The Analysis of Ionic Wind for the Model Electrostatic Precipitator

By Takayoshi ADACHI*

Abstract

It is the purpose of this paper to investigate the nature of ionic wind (*IW*) in corona discharging field for the model electrostatic precipitator (*EP*). On the basis of the results about *IW* velocity measured by a Thermistor-anemometer, ion density and the efficiency of *IW* were calculated. These calculated results were small values unexpectedly. Ion velocity by trial calculation was larger than *IW* velocity and *IW* velocity distribution at the place of plate electrode was such as characterised by normal functions. Moreover, it is an important problem for *EP* that the charging particle velocity due to Colomb force from trial calculation is smaller than the *IW* velocity.

1. Introduction

Recently, the study on *IW* influence for the phenomena of dust collection in EP has developed and its achivements have become a center of attraction. However, results so far are the consideration of *IW* behavior [1, 2] and *IW* velocity[3~6] as ion drag-pumping phenomena. The reports of analysis for the nature of *IW* have apparently not been published to date. Therefore in order to study the nature of *IW* more quantitatively the results of *IW* velocity measured by a Thermistor-anemometer was analysed, and the relation between particle velosity and *IW* velocity were considered. Satisfactory results were obtained.

2. Ion velocity in *EP*

With the increase of air temperature at the corona discharging field, corona starting voltage decreases and corona current increases. These results and considerations[7] have been reported so far. As one of the cause of these results, the increase of ion movility should be considered. Because, *IW* velocity increases in proportion to the increase of ion velocity which equals ion movility multiplied by electric field strength.

Ion movility μ changed by air temperature is shown as follow Langevin's formular[8, 9],

$$\mu=\mu_0\times\sqrt{\frac{273+t}{273}}\times\frac{1+\frac{\bar{S}}{273}}{1+\frac{\bar{S}}{273+t}}\times\frac{1}{P}, \qquad \cdots\cdots\cdots(1)$$

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* Department of Electrical Engineering

where, t is the temperature of air in °C; P is the atmospheric pressure; $\bar{S}$ is the constant of Sutherland; μ_0 is the ion movility for air at 0°C and normal atmospheric pressure or 760 mm of mercury column. μ_0 is either the negative ion movility μ_0^-(2.11 cm/sec/V/cm, at $\bar{S}=330$) or the positive ion movility μ_0^+ (1.32 cm/sec/V/cm, at $\bar{S}=509$).

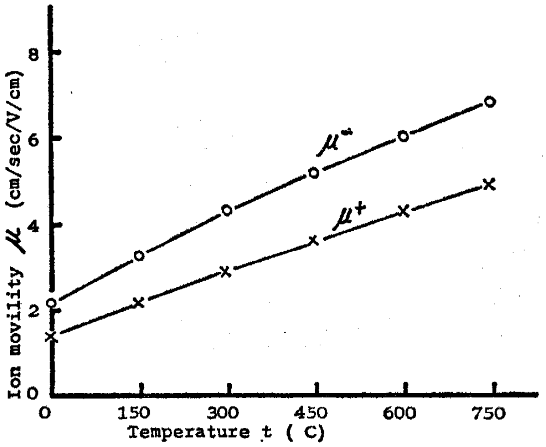


Fig. 1 Relation between ion movility and temperature at one atomosphere due to Langevin's formular.

Fig. 1 shows the characteristics of temperature versus ion movility as the the calculating results of equation (1). When the air temperature changes from 20°C to 720°C in Fig. 1, negative and positive ion movility become about 2.9 and 3.3 times as large as ion movility at 20°C, respectively.

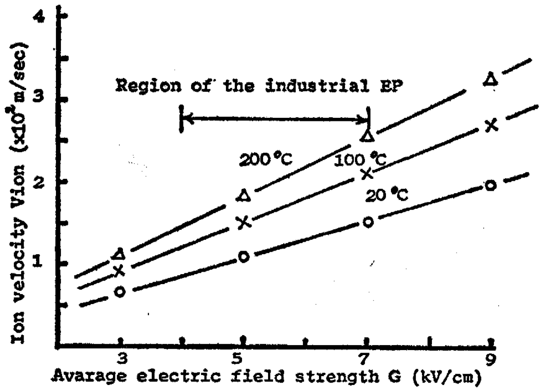


Fig. 2 Characteristics of the negative ion velocity in the negative corona discharging field.

Negative corona discharge is used in industrial *EP* because of high collection efficiency. Fig. 2 shows the characteristics of the negative ion velocity in the negative corona discharging field. Where, the negative ion velocity is the negative ion movility multiplied by the average electric field strength. The temperature of waste gas and the average electric field strength for the industrial *EP* are about the region of 100°C—200°C and 4kV/cm—7 kV/cm, respectively. In Fig. 2, the negative ion velocity at the preceeding regions is 100 m/sec—250 m/sec.

The negative ion velocity in the air of 20°C ranges about 90 m/sec—150 m/sec in the region of 4 kV/cm—7 kV/cm, but the maximum *IW* velocity is roughly in the region of 0.1 m/sec—1 m/sec and is about one-hundredths times as large as ion velocity. This cause is due to the collision of ion and the neutral molecules of air.

3. Ion density of *IW*

IW arrived at collecting electrode includes a small number of ions. The number N(number/sec) of this ion is given by

$$N=\frac{I}{e}. \qquad \cdots\cdots\cdots(2)$$

In equation (2), $e(C)$ is the electric charge of an electron.

In normal atomospheric condition, the number M (number/sec) of molecule in *IW* for wire to net electrode is given by

$$\begin{aligned} M&=2.67\times10^{19}\times Q,\\ &=2.67\times10^{19}\times S\times L. \qquad \cdots\cdots\cdots(3)\end{aligned}$$

In equation (3), Q(cm^3/sec) is the quantity of *IW*, S(cm^2/sec) is the area of *IW* velocity distribution, L(cm) is the effective length of discharging wire.

As one example, find the ion density at negative *IW* velocity distribution for wire to net electrode. The constants at 14kV in Fig. 3 are as follows:

$$\begin{aligned} e&=1.62\times10^{-19} && \text{(C)},\\ I&=74\times10^{-6} && \text{(A)},\\ S&=124.8 && \text{(cm}^2\text{/sec)},\\ L&=21 && \text{(cm)}.\end{aligned}$$

Then subustituting in equation (2) and (3), N and M is

$$\begin{aligned} N&=\frac{74\times10^{-6}}{1.62\times10^{-19}}\\ &=4.57\times10^{14}, \qquad \cdots\cdots\cdots(4)\\ M&=2.67\times10^{19}\times124.8\times21\\ &=7.00\times10^{22}. \qquad \cdots\cdots\cdots(5)\end{aligned}$$

Ion density of *IW* is the name given to ratio of N to M. From equation (4) and (5), ion density of *IW* is roughly one over followed by eight zeros.

As the results, *IW* due to the moving ion in corona discharging field is mainly the movement of neutral molecules of air.

4. Efficiency of *IW*

The efficiency of *IW* is name given to the ratio of the kinetic energy of *IW* to the electric energy of corona discharge. In the first place, the kinetic energy $W_i(W)$ of *IW* is described as follows. The *IW* velocity distribution in Fig. 3 is divided into a small section Δx (2 mm) and the kinetic energy $W_{ij}(W)$ of *IW* in the section of j is given by

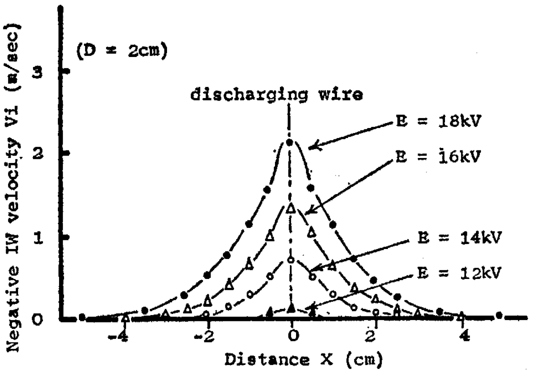


Fig. 3 Distribution of negative *IW* velocity for discharging wire to net electrode

$$W_{ij}=\frac{1}{2}\rho Q_j V_{ij}^2, \qquad \cdots\cdots\cdots(6)$$

where density of air ρ is 1.293 kg/m^3 at normal condition, Q_j and V_{ij} are the quantity and the mean velocity of *IW* in this small section. Therefore, the kinetic energy $W_i(W)$ of *IW* is the sum of all W_{ij}, j equals one to infinity, as follows:

$$W_i=\sum_{j=1}^{\infty} W_{ij}=\frac{1}{2}\rho \sum_{j=1}^{\infty} Q_j V_{ij}^2. \qquad \cdots\cdots\cdots(7)$$

On the other hand, the electric energy $W_e(W)$ of corona discharge is given by

$$W_e=E\,I_c, \qquad \cdots\cdots\cdots(8)$$

where E is applied voltage and I_c is corona current.

The efficiency η of *IW* from equation (7) and (8) becomes

$$\eta=\frac{W_i}{W_e}\times 100=\frac{\rho}{2EI_c}\sum_{j=1}^{\infty} Q_j V_{ij}^2 \times 100(\%). \qquad \cdots\cdots\cdots(9)$$

As one example, find the efficiency gievn by W_i and W_e at *IW* velocity distribution under 14 kV in Fig. 3. The constants are as follows:

$W_i=0.47\times 10^{-3}$ (W),

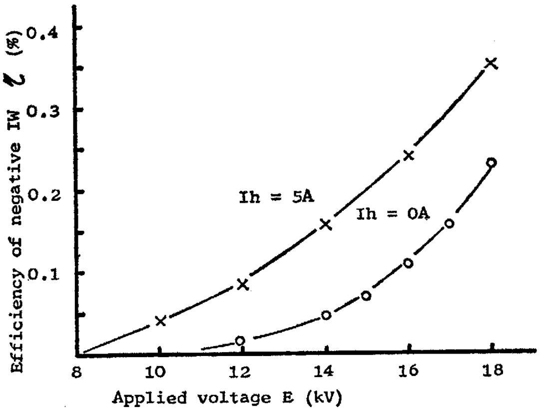
$E=14\times 10^3$ (V),

$$I_c = 74 \times 10^{-6} \quad (\mathrm{A}).$$

Then substituting in equation (9), the efficiency is

$$\eta = \frac{0.47 \times 10^{-3}}{14 \times 10^{3} \times 74 \times 10^{-6}} \times 100 = 0.045 \quad (\%). \qquad \cdots\cdots\cdots(10)$$

Fig. 4 Efficiency characteristics for negative *IW*



Equation (9) for the efficiency of wire to net electrode is shown graphically in Fig. 4, in terms of applied negative voltage and heated electric current of discharging wire. The efficiency increases with increasing applied voltage. The efficiency when the heated electric current of discharging wire is 5 A is higher values than the case of 0 A, because the condition of corona discharge due to the heated air in the case of 5 A differs from the case of 0 A.

The efficiency of *IW* is a small number and is in the region of 0.01%–0.3% from Fig. 4. It is considered that the electric energy of corona discharge is dissipated mainly as the heat in air, sound and light; and a small sum of this energy corresponded to the remainder is converted into the kinetic energy of *IW*. Therefore, the corona discharge where *IW* is in existence is unsuitable for the device of wind-souce by the cause of low efficiency.

5. Function for *IW* velocity distribution

The negative *IW* velocity distribution in Fig. 3 in reference (5) are symmetric with respect to the axis at which X is zero, and converge to zero with increasing X. Therefore, these distribution are described by the normal function, that is Gauss function. This function[10] is

$$F(X) = \frac{1}{\sqrt{2}\,\pi\sigma}\exp\left\{-\frac{(X-\mu)^2}{2\sigma^2}\right\}, \quad -\infty < X < +\infty, \qquad \cdots\cdots\cdots(11)$$

where the constants of σ and μ are decided by the form of distribution. When X equals μ, this function becomes the maximum value. However, according to *IW* velocity distribution for this experimental results, μ is zero.

The distribution which the heated electric current of discharging wire is zero shows the form as sharp mountain and is described by the function sumed two normal function. On the other hand, the distribution which the electric current is 5 A shows the form as flat mountain and is described only one normal function. At the latter, the form of distribution is due to the coefficient of viscosity[8] increased with increasing the temperature of the air.

As one example, find the normal function for *IW* distribution under 18 kV in Fig. 3 of reference (5). Substituting of the experimental data in equetion (11), the function of the distribution when the heated electric current is zero is

$$F(X)=F_1(X)+F_2(X)$$
$$=1.22\exp\left(-\frac{X^2}{434}\right)+0.88\exp\left(-\frac{X^2}{54.3}\right), \qquad \cdots\cdots\cdots(12)$$

and the case of 5 A is

$$F_3(X)=2.47\exp\left(-\frac{X^2}{393}\right). \qquad \cdots\cdots\cdots(13)$$

When the constants σ for $F_1(X)$, $F_2(X)$ and $F_3(X)$ are σ_1, σ_2 and σ_3 respectively, the relation between applied voltage and $\sigma_j^2 (j=1, 2, 3)$ is considered to be liner function in Fig. 5. The point of σ_3^2 at 18 kV in Fig. 5 slips out of linear line. This cause is due to incraesing the cooling effect of *IW* in proportion to applied voltage. In regard to these relation in Fig. 5, if the applied voltage be given, the constant will be decided and the negative *IW* velocity distribution will be used an approximation with $F_1(X)$ and $F_2(X)$ or $F_3(X)$. Moreover, the normal functions for the positive *IW* velocity distributions are similar to the case of negative *IW*.

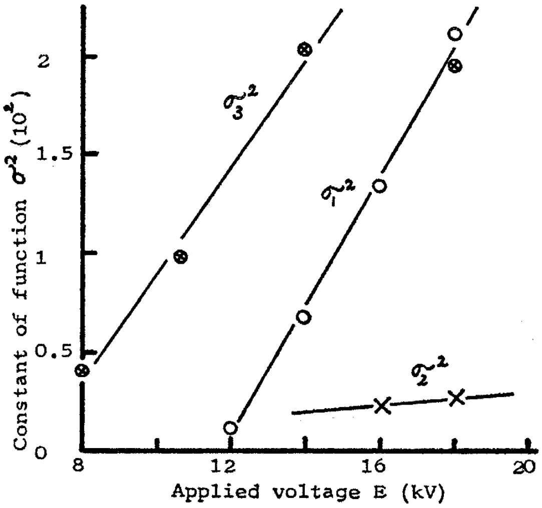


Fig. 5 Relation between constant σ^2 of function (11) and applied voltage.

6. Particle velocity in corona discharging field

The velocity of charged particle in corona discharging field is caused by a resultant force which is composed of many forces. The gravitational force for fine particle is very small comparing with Coulomb force in an electrostatic field, viscosity force and inertia force. Therefore, the gravitational force is entirely negligible. Assuming that gas velocity and *IW* velocity in corona discharging field are both zero, the differential equation for the motion of a particle is expressed as follow:

$$qG_p - 6\pi a \mu V_c - m\frac{dV_c}{dt} = 0, \qquad \cdots\cdots\cdots(14)$$

where q is the particle charge, G_p is the electric field strength of place where particle is in existence, a is the radius of particle, m is the mass of particle, μ is the coefficient of viscosity, and V_c is particle velocity due to Coulomb force. The second term of the equation gives the Stokes' force[11]. This equation is readily integrated as

$$V_c = \frac{qG_p}{6\pi a\mu}\left\{1 - \exp\left(-\frac{6\pi a\mu t}{m}\right)\right\} \quad \text{(m/sec).} \qquad \cdots\cdots\cdots(15)$$

As for the particle in an electrostatic precipitator, the second term of equation (15) is neglected, becouse $(6\pi a\mu/\mathrm{m})$ takes very large value. Assuming that the charging time of particle is a period long enough, the charge on a conductive particle is given by

$$q = 3a^2G_p \quad \text{(C),} \qquad \cdots\cdots\cdots(16)$$

where G_0 is the electric field strength of the place where the particle is charged. Substitution of (16) in (15) gives

$$V_c = \frac{G_0G_pa}{2\pi\mu} \quad \text{(m/sec).} \qquad \cdots\cdots\cdots(17)$$

The equation (17) is applicable to the region of Stokes' law.

If the diameter of particle is under 2μ, particle is some dielectricity or non-sphere, Laynol's number is over 0.5 and the space charge due to charged particles are in existance, the equation (17) shall be multiplied by the constant for the respective case. Assuming that the above conditions do not exist and G_0 equals to G_p, conductive particle velocity is calculated from equation (17) and this resultants is shown in Table 1.

The equation (14) holds on the assumption that *IW* velocity is zero. As it is, *IW* velocity is in existance in an electrostatic precipitator, and particle velocity V_c due to Coulomb force and *IW* velocity V_i are the same direction for the collecting plate electrode (grounded electrode). If the whirls caused

Table 1 Particle velocity V_C(cm/sec) due to Coulomb force in the electric field strength G(KV/cm), 2a (μ) is particle diameter.

K (KV/cm) \ 2a	V_C(cm/sec)				
	0.4	1.2	2.0	4.0	8.0
4	3.1	9.4	15.7	31.5	63.0
5	4.9	14.7	24.6	49.1	98.3
6	7.1	21.2	35.4	70.8	141.6
7	9.6	28.9	48.1	96.3	192.6

IW were not exist in electrostatic precipitator, particle velocity V will be considered as sum V_c and V_i. *IW* velocity V_i described in section 2 is about ten times V_c in Table 1 for the particle of 2(μ) in diameter. Therefore, V is used approximation with V_i, but near the plate electrode, V_c may be larger than V_i. As it is, the particle velocity is mainly the velocity due to Coulomb force so far. Therefore it is considered that the preceding consideration for particle velocity has direct effects upon the collecting particle phenomena and the efficiency of an electrostatic precipitator.

It is said that the big three forces[12] in many forces acting upon particles under collection in an electrostatic precipitator are Coulomb force, gravitational force and coagulating force. Nevertheless, the collecting force due to *IW* should be taken account through the preceding considerations. Then, the auther recommend that the main forces acting upon the particle in an electostatic precipitator may be said as the four instead of the three, that gravitational force, coagulating force, Coulomb force and *IW* force.

7. Conclusions

The results of these calculation and consideration are summarized as follows.

(1) The temperature of supply gas and the average electric field strength for the industrial electostatic precipitator are said as ranging about 100°C–200°C and 4 kV/cm–7 kV/cm, respectively. As the results of calculation, the negative ion velocity at these range is bout 100 m/sec–250 m/sec. *IW* velocity due to the collision of ion and the neutral molecules in air is measured as 0.1 m/sec–1 m/sec and is about one hundredths times as large as ion velocity.

(2) As the results of experimental data and calculation, the ion density of *IW* is estimated roughly one over one followed by eight zeros. Therefore, *IW* due to the moving ion in electric field is mainly the movement of the neutral molecules of air.

(3) The efficiency of *IW* increases with increasing applied voltage and the temperature of electrode wire. Electrode heating current 5 A gives higher values for efficency than the case of 0 A.

The efficiency of *IW* is for low range 0.01%–0.3% as the result of calculation based on experimental data. It is considered that the electric energy of corona discharge is dissipated mainly as the heat in air, sound and light, and the remainder of these energy is converted into the kinetic energy.

(4) The negative *IW* velocity distribution is shown as the function sumed two components of normal function. While the characteristics is shown with only one normal function, where the wire electrode is heated with 5 A. The linear relation between applied voltage and the constants σ^2 of these functions holds with a fairly good approximation. Moreover, the normal functions for the positive *IW* velocity distribution are similar to the case of negative *IW*.

(5) Under some convenient conditions of corona discharge, the velocity of a charged particle due to Coulomb force, trial calculation, is smaller than the *IW* velocity from the results of experiment. The direction of these two components are the same. Therefore, it is said that the particle velocity is given with the some of these two velocities.

(6) It is said those *IW* velocity, the efficiency of *IW* and particle velocity have much effects upon the particle collection phenomena and the efficiency of an electrostatic precipitator.

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