Building and Environment 44 (2009) 402–410

Contents lists available at ScienceDirect

Building and Environment

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

The airborne transmission of infection between flats in high-rise residential buildings: Particle simulation

N.P. Gao [a], J.L. Niu [a,*], M. Perino [b], P. Heiselberg [c]

[a] Department of Building Services Engineering, The Hong Kong Polytechnic University, Hong Kong
[b] DENER, Politecnico di Torino, Corso Duca degli Abruzzi, 24, I-10129 Torino, Italy
[c] Hybrid Ventilation Centre, Aalborg University, Sohngaardsholmsvej 57, DK-9000 Aalborg, Denmark

ARTICLE INFO

Article history:
Received 11 January 2008
Received in revised form
26 March 2008
Accepted 27 March 2008

Keywords:
Particles
Lagrangian method
Eulerian method
Transport
Deposition

ABSTRACT

Several case clusters occurred in high-rise residential buildings in Hong Kong in the 2003 SARS (the severe acute respiratory syndrome) epidemic, which motivated a series of engineering investigations into the possible airborne transport routes. It is suspected that, driven by buoyancy force, the polluted air that exits the window of the lower floor may re-enter the immediate upper floor through the window on the same side. This cascade effect has been quantified and reported in a previous paper, and it is found that, by tracer gas concentration analysis, the room in the adjacent upstairs may contain up to 7% of the air directly from the downstairs room. In this study, after validation against the experimental data from literatures, Eulerian and Lagrangian approaches are both adopted to numerically investigate the dispersion of expiratory aerosols between two vertically adjacent flats. It is found that the particle concentration in the upper floor is two to three orders of magnitude lower than in the source floor. 1.0 μm particles disperse like gaseous pollutants. For coarse particles larger than 20.0 μm, strong deposition on solid surfaces and gravitational settling effect greatly limit their upward transport.

1. Introduction

The SARS outbreak in 2003 stimulated a series of engineering investigations into the airborne infectious diseases transmission mechanisms in the built environment. A few studies attempted to combine epidemiologic investigations with airflow analysis, but the airflow analysis remained to be preliminary [1,2]. In the investigation of the outbreak in a high-rise residential estate in Hong Kong, the CFD simulation did indicate that the transmission pattern between adjacent high-rise blocks qualitatively agrees with the wind direction. In the related study aiming to reveal the vertical transmission pattern in one building, multi-zone modeling technique was employed, which had inadequacies in modeling airflow through large window openings [3]. Niu and Tung [4] used on-site tracer gas measurement to experimentally investigate the re-entry possibility of exhaust air from the lower floor into the immediate upper floor for high-rise residential buildings with single-sided natural ventilation conditions (Fig. 1). It was revealed that the upstairs room may contain 7% of the exhaust air from the lower floor, which can help explain the presence of SARS-CoV RNA found on the window sill deposits in the upstairs of an index patient. Gao et al.'s [5] CFD study on the dispersion of one tracer gas agrees with the on-site measurement. With the help of the Wells–Riley infection risk model, Gao et al. [5] estimated the vertical cross-household infection risk in the upper floor using the data of tuberculosis. It was found that a significant infection risk up to 6% for the upstairs residents can be resulted in, when merely assuming an 8 h continuous stay at home.

On the other hand, recent systematic reviews [6,7] concluded that person to person respiratory virus transmission could occur in three possible modes: airborne transmission, droplet transmission, and direct contact with secretions (or fomites). Currently, by droplets transmission it is meant short-distance (usually less than 1 m) transmission via large droplets (⩾5 μm diameter) generated during coughing, sneezing, or talking, and by airborne transmission it is meant long-distance transmission via the dissemination of virus-laden droplet nuclei (particles less than 5 μm that result from the evaporation of large droplets). But whether the three transmission modes are mutually exclusive and which mode is the most significant transmission route for a particular disease are debatable. In general, it is believed that respiratory droplets movements in the room air play a key role for airborne transmitted diseases. Arguably, airborne transmission does not necessarily cause long range infections since a wide range of other confounding factors are also playing important roles, and these include the shedding rate, viability and infectiousness of the pathogen and the wind, temperature and humidity conditions. In general, aerosol dynamics differs from gaseous pollutants due to

* Corresponding author. Tel.: +852 2766 7781; fax: +852 2774 6146.
E-mail address: Bejlniu@polyu.edu.hk (J.L. Niu).

0360-1323/$ - see front matter
doi:10.1016/j.buildenv.2008.03.016

Nomenclatures

C	particle concentration (g/m^3)
C_0	initial indoor particle concentration (g/m^3)
C_C	cunningham correction factor
C_D	drag coefficient
C_j	particle concentration in the jth cell (g/m^3)
C_t	indoor particle concentration at time t (g/m^3)
d_p	particle diameter (μm)
D_p	Brownian diffusivity (m^2/s)
$d_t(i,j)$	the ith particle residence time in the jth cell (s)
f_v	correction factor for turbulent kinetic energy
$\vec{F}_{addi}$	other additional force per unit mass (N/kg)
$\vec{F}_{drag}$	drag force per unit mass (N/kg)
$\vec{F}_{grav}$	gravity force per unit mass (N/kg)
$\vec{g}$	gravitational acceleration (m/s^2)
k	turbulent kinetic energy (m^2/s^2)
L_e	eddy length scale (mm)
M	flow rate of each trajectory (g/s)
S_C	particle source term (g/sm^3)
S_φ	pollutant source term (g/sm^3)
t	time (t)
t_{cross}	eddy crossing time (s)
t_{eddy}	eddy lifetime (s)
t_L	Lagrangian time scale (s)
$\vec{U}$	velocity vector (m/s)
u'_i	fluctuation part of instantaneous velocity in i direction (m/s)
$\vec{u}_p$	particle velocity (m/s)
u'_y	fluctuation part of instantaneous velocity normal to the wall (m/s)
u_τ	wall shear velocity (m/s)
V_j	the volume of the jth cell (m^3)
$\vec{V}_S$	gravitational settling velocity calculated from Stokes's law (m/s)
V_{met}	meteorological wind speed (m/s)
V_y	wind speed at the height of y (m/s)
y	height above the ground in the calculation of wind speed (m)
y_{cell}	the distance between the wall and the first cell center (m)
y^+	non-dimensional wall distance ($y^+ = \rho u_\tau y_{cell}/\mu$)

Greek letters

α	air change rate (h^{-1})
ε	viscous dissipation rate (m^2/s^3)
ε_p	particle eddy diffusivity (m^2/s)
κ	particle loss-rate coefficient caused by deposition (h^{-1})
λ	molecular mean free length (μm)
μ	molecular viscosity of the air (g/ms)
μ_{eff}	turbulent effective viscosity (g/ms)
ν_t	turbulent viscosity (m^2/s)
ς_i	a random number with Gaussian distribution
ρ	air density (kg/m^3)
ρ_p	particle material density (kg/m^3)
σ_c	non-dimensional number 1.0
τ_p	particle response time (s)

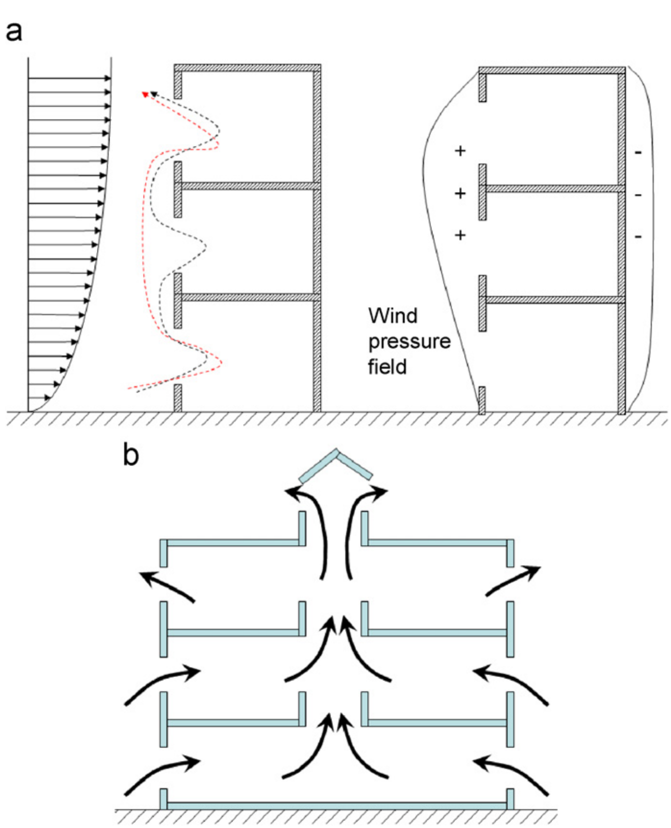

Fig. 1. Schematic view of pollutant transport by the cascade effect in natural ventilation.

the effects of gravity, inertia and deposition at solid surfaces. Therefore, as a companion paper of Gao et al. [5], which studied the airflow and gaseous pollutants between vertically adjacent floors, this study simulates the transport possibilities of droplet residuals by using both Lagrangian and Eulerian methods. The aim is to explore whether the virus-laden aerosols could be carried upward by inter-flat airflows between floors in high-rise residential buildings when the gravity and surface deposition effects are considered.

2. Numerical approaches

2.1. Airflow field

Prior to modeling particle movements, the airflow field is simulated by using a commercial code, Fluent [8], which solves the mass, momentum, and energy equations in a finite-volume procedure with a staggered grid system. The convection terms are discretized by second order upwind scheme and the diffusion term by central difference also with second-order accuracy. The variables at the near-wall cells and the corresponding quantities on the wall are bridged by the standard logarithmic law wall function. The turbulent effect is modeled by the RNG k–ε model [9]. Although large eddy simulation (LES) has been adopted to investigate wind field and indoor–outdoor airflows due to its capacity of handling the unsteadiness and intermittency of the flow as well as providing detailed information on the turbulence structure, the RANS models are extensively used in industrial and engineering practice because they generally use about one order of magnitude less CPU time than LES while keeping an acceptable accuracy.