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A probabilistic approach to the energy-saving potential of natural ventilation: Effect of approximation method for approaching wind velocity

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The approaching wind velocity is an important input parameter in wind-driven ventilation studies. The approaching wind velocity at a certain height must be approximated from the measured meteorological wind velocity because the wind data in weather data files are usually measured at a meteorological station at only one given height. The most commonly used approximation method is the power law, in which the power law index (PLI) is only one parameter. Its typical values are provided in some data sources, the use of which generally involves several assumptions. An important assumption is that it is constant. We conducted observations of the wind velocity profiles above a high-density area in Tokyo, Japan, using a Doppler LIDAR system. Our observations revealed that the PLI value is not a constant but rather a time-dependent variable. In ventilation studies, neglecting this phenomenon possibly limits the usefulness of the results because the ventilation airflows depend on the PLI value in given building characteristics and given weather data. This paper presents a probabilistic simulation model for evaluating the performance of natural ventilation, which takes the uncertainties in the PLI values into account. The simulation results provide a set of possible values for savings in cooling energy that are possible with natural ventilation. Different choices of PLI values can lead to errors of up to 45% in the estimation of potential savings in cooling energy when using natural ventilation. This study can support building designers and engineers in the reasonable design of naturally ventilated buildings.

1. Introduction

The building sector is one of the largest energy end-use sectors, making up a major proportion of total global energy consumption [1–4]. Furthermore, due to climate change, the increased need for cooling is leading to an increase in electricity usage [5]. This could be alleviated if passive ventilation strategies were to be applied to reduce summer energy demand [6–9]. Natural ventilation offers an effective passive cooling method in moderate climates. During the day, internal heat gains can be purged by natural ventilation when the outdoor air is suitable for cooling. At night, outdoor air flowing into a building cools the thermal mass, which then acts as a heat sink the following day. Hence, natural ventilation, particularly night ventilation, is effective in moderate climates in which there is a large temperature difference between day and night during the cooling season [10]. To fully exploit this potential and the cooling-energy savings that could be realized by using natural ventilation, there is a need for air conditioning systems that have an effective control strategy for natural ventilation openings. For the design of such systems or strategies, building energy simulation tools are often used for decision making.

Wind-driven ventilation airflow is calculated using Eq. (1). The airflow for the given characteristics of an opening is proportional to the reference wind velocity, which is often measured at rooftop height in a free-stream region, and the square root of the wind pressure coefficient difference. The wind pressure coefficient is related to a building's geometry and façade design, and to the local wind conditions, e.g., the approaching wind profile [5]. The approaching wind profile at the surface of a building is generally approximated from the measured meteorological wind velocity using Eq. (2).

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Nomenclature

Symbols

A_{open}	Area of ventilation openings [m^2]
A_{wall}	Area of wall element [m^2]
A_{win}	Area of windows [m^2]
a_o	Absorptivity of exterior wall, dimensionless
C_p	Wind pressure coefficient, dimensionless
C_d	Discharge coefficient, dimensionless
C_{wall}	Thermal capacity of wall element [J/K]
c_{air}	Specific heat of air [J/kgK]
g	Solar heat gain coefficient, dimensionless
h_o	Combined heat coefficient on external wall surface [W/m^{2}K]
I_T	Total solar radiation on external wall surface [W/m^2]
Q_{vent}	Ventilation airflow rate [m^3/s]
$Q_{vent,na}$	Ventilation airflow rate when natural ventilation is activated [m^3/s]
$Q_{vent,h}$	Required ventilation airflow for hygienic conditions [m^3/s]
$q_{cooling}$	Heat extraction from zone by active cooling system [W]
$q_{int,conv}$	Convective heat gain from internal sources [W]
$q_{int,rad}$	Radiant heat gain from internal sources [W]
q_{sol}	Solar heat absorbed by internal surfaces [W]
$q_{wall,rad}$	Heat gain of internal surface due to radiant heat exchange with other enclosing surfaces [W]
r_{wall}	Thermal resistance of wall element [m^{2}K/W]
$T_{air,i}$	Zone air temperature [°C]
$T_{air,i,na}$	Zone air temperature when natural ventilation is activated [°C]
$T_{air,o}$	Outdoor air temperature [°C]
T_{sol}	Sol-air temperature [°C]
T_{wall}	Temperature of wall element [°C]
$T_{wall,s}$	Internal surface temperature of wall element [°C]
t	Time step [s]
U_{win}	Thermal transmittance of window [W/m^{2}K]
$u(z)$	Wind velocity at height z [m/s]
u_n	Wind velocity at the height of the meteorological measurement z_n [m/s]
u_{ref}	Reference velocity [m/s]
V	Volume of air in zone [m^3]
x_1, x_2, x_3	Resistance share for each layer of wall element, dimensionless
y_1, y_2	Capacitance share for each layer of wall element, dimensionless

Greek

α	Power law index, dimensionless
ρ_{air}	Density of air [kg/m^3]

$$Q_{vent} = u_{ref} C_d A_{open} \sqrt{\Delta C_p} \quad (1)$$

$$u(z) = u_n \left(\frac{z}{z_n}\right)^{\alpha} \quad (2)$$

This is usually known as the power law that, because of its simplicity, is commonly used in engineering applications to describe a wind profile. The power law index (PLI, α in Eq. (2)) is regarded as being dependent on the ground surface roughness and is generally assumed to be a constant. That is, it can be stated that the wind-driven ventilation airflow is dependent on the approaching wind profile for a given set of building characteristics. Furthermore, the approaching wind profile is determined by the PLI value for given weather data. If energy-saving by natural ventilation is feasible, the degree of its contribution should be influenced by the PLI value; i.e., the PLI value is an important input parameter in ventilation studies using building energy simulation. Many studies have investigated the impact of the input parameters on building energy simulation and have quantified the consequent uncertainties of the simulation results [5,10–16]. Unfortunately, the influence of the approaching wind profile, including the PLI value, is rarely the object of detailed analysis, because practical or economic limitations usually prevent the detailed measurement of vertical wind velocity in built-up areas. The lack of this data may limit the accuracy of natural ventilation-related simulations and lead to a misunderstanding of the results. Although typical PLI values recommended by data sources [17,18] are derived from data that are mainly based on the results of experiments, the suitability of these values for natural ventilation-related simulations is at best questionable. The issue of the PLI value being other than a constant remains.

In this study, we undertook observations of the vertical wind profile above a high-density built-up area of Tokyo, Japan, using a Doppler LIDAR system (DLS) and identified variations in the PLI value. Then, we investigated and discussed the influence of the method used to approximate the approaching wind profile, including the choice of PLI value, on the uncertainty of the simulation results used to estimate the potential savings in cooling energy when using natural ventilation.

2. Observation of wind velocity profile

2.1. Power law index in building energy simulation

As briefly mentioned above, conventional building energy simulations use empirically defined PLI values. These are normally determined based on the surface roughness of the terrain. The ASHRAE Handbook [17] lists typical PLI values according to terrain, e.g., 0.22 for urban terrain, or 0.33 for a large city center. The PLI value is generally assumed to be constant. Unfortunately, this assumption may limit the usefulness of the natural-ventilation-related simulation results, given that the PLI values are not constant. Rather, they exhibit a diurnal variation (decreasing during the day and increasing during the night) as reported by Touma [19], Farrugia [20], and Kikumoto et al. [21]. Therefore, the actual PLI value may be lower than the above-mentioned typical values during the day. We can imagine that this uncertain nature of the PLI value would lead to errors in the estimated ventilation airflows, which can lead to poor decisions being made regarding the control strategies used to attain the maximum possible energy saving by using natural ventilation. For example, several studies, such as those by Breesch and Janssens [10] and Goethals et al. [13], set an upper limit on the outdoor wind velocity so that natural ventilation is not activated under strong wind conditions. When investigating the upper limit, an invalid choice of PLI value leads to the incorrect modification of the approaching wind velocity, and thus causes an estimation error for the periods during which natural ventilation is activated. As such, it is imperative that the decision maker is aware