Numerical investigation of the effects of environmental conditions, droplet size, and social distance on interpersonal droplet transmission in a deep urban street canyon

Xiaodan Fan[1], *Xuelin* Zhang[1,2*], *Jian* Hang[1,2], and *A. U.* Weerasuriya[3]

[1]Sciences, Sun Yat-sen University, Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai, China
[2]Guangdong Province Key Laboratory for Climate Change and Natural Disaster Studies, Sun Yat-sen University, Zhuhai, PR China.
[3]Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong

Abstract. This study investigated the interpersonal droplet transmission between a healthy and an infected person in a deep and narrow street canyon using Computational Fluid Dynamics (CFD) simulation. The CFD simulations modelled various droplet sizes (D_{p}), background wind speeds (U_{ref}), relative humidity (RH), and social distances (D) to estimate their effects on interpersonal droplet transmission. The results revealed noticeably opposite effects of these factors. For example, small background wind moved droplets upward and suspended them in the air for a longer time while high wind speeds distributed droplets in the street canyon with few of them retained in the air. Relative humidity had a trifling impact on dispersing small droplets (10μm, 25μm, 50μm), whereas it significantly modified the dispersion of large droplets, especially in small background wind speeds. Furthermore, small droplets travelled longer distances in dry air and were either deposited on the surrounding buildings' walls or suspended in the air. In contrast, larger droplets in moist air rapidly deposited on the ground or the infected person's body. In dry air, 45% of large droplets were inhaled or suspended in the air, exposing pedestrians to contaminated droplets. Large social distances significantly diluted the small droplets but increased the infection risk from large droplets because of the complex interaction of the ambient airflow and the gravity. It is recommended to keep social distances of 2 m and 4 m for pedestrians in deep urban street canyons in Windy condition and Calm-Wet condition, respectively.

1 Introduction

The novel coronavirus pneumonia (Covid-19) causes more than 5.7 million deaths globally up to date and poses a grave danger to human health for foreseen future. Unlike other respiratory infectious diseases, Covid-19 is particularly menacing public health due to its fast transmission route via interpersonal droplet transmission. The research community insofar overlooks the infection risk in outdoor spaces because of the presumption of less infection risk due to high ventilation rates and inadequate wind circulation in these spaces. However, emerging evidence confronts this common belief. Motivated by the importance of understanding and the challenges in modeling interpersonal droplet transmission in urban street canyons, the current study set its main goal as to investigate how airborne transmissions trigger outbreaks of respiratory diseases in urban outdoors under the effects of environmental conditions, droplet characteristics, and social distance as a preventive measure. Two wind velocities: 1.54m/s, and 6.68m/s, two relative humidity: 35% and 95%, and four social distances: 0.5m, 1m, 2m, 4m were selected in current study.

2 Methodology

2.1 Governing equations

CFD modelling of interpersonal droplet transmission requires solving the mass continuity, momentum conservation, energy conservation These governing equations were solved by using the Reynolds averaged Navier-Stokes (RANS) models. The Euler-Lagrangian approach was adopted to predict trajectories of droplets under the evaporation as:

$$\frac{d\overrightarrow{u_p}}{dt} = F_D(\vec{u} - \overrightarrow{u_p}) + \overrightarrow{F_g} + \overrightarrow{F_a} \quad (1)$$

where $\overrightarrow{u_p}$ is the particle velocity, and $\vec{u}$ is the wind velocity. F_D is the drag force, and $\overrightarrow{F_g}$ is the gravitational force. $\overrightarrow{F_a}$ is the additional force.

The infection risk of the healthy person by exposure to contaminated droplets in the street canyon is estimated by calculating the viral loads of droplets. The viral load of droplets (VL) was assumed to be proportional to the droplet initial volume without accounting for the effects of evaporation (Eq. 2).

Corresponding author: zhangxlin25@mail.sysu.edu.cn

$$VL = \frac{4\times10^{-6}}{3}\pi D_p^3 N \cdot vl_{mean} \quad (2)$$

where vl_{mean} is the mean viral load of Covid-19 (3.3×10^6 copies/ml) as detected by To et al. [1] with saliva specimen. N is the number of droplets that the healthy person inhales, and D_p is the droplet initial diameter.

2.2 Computational domain and solve settings

The current study modelled one of the street canyons of an urban street canyon model tested in a boundary layer wind tunnel by Zhang et al. [2]. The wind tunnel test model was fabricated on a length scale of 1:200 and had a total of 25 street canyons. The current study modelled the 12th street canyon from the upstream edge of the wind tunnel model in CFD simulation because the selected street canyon had a fully developed wind field (Figure 1).

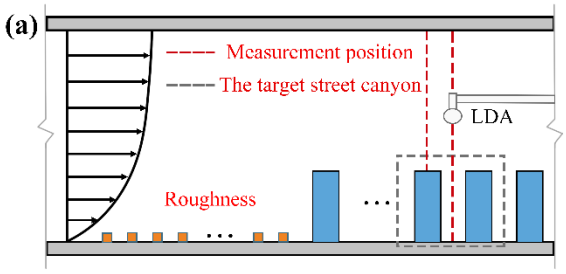

Figure 1. The experimental set-up of the wind tunnel test

The CFD simulations of this study modelled the target street canyon with the full-scale dimensions: Hs = 24m, Bs = Ws = 10m (Figure 2). The domain contained the street and portions of the upstream and downstream buildings and the atmospheric boundary layer up to a 4Hs height. The grid arrangement had the minimum wall-adjacent cell size of 0.1m. Two similar height (1.68m) persons – one infected with respiratory disease (i.e., infector) and other healthy – in an upright position were modelled in the middle of the street canyon. The tetrahedral grids were generated inside the street canyon, while hexahedral grids were applied from the building roof to the top boundary. The total cell count of this grid configuration is 1,767,195.

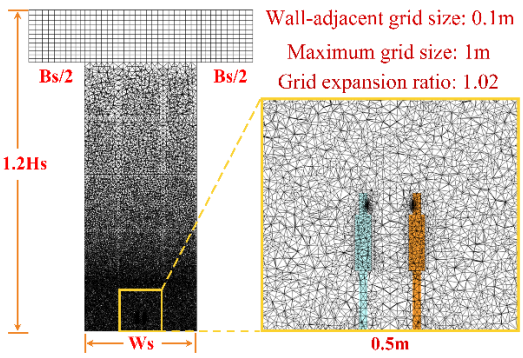

Figure 2. Computational grid in the vertical center plane of the street canyon up to 1.2Hs

All CFD simulations in this study were performed using ANSYS Fluent commercial software (v19.0) on the Tianhe-2 supercomputer with the support of the National Supercomputer Center in Guangzhou, China. The SIMPLE algorithm was employed for the pressure-velocity coupling. The second-order upwind scheme was applied for discretizing the convection and viscous terms of the governing equations. The diffusion-controlled model was used for modelling the heat and mass transfer of expelled droplets. The convergence of the simulation was assumed when residuals reached the following minimum values: of 10^{-8} for x-, y-, z-momentum, and k, and ε, 10^{-6} for the continuity and displayed no further decrease nor fluctuation with the number of iterations.

3 Results and discussion

3.1 Effect of wind speed

Figure 3 visualizes the distribution of mean streamwise wind speed (u) and droplet size in the street canyon under two background wind speeds: 1.54 m/s and 6.68 m/s. The streamlines moved upward near persons in the 1.54 m/s background wind speed (Figure 3(a)) while the streamlines in high background wind speed of 6.68 m/s moved westerly (Figure 3(b)). The upward wind circulation in the weak background wind governed by the buoyancy-driven wind flow near human bodies, whereas strong background wind suppressed it.

The trajectories of 50μm diameter droplets shown in Figure 3(b) closely followed the wind flow patterns and moved upward and westerly in weak, and strong background winds, respectively rather than moved downward under gravity. Dominant buoyancy-driven wind in the weak background wind transported droplets upward and away from the breathing zone of the healthy person, while strong advection in high background wind speeds carried droplets to the listener's face risking him to breath contaminated air.

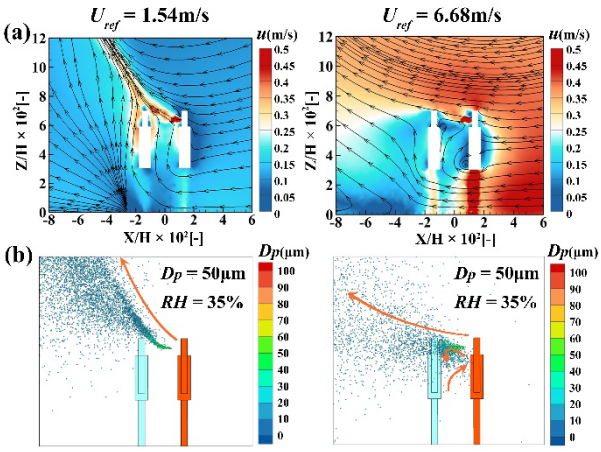

Figure 3. Distribution of (a) mean velocity u, (b) diameters of exhaled droplets D_p in the street canyon.

3.2 Effect of relative humidity

Figure 4 shows droplets dispersion for two droplet sizes: 25μm and 100μm at three RH levels: 35%, 60%, and 95% and in background wind speed of 1.54m/s. Figure 4(a)

shows very similar dispersion patterns for the droplets with 25µm in weak background wind for all RH levels. Insignificant effects of RH on the dispersion of small-sized droplets attribute to quick evaporation of small-sized droplets. In contrast, the dispersion patterns of large-sized droplets (100µm) in weak background wind showed noticeably variations with RH (Figure 4(b)). At low RH = 35%, large droplets mainly transmitted upward with the updraft and rapidly became smaller in size (diameter ~ 40 - 60µm) due to evaporation. Unlikely at low RH, large-sized droplets remained the same size at RH = 95% due to less evaporation at high relative humidity. Almost all large-sized particles at RH = 95% moved downward in between the two persons due to their heavy mass.

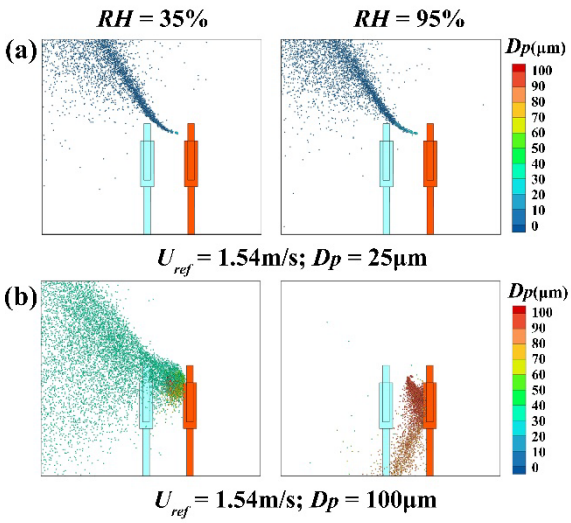

Figure 4. Dispersion of (a) small droplets (25µm) and (b) large droplets (100µm) in 35%, and 95 % RH and background wind speed of 1.54m/s.

3.3 Effect of droplet sizes

Figure 5 shows the fate of droplets with four diameters (10µm, 25µm, 50µm, and 100µm) in the street canyon. Small droplets in low background wind speeds such as U_{ref} = 1.54m/s tend to deposit on the walls of the surrounding buildings or suspend in the air for long periods, thus posing a little risk of inhaling them or deposited on the healthy person's body. In contrast, healthy people are at high risk of inhaling small particles, and deposition them on their bodies in high background winds such as U_{ref} = 6.68m/s. Therefore, in case of an outbreak, it is advisable to search for contaminated droplets on the ground, and buildings' walls if the street canyon is exposed to weak background wind. If the background wind is strong, pedestrians should be tested for infection and should search their bodies and clothes to detect evidence of contaminated droplets.

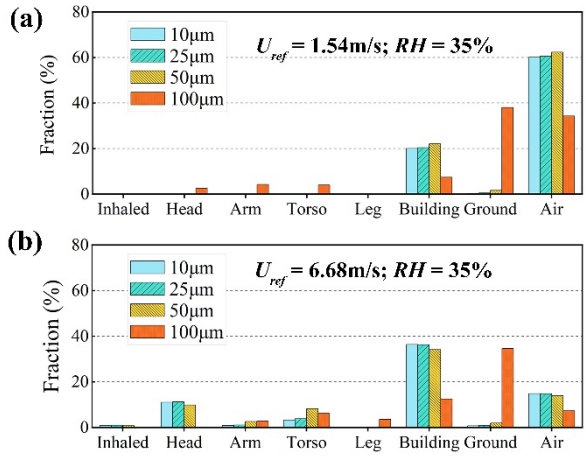

Figure 5. Fraction of droplets with different diameters distributed in the street canyon in two sets of environmental conditions (a) Calm-Dry (1.54m/s and RH = 35%), (b) Windy-Dry (6.68m/s and RH = 35%).

3.4 Exposure risk for droplets under four social distances

Figure 6 shows viral loads of contaminated droplets with four diameters in different environmental conditions and social distances. In addition, a threshold of 300 copies of virions is marked in every subplot as the infectious dose of COVID-19 as suggested by Saikat Basu [3]. The viral load of the droplet with a diameter of 100µm had noticeable variations with RH and social distances in weak background wind speed of 1.54 m/s (Figure 6(a)). In most cases, low RH levels led to higher viral loads (> 1000 copies) despite the difference in the viral load being minimal between RH = 35% and 60%. At 1 m distance from the infector, the viral load decreased 46% at RH = 35% and 17% at RH = 60%, and these reductions further grew into 70% for RH = 35% and 83% for RH = 60% at the 4 m social distance. Interestingly, the viral load was 23% higher at 1m social distance at RH = 60% than that at RH = 35%. In contrast to high viral loads in dry air, moist air (RH = 95%) resulted in the minimum viral loads (~ 0 to 40 copies) and also the minimum variations across all tested social distances.

The small-sized droplets (diameters 10µm and 25µm) in strong background wind (6.68 m/s) posed no infection risk to the healthy person at any social distance as the maximum viral loads were always smaller than 300 copies (Figures 6(b) and (c)). In addition, these cases displayed similar variations in viral load with social distances for all RH levels. Indeed, viral load at all RH levels steadily decreased with social distance as such the viral load reduced by 88% as the social distance increased from 0.5 m to 1m and eventually reached 0 at the 4 m social distance. In contrast. Moderate-sized droplets (diameter of 50 µm) at all RH levels posed some infection risks for the healthy person at 0.5 m away from the infector. The viral load at RH = 95% was 29% smaller than that at RH = 35% and 60%, this discrepancy diminished at 2m social distance and reached the zero viral load at 4m social distance (Figure 6(d)) for all RH levels. Viral load of large-sized droplets (diameter 100

μm) exhibited diverse variations in with social distance. However, they posed no infection risk to the healthy person as the maximum viral loads were less than 300 copies across all tested cases.

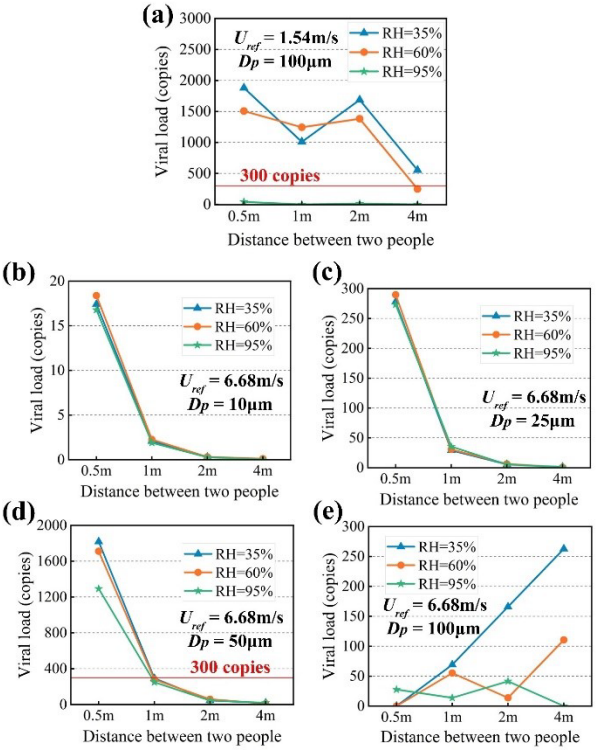

Figure 6. Viral load of droplets in the air with RH = 35%, 60%, and 95% inhaled by the healthy person stood 0.5m, 1m, 2m, and 4m from the infected person for the conditions: (a) D_p = 100μm, U_{ref} = 1.54m/s, (b) D_p = 10μm, U_{ref} = 6.68m/s, (c) D_p = 25μm, U_{ref} = 6.68m/s, (d) D_p = 50μm, U_{ref} = 6.68m/s, I D_p = 100μm, U_{ref} = 6.68m/s.

4 Concluding remarks

This study investigated the effect of wind speed, relative humidity, droplet size, and social distance on interpersonal droplet dispersion in a two-dimensional deep urban street canyon using CFD simulation. The followings are the valuable insights derived from this study to understand interpersonal droplet dispersion in deep, urban street canyons and to stipulate guidelines to preserve public health in cities in the post-pandemic era:

1. Low background wind speeds reduce the interpersonal droplet transmission in street canyons by moving droplets upward with the buoyancy-driven wind flows. Conversely, high background wind speeds pose a greater infection risk for healthy people with the strong advection. The numbers of small to moderate-sized droplets inhaled by a healthy person in high background wind speeds is nearly nine times larger than that in low wind speeds.

2. Relative humidity has insignificant impacts on the dispersion of small-sized droplets because of the rapid evaporation of droplets. However, relative humidity substantially affects the dispersion of large-sized droplets at low wind speeds.

3. Small droplets were either deposited on the surrounding buildings' walls or suspended in the air. In contrast, larger droplets in moist air rapidly deposited on the ground or the infected person's body.

4. A social distance of 4m is recommended for deep, urban street canyons filled with low wind speeds to minimize the infection risk by interpersonal droplet transmission. If the prevailing wind speeds are high, 2m social distance is adequate to reduce the infection risk of a person by 94% than he stands 0.5 m near to an infected person.

This study is partly supported by the Guangdong Science and Technology Fund (No. 2020A1515111105), Guangzhou Science and Technology Fund (No. 202102020303), Guangdong Province Key Laboratory for Climate Change and Natural Disaster Studies (No. 2020B1212060025), the National Natural Science Foundation of China (No. 42175180, 41875015, and 42175095) and the Innovation Group Project of Southern Marine Science and Engineering Guangdong Laboratory (No. 311020001). The CFD simulations of this research were conducted on the Tianhe II supercomputer at the National Supercomputer Center, Guangzhou, P.R. China.

References

1. To, K. K. W., Tsang, O. T. Y., Yip, C. C. Y., Chan, K. H., Wu, T. C., Chan, J. M. C., Leung, W. S., Chik, T. S. H., Choi, C. Y. C., Kandamby, D. H., Lung, D. C., Tam, A. R., Poon, R. W. S., Fung, A. Y. F., Hung, I. F. N., Cheng, V. C. C., Chan, J. F. W., & Yuen, K. Y. (2020). Consistent detection of 2019 novel coronavirus in saliva. Clinical Infectious Diseases, 71(15), 841–843.
2. Zhang, K., Chen, G., Wang, X., Liu, S., Mak, C. M., Fan, Y., & Hang, J. (2019). Numerical evaluations of urban design technique to reduce vehicular personal intake fraction in deep street canyons. Science of the Total Environment, 653, 968–994.
3. Basu, S. (2020). Close-range exposure to a COVID-19 carrier: transmission trends in the respiratory tract and estimation of infectious dose. MedRxiv, 2020.07.27.20162362. L. T. De Luca, Propulsion physics (EDP Sciences, Les Ulis, 2009)