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Study on the Performance of Wet Electroscrubber in Purifying Airborne Particles

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ABSTRACT

Background: In this study, an electroscrubber was designed and experimented for evaluation of integrating particle and droplet charging effects separately and jointly on collection efficiency of a spray tower and also to discover the optimal condition.

Methods: A homogenous concentration of relatively fine particles was introduced to influent air stream and electroscrubber efficiency in purifying them was determined through the measurement of input and output particles concentration. The effect of various conditions such as particles and droplets charging alone and together (bipolar) for several applied voltages has been studied.

Results: In all of experiments, the applied charging voltage has a key role in promotion of electroscrubber efficiency. Maximum collection efficiency has achieved for 15 Kilovolt (Kv). The effectiveness of bipolar charging of particles and droplets with 15 Kv was higher than that of no-charging and singly charging. In other words, efficiency can be increased from 84.43% to 93.22 for total particles and from 50.8% to 75.16% for submicron particles. The maximum improvement of collection efficiency (42.2%) relates to bipolar charging of the initial size group with diameter smaller than 0.3 micrometer (µm) and the minimum (0.5%) to sizing group of 11 with diameter 4-5 µm.

Conclusion: This approach can be an appropriate option for the purpose of purifying submicron particles in spray tower scrubbers.

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Introduction

Air borne particles that are produced and emitted from natural and artificial sources such as industries and industrial processes are one of the main components of air pollutants. As an environmental problem, may cause adverse effect on exposed people. The smaller particles, especially those with the aerodynamic diameter less than 2.5 µm ($PM_{2.5}$) are of particular importance, because they are not easy to settle after emission from the source and can spread to farther distances. $PM_{2.5}$ (fine particles) and PM_1 (submicron particles) has a greater health risk compared to coarse particles because more of them pass from upper and middle sections of respiratory tract and diffuse to pulmonary alveolar[1,2].

Various industrial equipments and processes such as crushing, grinding, screening, filling, combustion and packing can produce and emit fine particles into workplace and environment. Considering the adverse effects of these particles, different air pollutant cleaning devices or collectors have been designed for particle collection. The coarse particle can be removed easily by most of the collectors, but only some of them are appropriate for $PM_{2.5}$ and submicron removing. Initially applied for cleaning gas house pollutants from exited air, Scrubber is one of the collectors which have been used for particulate collection. The collection efficiency of scrubbers is high for particles with diameter of 5-10 µm and larger[3-5]. This higher collection efficiency for large particles was sufficient with respect to older environmental regulation but with new environmental legislations, the efficiency of the sescrubbers, especially that of the spray towers is in sufficient. Various options have been proposed in order to resolve this problem. The first option is applying collectors with high capital, operation or maintenance costs such as electrostatic precipitators, bag filters and venture

scrubbers. Another approach is integrating various dust collection mechanisms. These collectors are some times called hybrid collectors[6]. Integrating electrical charging with scrubbers is one of these methods[7]. Several types of wet scrubbers equipped with charging mechanisms have been developed including Electrohydrodynamic Venturi, Electrodynactor System, Charged Droplet Scrubber, Booster Scrubberand Ionizing Wet Scrubber[8]. Droplets were acted as an attractive electrical target that due to a few distances between them and particles, high electrostatic force is created. This electrostatic attraction helps to impaction of particles to droplet sand subsequently increases the collection efficiency. Higher collection efficiency is obtained if the particle sanddropletsarechargedwithoppositecharge[9,10]. Wet scrubber with augmented electrostatically charged has reported by several researchers[11,12,13]. The electrostatic fractional collection efficiency (η_c) of a single spherical charged drop for particles charged to the opposite polarity was described by Kraemmer's equation[14,15]:

$$\eta_c = \frac{4C_c q_p q_d}{3\pi^2 \mu_g D_d^2 U_d \varepsilon_0} \quad (1)$$

Where: Cc is the particle Cunningham Slip Correction factor; q_p is the particle charge; q_d is droplet charge, µg is the gas viscosity. D_d is the relative droplet velocity to the gas and ε0 is vacuum permittivity.

The charge induced on a droplet, q_d, depends on the electrical charging system and can be considered as a fraction of the so-called Rayleigh limit, q_R, which is the highest electrical charge that can be present on a droplet of a given diameter, D_d, with out making it unstable and eventually tearing it apart. The value of q_R is calculated by[16]:

$$q_R = 2\pi\sqrt{2\varepsilon_0 \Gamma_w D_d^3} \quad (2)$$

Where: Γ_w is the droplet surface tension

For the same collection efficiency, the electroscrubber has a less water and energy consumption and lower pressure loss compared with that of other types of scrubbers. Considering that most of the scrubbers have little efficiency for particles sized 0.1-1 µm, it is possible to increase the efficiency to 60-90% with electroscrubber[17].

The purpose of this study was the evaluation of integrating particle and droplet charging effects separately and jointly on collection efficiency of a spray tower and also to discover the optimal condition.

Methods

Electroscrubber Setup

Figure 1 illustrates the laboratory pilot scale set designed according for this study. Uniform concentration of relatively fine cement particles with concentration about 2500 mg/m3 during experiments period was produced and injected to pipe with a diameter of 5 centimeter by amodified Wright Dust Feeder[18]. Negative suction air flow rate of about 170 actual cubic meters per hour (m^3/hr) was supplied by a centrifugal fan. The collection efficiency of collector has been determined for several modes, including scrubber performance without electrical charging, particles electrical charging alone, droplets charging alone, and particles and droplets charging simultaneously with opposite charge (bipolar). Several voltages were used for droplet and particles' charging. Experiments were repeated three times for each of the scenarios, and the results were averaged. Particle charging system consisted of a direct current (DC) power supply connected to a wire electrode inside the pipe. The charge, the voltage and the amperage of external DC power were adjustable. In addition voltage and current meters were readable by a digital displayer embedded on the DC power supply. The potential difference across the resistance was measured to determination of consumed current to air volume for several voltages. The charged particles were injected to a wet scrubber. The used wet scrubber was a cylindrical spray tower with a diameter of 30 cm and height of 75 cm. The body of the spray tower has been constructed by plexiglass. Wet scrubber was equipped to an isolated water supply, pumping and spraying equipments. Water was supplied by a polyethylene tank connected to a centrifugal pump by non conductive polyvinylchloride (PVC) piping. The pump was electrically isolated from electromotor by a Teflon shaft. Pump and electromotor were mounted on a Teflon plate for isolation from earth. Furthermore, water was transferred to spray nozzle by PVC tubing. A valve and a pressure manometer were installed for adjusting and reading the water flow rate and the pressure. A wire electrode connected to a DC supply power (similar to a used system for particle charging) was used inside of the pipe near the spray nozzles for water charging. This device was also adjustable for voltage and amperage. The liquid charge to the mass ratio for several applied voltages wasdeterminedby[11]:

$$\frac{q}{m}, \left(\frac{\text{columb}}{\text{gm}}\right) = \frac{(\Sigma\, I,\text{amp})(t,\text{sec})}{(V,\text{mL})(\rho,\text{gm/mL})} \quad (3)$$

Four Teflon whirl nozzles were used in order to spray fine droplets into a wet scrubber. A multi layer plastic mesh pad was installed at the scrubber air outlet for removing water excited mists.

Measurements

The number and concentration of particles at influent and effluent air of the scrubber was measured by the Grimme 1.08 dust counter. All of the measurements were carried out under a condition of isokinetic sampling of particles inside the duct[19]. In order to cover all the cases studied, a total of 78 experiments were conducted. A special probe was inserted into the duct For Isokinetic sampling via embedded ports, and the airborne particles were suctioned by dust counter pump. This dust counter was displayed of measurements as partial and total mass

and number concentrations. The experimental removal efficiency of dust collector (E) was calculated by:

$$E_{(\%)} = \frac{C_i - C_o}{C_i} \times 100 \quad (4)$$

Where C_i is the influent particle's concentration and C_o is effluent particle's concentration.

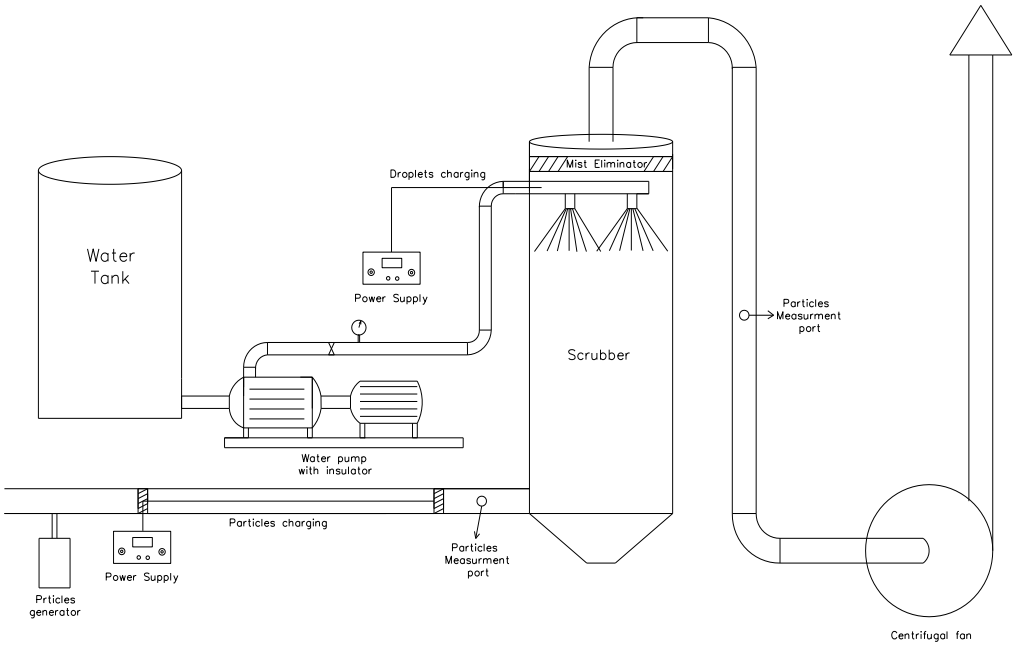

Figure 1: Wet electroscrubber setup

With respect to the study objectives, removal efficiency was determined for several induction voltages for particles and droplets charging individually and together. Tukey and *t*-test statistical methods are used to determine effectiveness of particles and droplets charging on electroscrubber' collection efficiency.

Results

Size Grouping

Grimme 1.08 dust counter could be detected for sampled airborne particles at 16 separate channels with respect to aerodynamic diameters. In order to facilitate the exhibition of results, particles were categorized based on their sizes (Table 1). According to the collector efficiencies measured in various situations of experiments, no significant difference was observed for particles larger than 5 µm; hence the results for these particles were ignored.

No-charging

Measurement of introduced and exited particle's concentrations from the scrubber, free of charging, showed the effectiveness of a scrubber for all size groups (P<0.01). The collection efficiency of the scrubber for large particles is higher than the submicron particles, so that the collection efficiency for particles with dp=1 µm reached 90%, while it decreased to <50% for dp<0.65 µm.

Particles charging

Consumption power of particle's electrical charging for various applied voltages is shown in Figure 2. This illustration helps better capture the effect of particles charging on scrubber collection efficiency.

The effect of particle's electrical charging on collection efficiency of the scrubber for various size groups is presented in Figure 3.

Table 1: Size grouping of measured particle diameter ranges

Group size	Particles diameter (µm)
1	0.00-0.30
2	0.31-0.40
3	0.41-0.50
4	0.51-0.65
5	0.66-0.80
6	0.81-1.00
7	1.01-1.60
8	1.61-2.00
9	2.01-3.00
10	3.01-4.00
11	4.01-5.00

Droplets charging

Effect of applied voltage on liquid to the mass ratio of droplet is plotted in Figure 4. The value of this ratio is very low for charging voltage of 2 Kv, but by increasing the voltage to 5 Kv, this ratio also slightly increases. The liquid charge to the mass ratio was amplified for charging voltage higher than 5 Kv so that the value of this rate has been enhanced from 1.68×10-2 microcolumb/g for 5 Kv to 0.084 and 0.144 microcolumb/g for charging voltages of 10 and 15 Kv, respectively.

Effect of droplet's electrical charging on collection efficiency of the scrubber for various size groups of particles is presented in Figure 5. Droplet charging can be effectively advertising collection efficiency for submicron particles (first 6 size groups).

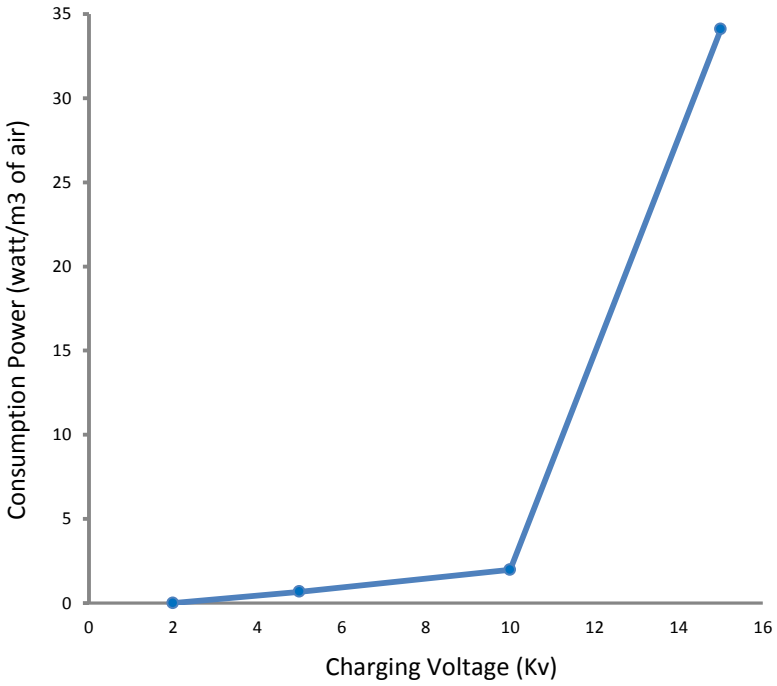

Figure 2: Relationship between applied voltage for particles charging and consumption power per air volume

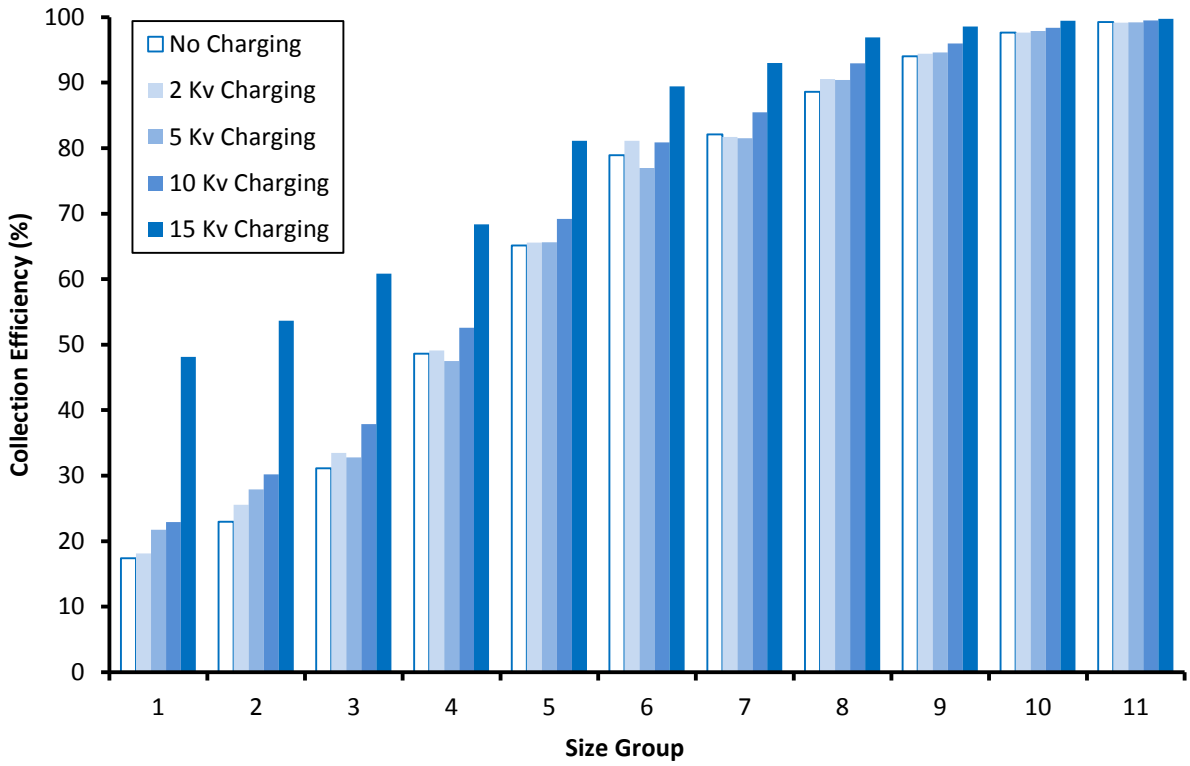

Figure 3: Effect of particle electrical charging on partial collection efficiency

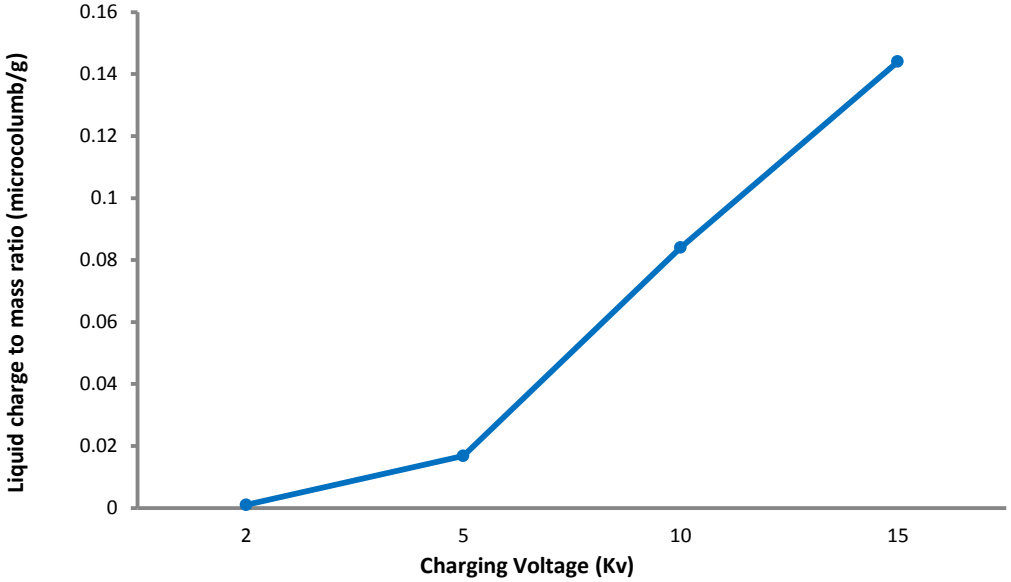

Figure 4: Relation of applied liquid charging voltage to mass ratio

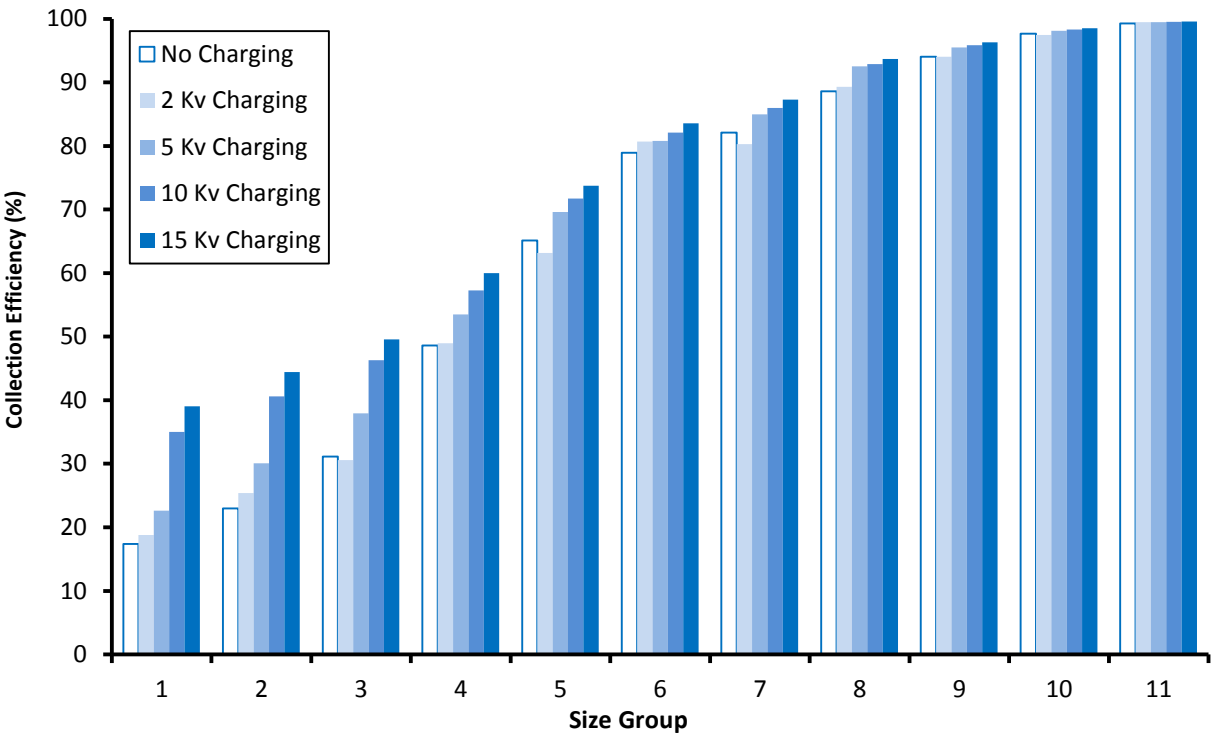

Figure 5: Effect of droplets electrical charging on partial collection efficiency

Bipolar charging

The effect of bipolar charging of particles and droplets on scrubbers' collection efficiency is illustrated in Figure 6. Simultaneously charging particles and droplets has a more efficiency compared to individual charging. Results showed that bipolar charging with 5 Kv, 10 Kv and 15 Kv, had a significant effect on scrubbers' performance for the first five size groups (d<0.8 µm), while in command of particles charging alone, only collection efficiency for the initial size group and responsible of droplets independently, collection efficiency of the first 3 size group had significantly been affected. Moreover, increase in the collection efficiency for bipolar charging was more than that for individual charging. Through bipolar charging with 15 Kv, Collection efficiency for the 3 preliminary size groups increased by 42.2%, 39.9% and 34.5% respectively in contrasted to No-charging state. The initial size group had the maximum improvement of collection efficiency (i.e. 42.2%) with 15 Kv of bipolar charging, and the minimum was that of the sizing group of 11 by 0.5%.

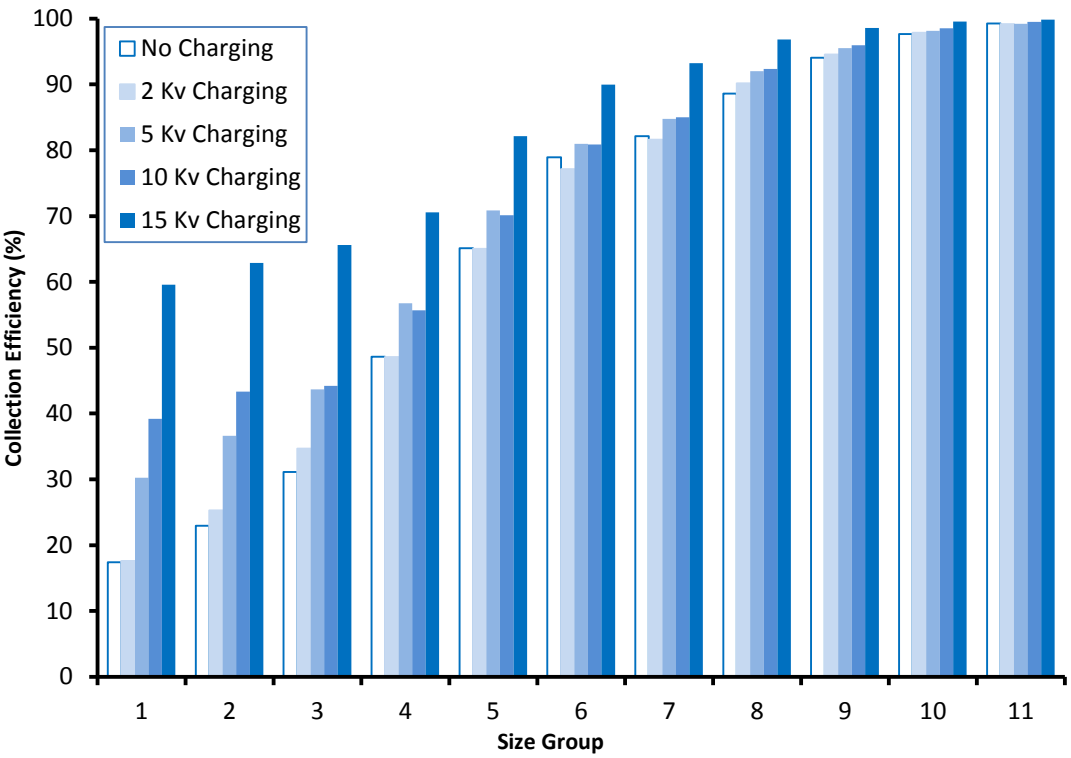

Figure 6: Effect of bipolar particles and droplets electrical charging on partial collection efficiency

Total collection efficiency

Figures 7-A and 7-B present variations of scrubbers' total collection efficiency for particles with diameters smaller than 5 µm and 1 µm by various charging scenarios. As can be seen in both figures, applied charging the 2 Kv has no significant effect on total collection efficiency for all of states. For 2 Kv to 10 Kv charging voltages, total collection efficiency was significantly promoted, with bipolar, droplet and particles charging having the highest improvement. For 10 to 15 kv charging voltages, particles' charging has a higher impact comparison with droplets' charging. The other important result is related to different levels of efficiency increase for two distinct particle ranges, i.e. total collection efficiency by bipolar charging with 15 kv was promoted from 84.43% to 93.22% (less than 9%) for particles with diameter ≤5µm whereas the promotion was from 50.8% to 75.16% (more than 24%) for particles with diameter ≤1µm.

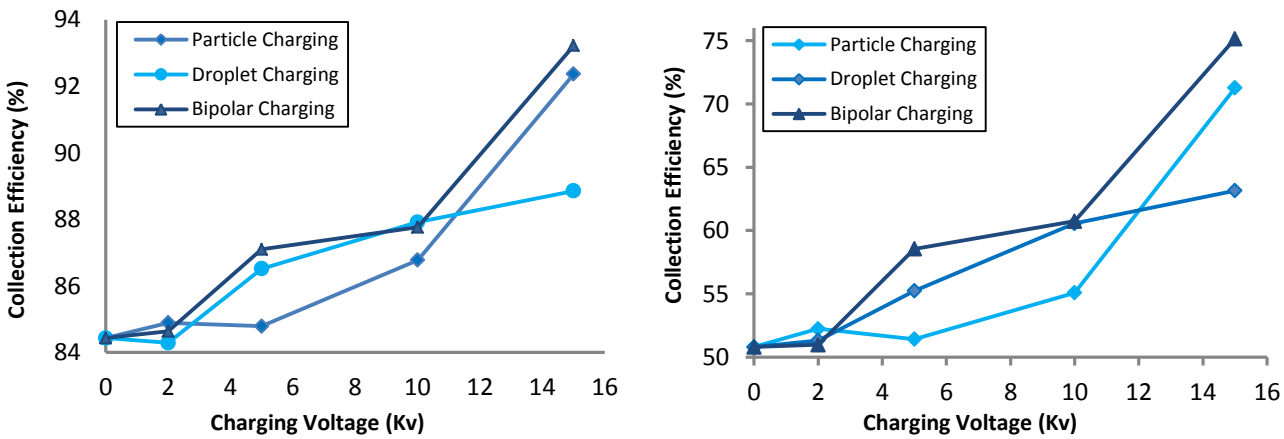

Figure 7: Effect of various charging scenarios on total collection efficiency for particles with A (left): diameters ≤5µm and B (right): diameters ≤1µm

Discussion

Spray tower scrubbers without particles or droplet charging has greater collection efficiency for larger particles. The main reason for this situation is relate to direct effect of inertial impaction mechanism on collection efficiency to particles diameter[3,20]. Particles or droplets charging can be helpful option for compensate the low

collection efficiency of scrubber for smaller particles. Before study of the effect of particles' charging on efficiency, power consumption for various voltages was surveyed. As shown from Fig-2, the rate of power consumption per volume of air increase with a slight slope, until the voltage increase to 10 Kv. With the voltage exceeding 10 Kv; a sudden increase of consumption power is observed in a way that with a voltage change from 10 Kv to 15 Kv, power consumption rises from 1.978 to 34.08 watt/m^3 of air. This might be due to small inlet of air pipe to the scrubber that charging electrode is located in its center. Selection of a larger pipe could reduce the air velocity and lead to particles settling in the inlet pipe.

Charging the introduced particles to the scrubber has a positive effect on collection efficiency for all particle size groups (Figure 3). This result is consistent with the study of Balachandran et al.[9] and Pilat et al.[11]. As can be seen in this figure, the effect of several voltages on efficiency was not identical, so that, despite promotion, the amount of efficiency for 2 Kv applied voltage was negligible and statistically not significant (P=0.202). In addition, applying 5Kv, the increase in collection efficiency was statistically significant only for the first two size groups (P<0.001) and not significant for other size groups, as well as for total collection efficiency. 10Kv and 15 Kv charging of particles had significant effects for collection efficiency of 7 size groups and all size groups respectively. In addition, influent particles' charging with 10 and 15 Kv significantly increased the total collection efficiency (P<0.05). Applying 15 Kv for particles charging, the collection efficiency of the scrubber was significantly increased especially for smaller particles. The increase in collection efficiency for the first three groups (with diameters less than 0.5 µm) was about 30 and 20% in comparison to no-charging and 10 Kv charging of particles, respectively. Furthermore, Collection efficiency of the scrubber was significantly improved for particle size groups of 4 to 8 by applying the 15 Kv voltages. The improvement ranged from 8.3% for size group of 8 to 19.8% for size group of 4 compared to the state of No-charging.

With respect to the findings of this study, 10 Kv can be considered as a boundary voltage for effective particle charging. The significant effect of higher voltages on collection efficiency is related to producing high energy and high speed free electron from discharge electrode. Higher energy and speeds produced more gaseous ions, resulting in more particles charging (Field charging). Moreover, higher voltage can be more effective for charging the fine particles via diffusion charging and electron charging in addition to field charging. Fine particles have a smaller surface, and with fewer gaseous ions or electron being saturated, they charge better and faster[11,16] .

The results of droplets charging for collection efficiency improvement are similar to those of particles' charging. Droplets' charging has a more effect for fine particles' collection. This event can be attributed to the higher number of fine particles than coarse ones. Accordingly fine particles require less columbic force for overcoming drag force and moving and impacting droplets[8,17,21].

As shown at Figure 5, charging voltages less than 5 Kv has a negligible effect on all size groups' collection efficiency promotion but charging droplet with voltages of 10 and 15 Kv, significantly increases the collection efficiency. The minimum promotions of submicron collection efficiency was 3.2% for size group of 6 through 10 Kv charging state, and the maximum was 21.6% for size group of 1 by applying 15 Kv droplet charging voltage.

Simultaneously charged particles and droplets (with opposite charge) had a higher effect on partial and total collection efficiency than individually charged one. This result was in line with previous studies[21,22,23]. Bipolar charging by virtue of equation 1 can be increased to columbic force and electrical attraction of its. Bipolar charging with 2 Kv and 5 Kv caused a statically significant increase in the collection efficiency of size groups one and nine respectively (P<0.05). Applying 10 and 15 Kv bipolar charging; all groups attained collection efficiency improvement.

Effects of various charging scenarios on total collection efficiency for particles are presented in figures 7-A and 7-B to evaluate a more comprehensive charging effect on total collection efficiency of submicrons particles (dp <1 µm) and total particles. As it can be seen in these figures, all charging scenarios are more effective for submicron particles compared with total particles. Three issues cause this phenomenon. The first is more agglomeration of submicron particles in the spray tower. This can be increased of particle size, and large particles are removed effectively by the scrubber. The second is more charge effect on submicron particles and easily polarized of them[24]. Third is that submicron particles are less influenced by inertial impaction and interception mechanisms[3,4,20] and so electrical charging can be more effective for collection. Particles charging was significantly effective than droplets charging for >10 Kv charging, while for applied voltages of ≤10 Kv, droplet's charging was slightly more effective.

Conclusion

Electrical charging of particles and droplets, especially as simultaneously with opposite charge, is an appropriate option for promoting the efficiency of submicron particles' collection in spray tower scrubbers. Electroscrubber can be a more cost-effective design for submicron airborne particle's collection.

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Conflict of interest statement

The authors have no conflict of interests to declare.

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