Energy and Buildings 127 (2016) 116–127

Contents lists available at ScienceDirect

Energy and Buildings

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

Ventilation of air-conditioned residential buildings: A case study in Hong Kong

Z.T. Ai, C.M. Mak*, D.J. Cui, P. Xue

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

ARTICLE INFO

Article history:
Received 24 February 2016
Received in revised form 17 May 2016
Accepted 18 May 2016
Available online 24 May 2016

Keywords:
Ventilation
Room air conditioner
Residential buildings
Carbon dioxide (CO_2)
On-site measurements

ABSTRACT

More and more studies reported that there were insufficient ventilation and excessive CO_2 concentration in air-conditioned residential buildings, but few solutions were provided. This study investigates the overnight evolution of CO_2 concentration in air-conditioned residential buildings and then focuses mainly on the evaluation of three ventilation strategies, including overnight natural ventilation, short-term mechanical ventilation and short-term natural ventilation. On-site measurements were conducted in a typical residential bedroom in Hong Kong in September. The indoor and outdoor CO_2 concentration, air temperature and relative humidity as well as the outdoor wind speed during the measurements were analysed. Ventilation rates were calculated based on the time series of CO_2 concentration. This study confirms that additional ventilation is usually needed in air-conditioned residential buildings. Overnight natural ventilation with even a small opening is associated with excessive energy consumption and deteriorated indoor thermal environment. Short-term natural ventilation strategies are inefficient and uncontrollable. Compared to the best short-term natural ventilation strategy, a reasonably designed short-term mechanical ventilation strategy requires only a 41% of ventilation period to complete one full replacement of indoor air and to reach a lower indoor CO_2 concentration. Nighttime case studies and a theoretical analysis suggest that a few several-minute mechanical ventilation periods could potentially maintain an acceptable indoor air quality for a normal sleeping period of 8 h.

1. Introduction

Air conditioner is almost indispensable in residential buildings in hot and humid regions to provide a thermally comfortable indoor environment [1–5]. Among others, the window-type and split-type air conditioners are the most popular room air conditioners [1,5]. A questionnaire survey [1] on the use status of air-conditioners in residential buildings in Hong Kong reveals that most people leave their air conditioners on overnight, while the period of using air-conditioners in a year has been becoming increasingly long, even over 6 months in some homes. Given that people spend more than 50% of their time in homes [6], ventilation to maintain an acceptable indoor air quality (IAQ) in air-conditioned residential buildings is thus of great importance.

One deficiency of room air conditioners is the provision of no or very little outdoor air. Many on-site measurements [3,5,7–9] show that ventilation rates in most air-conditioned residential buildings were largely less than the minimum requirement, namely 7.5 l/s/p, recommended by ventilation standards [10], even if there was only one occupant indoors. Accompanying with low ventilation rates, excessive CO_2 concentrations (>1000 ppm) in air-conditioned residential buildings were often reported [1–5,8]. Switching on the ventilation damper of window-type air conditioners could lower the indoor CO_2 concentration by approximately 100–200 ppm [2,3], but few occupants were aware of the existence or the function of such a damper [1]. Indoor CO_2 concentration was commonly used as a surrogate of the indoor concentration of human generated bioeffluents and thus as an indicator of the indoor ventilation levels [3,4,11–17]. ASHRAE Standard 62-1989 [18] suggested that the indoor CO_2 concentration levels should be less than 1000 ppm, which is nearly equivalent to a ventilation rate of 7.5 l/s/p. Such a level of ventilation rate is generally sufficient to control human body odor that approximately 80% of unadapted persons find the odor acceptable [19–23]. More recent (since 1999) series of ASHRAE Standards 62 (e.g., [10,24]) recommended that the same level of

* Corresponding author at: Department of Building Services Engineering, The Hong Kong Polytechnic University, Hong Kong.
E-mail addresses: zhengtao.ai@connect.polyu.hk (Z.T. Ai), cheuk-ming.mak@polyu.edu.hk, becmmak@polyu.edu.hk (C.M. Mak), jena.cui@connect.polyu.hk (D.J. Cui), kimi.xue@connect.polyu.hk (P. Xue).

http://dx.doi.org/10.1016/j.enbuild.2016.05.055
0378-7788/

Nomenclature

ACH	Air change per hour, [h^{-1}]
ACH*	Normalized air change rate, [-]
$(ACH)_0$	Reference infiltration rate, [h^{-1}]
A_D	Body surface area, [m^2]
A_f	Net floor area, [m^2]
Ar	Archimedes number, [-]
A_w	The largest possible area of indoor/outdoor flow exchange, [m^2]
C_{in}	Indoor CO_2 concentration, [ppm]
C_{in}^*	Normalized CO_2 concentration, [-]
$\bar{C}_{in}$	Average indoor CO_2 concentration during a ventilation period, [ppm]
$C_{in,i}$	Concentration at the moment i, [ppm]
$C_{in,ini}$	Initial indoor CO_2 concentration at the beginning of ventilation, [ppm]
$C_{in,i+\Delta t}$	Concentration at the moment $i + \Delta t$, [ppm]
C_{out}	Outdoor CO_2 concentration, [ppm]
D_w	Vertical distance of the window frame away from the open window, [m]
e	Correction factor for chinese people, [-]
g	Gravitational acceleration, [m/s^2]
Gr	Human generation rate of CO_2, [m^3/s]
H	Human height, [m]
Hw	Window height, [m]
i	a particular moment of time, [s]
M	Metabolic rate, [W/m^2]
Q	Ventilation rate, [m^3/s]
Q	Volumetric rate of CO_2 generation, [ml/s]
Q_{O_2}	Volumetric rate of oxygen consumption, [ml/s]
RQ	Respiratory quotient (the molar ratio of exhaled Q_{CO_2} to inhaled Q_{O_2}; 0.83 for light or sedentary activities of an average adult), [-]
t	Time, [s]
t^*	Normalized time, [-]
T_{in}^*	Normalized indoor air temperature, [-]
$T_{in}^*(t)$	Indoor air temperature at the time, [°C]
$T_{in,ini}$	Indoor air temperature at the beginning of ventilation, [°C]
T_{out}	Outdoor air temperature, [°C]
U_B	Mean outdoor wind speed at the building height in the free stream, [m/s]
U_O	Outdoor wind speed, [m/s]
V	Volume of the room, [m^3]
W	Human mass, [kg]
β	Thermal expansion coefficient, [1/°C]
Δt	Time interval, [s]
Δt_v	Ventilation period, [s]
ΔT	Indoor and outdoor air temperature difference, [°C]
φ	Perpendicular angle, 90°

body odor acceptability can be achieved when the indoor and outdoor (I/O) CO_2 concentration difference is less than 700 ppm.

Many evidences show that insufficient ventilation and excessive CO_2 concentration are strongly associated with the increased IAQ complaints and the prevalence of illnesses and sick building syndrome (SBS) symptoms in office buildings [14,25–31]. For residential buildings, the review by Sundell et al. [31] indicated that ventilation rates above 0.5 h^{-1} are associated with a reduced risk of allergic manifestations among children in a Nordic climate. Wong and Huang [2] reported that the low ventilation rates and high CO_2 concentrations are the basic reasons for that occupants who use air conditioners during sleeping periods exhibit more SBS syndromes than when they use natural ventilation. In addition, insufficient ventilation in bedrooms is also responsible for a poor sleep quality and a reduced next-day performance [5,32].

The possible ventilation strategies in air-conditioned residential buildings are open window, open door, switching on ventilation damper for window-type air conditioners, and mechanical ventilation using exhaust fan [1,4], even though most people do not apply any of them in practice [1]. Sekhar [4] reported that operation of a bathroom exhaust fan lowers very quickly the indoor CO_2 concentration from 2000 to 3000 ppm to 1000 ppm in a residential apartment with a floor area of nearly 20 m^2. Apart from mechanical ventilation, it is believed that opening window(s) to make an air-conditioned room naturally ventilated can also maintain a fairly good indoor IAQ. However, issues of energy loss, thermal comfort and noise ingress do not allow overnight mechanical ventilation or overnight natural ventilation with large openings in air-conditioned residential buildings. Recently, Perino and Heiselberg [33] and Heiselberg and Perino [34] investigated the ventilation of buildings in a very cold wintertime through window airing. They found that the optimum application of window airing is a relatively short opening period and a relatively high opening frequency. Different from the situation in cold regions, the I/O air temperature difference in air-conditioned residential buildings in hot and humid regions is mostly less than 10 °C, with cold indoor and hot outdoor.

It is imperative to explore feasible ventilation strategies that can maintain an acceptable IAQ while consuming minimum energy and causing a minimum influence on indoor thermal environment. In such a regard, this study investigated three types of ventilation strategies: (a) overnight natural ventilation with a narrow window opening, (b) short-term mechanical ventilation with an exhaust fan and (c) short-term natural ventilation with large window opening(s). These ventilation strategies were evaluated through on-site measurements in a typical bedroom in a high-rise residential building in Hong Kong. This study is intended to provide basic information and implications for ventilation design of air-conditioned residential buildings.

2. Materials and methods

2.1. Measurement site and instrumentation

The on-site measurements were conducted in Hong Kong in September 2015, when the outdoor air temperature was mainly between 27 and 32 °C. An air-conditioned bedroom located on the 11th floor of a 12-storey building was selected. The room was occupied with two adults. The building locations, its surroundings and the apartment location in the building are presented in Fig. 1. The room and window configurations are presented in Fig. 2. Note that for the 'Window-AC', only the half below the air conditioner was openable. After excluding indoor furniture, partitions, and some protrusive pillars on walls, the estimated net floor area and net volume of this room were 8.6 m^2 and 21.3 m^3, respectively. A room of such dimensions is typical in densely populated urban areas like Hong Kong [3,7]. There was a bathroom connected to the bedroom through an opening with 0.5 m × 2.0 m in area. The exhaust fan in the bathroom provided a nominal flow rate of 520 m^3/h. During all measurements, the door of this bedroom was always closed.

Parameters monitored during the measurements were indoor and outdoor CO_2 concentration, air temperature and relative humidity. The outdoor wind speed data during the on-site measurements was retrieved from the nearby King's Park Observatory (within 1500 m away from the measured building). All equipment was calibrated regularly according to the suggestions of manufacturers, which was further calibrated against known values before