J. Wind Eng. Ind. Aerodyn. 155 (2016) 74–88

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

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

Wind tunnel analysis of flow and dispersion in cross-ventilated isolated buildings: Impact of opening positions

Yoshihide Tominaga [a,*], Bert Blocken [b,c]

[a] Department of Architecture and Building Engineering, Niigata Institute of Technology, 1719 Fujihashi, Kashiwazaki, Japan
[b] Department of the Built Environment, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands
[c] Department of Civil Engineering, KU Leuven, Kasteelpark Arenberg 40 – bus 2447, 3001 Leuven, Belgium

ARTICLE INFO

Article history:
Received 21 August 2015
Received in revised form
2 May 2016
Accepted 15 May 2016

Keywords:
Wind tunnel experiment
Cross-ventilation
Pollutant dispersion
Validation
Experimental data set
Window opening position

ABSTRACT

This paper presents a detailed experimental analysis of flow and dispersion by cross-ventilation in five generic isolated single-zone buildings with different opening positions. First, flow visualization is performed illustrating the highly transient flow and dispersion process dominated by a flapping jet with pronounced Kelvin–Helmholtz instabilities. Next, the mean velocity field, the turbulent kinetic energy field, the mean concentration field and the concentration fluctuation field are presented and analyzed. Finally, time histories of the instantaneous concentration in the building are provided. The contaminant dispersion in the cross-ventilated flow is strongly influenced by the overall flow pattern that is largely determined by the inlet opening position, while the outlet opening position seems less important. The results provide new insights in the flow and dispersion process inside cross-ventilated buildings and can be used to validate Computational Fluid Dynamics (CFD) simulations of flow and dispersion by cross-ventilation and for the subsequent establishment of new CFD best practice guidelines. It is also shown that the use of different ventilation performance parameters yields a different ranking of the configurations in terms of ventilation performance. Care should therefore be applied when evaluating ventilation performance based on only flow rates or velocities as opposed to dispersion quantities.

1. Introduction

Natural ventilation is an important factor in the development of sustainable and healthy indoor environments (e.g. Finnegan et al., 1984; Etheridge and Sandberg, 1996; Carrilho da Graça et al., 2002; Awbi, 2003; Chen, 2009; Tablada et al., 2009; Heiselberg and Perino, 2010; Etheridge, 2011; Karava et al., 2011; van Hooff and Blocken, 2010a, 2014). It is driven by wind or buoyancy, or – most often – by a combination of both (e.g. Linden, 1999; Li and Delsante, 2001; Reichrath and Davies, 2002; van Hooff and Blocken, 2010a). In the past decades, a lot of research efforts have contributed to the evaluation of the natural ventilation performance of buildings. Comprehensive reviews on methods for ventilation performance assessment for buildings were provided by Etheridge and Sandberg (1996), Awbi (2003), Chen (2009), Ohba and Lun (2010) and Etheridge (2011). Ventilation performance can be assessed by experiments (e.g. Murakami et al., 1991; Kato et al., 1992; Kato et al., 1997; Linden, 1999; Jiang et al., 2003; Heiselberg et al., 2004; Karava et al., 2007; Tablada et al., 2009; Bu et al., 2010; Heiselberg and Perino, 2010; Ji et al., 2011; Karava et al., 2011; Karava and Stathopoulos, 2012), analytical and/or semi-empirical formulae (e.g. Linden, 1999; Li and Delsante, 2001; Karava et al., 2004; Etheridge and Sandberg, 1984; Haghighat et al., 1991; Etheridge, 2002; Costola et al.,2009), simulations with zonal and multizone network models (e.g. Li et al., 2000; Hensen, 2004; Hirano et al., 2006; Hensen and Lamberts, 2011) and Computational Fluid Dynamics (CFD) models (e.g. Kato et al., 1992; Kato et al., 1997; Reichrath and Davies, 2002; Jiang et al., 2003; Heiselberg et al., 2004; Evola and Popov, 2006; Norton et al., 2007; Meroney, 2009; van Hooff and Blocken, 2010a, 2010b; Ramponi and Blocken, 2012a; Peren et al., 2015).

Concerning the modeling of dispersion of pollutants, there is a large body of literature concerning dispersion in the outdoor environment (e.g. reviews by Robins, 2003; Meroney, 2004; Ahmad et al., 2005; Li et al., 2006; Tominaga and Stathopoulos, 2013; Di Sabatino et al., 2013; Blocken et al., 2013; Lateb et al., 2016) as well as dispersion in the indoor environment (e.g. Holmberg and Li, 1998; Nazaroff, 2004; Zhao et al., 2004; Zhang and Chen, 2006; Chen et al., 2006; Liu and Zhai, 2007; Gao and Niu, 2007; van Hooff et al., 2013, 2014). Several efforts have focused on dispersion between different indoor environments due to natural ventilation

* Corresponding author. Tel./fax: +81 257 22 8176.
E-mail address: tominaga@abe.niit.ac.jp (Y. Tominaga).

http://dx.doi.org/10.1016/j.jweia.2016.05.007
0167-6105/© 2016 Elsevier Ltd. All rights reserved.

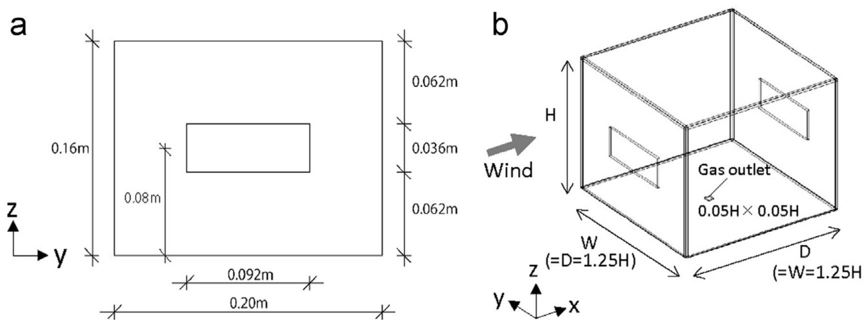

Fig. 1. (a) Front view of model with opening sizes; (b) Schematic view of configuration E.

bringing indoor air via the outdoor environment to another indoor environment. This is called inter-unit dispersion by natural ventilation. Many of these studies emerged from the SARS threat. Examples are the studies by Liu et al. (2007), Niu and Tung (2008), Gao et al. (2008), Ai et al. (2013), Ai and Mak (2014, 2015a, 2015b) and Cui et al. (2016). Two review papers on the topic of inter-unit dispersion by single-sided natural ventilation were provided by Ai and Mak (2015a, 2015b) and Mao and Gao (2015).

Several studies have analyzed the dispersion of CO_2 or other tracers in cross-ventilated buildings using CFD and/or measurements. Many of these studies were performed for greenhouses or livestock buildings in agricultural engineering, e.g. Bartzanas et al. (2004, 2007) and Norton et al. (2009, 2010) who applied 2D or 3D steady and unsteady RANS simulations to assess the air change ratio by natural ventilation. In addition to these studies in agricultural engineering, van Hooff and Blocken (2012, 2013) measured and modeled the dispersion of indoor CO_2 by natural cross-ventilation in a large semi-enclosed stadium in the Netherlands. The CFD simulations were performed with the unsteady RANS equations.

The above-mentioned studies of indoor dispersion by cross-ventilation are almost exclusively case studies. As opposed to case studies, the literature shows a clear lack of experimental – but also numerical – studies of cross-ventilation with indoor dispersion for generic building configurations. The importance of such experiments is twofold. First, they provide insights in the flow and dispersion process that might be very difficult to obtain from complex case studies in which a large number of parameters are acting simultaneously and jointly influencing the dispersion, e.g. building geometrical details, surrounding buildings and topography, meteorological conditions (temperature, relative humidity, …) and people, animals or plants. Second, they provide valuable data for dedicated CFD validation studies, which in turn can be used to establish CFD best practice guidelines for this type of flow and dispersion problems.

Given the lack of such studies, this paper presents detailed measurements of flow and dispersion in cross-ventilated buildings in an atmospheric boundary layer wind tunnel. The paper is an extension of a previous paper by the authors on flow and dispersion in a single building configuration (Tominaga and Blocken, 2015). To the best of our knowledge, the present paper is the first to provide detailed experimental data and a detailed analysis of the flow and dispersion process for a set of cross-ventilated generic building configurations. The paper is structured as follows: Section 2 outlines the materials and methods, including the building configurations, the wind tunnel and the wind tunnel set-up, and the measurement equipment. Section 3 presents flow visualization performed for the five configurations. Section 4 focuses on the velocity field and Section 5 on the concentration field. Finally, Section 6 summarizes the findings of the study and discusses future prospects.

2. Materials and methods

2.1. Building configurations

The configurations under study are five generic isolated single-zone buildings with two opposite openings, in the windward and leeward facade. This configuration was made similar to the model used in the extensive experiments by Karava (2008) and Karava et al. (2011) so that the results could be compared. This model was also used in the CFD studies by Meroney (2009) and Ramponi and Blocken (2012a, 2012b). The wind direction is selected to be perpendicular to these facades as in these previous CFD studies. The buildings are 1:100 scale models of a building with full-scale dimensions $W \times D \times H = 20 \times 20 \times 16$ m³ (Fig. 1). Fig. 1(a) indicates the size and locations of the openings for one of the configurations. The five building configurations only differ from each other by the position of the openings (Fig. 2). Three opening positions are considered: bottom, center, and top. The centers of these openings are at height $h = 40$, 80, and 114 mm at reduced scale, respectively. The opening area is $0.036\ \mathrm{m} \times 0.092\ \mathrm{m} = 3.3 \times 10^{-3}\ \mathrm{m}^2$ at reduced scale for all configurations. Due to the horizontally long opening shape, the air movement in the vertical plane is predominant over the lateral motion as shown in the previous paper (Tominaga and Blocken, 2015). This justifies focusing the analysis for the different configurations in the vertical centerplane. A gas outlet with dimensions 8 mm (0.05 H) × 8 mm (0.05 H) is located at the center of the floor for each configuration (Fig. 1b).

2.2. Measurement equipment

Wind velocity is measured with a split fiber probe (SFP) (Dantec Dynamics; 55R55) and a constant temperature anemometry (CTA) module (Dantec Dynamics; 90C10) for the three components of the velocity vector. The frequency response of this probe in CTA mode is 40 kHz. Time-averaging is conducted with a sampling rate of 100 Hz for a period of 60 s to obtain statistically stationary values. The uncertainty of the time-averaged velocity is estimated to be within approximately 10%. Ethylene (C_2H_4), which has a density similar to air, is used as tracer gas. The concentration is measured with a high-speed total hydrocarbon analyzer (Technica, HTHCA-01). The concentration resolution and time response of the hydrocarbon analyzer are 10 ppm and 25 ms, respectively. Uncertainty of the time-averaged data is estimated to be within approximately 15% in concentration. Fig. 3 displays the measurement positions in the vertical centerplane. Measurements are made at each position by the insertion of the measurement probe and sampling tube through the holes along the centerline in the ceiling of the building model. Unused openings, holes and interspaces are always sealed with tape during the measurements. The diameters of the support for the SFP and the sampling tube of the total hydrocarbon analyzer are 6 mm and 1 mm, respectively.