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비말 가림막과 휴대형 공기청정기 사용에 의한 대화 중 비말 및 공기전파 저감 효과

허 지 은 · 신 동 호 · 조 희 주 · 박 현 설 · 조 윤 행*
한국에너지기술연구원 기후변화연구본부

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Effectiveness of droplet protective screens and portable air purifiers against droplet and airborne transmission during conversation

Jieun Heo · Dongho Shin · Hee-Joo Cho · Hyun-Seol Park · Yun-Haeng Joe*
Climate Change Research Division, Korea Institute of Energy Research

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Abstract

Currently, droplet protective screens (DPSs) are used to prevent the spread of respiratory diseases. As virus particles can maintain their infective in indoor environments, recent studies have investigated the risk of airborne transmission. However, the ability of DPSs to block airborne transmission has not been verified yet. In this study, the preventive ability of DPSs against droplet and airborne transmission was evaluated. Moreover, the effectiveness of a Portable air purifier (PAP) was investigated. According to results, in a simulated room where an infectious person spoke, the DPS blocked more than 90% of the micron-sized droplets (with a diameter larger than 1 μm) transmitted to the front of the infectious person. However, sub-micron droplets (with a diameter smaller than 1 μm) passed through the DPS and spread in a room. However, the PAP reduced the amount of both micron and sub-micron droplets transmitted to the front of the infectious person. When the PAP airflow direction was set from the DPS surface to the free space near the infectious person, improved prevention against droplet and airborne transmission was recorded. However, airborne transmission was accelerated when the PAP airflow direction was set from the free space to the DPS surface.

Keywords: Airborne transmission, Conversation, Droplet Protective Screen, Portable Air Purifier

*Corresponding author.
Tel : +82-42-860-3636
Email : yhjoe@kier.re.kr

1. Introduction

In the past, the respiratory infection syndromes caused by virus particles, such as severe acute respiratory syndrome (SARS), influenza A, and Middle East respiratory syndrome (MERS), have led to significant epidemiological issues worldwide. The novel severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), which was first reported in the People's Republic of China, has infected more than 551 million people globally, and approximately 6 million deaths were reported by July 2022 (WHO COVID-19 Dashboard, 2022).

Virus-laden droplets are generated when an infectious person coughs, sneezes, or speaks. These droplets spread through various routes, namely, droplet and airborne transmission. Droplet transmission refers to the direct transmission of virus-laden droplets with a diameter larger than 5 μm to a person in close contact with an infectious person. Airborne transmission refers to the direct transmission of virus-laden droplets with a diameter smaller than 5 μm to a person in the same space as an infectious person (Asadi et al., 2020; Bourouiba, 2020; Mittal et al., 2020; Morawska and Cao, 2020). Because droplet transmission is known to be the major transmission route in respiratory infectious diseases, a droplet protective screen (DPS), which constitutes a wall placed in front of an infectious person, has been recommended and widely used worldwide. Foster and Kinzel (2021) analyzed the effectiveness of utilizing DPSs for preventing the spread of SARS-CoV-2 in a classroom using computational fluid dynamics (CFD). Lessler et al. (2021) reported that the mitigation measures, such as using a mask or DPS, could reduce the SARS-CoV-2 transmission during in-person schooling.

Even though a DPS can effectively block large droplet transmission, it may not be able to prevent the diffusion and spread of the droplets that are too small to be removed through inertial impaction. However, virus particles can maintain their infectivity for several days in an indoor environment and lead to airborne infection (Domingo et al., 2020; Eissenberg et al., 2020; Kumar and Morawska, 2019; Morawska and Milton, 2020). Recent studies have reported the risk of the airborne transmission of SARS-CoV-2 in locations with poor ventilation systems (Li et al., 2020; Liu et al., 2020; Setti et al., 2020; Wang and Du, 2020). In addition, the World Health Organization (WHO) provided a warning about the possible airborne SARS-CoV-2 transmission in a statement on July 9, 2020. Therefore, a method to block not only droplet transmission but also airborne transmission is required to effectively prevent the spread of viral respiratory disease. However, existing quantitative studies on the preventive ability of DPS against droplet and airborne transmission are lacking.

In this study, the preventive abilities of DPSs against droplet and airborne transmission were evaluated. Two types of DPSs were selected, and the change in the artificial saliva droplet concentration with respect to time was measured in a simulated room where an infectious person spoke while two recipients were in close contact with him. Moreover, it was investigated whether the preventive ability of DPSs could be improved by installing a portable air purifier (PAP).

2. Experimental Methods

2.1 Preparation of artificial saliva solution

An artificial saliva solution was prepared based on a previous study (Hu et al., 2015). Ten grams of carboxymethylcellulose sodium, 30 g of sorbitol, 1.2 g of potassium chloride, 0.052 g of magnesium chloride, 0.9 g of sodium chloride, 0.088 g of calcium phosphate, and 0.331 g of sodium phosphate were mixed with 1000 mL of distilled water and stirred for 30 min at 80 °C for complete dissolution. All chemicals used in this study were purchased from Sigma-Aldrich.

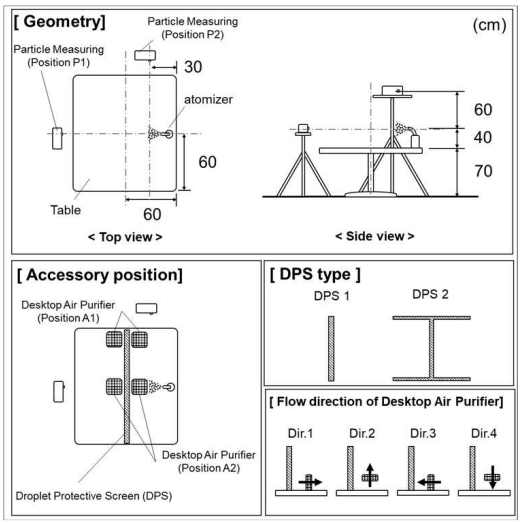

Figure 1. Experimental setup.

2.2 Experimental setup and data analysis method

Figure. 1 shows the experimental setup. A table (L × W × H = 120 × 120 × 70 cm^3) was placed in the middle of a test room (L × W × H = 660 × 320 × 270 cm^3), and an atomizer (9302, TSI Inc.) was installed on one side of the table. The exhaust flow velocity of the atomizer was kept at 3.0 m/s, which is the average flow velocity when a person speaks (Chao et al., 2009; Gupta et al., 2010; Kwon et al., 2012). Two optical particle counters (11A, Grimm Aerosol Technik GmbH & Co.) were installed in front of (P1) and next to (P2) the atomizer to simulate the cases of a person sitting while facing an infectious person and a person standing next to an infectious person, respectively. Two different types of DPSs were used in this study. DPS 1 was 120 cm wide and 50 cm high. DPS 2 was 90 cm wide and 50 cm high, and it contained a 100 cm wide wing on both sides. Moreover, two PAPs (PuriCare Mini, LG electronics) were applied to improve the prevention against airborne transmission. They were positioned on the side of DPS 1 (position A1 in Figure. 1) and at the middle of DPS 2 (position A2 in Figure. 1).

The background droplet concentration in the test room was measured for 5 minutes; then, artificial saliva was generated for 30 seconds. The generation was repeated five times at 30 seconds intervals, and the change in the droplet concentration with respect to time was measured for 50 minutes. When one experiment was finished, the residual droplets in the test room were removed using an air purifier. The experiment was repeated three times for each case. The details of the experiments are summarized in Table 1.

Table 1. Details of experimental cases.

Case	DPS type	PAP	
		Position	Airflow direction
1	Not used	Not used	
2	DPS 1	Not used	
3	DPS 2	Not used	
4	DPS 1	A1	Dir. 1
5			Dir. 2
6			Dir. 3
7			Dir. 4
8	DPS 2	A2	Dir. 1
9			Dir. 2
10			Dir. 3
11			Dir. 4

In this study, for future data analysis, we classified the change in particle concentration over time into two phases: droplet spraying and well-mixed phases. The preventive abilities of the DPSs and PAPs against droplet transmission were evaluated in the droplet spraying phase, while the effectiveness of DPSs and PAPs in preventing airborne transmission were evaluated in the well-mixed phase.

In general, the air cleaning ability of an air purifier is evaluated based on the clean air delivery rate (CADR), which is recognized by the Association of Home Appliance Manufacturers (AHAM) (Association of Home Appliance Manufacturers, 2006). In this study, the AHAM method was utilized to evaluate the preventive abilities of each experimental setup against airborne transmission in the well-mixed phase. The CADR was calculated by following equation.

$$CADR = \frac{V}{Nt}\left(\ln\frac{\overline{C}_{0,i}}{\overline{C}_{t,i}} - \ln\frac{\overline{C}_{0,case1}}{\overline{C}_{t,case1}}\right) \quad (1)$$

where V is the volume of the test room, N is the number of PAPs, t is time, and subscript i denotes the case number. $\overline{C_t}$ and $\overline{C_o}$ are the total number concentrations of the droplets (ranging from 0.265 to 34 μm in diameter) at time t and the start time of well-mixed phase, respectively.

Diffusion and spreading of droplets become more frequent as the particle size reduces, and particle inertia collision and adhesion on the DPS become more frequent as the particle size increases. Therefore, the risk of airborne transmission might increase as the size of the particles decreases. Moreover, according to the results of previous studies conducted by Gregson et al. (2021) and Johnson et al. (2011), the droplets generated by human speaking, singing, and breathing are mostly within 5 μm in diameter, especially, a high concentration of droplets are generated in the sub-micron region (1 μm or less in diameter). Accordingly, it is necessary to evaluate the removal ability of the proposed system according to the particle size. In this study, the removal fractions of the DPS and PAP system regarding sub-micron droplets (η_{sub}) and micron-sized droplets (having a diameter larger than 1 μm, η_{micron}) were calculated using the following formulas, respectively.

$$\eta_{sub} = \sum_{d_p=0}^{1}[f(d_p)\times(1-\frac{C(d_p)_i}{C(d_p)_{case1}})] \quad (2)$$

$$\eta_{micron} = \sum_{d_p=1}^{\infty}[f(d_p)\times(1-\frac{C(d_p)_i}{C(d_p)_{case1}})] \quad (3)$$

where $f(d_p)$ is the frequency function with respect to the droplet size for case 1, and $C(d_p)$ is the droplet number concentration with respect to the droplet size.

3. RESULTS AND DISCUSSION

Figure. 2 depicts the change in the droplet concentration with respect to time for cases 1 to 3. When artificial saliva droplets were generated, high

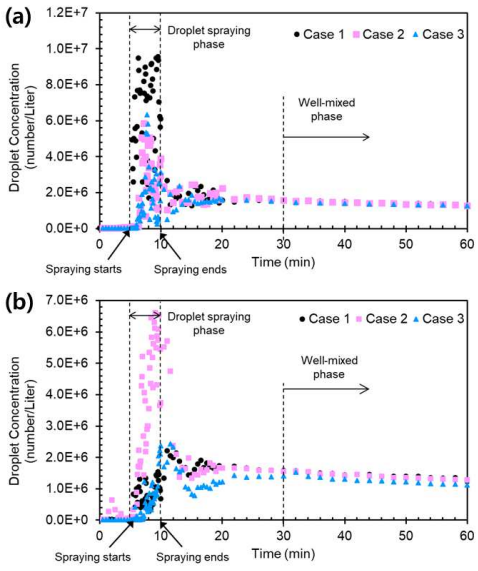

Figure 2. Change in droplet concentration with respect to time according to DPS application at (a) P1 and (b) P2.

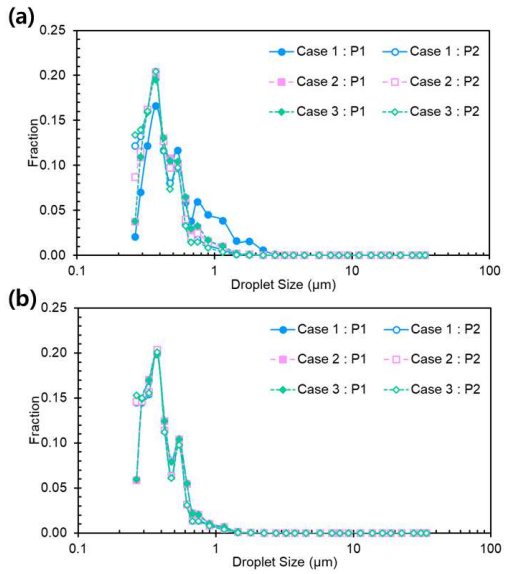

Figure 3. Droplet size fraction at P1 and P2 in the (a) droplet spraying phase and (b) well-mixed phase.

concentration droplets were observed at P1 and P2. The influence of the droplet generation for 20 min after the spraying was stopped. Thirty minutes after the start of the experiment, the droplet concentrations at P1 and P2 exponentially decreased. In addition, the droplet size distributions at P1 and P2 became almost the same regardless of the experimental conditions (Figure. 3b). It indicates that the generated droplets were well-mixed and distributed in the test room after 30 minutes from the start of the experiment. For this reason, periods of 5-15 min and 30-50 min from the start of the experiment were defined as the droplet spraying and well-mixed phases, respectively.

3.1 Effects of DPSs and PAPs on droplet spraying phase

Figure. 4 shows the droplet concentrations and droplet removal fractions at P1 and P2. In case 1, the droplet concentration at P1 was 8.1 × 10^6 particles/Liter during droplet generation. Approximately 90% of the generated droplets were sub-micron droplets, and 99% or more droplets were 5 μm or less in diameter. The median droplet diameter (diameter with 50% fraction in the accumulative distribution) was approximately 0.42 μm. In cases 2 and 3, the DPS removed more than 90% of the micron-sized droplets at P1. Thus, the median diameter slightly decreased to 0.36 μm. However, the removal fraction of the DPS decreased as the droplet size decreased, which was approximately 50% for sub-micron droplets. In case 2, the droplet concentration at P2 was approximately 2.5 times higher than that in case 1, while the droplet size fraction was similar to that observed in case 1 (see Figure. 3a). This implies that it is difficult to remove sub-micron droplets using DPS 1; rather, the droplets move to the side of the DPS, consequently, a recipient located next to an infectious person may be exposed to a high concentration of droplets. In case 3, the droplet concentration at P2 was slightly less than that observed in case 1.

The sub-micron virus-laden droplets can be emitted during breathing (Fabian et al., 2008; Papineni and Rosenthal, 1997) and speaking (Gregson et al., 2021; Johnson et al., 2011, Loudon and Roberts, 1967). According to the studies conducted by Asadi et al.

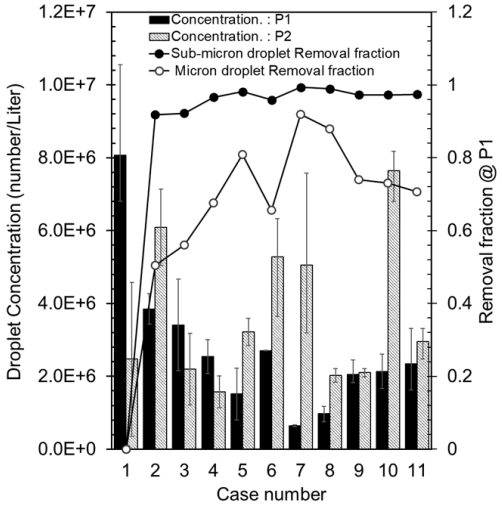

Figure 4. Droplet concentrations and removal fractions in the droplet spraying phase.

(2019), one to fifty particles having 1 μm in mode diameter were emitted for a second during normal speech. Moreover, up to 82.7 particles/cm^3 of nano size droplets can be emitted even during breathing (Holmgren et al., 2010). Theoretically, a water droplet with a 40 μm diameter evaporates to its original nuclei within 1.3 seconds under general indoor environmental condition (20 ºC and 50 RH%) (Hinds, 1998), and droplets with the diameter of 10 μm are perfectly evaporated within 0.2 seconds even 95 RH% of humidity (Yang et al., 2020). Because the diameter of SARS-CoV-2 is known to range from 50 to 200 nm (Guzman, 2020), the virus-laden droplets generated by infectious person can evaporate and become sufficiently small to cause an infection by air transmission.

In all cases with PAPs (cases 4−11), the droplet concentration at P1 was less than that observed in the cases with only the DPSs (cases 2 and 3). When the airflow direction of the PAPs was set from the DPS surface to the free space, such as in cases 4 and 8, the droplet concentration at P2 was similar or less than that measured at P1. However, when the airflow direction of the PAPs was set from the free space to the DPS surface, such as in cases 6, 7, 10, and 11, the droplet concentration at P2 was considerably higher than that measured at P1. This may be due to the differences between the suction flow velocities of the PAPs and droplets, and the flow pattern at the DPS surface. In this study, the droplet generation velocity was set as 3 m/s to simulate an infectious person speaking. This velocity was approximately three times higher than the PAP flow velocity. In this situation, it was difficult for the droplets to be sucked into the PAP. Instead, the droplets flowed to the DPS surface, where diffusional and rotational flow was created by the outlet flows. As a result, the droplets were rapidly spread in the room.

3.2 Effects of DPSs and PAPs on well−mixed phase

Figure. 5 shows the average droplet concentrations and CADR values. In all cases, the droplet concentrations at P1 and P2 were constant within the error range. In case 1, the droplet concentration at P1 was 1.4 × 10^6 particles/Liter; similar concentrations were measured in cases 2 and 3. In other words, it was difficult to eliminate the evenly distributed droplets in the room using the DPSs. The PAPs led to a significant decrease in the droplet concentration. In particular, cases 4 and 8 demonstrated superior preventive abilities against droplet and airborne transmission mechanisms. The CADR values in cases 2 and 3 were zero because the DPSs did not have an air cleaning function. The CADR values ranged between 0.19−0.21 m^3/min cases 4−11. However, a significant relationship between the PAP airflow direction and CADR was not observed in the experiments.

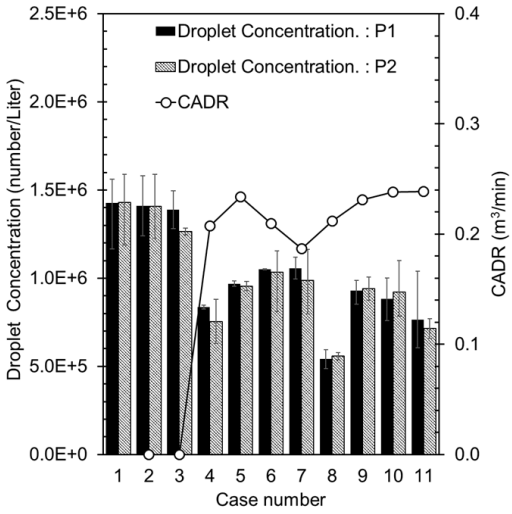

Figure 5. Droplet concentrations and CADR values in the well−mixed phase.

3.3 Effectiveness of DPSs and PAPs in prevention of droplet and airborne transmission

The DPSs effectively prevented droplet transmission to the recipient sitting in front of the infectious person. However, the DPSs could not eliminate the flow of sub-micron droplets to the side of the infectious person. In the case of DPS 1, a high droplet

concentration was measured at the side of the infectious person, and the DPS did not contribute to preventing of airborne transmission.

Installing PAPs improved the preventive ability against droplet transmission to the recipient sitting in front of infectious person, as compared with the cases that utilized only DPSs. For the recipient standing next to the infected person, the droplet concentration significantly differed based on the PAP flow direction. When the PAP airflow direction was set from the DPS surface to the free space, the prevention against droplet and airborne transmission was more effective. However, airborne transmission was further accelerated in the opposite airflow direction.

4. CONCLUSIONS

Four meaningful findings derived from our experiments, which are repoted below:

(1) It was hard to prevent the airborne transmission of sub-micron droplets using a DPS.
(2) If a DPS did not have wings on its both sides, it rather facilitated the transmission of sub-micron droplets to the side of the infectious person.
(3) When a PAP is installed with the DPS and its airflow direction was set from the DPS surface to the free space, the preventive abilities against both droplet and airborne transmission were improved.
(4) If the PAP airflow direction was set from the free space to the DPS surface, the spread of the droplets generated from an infectious person to the room was accelerated.

Although this study was conducted in a specific environment, our findings may underline the limitations of using DPS to prevent airborne virus-laden droplet transmission in indoor environments. Futhermore, our results can be used to define how to correctly use a PAP to prevent the transmission of respiratory infectious droplets.

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