Polyimide Surface Dielectric Barrier Discharge for Inactivation of SARS-CoV-2 Trapped in a Polypropylene Melt-Blown Filter

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ABSTRACT: Surface dielectric barrier discharge (SDBD) was used to inactivate the infectious severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) trapped in a polypropylene (PP) melt-blown filter. We used a dielectric barrier made of polyimide films with hexagonal holes through which air flowed. In a cylindrical wind tunnel, the SDBD device supplied reactive oxygen species such as ozone to the SARS-CoV-2 trapped in the PP filter. A plaque assay showed that SDBD at an ozone concentration of approximately 51.6 ppm and exposure time of 30 min induced more than 99.78% reduction for filter-adhered SARS-CoV-2. A carbon catalyst after SDBD effectively reduced ozone exhaust below 0.05 ppm. The combination of SDBD, PP filter, and catalyst could be a promising way to decrease the risk of secondary infection due to indoor air purifiers.

KEYWORDS: severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), surface dielectric barrier discharge (SDBD), ozone reduction catalysts, plaque assays, polypropylene (PP) melt-blown filters

1. INTRODUCTION

The COVID-19 pandemic has highlighted the risk of indoor aerosols spreading infectious diseases.1−3 Researchers have previously reported the transmission of infectious aerosols in hospitals and indoors.4,5 Aerosolized viruses could be infectious for a long time depending on indoor humidity and airflow conditions.6 Ventilation is the best way to exhaust aerosolized viruses. However, the virus has been spread through air duct of ventilation system.7 Thus, the virus capturing and inactivating functions are required for indoor air conditioners.

There are many studies for indoor air conditioners capable of capturing and inactivating viruses. Antiviral membrane filters, ultraviolet (UV) irradiation, and photocatalysts have been applied to air conditioners.9 A representative antiviral membrane filter is a copper-coated filter.9,10 Copper ions oxidize viruses and reduce infectivity.11 Copper-coated poly(ethylene terephthalate) filters effectively trapped aerosolized SARS-CoV-2 and inactivated it by 99% within 30 min.9 Polymer membrane filters are easily applied to indoor air conditioners. However, the antiviral ability could be decreased by accumulating dust on the filter surface and covering the antiviral copper layer.

Ultraviolet germicidal irradiation breaks the virus’s deoxyribonucleic acid (DNA) or ribonucleic acid (RNA) chains. Wavelengths between 200 and 280 nm affect the double-bond stability of adjacent carbon atoms in molecules, including pyrimidines, purines, and flavins. The UV inactivation was attributed to the formation of dimers in the RNA and DNA molecules.12 Viruses are highly UV sensitive, and the log-reduction dose (90% reduction) was approximately 10.6 mJ/cm².13 The log-reduction dose could be satisfied if a virus stays in front of UV lamp. However, a dose of UV irradiation could be insufficient to break the DNA or RNA chains of viruses in air conditioners moving in air flow because the irradiation time is too short due to the fast air speed (>1 m/s). Several lamps could be required for a sufficient UV irradiation dose. Alternatively, UV irradiation on viruses collected on a high-efficiency particulate air (HEPA) filter is possible, but frequent filter replacement is required due to the polymer membrane damage by UV irradiation.

A photocatalytic filter utilizes a reactive oxygen species (ROS) generated on the catalyst surface to inactivate viruses by oxidation.14−17 For example, irradiation with visible or UV light activates the photocatalytic reaction of TiO₂, generating...
ROS such as hydroxyl and superoxide radicals on the surface of TiO₂. Although the hydroxyl radical formed on the surface of catalyst has a short lifetime (on the order of microseconds), it can directly react with the virus trapped on the catalyst, enabling effective virus inactivation. However, aerosols with viruses could pass through a catalyst if a catalyst carrier has pores larger than the size of aerosols and viruses.

Another technique for indoor air purifiers is the low-temperature atmospheric-pressure plasma technique. Low-temperature atmospheric plasma oxidizes viruses by hydroxyl radical and ozone. A typical method of low-temperature plasma generation is corona discharge and dielectric barrier discharge (DBD). A corona discharge generally uses a pin-to-plate discharge method and utilizes the streamer discharge generated at the tip of a sharp pin. The air streamer discharge effectively generates ozone gas. DBD generates low-temperature plasma by placing a dielectric barrier between metal electrodes and applying an alternating voltage. The electric and chemical properties of the dielectric material can control the ozone concentration, and nonthermal or cold plasma devices can be applied to inactivate airborne viruses. In addition, various previous researchers have demonstrated that non-thermal plasma can exhibit antibacterial and antiviral effects on various surfaces. Kramer et al. used DBD with ambient air to disinfect the inside of the ambulance (10 m³). They showed that the reductions of Staphylococcus aureus at least 4 orders of magnitude were observed on all surfaces within 30 min. Bhartiya et al. also applied a DBD device, which exposed approximately 7 ppm of ozone for 4 h, leading to a reduction in viral titer of human coronavirus 229E.

Several improvements are required to apply cold plasma technology to indoor air purifiers for virus inactivation. An ozone concentration of 0.5—20 ppm is required for disinfection. In particular, a filter-type surface plasma device may be advantageous for virus inactivation of the surface of the PP filter installed in the ventilation duct. Also, the ozone concentration emitted after virus inactivation should <0.05 ppm, which is from the standard regulation of Korea air cleaning association. In this study, a plasma device that generates surface DBD (SDBD) on polyimide dielectric film was developed to inactivate the SARS-CoV-2 captured in a polypropylene (PP) melt-blown filter.
The SDBD has been investigated for disinfection and ozone production by controlling the electrode gap and AC voltage waveform. Our plasma device has hexagonal holes to pass air and is attached to the PP filter. A carbon catalyst for ozone removal was combined at the rear end of the filter to fabricate indoor air conditioners inactivating the captured virus.

2. MATERIALS AND METHODS

2.1. SDBD Device for Filter Disinfection. Figure 1 shows the details of the SDBD device and electrical circuit for plasma diagnostic. Figure 1a is the front view of the device with hexagonal holes. Figure 1b is a photo of the plasma generation taken in a dark room. The photo was captured by a CCD camera (canon SD Mark3) with an exposure time of 1 s. Figure 1c is the cross-sectional structure of the SDBD device along the red line shown in Figure 1a. The device was composed of a polyimide film (thickness: 100 μm) dielectric and copper electrodes placed above and below the dielectric. The dimensions of W1, W2, W3, and W4 shown in Figure 1c were 0.25 ± 0.05, 0.3 ± 0.05, 2 ± 0.5, and 8 ± 0.5 mm, respectively. To prevent arcing between electrode 1 and electrode 2 through the side surface of dielectric film, the exposed part of electrode 2 was insulated with a polyimide film, and the W3 was expanded to 2 mm. If the W3 is narrower than 2 mm, surface discharge at the side surface is generated, and it could cause fast degradation of the SDBD device. The surface discharge was focused on the area of mismatched region between electrode 1 and 2. The mismatched length of 0.25 mm was suitable to generate ozone without excessive heat generation by streamer discharge expansion on the PI film.

2.2. SDBD Operation Conditions and Diagnostics. Figure 1d shows the details of the SDBD device operation. A function generator (33220A, Keysight) and an amplifier (HVA4321, NF Corporation) supplied the sinewave voltage, whose maximum voltage and frequency is efficient range to generate air SDBD. The voltage at electrode 2 was 33 ± 20 V, and the voltage and current signals were collected by a digital oscilloscope (DPO3012, Tektronix, Inc.). The emission spectrum from SDBD was collected by a collimating lens (focal length: 10 mm) and analyzed by a spectrometer (Maya2000PRO, Ocean Optics).

2.3. Cylindrical Wind Tunnel for SARS-CoV-2 Aerosol Test. Figure 2 shows a structure of the closed wind tunnel for evaluating the inactivation performance of SDBD devices using aerosolized SARS-CoV-2 captured in a PP melt-blown filter (CNTUS-SUNGJIN Co., Busan, Korea). The wind tunnel is an assembly type with an inner diameter of 7 cm and has a structure in which external air flows into the upper part and is exhausted by a diaphragm pump (DOA-P704-AC, GAST), whose flow rate was 15 L/min. A HEPA filter is installed at the top to prevent unknown particles from entering the enclosed space. An SDBD device is positioned below the nebulizing zone, and the surface on which the plasma is generated faces the sampling filter. The collected virus is exposed to reactive species including ozone generated by the upper SDBD. A carbon catalyst for ozone decomposition is installed under the filter sample, and the ozone concentration was measured by a UV ozone monitor (UV-106Li, 2B Technologies) depending on the presence of a carbon catalyst. At the bottom, a HEPA filter is installed to prevent bioaerosol leakage.

2.4. SARS-CoV-2 Preparation. To propagate and perform viral infectivity assays, Vero 76 cells (CRL-1587; American Type Culture Collection, Manassas, VA) and SARS-CoV-2 (NCCP 43326; National Culture Collection for Pathogens, Cheongju, Korea) were prepared. Vero 76 cells were incubated at 37 °C with 5% CO₂ in Dulbecco’s Modified Eagle Medium (DMEM; Gibco, Waltham, MA). It was supplemented with 10% fetal bovine serum (FBS, Gibco) and 1% penicillin–streptomycin (Gibco). SARS-CoV-2 was added to 80–90% confluency Vero 76 cells and adsorbed at 37 °C for 1 h in a 5% CO₂ incubator. Following adsorption, DMEM containing 2% FBS was added to the cells. The flasks were incubated at 37 °C for 72 h in a 5% CO₂ incubator until cytopathic effects were observed. Virus-containing media were collected after centrifugation at 2000 g for 20 min (Allegra X-15R; Beckman Coulter, Fullerton, CA), and the virus titer was approximately 10⁷ plaque-forming units (PFU)/mL.

2.5. Viral Inactivation Testing Procedure. A SARS-CoV-2 inactivation test was conducted in a biosafety level 3 laboratory. The disinfected PP filter was assembled in a frame. An air pump was operated for a constant air flow in the chamber. SARS-CoV-2 was sprayed by the nebulizer at a flow rate of 320 μL/min for 5 min. The particle size of the aerosols was measured using a scanning mobility particle sizer. Fine aerosol particles (dₐ = 151.2 nm) were generated and sprayed. A diffusion dryer that reduces the moisture of aerosols was not used because the dryer components containing high-risk viruses have operation and maintenance difficulties. The aerosols passed through the SDBD part and were collected in a filter sample.
The distance between the SDBD and filter sample was 2 cm. After nebulization, the collected SARS-CoV-2 was exposed to a reactive oxygen species generated by the SDBD for 30 min. The same conditions without the SDBD were used for a control group. Immediately after treatment, the filter was transferred to a 50 mL tube containing 10 mL of DMEM containing 2% FBS. It was vortexed for 2 min to separate SARS-CoV-2.

2.6. SARS-CoV-2 Plaque Assay. A plaque assay was performed as previously described for directly quantifying infectious viruses. Vero 76 cells were seeded in 6-well plates for 24 h before infection in the presence of viral supernatants for 1 h. The infected cells were washed three times with a phosphate-buffered saline. They were cultured with 1% low-melting-point agarose and 2% FBS-containing DMEM at 37 °C for 72 h in a 5% CO₂ incubator. After aspirating the media from each well, the cells were fixed with 4% paraformaldehyde for 1 h. They were stained with 0.5% crystal violet for 15 min. The number of plaques was observed and expressed as log PFU/cm².

2.7. Durability Test of PP Melt-Blown Filter against Plasma Exposure. To evaluate the durability of the PP filter against long-term (48 h) plasma exposure (ozone concentration × contact time; CT value of 2570 ppm-h), X-ray photoelectron spectroscopy (XPS) signals were measured using a K-ALPHA+XPS System (Thermo Fisher Scientific, UK) equipped with a monochromatic Al Kα X-ray source (1486.6 eV). The surface of PP filter was also observed using a field emission scanning electron microscope (FE-SEM; JSM 7800F, JEOL, Tokyo, Japan) with an accelerating voltage of 5 kV.

3. RESULTS AND DISCUSSION

Figure 3a shows the voltage–current signal at 10 kHz when plasma is generated on an SDBD device. It maintained stable discharge at the maximum voltage of 2 kV without a dielectric breakdown. The device with a polymer dielectric film between the electrodes is a capacitor in an electrical circuit, and the voltage signal has a phase ahead of the current signal by 90°. The spiky conduction current by gas discharge was superimposed on the displacement current. Regions a and b in Figure 3a show different conduction current profiles. Two types of discharge have been observed in the SDBD: streamer discharge and microdischarge, which is called two-phase discharge. Two-phase discharge has positive and negative phases. In the positive phase, electrode 1 exposed to the atmosphere acts as an anode. In the negative phase, electrode 1 acts as a cathode. Streamer discharge is observed in the positive phase, and microdischarge is observed in the negative phase. In Figure 3b, streamer discharge is the bright filamentary discharge observed, and microdischarge is the glowing discharge. In the streamer discharge, the electron temperature of the streamer head is as high as several electronvolts, which is advantageous for generating ozone. In microdischarge, ozone generation is unproductive compared to streamer discharge because the electron temperature is low.

Figure S1 shows the emissions from the transition of nitrogen excited species in the 300–400 nm range. Main transitions were the second positive system (SPS) of N₂ (C¹Π_u→B¹Π_g) and the first negative system (FNS) of N₂ (B²Σ_u−X²Σ_g−). The emission intensity of the nitrogen-excited species increased as the frequency increased (4–10 kHz). The optical wavelength of air plasma is in the range of UVA, which is not effective for UV germicidal irradiation. Therefore, it could be difficult to expect virus inactivation by UV irradiation.

The formation of ozone from SDBD occurs through several pathways. This mainly occurs through the dissociation of oxygen molecule by electron collisions (R1)–(R3):

\[
e + O_2 \rightarrow e + 2O \quad (R1)
\]

\[
O + O_2 + O_2 \rightarrow O_3 + O_2 \quad (R2)
\]

\[
O + O_2 + N_2 \rightarrow O_3 + N_2 \quad (R3)
\]

This can also occur through the collision of oxygen molecules with the oxygen and nitrogen excited species (R4, R5):

\[
N_2(A^3Σ_u^+ + O_2 \rightarrow O(^3P) + O(^3D) + N_2) \quad (R4)
\]

\[
O(^3P) + O_2 + M \rightarrow O_3 + M \quad (R5)
\]

It is necessary to increase the ratio of streamer discharge in a period to generate a significant amount of reactive oxygen species for virus inactivation. The temporal ratio of streamer discharge in one period was adjusted by frequency. Figure 4a shows the streamer discharge (a in Figure 3a) and rest (b in Figure 3a) times according to the frequency. As the frequency increased from 4 to 10 kHz, the streamer discharge time remained constant, but the rest time gradually decreased. Therefore, the portion of streamer discharge in one discharge cycle increased from 13 to 28%. The power dissipation measured by the Q-V Lissajous diagram also increased from 0.43 to 0.79 W as the frequency increased (Figure 4b). The details of voltage–current signal and Q-V Lissajous diagram analysis are given in the Supporting Information (Figure S2). At the frequencies, the ozone production of SDBD device in the closed wind tunnel was measured. The ozone concentration increased to 51.6, 73.6, 98.7, and 113.3 ppm in volume ratio at 4, 6, 8, and 10 kHz, respectively (Figure 4c). Note that the power consumption increased by 1.8 times, but the ozone concentration increased by 2.2 times. The 22% increase of ozone generation efficiency is related to the energy yield as a function of energy density. The energy density can be expressed by the equation.
where $E_d$, $P_d$, and $Q$ are the energy density (J/L), power consumption to discharge (W), and gas flow rate (L/min), respectively. In this work, the air flow rate was 15 L/min, as indicated by the flow rate of a diaphragm pump. The power consumption $P_d$ was measured by a Q-V Lissajous diagram in Figure S2. The energy yield of ozone production (g/kW-h) is defined as the amount of ozone production per unit input energy and calculated as follows:

$$\eta = \frac{60QN}{22.4} \left( \frac{M}{P_d} \right) = \frac{7.7143 N}{E_d} \tag{2}$$

where $N$ and $M$ are the ozone concentration (ppm) and molecular weight of ozone (48 g/mol), respectively. The energy density $E_d$ of this work corresponds to 1.7–3.2 J/L, which was a region in which the energy yield $\eta$ rapidly increased in SDBD as the energy density increased. The energy yield $\eta$ has a maximum value at an energy density of 10 J/L, and the ozone concentration does not increase linearly with the energy density due to the increasing ozone decomposition. Ozone could be produced effectively because the SDBD was operated in the energy density range where the ozone production reaction was dominant. Thus, proper methods to decompose ozone for indoor applications should be considered. In this system, carbon catalysts were used to decompose ozone, and ozone produced from the SDBD was completely decomposed in all treatment groups (Figure 4c). Therefore, it showed the possibility of continuous plasma operation under nontoxic conditions, and for the subsequent experiment, a frequency of 4 kHz was selected as the optimal condition to minimize filter damage and ozone production.

Figure 5 shows the inactivation effect of SDBD against SARS-CoV-2 present in the filter sample. When SDBD at 4 kHz was operated for 30 min (CT value of 26 ppm-h), the number of SARS-CoV-2 decreased by more than 99.78% (detection limit: 0.18 log PFU/mL) compared to the control group. Various studies have been conducted applying plasma technology within ventilation ducts to control airborne bacteria and virus. Most of these are direct plasma treatments for airborne bacteria or virus particles. Lai et al. demonstrated that the microbial inactivation effect of cold plasma was different depending on the airstream velocities and relative humidity, and the effect was insignificant for Gram-positive bacteria that were less sensitive to oxidative stress. Xia et al. reported that the aerosolized MS2 phage decreased by 2.3 log in crossing the plasma reactor under conditions of 30 kV and an air flow rate of 170 L/min. They also found that an increase in the air flow rate to 330 L/min in the device had no significant effect on virus inactivation. Therefore, the direct plasma treatment for airborne bacteria or virus particles can be highly affected by environmental conditions, making it difficult to establish detailed discharge conditions accordingly.

Here, we tried to capture viral particles from air using conventional PP melt-blown filters and effectively inactivate them through plasma. Ozone, a major reactive oxygen species in the DBD system, is potentially the main effector for virus inactivation under surface treatment conditions. The antiviral effectiveness of ozone against human coronavirus (HCoV-229E) present in mask filters has already been proven, and Chen et al. demonstrated that cold atmospheric plasma is effective in inactivating SARS-CoV-2 on surfaces of various materials. In addition, Guo et al. reported that plasma-activated water effectively inhibits viral infection by inactivating the S protein of SARS-CoV-2. Therefore, plasma can potentially maintain the SARS-CoV-2 inactivation effect even in an environment where moisture coexists. Overall, polyimide-based SDBD devices can be installed close to the filter regardless of the air flow within the ventilation duct and potentially eliminate viruses captured in the filter.
Figure 6 presents the C 1s spectra and the corresponding chemical composition of the filter sample before and after 48 h of plasma treatment (CT value of 2570 ppm·h). All filters had C−C/C=C/C−H (284.8 eV), C−O (286.2 eV), C≡O (287.5 eV), and O−C≡O (288.4 eV) bonds (Figure 6a). The C−O, C≡O, and O−C≡O bonds present in the untreated PP filter are considered to be due to low-level natural oxidation.49 The intensity of the C−C/C=C/C−H bonds in the PP filter decreased by prolonged plasma treatment (Figure 6b). On the other hand, it was confirmed that the polar functional groups containing oxygen were introduced in the PP filter after 48 h of plasma treatment. The surface chemical composition of PP filter can be calculated through curve fitting (Figure 6c). The original PP filter contains 90.3% C−C/C=C/C−H groups, 6.32% C−O groups, 2.71% C≡O groups, and 0.68% O−C≡O groups. After plasma treatment, the concentration of the C−C/C=C/C−H groups decreases to 83.7%, while the concentration of the C−O groups, C≡O groups, and O−C≡O groups increases to 7.87%, 5.69%, and 2.71%, respectively. These results suggested that atmospheric-pressure plasma probably cleave the C−C/C=C/C−H bonds creating free radicals, which can react with the activated oxygen species leading to the formation of C−O, C≡O, and O−C≡O groups.49 However, according to previous studies, this change is likely to be limited as surface equilibrium,50,51 and no morphological damage or change of PP filter was observed due to prolonged plasma treatment (Figure 7), so it was confirmed that PP filter had adequate durability within the plasma exposure conditions applied in this study. However, further research needs to verify that changes in surface chemical composition can affect the ability of PP filters to capture viral particles.

4. CONCLUSIONS

Because of the COVID-19 pandemic, there are many attempts to apply plasma-generated reactive oxygen species to virus inactivation. Low-temperature plasma devices using conventional ceramic plates or beads are difficult to apply to air purifiers due to area expansion, cost efficiency, and shape restrictions. In this study, a film-based SDBD device was developed. Using a polymer film as a dielectric, the SDBD device is lightweight and flexible so that it can be applied to air purifiers in various forms. Although the power consumption cannot be maintained higher than that of the ceramic dielectric-based SDBD device due to heating, the polyimide-based SDBD device effectively inactivates SARS-CoV-2 trapped in the filter. Moreover, ozone concentration could be reduced to a level safe for humans at an air flow of 15 L/min by applying a carbon catalyst. The combination of membrane filter, plasma, and catalyst technology could be an
effective method when the disinfection of airborne bacteria and virus is important and urgent.

This study conducted a virus inactivation test at a relatively low airflow to demonstrate a SARS-CoV-2 aerosol in a level 3 biosafety facility. An SDBD should treat large air flow under higher frequencies and power consumption in practical indoor applications. As operating conditions become harsher, the durability of the polymer dielectric film will be required, and a plasma-resistant coating such as carbon or SiO2 would be applied.

■ ASSOCIATED CONTENT
Data Availability Statement
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Supporting Information
The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsapm.2c01086.

S1: optical emission spectra of the surface dielectric barrier discharge at different frequencies; S2: images of the discharge occurring on the surface of the plasma element, captured with a camera (PDF)

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K.H.B. was involved in conceptualization, data curation, formal analysis, investigation, methodology, validation, visualization, and writing—original draft. D.J., T.K., and J.-Y.Y. were involved in data curation, formal analysis, methodology, and resources. S.R. was involved in project administration, resources, supervision, writing—review and editing. J.P. and E.K. were involved in conceptualization and validation. S.L. was involved in conceptualization, funding acquisition, methodology, project administration, resources, supervision, writing—review and editing.

Notes
The authors declare no competing financial interest.

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■ ABBREVIATIONS
SARS-CoV-2, severe acute respiratory syndrome coronavirus 2; SDBD, surface dielectric barrier discharge; PP, polypropylene; ROS, reactive oxygen species; DBD, dielectric barrier discharge

■ REFERENCES
(1) Bhattacharyya, S.; Dey, K.; Paul, A. R.; Biswas, R. A novel CFD analysis to minimize the spread of COVID-19 virus in hospital isolation room. Chaos, Solitons & Fractals 2020, 139, 110294.
(2) Chen, B.; Jia, P.; Han, J. Role of indoor aerosols for COVID-19 viral transmission: a review. Environmental Chemistry Letters 2021, 19 (3), 1953–1970.
(3) Mittal, R.; Ni, R.; Seo, J.-H. The flow physics of COVID-19. J. Fluid Mech. 2020, DOI: 10.1017/jfm.2020.330.
(4) Guo, Z.-D.; Wang, Z.-Y.; Zhang, S.-F.; Li, X.; Li, L.; Li, C.; Cui, Y.; Fu, R.-B.; Dong, Y.-Z.; Chi, X.-Y.; et al. Aerosol and surface distribution of severe acute respiratory syndrome coronavirus 2 in hospital wards, Wuhan, China, 2020. Emerg. Infect. Dis. 2020, 26 (7), 1586.
(5) Buising, K. L.; Schofield, R.; Irving, L.; Keywood, M.; Stevens, A.; Keogh, N.; Skidmore, G.; Wadlow, I.; Kevin, K.; Rismarchan, B. Use of portable air cleaners to reduce aerosol transmission on a hospital coronavirus disease 2019 (COVID-19) ward. Infection Control & Hospital Epidemiology 2021, 1–6.
(6) Chong, K. L.; Ng, C. S.; Hori, N.; Yang, R.; Verzicco, R.; Lohse, D. Extended lifetime of respiratory droplets in a turbulent vapor puff and its implications on airborne disease transmission. Physical review letters 2021, 126 (3), 034502.
(7) Hwang, S. E.; Chang, J. H.; Oh, B.; Heo, J. Possible aerosol transmission of COVID-19 associated with an outbreak in an apartment in Seoul, South Korea, 2020. International Journal of Infectious Diseases 2021, 104, 73–76.
(8) Berry, G.; Parsons, A.; Morgan, M.; Rickert, J.; Cho, H. A review of methods to reduce the probability of the airborne spread of COVID-19 in ventilation systems and enclosed spaces. Environmental Research 2022, 203, 111765.
(9) Jung, S.; Yang, J.-Y.; Jang, D.; Kim, T.; Baek, K. H.; Yoon, H.; Park, J. Y.; Kim, S. K.; Hong, J.; Ryoo, S.; Jang, H. W.; Lee, S. Sustainable Antibacterial and Antiviral High-Performance Copper-Coated Filter Produced via Ion Beam Treatment. Polymers 2022, 14 (5), 1007.
(10) Jung, S.; Yang, J.-Y.; Byeon, E.-Y.; Kim, D.-G.; Lee, D.-G.; Ryoo, S.; Lee, S.; Shin, C.-W.; Jang, H. W.; Kim, H. J.; Lee, S. Copper-coated polypropylene filter face mask with SARS-COV-2 antiviral ability. Polymers 2021, 13 (9), 1367.
(11) Thurman, R. B.; Gerba, C. P.; Bitton, G. The molecular mechanisms of copper and silver ion disinfection of bacteria and viruses. Critical Reviews in Environmental Science and Technology 1989, 18 (4), 295–315.
(12) Cutler, T. D.; Zimmerman, J. J. Ultraviolet irradiation and the mechanisms underlying its inactivation of infectious agents. Animal Health Research Reviews 2011, 12 (1), 15–23.
(13) Heßling, M.; Hönes, K.; Vatter, P.; Lingenfelder, C. Ultraviolet irradiation doses for coronavirus inactivation—review and analysis of...
coronavirus photo-inactivation studies. GMS Hygiene and Infection Control 2020, 15.
(14) Nakano, R.; Ishiguro, H.; Yao, Y.; Kajoka, J.; Fujishima, A.; Sunada, K.; Minoshima, M.; Hashimoto, K.; Kubota, Y. Photocatalytic inactivation of influenza virus by titanium dioxide thin film. Photochemical & Photobiological Sciences 2012, 11 (8), 1293–1298.
(15) Matsuura, R.; Lo, C.-W.; Wada, S.; Somei, J.; Ochiai, H.; Murakami, T.; Saito, N.; Ogawa, T.; Shinjo, A.; Benno, Y.; Nakagawa, M.; Takei, M.; Aida, Y. SARS-CoV-2 disinfection of air and surface contamination by tio2 photocatalyst-mediated damage to viral morphology, RNA, and protein. Viruses 2021, 13 (5), 942.
(16) Khaiboulina, S.; Uppal, T.; Dhabarde, N.; Subramanian, V. R.; Verma, S. C. Inactivation of human coronavirus by titanita nanoparticle coatings and UVC radiation: throwing light on SARS-CoV-2. Viruses 2021, 13 (1), 19.
(17) Bono, N.; Ponti, F.; Punta, C.; Candiani, G. Effect of UV irradiation and TiO₂ photolysis on airborne bacteria and viruses: an overview. Materials 2021, 14 (5), 1075.
(18) Foster, H. A.; Ditta, I. B.; Varghese, S.; Steele, A. Photocatalytic disinfection using titanium dioxide: spectrum and mechanism of antimicrobial activity. Applied microbiology and biotechnology 2011, 90 (6), 1847–1868.
(19) Gerrity, D.; Ryu, H.; Crittenden, J.; Abbaszadegan, M. Photocatalytic inactivation of viruses using titanium dioxide nanoparticle and low-pressure UV light. Journal of Environmental Science and Health, Part A 2008, 43 (11), 1261–1270.
(20) Park, S. G.; Xiao, X.; Min, J.; Mun, C.; Jung, H. S.; Giannini, V.; Weissleder, R.; Maier, S. A.; Im, H.; Kim, D. H. 3D Plasmmonic Nanostructures: Self-Assembly of Nanoparticle-Spiked Pillar Arrays for Plasmonic Biosensing (Adv. Funct. Mater. 43/2019). Adv. Funct. Mater. 2019, 29 (43), 1970296.
(21) Bisag, A.; Isabelli, P.; Laurita, R.; Bucci, C.; Capelli, F.; Dirani, G.; Gherardi, M.; Laghi, G.; Paglianti, A.; Sambri, V.; Colombo, V. Cold atmospheric plasma inactivation of aerosolized microdroplets containing bacteria and purified SARS-CoV-2 RNA to contrast airborne indoor transmission. Plasma Processes and Polymers 2020, 17 (10), 2000154.
(22) Kramer, B.; Warschät, D.; Murayi, P. Disinfection of an ambulance using a compact atmospheric plasma device. J. Appl. Microbiol. 2022, 133, 696.
(23) Chen, Z.; Garcia, G.; Jr.; Arumugawasmi, V.; Wirz, R. E. Cold atmospheric plasma for SARS-CoV-2 inactivation. Phys. Fluids 2020, 32 (11), 111702.
(24) Bhartiya, P.; Lim, J. S.; Kaushik, N.; Shaik, A. M.; Shin, Y. O.; Kaushik, N. K.; Choi, E. H. Nonthermal plasma-generated ozone inhibits human coronavirus 229E infectivity on glass surface. Plasma Processes and Polymers 2022, e2200054.
(25) Quevedo, R.; Bastias, J. M.; Espinoza, T.; Ronceros, B.; Balic, I.; Muñoz, O. Inactivation of Coronavirus in food industry: The use of inorganic and organic disinfectants, ozone, and UV radiation. Scientia Agronomica 2020, 11 (2), 257–266.
(26) Murray, B. K.; Ohmine, S.; Tomer, D. P.; Jensen, K. J.; Johnson, F. B.; Kirsi, J. J.; Robison, R. A.; O’Neill, K. L. Virion disruption by ozone-mediated reactive oxygen species. Journal of virological methods 2008, 153 (1), 74–77.
(27) Alimohammadi, M.; Naderi, M. Effectiveness of ozone gas on airborne virus inactivation in enclosed spaces: a review study. Ozone: Science & Engineering 2021, 43 (1), 21–31.
(28) Williamson, J. M.; Trump, D. D.; Bletzinger, P.; Ganguly, B. N. Comparison of high-voltage ac and pulsed operation of a surface dielectric barrier discharge. J. Phys. D: Appl. Phys. 2006, 39 (20), 4400.
(29) Šimek, M.; Pekárek, S.; Pruknar, V. Influence of power modulation on ozone production using an AC surface dielectric barrier discharge in oxygen. Plasma Chemistry and Plasma Processing 2010, 30 (5), 607–617.
(30) Gao, G.; Dong, L.; Peng, K.; Wei, W.; Li, C.; Wu, G. Comparison of the surface dielectric barrier discharge characteristics under different electrode gaps. Physics of Plasmas 2017, 24 (1), 013510.
(31) Gershman, S.; Harreguy, M. B.; Yatom, S.; Raitses, Y.; Eftimion, P.; Haspel, G. A low power flexible dielectric barrier discharge disinfects surfaces and improves the action of hydrogen peroxide. Sci. Rep. 2021, 11 (1), 1–12.
(32) Corke, T. C.; Post, M. L.; Orlov, D. M. SDBD plasma enhanced aerodynamics: concepts, optimization and applications. Progress in Aerospace Sciences 2007, 43 (7–8), 193–217.
(33) Corke, T. C.; Enloe, C. L.; Wilkinson, S. P. Dielectric barrier discharge plasma actuators for flow control. Annu. Rev. Fluid Mech. 2010, 42, 505–529.
(34) Jiang, H.; Shao, T.; Zhang, C.; Li, W.; Yan, P.; Che, X.; Schamiloglu, E. Experimental study of QY’ Lissajous figures in nanosecond-pulse surface discharges. IEEE Trans. Dielectr. Electr. Insul. 2013, 20 (4), 1101–1111.
(35) Dong, L.; Gao, G.; Peng, K.; Wei, W.; Li, C.; Wu, G. Effects of surface dielectric barrier discharge on aerodynamic characteristic of train. AIP Adv. 2017, 7 (7), 075112.
(36) Mendoza, E. J.; Manguiat, K.; Wood, H.; Drebout, M. Two detailed plaque assay protocols for the quantification of infectious SARS-CoV-2. Current Protocols in Microbiology 2020, 57 (1), cpmc105.
(37) Baer, A.; Kehn-Hall, K. Viral concentration determination through plaque assays: using traditional and novel overlay systems. JoVE (Journal of Visualized Experiments) 2014, No. 93, e52065.
(38) Kourtzanidis, K.; Dufour, G.; Rogier, F. Self-consistent modeling of a surface AC dielectric barrier discharge actuator: in-depth analysis of positive and negative phases. J. Phys. D: Appl. Phys. 2021, 54 (4), 045203.
(39) Abdelaziz, A. A.; Ishijima, T.; Osawa, N.; Seto, T. Quantitative analysis of ozone and nitrogen oxides produced by a low power miniaturized surface dielectric barrier discharge: effect of oxygen content and humidity level. Plasma Chemistry and Plasma Processing 2019, 39 (1), 165–185.
(40) Abdelaziz, A. A.; Ishijima, T.; Seto, T.; Osawa, N.; Wadaa, H.; Otani, Y. Characterization of surface dielectric barrier discharge influenced by intermediate frequency for ozone production. Plasma Sources Science and Technology 2016, 25 (3), 035012.
(41) Guzel-Seydim, Z. B.; Greene, A. K.; Seydim, A. Use of ozone in the food industry. LWT-Food Science and Technology 2004, 37 (4), 453–460.
(42) Lai, A.; Cheung, A.; Wong, M.; Li, W. Evaluation of cold plasma inactivation efficacy against different airborne bacteria in ventilation duct flow. Building and Environment 2016, 98, 39–46.
(43) Lee, S.-G.; Hyun, J.; Lee, S. H.; Hwang, J. One-pass antibacterial efficacy of bipolar air ions against aerosolized Staphylococcus epidermidis in a duct flow. J. Aerosol Sci. 2014, 69, 71–81.
(44) Prehn, F.; Timmermann, E.; Kettlitz, M.; Schaufler, K.; Günther, S.; Hahn, V. Inactivation of airborne bacteria by plasma treatment and ionic wind for indoor air cleaning. Plasma Processes and Polymers 2020, 17 (9), 2000027.
(45) Terrier, O.; Essere, B.; Yver, M.; Barthelemy, M.; Bouscambert-Duchamp, M.; Kurtz, P.; VanMechelen, D.; Morfin, F.; Billaud, G.; Ferraris, O.; Lina, B.; Rosa-Calatrava, M.; Moules, V. Cold oxygen plasma technology efficiency against different airborne respiratory viruses. Journal of Clinical Virology 2009, 45 (2), 119–124.
(46) Liu, D.; Zhang, L.; Cheng, Y.; et al. Plasma-activated water: An alternative disinfectant for S protein inactivation to prevent SARS-CoV-2 infection. Chem. Eng. J. 2021, 421, 127742.

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(49) Morent, R.; De Geyter, N.; Leys, C.; Gengembre, L.; Payen, E. Evaluation between XPS-and FTIR-analysis of plasma-treated polypropylene film surfaces. *Surface and Interface Analysis: An International Journal devoted to the development and application of techniques for the analysis of surfaces, interfaces and thin films* 2008, 40 (3–4), 597-600.

(50) Cui, N.-Y.; Brown, N. M. Modification of the surface properties of a polypropylene (PP) film using an air dielectric barrier discharge plasma. *Appl. Surf. Sci.* 2002, 189 (1–2), 31–38.

(51) Kwon, O.-J.; Tang, S.; Myung, S.-W.; Lu, N.; Choi, H.-S. Surface characteristics of polypropylene film treated by an atmospheric pressure plasma. *Surf. Coat. Technol.* 2005, 192 (1), 1–10.