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Bipolar charged aerosol agglomeration and collection by a two-zone agglomerator

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Abstract: In older to collect fine particles more efficiently, a new-type electrostatic agglomerator with two zones was developed. The distinguishing feature of this electrostatic agglomerator is that the particles are bipolarly charged and coagulated in the same alternating electric field simultaneously. The silica flour with 2 μm mass median diameter and the smoke from burning wood powder were used as test aerosol. The comparison experimental results have shown that when the mean electric field is 4 kV/cm the collection efficiency of the new electrostatic agglomerator was 98.2% for silica flour and 67.4% for wood powder smoke. Under the same experimental condition, the collection efficiency of the electrostatic agglomerator with three zones was 97.4% for collecting silica flour and the collection efficiency of the electrostatic precipitator was 56.3% for wood powder smoke.

Key words: charged particle agglomeration; alternating electric field; electrostatic agglomerator (EA); electrostatic precipitator (ESP); collection efficiency

Introduction

Because of the low efficiency of the electrostatic precipitator (ESP) for collecting the submicron particles, the electrical agglomeration method has led to an increasing interest in reducing the emission of the fine particles. Many authors have studied electrical agglomeration recently. There are three agglomeration techniques: bipolar charged particle agglomeration in an electrostatic precipitator (Kanazawa, 1993), unipolar charged particle agglomeration in an alternating electric field (Watanabe, 1995), and bipolar charged particle agglomeration in an alternating electric field (Laitinen, 1996).

Bipolar charged particle agglomeration efficiency in an alternating electric field has been thought to be higher than that of unipolar charged particle agglomeration because like-charged particles repel each other. There are three zones in the electrostatic agglomerator (EA) proposed by Laitinen *et al*. (Laitinen, 1996). First, the particles are bipolarly charged in the charging zone. Then these bipolar charged particles are coagulated in the agglomeration zone with an alternating electric field. Finally, the coagulated particles are collected by the collection zone. In this type EA, however, the particles are charged only once. As the charged particles are coagulated, the charge-mass ratio decreases due to neutralization. Thus, the coagulation rate slows down in agglomeration zone.

In this work a two-zone EA is developed. That is, the particles are charged and agglomerated simultaneously in the alternating electric field. A comparison of collection efficiency between the two-zone EA, the three-zone EA, as well as the ESP has been investigated experimentally.

1 Theoretical estimation of the EA collection efficiency for the bipolar charged particles

The collection efficiency is a very important criterion to evaluate the characteristics of EA. In order to estimate the collection efficiency of EA theoretically, the following assumptions are made: (1) as agglomeration proceeds, the polydisperse particle follows a self-preserving distribution. That is, the geometric standard deviation does not change greatly (Frederlander, 1977); (2) there is no wall loss in the agglomeration zone; (3) the agglomeration coefficient remains constant and the total number-concentration of the agglomerated particles can be calculated by Smoluchowski agglomeration equation; (4) field charging charges the particles to the saturation level; (5) only the bipolar charged agglomeration coefficient in the alternating electric field is considered because this agglomeration coefficient is much larger than other agglomeration coefficients, for example, the Brownian agglomeration coefficient.

It is clear that to calculate the collection efficiency of EA is, actually, to calculate the collection efficiency of ESP from Fig.1. The investigation of Zhao and Pfeffer (Zhao, 1996) has proved that the geometric standard deviation has very little effect on the total collection efficiency of the ESP. The total collection efficiency of the ESP can be predicted by using the median diameter d_m into Duitsh equation:

$$\eta = 1 - \exp\left(- \frac{qEL}{3\pi\mu d_m vh} \right), \qquad (1)$$

where η is the total collection efficiency; q is the charge on the particle; E is the field strength; L is the length of the collection electrode; b is the distance between the corona electrode and the collection electrode; v is the flow speed. If the agglomerated particle median diameter d_m is found out, the total collection efficiency of the agglomeration apparatus can be determined.

Suppose the median diameter and the number concentration of the particles before interring the agglomeration zone are a_m and N_0. According to the assumptions of (1) and (2), the following relation can be obtained:

$$N(t)/N_0 = (a_m/d_m)^3, \quad (2)$$

where $N(t)$ is the number concentration of the particles after the coagulation time t. $N(t)$ is given by Smoluchowski equation:

$$N(t) = N_0/\left(1 + \frac{1}{2}KN_0 t\right), \quad (3)$$

where K is the agglomeration coefficient. From Equation (2) and (3), the agglomerated particle median diameter d_m is obtained:

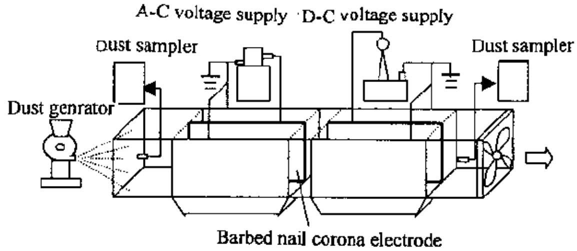

Fig.1 Experimental setup of the two-zone EA

$$d_m = \left(1 + \frac{1}{2}KN_0 t\right)^{1/3} a_m. \quad (4)$$

The agglomeration coefficient of the two different charged particles d_i and d_j in the alternating electric field is calculated approximately by (Kildes, 1995):

$$K = \frac{\varepsilon\varepsilon_0}{2(2+\varepsilon)\mu}EE_0(d_i + d_j)^3, \quad (5)$$

where ε is the relative permittivity; ε_0 is the vacuum permittivity; μ is the viscosity of the gas; E is the field strength of the charging field; E_0 is the amplitude of the alternating electric field.

The agglomeration coefficient has been assumed to be constant. Let $d_i = d_j = a_m$ in Equation (5), the underestimated agglomeration coefficient of the charged particles in an alternating electric field is

$$K = \frac{4\varepsilon\varepsilon_0}{(2+\varepsilon)\mu}EE_C a_m{}^3. \quad (6)$$

Sometimes, the initial mass concentration C_0 is easier to be found than the initial number concentration N_0. In this case the following relation can be used:

$$C_0 = \frac{\pi}{6}N_0 a_m^3 \rho, \quad (7)$$

where ρ is the particle density.

From the above equations we can see that the total collection efficiency of an agglomeration apparatus for bipolar charged particles is dependent on the initial particle concentration, the initial particle median diameter, the agglomeration coefficient and the residence time of the bipolar charged particles in the agglomeration zone.

2 Experimental setup

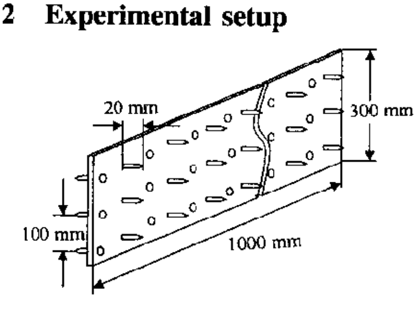

Fig.2 The structure of the barbed nail corona electrode

The measurements were carried out using the two-zone EA, the three-zone EA and the two-stage ESP. The two-zone EA is presented in Fig.1. Both the agglomeration zone and the collection zone are 1m in length. The barbed nail corona electrode was used in both the agglomeration zone and the collection zone. The structure of the barbed nail corona electrode is shown in Fig.2. The distance from the point of nail to the grounded electrode is 40 mm. An A-C voltage was applied in the agglomeration zone. Thus, the particles were bipolarly charged and coagulated in the agglomeration zone simultaneously. The three-zone EA is presented in Fig.3. The barbed nail corona electrode (Fig.2) was also used in the collection zone. Other geometric parameters of the three-zone EA are the same as the two-zone EA. When the A-C voltage power supply in Fig.1 is replaced by D-C voltage power supply, the two-zone EA becomes a two-stage ESP.

The silica flour with 2 μm mass median diameter was used in this comparison experiment. The dust mass concentrations of the inlet and outlet of the experimental apparatus were measured by the dust samplers.

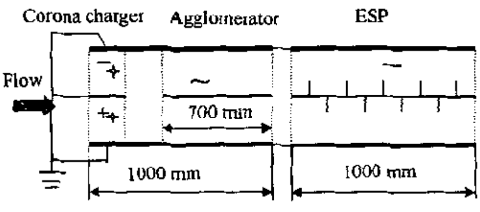

Fig.3 Three-zone EA proposed by Laitinen *et al*. (Laitinen, 1996)

3 Results

3.1 The comparison experiment of the two-zone EA and the three-zone EA

The experimental conditions in measuring the collection efficiencies of the two-zone EA and the three-zone EA are described in Table 1. The A-C voltage frequency in the agglomeration zone is a very important parameter. If the frequency is too high, the particles do not have enough time to be charged in the A-C electric field. On the other hand, if the frequency is too low, the vibrating speed of charged particles becomes very slow. This could be unfavorable to the charged particle agglomeration. Watanabe (Watanabe, 1995) has discussed the effect of the different efficiencies on the agglomeration rate. In this experiment the frequency was 4 Hz. The theoretical and experimental collection efficiencies of the two-zone EA and the three-zone EA under the different electric-field strengths are illustrated in Fig.4. The results have shown that the collection efficiency of the two-zone EA is higher than that of the three-zone EA.

3.2 Comparison experiments of the two-zone EA and the two-stage ESP

Table 1 Experimental condition

a_m, μm	ρ, kg/m³	C_0, kg/m³	μ, Pa·s	v, m/s	t, s
2	1.76×10^{3}	12.2×10^{-3}	1.8×10^{-5}	1	1

Notes: a_m: silica dust median diameter; ρ: silica dust mass density; C_0: mean dust concentration; μ: gas dynamic viscosity; v: gas velocity; t: residence time

Through measurements we found that the collection efficiency of the two-stage ESP for the silica dust with 2 μm mass median diameter is almost the same as, or even a little higher than the collection efficiency of the two-zone EA. Because it is not advantageous for the electrostatic agglomerator to collect the micron particles, the sub-micron particles, such as the smoke, have to be used to discuss the performance of the new EA and the two-stage ESP. In this experiment, the smoke from burning wood powder was used as the test aerosol in order to compare the collection efficiency of the two-zone EA and the two-stage ESP. The dust samplers in Fig. 1 must be replaced by an infrared concentration-measurement system (ICMS) shown in Fig.5 to measure the smoke concentrations.

In this experiment, the gas velocity is 0.3 m/s, the field strength is 4 kV/cm and the frequency of the A-C voltage is 4 Hz. Other experimental conditions are shown in Table 1. For the different smoke concentrations, the ICMS has different output voltages. The correlation coefficient of the output voltage of the ICMS and the smoke concentration is 0.996. According to the output voltages of the ICMS under the different smoke concentrations, the collection efficiency of the two-zone EA and the collection efficiency of the two-stage ESP for cleaning the smoke can be calculated respectively by:

$$\eta_{EA} = 1 - (U_{EAO} - U_B)/(U_i - U_B), \quad (8)$$

$$\eta_{ESP} = 1 - (U_{ESPO} - U_B)/(U_i - U_B), \quad (9)$$

where U_B is the background output voltage (without smoke) of the ICMS; U_i is the output voltage of the ICMS for measuring the smoke in the EA or ESP inlet; E_{EAO} and U_{ESPO} are the output voltages of the ICMS for measuring the smoke in the EA and ESP outlet.

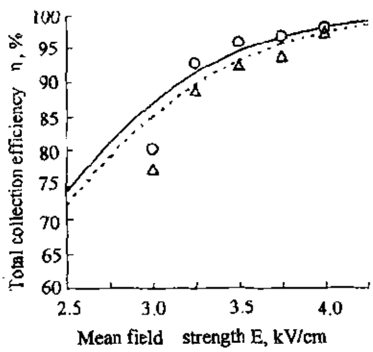

Fig.4 Collection efficiencies of the two-zone EA and the three-zone EA
—theoretical value of the two-zone EA; ----- theoretical value of the three-zone EA; ○: experimental value of the two-zone EA; △: experimental value of the three-zone EA

The experimental results are shown in Fig.6. We can see that the output voltages fluctuate greatly. The average value of the output voltage is taken. From Fig. 6, the average values of the output voltages are $U_B = 1.428$, $U_i = 2.530$, $U_{EAO} = 1.788$, and $U_{ESPO} = 1.910$. According to Equations (8) and (9), when the field strength is 4 kV/cm the collection efficiency of the two-zone EA and the collection efficiency of the two-stage ESP for the smoke from burning wood powder are 67.4% and 56.3% respectively. This comparison experiment has shown that the collection efficiency of the two-zone EA is higher than that of the two-stage ESP for the submicron particles.

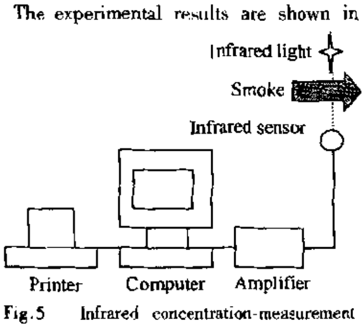

Fig.5 Infrared concentration-measurement system (ICMS)

4 Conclusion

The new idea of two-zone electrostatic agglomerator is that the particles are charged and agglomerated in an alternating electric field. There are two advantages: (1) the particles can be charged and agglomerated repeatedly. When the particles are agglomerated into a larger particle, the surface area becomes greater. The charge on the agglomerated particles is increases when this particle is charged again. Thus, the agglomeration rate goes up; (2) because the particles can be bipolarly charged in the alternating electric field, it is not necessary to have a precharging zone. Therefore, the total length of the electric field becomes shorter in the application.

This study has shown that the collection efficiency of the two-zone EA is not only higher than that of the three-zone EA for the fine particles, but also higher than that of the two-stage ESP for the submicron smoke particles.

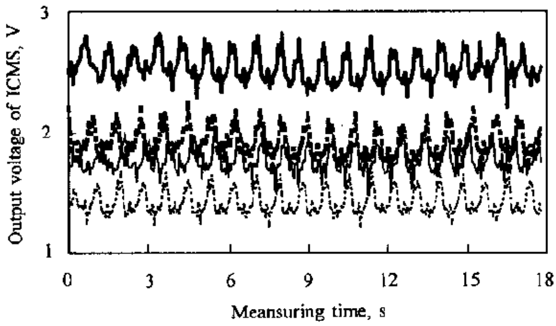

Fig.6 Output voltage of ICMS under the different smoke concentrations

-----Clean air; -----smoke cleaned by ESP;

—— original smoke; ——smoke cleaned by EA

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