportional to gas velocity. When the collector length decreases, the minimum value of the collection efficiency increases. Charged particles entering the collector region are linearly deflected towards the grounded plate by an electric field.

From the above experimental and numerical results, two empirical equations on the concentration ratio and the collection efficiency are derived, and are in good agreement with the experimental data.

Key Words : Electrostatic Precipitator, Two-Stage ESP, Positive Corona, Ionizer, particle motion, Collection Efficiency, Empirical Equation, Concentration Ratio

1. Introduction

Since the control of particulate emissions has been an important concern in large-scale industrial processes, the electrostatic precipitators (ESPs) have been widely used because of their high efficiency[1-5].

Large scale precipitators are using negative corona generated by negative high-voltage wire electrodes because it allows a higher voltage to be applied without the arc discharge[6-8]. However,

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small precipitators, such as the removal of cigarette smoke or dust filters in air conditioning units, may have a positive high-voltage electrode and minimize the occurrence of ozone. These small precipitators are usually designed featuring a two-stage system with a rather short charging section and a relatively long collector section.

The oldest model of a two-stage precipitator was designed by Penny[9]. With this type of precipitator, no automatic cleaning of collectors is carried out. They are simply replaced with a new module or washed for reuse. Although there are many different types of two-stage small precipitators in the market, few scientific papers describe the characteristics of this type[10].

This study aims to predict the collection performance and optimal design of an ESP. To this end, the motion of charged particles within the collector is investigated through measurement and analysis of the distribution of particle concentrations. Finally, empirical equations for the particle concentration ratio and the collection efficiency are derived from the numerical and experimental results.

2. Experiments

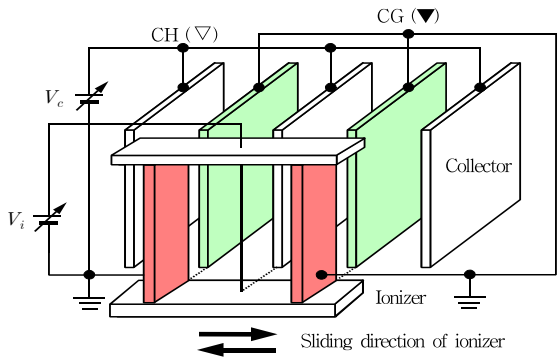
2.1 Experimental apparatus

The model apparatus used in this experiment is shown in Fig. 1. An ionizer part consists of a single wire and two plane electrodes while the collector part consists of five parallel plate electrodes. A corona wire is made of a tungsten wire of 100[㎛] diameter and the counter electrodes are made of two brass plates of 20[㎜] width and 40[㎜] separation.

The two dc power supplies are used in the ionizer section and the collector section, and they vary up to 20[kV] and 10[kV], respectively. A positive high voltage V_i, typically of +12[kV], is applied to the corona wire of the ionizer part, and the counter electrodes are grounded. A positive high voltage V_c, usually +6[kV], is applied to three of the collecting electrodes while two others are grounded.

The precipitator model is placed inside acrylic pipe (inner diameter: 155[㎜]). Two honeycomb boards are placed upstream and downstream of the precipitator in order to smoothen air flow inside the model precipitator. The schematic diagram of the measuring system is illustrated in Fig. 2.

The standard mist particles of DOP (Dioctyl Phthalate) is generated by a particle generator with compressed air. Gas velocity inside the precipitator can be changed by the voltage supplied to the blower. A particle concentration meter (ATI, model TDA-2EL), which detects the forward light intensity scattered by DOP particles is utilized.



CH (▽) : High voltage electrode, CG (▼) : Grounded electrode

Fig. 1. Two-stage electrostatic precipitator

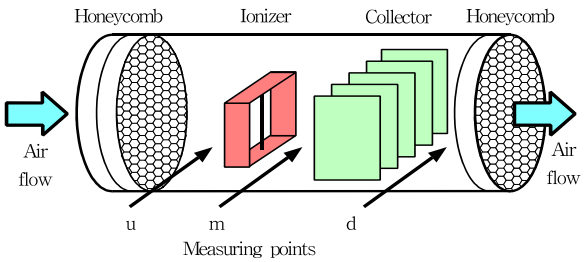


Fig. 2. Internal details of the experimental device

In the precipitator model, DOP particle concentrations are measured at three points denoted in Fig. 2 by "u" for upstream, "d" for downstream and "m" for the middle point between the ionizer and collector sections.

2.2 Experimental method

Since the effect of the relative position of the ionizer and the collector is already reported[11, 12], the experiments were performed only when the corona wire was aligned with the high voltage electrode as shown in Fig. 3. Three different lengths of collectors were used. The measuring coordinates are shown in the figure.

It was found that the concentrations of particles at "u" and "m" positions were almost identical as to varying y position in Fig. 3 and the concentration at "m" was slightly smaller than that at "u". Thus the particle concentrations were mostly measured both at "u" and "d" positions by moving the probe in y direction.

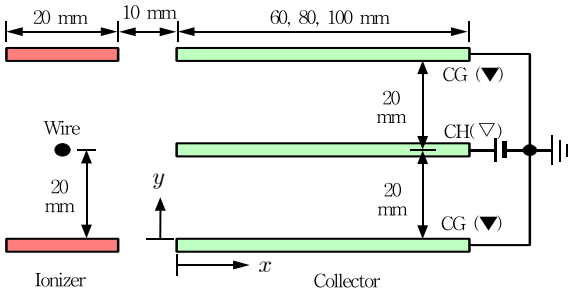


Fig. 3. Dimensions and the coordinates of the electrode

3. Theoretical aspects

If the concentration of particles is low enough, the motion of particles can be treated as a single particle which obeys the Newton's equation. In the experiment, the concentration of DOP particles is measured, and then assumed to be either 20 or 30 [mg/m^3], and the diameter of DOP particle is approximately 1[㎛.]

While the particles are passing inside the ionizer part, the surface saturation charge of a particle, q, is obtained from the sum of the electric charge Eq. (1) and the diffusion charge Eq. (2).

The electric charge, q_e, is defined as follows:

$$q_e = q_{\max}\left(\frac{t/\tau}{1+t/\tau}\right) \tag{1}$$

$$\begin{cases} q_{\max} = 4\pi\epsilon_0 a^2 \dfrac{3\epsilon_s}{\epsilon_s+2}E \\ \tau = \dfrac{4\epsilon_0}{\mu\rho} = \dfrac{4\epsilon_0 E}{J} \end{cases}$$

where the parameters are maximum charge, $q_{\max}$; vacuum permittivity, ϵ_0 (=8.85×10^{-12}[F/m]); particle radius, a (=0.5[㎛]); relative permittivity of particle, ϵ_s (=2.2); positive ion mobility, μ (= 5×10^{-5}[m^2/V·s]); and volume charge density, ρ (=0.15[mC/m^3]).

The diffusion charge, q_d, is defined as follows:

$$q_d = q_a \ln(1+t/\tau_a) \tag{2}$$

$$\begin{cases} q_a = \dfrac{4\pi\epsilon_0 akT}{e} \\ \tau_a = \dfrac{4\epsilon_0 kT}{aCe\rho} \end{cases}$$

where the parameters are maximum charge, q_a; Boltzmann constant, k (=1.38×10^{-23}[J/K]); absolute temperature, T (=300[K]); charge per particle, e (= 1.6×10^{-19}[C]) and thermal speed, C (=5.08×10^2[m/s]).

The surface saturation charge of a particle is obtained from the sum of the two equations (1) and (2). When the applied electric field is 2.1×10^5[V/m] with in the ionizer section whose length is 20[mm], the residence time of a 1[㎛] particle by air velocity is (i) 40[ms] under air velocity of 0.5[m/s], and (ii) 20[ms] under air velocity of 1.0[m/s], respectively. Under these conditions, the calculated results for the

particle charge are shown in table 1. The saturation charge, q, is approximately 2×10^{-17}[C].

Table 1. Particle saturation charge for residence time

Residence time t [ms]	Particle radius a [m]	Electric charge q_e [C]	Diffusion charge q_d [C]	Particle radius q [C]
20	0.5×10^{-6}	7.44×10^{-18}	1.0×10^{-17}	1.7×10^{-17}
40		8.26×10^{-18}	1.2×10^{-17}	1.9×10^{-17}

The viscosity of air for a particle, η, is 1.82×10^{-5} [Pa · s]. The mass of 1[㎛] DOP particle is 5.12×10^{-16} [kg], the particle concentration of 30[mg/m^3] means 5.86×10^{10}[particles/m^3]. From this concentration, the mutual distance is estimated to be 256[㎛].

The electrostatic force acting on a particle is 1.75×10^{-11}[N] because the applied electric field in the collector section is 3×10^5[V/m]. The mutual Coulomb force between two particles is only 1.72×10^{-16}[N], far smaller than the electrostatic force. Therefore, it is possible to handle particles individually using Newton's law.

Particle Reynolds number (Re) is defined as follows:

$$Re=\frac{dv_0}{\nu}=\frac{dv_0\rho}{\eta}=\frac{10^{-6}\times1\times978}{1.82\times10^{-5}}=54 \qquad (3)$$

where d is the particle diameter [m], v_0 is the air velocity [m/s], and $\nu\,(=\eta/\rho)$ is the kinematic viscosity of air for a particle [m^2/s].

If we assume the particle diameter is 1[㎛] and the maximum velocity is 1[m/s], the Re is only 54 and the assumption of Stokes resistance and Newton's law is possible simultaneously. By assuming these laws, the equations of motion can be calculated by the following equations. (The x-axis denotes the direction of air flow, the y-axis the direction of particle deflection under the assumption of the two-dimensional $x-y$.)

$$m\frac{d^2x}{dt^2}+6\pi\eta a\left(\frac{dx}{dt}-v_0\right)=0 \qquad (4)$$

$$m\frac{d^2y}{dt^2}+6\pi\eta a\frac{dy}{dt}=qE_y \qquad (5)$$

where m is the mass of a particle [kg], η is the viscosity of air [Pa · s], a is the particle radius [m], and E_y is the y-direction electric field [V/m], that is, E_y is the same as the applied electric field E in the collector section.

Substituting for the $dx/dt=v_x$, $dy/dt=v_y$ and $E_y=E$ in Eq. 4 and Eq. 5.

$$m\frac{dv_x}{dt}+6\pi\eta a(v_x-v_0)=0 \qquad (6)$$

$$m\frac{dv_y}{dt}+6\pi\eta a v_y=qE \qquad (7)$$

If we assume that the initial x-direction velocity is the same as gas velocity, the final particle velocity is the same. Thus, the solution of Eq. 6 is:

$$v_x=v_0 \qquad (8)$$

The solution of Eq. 7 with the initial condition of $v_{y0}=0$ at $t=0$ is as follows:

$$v_y=\frac{qE}{6\pi\eta a}\left\{1-\exp\left(-\frac{6\pi\eta a}{m}t\right)\right\} \qquad (9)$$

From Eq. 8 and Eq. 9, the final solutions are as follows:

$$x=v_0t \qquad (10)$$

$$\begin{aligned}y&=\frac{qE}{6\pi\eta a}\left\{t+\frac{m}{6\pi\eta a}\exp\left(-\frac{6\pi\eta a}{m}t\right)\right\}+y_0\\&=\frac{qE}{6\pi\eta a}\left\{t+\tau\exp\left(-\frac{t}{\tau}\right)\right\}+y_0\end{aligned} \qquad (11)$$

where τ is time constant.

The maximum elapsed time is only 0.1[s] and the maximum time constant τ is 2.98×10^{-6}[s] when $x=100$[㎜] and $v_0=1$[m/s]. Therefore, τ can be neglected

and substituting for $t = x/v_0$ from Eq. 10, Eq. 11 can be simplified as follows:

$$y = \frac{qE}{6\pi\eta a}t + y_0 = \frac{qE}{6\pi\eta a} \cdot \frac{x}{v_0} + y_0 \qquad (12)$$

where x is the collector length and y_0 is the initial position of a particle on y-axis. This equation shows particle trajectories within the collector section.

4. Experimental results and discussion

4.1 Experimental results

Fig. 4 shows the current-voltage (I-V) characteristic curves for a corona discharge in the ionizer section. The positive corona discharge current of the ionizer is affected by the applied voltage in the collector section but less so by the particle concentration. When applied voltage in the ionizer is 12[kV], the corona discharge current is about 95[μA].

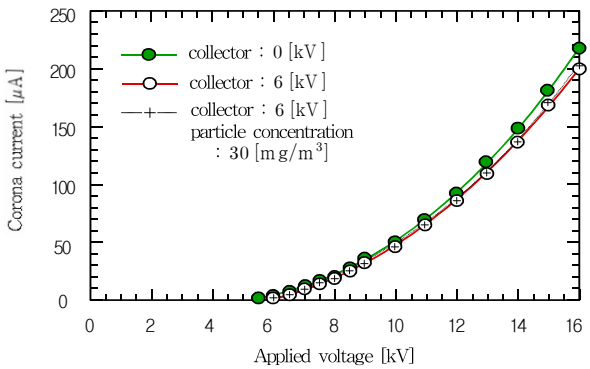


Fig. 4. Corona V-I characteristics for the ionizer

The DOP particle concentrations were measured at three different locations(u, m, d). The measuring probe was moved in y-direction from one of the ground electrodes to the other ($0 \le y \le 40$[㎜]) to measure the distribution of DOP concentration. The results at "u" and "d" are shown in Fig. 5. The particle concentration after the collector section, as designated by "d", varies with the probe position over the measuring region in contrast to the uniform distribution at inlet, as shown in Fig. 5.

The collection efficiency is defined as follows:

$$\eta_c = \frac{C_i - C_o}{C_i} \times 100 \ [\%] \qquad (13)$$

where η_c is the collection efficiency, C_i is the particle concentration at "u", and C_o is the particle concentration at "d".

The profiles of collection efficiency as a function of v_0 is shown in Fig. 6. As shown in the Fig. 6, the collection efficiency peaks on the high voltage electrode placed in the middle of the collector section. It is clear that collection efficiency lowers when the gas velocity becomes faster.

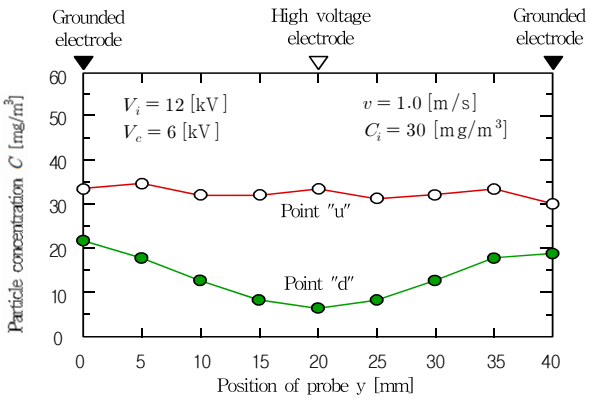


Fig. 5. Particle concentration inside the device

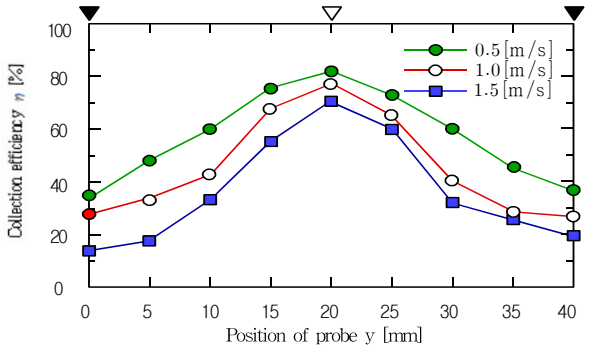
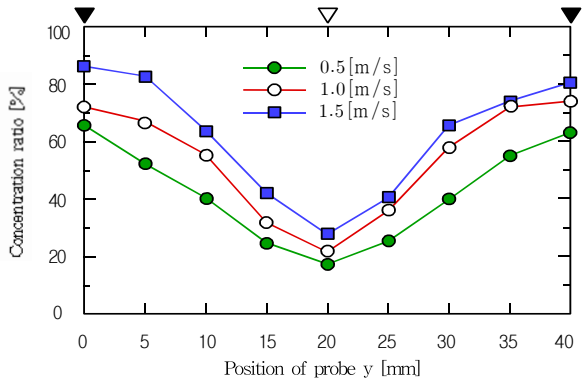
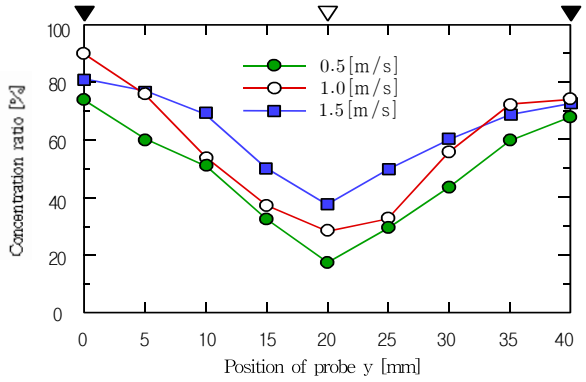


Fig. 6. Collection efficiency as a function of velocity

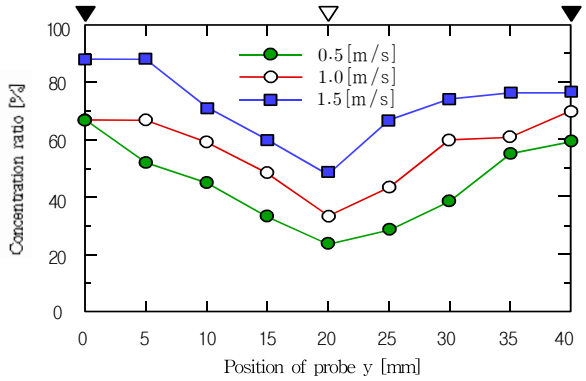
In order to analyze the particle motion within the collector section, the ratio of particle concentration is more useful than the collection efficiency. Thus, it is defined the concentration ratio as C_o/C_i.



(a) Electrode length of collector : 100[mm]



(b) Electrode length of collector : 80[mm]



(c) Electrode length of collector : 60[mm]

Fig. 7. Particle concentration ratio of the length of each electrode

Subsequently, Fig. 7, 9 and 10, will be described with the concentration ratio. Fig. 7 (a) shows the particle concentration ratio when the collector length is 100[㎜]; Fig. 7 (b) for collector length 80[㎜]; Fig. 7 (c) for collector length 60[㎜]. Gas velocity is changed from 0.5 to 1.5[m/s].

The V-shaped configuration of the concentration ratio indicates that the charged particles move toward grounded electrodes. Although the V-shaped tendencies are similar, there are dependencies on collector length and gas velocity.

When collector plates are shorter, the bottom of the V-shaped pattern for the concentration ratio is greatly affected by the gas velocity.

4.2 Discussion

Since the electric field is not high enough to collect all charged particles, a distinguished distribution curve of particle concentration can be obtained. By substituting the following values to Eq. 9, $a=0.5$ [㎛], $v_0=1.0$[m/s], $x=100$[㎜], $q=1.6\times10^{-17}$[C], $E=3\times10^5$[V/m], it is found that the deflection of a particle at the edge of the collector section is only 3[㎜] as shown in the Fig. 8.

When a charged DOP particle comes into the collector region at the point y_1, it is deflected towards the grounded plate by an electric field. The magnitude of the electrostatic force acting on the particle is a function of the charge-to-mass ratio of the particles. When the charge is zero, the particle will not be deflected at all and will reach the y_1' position. Supposing that y_1'' is the maximum deflection position, other charged particles will be distributed in the region f_1, represented as a triangle which has three corners y_1, y_1', and y_1''. The situation will be the same as long as the y_1'' does not reach the ground electrode. An extreme

case is shown as the triangle ($\triangle y_2 y_2' y_2''$) where a part of y_2''-b is collected by an a-b section of the electrode. If we know the particle size distribution and also charge values on each of the particles, the deflection pattern can be estimated. Without these data, the only possible way to estimate is to deduce an empirical equation for the concentration ratio.

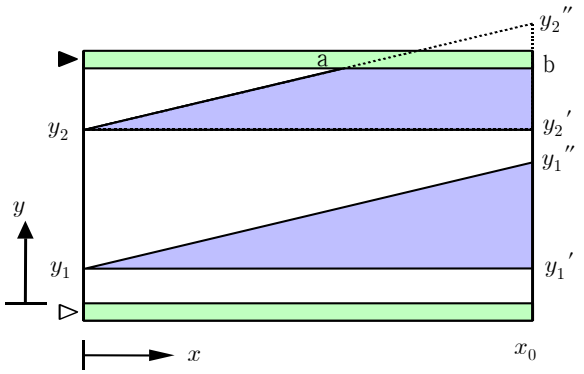
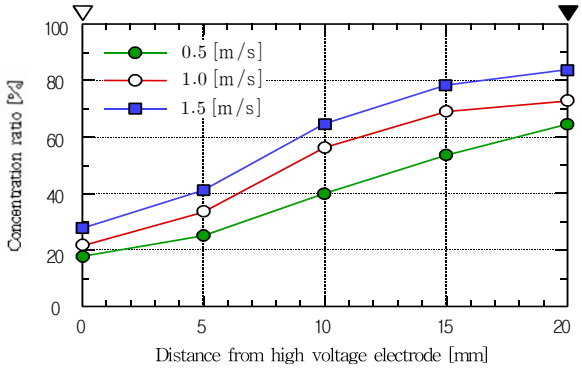


Fig. 8. Drift pattern of charged particles

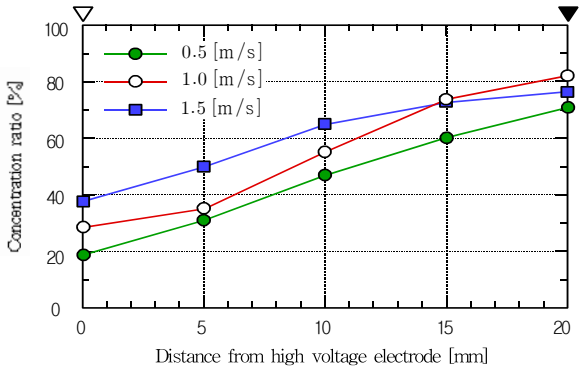
Since the Deutsch equation is well-known in electrostatic precipitator research [1], the exponential decay of particle concentration is the most probable nature of charged particle behavior.

Experimental results of Fig. 7 should be symmetrical if there is no error in the measurement. Thus, two values at the same distance from high voltage electrode are averaged[Fig. 9]. In order to deduce an equation from those data, the nature of experimental results is summarized as follows:

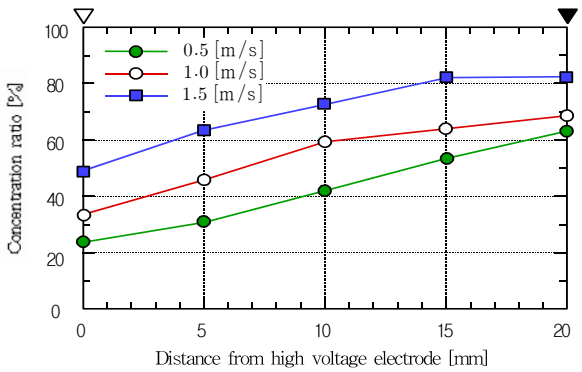
1. Concentration shows minimum near the high voltage electrode collector.
2. Change of concentration along y axis seems to be exponential.
3. When the collector length decreases, the minimum value of the collection efficiency increases.
4. The minimum value of the collection efficiency is almost proportional to gas velocity.
5. Exponential character is mostly a function of y. However, there is a week dependency on gas velocity in the range from 0.5 to 1.5[m/s].



(a) Electrode length of collector : 100[mm]



(b) Electrode length of collector : 80[mm]



(c) Electrode length of collector : 60[mm]

Fig. 9. Averaged curves of particle concentration ratio

Taking into account such experimental results, an empirical equation is proposed as follows:

$$\frac{C_o}{C_i} = 1.0 - \left(1.0 - \frac{k_1 v}{x}\right)\exp\left(-k_2 y v^{k_3}\right) \qquad (14)$$

where v is air velocity [m/s], x is collector length [mm], and y is distance [mm].

Constants k_1, k_2 and k_3 are determined by the experimental results of Fig. 9 (a~c). They are found $k_1 = 20$, $k_2 = 1/17$ and $k_3 = 0.3$.

Both numerical results and experimental data are shown in Fig. 10 (a~c). Although there are some deviations from the empirical equation, they are congruent to each other in general.

The empirical equation of the collection efficiency η_c can be deduced by substituting C_o/C_i in Eq. 14 into Eq. 13 as follows:

$$\eta_c = \left(1.0 - \frac{k_1 v}{x}\right)\exp\left(-k_2 y v^{k_3}\right) \qquad (15)$$

5. Conclusion

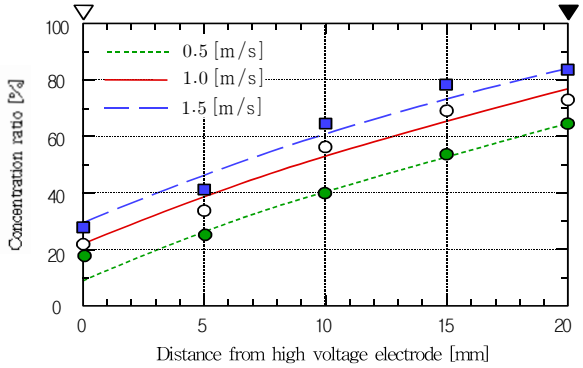
The particle deflection pattern is measured on varying the electrode lengths of collector and it shows the similar tendency as found in the theoretical prediction. Even if the quantitative derivation of a theoretical equation is difficult due to many unknown factors, the empirical equations are deduced from the experimental results. They show a reasonable agreement with the results.

The results are summarized as follows:

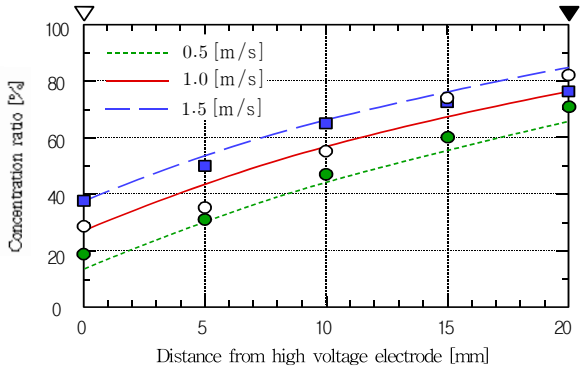
(1) The positive corona discharge current of the ionizer is affected by the applied voltage in the collector section but less so by the particle concentration.

(2) Particle concentration shows a minimum near the high voltage electrode of the collector section.

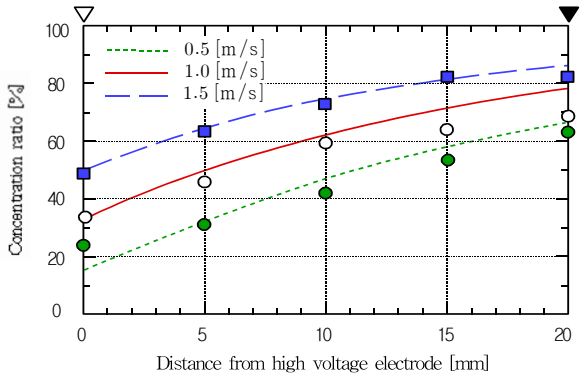
(3) The minimum value of the collection efficiency



(a) Electrode length of collector : 100[mm]



(b) Electrode length of collector : 80[mm]



(c) Electrode length of collector : 60[mm]

Fig. 10. Comparison between empirical curves and experimental results

is almost proportional to gas velocity.

(4) When the collector length decreases, the minimum value of the collection efficiency increases.

(5) Charged particles entering the collector region are linearly deflected towards the grounded plate by an electric field.

(6) The empirical equations for the concentration ratio C_o/C_i and the collection efficiency η_c from experimental results, are proposed as follows:

$$\begin{cases} \dfrac{C_o}{C_i} = 1.0 - \left(1.0 - \dfrac{k_1 v}{x}\right)\exp\left(-k_2 y v^{k_3}\right) \\ \eta_c = \left(1.0 - \dfrac{k_1 v}{x}\right)\exp\left(-k_2 y v^{k_3}\right) \end{cases}$$

where constants k_1, k_2 and k_3 are determined to $k_1 = 20$, $k_2 = 1/17$ and $k_3 = 0.3$.

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Biography

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He received B.S., M.S. and Ph.D. degrees in Electrical Engineering from Inha University, Incheon, Korea, in 1984, 1986 and 1999, respectively. He had worked at Construction Division of POSCO as engineer from 1986 to 1991. He had served as Visiting Professor at the University of Yamagata, Japan, from April 1997 to February 1998. He is Associate Professor in the Department of Electrical and Electronics Engineering, Daegu Technical College, where he has taught since 1992. He has been serving as a member of Daegu Metropolitan City Landscape Committee since 2011. His research interests include electrostatics, electrical materials, landscape lighting and renewable energy.