Building and Environment 115 (2017) 199–214

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Numerical study of inter-building dispersion in residential environments: Prediction methods evaluation and infectious risk assessment

Yan Wu, Jianlei Niu*

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

ARTICLE INFO

Article history:
Received 21 November 2016
Received in revised form
22 January 2017
Accepted 23 January 2017
Available online 24 January 2017

Keywords:
CFD
Inter-building dispersion
Residential environments
DES model
Risk assessment

ABSTRACT

This study aims at further investigating the respiratory infectious diseases transmission in typical high-rise residential (HRR) environments, and at developing reliable CFD modeling method. The inter-building dispersion under wind effect was focused on and the cross-infection risk was assessed. The URANS model and DES model were compared, and the representation of surroundings was evaluated to improve the prediction of airflow and pollutant dispersion among a group of buildings. The DES model can better reproduce unsteady fluctuations of airflow around the buildings, and can accurately predict the frequency of vortex shedding. The predicted Strouhal number is approximately 0.15, which is consistent with the reported value in literature, whereas the URANS model fails to reproduce the whole features of unsteady airflow and significantly under-estimates the vortex shedding frequency. Ignoring the surrounding buildings in the simulation will significantly over-estimate the downward dispersion and over-estimate the risks in lower heights. The tracer gas concentrations near the downstream buildings are four orders lower than the concentration in the index/source unit, but only one order lower than the concentration in the leeward side and on the roof of the index building, and therefore the risk is comparable to that of intra-building dispersion within the index building. The tracer gas can diffuse to a long distance with slow concentration decay in empty areas. The cross-infection risk of inter-building dispersion should not be overlooked, especially when a super infector with high pathogen generation rate exists.

1. Introduction

During the SARS outbreak in 2003, 321 cases were detected in the estate of Amoy Gardens in Hong Kong after an index patient visited Unit 7 on a middle floor of Block E. A total of 41% of the cases were in Block E and mainly concentrated in Units 7 and 8, which share a common vertical air shaft. Another 41% of the cases were scattered in some adjacent blocks, namely, Block B (13%), Block C (15%), and Block D (13%). The other 18% cases were in other further blocks in the estate. Studies after the outbreak of SARS revealed that buoyancy-dominant natural ventilation may be responsible for the vertical spread of the virus in the re-entrance space of Block E [1–4]. The risks in the upper floors are higher than those in the lower floors because of the rising plume in the air shaft. Yu et al. [4] and Li et al. [1] associated the variable distribution of infected cases in the Amoy Gardens to the dispersion of airborne aerosols using computational fluid dynamics (CFD) and multi-zone modeling. The hypothesis of the airborne spread of virus-laden aerosols was identified. The high incidence rate of SARS in Block E should be attributed to the "inter-unit dispersion" of pathogens, which entails a short time because of the moderately short transmission distance from the index unit to other units. When the dispersion time is much shorter than the survival time of infectious viruses, the infectious risk of diseases can be high. Other infection cases in adjacent blocks must be attributed to the possible "inter-building dispersion" of pathogens. The epidemiological study on the outbreak has revealed that the onset and peak times of symptoms in adjacent blocks have occurred only 1–2 days later than that in the index block. And the infectious risk of inter-building dispersion is also high [4]. Thus, both inter-unit dispersion and inter-building

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

http://dx.doi.org/10.1016/j.buildenv.2017.01.029
0360-1323/

dispersion have been subjects of in-depth investigations, especially in densely populated residential districts.

For inter-unit dispersion, a specific transmission route induced by single-sided natural ventilation through outdoor spaces has been comprehensively investigated. Niu and Tung [5] conducted on-site measurements in a multi-family residential building and verified and quantified the vertical upward transmission. In such transmission, air expired from open windows of lower floors re-enters the windows of upper floors because of buoyancy effects. This phenomenon could be used to explain the vertical cross-infection during the SARS outbreak. Gao et al. and Liu et al. further studied this transmission route using CFD method and wind tunnel experiments [6–8]. Both buoyancy-dominated and wind-dominated single-sided natural ventilation have been considered. Ai and Mak [9] evaluated and improved the prediction methods to investigate the inter-unit dispersion induced due to single-sided natural ventilation under wind effect. Using on-site tracer technique, our previous study revealed that air infiltration can cause cross-infection between the neighboring units on the same floor, and the infectious risk through this air infiltration route can reach 9%, which is higher than the risk of 6.6% via the vertical spread route through single-sided open windows [10].

The present study will focus on the near-field inter-building dispersion and cross-infection risk in densely built-up HRR areas. Determining airflow characteristics around buildings is essential in investigating contaminant transmission caused by wind flow. There have been many studies that are aimed at characterizing airflow patterns around isolated obstacles [11–15] and building arrays [16,17], and some of these studies focused on far-field transmission of upstream pollution to downstream buildings [8,16,18–21]. Besides, a number of studies are particularly focused at evaluating and improving the CFD method to model the airflow and dispersion around buildings [22–26]. Different k-ε models, such as standard k-ε model, RNG k-ε model, and realizable k-ε model, have been compared [25]. The standard k-ε model fails to reproduce some basic flow structures, such as the reverse flow on a roof. The RNG model is the best among the tested k-ε models and exhibits the highest consistency with the experiment. However, all the models under-predict the pollutant dispersion in leeward and lateral sides. Thus, transient simulation, especially large eddy simulation (LES) is recommended for modeling the dispersion in built environments, which has been compared with RANS models [24,27]. The RANS models over-predict the turbulence kinetic energy (TKE) of the windward side and under-estimate the turbulence diffusion in the horizontal directions. The LES modeling performed better than the RANS modeling for contaminant distribution and complex urban environments because of the improved prediction of the transient flow separation bubbles at sharp edges [28,29]. However, when the source is not located in the recirculation regions near the building, both the RANS and LES models produce accurate simulation results. The main limitation of the LES modeling is the substantial computational cost. The DES model, which combines LES model and RANS model, can achieve similar simulation results in the wake region with relatively less mesh requirement and computational time than the LES model [30].

In the present study, the unsteady RANS (URANS) model and delayed DES model were evaluated to reproduce the unsteady fluctuations of turbulence flow in typical HRR environments. The inter-building tracer gas dispersion was predicted, and the cross-infection risk was assessed. Besides, the effects of surrounding buildings on the inter-building airflow and dispersion were investigated.

2. Computational setting and validation

2.1. Geometry model and computational domain

For modeling the inter-building tracer gas dispersion in typical HHR environments, a geometric model of a building group with seven cross-type building blocks was built on the basis of the detailed structures of the Amoy Gardens. The geometric model and the computational domain are shown in Fig. 1. The positive direction of the x-axis actually represents the prevailing wind direction of northeast. A 1:100 scaled geometric model was employed to reduce the required grids. The computational domain is sufficiently large with blockage ratio below 3%, as recommended in the Architectural Institute of Japan (AIJ) guidelines [17]. The lateral and top boundaries are 5 H away from the outer edge of the building group where H is the building height and the characteristic length of 106 m. The upwind inflow boundary is also 5 H to the target building group, and the outflow boundary is 10 H away.

2.2. Mesh arrangement and independence test

Structured hexahedral cells were constructed in the computational domain using the software ANSYS ICEM. The mesh distributions and independence test results are shown in Fig. 2. The grids in the near-building region were finer than those in the distant region.

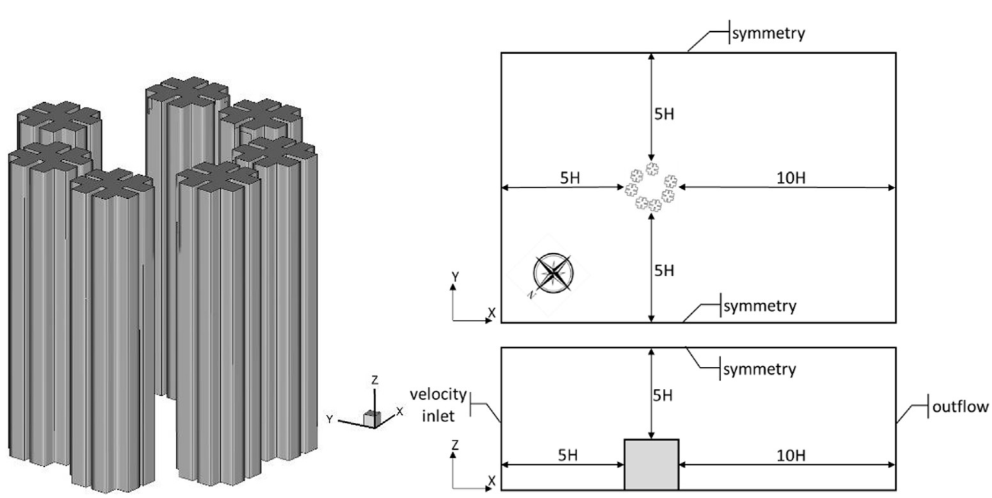

Fig. 1. Geometry model and computational domain.