

# Experimental investigation of integrated air purifying technology for bioaerosol removal and inactivation in central air-conditioning system

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**Abstract** In this research, high voltage static electricity and ultraviolet technologies were integrated to an air purifying device which can be used to trap and kill airborne bacteria and viruses in central air-conditioning systems. An experimental platform was built to mimic the central air system, in which the efficacy of the newly built device was examined. In addition to the standard physical and chemical tests, bacteriophages were used to simulate airborne viruses in the experimental system. The bacteriophage suspension was aerosolized into the air with ultrasonic wave atomization. The result showed that more than 86% removal efficiency of micro-particles (<10 micron in diameter) were removed after the device was in operation in a building and more than 95% of bacteriophages in the experimental system. It is concluded that the integrated air purifier is suitable for controlling air quality and preventing virus transmission through the central air system.

**Keywords:** high voltage static electric field, ultraviolet ray, bacteriophages, central air-conditioning platform.

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Since the winter of 2002, severe acute respiratory syndrome (SARS) affected nearly 40 countries in all the continents, resulting in 812 deaths by July 1, 2003 as reported by World Health Organization (WHO)<sup>[1,1,2]</sup>. Some research indicated that the SARS virus was predominantly spread by liquid droplets, and/or by direct and indirect close contact<sup>[2]</sup>. The central air-conditioning system has been considered as a probable means of SARS transmission in hospitals or office buildings. International scientific community has been in the forefront of fighting

against SARS in discovering the means of SARS transmission and searching for effective ways of prevention<sup>[3–5]</sup>. Fresh air circulation can dilute the virus concentration inside a room and was found effective in preventing virus spread. But it cannot completely eliminate the SARS virus from an air conditioned environment. Thus, it is necessary to trap and kill bacteria and viruses in the central air conditioning system.

In this work, a central air purifying device was developed by integrating high voltage static electric field and ultraviolet irradiation technologies. An experimental platform simulating central air-conditioning system was built to perform some physical and chemical tests of the device. Further, one bacteriophage strain JD-II-3 isolated from the environment was used as a viral simulant to examine the efficiency of the device for bioaerosol removal and inactivation.

## 1 Experimental studies

(i) Test system. This test system consists of an experimental chamber of 15 m<sup>3</sup>, a test section and an air-conditioning section including an ultrasonic humidifier, a finned tube heater, a finned tube heat exchanger and a fan.

Fig. 1 shows the schematic of the whole system which is completely sealed. Air flow is uniform and re-circulated from the chamber to the test section, and then the air-conditioning section. Air change per hour (ACH) can be adjusted with the speed of the fan. The rest section could be easily replaced by any kind of air

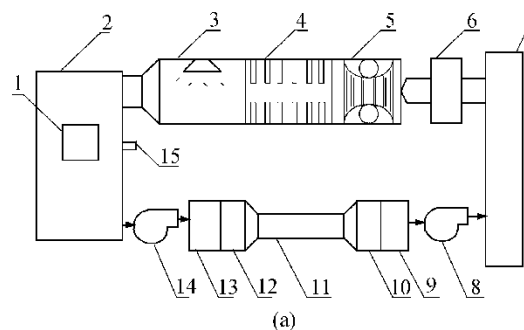


Fig. 1. Test system. (a) Experimental flowchart. 1, Window; 2, small chamber; 3, humidifier; 4, finned tube heater; 5, finned tube exchanger; 6, air-conditioning processing section; 7, wind pipe; 8 and 14, fan; 9 and 13, test chamber; 10 and 12, test section; 11, working section; 15, sampling pore. (b) Experimental system picture.

1) <http://www.who.int/csr/sars/en/>

2) <http://cmbi.bjmu.edu.cn/cmbidata/sars/index.htm>

purifying device and used to examine the dust-cleaning and bacteria-killing efficiency of the device by circulating micro-particles and bacteriophages in the system. Furthermore, the micro-environment (i.e. temperature, relative humidity, etc.) can be adjusted in the system to investigate the climate effect on the virus sensitivity, infectivity, and transmissivity.

(ii) Integrated air purifier. Fig. 2 shows the integrated air purifier installed in the test section. It was built by integrating high voltage static electric field, ultraviolet ray, composite silver electrodes, and an active carbon fiber filter. Large particles can be first filtrated by active carbon fibers. Small particles and virus aerosols are mainly polarized and trapped by high voltage static electrical field. The silver electric plates of 10000 V high voltage together with ultraviolet ray completely kill the trapped bacteria and viruses within minutes. Upon binding onto the bacteria cell membrane, silver ion can penetrate and react with sulfhydryl (-SH) to damage the cell synzyme activity, leading to cell death<sup>[6,7]</sup>. But the silver ion does not react on mammal cells because of the totally different cell membrane structure. The major emission band of the C waveband ultraviolet light is around 254 nm wavelength which is mainly adsorbed by nucleoprotein (>80%). When the nucleic acid absorbs high-frequency ultraviolet waves, the chemical bond of the nucleic acid molecule would be damaged, resulting in abnormal decompose or denaturalization to cause death of bacteria and viruses.

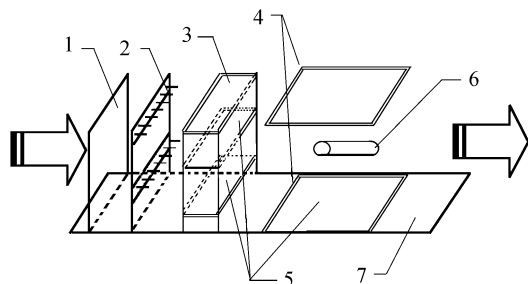


Fig. 2. The schematic of hybrid air purifier in air-conditioning system. 1, Active carbon fiber film; 2, needle negative-high voltage ionized electrode; 3, positive voltage adsorption electrode; 4, high voltage plate electrode; 5, silvering conduction film; 6, ultraviolet light; 7, basement.

## 2 Measurements

(i) Bacteriophage as a viral simulant for SARS and other airborne viruses. Bacteriophages are the viruses of bacteria and they have specific host range, one phage strain only infects a limited number of strains in one bacterial species. They do not infect animals or human beings. It is thus safe to use bacteriophage as viral simulant in the place of SARS or other severe animal or human viruses<sup>[8]</sup>. The amount of the viral simulant particles in the air can be collected and measured for plaque formation units per sample by using a double layer plating technique.

Four phage strains named JD-II-1, JD-II-2, JD-II-3 and JD-II-4 were isolated from an aquatic sample by using

*E. coli* MG1655 as the host strain. Resistance to environmental extremes including temperature and dryness was tested for all the four phage strains. Table 1 shows that the resistance of JD-II-3 to both temperature and dryness was superior to SARS CoV virus. This provides a basis for using this particular phage strain as a viral simulant in place of SARS CoV and other airborne viruses in the tests for evaluation of bioaerosol removal and inactivation by different types of air purifiers.

Table 1 Bacteriophage survival rate after treatment under different environmental conditions<sup>a)</sup>

Conditions	JD-II-1	JD-II-2	JD-II-3	JD-II-4
50°C for 15 min	70%	50%	90%	20%
60°C for 15 min	40%	30%	50%	10%
70°C for 15 min	0	5%	10%	0
24 h on dried surface	10%	10%	10%	10%
Disinfectant 84	0	0	0	0

a) The initial bacteriophage titer was  $5 \times 10^9$  pfu/mL. The data were expressed as the percentage of phage particles survived from the treatments.

(ii) Bioaerosol generating and sampling technique for the viral simulant. It is a key technology in this research to disseminate the bacteriophage stock culture in the air to simulate the virus aerosol caused by actions such as sneezing. Ultrasonic humidifier was used to evaporate the phage suspension to create the bioaerosol of the viral simulant. The bacteriophage suspension was aerosolized into the air with ultrasonic wave atomization. Aerosolization velocity was measured by quantifying the mass difference of the suspension before and after atomization per unit time. The effects of viral concentration, ion strength and viscosity of the viral suspension on aerosolization speed were also measured in this work.

No significant differences were found between the aerosolization speed of pure water and viral suspension containing different ratios of culture medium (between 0.1%—10%). The aerosolization speed remained constant at  $4.84 \pm 0.13$  mL/min with all the tested variables. No significant impact on viability of the phage particles was observed with repeated and lengthened treatment under ultrasonic wave in the humidifier.

The bacteriophage particles were collected by using a semisolid plate via the impaction of the airflow at 2 m/s in the test tube. Gelatin is viscous and becomes liquid after incubation at 37°C for 30 min. Three kinds of gelatin plates were prepared for testing their sampling efficiency of airborne phage particles. The MP plate contained 3% of gelatin. Ten milliliter 3% gelatin was added on LB plate to compose GLB double layer plate. The GSM double layer plate was constituted with 1.8% agar as bottom layer and 3% gelatin in SM buffer solution as top. The 9 centimeter diameter plates were arranged at different sites horizontally or tilted toward the incoming airflow to collect phage

## ARTICLES

aerosol.

(iii) Testing the dust-cleaning efficiency of the integrated air purifier. The particle generation source, such as mosquito-repellent incense, was ignited in the experimental chamber at the beginning of the experiment and closed until the  $PM_{10}$  concentration measured by the TSI DustTrak monitor reached a preset value. The humidity was controlled around 50%. The air was circulated through the system and the chamber temperature was controlled by the air-conditioning section. All experiments were performed at a constant air velocity of 2 m/s, a constant temperature of 25°C. The deposition of particles onto the inner surfaces of the system were researched by measuring the  $PM_{10}$  concentration in the center of the experimental test chamber with respect to time, to establish the baseline measurement. Then, the  $PM_{10}$  concentration was measured with the air purifier at 10000 V voltage in operation under the same condition.

(iv) Testing the sterilizing efficiency of the integrated air purifier. The ultrasonic humidifier containing bacteriophage suspension generated homogeneous bacteriophage droplets into recycling airflow. The GSM plates were used to collect bacteriophage particles in the airflow at the beginning and end site in the test tube with airflow at 2 m/s for 1 min. Each test repeated 3 times. The plates containing bacteriophage were incubated at 37°C for 1 h to melt the gelatin. All the liquid was transferred to a centrifuge tube. 1 mL of the phage liquid was mixed well with 0.5 mL of the host bacterial suspension (at  $OD_{650} \text{ nm} = 1.5$ ). After standing still for 30 min at room temperature, the suspension was mixed with 5 mL melted soft agar and poured quickly onto LB plate. The solidified plates were incubated at 37°C overnight. The number of plaques per plate was recorded to calculate phage particles collected.

### 3 Results and discussion

Fig. 3 shows that the  $PM_{10}$  concentration decreases with time or without the air purifier in the experimental chamber. With the air purifier, the  $PM_{10}$  concentration decreased from 77.6 to 0.5  $\text{mg}/\text{m}^3$  following an exponential decay over one-hour period while it took more than 5 h to reach the same level via natural deposition. To simplify the analysis, it is reasonable to assume that the air is fully mixed and the particulate concentration is uniform inside the test chamber. The air purifier has a filter system capable of trapping and retaining 71.35% to 99.36% of all mono-dispersed particles of 10 micrometers or less in diameter<sup>1)</sup> when the effect of deposition, resuspension and

adsorption with chamber inner surface are considered. The high concentration smoke particle was extraordinary irritant to eyes and nose of tester. The device helped eliminate the irritating smoke and odor in one hour. The pressure drop of the device meets the standard of a high efficiency filter which is around 126 Pa at 2 m/s wind velocity measured by an inclined tube micronanometer<sup>9,10)</sup>.

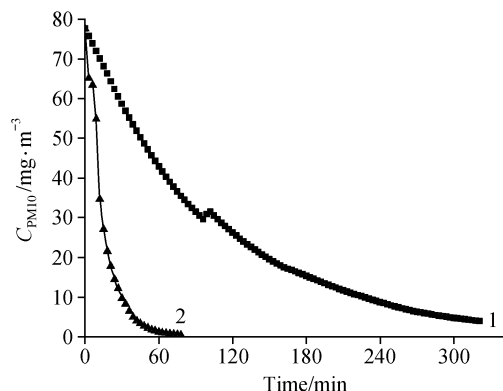


Fig. 3. The  $PM_{10}$  concentration with or without the air purifier. 1, Natural; 2, using hybrid air purifier.

According to the Indoor Air Quality Standard in China GB/T18883-2002<sup>2)</sup>, the ozone in indoor air should be less 0.16  $\text{mg}/\text{m}^3$ . It is possible that the hydroxyl and negative oxygen ion might be ionized from water vapor in air with the high voltage and ultraviolet ray. The ozone density can be tested with ECO ozone monitor. Under the situation of using high voltage static electric field and ultraviolet ray, the ozone density fluctuated from 0.06 to 0.10  $\text{mg}/\text{m}^3$ , while the average ozone density is 0.08  $\text{mg}/\text{m}^3$  using high voltage static field only and 0.06  $\text{mg}/\text{m}^3$  using ultraviolet ray only. Therefore, the air purifier does not introduce the secondary ozone pollution.

Fig. 4(a) shows that the plaques formed on a GSM plate were used to sample the airflow containing phage aerosol generated with a source suspension with  $10^5$  pfu/mL when the integrated air purifier was turned off. More than 100 plaques were formed in one such plate. Shown in Fig. 4(b), less than 5 plaques were found in one plate when the integrated air purifier was turned on. A 95% bioaerosol removal efficiency was thus achieved with the integrated air purifier in action. After the treatment of the integrated air purifier, phage concentration in the airflow was reduced to a minimum. It is very important to assure enough accuracy for phage measurement at such a low concentration. In this experiment, removal rate of bacteriophage solely depended on the high voltage static equipment without active carbon fiber film, and no plaque was detectable when the system coupled with the

1) National Standard of the People's Republic of China, Air Cleaner, GB/T18801-2002.

2) National Standard of the People's Republic of China, Indoor Air Quality Standard, GB/T 18883-2002.

active carbon fiber film. Thus, we need to increase the phage titer at the source suspension to ensure accurate detection of airborne phages.

Fig. 5 shows the phage particles collected from the test tube with the air purifier on or off when the concentrifier was installed in place and turned on. The integrated air purifier reduced airborne viral particles by 2—4 orders of magnitude. It was demonstrated that the aerosol generation and sampling technology used in this work was able to evaluate the performance of the integrated air purifier effectively in a biologically and statistically sound way.



(a) The integrated air purifier on



(a) The integrated air purifier off

Fig. 4. The bacteriophage collected by GSM plates from the test tube under different conditions. (a) With the integrated air purifier off; (b) with the integrated air purifier on.

tration of bacteriophage stock culture in the humidifier was at a titer of  $10^7$  pfu/mL with one minute sampling time. Through the statistic test, the difference of removal efficiency was significant under 0.5% degree of confidence with or without turning the air purifier on. The aerosolization and collection of phage particles were thus reproducible. When the test tube was void of any purifying measures, phage particles collected at the end of the test tube was  $(1.14 \pm 0.85) \times 10^5$  pfu/plate, the number dropped to  $(41.2 \pm 58.5)$  pfu/plate if the integrated air pu-

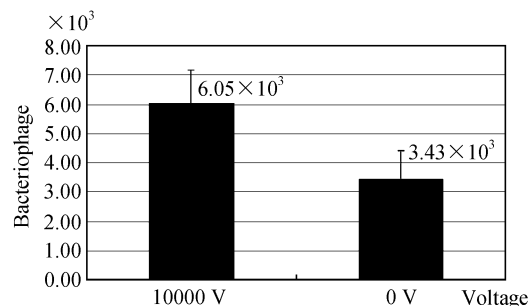


Fig. 5. Removal efficiency of JD-II-3 bacteriophage by the integrated air purifier.

#### 4 Application in office building

The air purifier was also used in the central air-conditioning system of an office building at Shanghai Jiao Tong University and The Sixth People's Hospital of Shanghai. Two supply diffusers were disposed on the right side wall and two exhaust grilles were laid on the upper side wall in the test room of the building. The particle removal efficiency was tested in a low initial concentration with one or two air purifiers installed in the exhaust or without fresh air to avoid the environmental effect. Fig. 6 shows the total average removal efficiency of 86.2% and thus the bacteria removal efficiency is estimated to be more than 96% according to the ASHRAE Applications Handbook<sup>[11]</sup>.

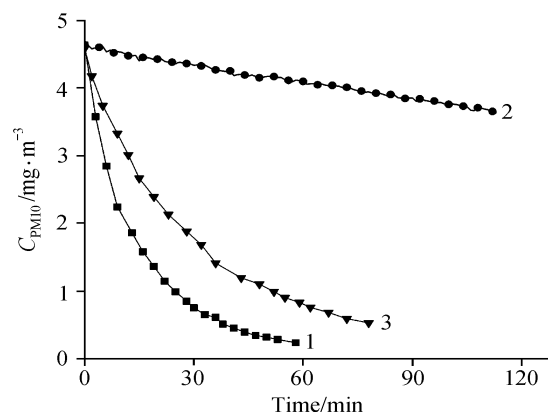


Fig. 6. Removal rate of particles by the air purifier in the central air-conditioning system in an office building. 1, Natural deposition; 2, using one hybrid purifier in one supply diffuse; 3, using two hybrid purifier in two supply diffuse.

In addition to particle removal test, airborne bacteria were also sampled in the experimental room with the integrated air purifier. Two sampling methods were used to collect the airborne bacteria. Depositional sampling was used to sample airborne bacteria by placing culture plates at 5 sites in the room. Impaction sampler was used at 2.5 L/min speed to measure bacteria in per unit volume of the air. The result showed that the bacteria decreased from 6.6 to 3.2 cfu/plate, falling by 51.5% after the integrated air

## ARTICLES

purifier was in action for 90 min. The bacteria collected with the impaction sampler showed a decrease by one to two order of magnitude. This demonstrated a significant effect of the integrated air purifier for cleaning the indoor air in a real world building.

### 5 Conclusions

Based upon the integrated technology of high voltage electric field, ultraviolet ray, composite silver material, and activated carbon fibers, an air purifying device has been developed to prevent airborne bacteria and virus spread through central air-conditioning system. An experimental platform mimicking the central air-conditioning system was built to examine the efficacy of the device. In addition to the physical and chemical tests, bacteriophage was successfully used as a viral simulant in the place of SARS CoV virus to evaluate the viral removal efficiency of the air purifier. It has been demonstrated that the test methods are feasible and that the integrated air purifier has significant removal and inactivation effects both in the laboratory and in real world building. The integrated air purifier holds great promise in prevention of airborne viral transmission and improvement of indoor air quality in the future.

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