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Respiratory droplets transmission in urban street canyons

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SUMMARY:
This study investigated the indoor-outdoor coupling effects on droplet transmission in both two-dimensional (2D) and three-dimensional (3D) street canyons using Computational Fluid Dynamics (CFD) simulation. In the 2D street canyon, the effects of wind speed, relative humidity (RH), droplet sizes (D_p) and social distances (D) on droplet transmission were estimated. The results revealed that ambient winds and relative humidity significantly modify the dispersion of droplets by altering airflow patterns and droplet mass. A 2 m social distance is recommended for pedestrians with high wind speed, and 4 m if the wind speed and RH are low. We further discussed the risk of exposure to residents and pedestrians when patients are in different rooms of 3D street canyons. It was shown that droplets emitted from windward rooms were diluted by the fresh air and hardly affected the pedestrians. The droplets spread vertically to lower floors under single-sided ventilation, while they spread horizontally to the leeward side under the cross-ventilation condition. For the outdoor patients, 37% of droplets emitted from the pedestrian were deposited and inhaled by the healthy person facing him, but the indoor concentration was low. Based on the current results, anti-pandemic measures can be implemented separately indoors and outdoors.

Keywords: Indoor and outdoor, Urban street canyons, Airborne transmission

1. INTRODUCTIONS

The coronavirus disease 2019 (COVID-19) is a particularly menacing respiratory infectious disease, which has attracted special attention. More efforts have been made to investigate airborne transmission in enclosed spaces or interunit dispersion. Occupants were suggested to open windows regularly to replace exhaled virus-laden air with outdoor air. However, it is probable that outdoor aerosols transmit into indoor rooms during the ventilation process (Santos et al., 2011). Moreover, emerging evidence indicates that outbreaks may also occur in outdoor environments (Leclerc et al., 2020). These findings highlight the urgent need to accurately understand interpersonal droplet transmission indoors and outdoors to stipulate precautions.

Urban street canyons, involving both residential areas and streets, are at high risk of contracting respiratory infectious disease due to the low wind velocities, flow recirculation, and complex vortices inside. Attempting to provide insight into potential risk in ideal street canyons, this study comprehensively models: (1) outdoor droplet transmission in a 2D street canyon with various environmental conditions, droplet characteristics, and distances between the infected and healthy agents; (2) coupled indoor-outdoor transmission of respiratory droplets in 3D urban street canyons with different patient locations and natural ventilation types.

2. METHODS

The 2D street canyon modeled in this study was previously tested in a boundary layer wind tunnel (Zhang et al., 2019). The wind tunnel test model has 25 street canyons. The current study models the 12th street canyon because it has a fully developed wind field (Fig. 1(a)). An outdoor conversation between two persons was modeled in the 2D street canyon. The infected person (speaker) expels an expiratory flow with a velocity of 3.9 m/s and the healthy person (listener) inhales the air at 0.6 m/s. The 3D street canyons comprise a central six-story building and 24 surrounding buildings with dimensions of $B \times D \times H$ = 9.8m×9.8m×18.9m (B, D, and H are buildings' breadth, depth, and height). Buildings are equidistantly spaced with a planar area ratio of λ_p= 0.25. The interior structure of one floor of the central building is illustrated in Fig. 1(b). Contaminated droplets were released by the patient located in the rooms or on the streets to investigate the droplet dispersion between indoor and outdoor spaces. All CFD simulations were conducted on ANSYS Fluent software by using Reynolds-Averaged Navier-Stokes based equations and realizable k-ε turbulence models. The SIMPLE algorithm was used for the pressure-velocity coupling.

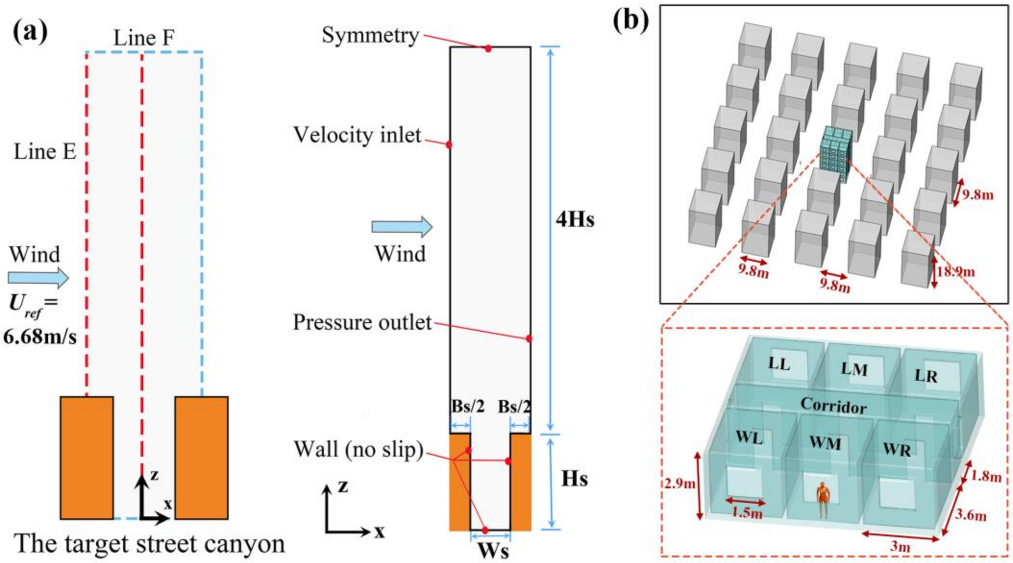

Figure 1. Schematic diagram of (a) the 2D urban street canyon, and (b) the building arrays and the fourth floor of the central building in 3D urban areas.

3. RESULTS AND DISCUSSION

3.1. Effects of environmental conditions and social distances on droplet transmission in 2D street canyons

Fig. 2(a)-(b) shows the distribution of the droplets of four diameters under various environmental conditions in the 2D street canyon. Small percentages of the largest droplets are found on the healthy person's body in low wind speed conditions because droplets were lifted by the thermal plumes emitted from human bodies. Conversely, high ambient wind speeds exacerbate the risk of infection, as strong advection carries pathogen-laden droplets from the patient's mouth to the healthy person's breathing zone. RH has a trifling influence on the dispersion of small droplets (D_p = 10, 25, and 50 μm), but significantly modifies the dispersion of large droplets (D_p = 100 μm), especially under low ambient winds. Nearly no large droplets are found on the healthy person's body under high RH. With slow evaporation, they would rapidly fall to the ground or land on the pedestrians' lower bodies due to heavy mass. Fig. 2(c)-(f) shows viral loads of contaminated droplets with four diameters in different environmental conditions and social distancing. When exposed to low wind speeds (U_{ref} = 1.54m/s) and low relative humidity, a social distancing of 4 m is recommended to minimize the exposure risk in deep urban street canyons. If the prevailing wind speeds are high (U_{ref} = 6.68m/s), a 2 m social distance is adequate to reduce the exposure risk of a person by 94% compared to a social distance of 0.5m.

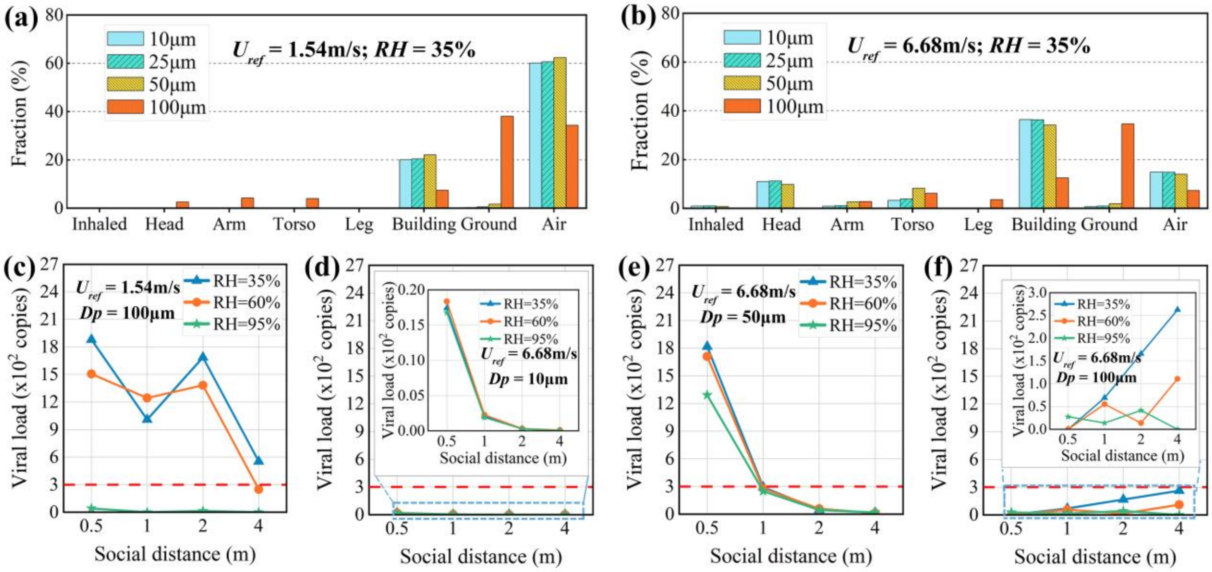

Figure 2. (a)-(b) Fraction of droplets distributed in the street canyon in two sets of environmental conditions. (c)-(f) Viral load of droplets in the air inhaled by the healthy person stood 0.5 m, 1 m, 2 m, and 4 m.

3.2. The coupled indoor-outdoor droplet transmission in 3D street canyons

Given that the airflow field should be different when experiencing different ventilation types, the dispersion pattern under singled-sided and cross ventilation in 3D street canyons were compared. All windows are open and doors are closed to represent single-sided ventilation, while all windows and doors are open to represent cross ventilation. Fig. 3(a)-(b) displays the fraction of droplets exhaled from the WM room on the fourth floor into other units of the central building. Under single-sided ventilation, droplets tend to spread downward and the maximum fraction appears at the unit immediately below the source location. Except for f3WM, the fraction of the f1WM unit is high due to the counter-clockwise vortex at the bottom of the street canyon. A similar trend is found when the patient is located in the f6WM. However, most of the droplets emitted from f1UM were trapped by the ground, which is not shown here. Under cross-ventilation, droplets tend to transfer horizontally to the corridor and lateral units. The expelled droplets were diluted in the street canyons. In all of the above cases, an average of 0.07% of contaminated droplets were deposited on the pedestrians in the street. Fig. 3(c) depicts the fate of the droplets exhaled by a pedestrian after fifteen minutes of conversation with a healthy person in the street. The majority of droplets were inhaled by the healthy person or deposited on his body (37.4%), which confirms the potential risk of talking on outdoor streets. However, only a small percentage of droplets entered the indoor rooms (1.4%).

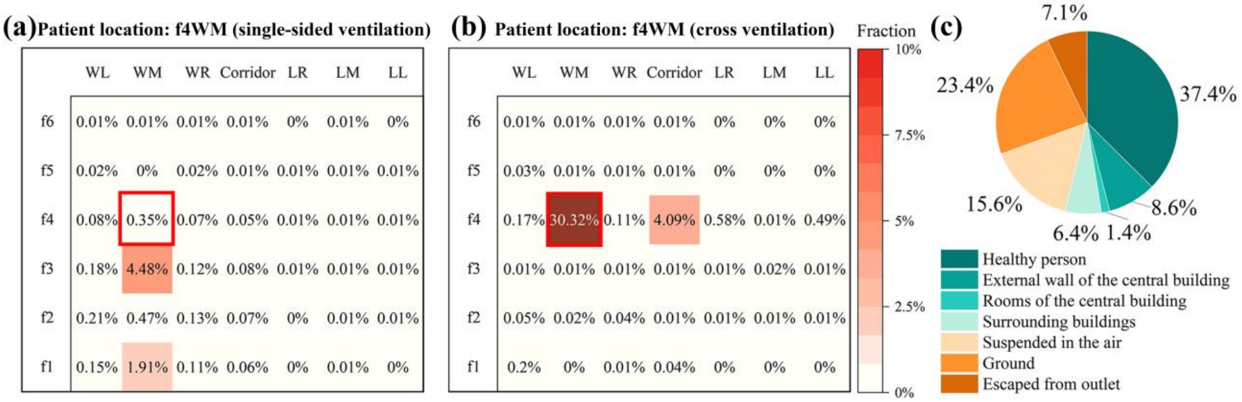

Figure 3. (a)-(b) Fraction of re-entry droplets in each unit. The source units are outlined with red boxes. (c) The fate of droplets emitted by a patient standing in the street canyon. The healthy person was facing him at a distance of 0.5m.

4. CONCLUSIONS

This study investigated the effects of environmental conditions, patient locations, and natural ventilation types on interpersonal droplet transmission in urban street canyons using CFD simulations. The results revealed that droplets had more upward movements and longer airborne time under weak ambient winds, but strong dispersions under high winds. *RH* has a trifling influence on the dispersion of small droplets (D_p = 10, 25, and 50 μm), but significantly modifies the dispersion of large droplets (D_p = 100 μm), especially under low ambient winds. A 2 m social distance is recommended for pedestrians in deep urban street canyons with high winds, and 4 m if winds and RH are low. Under the single-side ventilation, droplets emitted from indoor rooms were transported vertically downward and the fraction decayed, except on the first floor due to the counter-clockwise vortex in the street. Droplets spread horizontally to the corridor and lateral unit in case of cross-ventilation. Pedestrians were exposed to concentrations of droplets because of high ventilation. When the droplets were expelled by a pedestrian, the potential risk is high for the healthy person facing him but low for indoor residents.

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