Transmission and infection risk of various pathogen-laden expiratory droplets in a coach bus with COVID-19

Qiqi Luo[1]*, Cuiyun* Ou[1], *Jian* Hang[1]*, *Hongyu* Yang[1] and *Xia* Yang[1]

[1]Sun Yat-Sen University, Zhuhai, China

Abstract. The study about droplet transmission in crowded, poorly ventilated buses and the resulting infection risk(IR) remains rare. Based on a COVID-19 outbreak which the index patient located at bus rear, we performed CFD simulations to study the effect of initial droplet diameters and hourly ventilation rate(ACH) on droplet transmission and IR. The outdoor pressure differential creates the natural ventilation enters from theskylight at bus rear and exits from the front one. With increased ACH, the IR of tracer gas reduced quickly, from 11.1-15.3% under 0.62ACH to 1.3-3.1% under 5.66ACH. Furthermore, the IR of 100μm/50μm droplets was almost independent of ACH as most droplets were deposited due to gravity. Furthermore, 5μm droplets are more widely dispersed than larger droplets, and can spread further with increasing ACH with a low $IR(\leqslant 0.4\%)$. Unlike general rooms, most droplets are deposited on the route passing through the long-distance bus space(~9.46m). But the tracer gas will not deposit, so the tracer gas can only be used to simulate the fine droplet dispersion process in the long-distance bus. Our research results provide a reference for future research on droplet transmission in the bus environment, and also provide a guidance for epidemic prevention.

1 Introduction

Human exhaled droplets are an important carrier of respiratory disease pathogens, and their indoor transmission is an important link in the respiratory disease infection chain. Due to factors such as built-in air conditioning, closed space and large number of passengers on long-distance coach buses, viral respiratory infectious diseases are easily spread in this situation. At present, a large number of scholars have conducted research on indoor environments such as supermarkets, hospital wards, and dormitories. However, as one of the most commonly used means of transportation, long-distance buses have relatively little research on the spread of internal droplets.

Table 1. Parameters and setups.

Experimental variables	Setups
Hourly ventilation rates (*ACH*)	0.62 h^{-1}
	2.27 h^{-1}
	5.66 h^{-1}
Initial droplet diameter (d_p / μm)	Tracer gas
	5 μm
	50 μm
	100 μm

This paper investigates droplet transmission and the resulting infection risk in a coach bus based on a COVID-19 outbreak in Hunan. Three kinds of hourly ventilation rates (*ACH* = 0.62 h^{-1}, 2.27 h^{-1}, 5.66 h^{-1}),

tracer gas and three initial droplet diameters (5 μm, 50 μm, 100 μm) were considered (Table 1). By adopting *Wells-Riley equation, we calculated the infection risk (*IR*) of each passenger to explore the aerosol inhalation transmission in this coach bus. This research provides a theoretical reference for preventing and avoiding the spread of respiratory infectious diseases in crowed coach buses.

2 Method

This paper built a model with dimensions of 11.4 m × 2.5 m × 2.12 m (length × width × height) based on the real long-distance bus which occurred the outbreak (Fig. 1(a)). The internal design was constructed based on the field measurement data, and the infected persons and the index patient were respectively marked by the epidemiological survey results. The real human body model (Fig. 1(b)) is used to construct an unstructured mesh, and the key research areas such as the mouth and nose of the human body are encrypted. The model generates a total of 5,379,993 meshes, and the mesh size refers to the model of Zhang and Li [1].

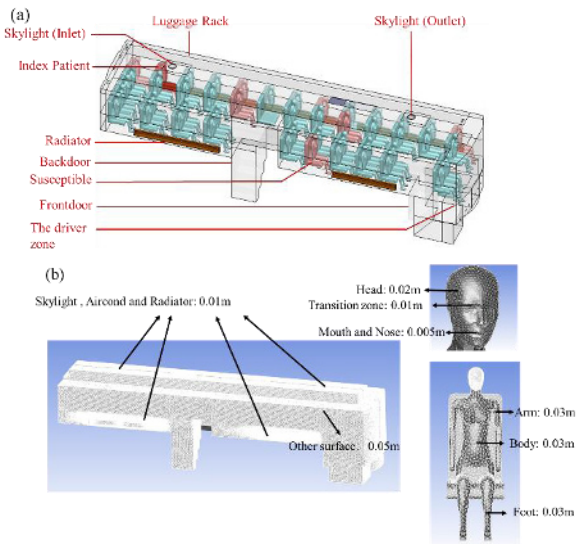
* Corresponding author : hangj3@mail.sysu.edu.cn

Fig. 1. Bus model and grid arrangements.

In this simulation, the RNG k-ε turbulence model was used to simulate the turbulent flow inside the bus. The boundary conditions such as ventilation rates and indoor and outdoor temperature were set according to the experimental data in the coach bus which occurred the outbreak [2] (Table 2). All the governing equations were discretized by the finite volume method under the second-order upwind scheme, the SIMPLE scheme are adopted to couple pressure and velocity, and the Boussinesq hypothesis was selected to consider the influence of buoyancy [3]. This study also considered human respiration and body surface heat fluxes.

Table 2. Boundary condition setups

Experimental variables	Boundary condition
Skylight(inlet)	**Velocity inlet**, velocity is different with different *ACH*，temperature equals to 284K.
Skylight outlet	**Outflow**, velocity is same as skylight inlet, temperature is different with various *ACH*
Glass	**No slip wall**, heat flux is determined by energy balance estimates
Index-patient side radiator	**Standard wall function, no slip wall**, heat flux is 100 W/m^2
Nose (except the index patient)	**Mass-flow-outlet**, mass flow rate is 9.23×10^{-5} kg/s
Mouth of the index patient	**Velocity inlet,** respiration rate is 1.5 m/s, temperature is 32 °C.

The simulation utilized the Lagrangian method to track the path of each droplet. The droplets were released from the index patient's mouth with an initial velocity of 1.5 m/s and a total of 360,000 droplets were released in 30 min. In the calculation process, Stokes-Cunningham was used to consider the drag effect of air on droplets, and droplets were also affected by Brownian force and Saffman lift. The solid-liquid ratio of exhaled droplets from the population was set to 1:9.

The droplet nuclei of 5 μm after evaporation were 1.8 μm, 50 μm were 18.3 μm and 100 μm were 36.5 μm. Part of the research in this paper was done on the Tianhe II supercomputer with the support of the National Supercomputer Center in Guangzhou.

Wells-Riley equation was utilized to calculate the infection risk of each passenger. The Wells-Riley equation is defined as follows [4] :

$$P = C / S = 1 - e^{-Ns} \qquad (1)$$
$$Ns = - (Iqpt / Q) \qquad (2)$$

where *P* is the infection risk; C is the number of infected cases; S is the number of susceptible people; N_S is the number of pathogen-laden droplets inhaled by susceptible person; *I* is the number of infectors; *q* is the quanta generation rate; *p* is the pulmonary ventilation rate of each susceptible; *Q* is the room ventilation rate; *t* is the exposure time. According to the outbreak, $q = 36.6$ h^{-1} was adopted in this paper. Meanwhile, the virus decay was not considered in this study.

3 Results

3.1 Spatial distribution of 5 μm droplets under different ventilation rates

As shown in Fig. 2, after the droplets are exhaled from the patient's mouth, they are affected by the initial velocity, the inertial force dominates, and they spread forward. Then, under the action of the human body thermal plume and the ambient air flow, they spread to the upper part of the cabin, reaches the top of the cabin, and then follows the flow field and transports it backward.

Comparing the droplet dispersion images at different ventilation rates, it can be seen that the larger the number, the more evenly the droplets are mixed in the bus. Due to flow field in the cabin is stronger and the velocity field is larger under 5.66 ACH, there are more droplets in the front of the bus. In the case of 0.62 ACH, the forward transmission speed of droplets is slow, which causes a large number of droplets to accumulate in the rear of the car, and it is difficult to discharge them from the skylight in the front of the bus.
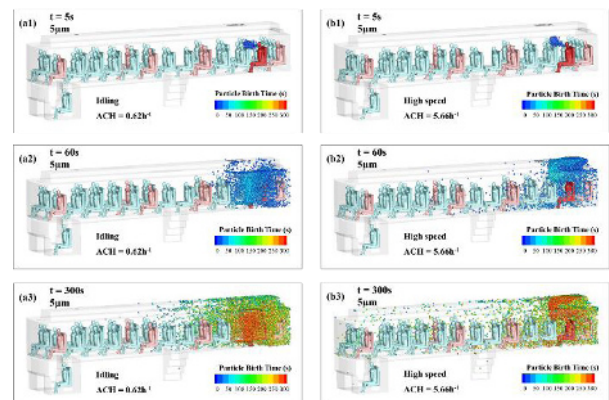

Fig. 2. Distribution of 5 μm droplets (the color of droplets indicates their birth time): (a) 0.62 ACH; (b) 5.66 ACH

3.2 Spatial distribution of droplet dispersion with different initial droplet diameters

Initial droplet diameter determines what is the main force that the droplets are subjected to during the dispersion process. The small-sized droplets (5 μm) are dominated by the drag force and follow the movement of the flow field, so they can spread in the entire cabin (Fig. 3a). In addition, the large-sized droplets (50 μm, 100 μm) are dominated by gravity and deposited near the index patient at a higher gravitational sedimentation velocity (Fig. 3b-c). The 50 μm droplets can only spread in the rear of the bus, while 100 μm droplets deposited immediately and just disperse near the index patient. Basically, the larger the initial particle size, the faster the droplet settles, the smaller the spread, and the more left on the bus.
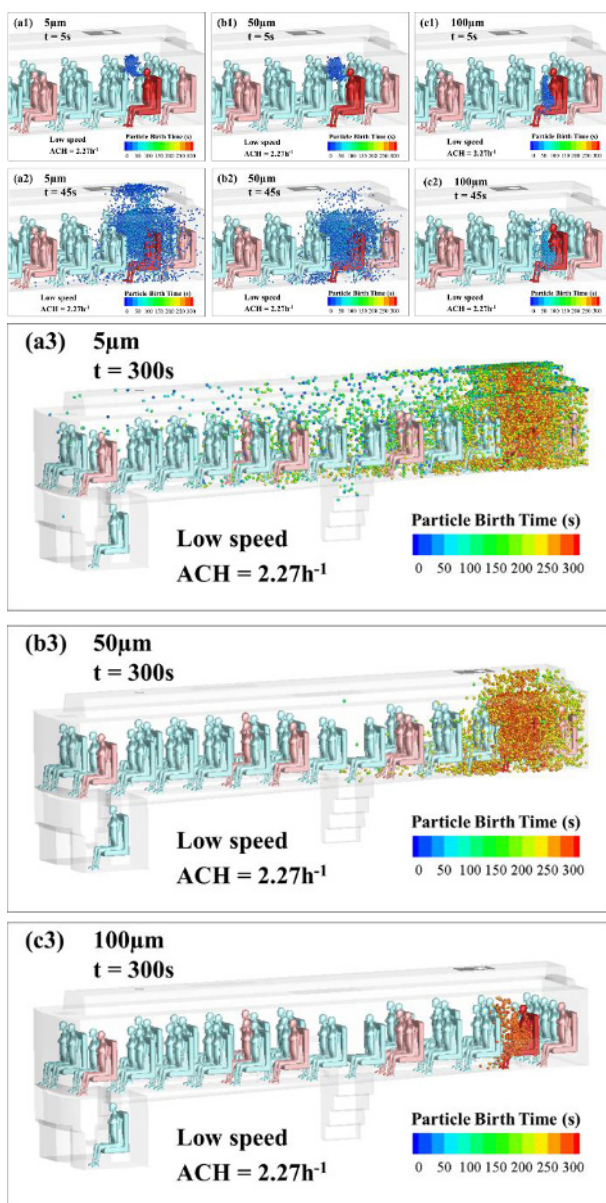

Fig. 3. Distribution of droplets with variable initial diameters (the color of droplets indicates their birth time): (a) 5 μm; (b) 50 μm ; (c) 100 μm

3.3 Infection risk of droplets under various ventilation rates

We adopt the Wells-Riley equation to calculate the infection risk for 30 minutes of exposure under different ventilation rates. Passengers without data indicates that they have not inhaled droplets. As shown in Fig. 4, we can found that with the increase of ventilation rates, the passengers with infection risk of 5 μm droplets has expanded. Although there are more passengers with infection risk of 5 μm droplets, the infection risk of 5 μm is very low with $\leqslant 0.4\%$. However, when the *ACH* raised from $0.62h^{-1}$ to $5.66h^{-1}$, the infection risk of tracer gas has greatly dropped an order of magnitude, from 11.1-15.3% to 1.3-3.1%. For 50 μm droplets, as they can only spread in the rear of the bus, the infection risk only appears in passengers near the index patient. The droplets exhaled by people are a combination of various particle sizes, which together determine the passenger's infection risk. Therefore, the infection risk of passengers decreases with increasing ventilation.

Moreover, compared with the infection risk of 5 μm droplets, we can find that the infection risk of tracer gas is much higher and more uniform. This is because that droplet will deposit on the surface (i.e., human body surfaces, floor, seats) on the route spread throughout the cabin. However, the tracer gas will not deposit, and only discharge from the outlet. Hence, different from general room environments, the tracer gas cannot replace 5 μm droplets in the long-and-narrow coach bus. But for more fine droplets that barely deposit, the behavior of the droplet and surrounding airflow requires the kinetic theory of gases, in this condition, tracer gas can be adopted as a surrogate. The specifical critical value needs more exploring.
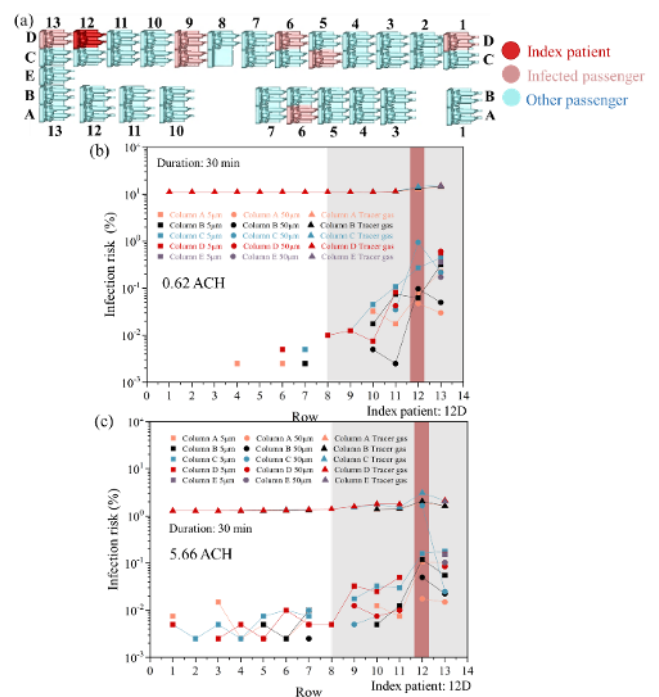

Fig. 4. Infection risk for 30 minutes of exposure: (a) seat arrangement; (b) 0.62 ACH; (c) 5.66 ACH

3.4 Infection risk of realistic outbreak

We calculated the infection risk of the real case based on the driving time of the coach bus in different states at the time of the outbreak. From Fig. 5, it can be seen that as the initial diameter of the droplets increases, the infection risk decreases and the scope of influence decreases. However, passengers near the index patient always have a greater infection risk. The long-distance infection is highly likely to be caused by small droplets below 5 µm, and the 50 µm droplets are only at risk of infection in the middle and rear of the bus. This incident can prove that in a crowded and insufficiently ventilated bus, there is long-distance inhalation aerosol transmission, and the longest transmission distance is 9.46 m!

The position of the infected persons in relation to the passengers with high calculated infection risk exist some deviation. This is because that we only calculated the infection risk of the aerosol inhalation transmission, which represented the probability of infection through inhaling pathogen-laden droplets. There are many other factors that may affect passengers being infected, such as other transmission routes, passengers' own immunity, the activity status of passengers in the bus, whether to wear a mask, etc. During this outbreak, all the passengers who wear a mask didn't be infected, even the passenger next to the index patient who had the highest infection risk. All seven infections occurred in passengers who did not wear a mask. Even in the bus front, where had a relatively low infection risk, still existed infection in passengers who did not wear a mask. This indicated that wearing masks has a very effective role in epidemic prevention and control.
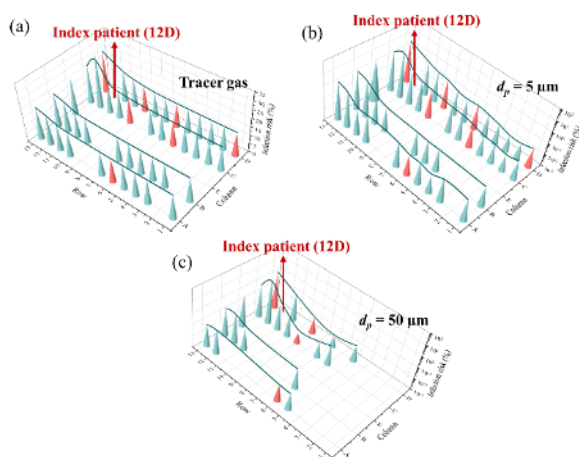
discharge of droplets, which can significantly reduce the risk of infection. Our study also indicate that tracer gas can only be adopted to simulate the dispersion process of fine droplets which barely deposied in the long-distance bus environmet.

For public transportation environments such as buses, sufficient ventilation should be ensured. When the ventilation volume is insufficient, it is recommended to open the windows at the rear of the car to effectively improve ventilation, thereby reducing the risk of disease infection

References

1. Z. Lei, Y. Li. Build. Environ. **47**, 58-66 (2012)
2. C. Ou, S. Hu, K. Luo, H. Yang, J. Hang, P. Cheng, Z. Hai, S. Xiao, H. Qian, S. Xiao. Build. Environ. **207**, 108414 (2022)
3. X. Yang, C. Ou, H. Yang, L. Liu, T. Song, M. Kang, H. Lin, J. Hang. J. Hazard. Mater. **397**, 122609 (2020)
4. E. Riley, G. Murphy, R. Riley. Am. J. Epidemiol. **107**, 421-432 (1978)

Fig. 5. Infection risk of realistic outbreak: (a)tracer gas; (b) 5 µm droplets; (c) 50 µm droplets

4 Conclusion

In long-distance coach bus environments, increased ventilation can significantly reduce the infection risk of passengers. Small droplets can spread throughout the cabin, while large droplets can only cause infection risks at close range. The larger the particle size, the smaller the impact scope. This study can prove that in the bus environment, ventilation is conducive to the dilution and