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Effect of diurnal variation in wind velocity profiles on ventilation performance estimates

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ABSTRACT

We conducted observations of wind velocity profiles above a high-density area in Tokyo, Japan, using a Doppler LIDAR system. The observation data of an exponent index for the power law, which is commonly used to describe the wind velocity profile, displayed diurnal variation, decreasing in the daytime. Building simulations considering diurnal variation of the exponent index are not often performed, and most cases use a constant value. This paper provides information on the error in the calculated ventilation airflow rate due to the use of a constant value for the exponent index, on the premise that a variation of an exponent index obtained from observation is the true value. The error in the calculated ventilation airflow rate was quantified based on comparison of the ventilation airflow rate calculated using a constant value of 0.22, and the ventilation airflow rate calculated considering a diurnal change in the exponent index. The results indicate that the ventilation airflow rate obtained from a constant value for the exponent index for an isolated building with two openings is underestimated by up to 8% in the daytime and overestimated by up to 14% in the nighttime.

1. Introduction

Passive ventilation strategies such as natural ventilation are applied to reduce energy consumption for air conditioning in many moderate climates [1,2]. These strategies have been reviewed and discussed in many previous studies [3–6], in which the potential of natural ventilation driven by wind is analyzed using numerical simulations. However, because wind-driven ventilation involves complexities, the calculation procedures are often simplified and/or handled using several assumptions. Cóstola et al. [7] indicated various aspects of the introduction of these simplifications: the calculation method, the characteristics of building openings, wind data, and wind pressure distribution over the building surfaces. Although the uncertainty due to various simplifications and assumptions has been addressed in previous studies [8–11], there is little evidence of consideration of the uncertainty due to wind data. In this paper, the impact of a method for approximating the approaching wind velocity, on the ventilation airflow rate of an isolated natural-ventilated building is investigated and discussed. This information has implications for the uncertainties in ventilation airflow rate calculations due to wind data.

The local wind velocity affects ventilation performance. Because the wind data in weather data files are usually measured at a meteorological station at a given height, the approaching wind velocity $U(z)$ for each height z of the building surface is modified from the measured meteorological wind velocity by Eq. (1), which is well known as the power law:

$$U(z) = U_n \left(\frac{z}{z_n} \right)^{\alpha} \tag{1}$$

where U_n [m/s^2] is the wind velocity at the height of the meteorological measurement z_n [m] and α [−] is the exponent index. It is common in engineering applications to describe the wind velocity profile using the power law because of its simplicity. The acceptability of the power law profile as an approximation has been discussed in a classic textbook [12], and several measurements have indicated that measured wind velocities are in good agreement with the power law profile [13–17]. The exponent index for the power law (α in Eq. (1)) is regarded to depend on ground roughness, and is taken to be constant. Several data sources have provided the relationship between α and terrain types (e.g., 0.22 for urban terrains, or 0.33 for towns and cities) as found in the ASHRAE Handbook [18]. Thus, many wind tunnel experiments and numerical simulations for urban areas have used the inlet profile imposed by the power law, using a value between 0.2 and 0.3 for α [19–24]. However, these standard values are based on a predominant mechanical turbulence (very strong wind). Panofsky and

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Dutton noted that α should be modified further when the contribution of convective turbulence becomes significant [12]. This implies that the use of a constant value (e.g., 0.22 or 0.33) for α contains an approximation error in calculating the approaching wind velocity when the effect of stratification becomes strong, because of unstable atmospheric conditions. This error will contribute to the error in calculating the ventilation airflow rate Q [m^3/s], which is a function of wind velocity, as shown in Eq. (2),

$$Q = U_{ref} C_v A \sqrt{\Delta C_p} \quad (2)$$

where U_{ref} [m/s] is the reference wind velocity, which is often taken at the height of the rooftop in the free stream region, C_v is the discharge coefficient of openings, A is the area of the openings, and C_p is the wind pressure coefficient.

The ventilation airflow rate is also a function of the wind pressure coefficient, which is defined in Eq. (3):

$$C_p = (P - P_0)/(\rho {U_{ref}}^2/2) \quad (3)$$

where P [Pa] is the static pressure at a given point on the building surface, P_0 [Pa] is the static reference pressure of the free stream, and ρ [kg/m^3] is the air density.

It is difficult to perform an accurate evaluation of C_p [25] because of the various influencing parameters, including building configuration, details of the building surface, surrounding elements, and the characteristics of the approaching wind. Although the most reliable and effective method for evaluating the value of C_p for a specific building is wind tunnel experiments, such experiments are not generally used to evaluate C_p because of the cost, time, and level of expertise required. We generally used databases of C_p (e.g., the AIVC database [26] or the data in the ASHRAE Handbook [18]) and analytical models (e.g., the model proposed by Swami and Chandra [27], CpCalc+ [28], and the C_p Generator [29]). The drawback to using C_p values from various sources is that these sources do not agree with each other. In this regard, Cóstola et al. [30] noted, in an overview of C_p data in building energy simulation and airflow network programs, that "*pressure coefficients from different data sources, for the same building in the same conditions, show large variations, even for simple configurations like fully exposed cubic buildings*". Of course, full-scale experiments provide the most representative information, because there is no need to reproduce boundary conditions such as inlet wind profile and surface roughness, and because there are no scaling issues such as Reynolds number. Nonetheless, in this work, we did not include full-scale experiments because they are mainly used for validation purposes. Recently, with increasing application of computational fluid dynamics (CFD) to study the flow field around buildings, evidence where CFD has been used as a source of custom C_p data for building energy simulation has surfaced [31]. CFD, along with the wind tunnel experiments, is regarded as a primary data source that can provide data for a specific building and take into account the various influencing parameters in both methods [30]. However, when the inlet flow for a wind tunnel experiment or CFD is defined by the power law, the approximation error mentioned above, which results from using a constant α value, will also contribute to error in the C_p value. As shown in Eq. (3), C_p does not depend on the reference wind velocity (U_{ref}) because wind pressure is normalized with the wind velocity, which is also noted in [30]. However, the difference in α can cause changes in the approaching wind velocity profile, and subsequent changes in the C_p profile on the building surface. Moreover, several studies have actually defined the inlet flow by the power law [31–33].

It can be concluded that the value of α affects the estimation of both U_{ref} and C_p values in Eq. (2), and consequently leads to the difference in calculation of the ventilation airflow rate Q in Eq. (2). This paper defines this difference between the ventilation airflow rate calculated using a constant value of α, and the ventilation airflow rate calculated considering a diurnal change of α as the error, and quantifies the error on the premise that a diurnal variation obtained from observation of the wind velocity profile using a Doppler LIDAR system (DLS) is the true value.

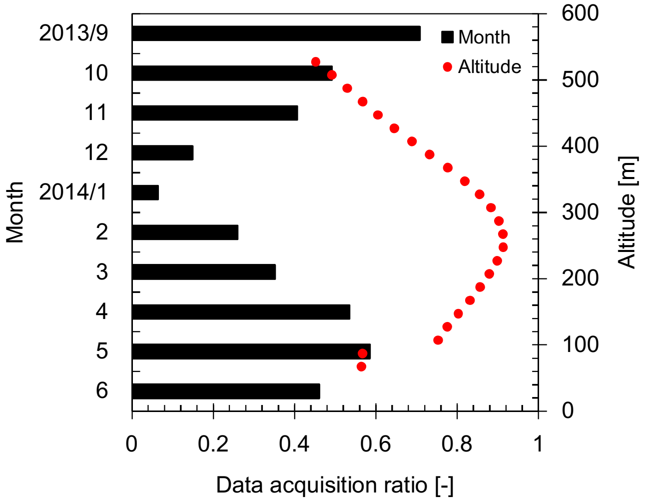

Fig. 1. Data acquisition ratio at each altitude for all observation periods, and for each month.

2. Observation of wind velocity profile using Doppler LIDAR system

2.1. Overview of observations

The wind velocity profile data used here were collected from a DLS (WindCube8, manufactured by LEOSPHIERE), that was set up on the rooftop of the Institute of Industrial Science of the University of Tokyo, Japan (35°39′46″N, 139°40′41″E, 27.5 m altitude). A field of about 1-km radius surrounding the DLS was comparatively flat, and was mainly occupied by residential housing with varying heights (3–9 m: 73.8%, a few buildings with heights under 3 m: 7.9%, and a few over 30 m: 0.5%). The mean height of the roughness elements was about 7 m, and the standard deviation of the heights of the roughness elements was about 4 m.

The observations were conducted from September 1, 2013 to June 30, 2014. The DLS used in this observation transmits a pulsed laser with a wavelength of 1.54 μm, receives the light backscattered by aerosols such as dust and other particles in the air, and measures the line-of-sight component of wind velocity using the Doppler frequency shift of the backscattered light. The orientation of transmission changes in the four cardinal directions, so that three components of wind velocity can be calculated. This DLS could cover 0–60 m/s of wind velocities with ±0.2 m/s accuracy. We obtained the wind velocity data from 67.5 m to 527.5 m (20 m apart, 24 altitudes) with a temporal resolution of about 30 s.

The vertical component of the measured wind velocity is one or more orders of magnitude smaller than the horizontal components. Hence, this analysis applies only to the horizontal components. We use wind velocity in this paper to refer to the scalar quantity of the horizontal velocity components. In inhomogeneous regions such as dense urban areas, the surrounding urban morphology often varies with direction, causing different wind profiles in each direction. However, in this paper, we discuss the wind profile obtained from the scalar quantities of the horizontal velocity components, without consideration of wind direction.

A total of about 3.5 million steps of data were obtained. Fig. 1 shows the data acquisition ratio at each altitude for all observa-