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ENHANCED COLLECTION EFFICIENCY FOR CYCLONE BY APPLYING AN EXTERNAL ELECTRIC FIELD

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ABSTRACT

This study investigates if the performance of a cyclone can be enhanced as the electric force is incorporated into the centrifugal force. An electrocyclone is utilized to collect the fly ash by combining a cyclone and an electrostatic precipitator. The applied voltage is 25 KV and the flow rates tested are 15.75, 28.75, and 44.26 m^3/min. The Particle Counter-Sizer-Velocimeter is used to measure the particle size distribution upstream and downstream of the cyclone and the electrocyclone.

The experimental results show that a high electric field has a significant effect on the grade efficiency. The grade efficiency of the electrocyclone is much larger than that of the cyclone at the low flow rate. The improvement effect is decreased as the flow rate increases. At the highest flow rate, the grade efficiency of the electrocyclone is close to that of the cyclone.

Key Words: Electrocyclone; Cyclone; Electrostatic precipitator; Grade efficiency.

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INTRODUCTION

The main reasons for the widespread use of cyclone are that they are inexpensive, they have no moving parts, and they can be constructed to withstand harsh operating conditions (1). Although cyclone has been adequate for many applications, the increasing emphasis on environmental protection is dictating that finer and finer particles must be removed. To meet this challenge, improvement in cyclone efficiency is required.

A number of researchers have begun to study the methods for improving the cyclone efficiency by applying an electric field of high voltage in the cyclone. By applying an electric field of high voltage in a cyclone, the electric forces are incorporated into the centrifugal forces so that the cyclone efficiency can be enhanced. The electrocyclone concept is a synthesis of a cyclone and an electrostatic precipitator.

Dietz (2) developed a model to describe the performance of a cyclone, as the electric forces were employed to supplement the inertial forces. By precharging the particles and applying a radial electric field within the cyclone, the collection efficiency was improved. The results showed that at lower flow rates, the electrostatic forces were important, and a significant enhancement of the collection efficiency was obtained. Boericke et al. (3) used an electrocyclone 0.46 m in diameter to test the overall collection efficiency of coal fly ash. The applied voltages were 0, 60, 70, and 75 KV. The results showed that the overall collection efficiency of electrocyclone at various applied voltages was much higher than that of cyclone at the lower air flow rates because of more residence time. The improvement effect was decreased as the flow rates increased. An existing theoretical model for a conventional cyclone was extended to include the effect of an applied electric field by Plucinski et al. (4). The effect of the electric field was most significant for the small particles and at the low gas velocities. A qualitative experimental verification of this effect was also carried out for particles of silica with diameter ranging from 0.5 to 5 μm at 8 KV. The results demonstrated that the overall collection efficiency was decreased as the inlet gas velocity increased.

Few studies have been done on the grade efficiency of an electrocyclone experimentally. Dietz (2), Boericke et al. (3), and Plucinski et al. (4) have developed a model based on the existed theories and models of the cyclone to predict the grade efficiency of an electrocyclone respectively, but Iozia and Leith (5) showed that the existed theories and models of the cyclone have not consistently shown the ability to predict the cyclone grade efficiency well. Chen (6) also pointed out that the grade efficiency predicted by Lapple (1950), Barth (1956), Leith and Licht (1972), Dietz (1981), Dirgo and Leith (1985a), and Iozia and Leith (5) did not appear consistent. Plucinski et al. have ever verified that the overall collection efficiency of an electrocyclone was larger than that of a cyclone experimentally, but they did not investigate the grade efficiency. Although Boericke et al. have investigated and compared the grade efficiency of a cyclone and an electrocyclone experimentally, the particle size distribution was not presented and the data were too few because the resolution of the measuring instrument was not high enough. To date, however, no studies have attempted to measure the particle size distribution and compare the grade efficiency of an electrocyclone to that of a cyclone by a measuring instrument of high resolution.

The purpose of this study is to investigate the effect of an external applied electric field on the grade efficiency of a cyclone at various flow rates and particle sizes. The synthesis effect of the electric force and the centrifugal force on the grade efficiency of the electrocyclone is to be decomposed by calculating the electric migration velocity and the terminal velocity.

Electrocyclone Theory

The electric field is imposed by applying a high voltage to an electrode within the cyclone. The electrode structure is a coaxial rod of radius R_e. Being insulated from the grounded cyclone wall, the electrode produces a radially directed electric field. The strength of the electric field in the electrocyclone can be described by Boericke et al. (3).

$$E = V_0/[r \ln(R_c/R_e)] \quad (1)$$

where E is the strength of electric field, V_0 is the imposed high voltage, r is the distance away from the electrode, R_c is the cyclone radius, and R_e is the electrode radius.

The electrostatic efficiency is calculated assuming that the electrocyclone behaves like a cyclone and an electrofilter behind each other. The efficiency of an electrocyclone can be described by

$$\eta_t = 1 - (1 - \eta_c)(1 - \eta_e) \quad (2)$$

Where η_t is the grade efficiency of the electrocyclone, η_c is the grade efficiency of the cyclone, and η_e is the grade efficiency of the electrofilter. Equation (2) can be rewritten as

$$\eta_e = (\eta_t - \eta_c)/(1 - \eta_c) \quad (3)$$

Considering that the efficiency of the electrofilter can be described by Deutsch Equation, an electric migration velocity can then be deduced

$$\eta_e = 1 - e^{-AWe/Q} \quad (4)$$

where A is the collection surface, W_e is the electric migration velocity, and Q is the air flow rate. Comparing Eq. (3) to Eq. (4), the electric migration velocity W_e at the various flow rates and particle sizes can be calculated.

$$W_e = -\ln\{1-[(\eta_t - \eta_c)/(1 - \eta_c)]\}/[(A/Q)] \quad (5)$$

In order to compare the effect of the electric force and the centrifugal force on the grade efficiency, the radial velocity in the electrocyclone caused by the centrifugal force should be given. The centrifugal force can be described by (7)

$$V_t = d_p^2\,(\rho_p - \rho_g)V_i^2/18\,\mu R \quad (6)$$

where V_t is the terminal velocity, d_p is the diameter of the particle, ρ_p is the density of the particle, ρ_g is the gas density, V_i is the gas inlet velocity, μ is the gas viscosity, and R is the cyclone radius.

EXPERIMENTAL METHODS

Experimental Devices

An axial Stairmand high-efficiency cyclone 0.22 m in diameter with an electrode that is inserted in the center of the vortex finder has been designed for the tests. The electrode made of cast iron is 1 m in length and 0.025 m in diameter. The inlet duct of this axial Stairmand high-efficiency is circular and the diameter is 0.15 m. This gives an inlet area of 0.0177 m^2. The schematic diagram of the experimental system is shown in Fig. 1. Table 1 summarizes the dimensions of this axial Stairmand high-efficiency cyclone. This gives a volume of 0.0195 m^3. The system consisted of a dust feeder, an electrocyclone, and two aerosol detectors. Air was drawn through the system by a fan located near the outlet. A screw feeder was used to introduce the fly ash at a feed rate in the range 7.2–21.2 g/min.

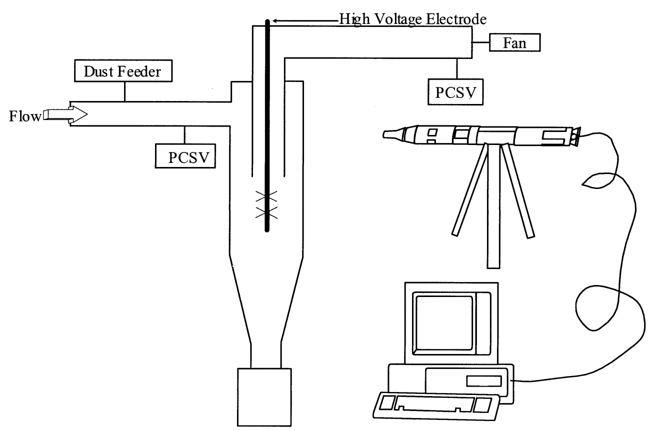

Figure 1. Schematic diagram of electrocyclone.

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Table 1. Dimensions of Stairmand High-Efficiency Cyclone (m)

D	D_e	S	L_b	L_c	D_d
0.22	0.11	0.11	0.33	0.55	0.083

The electrocyclone, which used a high voltage electrode to charge the particles and improved the separation efficiency, was the combination of a traditional cyclone and an electrostatic precipitator. Throughout the experiment, the particles of a polydispersed size produced by a dust feeder were used to feed the fly ash continuously into the gas.

Experimental Procedures

The experimental procedures for measuring the cyclone efficiency were designed to first generate the particles, then to pass the particle-laden air through the cyclone with and without applying a high voltage at a desired flow rate, and then to measure the particle concentration and size distribution upstream and downstream of the cyclone and the electrocyclone in order to compare the improved efficiency derived from the electric field. The polydispersed sizes of the particles produced were controlled by the operating conditions of the dust feeder. The flow rates tested were 15.75, 28.75, and 44.26 m^3/min, which corresponded to 0.26, 0.48, and 0.74 m^3/s, respectively. The inlet flow velocities were 14.7, 27.1, and 41.8 m/s, respectively. The average gas residence time in the cyclone was 0.0743, 0.0407, and 0.0264 s, respectively. The particle measuring instruments simultaneously measured the incoming and outgoing dust streams to permit real-time computation of the size distribution and the particle concentration.

Measuring Instruments

For measuring the particle size distribution and concentration, a Particle Counter-Sizer-Velocimeter, INSITEC PCSV-P TYPE, was used. The PCSV are laser-based instruments for in-line, in situ particle measurements. The PCSV principle of operation is based on measuring the light scattered by single particles moving through the sample volume of a focused laser beam. For each scattered light pulse, the signal processor measures the peak signal intensity, which is related to the particle size. They provide information on particle concentration and size distribution. The primary benefit of in-line or in situ techniques is the potential for real-time analysis under actual system conditions.

RESULTS AND DISCUSSION

Strength of Electric Field

In this study, V_0 is 25 KV, R_c is 11 cm, and R_e is 1.25 cm. Substitution into Eq. (1) leads to the relationship between the strength of the electric field strength and the distance away from the electrode. As shown in Fig. 2, the distribution of the electric field strength varies between 1.04×10^5 V/m and 11.5×10^5 V/m. The average strength of the electric field is about 5×10^5 V/m, which is the same as the typical field strength of the electrocyclone with saturation charging (3).

Particles Size Distribution

An experimental study of the high-voltage electric field on the collection efficiency has been carried out for the polydispersed particles of the fly ash. The size distribution upstream and downstream of the cyclone and electrocyclone measured by the Particle Counter-Sizer-Velocimeter at various flow rates are shown in Figs. 3 to 5.

The particle size distribution at the cyclone entry is shown to vary widely with the flow rates. At the low flow rate, as shown in Figs. 2 and 3, the particle size distribution is found to be bimodal. The similar observation was also made by McElroy et al. (8) and Kauppinen and Pakkanen (9). This can be explained based on the mechanism of formation of coal fly ash. As the flow rate is increased up to 44.26 m^3/min, Fig. 4 shows that the particle size distribution is seen to be very different from that of 15.75 m^3/min and 28.75 m^3/min. The size distribution curve is not bimodal, and the mass concentration below 10 μm is much lower than that of 15.75 m^3/min and 28.75 m^3/min because of agglomeration effect. This phenomenon has been found and published by Mothes and Löffler (10).

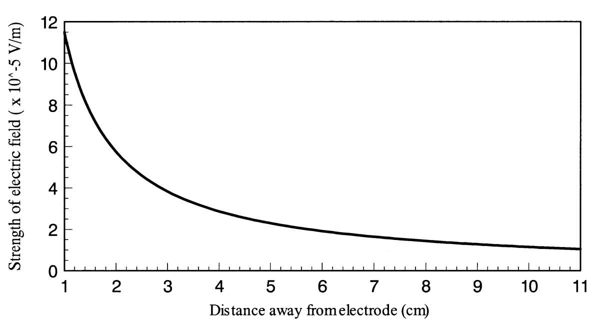

Figure 2. Distribution of the electric field strength in the electrocyclone.

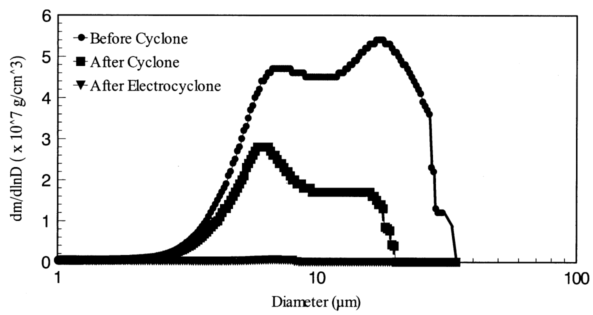

Figure 3. Size distribution of fly ash (Flowrate = 15.75 m^3/min).

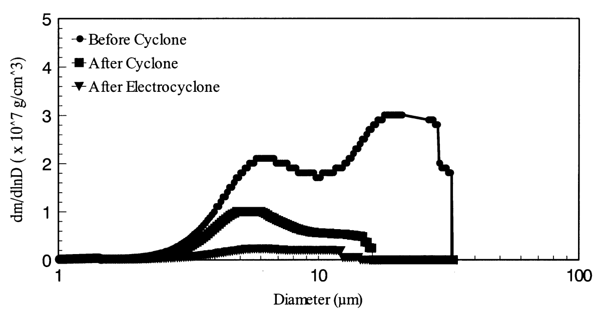

Figure 4. Size distribution of fly ash (Flowrate = 28.75 m^3/min).

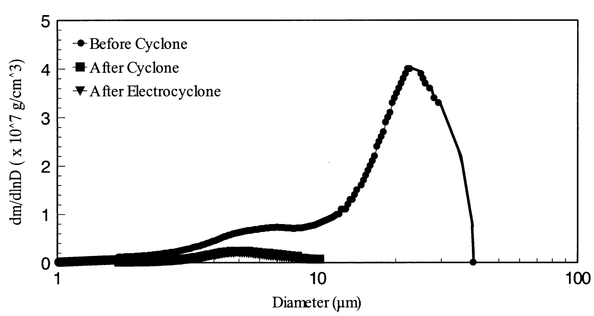

Figure 5. Size distribution of fly ash (Flowrate = 44.26 m^3/min).

Because of very high resolution of the PCSV, the size distribution exhibits almost a smooth curve. The size distribution upstream of the cyclone is denoted by “Before Cyclone,” downstream is denoted by “After Cyclone,” and after applying an electric field of high voltage is denoted by “After Electrocyclone.” At the low flow rate, as shown in Fig. 3, the concentration of “After Cyclone” is quite high and very close to the concentration of “Before Cyclone” for the smaller particles. In contrast to “After Cyclone,” the concentration “After Electrocyclone” is very low for all of the particle sizes. It means that the grade efficiency of the electrocyclone is very high at the low flow rate. As the flow rate is increased, the concentration “After Cyclone” decreases but “After Electrocyclone” increases. At the highest flow rate, as shown in Fig. 5, the particle size distribution curve of the cyclone is very close to that of the electrocyclone.

Grade Efficiency of Cyclone and Electrocyclone

The grade efficiency of the cyclone at various flow rates and particle sizes are calculated based on the size distribution obtained from Figs. 3 to 5 by the following equation:

$$\eta = 1 - C_{out}/C_{in}$$

where η is the grade efficiency of the cyclone, C_{out} is the concentration downstream of the cyclone, and C_{in} is the concentration upstream of the cyclone. The same method is also suitable for the grade efficiency calculation of the electrocyclone. The calculated results are shown in Figs. 6 to 8. An increase in particle grade efficiency has been obtained with the electric field applied within the studied range of the flow rates in comparison with the zero-current conditions. The results show that the grade efficiency is increased as the particle size increases for both the cyclone and the electrocyclone. The grade efficiency of the electrocy-

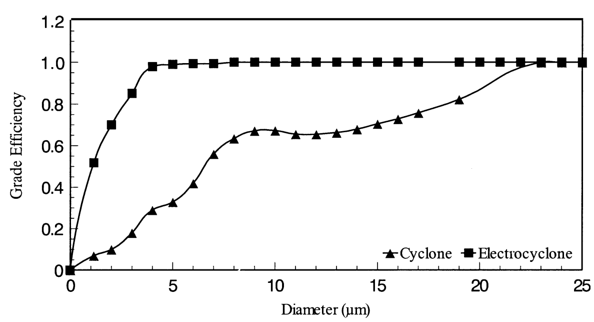

Figure 6. Grade efficiency of cyclone and electrocyclone (Flowrate = 15.75 m^3/min).

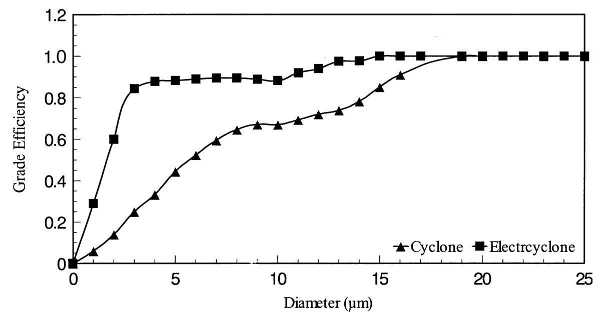

Figure 7. Grade efficiency of cyclone and electrocyclone (Flowrate = 28.75 m^3/min).

clone is larger than that of the cyclone at every particle size and every flow rate due to the applied electric field of high voltage.

Centrifugal and Electric Components of the Particle Radial Velocity

In order to compare the effect of the electric force and the centrifugal force on the grade efficiency of the electrocyclone, the electric migration velocity and the terminal velocity caused by the electric forces and the centrifugal forces should be given. The electric migration velocity is calculated based on Eq. (5), and the terminal velocity is calculated based on Eq. (6). At the low flow rate, as shown in Fig. 9, the electric migration velocity is much larger than the terminal velocity. As the flow rate is increased to 28.75 m^3/min, Fig. 10 shows that the migration velocity is larger than the terminal velocity at the particle size smaller than 5 μm.

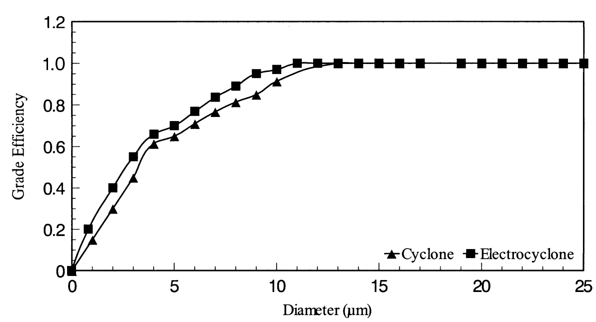

Figure 8. Grade efficiency of cyclone and electrocyclone (Flowrate = 44.26 m^3/min).

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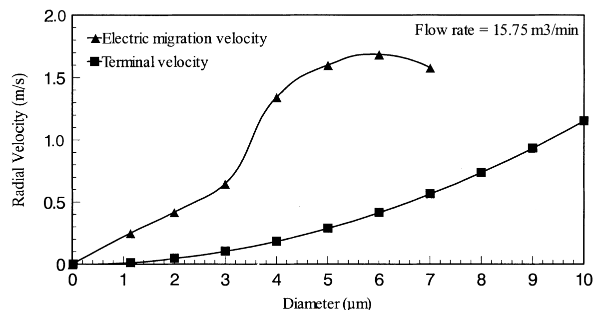

Figure 9. Centrifugal and electric components of particle radial velocity (Flowrate = 15.75 m^3/min).

The terminal velocity is larger than the migration velocity at the particle size bigger than 5 µm, and the difference is increased as the particle size increases. At the highest flow rate, as shown in Fig. 11, the terminal velocity is larger than the migration velocity at every particle size, and the difference is increased as the particle size increases.

Effect of Electric Field on Grade Efficiency

The effect of the electric field on grade efficiency can be obtained by comparing the grade efficiency of the electrocyclone to that of the cyclone at various particle sizes and flow rates. At the low flow rate, as shown in Fig. 9, the electric migration velocity is much larger than the terminal velocity. Figure 6 shows that

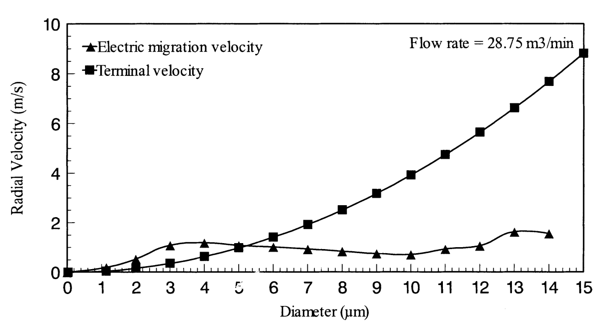

Figure 10. Centrifugal and electric components of particle radial velocity (Flowrate = 28.75 m^3/min).

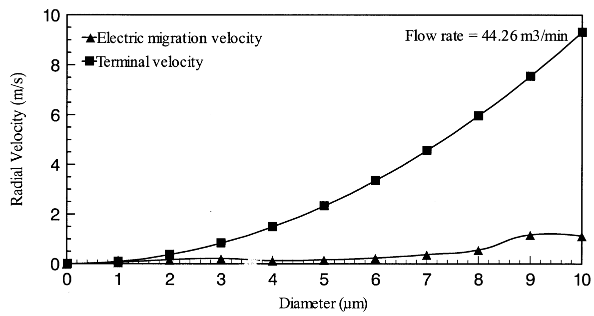

Figure 11. Centrifugal and electric components of particle radial velocity (Flowrate = 44.26 m^3/min).

the grade efficiency of the electrocyclone is larger than that of the cyclone, especially at the particle size smaller than 10 μm. It can be concluded that the electric force on the grade efficiency is dramatic, and the electric force dominates the fly ash removal mechanism at the low flow rate.

Figure 10 shows that the terminal velocity at the flow rate of 28.75 m^3/min is larger than that of 15.75 m^3/min, but the electric migration velocity is smaller. Thus, the grade efficiency of the cyclone is increased, but the synthesis effect of the electric forces and the centrifugal forces causes a decrease in the grade efficiency of the electrocyclone. As shown in Fig. 7, the difference of the grade efficiency between the cyclone and the electrocyclone at the flow rate of 28.75 m^3/min is smaller than that of 15.75 m^3/min in Fig. 6. It can be concluded that the electric forces on the grade efficiency are decreased, but the centrifugal forces are increased as the flow rate increases. There is less improvement effect on the grade efficiency at the flow rate of 28.75 m^3/min.

At the highest flow rate of 44.26 m^3/min, as shown in Fig. 11, the terminal velocity is much larger than the electric migration velocity. The difference between the electric migration velocity and the terminal velocity is increased as the particle size increases. The grade efficiency of the cyclone is further increased, but the synthesis effect of the electric forces and the centrifugal forces results in a decrease in the grade efficiency of the electrocyclone. As shown in Fig. 8, the grade efficiency curves of the cyclone and the electrocyclone are very close. Additionally, the residence time of the particles in the electrocyclone becomes shorter (0.0264 s) at the highest flow rate. This causes the particles to not have enough time to carry the electric charges to enhance the efficiency. Thus, we can conclude that the centrifugal forces on the grade efficiency of the electrocyclone dominate the fly ash removal mechanism and the contribution of the electric forces is small at the highest flow rate.

Effect of Particle Size on Grade Efficiency

An increasing efficiency of the particle size is shown in Figs. 6 to 8 when applying an electric field of high voltage. The grade efficiency of the electrocyclone is larger than that of the cyclone, especially for the particle size smaller than 10 μm because the centrifugal forces of the small particles are small based on Eq. (6) and there is a large space for improving by an electric field. As the particle size increases, the difference in the grade efficiency between the cyclone and the electrocyclone is decreased because the bigger particles have the larger centrifugal forces as well as the larger efficiency. There is less space for improving by the electric forces. Thus, the difference in the grade efficiency between the cyclone and the electrocyclone is decreased as the particle size increases.

CONCLUSIONS

This study investigates the improvement effect on the grade efficiency of a cyclone by applying an electric field of high voltage. The results presented in this paper indicate that a significant effect of an external electric field on the grade efficiency in a cyclone. At the low flow rate, the grade efficiency of the electrocyclone is much larger than that of the cyclone because the electric migration velocity is much larger than the terminal velocity. The improvement effect is decreased as the flow rate increases because of the decreased electric migration velocity and the increased terminal velocity. At the highest flow rate, the grade efficiency of the cyclone and the electrocyclone is very close. Therefore, the particle removal mechanism of the electrocyclone is dominated by the electric forces at the low flow rate and dominated by the centrifugal forces at the high flow rate.

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