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Impact on airborne virus behavior by an electric heat pump (EHP) operation in a restaurant during winter season

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ARTICLE INFO

Keywords:
EHP systems
Airborne virus transmission
COVID-19
Indoor airflow
Long-distance transmission
Restaurant

ABSTRACT

The world is having an unprecedented time due to the pandemic. Currently, more than 93 million people have been infected, and over 2 million people have passed away since 2020. SARS-CoV-2 has forced people to change their lifestyles and patterns. Under the pandemic, buildings are no longer safe shelters. The infected transmit infectious viruses to other occupants by direct contact or indirect contact (i.e., indoor airflow). In addition, the airflow from electric heat pump systems can propel indirect contact in indoor spaces. However, the impact of airflow is still not sufficiently identified to develop virus control strategies in buildings. Therefore, this study selected a restaurant in Seoul, Korea, to experiment with airborne virus transmission of direct airflow in winter using virus-similar particles. The results of this study verified the potential exposure of droplets or aerosols to occupants that can be delivered by air current from heating systems in winter. The effect of kitchen hoods was also confirmed as additional ventilation equipment without additional budget investment in restaurants. The recommendations of this study are expected to improve the guidelines for restaurants to ensure occupant’s safety during the COVID-19 period.

1. Introduction

Recently, the world is experiencing social, economic, and environmental difficulties due to the spread of SARS-CoV-2. More than 93 million people have already been infected, and hundreds of thousands of infectious new occur every day in the world [1]. The building is the primary activity space for people to spend the majority of the day working, sleeping, eating, and raising children [2]. However, the building is vulnerable to prevent indoor airborne contaminant transmission when an infected occupant is present in a closed space. Therefore, buildings would be used as a transmission route for new infections, which may carry potential contaminants from the infected in confined spaces. For example, COVID-19 outbreaks of closed places (i.e., restaurants, churches, meeting rooms, conferences) have shown the risk of uncontrolled transmission in indoor space [3]. Closed spaces without sufficient disinfection and ventilation efforts can potentially increase the exposure of SARS-CoV-2 to occupants.

To date, one of the best ways to control the spread of SARS-CoV-2 is to suppress indoor transmission by introducing fresh air through frequent ventilation [4–6]. An increase in outdoor air using mechanical and natural ventilation helps circulate fresh air into the building and lowers the concentration of potential air contaminants, including SARS-CoV-2 [7]. However, some spaces in a building may not be advantageous to operate natural or mechanical ventilation, so it is significant to develop mitigation strategies to provide adequate ventilation and airflow controls for closed spaces [4].

In closed spaces, indoor airflow is a key factor contributing to the spread of SARS-CoV-2 in buildings [8]. Direct airflow from heating, ventilation, and air conditioning (HVAC) systems can increase the risk of COVID-19 infection to other occupants who occupy the closed space along the airflow direction. The spread of SARS-CoV-2 by direct indoor airflow has been verified in restaurant outbreaks in Guangzhou, China, and Jeonju, Korea [8,9]. Both cases showed virus infection where the occupants were located in the direction of the HVAC system’s airflow. These cases represented that direct airflow from air conditioners could be used as a path for virus transmission in confined spaces. The results warned potential exposure of SARS-CoV-2 infection that would be possible even at a distance of 6.5 m or more depending on the indoor airflow. This fact proved the significance of the direct airflow controls in buildings during air-conditioning to prevent the spread of SARS-CoV-2.

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https://doi.org/10.1016/j.buildenv.2021.107951
Received 22 March 2021; Received in revised form 30 April 2021; Accepted 5 May 2021
Available online 10 May 2021

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Among the space types, restaurants are the most infectious spaces of COVID-19. For example, in the United States, fully occupied restaurants caused the largest outbreaks in SARS-CoV-2 [10]. In the restaurant, the occupants typically stay for as little as 30 min and as long as 2 h during mealtime in the closed space. Extended stays in restaurants can pose a potential exposure of occupants to airborne contaminants during the COVID-19 pandemic. Also, the outbreak in a Korean call center reminds us of the risk of long exposure time to SARS-CoV-2 in closed spaces [11]. Therefore, in order to ensure safety in a restaurant, it is necessary to understand indoor airflow behavior by ventilation and HVAC systems in order to develop effective mitigation strategies.

Under COVID-19, ventilation and indoor airflow controls are practical approaches to restrain the virus spread and reduce the concentration of air contaminants ins dining rooms of restaurants. In general, HVAC systems, windows, and kitchen hoods can be used to generate airflow for air-conditioning and ventilation in restaurants. Researchers in previous studies have performed epidemiological investigations [3,9, 11,13] or Computational Fluid Dynamics (CFD) simulations [13,14] to identify the infection routes of SARS-CoV-2 associated with indoor airflow and ventilation in the building spaces. However, experimental research is not common in previous literature in public spaces such as restaurants. Therefore, the aim of this study is to conduct an experiment using virus-similar particles to investigate the indoor airflow behavior by HVAC and ventilation systems in a restaurant during winter. Based on the experiment, this study diagnosed potential infection risks in restaurants and suggested recommendations to improve the control strategies of infectious matters for re-opening restaurants. For this, this study selected a restaurant located within a university in Seoul, Korea. The indoor airflow behavior by the heating and ventilation systems was monitored using virus-similar particles (i.e., droplet or aerosol-sized oil and smog) in the restaurant. The spread and concentration of virus-similar particles were tracked depending on heating and ventilation operating methods. The findings of this study are expected to contribute to understanding the uncontacted transmission of SARS-CoV-2 in restaurants and reducing the potential risk of virus exposure to occupants.

2. Literature review

Since last year, COVID-19 has been globally transmitted. The increased threat of infectious requires a change in our everyday lifestyle. For example, it becomes important to keep social-distancing between people and lower occupancy density in confined spaces. In addition, face coverings and ventilation became mandatory in many countries, and it is people and lower occupancy density in confined spaces. In addition, face coverings and ventilation became mandatory in many countries, and it is not optional anymore [15,16]. However, in current building energy codes and standards have been striving to improve energy efficiency and ultimately achieve zero energy buildings [17,18]. Thus, the occupants are vulnerable in buildings to abnormal circumstances such as the SARS-CoV-2 pandemic [19]. Also, the restaurant is regarded as a susceptible facility to airborne virus transmission during the pandemic [20]. Therefore, in order to operate restaurants in extreme conditions (e.g., SARS-CoV-2), it is necessary to explore the airflow behavior by HVAC and ventilation systems in buildings.

2.1. SARS-CoV-2 transmission in restaurants

To date, droplets are known as a primary inspection route of COVID-19 [4,21]. Droplets mainly occur in the process of coughing, sneezing, and conversation of occupants, and the amount of droplets varies depending on gender, age, and activity. Typically, the size of the droplets is larger than 5–10 μm, and if the droplets contain viruses during the breathing process, respiratory droplets can be a path for virus transmission in the air [22]. Although there is no clear consensus on the definition of aerosols, small droplets and nuclei of 5 μm or less are defined as aerosols. Recent studies pointed out the potential risk of COVID-19 spread through aerosols in the air [4].

In buildings, SARS-CoV-2 infection is primarily occurred by direct contact (e.g., from index case) and indirect contact (e.g., indoor airflow). The spread of contagious disease can be reduced through social distancing, wearing a mask, teleworking from home. However, restaurants are representative spaces where people stay densely and for a long time to eat meals, which would make direct contact and indirect contact to infectious contaminants. Indoor airflow in restaurants can cause unintended long-distance transmission of airborne contaminants when operating HVAC systems in closed spaces. Therefore, in order to reopen restaurants, a detailed understanding is required to prevent the virus transmission by indoor airflow.

Restaurants have been confirmed in many countries as primary transmission routes for SARS-CoV-2. For instance, research using U.S. mobile data verified that restaurants worked as the largest propagation path in the COVID-19 spread process across the United States [20]. According to this study, occupant exposure in restaurants is mainly related to air circulation in confined spaces. Indoor airflow direction, speed, and ventilation can affect the SARS-CoV-2 transmission even if occupants comply with social distancing or face coverings. The exposure risk in a restaurant also increases in restaurants due to no face covering while eating or drinking. In reports from the epidemiological investigation conducted by the Korea Disease Control and Prevention Agency (KDCPA) [Table 1], significant causes of indoor infection in restaurants and cafes were identified, such as unventilated interior structure, insufficient natural ventilation, high occupant density, eating and talking without covering faces, and extended stays in closed spaces [3]. In addition, the outbreak of restaurants in Guangzhou, China, showed that droplets would be delivered by air conditioners. The results represented that airflow direction from HVAC systems is an important factor in an enclosed space to control infectious diseases. COVID-19 outbreaks in restaurants informed that if an index case visits a restaurant, the airflow direction and airspeed can significantly influence long-distance transmission of air contaminants [9].

2.2. Role of HVAC systems in SARS-cov-2 transmission

In buildings, HVAC systems play a role in supplying cooling, heating, and ventilation to maintain thermal comfort and indoor air quality. Traditionally, the control of HVAC systems has more focused on energy savings in buildings. For example, the current building energy codes and standards have been striving to improve energy efficiency and ultimately achieve zero energy buildings [18,24–26]. Thus, energy conservation measures, such as air recirculation [27,28] and heat recovery [29–31] in HVAC systems, were preferred to be investigated in previous literature. However, in the current perspective, HVAC systems may increase the chances of SARS-CoV-2 infection to occupants in buildings due to insufficient ventilation or no indoor airflow controls in extreme situations such as a pandemic. Therefore, the role of HVAC systems in SARS-CoV-2 transmission should be interpreted to lower the potential exposure and support reopening during the pandemic period. In terms of the nature of COVID-19, The World Health Organization (WHO) described that COVID-19 could be easily transmitted in situations, such as “3C” [32]: 1) Crowded places with many people nearby; 2) Close-contact settings, especially where people have conversations very near each other; 3) Confined and enclosed spaces with poor ventilation. Thereby, poor ventilation in closed rooms represents the necessity of the HVAC systems to mitigate the spread of SARS-CoV-2 and supply fresh air into buildings. Also, if sufficient filtering or sterilization is not performed in HVAC and duct systems, the HVAC systems can be used as a potential infection path through the spread of droplets or aerosols. Although there are concerns of indoor transmission by HVAC systems (i.e., ducts), no clear evidence has been reported associated with airborne spreading through air conditioning systems [4]. Also, the risk of the COVID-19 transmission through ventilation systems is currently not well-known [33].
Typically, HVAC systems are frequently used in summer and winter. However, heating, cooling, and ventilating during the COVID-19 period would accelerate the spread of SARS-CoV-2 in buildings due to indoor airflow. Therefore, indoor airflow and direction in enclosed spaces should be observed to prevent potential exposure to any infectious materials [3,8,9]. Some countries have recommended limiting the indoor airflow speed to within 0.4 m/s [4], and the reduced wind speed plays a role in reducing potential virus infection by slowing the transmission rate of air contaminants. Therefore, in order to reduce the number of infected cases due to artificial airflow from HVAC systems in summer and winter, it is required to know the role of HVAC systems in the indoor spreading of contagious diseases, such as SARS-CoV-2, more precisely.

### 2.3. Mitigation strategies of airborne contaminant exposure in restaurants

During this pandemic, scientists discovered that building spaces are susceptible to the spread of viruses, and thus, the indoor spaces are required to be controlled to dilute the concentration of COVID-19 through ventilation, filtering, and airflow controls. The WHO described that a well-maintained and operating system is able to reduce the transmission of SARS-CoV-2 in indoor spaces by increasing the ventilation rate, decreasing recirculation of air, and expanding the use of outdoor air. Also, to operate correctly, they recommended that HVAC systems should be regularly checked, maintained, and cleaned [34]. Among all building types, restaurants are considered a high-risk group in many countries due to virus infection vulnerability (e.g., eating/talking without a mask, extended stay, high occupancy) during mealtimes in closed spaces. Direct airflow from an infectee may boost the risk of virus transmission from one person to another [34], especially in restaurants. Therefore, health authorities and professional societies have guided building reopening and HVAC system operations, including restaurants, to ensure occupant safety. From previous studies and guidelines, the primary guidelines of SARS-CoV-2 viruses, especially for HVAC systems, can be broadly classified into four types of control methods in restaurants: 1) monitoring (M), 2) direct contact (D), and 3) indirect contact (I), 4) Contaminant removal (C). Table 2 summarized the strategies based on the previous literature to alleviate airborne infection considering the role of the HVAC systems in closed spaces. The monitoring strategy (M) is basically to detect the infected person before entering the building and prevent the spreading of infectious materials into the building. The key to the direct contact (D) strategy is to lower the indoor occupancy density or minimize the direct physical contact of occupants by keeping social distancing. Indirect contact (I) aims to prevent or slow the indirect transmission of SARS-CoV-2 viruses by indoor airflow accompanying droplets or aerosols when an infected person occupies an indoor space. Since the HVAC systems significantly influence the creation of indoor airflow, the heating/cooling air direction and airspeed must be determined based on the indoor occupant density and placement. Finally, the purpose of contaminant removal (C) is to improve occupant safety by lowering the concentration of indoor potential contagious pollutants through natural ventilation, mechanical ventilation, and air cleaning.

Many guidelines have provided useful measures to fight against SARS-CoV-2. However, further research is still needed to identify how these guidelines could potentially reduce or eliminate the spread of the airborne virus in restaurants. In that respect, this study can conduct an experimental approach to understand potential COVID-19 outbreaks using virus-similar particles in a case restaurant. The outcome of this study will be used to improve the current guidelines for better safety in restaurants.

### 3. Methodology

This study investigated airborne contaminant transmission in a case study restaurant using virus-similar particles (i.e., droplet or aerosol-sized oil and smog) depending on heating and ventilation controls in winter. The experiment was performed to analyze possible exposure due to indoor airflow and ensure the health of employees and customers using various ventilation measures in the restaurants during the pandemic. Therefore, the spread of virus-similar particles was tracked based on the direction of indoor airflow from a floor-standing electric heat pump system (EHP) in the dining room. The experiment was performed to confirm the accelerated spread of virus-similar particles by the direct airflow from the EHP heating system and verify the removal effect of potential airborne contaminants by the ventilation methods. Based on the results, this study suggested recommendations to develop the heating system guidelines for the restaurants during the heating period.

#### 3.1. Overview

To conduct the experiment, this study selected an underground restaurant located in a university in Seoul, Korea, to monitor the spread of air contaminant particles in the restaurant due to the different heating and ventilation controls in winter. A restaurant is a place where university students usually visited, and some of the external walls are
Table 2
Mitigation strategies to control airborne transmission in closes spaces.

| Reference     | Considerations                                                                                     | Control Type |
|---------------|----------------------------------------------------------------------------------------------------|--------------|
| WHO [34]      | • Increased air change and no use of recirculation modes                                             | C/I          |
|               | • Avoiding fan operations when people are visiting, since some people may be infected despite not having any symptoms | I            |
|               | • Ceiling fans to improve circulation of outside air and to be avoided about pockets of sluggish air in occupied rooms | C/I          |
|               | • Opening windows to increase outdoor air exchange                                                   | C            |
|               | • Increased natural ventilation                                                                      | C            |
|               | • Separation of direct airflow from groups of individuals to prevent transmission of SARS-CoV-2 from infected individuals to others | C            |
|               | • MERV 13 or higher filters, ultraviolet germicidal irradiation (UVGI)                               | C            |
|               | • Increased outdoor air ventilation                                                                 | C            |
|               | • Fans to increase the effectiveness of open windows                                                 | I            |
|               | • Avoiding fan placement that could potentially bring about infectious airflow directly from one person over another. | C            |
|               | • Decreased occupancy in areas where fresh air cannot be ventilated                                  | C            |
|               | • Acceptable indoor air quality for the current occupancy rate for indoor space.                    | C            |
|               | • Increased airflow in occupied spaces if possible.                                                  | C            |
|               | • Improved central air filtration and installation of ultraviolet germicidal irradiation (UVGI)      | C            |
| Korea [15]    | • Ventilation with outside air as often as possible                                                  | C            |
|               | • When using HVAC systems, recirculated indoor air could increase the risk of the long-distance virus spreading through droplets, so make sure to ventilate frequently and carefully use HVAC systems with the controls of wind direction and volume | I            |
|               | • Avoiding direct wind from air conditioners and air purifiers to people, and use lower wind speed as low as possible | C            |
|               | • Removal of air contaminants by running the air conditioner at the maximum air volume for at least 30 min with both the door and the window open before and after occupancy | C            |
| France [4]    | • Sufficient ventilation, no or reduced recirculation, and increased outdoor air                      | C            |
|               | • Natural ventilation through windows at least twice a day for 10–15 min                             | I            |
|               | • No ceiling fan operation                                                                          | I            |
|               | • Mild airflow for occupants not to feel the air draft (i.e., ≤0.4 m/s)                              | C/I          |
| Germany [4]   | • Air purifiers using HEPA filters                                                                   | C            |
|               | • Stand-alone air conditioners can lower the virus concentration when operating without recirculation of air, but they can also increase the risk of virus infection by sending airflows containing infectious aerosols to other occupants in the same space | C/I          |
| Italy [4]     | • Close doors in adjacent rooms to limit potential transmission when using natural ventilation       | I            |
|               | • When occupied by visitors, stop the HVAC system operation or reduce the indoor airspeed. Natural ventilation (i.e., windows) preferred after leaving | I            |
| Netherlands [4] | • Regular ventilation using windows or mechanical ventilation systems                                 | C            |
|               | • Recirculation systems supplying outdoor air must be controlled so that sufficient fresh air is provided to the rooms | C/I          |
|               | • No use of devices that generate strong airflow (especially airflow between people and people) in public spaces | C/I          |

[a] European Centre for Disease Prevention and Control.
[b] U.S. Centers for Disease Control and Prevention.
monitoring of virus-similar particle concentration using OPC, and Step 2 to Step 3 are the experiments to analyze the behavior of the virus-similar particles using PIV equipment. Table 4 represents the Step 1 experimental cases, which traced the spreading of airborne particles in the restaurant from the potential contaminant source (e.g., oil generator) when operating the EHP heating system and kitchen hoods. Table 5 is the Step 2 PIV experiment that observed the indoor airflow mobility on the vertical section using smog from the EHP heating system. Table 6 is the Step3 experiment to monitor the spreading route of virus-similar particles on the horizontal plane. The patterns of PIV were observed and analyzed in real-time using smog. Based on the experimental results, this study confirmed the possibility of air transmission through virus-containing droplets and aerosols in direct airflow, which may lead to the increased exposure of occupants to air contaminant materials. In addition, the results informed that natural ventilation through windows and kitchen hoods could be used to dilute the concentration of infectious air contaminants in restaurants.

Table 3
Experimental conditions of a case study restaurant.

| Restaurant A                      | Seoul, Korea   |
|-----------------------------------|---------------|
| Location                          | Restaurant (dining room) |
| Type                              | Restaurant (dining room) |
| Area (m²)                         | 62.2 m²       |
| Experiment                        | Dec 10–11, 2020 (OPC) Dec 16, 2020 (PIV) |
| HVAC System                       | EHP Heating systems, 5 Fan coil units, Central HVAC systems |
| Kitchen Hood                      | 536 m³/h      |
| Window                            | 3 swing windows |

Table 4
Long distance transmission by heating and ventilation system controls.

| Case No. | Experimental Conditions | Kitchen Hoods | Natural Ventilation |
|----------|-------------------------|---------------|---------------------|
| Case A-1 | EHP heater: ON (4.84–4.93 m/s) | Kitchen hoods: OFF | Windows and doors: Closed |
| Case A-2 | EHP heater: ON (4.29–4.35 m/s) | Kitchen hoods: ON | Windows and doors: Closed |

Fig. 1. Field experiment in a case study restaurant.
Table 5
Airflow behavior by adjusted airflow direction in heating system.

| Case No. | EHP Heating System | Kitchen Hoods | Natural Ventilation |
|----------|--------------------|---------------|---------------------|
| Case B- 1 | EHP heater: OFF    | Kitchen hoods: OFF | Windows and doors: Closed |
| Case B- 2 | EHP heater: OFF    | Kitchen hoods: OFF | Windows and doors: Closed |
| Case B- 3 | EHP heater: ON (0°, 1.7 m/s) | Kitchen hoods: ON | Windows and doors: Closed |
| Case B- 4 | EHP heater: ON (25° upward, 2.7 m/s) | Kitchen hoods: ON | Windows and doors: Closed |
| Case B- 5 | EHP heater: ON (30° downward, 4.0 m/s) | Kitchen hoods: ON | Windows and doors: Closed |

Table 6
Airflow behavior by heating system and natural ventilation.

| Case No. | EHP Heating System | Kitchen Hoods | Natural Ventilation |
|----------|--------------------|---------------|---------------------|
| Case C- 1 | EHP heater: OFF    | Kitchen hoods: OFF | Windows and doors: Closed |
| Case C- 2 | EHP heater: OFF    | Kitchen hoods: OFF | Windows and doors: Open (1.6–2.6 m/s) |
| Case C- 3 | EHP heater: ON (1.7 m/s) | Kitchen hoods: OFF | Windows and doors: Closed |

4. Results

This study investigated the spread of indoor air contaminants by the EHP heating and ventilation controls (e.g., kitchen hoods, windows) in the restaurant. The mobility patterns of virus-similar particles showed that the potential exposure to virus-containing droplets and aerosols (i.e., SARS-CoV-2) might be propelled by the indoor airflow from the heating system. In addition, the experimental results provide recommendations to improve heating and ventilation system operations in a restaurant during a pandemic. The results of the experiment in this study are summarized as follows.

4.1. Long-distance transmission of virus-similar particles by indoor airflow during heating system operation

This study analyzed the risk of spreading airborne contaminants by indoor airflow from the EHP heating system during winter, which can represent non-contact COVID-19 cases that recently occurred in restaurants. To this end, droplets and aerosol-sized virus-similar particles were sprayed using an oil generator into the dining room in the case restaurant. During the experiment, virus-similar particles were generated evenly at the same pressure. The concentration of virus-similar particles was tracked at three OPC points with a 1-min interval, categorizing the air contaminant particles by size. Fig. 2 shows the OPC installation plan and dimension for this study.

Table 7 represents the monitoring results about the long-distance spread of virus-similar particles in Case A-1 and Case A-2. Case A-1 and Case A-2 showed the spreading patterns of virus-similar particles when the EHP was operated without natural ventilation. According to the results of Table 7, the concentrations of virus-similar particles at each OPC point were in the order of OPC2 > OPC3 > OPC1 in both particulate matter (PM) 2.5 and 10. This fact indicates that the virus-similar particles from the air contaminant source had been transmitted further away due to the influence of the direct airflow by the EHP system. Even though OPC1 was located closer to the EHP heating system and air contaminant source, the concentration of OPC1 was lower than OPC2 and OPC3. This is because OPC1 was located out of the direct airflow paths containing virus-similar substances on horizontal and vertical sections. The concentration of virus-similar particles at each OPS point showed that when the heating is running in the restaurant, airflow from the EHP heater could be used to transmit the virus-containing droplets or aerosols as a pathway or carrier. Also, the results describe that when an infected person is near the EHP systems, customers can be potentially exposed to the infectious virus even if they maintain social-distancing of 2 m (6 ft) or more. Such results were similarly verified in previous outbreaks of the restaurant and cafe in Guangzhou, China [9] and Paju, Korea [3], which confirmed that the direct wind from air conditioners would cause long-distance virus transmission in confined spaces. This fact refers that 2 m (6 ft) social-distancing for COVID-19 may not guarantee complete safety from infectious diseases in closed spaces.

On the other hand, when operating all kitchen hoods in the restaurant (Case A-2), the concentration of droplets and aerosol-sized virus-similar substances showed decreased patterns at OPC points. Although kitchen hood operation affected the increase of the minimum concentration in OPC1-3, it reduced the standard deviation, mean, and maximum values of the virus-similar particles. The results of Case A-2 indicate that kitchen hoods can offer a likelihood to lower the virus-similar contaminant density in the restaurants when operating the EHP heating system in winter. However, further studies will be needed to identify whether the reduced density of the virus-similar particles can ensure the virus safety to the occupants and whether the virus infectivity in airflow can be sufficiently lowered by kitchen hoods in the...
restaurants.

4.2. Impact of kitchen hoods on the controls of virus-similar particle concentration

In general, a restaurant is a place where a large number of unspecified people eat meals in an enclosed space, which is ranked at a high risk of infection during COVID-19. The restaurant comprises dining spaces and kitchens, and the purpose of the space types in the restaurant is clearly separated. Therefore, in order to safely run a restaurant during the pandemic, it should always be ready to minimize the potential outbreaks and dilute or remove infectious air contaminants. However, natural ventilation is inevitably limited in winter due to cold weather, and accordingly, kitchen hoods can be considered to assist natural ventilation and eliminate virus-similar pollutants in restaurants.

In Fig. 3, the trends of virus-similar substances at each point of OPC 1–3 show the removal effect of the kitchen hoods, which mitigated potential air contaminant concentration (i.e., droplet and aerosol sizes). PM 2.5 and PM 10 refer to the virus-similar particle density of 0–2.5 μg/m³ and 2.5–10 μg/m³, respectively. Case A-1 is a case with no kitchen hoods during heating in the restaurant, and Case A-2 is the results of the kitchen hoods being operated. The experimental results show that when increasing the concentration of indoor virus-similar particles, the patterns of airborne particles were differentiated around 6 min in OPC 1–3. It seems that the large-scale hoods in the kitchen exhausted a large amount of indoor air with droplets or aerosol-sized particles, thereby affecting the reduction of virus-similar particles in the case restaurant.

Table 7 analyzes the reduction effect of virus-similar particles in OPC1-3 due to the operation of the kitchen hoods. In the results, the droplet size concentration (PM 10) was reduced by an average of 35.4–6.5%, and the aerosol-size concentration (PM 2.5) was decreased by an average of 42.2–12.3%.

The reduction ratios of kitchen hoods showed that the operation of the kitchen hoods was most effective at OPC2, followed by OPC1 and

Table 7

| Long-distance transmission of virus-similar particles at OPC points. |
|---|
| Case A-1: PM2.5 (w/o kitchen hoods) | Case A-1: PM10 (w/o kitchen hoods) | Case A-2: PM2.5 (w/kitchen hoods) | Case A-2: PM10 (w/kitchen hoods) |
| OPC1 | OPC2 | OPC3 | OPC1 | OPC2 | OPC3 | OPC1 | OPC2 | OPC3 | OPC1 | OPC2 | OPC3 |
| Mean | 3.15 m | 5.50 m | 8.80 m | 3.15 m | 5.50 m | 8.80 m | 3.15 m | 5.50 m | 8.80 m | 3.15 m | 5.50 m | 8.80 m |
| Mean | 480.9 | 1050.3 | 856.2 | 582.8 | 1993.1 | 1541.3 | 63.9 | 146.9 | 137.1 | 81.3 | 283.2 | 249.4 |
| S.D. | 193.0 | 366.6 | 292.2 | 210.3 | 645.9 | 473.6 | 31.5 | 120.1 | 144.1 | 48.1 | 264.4 | 303.6 |
| Min | 8.6 | 14.2 | 12.1 | 18.2 | 38.3 | 35.0 | 276.8 | 731.2 | 755.4 | 369.3 | 1482.3 | 1449.1 |
| 25% | 411.6 | 943.2 | 719.7 | 544.8 | 1913.3 | 1384.4 | 311.5 | 803.4 | 822.6 | 420.4 | 1602.3 | 1558.5 |
| 75% | 630.4 | 1330.9 | 1078.2 | 726.8 | 2428.4 | 1837.3 | 339.8 | 846.4 | 842.7 | 467.1 | 1696.8 | 1605.0 |
| Max | 703.6 | 1417.8 | 1222.7 | 765.4 | 2554.0 | 2103.0 | 396.8 | 100.4 | 902.7 | 430.4 | 1602.3 | 1558.5 |

b. Airflow angle from the EHP heating system grill is 0° horizontal (default).

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**Fig. 3.** Time-Series Distribution of Virus-Similar Particles Concentration at OPC Points during Heating operation (EHP System).
facilitated by indoor air-conditioned ventilation, and the influential indoor spaces. According to Lu et al. [9], droplet transmission was likely when the dining space is connected to the kitchen space. This role of kitchen hoods can also be utilized to shorten the operation time of flush-out before and after occupancy or to remove the potential airborne virus presented in Table 9. In Case B-1, the ventilation and kitchen hoods were set upward (25° upward), droplets or aerosols from infectors and the direct airflow from the floor standing EHP systems. Therefore, the EHP heating system during the winter season should be carefully operated to prevent long-distance transmission, accompanying infectious diseases. Therefore, in order to reduce the possibility of long-distance propagation by infectious air contaminants, facility managers should develop effective strategies by considering their indoor environment as much as they can do. For instance, the lower airflow speed of the EHP systems or heating with no direct airflow can be recommended for the occupants. Also, when the stand-type heating system is operated in dining rooms, the airflow direction should be set upward to prevent the mixing of droplets or aerosols from infectors and the direct airflow from the floor standing EHP systems.

Table 8
Effect of kitchen hoods on potential airborne contaminant reduction.

|                | Case A-1 | Case A-2 | PM2.5 Reduction (%) | Case B-1 | Case B-2 | PM10 Reduction (%) |
|----------------|----------|----------|---------------------|----------|----------|--------------------|
|                | µg/m³    | µg/m³    |                     | µg/m³    | µg/m³    | µg/m³              |
| Mean           | 480.9    | 277.8    | 203.1               | 582.8    | 376.3    | 206.5              |
| S.D.           | 193.0    | 63.9     | 129.1               | 210.3    | 81.3     | 129.0              |
| Max            | 703.6    | 339.8    | 363.7               | 765.4    | 467.1    | 298.3              |

**OPC2**

|                | Case A-1 | Case A-2 | PM2.5 Reduction (%) | Case B-1 | Case B-2 | PM10 Reduction (%) |
|----------------|----------|----------|---------------------|----------|----------|--------------------|
|                | µg/m³    | µg/m³    |                     | µg/m³    | µg/m³    | µg/m³              |
| Mean           | 1050.3   | 730.6    | 319.7               | 1992.1   | 1473.4   | 519.7              |
| S.D.           | 366.6    | 146.9    | 219.7               | 645.9    | 283.2    | 362.8              |
| Max            | 1417.8   | 846.4    | 571.3               | 2554.0   | 1696.8   | 857.2              |

**OPC3**

|                | Case A-1 | Case A-2 | PM2.5 Reduction (%) | Case B-1 | Case B-2 | PM10 Reduction (%) |
|----------------|----------|----------|---------------------|----------|----------|--------------------|
|                | µg/m³    | µg/m³    |                     | µg/m³    | µg/m³    | µg/m³              |
| Mean           | 856.2    | 751.2    | 104.9               | 1541.3   | 1441.8   | 99.5               |
| S.D.           | 292.2    | 137.1    | 155.1               | 473.6    | 249.4    | 224.2              |
| Max            | 1222.7   | 842.7    | 380.1               | 2103.0   | 1605.0   | 498.0              |

OPC3. In particular, the standard deviation (s.d.) of virus-similar substances was significantly reduced due to the mechanical forced ventilation by the kitchen hoods. Therefore, the kitchen hoods in restaurants would help remove airborne infectious pollutants (e.g., SARS-CoV-2) when the dining space is connected to the kitchen space. This role of kitchen hoods can also be utilized to shorten the operation time of flush-out before and after occupancy or to remove the potential airborne virus in the restaurant.

4.3. Virus-similar particle behavior by airflow direction from the heating system

As the outbreak of COVID-19 has recently increased through unidentified routes, the operations of HVAC systems need to be more cautious to prevent the potential transmission of infectious diseases in indoor spaces. According to Lu et al. [9], droplet transmission was likely facilitated by indoor air-conditioned ventilation, and the influential factor for the outbreak would be the direction of the airflow. Currently, the building system (e.g., HVAC) was not designed to control indoor cases [12], and the operation method mainly focused on maintaining thermal comfort and indoor air quality with minimum cost. However, a new normal method during the pandemic requires wise strategies to constrain the spread of infectious diseases or remove air contaminants. Proper operation of HVAC systems can assist in lowering potential exposure to airborne viruses [42]. Therefore, in this section, the trends of the airflow behavior of virus-similar particles were analyzed using different air angles by grill settings in the EHP heating system. PIV experiment was conducted using smog to track and monitor virus-similar particles on the vertical section nearby the EHP system.

The airflow mobility from the heating system was evaluated in five operating methods (i.e., Case B-1 to B-5). The upward and downward angles in this experiment are the maximum angles that can be adjusted in the grill of the EHP heating system. Also, in all five cases, the windows and doors were closed, and natural ventilation was not operated. In Table 9, Case B-1 is a default case where no airflow or ventilation was performed in the restaurant. This case represents the restaurant with no EHP heating, kitchen hood ventilation, and natural ventilation. Case B-2 tracked the patterns of indoor airflow and airspeed when operating only kitchen hoods without heating in winter. Case B-3 was the result when running the EHP heating system and the kitchen hoods together. The indoor wind was blown horizontally (0°) from the EHP grill. Case B-4 monitored the airflow behavior when the EHP heating system blew warm wind at 25° upward. Finally, Case B-5 analyzed the indoor airflow when the air direction of the EHP was fixed at 30° downward.

The measurement results for airflow behavior using PIV were presented in Table 9. In Case B-1, the ventilation and kitchen hoods were all turned off, and in Case B-2, only the kitchen hoods were operated without ventilation. In Cases B-1 and B-2, there was no obvious airflow in the dining room, and the average wind speeds for Case B-1 and Case B-2 were 0.10 m/s and 0.11 m/s, respectively. The maximum wind speeds were similarly 0.36 m/s at Case B-1 and 0.39 m/s at Case B-2.

On the other hand, when the airflow angles of the EHP heating system were set upward (25°) or downward (30°), the airflow speeds were increased because the areas of the grill became narrower than when it was set to horizontal (0°). In Case B-3 (30° downward), droplets and aerosol-sized air particles directly arrived on the tables in seconds where the customers may occupy in the restaurant. Contrariwise, in Case B-4 (upward 25°), the airflow was directed toward the ceiling, which relatively delayed the spreading time of air contaminants to reach the tables. In Case B-3 (0°), the average wind speed was 0.38 m/s, and the maximum wind speed was 2.38 m/s. In Case B-4 (upward 25°), the average wind speed was 0.50 m/s, and the maximum wind speed was 2.39 m/s. In Case B-5, where the airflow direction was 30° downward, the average wind speed was 0.50 m/s, and the maximum was 3.22 m/s.

In the PIV experiment, the operation of the EHP heating system clearly affected the indoor airflow, and the airflow behavior due to grill angle settings identified the potential concerns of direct airflow from the floor standing EHP systems as virus containers. Therefore, the EHP heating system during the winter season should be carefully operated to prevent long-distance transmission, accompanying infectious diseases. Therefore, in order to reduce the possibility of long-distance propagation by infectious air contaminants, facility managers should develop effective strategies by considering their indoor environment as much as they can do. For instance, the lower airflow speed of the EHP systems or heating with no direct airflow can be recommended for the occupants.
4.4. Transmission of virus-similar particles by heating and ventilation conditions

The direct airflow from the floor standing EHP heating system in winter can affect the spread of indoor air contaminants. During the pandemic, infectious substances can be delivered to long-distanced customers in the restaurants despite 2 m (6 ft) social-distancing. Therefore, in this section, researchers investigated how virus-similar particles can be transmitted by airflow in the dining room using the PIV technique. To monitor virus-similar particle mobility, smog was sprayed for 5 s at the beginning of each case. The PIV experiment was performed on horizontal sections to detect the spread of airflow. The average outside air temperature and wind speed were \( 5.8^\circ C \) and 3.8 m/s, respectively, and the average indoor temperature was \( 20.3^\circ C \) during the experiment.

In Table 9, when spraying virus-similar particles in front of the EHP heating system to visualize the airflow behavior by experiment condition, in Case C-1 with no natural ventilation and heating, virus-similar particles flowed slowly throughout the dining room and remained less undiluted. Virus-similar particles took 23 s to reach OPC2 (particle movement speed: \( 0.24 \) m/s) and 37 s to arrive the farthest OPC3 (0.23 m/s). In Case C-2 (windows and doors open, no heating; kitchen hoods), the fresh outdoor airspeed from the two windows was 1.6 m/s-2.6 m/s. At this time, the smog spread took 7 s (0.79 m/s) to arrive at OPC2 and 37 s (0.23 m/s) to reach OPC3 due to the outdoor air inflow. In addition, the concentration of the airborne virus-similar particles gradually decreased as time passed due to air exchange with outdoor air. In Case C-3, the virus-similar particles moved to OPC2 in 7 s (0.79 m/s) and reached OPC3 just in 11 s (0.80 m/s). Relatively few particles were distributed near the EHP heating system. In the three cases (Cases C1-3), the virus-similar particles of Case C-3 diffused the fastest, and the particles were almost uniformly transmitted throughout the dining room after about 60 s.

In summary, in the monitoring of virus-similar substance behavior, the indoor airflow was stagnant when heating or ventilation was not operated, but the indoor air mobility increased when natural ventilation or heating equipment was performed due to the outdoor air inflow or direct airflow. Above all, the results of Case C-3 showed that if there is an infected person in the airflow route from the EHP heating system, virus-similar particles can reach OPC2 5.5 m away in just 7 s and OPC3 8.8 m away in only 11 s. Since droplets or aerosols with the infectious virus may be transmitted by the airflow to customers, the current social-distance of 2 m (6 ft) may not be sufficient to ensure virus safety in the restaurants during winter, which was already verified in cases of HVAC systems in China and Korea [8,9]. A previous study pointed out that airborne routes and inadequate use of ventilation systems should

### Table 9

| Case No. | PIV Analysis of Airspeed and Wind Direction | Note |
|----------|---------------------------------------------|------|
| Case B-1 | ![PIV Image] | Average sectional wind speed: 0.11 m/s  Max sectional wind speed: 0.39 m/s |
| Case B-2 | ![PIV Image] | Average sectional wind speed: 0.10 m/s  Max sectional wind speed: 0.36 m/s |
| Case B-3 | ![PIV Image] | Average sectional wind speed: 0.38 m/s  Max sectional wind speed: 2.38 m/s |
| Case B-4 | ![PIV Image] | Average sectional wind speed: 0.50 m/s  Max sectional wind speed: 2.39 m/s |
| Case B-5 | ![PIV Image] | Average sectional wind speed: 0.50 m/s  Max sectional wind speed: 3.22 m/s |
not be overlooked in the spread of SARS-CoV-2 [43]. Therefore, to minimize the potential of air contaminant transfer (i.e., SARS-CoV-2) by direct airflow, improved mitigation strategies beyond social-distancing should be applied to provide the customer’s safety in the restaurants during the pandemic.

5. Discussion

This study aims to present the recommendations of heating systems and ventilation controls in winter to respond to the pandemic in restaurants. The experiments using virus-similar particles showed the potential exposure due to the spread of the indoor airborne contaminants through airflow from the heating system. The results of this study provided the implications for opening restaurants to ensure better safety from COVID-19.

5.1. Potential risk of long-distance SARS-cov-2 exposure by airflow in restaurants

After the outbreak of COVID-19, a number of people have been infected in buildings by unknown paths of infection. This invisible threat has rushed people to develop strategies to protect public health from infectious diseases in restaurants. Many customers in restaurants stay and eat for 1–3 h with the conversation, and thus, in this environment,
the airborne infectious contaminants can be easily transmitted by direct or indirect contacts. In particular, in winter, due to the cold climate, limited natural ventilation is possible through the windows, so all customers in the restaurants should be careful to avoid the chances of indoor virus exposures. The results of this study verified that the indoor airflow by the EHP heating system has the ability to deliver virus-containing droplets and aerosols to a long-distanced occupant.

Fig. 4 shows the result of Case C-3. In the experiment, the air particles reached a place 8.8 m away in just 11 s by the airflow from the EHP heating system. On the contrary, although the location of OPC1 was only 3.15 m away from the EHP heating system, it was less affected by the direct airflow due to low airspeed, so the arrival time of virus-similar particles was relatively slow. This behavior pattern of airborne contaminant particles shows an effective strategy that occupants in the restaurants should avoid direct airflow or slow down the heating airspeed in order to reduce the spread of infectious matters (i.e., SARS-CoV-2) in closed spaces.

Also, the results of Case A-1 and Case A-2 in Table 11 represent the time to reach a specific concentration (i.e., 100, 200, 300, 400, 500 μg/m³) of virus-similar particles at each OPC point. The initial time to reach a specific concentration of virus-similar particles was in the order of OPC3 > OPC2 > OPC1. This fact indicates that the controls of the non-contact virus spread are significant during winter due to the potential risk of the airflow transfer by heating systems beyond social-distancing. It also reminds us that distant customers would be exposed to air infectious substances if the virus is transmitted by direct airflow from heating systems in the restaurants.

5.2. Mitigation strategies of potential SARS-cov-2 exposure in restaurants

This study observed the potential impact of the direct airflow on the indoor spread of airborne virus-similar particles to ensure the occupants' health in restaurants in winter. In addition, the effect of the kitchen hoods was traced to monitor the role of the virus removal and transmission using virus-similar particles. The results of the experiment showed that the direct airflow from the EHP heating system might serve as a container for delivering droplets or aerosols with COVID-19 in winter. Table 12 summarizes the expected effects of heating and ventilation controls in restaurants based on the experimental results. The evaluation result in Table 12 shows the potential effect of individual controls in the dining room.

The results of the experiment verified the need for improved mitigation strategies beyond social-distancing to control indoor COVID-19 outbreaks. Several mitigation strategies were confirmed in this study. For example, to protect occupants in restaurants, the operation of the kitchen hoods can be effective in removing air contaminants and diluting the concentration of the virus-similar particles by discharging it to the outside in the restaurant. In restaurants where do not install ventilation systems and exhaust fans, kitchen hoods can be effective as an alternative measure to lower concentrations of potential air contaminants. Also, if possible, adjusted airflow angles (e.g., upward) and low-speed heating should be considered during the heating season to avoid occupant exposure. The best way is to avoid occupants’ seating in the direct airflow paths of the heating systems, which can prevent the potential risk of SARS-CoV-2. The findings of this study are expected to be used as a reference to improve COVID-19 guidelines for reducing the spread of indoor infectious viruses in restaurants.

6. Conclusion

This study analyzed the indoor behavior of virus-similar particles based on the heating and ventilation conditions to ensure the safety of occupants in restaurants during the pandemic. To this end, an underground restaurant in the university campus in Seoul, Korea, was selected to conduct the experiment in December 2020. The results of the investigation confirmed that the direct airflow by the EHP heating systems might be used as a transmission route of droplets or aerosols containing the infectious virus when an infected person occupies in the direct airflow paths in the restaurants. In this case, even if a social-distancing of more than 2 m is maintained, distant occupants on the direct airflow path would be exposed to airborne contaminants (i.e., SARS-CoV-2). Therefore, mitigation strategies should be applied in restaurants to prevent potential outbreaks of SARS-CoV-2. Based on the results of this study, recommendations to improve COVID-19 controls are suggested for restaurants as follows.

- Direct airflow by the EHP systems (i.e., floor-standing heating systems) can play a role as a potential virus transmission route of droplets and aerosols, which may affect the COVID-19 outbreaks in restaurants by increasing the exposure of air contaminants to remote occupants. This fact indicates that if the occupant avoids the direct airflow, the exposure of the infectious virus can be lowered.
- It is recommended to avoid occupants sitting in the direct airflow paths. The change of the heating air angles (e.g., toward the ceiling or walls) can help prevent the potential risk of COVID-19 in restaurants. Also, slowing the wind speed of the HVAC systems (e.g., EHP heater) can be an effective measure to delay the spreading rate of infectious materials.
- Kitchen hoods can be used to alleviate or remove airborne contaminants by discharging infectious contaminants to the outside. Therefore, considering the restaurant occupancy density and operating schedule, kitchen hoods can be considered during the daytime or before and after occupancy for flush-out. Also, with natural ventilation through windows, kitchen hoods can show better virus removal effects in restaurants during winter.

Lastly, since this study performed the experiment by spraying droplets or aerosol-size oil and smog at a high concentration for tracking the spread of virus-similar particles, the results do not show the actual concentration of virus transmission from an inspected person in a restaurant. Also, the results of this study only show the potential
Table 11
Time to reach initial concentration levels of virus-similar particles at OPC points.

| OPC1 | OPC2 | OPC3 | OPC1 | OPC2 | OPC3 | OPC1 | OPC2 | OPC3 |
|------|------|------|------|------|------|------|------|------|
| Distance (μm) | 3.15 m | 5.50 m | 8.80 m | 3.15 m | 5.50 m | 8.80 m |
| 100 | 4-5 | 3-4 | 2-3 | 4-5 | 2-3 | 2-3 |
| 200 | 5-6 | 3-4 | 2-3 | 4-5 | 3-4 | 2-3 |
| 300 | 5-6 | 3-4 | 2-3 | 5-6 | 3-4 | 2-3 |
| 500 | 10-11 | 3-4 | 2-3 | 7-8 | 3-4 | 3-4 |

Table 12
Effect of heating and kitchen hood system modes on potential virus transmission.

| Cases | Transmission (Direct Airflow) | Ventilation (Removal Effect) | Thermal Comfort | Energy Use |
|-------|------------------------------|------------------------------|-----------------|-----------|
| EHP   | On (0°)                      | X                            |     *           |   *       |
| Heating System | (+25°)                  | X                            |     *           |   *       |
|       | (-30°)                      | X                            |     *           |   *       |
| Kitchen | Off                          | X                            |     *           |   *       |
| Hoods | Off                          | X                            |     *           |   *       |
| Window/ Door | Closed                  | X                            |     *           |   *       |

a. Evaluation index: positive: *; neutral: =; negative: X.

exposure risk due to the spread of virus-containing droplets or aerosols (i.e., COVID-19) by direct airflow in restaurants. No experiments have been conducted to identify how much virus can be accompanied in the actual droplets and aerosols in indoor spaces. Because this study was performed based on the experimental conditions in the case restaurant, there would be differences in the patterns of the indoor airflow behavior depending on the HVAC system types and control methods. Therefore, further studies will be considered to identify relationships between direct airflow and infectivity in buildings.

Funding

This work was supported by the Research Program funded by the Korea Disease Control and Prevention Agency (funding code 2020-ER5332-00) and the ‘National Research Council of Science & Technology (NST)’ – ‘Korea Institute of Civil Engineering and Building Technology (KICT)’ Postdoctoral Fellowship Program for Young Scientists at KICT in South Korea.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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