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Indoor Air Purifiers in the Fight against Airborne Pathogens: The Advantage of Circumferential Outflow Diffusers

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Abstract: Airborne particles containing pathogens such as bacteria (e.g., *M. tuberculosis*) or virions (e.g., influenza or severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2)) can cause infections. It has been speculated that the outflow from indoor air purifiers with a directional outlet could entrain and spread pathogen-containing aerosol particles. To date, only the case of indoor air purifiers with a directional outflow has been considered, and here we investigate an indoor air purifier with a circumferential outflow diffuser—an alternative design solution that is already commercially available. We measured the airflow velocity at two different angles to the surface of the circumferential outflow diffuser and two blower speeds. We visualized in scattered light the deflection of a vertical mist spray cone from a sneeze-simulating nebulizer parallel to the side of the air purifier. We found a significant difference in airflow velocities for different angles to the circumferential outflow diffuser: 0.01–0.02 m/s for 0° vs. 0.01–0.65 m/s for 45° at 1 m distance. We observed no significant deflection of the sneeze-simulating spray cone at the minimum blower speed and a 5 cm deflection at the maximum speed. The deflection of the sneeze-simulating spray mist particles by the tested indoor air purifier with the circumferential outflow, under the experimental conditions, is low relative to the recommended safer distances between people in indoor spaces. We conclude that indoor air purifiers with circumferential outflow diffusers have a lower potential to spread infectious aerosols in indoor spaces compared to devices with unidirectional outflow.

Keywords: air purifier; air filter; airflow; indoor air; aerosol; sneeze; diffuser; coronavirus; SARS-CoV-2; COVID-19

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1. Introduction

Transport of pathogens through the airborne route is a concern in various environments where people interact [1]. Transmission of infections via the aerosol phase is a major occupational and public health and safety problem in various settings, especially indoors in hospitals and other healthcare facilities, educational institutions, public transit, and public venues [2,3]. The recent COVID-19 pandemic highlighted the importance of airborne pathogen transmission control in occupational, public and private settings. The numerous studies conducted in response to the global health emergency associated with the COVID-19 pandemic have generally advanced our knowledge of airborne pathogen transmission. Research early in the COVID-19 pandemic showed that airborne transport is possible for particles containing virions or the ribonucleic acid (RNA) of the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) [4]. When SARS-CoV-2 virions were aerosolized, some of them were observed to remain airborne and viable for at least three hours [5], which is sufficient for virions to be transported across a room and possibly beyond, limited by the indoor air circulation, affecting residents in a building. In another study, the RNA of SARS-CoV-2 was found in airborne particles of 1 μm in diameter and larger in the indoor spaces where patients with coronavirus disease 19 (COVID-19) were housed [6]. SARS-CoV-2 RNA was found in the indoor air at least 3 m from people with COVID-19 [7]. SARS-CoV-2 RNA was also detected in some particles that constitute ambient air pollution [8]. Most recently, the infectivity of fine (<1 μm) and coarse (>1 μm) patient-generated aerosol particles containing SARS-CoV-2 was demonstrated using Vero E6 lung cell cultures [9]. These findings are being considered in managing the spread of all airborne pathogens. Droplet and airborne transmission are distinguished by a cut-off droplet diameter, most commonly 5 μm [10].

The SARS-CoV-2 virion is around 60–140 nm in diameter [11]. However, it has been found within larger aerosol particles, including droplets emitted by people infected with COVID-19 [7]. Droplets can partially evaporate, resulting in a reduction in their aerodynamic diameter [12,13]. Aerosol particles with a smaller aerodynamic diameter can stay airborne longer. A recent study found 12–21 μm speech-generated wet droplets drying and shrinking to ~4 μm diameter [14]. These smaller desiccated droplets were observed to fall in the air by only 30 cm in about 8 min [14]. Such a low settling rate aligns with numerous observations that viable or non-viable SARS-CoV-2 virions can travel considerable distances through the air.

Using ventilation, indoor air purification, and personal protective equipment, such as masks and respirators, is an intervention recommended by the World Health Organization to reduce the spread of COVID-19 and other air-transmitted infections, such as tuberculosis [15]. In addition to air filtration systems that mechanically move air through filters and sorbents, air ionizers are increasingly used to remove particles from indoor air, and they have been shown to be especially practical for larger indoor spaces and highly effective at removing ultrafine and fine particles [16]. The ionizer generates ions through an electrical discharge and releases them into the indoor space. These ions attach themselves to air pollution particles in the air. The particles that acquire charge are attracted to each other and to surfaces in the indoor space, and so their removal from the air is enhanced. However, there is no mechanized airflow through the ionizers that would potentially deflect any sneeze or cough spray cone, so this type of indoor air purifier was not investigated in this study.

A recent perspective by Ham [17] raised the question of whether air currents generated by the outflow from indoor air purifiers could push unpurified surrounding air within indoor spaces, thereby increasing the distance at which aerosol particles emitted by people infected with COVID-19 could spread [17]. This perspective by Ham [16] included a visualization of an experiment with an indoor air purifier that had a unidirectional outflow with a speed of 10 m/s. The authors mentioned the study limitation that only one model of indoor air purifier was tested. Nevertheless, a unidirectional outflow from many different models of air purifiers is expected to be relatively similar.

To fill the knowledge gap in understanding how the configuration of the outflow from indoor air purifiers can affect the spread of infectious aerosol particles indoors, here we set out to test a model of the indoor air purifier that does not have a unidirectional outflow but rather a circumferential diffuser is used to release the cleaned air into the indoor space. This is the second of two types of outflow configurations used in indoor air purifiers. A circumferential diffuser releases the purified air through multiple openings located all around (360°) a section of the device (Figure 1).

We explored whether a replication of the experiment by Ham [17] would show a considerably less significant deflection of the spray mist cone in the case of an indoor air purifier with a circumferential outflow through a 360° diffuser. The results of this study inform decision-makers within the design and manufacturing departments of indoor air purifier manufacturers, as well as non-government and government agencies globally, regarding the design of outflow ducts and diffusers for indoor air purification and ventilation systems and the choice of existing products for indoor spaces ranging from hospitals and other healthcare facilities to private houses.

Figure 1. Circumferential diffuser of an indoor air purifier.

2. Materials and Methods

2.1. Characterization of the Spray Cone Deflection by the Air Purifier Outflow

Two configurations of the outflow ducts or diffusers are available on the global market: the directional outflow configuration and the circumferential outflow configuration. The circumferential outflow diffuser does not vector the outflow vertically at a 90° angle or another defined angle to the horizontal plane. Circumferential outflow diffusers release the outflow in multiple directions at once. Therefore, there is a major difference between the circumferential outflow diffuser configuration and the other common indoor air purifier configuration, which has an air outlet on top of the indoor air purifiers and has been the subject of concerns [17] regarding the potential for indoor air purifier outflow air currents to facilitate directional transport of airborne infectious particles indoors. The indoor air purifier used in the experiments was model C600 (Airpura Industries, Inc., Laval, QC, Canada) and did not include any ionizer or UV light source, so it did not produce ions or ozone. The air purifier was placed on the floor. The indoor air purifier has a circumferential diffuser with a height of 7 cm all around the perimeter of the air purifier. The indoor air purifier was operated at the lowest and highest speed of the blower. We measured the air velocity at 0° and 45° angles to the vector perpendicular to the surface of the outflow diffuser at ten distances between 0 cm and 100 cm using an air velocity meter, model 9515 VelociCalc (TSI Inc., Shoreview, MN, USA) (Figure 2).

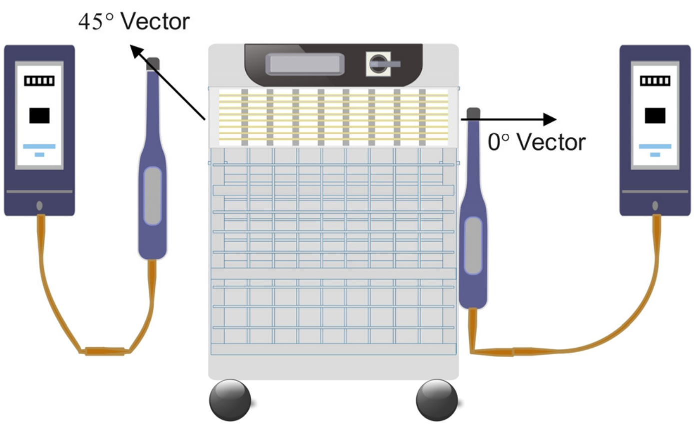

Figure 2. Air velocity measurement at different angles and distances from the indoor air purifier.

The instrument has a velocity measurement range of 0 to 4000 ft/min (0 to 20 m/s), a temperature range of 0 to 200 °F (−18 to 93 °C), an accuracy of ±5% of reading or ±5 ft/min (±0.025 m/s), whichever is greater, and a resolution of 1 ft/min (0.01 m/s).

We generated a vertical upward spray cone using a typical pressurized propellant-powered indoor air freshener nebulizer located approximately 5 cm from the floor and 1 cm to 8 cm from the side of the air purifier. Fluorescent light was used to illuminate the setup from above to make the mist particles in the spray cone visible due to light scattering by the mist particles. A ruler was placed along the airflow vector. A Panasonic Lumix TS7 digital camera was used to take photographs of the spray cone. Spray particle propagation velocity was determined based on visual observations of timed image sequences, the angle of deflection, and airflow velocity. Additional information on aerosol particles emitted by such air fresheners has been published elsewhere [18]. Aerosol size distributions of sneeze and speech aerosols have also been previously measured [19,20].

2.2. Characterization of the Test Spray Aerosol Size Distribution

We measured the aerosol size distributions produced by the spray generator with a component scanning mobility particle sizer (TSI Inc.) using an experimental setup consisting of a chamber with organic glass walls with inner dimensions of 560 mm × 560 mm × 760 mm (Figure 3).

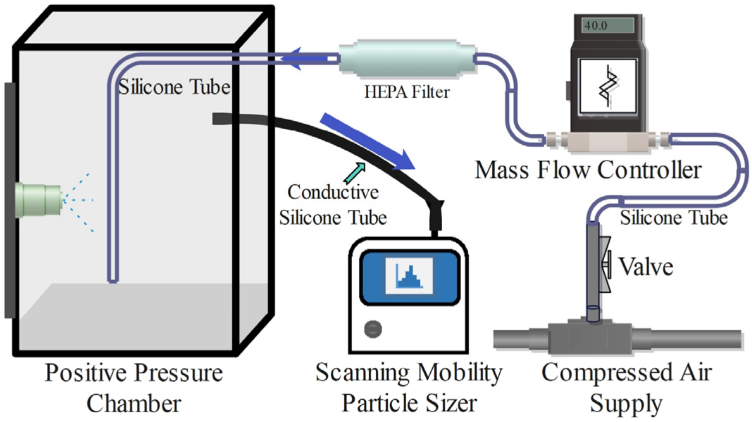

Figure 3. Schematic of the positive-pressure chamber setup for the investigation of the size distribution of the aerosol generated by the sprayer. The component SMPS real-time aerosol sizer and the metered clean air delivery system are shown.

The front wall of the chamber was removable and only partially sealed to allow a constant escape of the air injected into the chamber. Clean air was constantly injected into the chamber at 40.0 SL/min, controlled by a mass flow controller, model C100L-DD-3-OV1-SV1-PV2-V1-S0-C10 (Sierra Instruments Inc., Monterey, CA, USA). This airstream was filtered through a large HEPA (high-efficiency particulate arrestance) filter, Whatman HEPA-Cap 150 (Little Chalfont, Buckinghamshire, UK). Thus, the chamber had a constant through-flow of 40 SL/min and was under slight positive pressure (<0.1 in. water, measured with a MARK II 25 manometer (Dwyer, Michigan City, IN, USA)). This design ensured a nearly particle-free environment inside the chamber when no source of aerosol particles was present inside the chamber. The component SMPS system confirmed the nearly particle-free environment. The same sprayer used in the spray cone deflection experiments described above was positioned against an opening on the left side of the chamber. Three spray activation events were conducted. Each spray activation event lasted 2 s and was followed by a 30 min pause until the next spray activation event. This spray activation cycle allowed the aerosol size distribution to be measured by the component SMPS system as the aerosol particle concentration in the chamber peaked and decayed back to the background level near zero. Each SMPS measurement cycle lasted 1 min 15 s.

3. Results

3.1. Characterization of the Test Spray Aerosol Size Distribution

Following three consecutive activations of the sprayer, the total concentration of aerosol particles reached 1.5×10^5–2.5×10^5 cm^{-3} (Figure 4). The gradual decay of the total aerosol particle concentration following three aerosol particle concentration spikes in the test chamber showed a return to baseline levels close to zero after 15 min following each of the three spray activation events.

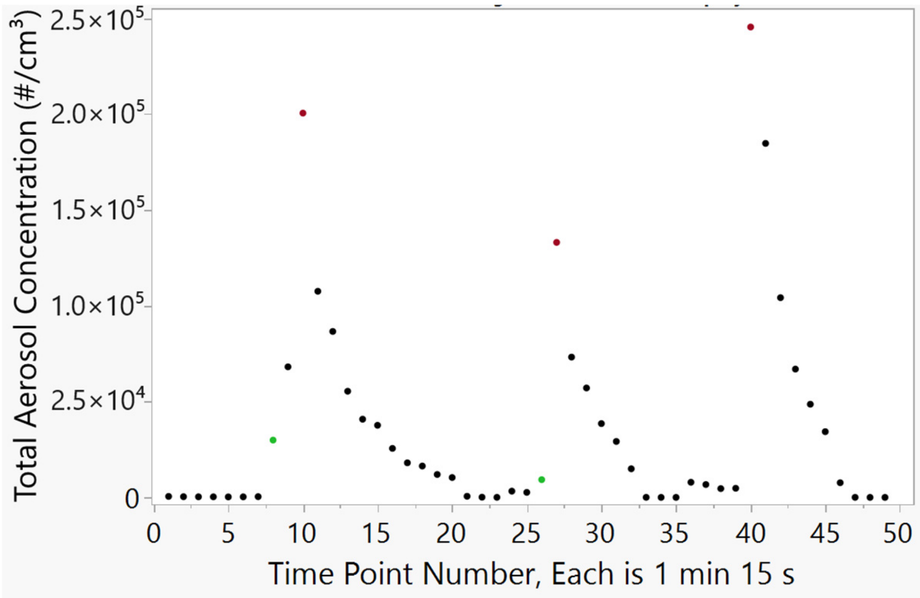

Figure 4. Total concentration in the chamber during three activations of the sprayer. The green data points correspond to the first observed aerosol particle concentration increase after each activation of the sprayer. The red data points correspond to the peak aerosol particle concentration after each activation of the sprayer.

A wide size distribution was measured in the aerosol generated by the sprayer (Figure 4); it was reproducible. The mode diameter of the aerosol size distribution was around 15–18 nm and remained around this size as the aerosol aged over half an hour. At the same time, the concentration of aerosol particles in the chamber gradually decreased. The color gradient from dark blue to light blue represents the time scale from sprayer activation to near-zero total concentration over about 30 min; each of the three graphs shows data for one of the three consecutive sprayer activation events (Figure 5).

At the maximum aerosol particle concentration in the chamber shortly following each sprayer activation event, the mode diameter of the aerosol size distribution was similarly around 15–18 nm (Figure 6). The original SMPS spray size distribution data used to construct Figures 4–6 is available as Supplementary Material.

3.2. Characterization of the Spray Cone Deflection by the Air Purifier Outflow

The highest outflow velocity was measured at the surface of the diffuser, with the blower of the indoor air purifier running at the highest speed (3.83 $\pm$ 0.03 m/s). The airflow velocity decreased sharply with the increasing distance from the surface of the outflow diffuser of the tested indoor air purifier (Table 1).

Table 1. The velocity of airflows around the indoor air purifier.

Distance, cm	Airflow, m/s							
	Horizontal Anemometer Position				45° Anemometer Position			
	Max 1	Max 2	Min 1	Min 2	Max 1	Max 2	Min 1	Min 2
0	3.85	3.81	0.42	0.54	3.85	3.81	0.30	0.45
3	1.05	1.68	0.34	0.46	2.00	2.31	0.20	0.35
5	1.02	1.20	0.14	0.28	2.00	2.03	0.40	0.29
7	0.36	0.47	0.12	0.13	2.00	1.90	0.45	0.50
10	0.24	0.31	0.10	0.10	0.81	1.92	0.70	0.58
15	0.19	0.20	0.05	0.05	0.81	1.90	0.60	0.41
20	0.12	0.16	0.01	0.01	0.80	1.36	0.40	0.25
30	0.05	0.07	0.01	0.01	0.80	1.30	0.20	0.19
50	0.03	0.02	0.01	0.01	0.80	0.80	0.01	0.02
100	0.02	0.01	0.01	0.01	0.60	0.65	0.01	0.02

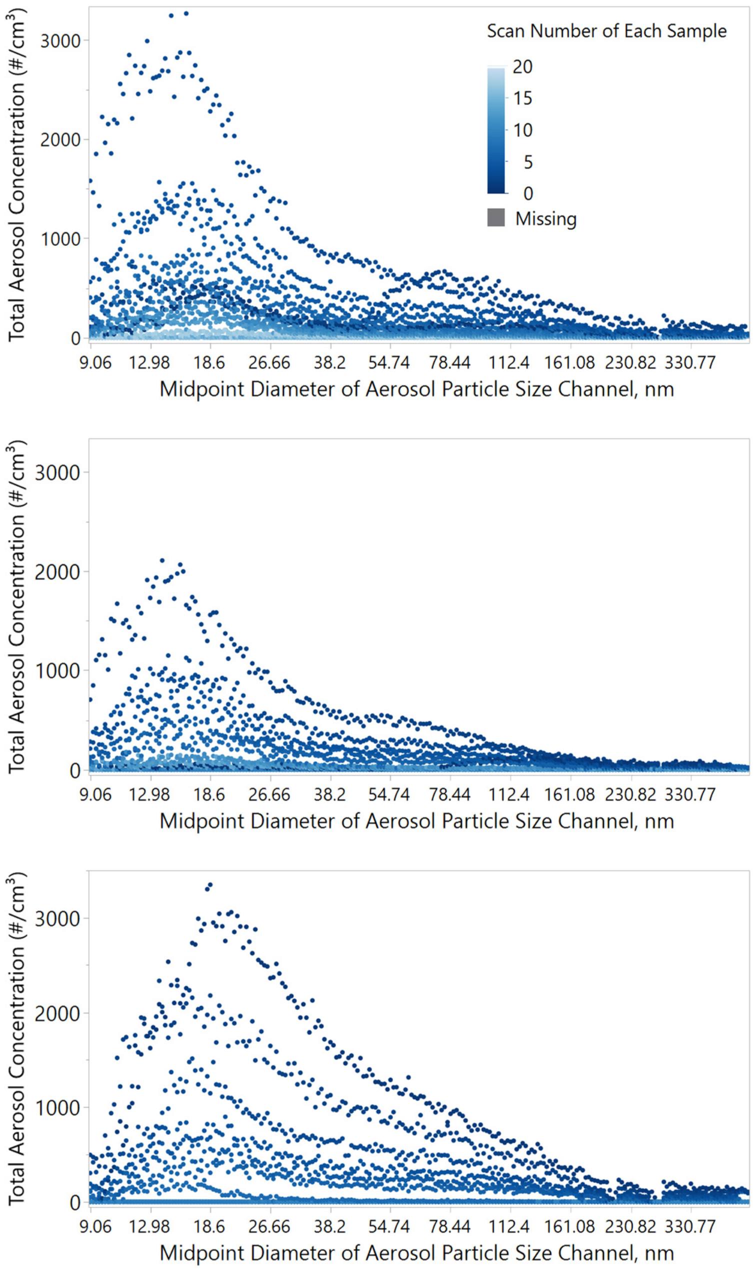

Figure 5. Changes in aerosol size distribution in the chamber following three separate consecutive activations of the sprayer.

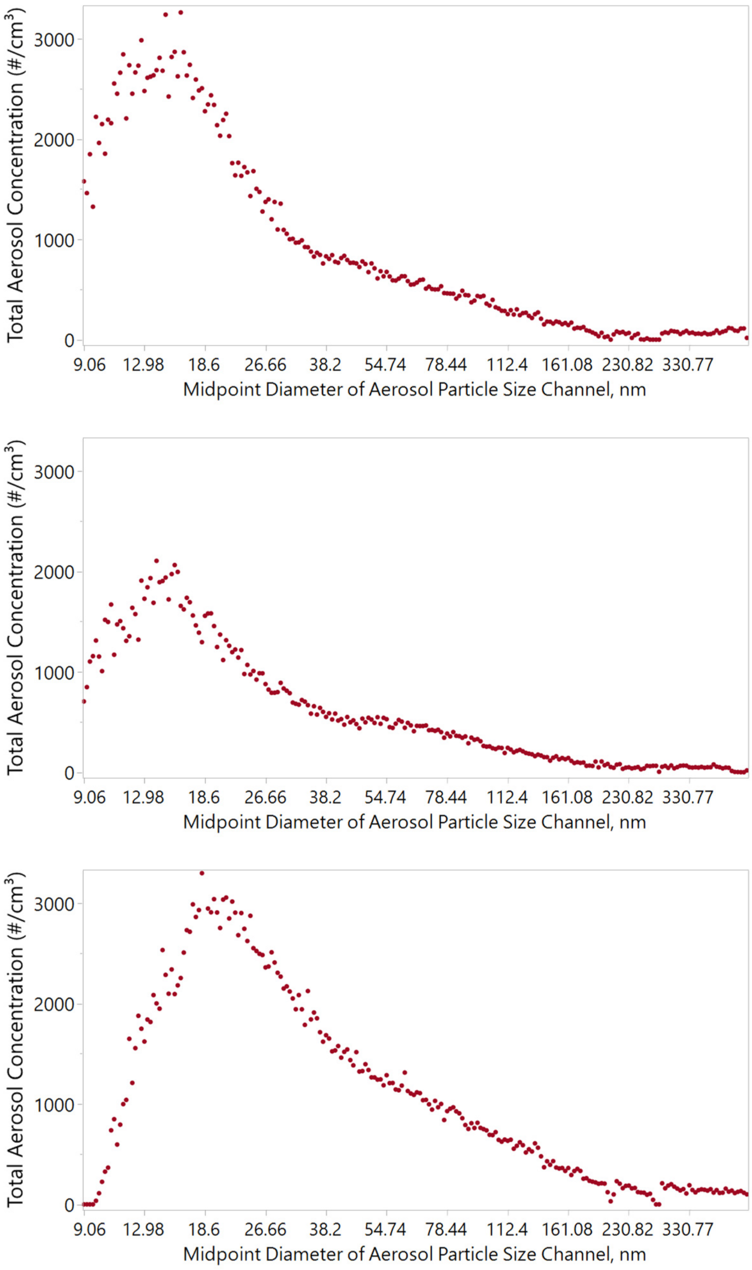

Figure 6. Aerosol size distribution in the chamber at three peak concentrations following three separate consecutive activations of the sprayer.

With the distance from the diffuser increasing, the airflow velocity dropped sharply. At the minimum blower speed, the outflow velocity decreased to between 1 cm/s and 2 cm/s at a distance of 20 cm horizontally (0° angle). At a 45° angle from the outflow diffuser of the indoor air purifier, the outflow velocity decreased to between 1 cm/s and 2 cm/s at 50 cm. At the maximum blower speed, the airflow velocity decreased to 2–3 cm/s at 50 cm horizontally (0° angle). At a 45° angle from the outflow diffuser, the outflow velocity decreased to 0.6–0.65 m/s at a distance of 1 m. A significant difference in the airflow pattern farther than approximately 50 cm from the circumferential outflow diffuser of the indoor air purifier was observed only at the maximum blower speeds and at a 45° angle: 0.6–0.8 m/s for a 45° angle at a distance of 0.5 m to 1 m from the diffuser vs. 0.01–0.03 m/s for 0° at both the minimum and maximum blower speeds (Figure 7).

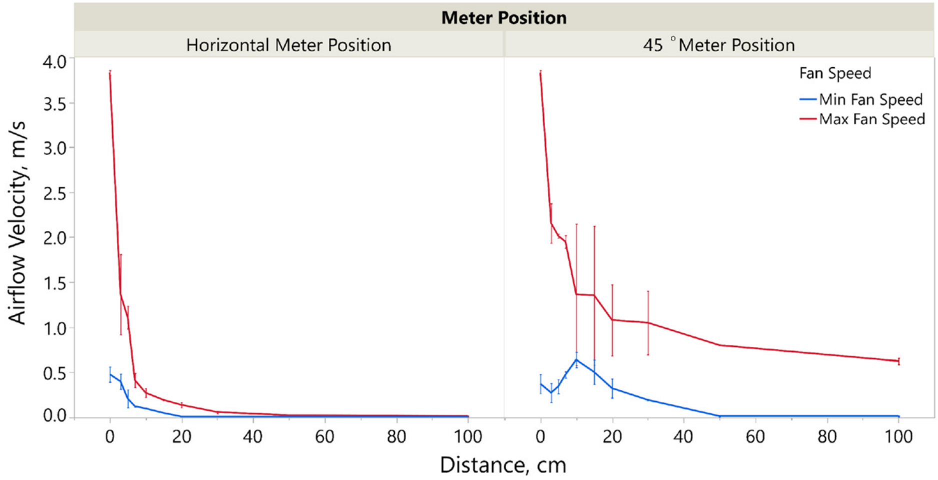

Figure 7. Average airflow velocity drop with increasing distance from the outflow diffuser of the indoor air purifier. Each error bar is constructed using 1 standard deviation from the mean.

In the case of the minimum blower speed, the drop in airflow velocity with increasing distance from the outflow diffuser was rapid at both the 0° and the 45° angles. At the maximum blower speed, the difference between the 0° and 45° angles was more pronounced. At a 0° angle with the blower at the maximum speed, the drop in airflow velocity was rapid and reached airflow velocities like those at the minimum blower speed, already around 50 cm from the diffuser. At 45°, the drop in airflow velocity was rapid, with distancing from 0 cm to 20 cm from the outflow diffuser. After 20 cm, the rate of decrease of the airflow velocity at 45° slowed down, dropping from 1.08 ± 0.40 m/s to 0.63 ± 0.04 m/s.

We observed no significant deflection of the spray mist particles visible in scattered light by the circumferential diffuser outflow from the indoor air purifier when the air purifier was operated at the lowest speed of the blower (Figure 8A,B).

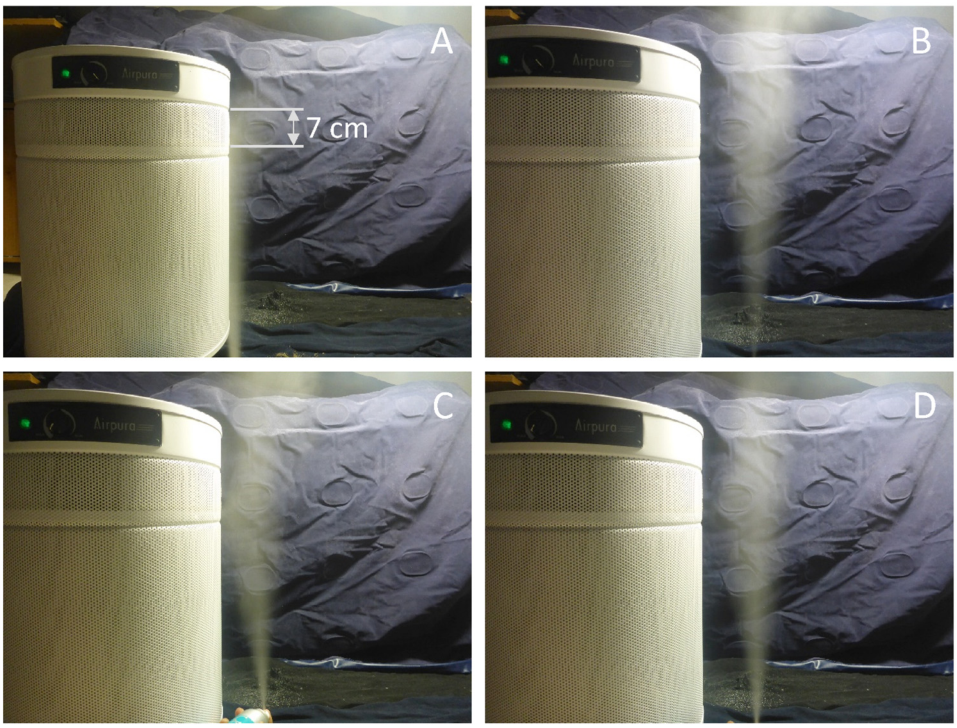

Figure 8. Photographs of the mist cone parallel to the side of the indoor air purifier. (**A**,**B**) Air purifier operating at the lowest blower speed. (**C**,**D**) Air purifier operating at the highest blower speed.

When the air purifier was operated at the highest speed, the deflection of the spray mist particles visible in scattered light was approximately 2 cm along the 7 cm vertical stretch of the outflow diffuser. The deflection distance was an additional ~3 cm extending to the top of the air purifier, which is a further 6.5 cm vertical distance when the spray cone just touched the outflow diffuser (Figure 8C). The deflection was similar when the spray cone was 3 cm farther away from the air purifier (Figure 8D).

4. Discussion

The highest velocity of the outflow measured at the surface of the circumferential diffuser with the blower of the indoor air purifier running at the highest speed (3.83 $\pm$ 0.03 m/s) was below even the lowest velocity of cough and sneeze ejecta reported in the literature (4.5–5 m/s) [12]. It was considerably lower than the velocity of cough and sneeze ejecta reported in other studies (10–35 m/s) [13,14].

When the air purifier was operated at the highest speed, a minimal deflection of the spray mist cone was observed (Figure 4). The observation means that the propagation velocity of the visible spray particles was 13.4 $\pm$ 0.1 m/s, which is between the minimum and maximum velocities of the visible cough and sneeze particles reported previously: 4.5–5 m/s [12] and 10–35 m/s [13,14]. Therefore, the propagation velocity of the visible spray particles used in this study is a good match to the real-world scenario with the real visible cough and sneeze particles.

The outflow from the circumferential outflow diffuser of the indoor air purifier showed a rapid drop in airflow velocity with a distance of only 20 cm from the indoor air purifier. We observed no visible deflection of sneeze-mimicking mist by the outflow from the circumferential diffuser of the tested indoor air purifier at the lowest blower speed. The increased airflow through the tested indoor air purifier at the highest blower speed led to a slightly slower airflow velocity drop horizontally and a less significant drop at a 45° angle. The highest blower speed caused a deflection of the sneeze-mimicking mist particles around the outflow diffuser by approximately 5 cm horizontally. We note the importance of the velocity and the direction of movement of potentially infectious respiratory droplets emitted by people relative to the air currents around an indoor air purifier. We expect the outflow to push aerosol particles that remain in front of the outflow diffuser farther.

The aerosol generation method, the initial position of the spray cone, and the dynamics of the aerosol size distribution are expected to influence the time that potentially infectious particles would spend in different positions within the air currents next to the outflow diffuser of an indoor air purifier. Aerosol dynamics is highly complex and varies greatly depending on the environmental conditions [15]. Therefore, testing for all possible scenarios of indoor air purifiers and indoor environments is impossible. However, it is reasonable to expect that aerosol particles would be pushed farther if they spent more time in front of the outflow diffuser, which is the case when they moved at a slower velocity parallel to the surface of the diffuser. The airflow dynamics around the circumferential outflow diffuser show that the potentially infectious particles, in the worst-case scenario of the highest blower speed, could be moved by the airflow exiting a circumferential airflow diffuser only at velocities many times slower than those sneeze or cough particles typically reach. At the lowest blower speed, air current velocities drop to negligible levels at 0.5 m from the indoor air purifier with a circumferential outflow diffuser.

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The test aerosol includes ultrafine and fine particles that are more readily entrained in airflows, representing the worst-case scenario. Particles with smaller aerodynamic diameters can be carried farther through the air. The lower the aerodynamic diameter of the aerosol particles, the farther they may be transported after being entrained in an airflow. We tested the worst-case simulation scenario of infectious aerosol emissions using a propellant-powered sprayer. Propellant-powered sprayers are the type known to generate overwhelmingly ultrafine and fine particles [17–20], substantially smaller than most respiratory droplets [13,14], and our measurements of the aerosol size distribution of the aerosols used in the present study confirmed these previously published findings.

The experiments used a sneeze-simulating aerosol rather than human subjects producing real sneeze droplets, which is a limitation of this study. However, the sneeze-simulating aerosol spray cone could be produced in this study in a repeatable, strictly controlled way, which would not be possible with a real human-generated sneeze aerosol. The absence of significant variability in the aerosol size distribution allowed for isolating the effect of angle and outflow velocity on spray cone deflection. The aerosol spray cone was characterized by a fixed pattern of movement of the aerosol particles in the vicinity of the indoor air purifier, in contrast to the real-world situation where air currents and turbulence in indoor spaces can vary from one indoor space to another in an infinite number of ways. Likewise, cough or sneeze aerosol generation occurs in a great diversity of patterns and directions. However, the specific experimental design in this study allowed for targeted investigation of the deflection of the sneeze-simulating aerosol spray cone by the air purifier outflow without interference from uncertain airflows indoors due to any drafts, or any heating, ventilation, or air conditioning (HVAC) system operation.

The aerosol spray cone that was tested is characterized by a fixed pattern of movement of the aerosol particles in the vicinity of the indoor air purifier, in contrast to when air currents and turbulence in indoor spaces are varied, and the cough or sneeze aerosol generation occurs in a great diversity of patterns and directions. While conducting experiments with all possible configurations of cough and sneeze spray cones and environmental air currents is impossible, the directional spray cone investigated herein provides a straightforward system that future experimental and modeling studies can build on to explore more complex scenarios.

5. Conclusions

We conclude that the maximum air velocities generated immediately at the outer casing of the tested indoor air purifier with a circumferential outflow diffuser are lower than the velocities of the sneeze or cough droplets under the experimental conditions. However, we cannot overrule the possibility of pathogen transmission in all the different conditions possible indoors. The outflow velocities from the investigated circumferential outflow diffuser drop considerably below the sneeze or cough droplet velocities within a few centimeters to a fraction of a meter distance from the indoor air purifier equipped with such a circumferential outflow diffuser, marking their advantage over directional outflow ports. Indeed, our findings demonstrate that the infectious droplet spray cone generated by a sneezing or coughing person is unlikely to be significantly deflected by the outflow from circumferential air diffusers.

Future research should explore a broader range of real-world indoor environments, accounting for room size, occupancy, and common configurations of natural and forced-airflow ventilation. Different types of outflow diffusers and ducts are used in stationary HVAC systems, with effects on airborne pathogen transmission that are not well investigated.

Like indoor air purifiers, stationary HVAC systems use directional outflow ducts and airflow diffusers. Therefore, our results should be used to inform future research on the effects of outflow configuration on the deflection of cough and sneeze spray cones.

Human behavior factors need to be investigated, including preferences for placement of different types of indoor air purifiers in different indoor settings, the preferred location and position of people relative to indoor air purifiers, and posture.

Interventional research should be conducted in indoor spaces where airborne infection transmission is common, in occupational settings, private and public settings. These studies will shed light on the potential effectiveness of indoor air purifiers and HVAC systems with different configurations of outflow diffusers in reducing infection spread.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/atmos14101520/s1.

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References

1. Wei, J.; Li, Y. Airborne spread of infectious agents in the indoor environment. *Am. J. Infect. Control* **2016**, *44*, S102–S108. [CrossRef] [PubMed]
2. Byers, K.B.; Wooley, D.P. *Biological Safety: Principles and Practices*; Wiley: Washington, DC, USA, 2017.
3. Hughes, R. *Patient Safety and Quality: An Evidence-Based Handbook for Nurses*; Agency for Healthcare Research and Quality, U.S. Department of Health and Human Services: Rockville, MD, USA, 2008.
4. Lednicky, J.A.; Lauzardo, M.; Fan, Z.H.; Jutla, A.; Tilly, T.B.; Gangwar, M.; Usmani, M.; Shankar, S.N.; Mohamed, K.; Eiguren-Fernandez, A.; et al. Viable SARS-CoV-2 in the air of a hospital room with COVID-19 patients. *Int. J. Infect. Dis.* **2020**, *100*, 476–482. [CrossRef] [PubMed]
5. Van Doremalen, N.; Bushmaker, T.; Morris, D.H.; Holbrook, M.G.; Gamble, A.; Williamson, B.N.; Tamin, A.; Harcourt, J.L.; Thornburg, N.J.; Gerber, S.I.; et al. Aerosol and Surface Stability of SARS-CoV-2 as Compared with SARS-CoV-1. *N. Engl. J. Med.* **2020**, *382*, 1564–1567. [CrossRef] [PubMed]
6. Chia, P.Y.; Coleman, K.K.; Tan, Y.K.; Ong, S.W.X.; Gum, M.; Lau, S.K.; Sutjipto, S.; Lee, P.H.; Son, T.T.; Young, B.E.; et al. Detection of Air and Surface Contamination by Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) in Hospital Rooms of Infected Patients. *Nat. Commun.* **2020**, *11*, 2800. [CrossRef] [PubMed]
7. Liu, Y.; Ning, Z.; Chen, Y.; Guo, M.; Liu, Y.; Gali, N.K.; Sun, L.; Duan, Y.; Cai, J.; Westerdahl, D.; et al. Aerodynamic analysis of SARS-CoV-2 in two Wuhan hospitals. *Nature* **2020**, *582*, 557–560. [CrossRef] [PubMed]
8. Setti, L.; Passarini, F.; De Gennaro, G.; Baribieri, P.; Perrone, M.G.; Borelli, M.; Palmisani, J.; Di Gilio, A.; Torboli, V.; Pallavicini, A.; et al. SARS-Cov-2 RNA Found on Particulate Matter of Bergamo in Northern Italy: First Preliminary Evidence. *medRxiv* **2020**, *188*, 109754. [CrossRef]
9. Santarpia, J.L.; Herrera, V.L.; Rivera, D.N.; Ratnesar-Shumate, S.; Reid, S.P.; Denton, P.W.; Martens, J.W.S.; Fang, Y.; Conoan, N.; Callahan, M.V.; et al. The Infectious Nature of Patient-Generated SARS-CoV-2 Aerosol. *medRxiv* **2020**. [CrossRef]
10. Drossinos, Y.; Weber, T.P.; Stilianakis, N.I. Droplets and aerosols: An artificial dichotomy in respiratory virus transmission. *Health Sci. Rep.* **2021**, *4*, e275. [CrossRef] [PubMed]

11. Zhu, N.; Zhang, D.; Wang, W.; Li, X.; Yang, B.; Song, J.; Zhao, X.; Huang, B.; Shi, W.; Lu, R.; et al. A Novel Coronavirus from Patients with Pneumonia in China, 2019. *N. Engl. J. Med.* **2020**, *382*, 727–733. [CrossRef] [PubMed]
12. Vejerano, E.P.; Marr, L.C. Physico-chemical characteristics of evaporating respiratory fluid droplets. *J. R. Soc. Interface* **2018**, *15*, 20170939. [CrossRef] [PubMed]
13. Wells, W.F. On Air-Borne Infection*: Study II. Droplets and Droplet Nuclei. *Am. J. Epidemiol.* **1934**, *20*, 611–618. [CrossRef]
14. Stadnytskyi, V.; Bax, C.E.; Bax, A.; Anfinrud, P. The airborne lifetime of small speech droplets and their potential importance in SARS-CoV-2 transmission. *Proc. Natl. Acad. Sci. USA* **2020**, *117*, 11875–11877. [CrossRef] [PubMed]
15. World Health Organization. *Severe Acute Respiratory Infections Treatment Centre: Practical Manual to Set Up and Manage a SARI Treatment Centre and a SARI Screening Facility in Health Care Facilities*; WHO: Geneva, Switzerland, 2020.
16. Pushpawela, B.; Jayaratne, R.; Nguy, A.; Morawska, L. Efficiency of ionizers in removing airborne particles in indoor environments. *J. Electrost.* **2017**, *90*, 79–84. [CrossRef]
17. Ham, S. Prevention of exposure to and spread of COVID-19 using air purifiers: Challenges and concerns. *Epidemiol. Health* **2020**, *42*, e2020027. [CrossRef] [PubMed]
18. Rogers, R.E.; Isola, D.A.; Jeng, C.-J.; Lefebvre, A.; Smith, L.W. Simulated Inhalation Levels of Fragrance Materials in a Surrogate Air Freshener Formulation. *Environ. Sci. Technol.* **2005**, *39*, 7810–7816. [CrossRef] [PubMed]
19. Yan, J.; Grantham, M.; Pantelic, J.; Bueno de Mesquita, P.J.; Albert, B.; Liu, F.; Ehrman, S.; Milton, D.K.; Consortium, E. Infectious virus in exhaled breath of symptomatic seasonal influenza cases from a college community. *Proc. Natl. Acad. Sci. USA* **2018**, *115*, 1081–1086. [CrossRef] [PubMed]
20. Shen, Y.; Courtney, J.M.; Anfinrud, P.; Bax, A. Hybrid measurement of respiratory aerosol reveals a dominant coarse fraction resulting from speech that remains airborne for minutes. *Proc. Natl. Acad. Sci. USA* **2022**, *119*, e2203086119. [CrossRef] [PubMed]