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Full-scale measurements of indoor environmental conditions and natural ventilation in a large semi-enclosed stadium: Possibilities and limitations for CFD validation

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ABSTRACT

The use of Computational Fluid Dynamics (CFD) to study complex physical processes in the built environment requires model validation by means of reduced-scale or full-scale experimental data. CFD studies of natural ventilation of buildings in urban areas should be validated concerning both the wind flow pattern around the buildings and the indoor airflow driven by wind and buoyancy. Reduced-scale wind tunnel measurements and full-scale on-site measurements both have particular advantages and disadvantages. A main disadvantage of reduced-scale experiments is the difficulty to fulfill the similarity requirements, especially when wind flow and buoyancy effects are combined. This paper presents the results of unique full-scale measurements for a situation in which accurate wind tunnel experiments are not possible: natural ventilation and thermal, humidity and CO_2 concentration conditions inside a large semi-enclosed multifunctional stadium with relatively small ventilation openings. The emphasis is on three consecutive evenings on which concerts took place in the stadium. Although the repeatability of full-scale on-site measurements is in general quite low, nearly identical meteorological and indoor environmental conditions were present on the three concert evenings. Furthermore, the calculated air exchange rate based on CO_2 concentration decay measurements shows that also the natural ventilation on the three evenings was almost equal. The paper addresses the possibilities and limitations of this type of experimental data for the validation of CFD simulations. The data will be used in future studies for validation of CFD models for wind flow, natural ventilation and indoor environmental conditions in buildings.

1. Introduction

The use of numerical models requires model validation by means of reduced-scale or full-scale experimental data. In the past decades, an increasing amount of guidelines and papers have stipulated the importance of validation of numerical models in general, and of Computational Fluid Dynamics (CFD) in particular to ensure the trustworthiness of the simulation results (e.g. Schatzmann et al., 1997; Casey and Wintergerste, 2000; Dalgliesh and Surry, 2003; Franke et al., 2004, 2007; Tominaga et al., 2008; Schatzmann and Leitl, 2011; Blocken et al., 2011; 2012; Blocken and Gualtieri, 2012). The validation of numerical models that are used to analyze natural ventilation is not always straightforward. Numerical natural ventilation studies can use either a coupled or a decoupled approach, where the former consists of modeling the urban wind flow and the indoor air flow simultaneously and within the same computational domain (e.g. Kato et al., 1992; Jiang and Chen, 2002; Evola and Popov, 2006; Mochida et al., 2006; Hu et al., 2008; Norton et al., 2010; Kobayashi et al., 2010; van Hooff and Blocken, 2010a, 2010b; Ramponi and Blocken, 2012, this issue). Validation of these coupled models should focus on the wind flow pattern around the buildings as well as on the indoor airflow driven by wind and buoyancy. This requires high-quality experimental data, either from reduced-scale measurements in an Atmospheric Boundary Layer (ABL) wind tunnel, or by full-scale on-site measurements. The first has the advantage that the measurements are performed under controlled boundary conditions and have a strong degree of repeatability. On-site measurements on the other hand suffer from uncontrollable boundary conditions and lack of repeatability, due to the inherent variability of ABL meteorology (Schatzmann and Leitl, 2011). Schatzmann et al. (1997) and Schatzmann and Leitl (2011) elaborated on the issues that are associated with the validation of CFD models for urban

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wind flow and dispersion simulations. The advantage of full-scale on-site measurements is that the real conditions are measured. In addition, many physical problems in wind engineering and building physics, such as wind-driven rain on buildings and heat and moisture transfer in porous building components require on-site measurements because these phenomena cannot (fully) be reproduced at reduced scale (e.g. Dalgliesh and Surry, 2003; Blocken and Carmeliet, 2005). The same holds for natural ventilation due to the combined effect of wind and buoyancy, as explained below.

Natural ventilation can be driven by wind and/or buoyancy (e.g. Linden, 1999; Hunt and Linden, 1999; Li and Delsante, 2001; Heiselberg et al., 2004). For buoyancy-driven ventilation of buildings, the representation of the indoor thermal conditions and the vapor concentration is very important. Reduced-scale measurements can be deficient to reproduce these conditions, as pointed out by among others Chen (2009), since these measurements can suffer from scaling problems associated with the combined modeling of inertial and buoyancy forces. For the inertial forces the Reynolds number should be the same, or at least high enough to ensure a fully turbulent flow field which is Re-independent. This holds for the building Reynolds number as well as for the Reynolds number of the ventilation openings. Ruck (1993) recommends a building Reynolds number of at least 10,000 for wind tunnel measurements of ABL flow. Special attention however should be given to the ventilation flow through relatively small openings in the building facade, which might lead to Reynolds number effects due to the reduced length scale in the wind tunnel. A too large reduction of the opening size might lead to either transitional or laminar flow through the model-scale openings, instead of turbulent flow. In addition, reduced-scale measurements including thermal effects require similarity of the Grashof and Richardson numbers. The Grashof number is given by:

$$\mathrm{Gr} = \frac{\beta g H^3 (T_w - T_{ref})}{\nu^2} \quad (1)$$

with β the thermal expansion coefficient (K^{-1}), g the gravitational acceleration ($=9.81\ m/s^2$), H the height of the building, T_w the average wall temperature (K) and T_{ref} the average reference temperature (K). Grashof numbers above 10^9 indicate turbulent convection close to the heated surface, whereas values lower than 10^8 indicate laminar convection (Bejan, 1984; Ruck, 1993). In addition to the Grashof number, one should also consider the Richardson number, which represents the importance of natural convection compared to forced convection, and which is defined as $\mathrm{Ri} = \mathrm{Gr}/\mathrm{Re}^2$. The Richardson number is equal to the inverse Froude number (1/Fr). When $\mathrm{Ri} \approx 1$, thermal and mechanical effects are equally important, whereas for $\mathrm{Ri} \gg 1$ thermal effects dominate the flow. Note that the similarity requirement for Ri is automatically fulfilled when both Re and Gr for the reduced-scale experiments are equal to the full-scale values. However this is not always the case; e.g. the Re values in the wind tunnel are often several orders of magnitude smaller than in reality. As a result of these similarity requirements, the collection of a proper set of experimental validation data for numerical models dealing with non-isothermal natural ventilation studies is far from straightforward.

In literature, several studies can be found that describe wind tunnel measurements that include thermal effects. Ruck (1993) studied the airflow around a heated cubic building model in the wind tunnel. From his measurements it was concluded that the reattachment length altered significantly, starting from a Richardson number of about 0.2. Kovar-Panskus et al. (2002) studied the influence of solar radiation on the flow pattern in a 2D urban street canyon. Their measurements were conducted for Froude numbers in the range 0.27 to 2 and also indicated the influence of the heated building surfaces on the flow pattern inside the urban street canyon. Richards et al. (2006) performed wind tunnel measurements of wind flow around an isolated building with a heated leeward wall. They stated that it was almost impossible to fulfill all similarity requirements and therefore decided not to replicate typical full-scale conditions but to model the scaled conditions for mixed and forced convection. The vast majority of reduced-scale natural ventilation studies in ABL wind tunnels were performed for isothermal conditions, e.g. Kato et al. (1992), Straw et al. (2000), Ohba et al. (2001), Jiang et al. (2003), Karava et al. (2007, 2011), Kobayashi et al. (2010), whereas experimental studies on natural ventilation including thermal effects are often conducted without the effects of ABL wind flow, e.g. Holford and Hunt (2003), Liu et al. (2009).

An example of a study in which the natural ventilation needs to be assessed is that of the Amsterdam ArenA (Fig. 1) multi-functional stadium in the Netherlands. For this stadium with its very large indoor volume of $1.2 \times 10^6\ m^3$, natural ventilation is important to ensure a comfortable and healthy indoor environment. A previous study by van Hooff and Blocken (2010b) has indicated the necessity of explicitly modeling the urban surroundings of the stadium in order to obtain accurate natural ventilation rates. The urban area that was taken into account in their study was about $700 \times 700\ m^2$. The modeling scale for this area, in a typical ABL wind tunnel with a cross-section of $2 \times 2\ m^2$, would then be at least 1:500. For a 1:500 scale model, the minimum building Reynolds numbers for a wind tunnel experiment are still achievable without too much effort; the

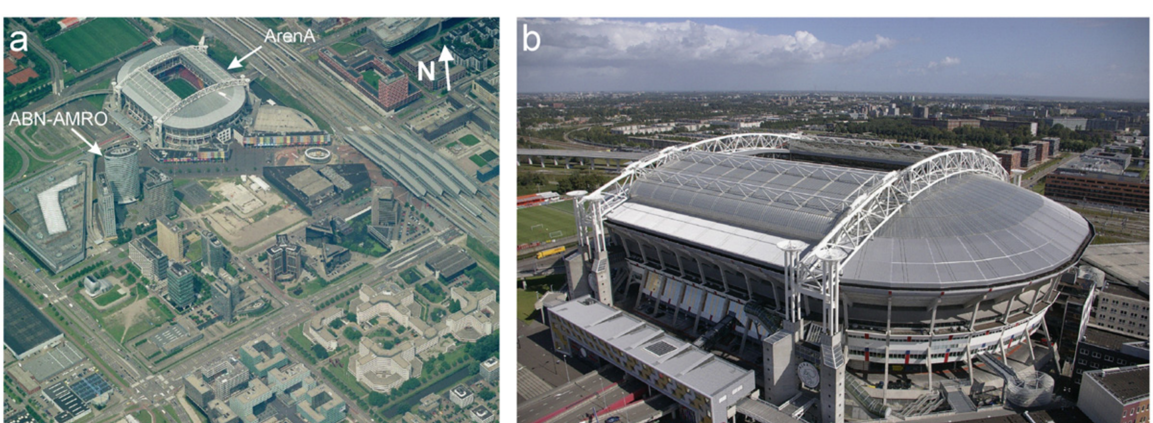

Fig. 1. (a) Aerial view of the ArenA and its surroundings, including the ABN-AMRO office tower building. (b) Picture of the stadium taken from the ABN-AMRO office tower.