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An experimental investigation of how human activities affect the behaviour of indoor airborne particles

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Abstract: The outbreak of COVID-19 in 2019 triggered soaring public concern about respiratory infectious diseases. The motion of virus-carrier particles has also been researched by academia due to its susceptible characteristics caused by various factors. Particle behaviours can be influenced by human activities inducing effects, which can be regarded as an opportunity to support the development of efficient strategies for coping with infectious diseases. By performing simulation experiments, this paper investigated how door opening and human walking influence the behaviour of indoor PM0.5 and PM2.5. The results show that better understanding the effect of human activities may help control virus-carrying particles indoors.

Keywords: Particle behaviour, indoor particle, infectious disease, human activity, relative humidity

1. Introduction

Worries about the transmission of respiratory infectious diseases have mounted in the past two years. The outbreak of a novel coronavirus disease 19 (COVID-19) in late December 2019 has spread across over 175 countries (Iyanda et al., 2020), plunging the world's social and economy into a steep recession as well as causing more than 6.3 million deaths as of June 2022 (WHO, 2022). On 11 March 2020, the World Health Organization announced the coronavirus outbreak as a public health emergency and a global pandemic. It is an infectious disease caused by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), emerging as a renewed public concern of respiratory infectious diseases. Overwhelming evidence proves that indoor infectious disease transmission predominates in the spreading (Biribawa et al., 2020; Centers for Disease Control and Prevention (CDC), 2004a, 2004b; Curmei et al., 2020). The study of indoor airborne transmission can therefore be useful in controlling the spread of infectious diseases.

Although airborne transmission depends on several physical variables specific to infectious particles (e.g., particle size and particle types), human behaviours can significantly influence airborne disease transmission. Considering the still existing risk of COVID-19 and the possible risk of future infections, it would be helpful if potential interventions to the indoor environment were identified that could limit the spread of respiratory infections. This project aimed to explore how different activities carried out by occupants may influence the behaviour of indoor airborne particles and to develop potential strategies to help reduce the transmission of infectious diseases.

2. Materials and methods

An experimental campaign was designed to identify the influence of three activities on particle counts at different positions. PM0.5 and PM2.5 were chosen to assess the changes in particle behaviour. The experiment was carried out in an environmental chamber (W2.35 x L4.55 x H3.00 m). The particle counts for PM0.5 and PM2.5 before and after the activities were logged for analysis.

Twelve laser particle counters (Plantower PMS 5003, range of measurements: 0.3 µm to 10 µm), efficiency: 50%@0.3 µm & 98% ≥ @0.5 µm, working temperature: -10 °C to 60 °C, working humidity: 0-99% RH) were placed at three heights (0.4 m, 1.5 m, and 2.25 m) on four vertical poles to monitor the variation of different sized particles (Figure 1). All sensors were calibrated in advance by the manufacturer and operated remotely.

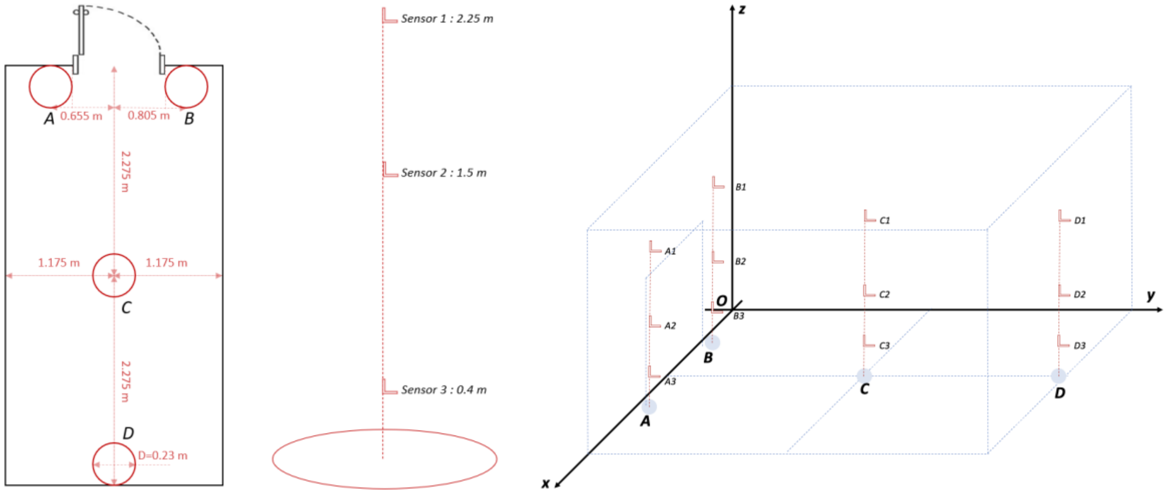

Figure 1. a) Environment chamber plan with the location of 4 poles and acres to the chamber (door opens to the outside); b) A pole and sensors located at three heights; c) 3D view of 12 particle sensors

2.1 Experimental procedure

The clocks (Maxim Integrated DS1307 and DS3231 RTCs) for achieving the real-time response of the counting were synchronised remotely. The environmental chamber was stabilised for two days, and the readings of particles were monitored to ensure the chamber had reached a steady state. Three activities were conducted individually to investigate the impact of human activities on particle counts: (1) The door was opened by a slider bar (85 cm NEEWER wireless control slider, the operation time: 20s, speed: 4.25 cm/s) and kept it opened for two minutes. During this time, no one entered the environmental chamber; (2) Opened the door, and a participant walked a meter into the chamber; (3) Opened the door, and a participant walked two meters into the chamber. The direction and the paths of participants walking into the chamber are presented in Figure 2. Particle counters were set up to start recordings two hours before the activities and lasted for around six after the activities. The interval set for the data logging was five minutes and the final logs output corresponding to the average number of particles during the 5 minutes intervals.

2.2 Statistical analysis

Particle counts were compiled for statistical analysis, which consisted of an ANOVA test followed by Pearson's correlation analysis. All data were analysed using Microsoft Excel and Python 3. Statistical significance was defined as P<.05. Then, three evaluation indicators were defined to evaluate different effects, as shown in Figure 3. *Rate of change* describes the percentage change in particle counts over one hour after opening the door, reflecting the transient effect. *Standard deviation difference* is the gap between the particle counts two hours after and two hours before opening the door, reflecting the effect on variation. *Resilient* describes the difference between the number of particles at the end of logging time and before opening the door, reflecting the sustained effect.

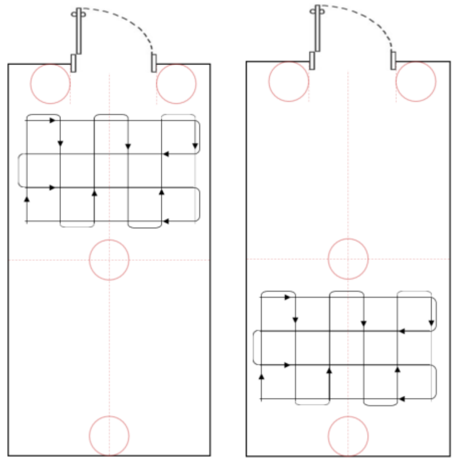

Figure 2. The walking direction and paths of a human walking to one (left) and two (right) meters

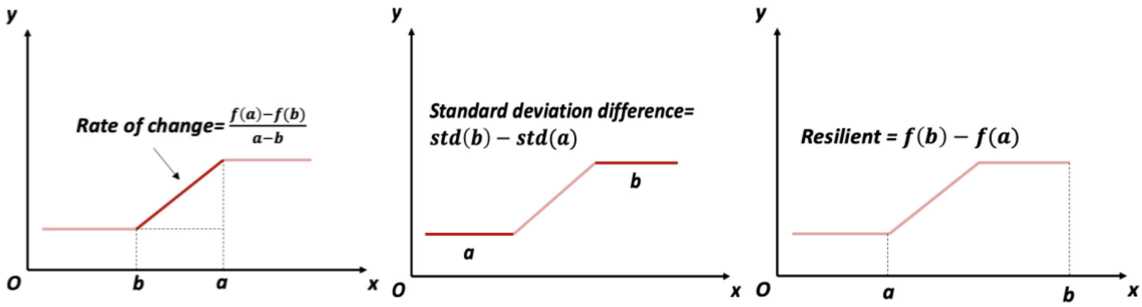

Figure 3. Three evaluation indicators used to assess the different impacts on particles

3. Results and discussion

The trend of PM0.5 and its hourly mean values with trendlines regarding different activities are shown in Figure 4.

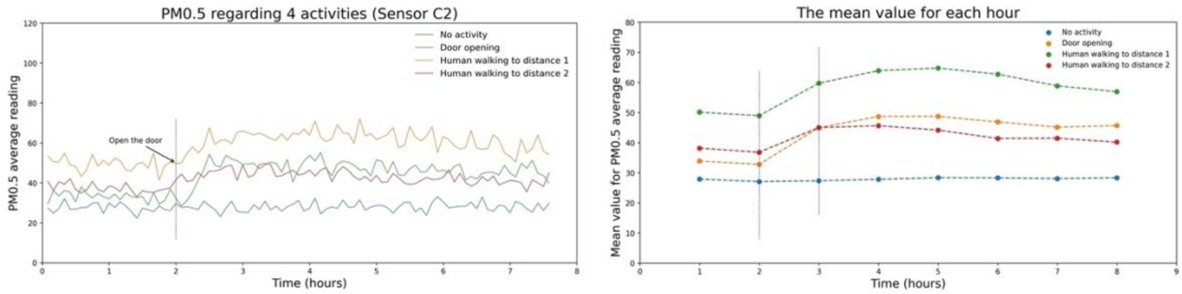

Figure 4. The trend and hourly average value and trendlines of PM0.5 regarding different activities

Table 1. Rate of change, difference of standard deviation and resilient evaluation for three activities on PM0.5

	ROC	Std diff.	Resilient
Door opening (orange line)	12.18	4.43	12.88
Human walking to distance 1 (green line)	10.76	0.92	7.95
Human walking to distance 2 (red line)	8.21	0.32	3.35

Figure 4 (left) describes the trend for PM0.5 testing under three activities. The blue line represents the steady state or not activity. The initial particle counts for three activities are slightly higher than the steady state, ranging from around 40 particles to 60. There is a clear increase after opening the door in all three activities. The green and orange lines illustrating door opening and human walking to distance 1 show a peak within an hour after the disturbance, while the red line describing human walking to distance 2 shows a gentle and lagging rise and fluctuation. Since it is difficult to distinguish the most influential activity on the particle from Figure 4 (left), the hourly average counts for PM0.5 and the corresponding trendlines and three evaluation indicators describing the changes are presented in Figure 4 (right) and Table 1. The green and orange lines have similar rates of increase from the second to the third hour and steeper slopes than the red line. As shown in Table 1, the orange line has the largest rate of change, illustrating that door opening has the most significant transient effect on PM0.5. Comparing the variation difference before and after door opening, the orange line has a much greater difference than others, describing that opening the door without a human walking in causes PM0.5 to exhibit more erratic fluctuations. Door opening also has the most considerable effect as the counts of PM0.5 several hours after the activity was still much higher compared to the initial values, suggesting that door opening makes the indoor PM0.5 environment less able to recover. Human walking to distance 1 also significantly affects PM0.5, especially by observing the instant rate of change and rebound indicators, and the variation follows the same pattern as the door opening.

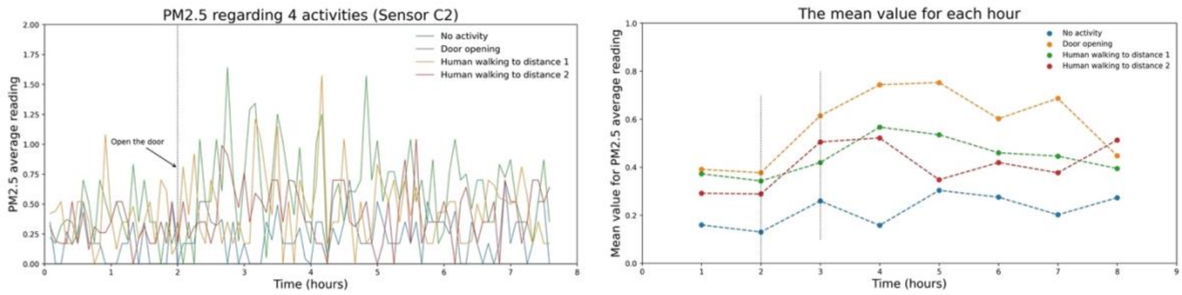

Figure 5. The trend and hourly average value and trendlines of PM2.5 regarding different activities

Table 2. Rate of change, difference of standard deviation and resilient evaluation for three activities on PM2.5

	ROC	Std diff.	Resilient
Door opening (Orange)	0.24	0.25	0.07
Human walking to distance 1 (Green)	0.08	0.11	0.05
Human walking to distance 2 (Red)	0.22	0.07	0.22

PM2.5 has a more hectic variation. The drastic variation can result from a lower number of particles being recorded. The relatively small axis unit presents detailed changes of particles no matter how tiny it changes. The orange and green lines show a more active behaviour after opening the door. The activity represented by the red line also generated a rise in particles. As presented in Figure 5 (right) and Table 2, door opening has a higher influence on instant change and indoor environment disturbing while a human walking to distance 2 has a greater sustained impact on PM2.5. A person walking to the middle of the chamber has no significant effect on PM2.5. It should be noted that the red line, which stands for human walking to distance 2 had irregular larger fluctuations, including a fall followed by another rise in particle counts. In other words, opening the door without human walking has the most significant effect on the rapid rise in the number of PM2.5 particles and makes the standard deviation of PM2.5 more erratic. However, this erratic standard deviation can be attributed to the regular fall in the number of particles after several hours. Due to the calculation mechanism of the standard deviation, the apparent drop is considered. Over time, PM2.5 tends to settle, making its detection harder by the sensors. Therefore, the greatest standard deviation of door opening does not indicate the greatest effect of the fluctuations in PM2.5. When considering the persistence effect on indoor PM2.5, it is instead the human walking to distance 2 that may disturb the indoor particle and keep the particles active for a longer period, exerting a

longer-lasting effect, so it could be said that human walking to the farthest distance of the chamber makes PM2.5 exhibit more erratic fluctuations.

In summary, the door opened without a human walking strongly impacts PM0.5 and PM2.5. The reason may be that indoor particles reach an equilibrium that cannot be broken during long periods of steady state. Due to the closure, this unbreakable state can be attributed to the chamber's higher pressure and warmer air compared to the outdoor environment. Opening the door would create turbulence and a large exchange flow by reducing the temperature and pressure gradient between spaces (Tang et al., 2005). The turbulent airflow blows into the chamber, rapidly increasing the number of particles (Scaltriti et al., 2007). However, after a period of unilateral particle transport, particles from indoors also become more involved in particle exchange, leading to a decrease in the particle count. Moreover, opening the hinged door leads to a sweeping action, forcing many particles through the open doorway (Sadrizadeh et al., 2018; Tang et al., 2006). The door opening has a more significant impact than a person walking; probably, the particles will be taken by a person from the indoor environment, and the particles rolled up by a person walking compensate for the instant increase in particles due to door opening. Therefore, a person walking into the room when the door is opening may have an antagonistic effect rather than an accumulated or synergistic effect on the change of particles in the chamber. The effect of distance of a human walking inside on particles is not clear yet as human walking to distance 1 impacts PM0.5 while human walking to distance 2 affects PM2.5. An ANOVA test shows a significant difference between the PM0.5 counts and the depth of human walking inside ($P<.05$), indicating no homogeneity of the two patterns brought by different depths of human walking. A significant level of $P>.05$ suggested that no significant difference was investigated between the distance of human walking inside the chamber and the counts of PM2.5. The differences may be due to the small size and mass of PM0.5 being more susceptible to human walking.

Table 3. Correlation coefficient for same-sized particles at different location

	PM0.5 high sensor Pole A	*PM0.5 high sensor Pole B*	*PM0.5 high sensor Pole C*	*PM0.5 high sensor Pole D*
PM0.5 high sensor Pole A	1.000			
PM0.5 high sensor Pole B	0.925	1.000		
PM0.5 high sensor Pole C	0.881	0.878	1.000	
PM0.5 high sensor Pole D	0.893	0.843	0.853	1.000
	PM0.5 middle sensor Pole A	*PM0.5 middle sensor Pole B*	*PM0.5 middle sensor Pole C*	*PM0.5 middle sensor Pole D*
PM0.5 middle sensor Pole A	1.000			
PM0.5 middle sensor Pole B	0.921	1.000		
PM0.5 middle sensor Pole C	0.874	0.863	1.000	
PM0.5 middle sensor Pole D	0.866	0.843	0.825	1.000
	PM0.5 low sensor Pole A	*PM0.5 low sensor Pole B*	*PM0.5 low sensor Pole C*	*PM0.5 low sensor Pole D*
PM0.5 low sensor Pole A	1.000			
PM0.5 low sensor Pole B	0.934	1.000		
PM0.5 low sensor Pole C	0.829	0.847	1.000	
PM0.5 low sensor Pole D	0.843	0.847	0.831	1.000
	PM2.5 high sensor Pole A	*PM2.5 high sensor Pole B*	*PM2.5 high sensor Pole C*	*PM2.5 high sensor Pole D*
PM2.5 high sensor Pole A	1.000			
PM2.5 high sensor Pole B	0.135	1.000		
PM2.5 high sensor Pole C	0.114	0.203	1.000	
PM2.5 high sensor Pole D	0.238	0.315	0.070	1.000
	PM2.5 middle sensor Pole A	*PM2.5 middle sensor Pole B*	*PM2.5 middle sensor Pole C*	*PM2.5 middle sensor Pole D*
PM2.5 middle sensor Pole A	1.000			
PM2.5 middle sensor Pole B	0.160	1.000		
PM2.5 middle sensor Pole C	0.113	-0.033	1.000	
PM2.5 middle sensor Pole D	0.123	0.235	0.147	1.000
	PM2.5 low sensor Pole A	*PM2.5 low sensor Pole B*	*PM2.5 low sensor Pole C*	*PM2.5 low sensor Pole D*
PM2.5 low sensor Pole A	1.000			
PM2.5 low sensor Pole B	0.171	1.000		
PM2.5 low sensor Pole C	0.230	0.438	1.000	
PM2.5 low sensor Pole D	0.047	0.306	0.211	1.000

The results of Pearson's correlation implied that the number of PM0.5 has a robust correlation ($R \geq 0.825$) with each other regardless of the position when opening the door. For PM2.5, only moderate or weaker correlations were found between the number of particles and the position of sensors at the same height ($R \leq 0.438$). The maximum coefficient happened in the lowest height, and both higher and lower groups present a stronger correlation than the middle height. It is suggested that PM0.5 tends to co-vary than PM2.5. The effects of PM0.5 and PM2.5 are similar but more significant on PM0.5.

4. Conclusion

As a threat to human beings, infectious diseases remain major public health problems that need to be addressed. This project evaluated the impact of human activities on particle by designing an experiment measuring the counts of PM0.5 and PM2.5 at 12 positions when conducting various human activities. The findings were listed as follows. 1) Door opening affected particles the most. The reason may be that the instant particle exchange occurs due to temperature and pressure gradients, and the sweeping action of the hinged door forces more particles to pass through the opening. 2) The counts of PM0.5 has a robust correlation with each other regardless of the position, while only moderate or weak correlations were found between the number of PM2.5 and the position. Therefore, PM0.5 can co-vary with other particles more than PM2.5 when opening the door. 3) It was confirmed that different distances of a person walking inside would statistically impact the counts of PM0.5 ($P<.05$). In contrast, a limited effect was found on PM2.5 ($P>.05$). The insights gained from this study may be that sufficient fresh air exchange rate can be achieved simply by leaving doors opened when the space is unoccupied which may help control the increase in virus-carrying particles indoors. Also, the movement of people can take some particles out of the room, reducing the number of infectious disease particles, but it may also disrupt indoor airflow and lead to an increase in the number of particles in turn.

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