Building and Environment 94 (2015) 543–557

Contents lists available at ScienceDirect

Building and Environment

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

The transport of gaseous pollutants due to stack and wind effect in high-rise residential buildings

Jiachen Mao, Wenwen Yang, Naiping Gao*

Institute of Thermal and Environment Engineering, College of Mechanical Engineering, Tongji University, Shanghai 201804, China

ARTICLE INFO

Article history:
Received 16 August 2015
Received in revised form
28 September 2015
Accepted 19 October 2015
Available online 11 November 2015

Keywords:
Pollutant transport
Stack effect and wind effect
High-rise residential building
Inter-flat dispersion
Multi-zone model
Tracer gas

ABSTRACT

Several outbreaks of severe infectious diseases occurred recently in high-rise residential (HRR) buildings have motivated a series of engineering investigations into possible airborne transmission routes. It is suspected that, driven by stack and/or wind effect, the polluted air may transport between flats through leakage cracks of doors and windows inside HRR buildings. The pure stack effect has been quantitatively studied and reported in a previous paper. This study further investigates the temporal and spatial distribution of gaseous pollutants due to combined stack and wind effect in an HRR building in Shanghai (China) with doors and windows closed. A well-established multi-zone (CONTAM) model, based on reliable boundary conditions from CFD simulations, is used to analyze the airflow movements and pollutant transport between flats via door and window leakage cracks under different scenarios. It is found that the combined stack and wind effect can cause the pollutant spread in both vertical and horizontal directions. In general, the concentrations in the top rooms are about 3–4 orders of magnitude lower than in the source room in a 33-floor building, and the concentrations on the leeward side are mainly higher than on the windward side before steady state. The effects of the outdoor/indoor temperature difference, wind field, air tightness level and source location are quite complicated due to the interaction between physical forces and the building shape. Despite the complexities, these findings have many implications that cannot be overlooked for the infectious disease control and ventilation design in HRR buildings.

1. Introduction

The spread of infectious diseases has become of great concern in the modern society, as more and more people live in highly dense communities in many parts of the world. Meanwhile, people spend about 80–90% of their time indoors [1–3], showing the great importance of indoor air quality for human health. The airborne transmission, as one of the main person-to-person respiratory virus transmission modes [4,5], is defined as the infection via inhalation of pathogen-carrying droplet nuclei [6]. With the lessons from recent outbreaks of tuberculosis [7], SARS [8], bird flu [9], A (H1N1) influenza [10] and MERS [11], our concern about aerosol-transmitted infections in built environments has been refreshed, stimulating a series of epidemiological and engineering investigations into the airborne infectious diseases and gaseous pollutant transmission mechanisms [12–14].

High-rise residential (HRR) buildings where doors and windows are generally closed have more infection risk from indoor airborne diseases transmission. This is because during cold seasons, when airborne pathogens are prevalent, the outdoor temperature is low and wind is strong. The diseases spread inside HRR buildings not only horizontally but also vertically through elevator or stairwell shafts due to the stack and/or wind effect (Fig. 1). The relative importance of stack and wind effects in a building may cause different pressure profiles (Fig. 2), which could lead to different indoor airflow movements and gaseous pollutant transport patterns. Furthermore, the floor plans of residential buildings are usually complicated, making the characteristics of pressure profiles in or around the HRR buildings extremely complex. Thus, it is necessary to figure out the characteristics of airflow movement and gaseous pollutant transmission inside HRR buildings, and to distinguish where and how related problems may occur.

The stack effect and related problems (such as energy loss, sticking elevator doors, annoying noise, etc.) have been widely studied [15–21] with some solutions presented. In particular, many

* Corresponding author. Institute of Thermal and Environment Engineering, College of Mechanical Engineering, Tongji University, No. 4800 Cao'an Road, Shanghai 201804, China.
E-mail address: gaonaiping@tongji.edu.cn (N. Gao).

http://dx.doi.org/10.1016/j.buildenv.2015.10.012

Nomenclature

A_C	crack area (m^2)
Ar	Archimedes number
C_D	discharge coefficient
D	depth of the room (m)
g	gravity acceleration (m/s^2)
Gr	Grashof number
h	window height (m)
H_{met}	height measured by the meteorology station (m)
k	turbulent kinetic energy (m^2/s^2)
n	flow exponent
P_i	air pressure in zone i (Pa)
P_j	air pressure in zone j (Pa)
Q_{CONTAM}	volume flow rate predicted by CONTAM (m^3/h)
Q_{CFD}	volume flow rate predicted by CFD (m^3/h)
Q_{ji}	airflow rate from zone j to zone i (m^3/h)
Re	Reynolds number
T	air temperature (°C)
ΔT	indoor/outdoor temperature difference (°C)
T_{ref}	reference air temperature (°C)
U	wind speed at the building height (m/s)
U_H	wind speed at reference height H (m/s)
U_{met}	wind speed measured by the meteorology station (m/s)
U_Z	wind speed at the height of Z (m/s)

Greek symbol

α	power exponent
α_{met}	power exponent measured by the meteorology station
β	thermal expansion coefficient (K^{-1})
δ	boundary layer thickness (m)
δ_{met}	boundary layer thickness measured by the meteorology station (m)
ε	turbulence viscous dissipation rate (m^2/s^3)
κ	Von Karman's constant, 0.41
ρ	air density (kg/m^3)
ρ_{ref}	reference air density (kg/m^3)
ν	kinetic viscosity (m^2/s)

Abbreviation

ACH	air change rate per hour (h^{-1})
CFD	computational fluid dynamics
ELA	equivalent leakage area
HRR	high-rise residential
lms	linear meter of sash
MERS	middle east respiratory syndrome
NPL	neutral pressure level
RNG	renormalization group
SARS	severe acute respiratory syndrome

recent studies [22–24] have been performed on the fire-induced smoke movement driven by stack effect along vertical shafts in tall buildings, including the characteristics of thermal plumes [25], the NPL position [26], and the distribution of pressure and temperature [27]. For airborne transmission of diseases inside high-rise buildings, the stack effect has also been investigated by some researchers. For example, the on-site measurements and tracer gas simulations by Lim et al. [28,29] have demonstrated the vertical spread of indoor airborne diseases due to stack effect in high-rise hospitals in Korea. Besides, Yang and Gao [30] have quantitatively investigated the temporal and spatial distribution of gaseous pollutants due to stack effect in an HRR building in Shanghai (China) through multi-zone modeling. However, studies of the airflow and gaseous pollutant transport patterns driven by wind effect or combined stack and wind effect in residential buildings with doors and windows closed are still scarce [31,32]. Moreover, HRR buildings with complex spatial structures have been rarely studied in terms of pollutant concentration dispersions at various times and spaces [33].

Therefore, as a companion paper of Yang and Gao [30], this study further investigates the temporal and spatial distribution of gaseous pollutants due to combined stack and wind effect in an HRR building with doors and windows closed. For the investigation method, a validated multi-zone model is adopted to analyze the combined effect and the airflow of the entire building. Then, tracer gas modeling technique is used to further investigate the gaseous pollutant transport patterns through door and window cracks due to such effect. The results are expected to be useful in fully understanding the concerned pollutant transmission and dispersion mechanism, and in implementing more effective measures and strategies to prevent future spread of infection in HRR buildings.

2. Methodology

2.1. Multi-zone method

The multi-zone method [34] enables us to obtain the airflow rates between flats and corridors, as well as the concentration

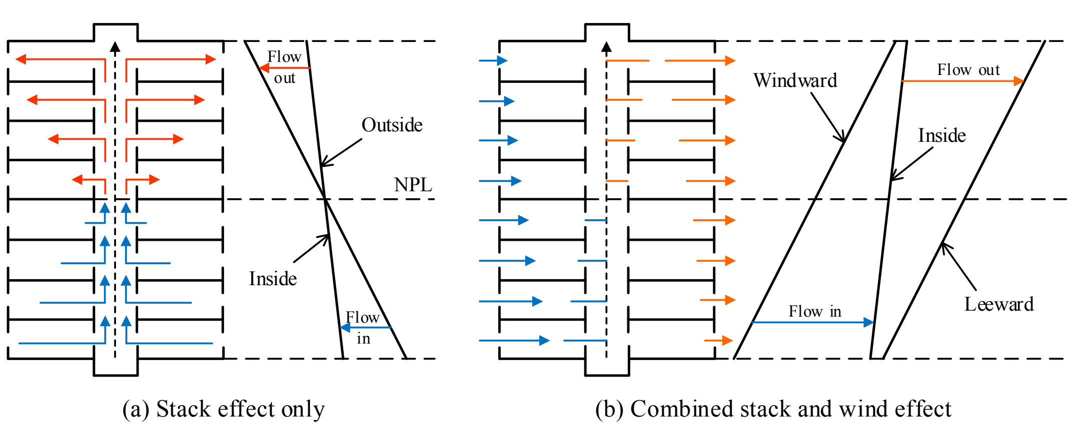

Fig. 1. Airflow movements and pressure distributions in HRR buildings. There is no restriction to vertical (floor to floor) air movement through the building interior.