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Assessment of mechanical exhaust in preventing vertical cross-household infections associated with single-sided ventilation

Yan Wu, Jianlei Niu*

Department of Building Services Engineering, The Hong Kong Polytechnic University, Hong Kong, China

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ABSTRACT

Single-sided natural ventilation is an energy efficient ventilation strategy that could provide satisfactory indoor air quality and thermal comfort. However, one of its possible negative influences is the cross-infection between households due to the two-way airflow. The present study aims at assessing the efficacy of mechanical exhaust (ME) devices to eliminate this possible cross-infection. CFD method was employed to simulate the buoyancy driven single-sided natural ventilation and the cross-contamination. Different occupant behaviour scenarios, such as ME-on centrally or ME-on individually, were compared with the no-ME case. It is found that mechanical exhaust could reduce the outflow of indoor air and increase the inflow of fresh air. However, the weakened outflow tends to be more attached to the façade and the re-entry risk may be increased. As the exhaust rate is large enough, the two-way airflow will turn into one-way inflow, and accordingly the vertical cross-household infection can be avoided. With ME-on in both floors, a low exhaust rate of 5 h^{-1} could reduce the presence of the tracer from the lower floor in the upper floor by an order of magnitude. But if the ME is on only in one of the two floors, the re-entry of outflow to the upper floor may be aggravated at some specific exhaust rate. Therefore, in epidemic seasons, appealing residents to switch on their individual exhaust fans, or alternatively switching on a central exhaust system is recommended. The results will contribute to the control of airborne transmission infectious diseases in high-rise residential buildings.

1. Introduction

Natural ventilation is an energy efficient ventilation strategy which could provide high air change rate and acceptable indoor air quality and thermal comfort [1–3]. Moreover, it meets people's requirements of accessing to fresh air, especially in epidemic or transit seasons. Natural ventilation includes single-sided ventilation and cross ventilation, and the former one is more acceptable in large buildings for security and privacy concerns [4]. Single-sided natural ventilation has been studied widely, mainly concerning the ventilation efficiency, such as the airflow rate, effective depth of fresh air distribution and thermal comfort [4–8]. However, natural ventilation may also have undesirable consequences. For example, in hospital wards, opened doors or windows may induce the spill of virus to the passageway or outdoor space [9]. Studies after the outbreak of SARS in 2003 also revealed that the buoyancy-dominant natural ventilation might have been responsible to the vertical spread of virus in the re-entrance space of high-rise buildings [10–13].

Niu et al.'s on-site measurements [14,15] revealed that transmission of infectious disease between households could be both vertical and horizontal associated with the natural ventilation airflow. Specifically, with the single-sided open window, 7% of expired air from the lower floor could re-enter the upper floor. This vertical pollutants transport induced by single-sided two-way airflow were further studied with wind tunnel experiments and CFD simulations [16–19]. The airflow and dispersion characteristics were investigated, and the pollutants re-entry ratio and the infection risk were also predicted. It was found that the infectious risk in the upper floor is one order of magnitude lower than that in the lower source room, which is still significantly high [16]. Besides, under the combined effects of buoyancy force and wind force, not only the vertical upward but also vertical downward and horizontal transmission can be observed.

To eliminate the possible cross-infection caused by the single-sided natural ventilation, employing mechanical exhaust (ME) devices in the residential buildings has attracted our attentions. In

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* Corresponding author.
E-mail address: jian-lei.niu@polyu.edu.hk (J. Niu).

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protective hospital environments, pressure control methods are mature techniques to control the spread of pathogens [20–22]. They include the positive pressure control and the negative pressure control [23]. In high-rise residential buildings, central air supply and exhaust systems are seldom used. But, exhaust fans in the kitchen or the bathroom always exist in each household, which may be employed to control the cross-infection. In a room dominated by buoyancy-driven single-sided ventilation, the pressure difference between indoor and outdoor drives the two-way airflow through the window. Opening the exhaust fans in the room could reduce the indoor pressure, which may restrain the outflow from the window and accordingly reduce the re-entry of polluted indoor air to other rooms.

The present study aims at assessing the efficacy of indoor mechanical exhaust to eliminate the possible cross-infection induced by the two-way airflow of the single-sided natural ventilation. The airflow around a building induced by the wind is complex, and the outflow of the room air can be in any directions depending on its location in the building [24]. In this study, low-wind, buoyancy driven airflow conditions are focused upon for a start. The effects of a mechanical exhaust on the airflow patterns of single-sided natural ventilation were investigated, as well as the effects on the tracer gas dispersion to the upper floor. Considering the practical occupant behavior in residential buildings, the exhaust fans in different households are not controlled centrally and can hardly be switched on at the same time. Different ME use scenarios were investigated and compared with the no-ME case. The results will contribute to the control of airborne transmission infectious diseases in high-rise residential environments.

2. Methodology

2.1. Physical model

To simulate the buoyancy driven single-sided natural ventilation and cross-contamination between two vertically adjacent rooms, a computation domain for CFD simulation as depicted in Fig. 1 was constructed. The dimensions of the rooms are 4 m length (L), 3 m width (W) and 2.7 m height (H). The windows are 0.8 m width and 1.2 m height, and the bottom edge of the window is 0.8 m above the room floor. Besides, to investigate the impact of mechanical exhaust, exhaust outlets were settled near the ceilings with dimensions of 0.25 m × 0.25 m. SF_6, as the tracer of gaseous pollutants, was released with constant rate of 10 ml/s in the centre of the lower room at the height of 1.5 m above the floor. Considering that it is near the window where the airflow and dispersion characteristics are concerned and the outdoor wind effects were not involved, outdoor domain was only constructed in front of the rooms. The domain size is 10.8 m (4H) in the Z direction, which includes two adjacent floors below and above the target floors, and 16 m (4 L) in the X direction, which is large enough to simulate the still ambient air at no wind conditions. As the boundary is large enough, the airflow velocities at the boundary will be very small so that the inflow and outflow boundaries could be set fairly arbitrarily without affecting the simulation results [25]. In the whole computational domain, a mesh with more than 2 million structured grids was constructed after the grid sensitivity check.

Since only pure buoyancy driven natural ventilation was focused on, there was no prescribed inflow velocities across the boundary. When the exact locations of the inlet and outlet are not known in free convection, a CFD programme would need to switch between the two sets of boundary conditions depending on the direction of the velocities at the boundary during the iteration. To speed up the numerical iteration, the lower surface and the upper surface of the outdoor domain were defined as pressure-inlet and pressure-outlet, following what's described in Niu and Vanderkooi [26], and the lateral surfaces of the outdoor domain were defined as symmetries, which means that the building is a slab-typed building and is extended in Y direction. The left surface of the domain was also set as symmetric to make the computation more stable, in which normal velocity component and normal gradients of tangential velocity components were all zero [25]. In making these assumptions, the lower boundary is the only inlet and the upper boundary is only outlet, and this setting is based upon the experience of Tominaga [25] that when the domain is large enough, the accuracy of the inlet low velocity would bear little influence on the flow field within the computational domain where the flow is initiated. Surfaces of the target rooms were set as wall boundaries as well as adjacent rooms below and above. The mechanical exhaust outlets were defined using velocity outlet conditions with specific flow rates for different cases. The walls of the target rooms have a higher temperature than the ambient air. The temperature difference between the room surfaces and outdoor air is defined as indoor-outdoor temperature difference ΔT, and ΔT for all cases is

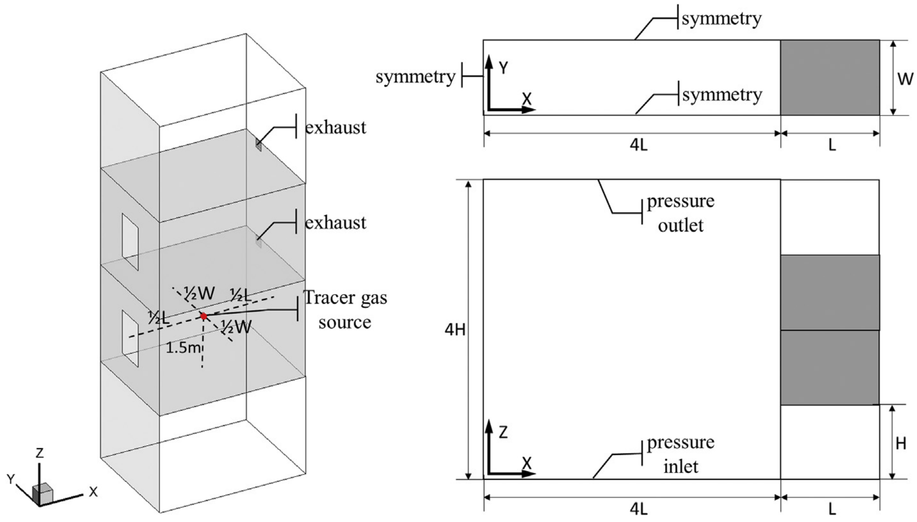

Fig. 1. Geometry model and computational domain for CFD simulation.