Humidification Effect on Inactivation of *Staphylococcus aureus* in an Electrostatic Precipitator

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Abstract—This study is aimed at inactivating microorganisms collected by a two-stage type electrostatic precipitator. The experimental system consisted of a discharging section and an electrostatic section. The discharging section consisted of a wire and plates. The electrostatic section had a parallel-plates configuration. A bacterial culture of *Staphylococcus aureus*, as a model of airborne microorganisms, was put on the surface of grounded plate electrodes in the discharging and electrostatic sections. Negative DC high voltage was applied to the discharging section to generate negative corona discharge for inactivation. DC -5 kV was applied to the electrostatic section, and reactive oxygen species (ROS) generated by the discharging section was used for inactivation. The applied voltage to the discharging section was controlled between DC -8.5 kV and -9.5 kV to adjust ozone concentration to approximately 1ppm, which was one of ROS. The gas flow velocity in the experimental system was 0.5 m/s. The relative humidity (RH) in the gas was controlled between 5% and 95% using a humidifier.

The result showed that inactivation effect in the discharging section was greater than that in the electrostatic section. Inactivation effect was improved by humidification. Effects both discharging and electrostatic sections are significantly improved by humidification. The survival decreased with increasing relative humidity; it is desirable to increase RH to 60% or higher by humidification.

Keywords—Inactivation, electrostatic precipitator, *Staphylococcus aureus*, corona discharge, humidification

I. INTRODUCTION

Electrostatic Precipitators (ESPs) have been extensively used for the cleaning of industrial process flue gases, combustion flue gases and ventilation flue gases for road tunnels, etc. A home air cleaner is also one application of ESP. Such air cleaners must be capable of eliminating and inactivating airborne microorganisms to improve indoor air quality. It is known that microorganisms are inactivated by non-thermal plasma [1], [2]. An ESP using corona discharge is expected to be effective for such purposes.

Botvinnik et al. reported an experimental result carried out to investigate an elimination effect of *Serratia marcescens* in the air using ESP [3]. The microorganism concentration was measured using the fifth stage of an Anderson six-stage impactor. As a result, colonies on the Petri dishes decreased with ESP-operation time. Takimoto et al. suggested a bacteria collection system using negative ions and ozone with mist formation in an ESP [4]. They reported that airborne microorganisms were collected on a collection electrode and collected microorganisms were inactivated in the ESP. As for the effects of corona discharge, several experiments were carried out. Mizuno et al. showed the case of sterilizing *S. cerevisiae* and *B. subtilis* spores on an electric filter using DC corona discharge [5]. Okubo et al. also showed an inactivation effect on *E. coli* by corona discharge plasma jet [6]. Tanimura et al. reported that negative ions and ozone generated by corona discharge are effective for sterilizing *E. coli* [7]. Timoshkin et al. reported inactivation effects of negative and positive corona discharge [8]. The inactivation mechanism of corona discharge was also studied. Mizuno et al. reported that φX174 phage was inactivated as a result of the degradation of coat protein [9]. Ohshima et al. showed that the cell-surface and DNA of *S. epidermidis* on a plate electrode was damaged due to corona discharge [10].

There are many literatures describing the inactivation with ozone gas. It is known that survival ratios of *B. subtilis* and *S. aureus* are proportional to *CT* [ppm-min], which is the product of ozone concentration *C* and exposure time *T* [11], [12]. It was reported to need 50 or 60ppm-min at the ozone concentration between 60 and 65% for inactivating *S. aureus* [12], [13].

The aim of this study is to investigate the inactivation characteristic, and to improve the effect of inactivating microorganisms collected on a plate electrode in an ESP. The influence of the location of collection, ozone concentration, elapsed time and relative humidity (RH) on inactivation of microorganisms was experimentally investigated. The ESP had a two-stage structure of discharging and electrostatic sections. A bacterial culture of *Staphylococcus aureus*, which was used as a model of airborne microorganisms, was applied to the surface of grounded plate electrodes in the discharging and electrostatic sections. Negative DC high voltages were applied to both sections, and ozone generated by the discharging section was used for inactivation. The applied voltage to the discharging section was controlled to vary ozone concentration between 0.06 and 5ppm. The gas flow velocity was 0.5 m/s. The relative humidity (RH) in the gas was controlled between 5% and 95% using a humidifier.
II. METHODOLOGY

The schematic diagrams of experimental ESP systems are shown in Fig. 1. Two types of ESPs were used for experiments, and placed in a clean bench. Type A was used to investigate the influences of ozone concentration, location of collection and elapsed time. It has a parallel-plate electrode structure composed of a high-voltage application electrode (70×160 mm) sandwiched between grounded plate electrodes (70×270 mm) with a gap of 10 mm. The high-voltage application electrode has a sawtooth edge on its upstream side, while the grounded electrodes have no such edges. All electrodes are made of stainless steel with a thickness of 0.8 mm. A solution of bacterial culture of Staphylococcus aureus (NBRC13276, 10⁴ CFU) diluted with saline was put at four locations on the surface of one grounded plate electrode to simulate collected microorganisms. The locations were 6 mm upstream from the tip of the sawtooth edge (Location A1), as well as 40, 80 and 120 mm downstream from the tip (Location A2-A4). A control was located at 185 mm on the upstream side to except natural decrement of the microorganisms. In the preliminary experiment, it was obtained that the survival on the control decreased by approximately 6% for 60 min at RH between 60 and 65% due to natural decrement. The gas flow velocity was adjusted to 0.5 m/s by a fan located on the downstream side of the ESP. The high-voltage application electrode was supplied with DC voltage to generate negative corona discharge and electrostatic field. The applied DC voltage was changed between -6.2 kV and -10 kV to vary ozone concentration in the gas flow between 0.06 ppm and 5 ppm. The microorganisms put on those locations were inactivated by corona discharge or ozone. The experiments were carried out under room temperature and normal humidity.

Type B was used to investigate the influence of relative humidity (RH), location of collection and elapsed time. It has a two-stage structure of discharging and electrostatic sections. The discharging section has a wire-and-plates configuration composed of a high-voltage application wire electrode (ø: 0.45 mm, L: 70 mm, SUS304) placed between grounded plate electrodes (70×270 mm) with a gap of 10 mm. The electrostatic section has a parallel-plate electrode structure composed of a high-voltage application electrode (70×174 mm) sandwiched between grounded plate electrodes (70×174 mm) with a gap of 10 mm. All plate electrodes are made of stainless steel with a thickness of 0.8 mm. Six samples of the bacterial culture (10⁴ CFU) were put on two grounded plate electrodes 40, 80, 120, 160, 185 and 270 mm downstream from the tip (Location B1-B6). The control was located at 70 mm upstream from the grounded electrode in the discharging section. The discharging section was supplied with DC voltage of -8.5 to -9.5 kV to generate negative corona discharge, whereby the discharge current was adjusted to 0.024 mA, which ozone concentration was approximately 1 ppm. The electrostatic section was supplied with DC voltage of -5 kV to form an electrostatic field. RH was controlled between 5% and 95% by a heating type humidifier with pure or tap water. The gas temperature was between 20°C and 30°C.

The operating time was a maximum of 8 hours. After the operation, S. aureus on the electrode was wiped using RASPER CHECK™, which was a wiping swab, and then incubated for 24 hours. The survival \( \eta \) defined as Eq. (1), or the survival ratio \( \log(N/N_0) \) were calculated from the colony counts.

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\eta = \frac{N}{N_0} \times 100 \% \tag{1}
\]

where \( N \) and \( N_0 \) are the colony counts at each location on the grounded electrodes and the control, respectively.

III. RESULTS AND DISCUSSION

A. Influence of ozone concentration and elapsed time

Influence of ozone concentration and elapsed time was measured using the type-A apparatus. The relationship between survival and ozone concentration for an operating time of 1 hour is shown in Fig. 2. A survival ratio less than 100% means inactivation, while a ratio greater than 100% means an increased number of microorganisms. Survival at Location A1 was 78% at an ozone concentration of 0.06 ppm, which decreased with increasing ozone concentration, to be eventually stabilized at the levels between 12% and 21%. Survivals at Locations A2, A3 and A4 were between 126% and 136% at an ozone concentration of 0.06 ppm, which tended to decrease with increasing ozone concentration. However, the value was between 59% and 95% within the range from 3 ppm...
Fig. 2. The relationship between survival and ozone concentration (Apparatus: type A. Operation time: 1 hour).

Fig. 3. The influence of elapsed time on survival at ozone concentration of 1ppm (Apparatus: type A).

to 5ppm and the inactivation effect was barely improved with increasing ozone concentration by 1 hour operation.

The influence of the elapsed time on the survival at an ozone concentration of 1ppm is shown in Fig. 3. The survival at Location A1 tended to decrease with time, reaching 12% at 8 h. The survivals on Location A2, A3 and A4 decreased with time, which reached between 30% and 35% at 8 h.

These results demonstrate that the inactivation effect in the discharging section is greater than in the electrostatic section due to radicals other than ozone, and it takes more than 8 hours to inactivate microorganisms on the electrode by ozone with a concentration of 1ppm.

B. Effect of humidification

Inactivation effect of corona discharge was confirmed in Figs. 2 and 3. However, it is necessary to more quickly inactivate microorganisms. Therefore, the effect of humidification on inactivation was investigated using the type-B apparatus at an ozone concentration of 1ppm, and for 60 min. The relationship between survival and elapsed time for the six locations with RH between 20 and 75% is shown in Fig. 4. This is the result obtained without the humidifier. In Fig. 4(a), the survival at Location B1 in the discharging section at elapsed time of 60 min was 98%, which barely changed for 60 min, because radicals barely reach the upstream side of the wire electrode. The survivals at B2 and B3 gradually decreased with time, reaching 28% and 33% at 60 min. In Fig. 4(b), the survivals at B4, B5 and B6 in the electrostatic section were greater than 100% for 30 min after the operation began. Corona discharge may also have enhancement effect of microorganism. Further study is needed to investigate this phenomena. In elapsed time between 30 and 60 min, the survivals tended to decrease, reaching 82%. However, this result indicates that it is difficult to quickly inactivate microorganisms by only ozone, as has already been shown in Fig. 2.

The relationship between survival and elapsed time for the six locations with RH between 75% and 95% is shown in Fig. 5. This is the result obtained using the humidifier with pure water. In Fig. 5(a), the result at Location B1 on the upstream side of the wire electrode in the discharging section significantly fluctuated, whereas the survivals at B2 and B3 immediately decreased after the operation began. The survivals at B2 and B3 reached 27% and 11% after 10 minutes of operation, while those without the humidifier were 81% after 10 minutes of operation as shown in Fig. 4(a). In Fig. 5(b),
the survivals at any locations in the electrostatic section also significantly decreased with time. The survivals at B4, B5 and B6 achieved the levels between 16% and 23% after 10 minutes of operation, while the values achieved without the humidifier were between 122% and 170% at the same operation time as shown in Fig. 4(b).

From these results, it is clear that the inactivation effects both discharging and electrostatic sections are significantly improved by humidification. This is most likely due to the fact that the ROS is held in the moisture on microorganisms’ surface.

C. Characteristic of inactivation effect in relation to RH

The survival ratio as a function of RH in the discharging section is shown in Fig. 6. Pure water was used for humidification with RH greater than 75%, the operation time was 60 minutes, and the discharge current was adjusted to 0.024 mA which the ozone concentration was 1ppm. The survival ratio at Location B1 was almost constant when RH was between 5% and 60%, which increased at RH greater than 60%. The reason for this increase needs to be studied in the future. The ratios at Location B2 and B3 at RH less than 60% barely changed. However, those at RH greater than 60% decreased with increasing RH. Survivals decreased by three orders of magnitude at RH greater than 85%, which is a significant improvement in inactivation effect.

The survival ratio as a function of RH in the electrostatic section is shown in Fig. 7. The experimental condition is the same with Fig. 6. No significant decrease in the survival ratio was observed at RH less than 60%, while the ratio at any location decreased when RH was greater than 60%. Some data obtained at RH of 85% or greater were lower than the initial level by two or more orders of magnitude.

These results show that RH should desirably be increased to 60% or higher by humidification to improve the inactivation effect, and to 85% or higher to achieve high values.

In practical applications of this system, tap water is more readily available than pure water for humidification. Thus, the effect of tap water was confirmed. The comparison of inactivation effect between pure water and tap water is shown in Fig. 8. This is the result obtained using the type-B apparatus at ozone concentration of 1ppm for 1 hour operation, with RH between 75% and 95%. The values indicated are average ratios, and the error bar represents the standard deviation. In Fig. 8(a), the survival ratio obtained with humidification by tap water at each location in the discharging section is equal to or
lower than that by pure water. In Fig. 8(b), the survival ratio obtained with humidification by tap water at each location in the electrostatic section is also lower than that by pure water. These results show that tap water can be similarly used instead of pure water to improve the inactivation effect by humidification.

IV. CONCLUSION

In this study, we investigated the influence of the location of collection, ozone concentration, elapsed time and relative humidity (RH) on inactivation of microorganisms collected on electrodes in an ESP. Results are as follows:

1) Inactivation effect in the discharging section is greater than that in the electrostatic section due to radicals other than ozone.
2) Inactivation effects in the discharging and the electrostatic sections are significantly improved by humidification.
3) The survival decreased with increasing relative humidity; it is desirable to increase RH to 60% or higher by humidification.
4) Tap water can be used instead of pure water to improve inactivation effect by humidification.

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