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Research

Improvement of indoor air quality using a smart gate that can lessen viral aerosol (MS2 virus) and particulate matter (PM): Experimental findings

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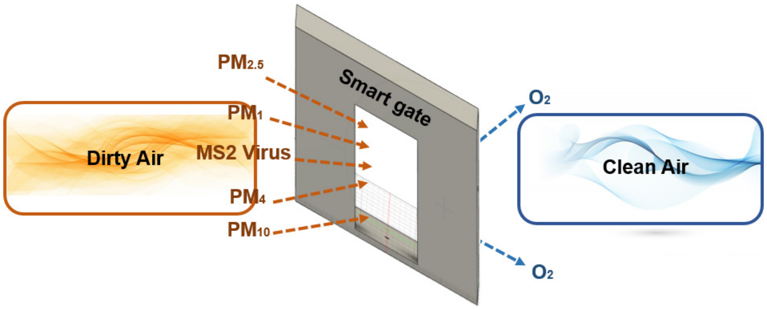
ABSTRACT

Fine particulate matter (PM) and viruses have more detrimental impacts on human health when present in an indoor setting than when present in an outdoor environment. With the COVID-19 epidemic, a healthy indoor environment has emerged as a crucial necessity. There are many different cleaning technologies available, but most of them have drawbacks and are challenging to utilize in daily-use indoor venues including workplaces, retail malls, movie theaters, subway stations, and many other locations. We created a portable, smart gate that is simple to use at a commercial level and evaluated it for effectiveness in lowering particulate matter concentrations of various sizes. The results show that 97.76% for PM10, 97.72%PM4, 97.44% for PM2.5, and 96.91% for PM1. reduction. Also, the aerosolized MS2 virus was used to test its ability to decrease viral transmission and the viral reduction efficiency of the smart gate was found around 82%. The experimental results show that the smart gate is better than all the current available cleaning technologies along with its user-friendly and easy use.

Keywords: Aerosolized virus reduction, Clean air technology, Particulate matter reduction, Smart gate

Graphical Abstract



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1. Introduction

People spend 80% of their time inside, making indoor air quality (IAQ) extremely important. This is especially true now that the SARS-CoV-2 or novel coronavirus pandemic has brought increased attention to the issue. Over the world, more than 758.3 million people have contracted SARS-CoV-2 (COVID-19) (by 2023 February 23). Together with other pollutants like ozone, nitrogen oxides, and sulfur oxides, particulate matter (PM_{10}, $PM_{2.5}$, and PM_1) are some of the most dangerous air pollutants [1–4]. Numerous studies have examined in detail the harmful effects that these pollutants can have on human health, and a variety of adverse outcomes, such as a high risk of cancer and early death [5–9], have been established. For some socioeconomic categories of people, such as those who are particularly sensitive, including small children, the elderly, and people with specific illnesses, a healthy environment is even more important. Children who spend the majority of their time at school, for example, as well as workers and employees in the transportation industry, such as those working at subway stations and traffic police [6,10], are constantly exposed to indoor pollutants even though the majority of the particles they inhale come from outdoor sources. It has been widely demonstrated that, on exposure to low-ventilation and enclosed spaces, an individual can come in contact with these airborne pollutants [5].

In order to improve indoor air quality, a variety of air cleaning technologies are available, ranging from fibrous-media filters and ultraviolet germicidal irradiation (UVGI) to numerous different electronic air cleaners (EACs), such as plasma generators, hydroxyl radical generators, ionizers, photocatalytic oxidizers, and more [6–8]. An overview of the development of ultraviolet-based air filtration technology was provided by several prior publications, such as [9]. In 2009,[10] investigated the efficacy of several technologies for eradicating germs from indoor air, including filtration and UV, as well as how well they integrated with existing HVAC systems. The issue with HVAC systems is that they have significant concentrations of germs and fungus, which can spread through air movements [11]. As a result, the HVAC systems might lead to an increase in the spread of diseases including TB, influenza, and bronchial asthma [12]. In addition to a few specialized technologies (such as photocatalysis and ionization radiation), the employment of plasma technology and UVC radiation can reduce virulence [13–15]. Using cold ionizing plasma, sometimes referred to as non-thermal plasma, air ionization, or dielectric-barrier discharge, which is created by electrostatic discharge in the kilovolt range between many electrodes and has a potent virucidal effect, as radiation is applied as part of the first method. This method's disadvantage, as of yet, is that it produces residual ozone, a significant pollutant, and a small number of reaction products of concern during the brief exposure intervals and relatively low plasma temperatures [13,16,17].

Even when the global market for indoor air purification is anticipated to reach $3.8 billion by 2027, according to the Manufacturing Industry Market Research Report, and as public awareness of airborne pathogens and overall air quality continues to rise a comprehensive knowledge of any such technology in its mature state is still lacking which can reduce both particulate matter and air-borne pathogenic microorganisms at once is lacking [18]. Research and evaluation of the most recent air cleaning technologies are necessary in order to maintain public health improvements and meet the expanding market. The development of air cleaning technology is crucial to public health to avoid transmission of airborne infections. Additionally, due to the COVID-19 pandemic situation, indoor air quality is receiving more attention [19–21].Some research mentioned in the literature, address the evaluation of the improvement of indoor air quality through the use of various air cleaning technologies, like, filtration, heat treatment, UV, electrostatic, microwave, photocatalysis, plasma, ozonation, and chemical aerosolization technologies, are few examples of physicochemical technologies. Various other ways include filtration, heat treatment, UV, electrostatic, microwave, photocatalysis, plasma, ozonation, and chemical aerosolization technologies are examples of physicochemical technologies. Botanical disinfectants, herb fumigation, and lysozyme are examples of biochemical technology [9,10,22–24]. However, all of the above mentioned technologies have some limits and are less feasible to use in real-time conditions [6–8,13–17]. As a result, the effectiveness of smart gate, like the one validated in the present study, is being studied because this can significantly improve the quality of the air in enclosed spaces such as shopping complexes, public rest areas, offices, school, and many more.

A smart-gate has been created by the combined effort of the Korea Railroad Research Institute (KRRI) and Anytech Co. Ltd. to reduce the levels of viruses and particulate matter in confined areas in order to provide a healthy indoor environment. In this work, we evaluated how well our smart-gate reduced particulate matter (of various sizes) as well as aerosolized virus particles. Our research results aim to expand our knowledge of indoor air pollutant concentration decrease and overcome some obstacles. Here, we conduct an experimental evaluation of the smart gate's effects on aerosolized MS2 bacteriophage and particulate matter. Tests were also conducted to determine the smart gate's filtering effectiveness in interior environments, both with and without the smart gate. We also study the smart gate's effects to determine how well it will prevent viruses from spreading indoor spaces.

2. Material and Methods

2.1. Smart Gate Unit

A smart gate unit (length=3000mm, breadth=1770mm and width=300mm each side) that was employed in this investigation is shown in Fig. 1 together with all of its essential parts and dimensions. The smart gate is made up of a ceiling air conditioning unit (length=757mm, breadth=407, width=157mm) that purifies outside air before delivering it inside, generating a positive pressure inside while preventing the entry of infectious pollutants. Air curtain units (length=1205mm, breadth=198mm, width=220mm) are installed on both sides which can perform brushing off the particulate matter infectious contaminants attached to the body and clothing, after entering the smart gate. The bottom air conditioning unit (length=700mm, breadth-320mm, width=212mm) ejects fine dust and infectious pollutants suspended in the air to the

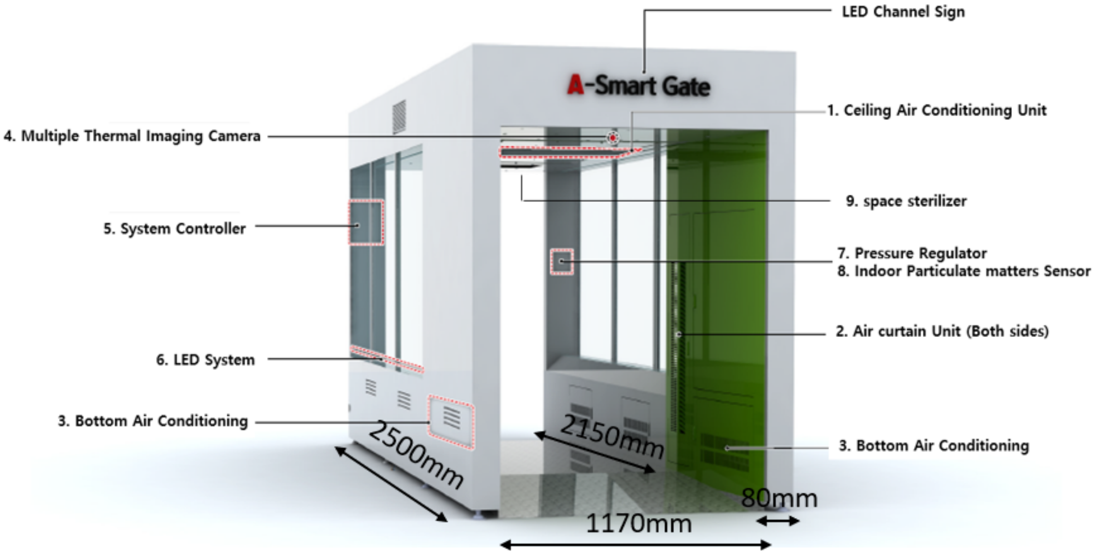

Fig. 1. A representative of the smart gate unit with all the main components and dimensions.

bottom by creating the down air flow and also helping in maintaining internal positive pressure. A system controller is installed which can be connected from outside with a tablet. The main function of this is internal function control with the display of particulate matter and pressure measurement values. A lot of multiple thermal imaging cameras have also been installed in it to detect specific temperatures to measure the body's high heat. Inbuilt indoor particulate matter is also installed inside it. For virus removal and sterilization, a mini unit of space sterilizer has been installed which comprises high-performance filters and UVC lights.

Table 1. The set of experimental conditions used in this experiment

Experimental Setup	Abbreviation
Without Smart Gate on (standard)	**WSMG-M**
With Smart gate on but both Air curtains off	**SMGON-ACOFF-M**
With Smart gate on and both air curtain at lowest setting	**SMGON-AC_1-M**
With Smart gate on and one air curtain at lowest and one air curtain at highest setting	**SMGON-AC_2-M**
With Smart gate on and both air curtain at highest setting	**SMGON-AC_3_M**

2.2. Experimental Description

The entire smart gate unit was covered completely with plastic sheets in such a way that everything except for the inlet pipe was sealed. For the standard values, the first experiment was performed with turning on the smart gate. For this, we used TOPAS (SAG Series) dust generator in order to produce dust, filling the space. Through an inlet the dust generated from the dust generator was sprayed inside the sealed smart gate. A smart size fan was also installed in order to promote the even distribution of the dust particles. A wide-range aerosol spectrometer and optical particle counter (Mini-WRAS, Model 1.371, Grimm Aerosol Technik, Germany) were used to assess the size distributions of all particulate matter over the study period for every 6 sec. PM mass concentration (g/m^3) was recorded for the aerodynamic diameter less than 1 μm, 2.5 μm, 4 μm, and 10 μm (PM10) (representing 17 size channels). Every time, a jet of fresh compressed air was used to clean the analyzer's input ducts before sampling. Mini WRAS has a time resolution of 1 minute and runs at a flow rate of 1.2 L/min. Apart from the standard condition, the reduction efficiency of the smart gate for particulate matter was tested for three different settings. Each experiment cycle was performed for 20 mins with a 15 mins gap in between each setting. Detailed information about all the conditions is mentioned in the Table 1. The temperature was 22℃ and the RH ranged between 55-65%. For measuring the viral inactivation efficiency of the smart gate, through the inlet aerosolized virus was sprayed inside. Bioparticle counter MBio 150 device (Mediaever Co. Ltd.) was used to measure the amount of aerosolized virus. For standard condition, the aerosolized virus spray was done with smart gate off and later on with smart gate on.

2.3. MS2 Bacteriophage Virus Preparation

The MS2 bacteriophage, commonly utilized as a viral model system [25,26], has been demonstrated to be acceptable for this investigation. MS2 bacteriophages (MS2, ATCC 15597-B1, Manassas, VA, USA) was used in this experiment as a virus model for these does not cause any harm to human health. To aerosolize the MS2, a diffusion drier (silica gel tube) was coupled to an atomizer (model 9302, TSI Inc., Shoreview, MN, USA). The particle generation capacity of the atomizer was more than 10^7 particles/cm^3 with a flow rate of 6.5L/min. A mass flow controller (MFC) was used to pump, clean, and regulate compressed air. The aerosolized virus solution was then fed through the tube connected to the inlet opening. A total of 10 vials (0.1mL) of stock solution of MS2 bacteriophages were used and diluted up to 50 mL of Deionized water. The use of such an amount of stock solution was performed due to the nature of the size of the UV system of the Smart Gate. Prior experiments were done using the subunit of the smart gate had yielded poorly due to low initial concentrations of viruses. Ten (0.1 ml) stock vials, each diluted in 50 ml of deionized water, total of 500 ml solution was then used on the actual site.

2.4. Production, Deposition, and Removal of Aerosol Particles

The four size fractions of 10 μm, 4 μm, 2.5 μm, and 1 μm are taken into consideration. Let G be the rate at which the dust generator produces aerosol particles. The effectiveness of the smart gate was measured using the following equation:

$$E(\%) = [\frac{(Cs-Co)}{Cs}] \times 100 \qquad (1)$$

where is concentration for the standard condition (when the smart gate was turned off) whereas the represents concentration for each experimental setup.

3. Results and Discussion

3.1. Effectiveness of Smart Gate in Reducing the Particulate Matter

The conditions used during the experiments are mentioned in Table 1. The results for the same are mentioned in Table 2 showing the efficiency of the smart gate in reducing the particulate matter and the aerosolized viral concentration.

In order to measure the ability of the smart gate to reduce atmospheric particulate matter, the initial concentrations were measured without turning it on (WSMG-M). The average PM_{10} concentration for this was found to be 8489.562 $\mu g/m^3$ whereas, the average concentration for PM_4, $PM_{2.5}$ and PM_1 were found to be 5069.621 $\mu g/m^3$, 3103.717$\mu g/m^3$and, 461.83 $\mu g/m^3$ respectively (these values were taken after 20 mins of stabilization of the dust injected). Without entering inside the smart gate, using the tablet, the smart gate was turned on which showed significant reduction in the particulate matter. For the first case, both the air curtains were turned off. This case is represented as SMGON-ACOFF-M. It is important to measure the reduction efficiency of the smart gate without turning on the air curtains because of the research conducted previously suggesting that air curtains even though they provide a better protection than single or vestibule doors, they are not best suited for leaky buildings under windy condition [27,28]. The readings of PM_{10}, PM_4, $PM_{2.5}$ and PM_1 showed significant reduction with an average value of 189.65 $\mu g/m^3$, 115.29 $\mu g/m^3$, 79.38 $\mu g/m^3$, and 14.26 $\mu g/m^3$. There are three basic operating conditions for air curtains, according to the findings of [29,30] numerical studies. One in which the air curtain flow reaches it and seals the door is the ideal situation. Inflow breakthrough is

Table 2. The average concentration of each pollutant for all the experimental cycles and reduction efficiency of the smart gate for each case.

Experiment cycle	PM_{10}($\mu g/m^3$) (Avg conc)	PM_4($\mu g/m^3$) (Avg conc)	$PM_{2.5}$($\mu g/m^3$) (Avg conc)	PM_1($\mu g/m^3$) (Avg conc)
WSMG_M	8489.562	5069.621	3103.717	461.833
SMGON-AC OFF_M	189.654	115.296	79.389	14.266
SMGON-AC_1_M	8.002	4.673	3.438	1.205
SMGON-AC_2_M	502.660	285.196	169.953	27.134
SMGON-AC OFF_M	62.110	36.434	24.800	5.889

Pollutant	Condition	Reduction Efficiency (%)
PM_{10}	WSMG-M (control)	
	SMGON-ACOFF-M	97.76%
	SMGON-AC_1-M	99.9%
	SMGON-AC_2-M	94.07%.
	SMGON-AC_3-M	99.26%
$PM_{2.5}$	WSMG-M(control)	
	SMGON-ACOFF-M	97.44%
	SMGON-AC_1-M	99.88%
	SMGON-AC_2-M	94.52%
	SMGON-AC_3-M	99.2%
PM_4	WSMG-M(control)	
	SMGON-ACOFF-M	97.72%
	SMGON-AC_1-M	99.9%
	SMGON-AC_2-M	94.37%
	SMGON-AC_3-M	99.28%
PM_1	WSMG-M(control)	
	SMGON-ACOFF-M	96.91%
	SMGON-AC_1-M	99.73%
	SMGON-AC_2-M	94.12%
	SMGON-AC_3-M	98.72%

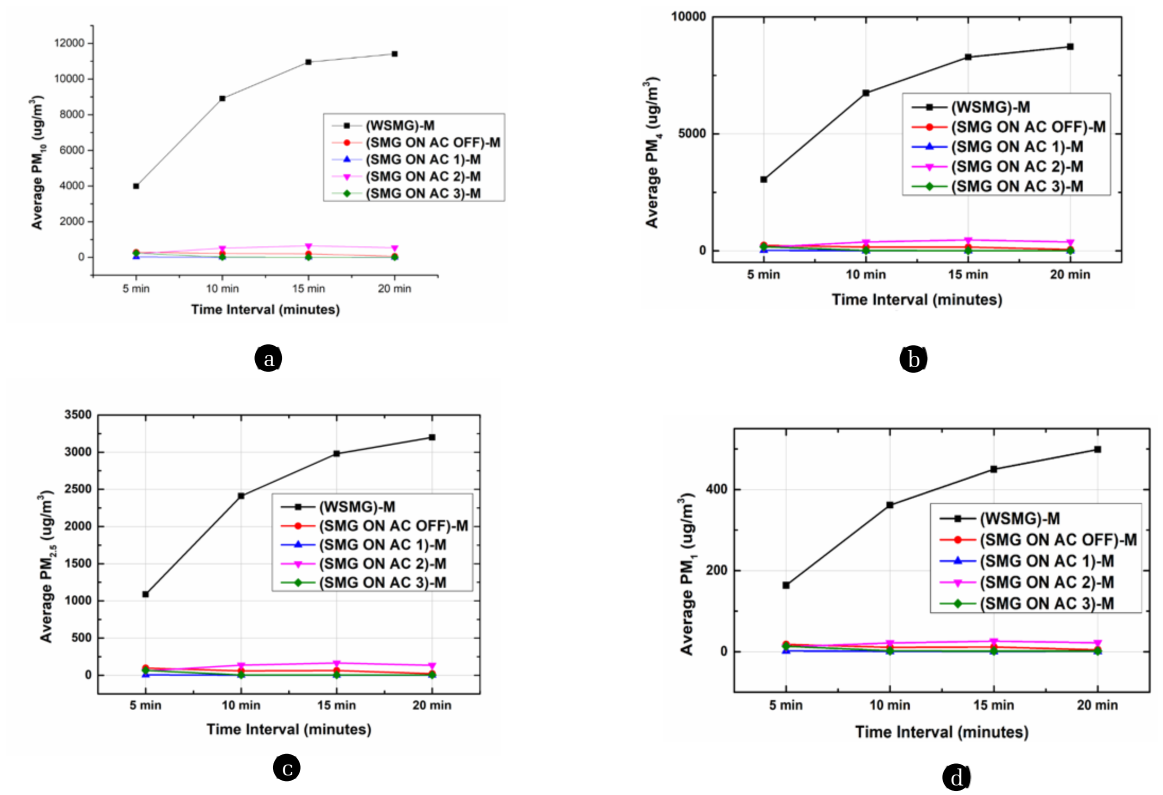

Fig. 2. (a) Average concentration of PM10 for various experimental conditions. (b) Average concentration of PM4 for various experimental conditions. (c) Average concentration of PM2.5 for various experimental conditions. (d) Average concentration of PM1 for various experimental conditions.

the second condition, which occurs when the air curtain flow curves inward but does not reach the floor. Outflow breakthrough is the third condition, which occurs when the air curtain flow curves outward but does not reach the floor. With these three air curtain settings in mind, three experimental setups were created, the first of which retained both air curtains at their lowest setting. This case is represented as SMGON-AC_1-M. In the second scenario, one air curtain was left at its lowest setting while the other was raised to its highest, represented as SMGON-AC_2-M; in the third scenario, both air curtains were raised to their highest positions denoted as SMGON-AC_3-M.

The average concentration of PM_{10}, PM_4, $PM_{2.5}$ and PM_1 (Fig. 2) for SMGON-AC_1-M condition was 8.00 $\mu g/m^3$, 4.67 $\mu g/m^3$, 3.43 $\mu g/m^3$ and, 1.2 $\mu g/m^3$. The results obtained using smart gate, agree with the several studies conducted in the past, suggesting that the air curtains can also help in the particulate matter reduction [4,29,30,32].

The average concentration of PM_{10}, PM_4, $PM_{2.5}$ and PM_1 (Fig. 2), for SMGON-AC_2-M condition was 502.66 $\mu g/m^3$, 285.19 $\mu g/m^3$, 169.95 $\mu g/m^3$, and 27.13 $\mu g/m^3$. Also, the average concentration of PM_{10}, PM_4, $PM_{2.5}$ and PM_1 (Fig. 2), for SMGON-AC_3-M condition was 62.11 $\mu g/m^3$, 36.43 $\mu g/m^3$, 24.80 $\mu g/m^3$, and 5.88 $\mu g/m^3$.

Even though the guide vane angle and position of the air curtain are important factors in the reduction of particulate matter, prior studies have only shown a reduction of particulate matter of up to 75% [4], which is still below the results shown by the smart gate even when the air curtains are not in use (Table 2). The reduction efficiency of the smart gate even the air curtains are turned off is 97.76% for PM_{10}, 97.72% for PM_4, 97.44% for $PM_{2.5}$ and 96.91% for PM_1. When both air curtains are turned on, the smart gate shows much superior performance in lowering the PM concentration than when they are off (Table 3). These findings support earlier research that found air curtains can help with particulate matter reduction [4,29,30,32]. It should be noted that under the SMGON-AC_2-M condition, the two air curtain flow conditions—the optimal and the inflow break-through conditions—are confirmed by the experimental design. The zones of the best operation for both supply speed tests are in the zone of negative flow rate, meaning that the net flow through the door is negative. When the flows, or volume flow rate, are almost zero and turn positive (inflows), it means that inflow breakthrough circumstances have changed. The current study is restricted to depressurization or mild pressurization since pressurizing the chamber at high pressures might potentially cause the blower fan flow to interact with the air curtain jets, complicating the airflow inside the chamber. This is comparable to [32,33] studies and, where many blower door tests were depressurization rather than pressurization.

Numerous researchers, including [22,34,35], have also used commercially available air purifiers to reduce PM_{10} and $PM_{2.5}$, but these only achieve reductions of up to 90% and 80%, respectively, which is significantly less than the results attained using the smart gate (Table 2). The reduction efficiency for the particulate matter supplied by the smart gate is significantly higher than the other solutions now available, making it a better alternative.

3.2. Virus Reduction Using Smart Gate

The SARS-CoV-2 virus can remain infectious in the air for hours, according to [36]. A number of research, including [37,38], demonstrated a positive association between PM levels and COVID-19 viral strains and transmission. As a result, since the virus may remain contagious in the form of aerosols for hours and on surfaces for days, the SARS-CoV virus can spread by aerosol. The COVID-19 illness can be brought on by droplet particles having an aerodynamic diameter $<5\ \mu m$ that are ejected from the coughing or sneezing of the carrier. Many specialized technologies, including photocatalysis, ionization radiation, plasma technology use, UVC radiation, and liquid air purification systems, can lessen pathogenicity [13–15]. It has been discovered that using various filters and purifiers to filter or purify the air in interior places might reduce the viral load there, hence reducing the risk of virus transmission [2,39]. The procedures include the use of mechanical air filters, MERV and HEPA filters, electronic air cleaners, gas-phase air cleaners, ultraviolet disinfection systems, etc. in areas with significant levels of outside pollution, such as metropolitan centers, where natural ventilation is problematic and impractical. The HEPA filter has a cheap initial investment cost, but significant operating and energy expenditures. When HEPA filter-based air purifiers were evaluated in a lab environment in China, there was a reported loss in effectiveness with a 200-250 nm particle size range. This is significant because the particles with these size ranges are prevalent in megacities, may penetrate the building envelope, remain suspended in the air, and can operate as a virus carrier [40]. Apart from these, other air cleaning techniques also have similar issues and cannot be applied in spaces such as offices, schools etc.

As seen from the Fig. 3, the concentration of the aerosolized bioparticle significantly decrease as we turn on the smart gate. This is due to the components present inside the smart gate (Fig. 1). The average concentration before the start of the smart gate was found to be 1467.86 particles where after starting the smart gate the bioparticle concentration drops to the average of 259.2 particles demonstrating its reduction efficiency of approximately 82.29%. The ceiling air conditioning unit consists of sterilization unit. This unit comprises of UV-C lamp along with the MERV-filters. As, the ceiling air condition unit created positive pressure by supplying a large amount of air inside, the sterilization unit treats the infectious contaminants such as aerosolized virus. Previous studies have shown that the UV-C lamp along with the MERV filter has shown their ability to reduce airborne micro-organisms [27,28,31]. However, it is challenging to use UV light everywhere because of restrictions like installation over 1.8 m above the floor to prevent any health risks as adverse health effects on skin, such as erythema, photokeratitis, etc. are known to occur with excessive exposure. In addition, the level of relative humidity must be maintained up to 50% as with increase in RH, UV irradiation efficiency decreases by 40% [10,41]. Considering these issues and the findings of the smart gate study, it may also be used as a substitute for virus reduction.

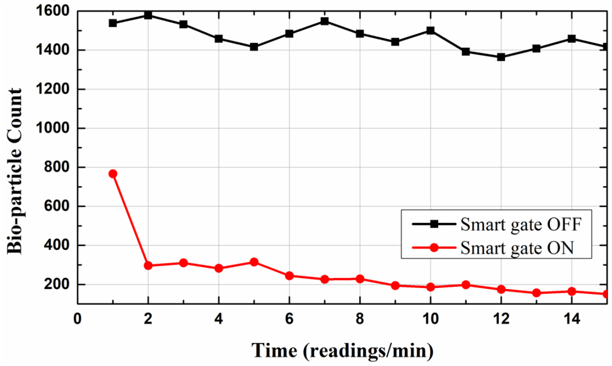

Fig. 3. Bioparticle (aerosolized virus) concentration with and without smart gate.

4. Conclusions

The knowledge gap on the indoor pollutant along with the virus/infectious disease transmission risks in indoor built spaces and to provide fundamental insight into the significance of indoor air quality (IAQ). Although IAQ has been widely discussed in the literature in terms of the overall health of an individual, but the influence of IAQ on viral transmissions risk, especially on COVID-19 related information, is limited. Complimentary effects of various meteorological parameters along with its role in pollutant and viral transmission risks are not widely discussed in the literature as per authors knowledge. Based on the results of the tests conducted on the reduction of PM and viruses, it can be said that the smart gates are a better alternative and is successful in lowering the concentration of airborne particles. Because of the different components Fig. 1 that are within the smart gate, which contribute to its efficiency it is the greatest option for reducing viruses and particulate matters. Moreover, smart gate might be effectively used in congested and crucial situations, considering the requirement for enhanced indoor air quality in relation to the COVID-19 pandemic (for example shopping malls, schools, hospitals or waiting rooms in public transportation areas and so on). Also, a noticeable decrease in particle count, particularly in the fine fraction, was seen while the smart gate was operating along with the aerosolized virus, and this finding has a favorable effect on indoor air quality since finer particles are the ones that enter the pulmonary alveoli. The results show that 97.76% for PM_{10}, 97.72%PM_4, 97.44% $PM_{2.5}$ and 96.91% PM_1. reduction. Due to its size and the results, it has produced, it may be used as a better alternative for reducing indoor air pollution in public areas like shopping centers, subway platforms, and movie theater entrances, among other places instead of the commercially available air purifiers.

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Author Contributions

S.S. (PhD student), P.D. (Professor) came up with the design and concept for the study. L.J. (Researcher), P.C. (Professor), P.D. (Professor) designed the smart gate. S.S. (PhD student), M.J. (PhD student) performed the experiment. Data analysis was done by S.S. (PhD student), A.B. (PhD student). S.S. (PhD student) wrote the manuscript. The final manuscript was reviewed by P.D., L.H. (Professor), M.J. (PhD student), A.B. (PhD student).

Conflict of Interest

The authors declare that they have no known conflict of interest.

References

1. Sharma S, Bakht A, Jahanzaib M., Lee H, Park D. Evaluation of the Effectiveness of Common Indoor Plants in Improving the Indoor Air Quality of Studio Apartments, *Atmosphere*. 2022;13:1863. https://doi.org/10.3390/atmos13111863.
2. Bakht A, Sharma S, Park D, Lee H. Deep Learning-Based Indoor Air Quality Forecasting Framework for Indoor Subway Station Platforms, *Toxics*. 2022;10:557. https://doi.org/10.3390/ toxics10100557
3. Jahanzaib M, Irshad P, Park D. Development of Driving Cycle for Passenger Cars and Estimation of Vehicular Exhaust Emission Factors, *J. Environ. Pollut. Control*. 2022;5:1–11. https://doi.org/10.15744/2639-9288.5.103.
4. Jahanzaib M, Sharma S, Bakht A, Heo J, Park D. Analyzing the effectiveness of air curtain in reducing particulate matter generated by human-induced slipstream, *Process Saf. Environ. Prot.* 170;(2023):834–841. https://doi.org/10.1016/j.psep.2022.12.013.
5. Pluschke P, Schleibinger H. Indoor Air Pollution. 2nd Edition, 2018. https://linkinghub.elsevier.com/retrieve/pii/S0166526X16300162.
6. Melikov AK, Human body micro-environment: The benefits of controlling airflow interaction, *Build. Environ.* 2015;91:70–77. https://doi.org/10.1016/j.buildenv.2015.04.010.
7. Kim KH, Szulejko JE, Kumar P, Kwon P, Adelodun AA, Reddy PAK, Air ionization as a control technology for off-gas emissions of volatile organic compounds, *Environ. Pollut.* 2017;225:729–743. https://doi.org/10.1016/j.envpol.2017.03.026.
8. Zeng Y, Manwatkar P, Laguerre A et al. Evaluating a commercially available in-duct bipolar ionization device for pollutant removal and potential byproduct formation, *Build. Environ.* 2021;195. https://doi.org/10.1016/j.buildenv.2021.107750.
9. Huang H, Lu H, Huang H, Wang L, Zhang J, Leung DYC. Recent development of VUV-based processes for air pollutant degradation, *Front. Environ. Sci*. 2016;4:1–13. https://doi.org/10.3389/fenvs.2016.00017.
10. Bolashikov ZD, Melikov AK. Methods for air cleaning and protection of building occupants from airborne pathogens, *Build. Environ*. 2009;44:1378–1385. https://doi.org/10.1016/j.buildenv.2008.09.001.
11. Menzies D, Popa J, Hanley JA, Rand T, Milton DK. Effect of ultraviolet germicidal lights installed in office ventilation systems on workers' health and wellbeing: Double-blind multiple crossover trial, *Lancet.* 2003;362:1785–1791. https://doi.org/10.1016/S0140-6736(03)14897-0.
12. Luongo JC, Brownstein J, Miller SK. Ultraviolet germicidal coil cleaning: Impact on heat transfer effectiveness and static pressure drop, *Build. Environ*. 2017;112:159–165. https://doi.org/10.1016/j.buildenv.2016.11.022.
13. Assadi I, Guesmi A, Baaloudj O et al. Review on inactivation of airborne viruses using non-thermal plasma technologies: from MS2 to coronavirus, *Environ. Sci. Pollut. Res.* 2022;29:4880–4892. https://doi.org/10.1007/s11356-021-17486-3.
14. Snelling WJ, Afkhami A, Turkington HL et al. Efficacy of single pass UVC air treatment for the inactivation of coronavirus, MS2 coliphage and Staphylococcus aureus bioaerosols, *J. Aerosol Sci.* 2022;164:106003. https://doi.org/10.1016/j.jaerosci.2022.106003.
15. Thornton GM, Fleck BA, Fleck N et al. The impact of heating, ventilation, and air conditioning design features on the transmission of viruses, including the 2019 novel coronavirus: A systematic review of ultraviolet radiation, *PLoS One.* 2022;17:1–25. https://doi.org/10.1371/journal.pone.0266487.
16. Thirumdas R, Sarangapani C, Annapure US. Cold Plasma: A novel Non-Thermal Technology for Food Processing, *Food Biophys*. 2015;10:1–11. https://doi.org/10.1007/s11483-014-9382-z.
17. Lai ACK, Cheung ACT, Wong MML, Li WS. Evaluation of cold plasma inactivation efficacy against different airborne bacteria in ventilation duct flow, *Build. Environ.* 2016;98:39–46. https://doi.org/10.1016/j.buildenv.2015.12.005.
18. Song L, Zhou J, Wang C et al. Airborne pathogenic microorganisms and air cleaning technology development: A review, *J. Hazard. Mater.* 2022;424:127429. https://doi.org/10.1016/j.jhazmat.2021.127429.
19. Buonanno G, Stabile L, Morawska L. Estimation of airborne viral emission: Quanta emission rate of SARS-CoV-2 for infection risk assessment, *Environ. Int.* 2020;141: 105794. https://doi.org/10.1016/j.envint.2020.105794.
20. Setti L, Passarini F, Gennaro GDe et al. SARS-Cov-2RNA found on particulate matter of Bergamo in Northern Italy: First evidence, *Environ. Res.* 2020;188:109754. https://doi.org/10.1016/j.envres.2020.109754.
21. Linillos-Pradillo P, Rancan L, Ramiro ED, Vara E, Artíñano B, Arias J. Determination of SARS-CoV-2 RNA in different particulate matter size fractions of outdoor air samples in Madrid during the lockdown, *Environ. Res*. 2021;195. https://doi.org/10.1016/j.envres.2021.110863.
22. Fermo P, Artíñano B, Gennaro GDe et al. Improving indoor air quality through an air purifier able to reduce aerosol particulate matter (PM) and volatile organic compounds (VOCs): Experimental results, *Environ. Res.* 2021;197:1–8. https://doi.org/10.1016/j.envres.2021.111131.
23. Kim JS, Lee MH. Effect of filter collection efficiency on the clean air delivery rate in an air cleaner, *Indoor Air.* 2021;31:745–754. https://doi.org/10.1111/ina.12757.
24. Fermo P, Comite V, Falciola L, Guglielmi V, Miani A. Efficiency

of an air cleaner device in reducing aerosol particulate matter (PM) in indoor environments, *Int. J. Environ. Res. Public Health.* 2020;17. https://doi.org/10.3390/ijerph17010018.

25. Korajkic A, McMinn B, Herrmann MP et al. Viral and bacterial fecal indicators in untreated wastewater across the contiguous united states exhibit geospatial trends, *Appl. Environ. Microbiol.* 2020;86:1–14. https://doi.org/10.1128/AEM.02967-19.
26. Mikel P, Vasickova P, Kralik P. Methods for Preparation of MS2 Phage-Like Particles and Their Utilization as Process Control Viruses in RT-PCR and qRT-PCR Detection of RNA Viruses From Food Matrices and Clinical Specimens, *Food Environ. Virol.* 2015;7: 96–111. https://doi.org/10.1007/s12560-015-9188-2.
27. Fino VR, Kniel KE. UV light inactivation of hepatitis A virus, aichi virus, and feline calicivirus on strawberries, green onions, and lettuce, *J. Food Prot.* 2008;71:908–913. https://doi.org/10.4315/0362-028X-71.5.908.
28. Sherchan SP, Snyder SA, Gerba CP, Pepper IL. Inactivation of MS2 coliphage by UV and hydrogen peroxide: Comparison by cultural and molecular methodologies, *J. Environ. Sci. Heal. - Part A Toxic/Hazardous Subst. Environ. Eng.* 2014;49:397–403. https://doi.org/10.1080/10934529.2014.854607.
29. Neto LPC, Influence of the jet initial inclination angle on the performance of an air curtain device Influence of the jet initial inclination angle on the performance of an air curtain device, (2003). Available from: https://www.researchgate.net/profile/Luis-Neto-11/publication/313899112_Influence_of_the_jet_initial_inclination_angle_on_the_performance_of_an_air_curtain_device/links/58aedb33aca2725b5410f55b/Influence-of-the-jet-initial-inclination-angle-on-the-performance-of-an-air-curtain-device.pdf
30. Wang LL, Zhong, Z. An approach to determine infiltration characteristics of building entrance equipped with air curtains. *Energy and buildings*. 2014;75:312-320. https://doi.org/10.1016/j.enbuild.2014.02.020
31. Pecson BM, Martin LV, Kohn T. Quantitative PCR for determining the infectivity of bacteriophage MS2 upon inactivation by heat, UV-B radiation, and singlet oxygen: Advantages and limitations of an enzymatic treatment to reduce false-positive results, *Appl. Environ. Microbiol.* 2009;75:5544–5554. https://doi.org/10.1128/AEM.00425-09.
32. Goubran S, Qi D, Saleh WF, Wang LL, Zmeureanu R. Experimental study on the flow characteristics of air curtains at building entrances, *Build. Environ.* 2016;105:225–235. https://doi.org/10.1016/j.buildenv.2016.05.037.
33. Yuill GK, Upham R, Hui C. Air leakage through automatic doors, ASHRAE Trans. 2000;106. Available from: https://spectrum.library.concordia.ca/id/eprint/984024/
34. Zhan Y, Johnson K, Norris C et al. The influence of air cleaners on indoor particulate matter components and oxidative potential in residential households in Beijing, *Sci. Total Environ.* 2018; 626:507–518. https://doi.org/10.1016/j.scitotenv.2018.01.024.
35. Jeong CH, Salehi S, Wu J et al. Indoor measurements of air pollutants in residential houses in urban and suburban areas: Indoor versus ambient concentrations, *Sci. Total Environ.* 2019;693:133446. https://doi.org/10.1016/j.scitotenv.2019.07.252.
36. Hyun J, Lee SG, Hwang J. Application of corona discharge-generated air ions for filtration of aerosolized virus and inactivation of filtered virus, *J. Aerosol Sci.* 2017;107:31–40. https://doi.org/10.1016/j.jaerosci.2017.02.004.
37. Borro M, Girolamo PD, Gentile G et al. Evidence-based considerations exploring relations between sars-cov-2 pandemic and air pollution: Involvement of pm2.5-mediated up-regulation of the viral receptor ace-2, *Int. J. Environ. Res. Public Health.* 2020;17:1–13. https://doi.org/10.3390/ijerph17155573.
38. Amoatey P, Omidvarborna H, Baawain MS, Al-Mamun A, Impact of building ventilation systems and habitual indoor incense burning on SARS-CoV-2 virus transmissions in Middle Eastern countries, *Sci. Total Environ.* 2020;733:139356. https://doi.org/10.1016/j.scitotenv.2020.139356.
39. Elias B, Bar-Yam Y, Could Air Filtration Reduce COVID-19 Severity and Spread?, New Engl. Complex Syst. Inst. (2020). Available from: https://static1.squarespace.com/static/5b68a4e4a2772c2a206180a1/t/5e67a58357b4e0440343e1fa/1583850883797/SpeculationOnAirFIlters.pdf
40. Lowther SD, Deng W, Fang Z et al. How efficiently can HEPA purifiers remove priority fine and ultrafine particles from indoor air?, *Environ. Int.* 2020;144. https://doi.org/10.1016/j.envint.2020.106001.
41. Peccia J, Hernandez M. Photoreactivation in Airborne Mycobacterium parafortuitum, *Appl. Environ. Microbiol.* 2001; 67:4225–4232. https://doi.org/10.1128/AEM.67.9.4225-4232.2001.