Application of a pressurized electrostatic precipitator for control of submicrometer particles

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Abstract This study was focused on examining the effect of high pressure on the performance of a wire-cylinder electrostatic precipitator (ESP). To investigate ionization process in pressurized ESP, the relationship between current (*I*) and voltage (*V*) was characterized using air as the feed gas under different gas pressures. High pressure was experimentally proven to suppress corona inception. Removal efficiencies of NaCl particles and fly ash particles over a submicrometer size range were measured under different gas pressures. It is concluded that current can be lower as a result of higher pressure under similar voltages and remarkably impairs the ESP performance, while voltage tends to be higher as pressure rises under controlled current. How the pressure affects the removal efficiency is also greatly dependent on charging status of the inflow particles.

Keywords: Submicrometer particles, Fly Ash, High Pressure, Electrostatic Precipitator

1. Introduction

Advanced coal technologies, such as gasification, pressurized fluidized bed combustion, and pressurized oxy-combustion have been gradually accepted to be prospective next generation energy generation processes because of their relatively high efficiency and potential benefits in CO_2 capture. The popularity of these pressurized techniques encourages the development of associated pollution control technologies under high pressure. In the meantime, severe haze pollution issues in some developing countries are shifting research focus more on controlling submicrometer particles, which are substantially reported to be harmful to human respiratory health [1]. Electrostatic precipitators (ESPs) have been widely utilized in industrial particle control for over half a century due to their nearly 100% removal efficiency of particles in flue gas and economical feasibility. Nevertheless, there is few studies on how the ESPs would perform in terms of capturing submicrometer particles if they were connected to pressurized coal conversion systems and operated under pressure over 1 atm. Although corona discharge in the ESP was reported to be experimentally generated over atmospheric pressure [2] and mass removal efficiency of particles has been experimentally evaluated [3], there is little knowledge about how the pressure change affects the removal efficiency of particles, especially of those submicrometer particles, which do not contribute to the total mass of the particles but are intractable as well as hazardous.

In this study, fundamental experiments on current-voltage characteristics of a lab-scale ESP under high pressures was performed and the removal efficiencies of submicrometer particles generated by an aerosol generator and a drop-tube coal combustor in the ESP were evaluated by using a state-of-the-art particle sizer.

2. Experimental system and design

The lab-scale ESP is a wire-cylinder type ESP as shown in Figure 1.

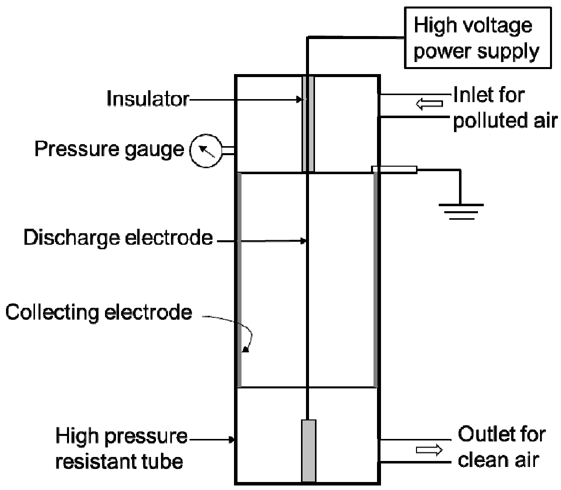


Figure 1. Schematic drawing of the wire-cylinder type ESP

The collecting electrode is made of stainless steel, 0.254 m in height and 0.048 m in diameter. The central conductive wire is made of stainless steel and 0.3 mm in diameter. The high pressure environment was created by setting up a nozzle at the outlet. Pressure tolerance test for the ESP showed that the pressure inside the cylinder can reach up to 10 bar. The high voltage was provided by a Bertan power supply (Model 230-20R, Spellman, Hauppauge, New York, USA).

The experimental setup and design of different experimental sets are illustrated in Figure 2.

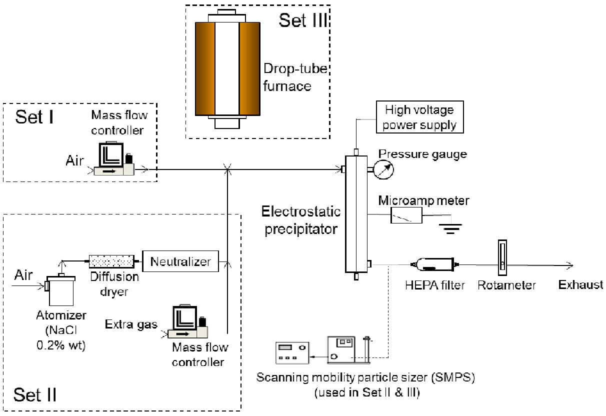


Figure 2. Experimental setup and illustration of experimental design (set I, II & III are three separate experiments)

First, the current-voltage characteristics using air as feed of the ESP was tested under high pressure by using a microamp meter (Model 17424, Simpson Electric, Lac du Flambeau, Wisconsin, USA). Next, the particle size distributions of NaCl particles generated by an atomizer (Model 3076, TSI Inc., Shoreview, Minnesota, USA) upstream and downstream the pressurized ESP were measured by using a scanning mobility particle sizer (SMPS, Model 3080, TSI Inc., Shoreview, Minnesota, USA). With the size distributions, the removal efficiency (η) of particles in discrete sizes can be determined by

$$\eta = 1 - p = \frac{N_{off}}{N_{on}}, \qquad (1)$$

where p is particle penetration, N_{off} is number concentration downstream the ESP when the ESP is offline and N_{on} is number concentration downstream the ESP when the ESP is online. In experimental set III, the removal efficiency of particles in real flue gas generated by a drop-tube furnace, whose configuration was elaborated in previous relevant papers [4, 5], was evaluated by the same SMPS. The coal burned in the furnace is Powder River Basin (PRB) coal. The coal feed rate is 1.5 g/h and the temperature is 1100°C. It should be noted that both two types of particles, NaCl and fly ash, flew through a Po-210 radioactive neutralizer to obtain the same known charge distribution. Table 1 summarizes the detail of the objectives and parameters of each experimental sets.

3. Results and Discussion

3.1. Current-voltage characteristics of the pressurized ESP

The current-voltage characteristics of the ESP with positive and negative applied voltages under 1, 2 and 3 atm are shown in Figure 3. It can be seen that for all the six cases, the electrode-to-electrode current within the ESP increases rapidly once the corona discharge was established. Under the same current, a stronger corona inception voltage is needed as gas pressure becomes higher for both positive and negative voltages. Theoretically, in a negative ESP, electrical breakdown depends on the likelihood of electrons accelerating to ionizing energies in the space of a mean free path under the force of electric field. When pressure rises, the mean free path of the gas decreases, which provides less space for electrons to freely migrate till the ionizing threshold speed is reached. That is, it is more unlikely for molecules to be ionized under the same voltage. This assumption is consistent with the monitored results presented in Figure 3. Therefore, high gas pressure suppresses the corona discharge under the same current.

Table 1. Summary of conducted experiments

Set	Inflow composition	Pressure (atm)	Flowrate (LPM)	Objective
I	Air	1, 2, 3	15	Test current-voltage characteristic
II	Air, NaCl particles	1, 1.5, 2, 2.5, 3	15	Measure removal efficiency of NaCl particles
III	Flue gas (containing particles)	1, 2, 3	25	Measure removal efficiency of fly ash particles

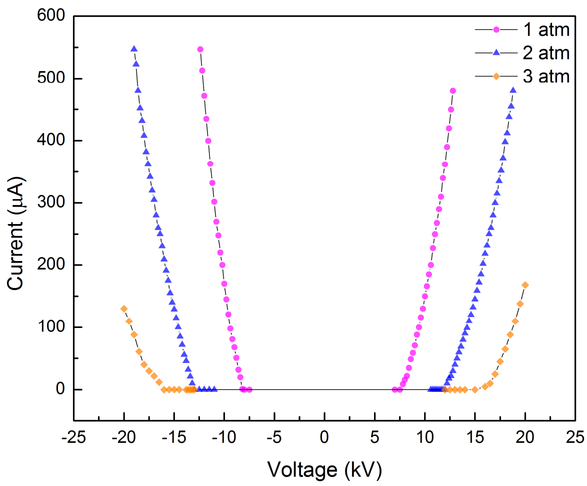
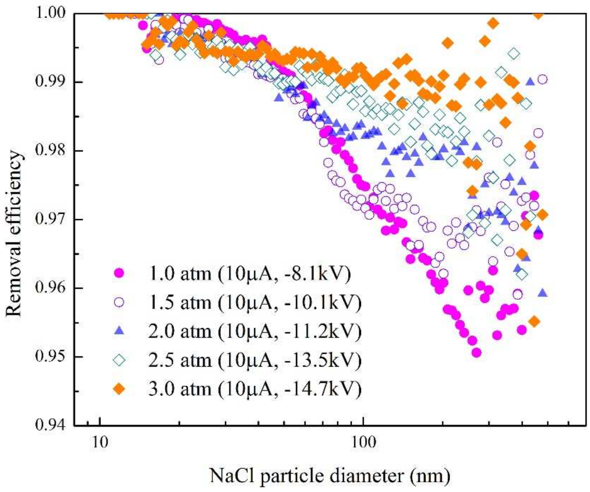


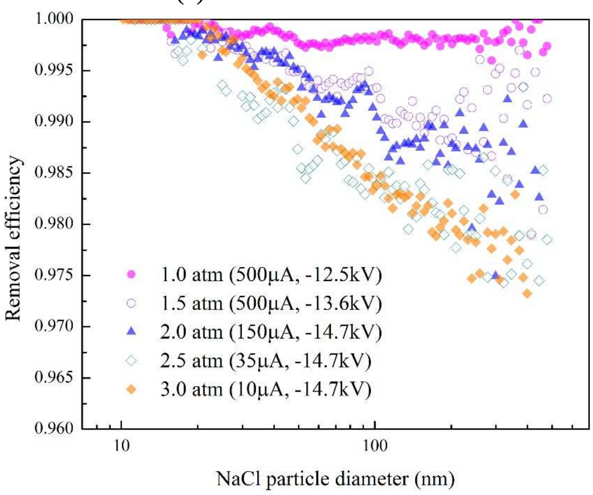
Figure 3. Current-voltage characteristics of the pressurized ESP with positive and negative applied voltages

3.2. Capture of the NaCl particles using the pressurized ESP

In order to evaluate the removal efficiency of submicrometer particles in the pressurized ESP, NaCl particles with air was used as feed in the ESP and the particle number concentrations of different sizes was measured under 1, 1.5, 2, 2.5 and 3 atm. Since voltage is one of the most important operation parameter of the ESP, the influence of pressure on the applied voltage was first studied under a constant current. It can be concluded from Figure 4(a) that for most of the particles in various sizes, the removal efficiency of the ESP increases as the gas pressure varies from 1 atm to 3 atm and corona voltage is raised up at the same time. It can be inferred that although current stays the same, the increasing voltage, or saying electric field, enhances the radial migration of the particles and thus let them be more easily collected on the collecting electrode. Fig. 4(b) shows the comparison among removal efficiencies under different pressures with voltage controlled at approximately the same level. Since the current is an indicator of ion concentration inside the ESP, this comparison can illustrate the impact of changing pressure on the ion concentration. For the experiment under 1 and 1.5 atm, the voltage cannot be reached to –14.7 kV because the measuring upper limit of current is 500 μA. It is indicated from Fig. 4(b) that the removal efficiency of the ESP is reduced as a result of rising pressure. This phenomenon might be primarily induced by lower ion concentration because the ionizing process is hinder by increasing pressure under unchanged voltage.



(a) Current controlled



(b) Voltage controlled

Figure 4. Removal efficiency of NaCl particles in ESP under different pressures

Another observation from the removal efficiency size distribution curves is that in the concerned size range from 15 nm to 450 nm, the removal efficiency decreases as particle diameter increases. It might be explained by that large particles tend to have lower electrical mobility than small particles [6]. This conclusion can be more clearly illustrated by the following electrical mobility equation, which is derived based on Stokes' law [7]:

$$Z = \frac{neC_c}{3\pi\mu d_p}, \qquad (2)$$

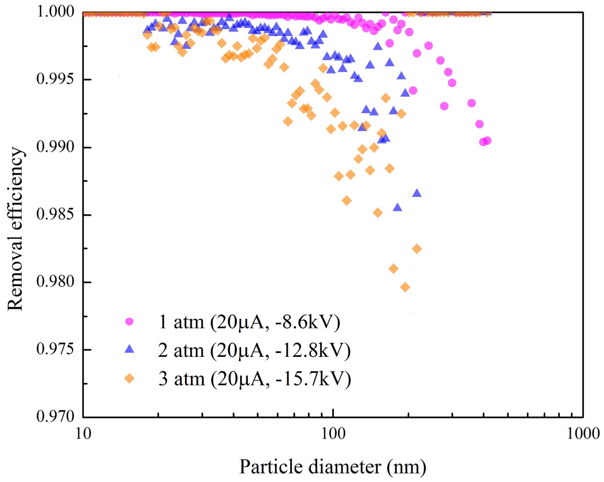
where Z is electrical mobility, n is number of elementary charges on the particle, e is elementary charge, C_c is Cunningham correction factor, η is dynamic viscosity of air and d_p is diameter of particle. As indicated by Eq. (2), when the charge number is fixed, particle in larger diameter will have smaller electrical mobility, which leads to slower radial migration to the collecting electrode and thus lower removal efficiency.

3.3. Capture of the fly ash particles using the pressurized ESP

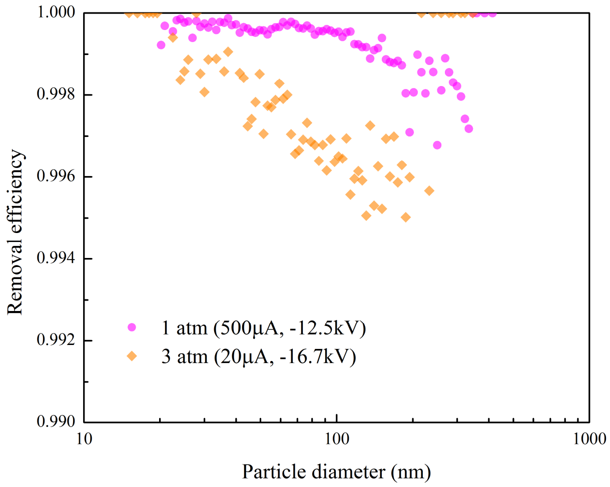
Apart from using single component particles, real fly ash particles produced by coal combustion were also used in assessing the practical performance of the pressurized ESP. Figure 5 summarizes the two types of comparisons among different pressure conditions.

As suggested in Figure 5(a), the removal efficiency for three pressure conditions still increases with particle diameter, but in a relatively shorter range than in NaCl cases. Particles with larger sizes seem to be completely removed. Based on the electrical mobility equation, it is reasonable to believe that some larger particles may catch more charges than in NaCl cases and gain higher electrical mobility. Comparing the removal efficiencies of particles in diameters lower than 120 nm under different pressure conditions, it can be observed that higher pressure still results in higher voltage but does not lead to higher removal efficiency. It is hypothesized that positive charges dominate on these relatively small particles so that their migration towards the collecting electrode is actually inhibited by enhancing voltage under higher pressure.

Figure 5(b) shows the removal efficiencies of particles in most of the sizes are higher when the current is high under 1 atm. This result is consistent with the trend obtained from Figure 4(b), which again proves that the current, indicating ion concentration, is a strong factor affecting the removal efficiency. In practice, the removal efficiency of submicrometer particles will significantly drop as pressure rises if the voltage is not enhanced.



(a) Current controlled



(b) Voltage controlled

Figure 5. Removal efficiency of fly ash particles in ESP under different pressures

4. Conclusion

From the observations and discussions of the experimental results, it can be implied that pressure influences the performance of the ESP in two types of pattern by affecting current and voltage, respectively.

When current is kept constant, the pressure increase will be associated with voltage increase, which reflects the fact that the gas inside the ESP is much harder to be ionized. In the meantime, higher voltage facilitates the radial migration of particles and results in higher removal efficiency. However, the charging status probably plays a more dominating role in determining the removal efficiency of the particles. Further investigation into charging status of fly ash particles and its effect on the ESP performance is definitely needed.

If voltage is controlled approximately at the same level, the ionization effect can be substantially inhibited by increasing pressure. In this case, the removal efficiency is primarily dependent on the current.

Acknowledgement

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