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Estimating natural ventilation potential for high-rise buildings considering boundary layer meteorology

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HIGHLIGHTS

- The vertical profiles of NV potential are estimated for high-rise buildings.
- Atmospheric stability has a great impact on NV potential.
- An in-house ABL meteorology model is developed.
- The ABL meteorology model can be coupled with building-resolved CFD simulation.
- Los Angeles displays the greatest NV potential with about 7000 NV hours per year.

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ABSTRACT

The design of energy conservative buildings that incorporates natural ventilation (NV) strategy has become increasingly popular around the world. Natural ventilation is a key solution for reducing energy consumption of buildings and for maintaining a healthy indoor environment. However, the adoption of natural ventilation in high-rise buildings is less common. As rapid population growth and urbanization take place in cities, it is important to explore the substantial energy saving potential of high rises by utilizing natural ventilation. In this study, we have provided the early effort to estimate quantitatively the vertical profiles of NV potential for high rises at major cities from six climate zones in the U.S. (i.e., Miami, Houston, Los Angeles, New York City, Chicago, and Minneapolis), using an in-house boundary layer meteorology model. The diurnal cycle of atmospheric boundary layer (ABL) and local climate characteristics are found to have a great effect on the vertical structure of NV potential. In general, negative vertical gradients of NV hours are observed for all cities except Miami where the vertical distribution is nearly uniform. For example, the annual NV hour decreases from 7258 at ground level to 4866 at 300 m above the ground in Los Angeles. Our analysis shows that outdoor temperature is a key meteorological parameter that determines vertical profiles of NV hours in New York City, Los Angeles, Chicago, and Minneapolis. In contrast, humidity plays a greater role in cities like Miami and Houston where the outdoor temperature is often favorable for using natural ventilation except in the summer. Among studied cities, Los Angeles provides the ideal climate (warm and dry) for utilizing natural ventilation, displaying the greatest NV potential (7258 NV hours or 83% time of the year at ground level), followed by New York City with 3360 NV hours. The remainder of the four studied cities display comparable numbers of NV hours of approximately 2500 at ground level. The methodology and findings from this study are intended to assist architects and policy makers in quantifying the potential energy savings of natural ventilation, and illustrating the importance of considering the vertical variations of elevated thermal environment in high-rise buildings across different climate zones in the U.S.

1. Introduction

Rapid population growth and urbanization have led to increasing energy demand in many cities of the world. Given the large volume and occupancy of the fast-growing number of high-rise buildings, the energy consumption of these buildings is enormous

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in which the heating, ventilation and air conditioning (HVAC) systems account for roughly 33% of the overall energy consumptions [1]. Many advanced technologies have been developed to reduce building energy consumption [2–20]. Among them, natural ventilation (NV) that supplies and removes air to and from an indoor space using natural forces of wind and buoyancy shows great potential to reduce energy consumption, and to reduce the cost of the HVAC system in high-rise buildings [10,21–23].

Although most high-rise buildings are fully sealed, the number of successful examples that incorporates natural ventilation principle is growing globally. For instance, the Commerzbank Tower is perhaps the most well-known high rise that utilizes mixed-mode ventilation (i.e., using natural ventilation for periods when the external weather conditions are allowed, but mechanical ventilation takes over when external weather conditions are not suitable). It was built in 1997 in Frankfurt (temperate climate), with a floor area of about 70,000 m^2 providing working space to 2500 employees. The tower features a double-skin façade with automated opening control, central atrium (every 12 stories) and 4-story high sky gardens. The building operates on mixed-mode ventilation, in which natural ventilation is utilized approximately 80% of the year. Another well-known example that features natural ventilation is 30 St. Mary Axe in London. It was completed in 2004 with a gross area of 64,470 m^2. The building was designed with double-skin façades and stepping atria that tempers air before being distributed to office. It is designed to rely on natural ventilation for about 40% of the year.

There are many advantages of utilizing natural ventilation in high-rise buildings. For instance, high rises are less influenced by the surroundings as opposed to low-rise buildings, which results in sufficient driving force from ambient wind to achieve desired air change rate (ACH) for natural ventilation [24]. Additionally, in comparison to low-rise buildings, buoyancy-driven natural ventilation can be utilized more effectively due to vertical pressure variation in high rises through atria, sky gardens, solar chimneys, etc. A number of studies have looked at various aspects with regard to the design of naturally ventilated high-rise buildings. Zhou et al. [25] employed CFD simulation to optimize natural ventilation for high-rise residential buildings by adjusting the building orientation, building spacing, window opening positions, etc. Pasquay [26] conducted a series of onsite measurements of buildings with double skin façades that are commonly seen on high-rise buildings to regulate incoming wind speed, air temperature, and outside noise. The results from his study confirmed some advantages of double-skin façade in noise control, shading device integration and night cooling, but also raised some concerns about overheating in the summer. Niu [27] proposed using window vents as an alternative for natural ventilation in high-rise buildings. His analysis shows that window vents can provide constant air flow by self-regulating the opening degree in response to pressure differences. Prajongsan and Sharples [28] demonstrated that a ventilation shaft is an effective way to enhance single-sided natural ventilation in tall residential buildings in Bangkok, in which the shaft can increase the pressure difference between windows and the shaft's exhaust at roof level. Similar stack systems have been evaluated through experiments by Priyadarsini et al. [29]. They found that the fan-assisted active stack system substantially increased the air change rate in the room with limited access to external windows.

Existing studies mostly focused on specific design strategies for naturally ventilated high rises. The effect of boundary layer meteorology on natural ventilation potential has never been investigated. Atmospheric boundary layer (ABL) is the lowest portion of the troposphere that directly interacts with the built environment on the ground surface, and responds to surface forcing with a time scale of about an hour or less. The influence of surface friction, heating and evaporation is transmitted to the entire ABL through the mechanism of turbulent mixing. The height of the ABL over the land surface varies depending on the rate of heating or cooling of the surface, wind speed, surface roughness, etc. High-rise buildings that either fully rely on natural ventilation or operate on mixed-mode closely interact with the ABL. Therefore, to quantify the NV potential of high rises, it is critical to understand the vertical structure of ABL, because many meteorological parameters (e.g., wind speed, temperature, and humidity) vary considerably with altitude and time.

In this study, we have provided an early effort to understand and estimate the vertical profiles of NV hour at major U.S. cities from six climate zones using an in-house ABL meteorology model. The paper is organized as follows. We first describe the climatic characteristics in the U.S., and sources of surface observation and upper air weather data. Next we elaborate the in-house boundary layer meteorology model for estimating the vertical profiles of meterological variables. In the second part of the paper, we present and discuss the results, followed by a summary of key findings.

2. Methodology

2.1. Climate characteristics of selected cities

Climate varies widely across the U.S. due to the massive expanse of land and complicated terrain. The classification of climate zones developed by U.S. Department of Energy's Pacific Northwest National Laboratory (PNNL) is adopted in this study to differentiate various climates (Table 1). The map shown in Fig. 1 is based on analysis of National Oceanic and Atmospheric Administration (NOAA) weather sites, and is a widely accepted classification of U.S. climate [30]. This map divided the U.S. into eight temperature-oriented climate zones (Zone 1 to 8, Very Hot to Subarctic). Each zone is further divided into three moisture regimes designated A (moist), B (dry), and C (marine).

We selected one populated city (i.e., Miami, Houston, Los Angeles, New York City (NYC), Chicago, and Minneapolis), from six climate zones in the U.S. (Fig. 1). The boxplots of temperature and wind speed by month collected at airport surface observation stations at each city for the year of 2011 are presented in Fig. 2. In hot and humid climate, such as Houston and Miami, it is often challenging to utilize natural ventilation. However, large air change rates (ACH) as a result of natural ventilation helps to remove unwanted humidity, and to widen the thermal comfort range. In hot summer and cold winter climates, such as Chicago and NYC, buildings can be naturally ventilated for the majority of time from March to October. In the summer, night-purge ventilation, coupled

Table 1
Definition of eight climate zones in the U.S.

Zone number	Zone name	Thermal criteria (SI Units)
1A and 1B	Very hot – humid (1A) Dry (1B)	5000 < CDD10 °C
2A and 2B	Hot-humid (2A) dry (2B)	3500 < CDD10 °C ≤ 5000
3A and 3B	Warm – humid (3A) dry (3B)	2500 < CDD10 °C < 3500
3C	Warm – marine (3C)	CDD10 °C ≤ 2500 AND HDD18 °C ≤ 2000
4A and 4B	Mixed-humid (4A) dry (4B)	CDD10 °C ≤ 2500 AND HDD18 °C ≤ 3000
4C	Mixed – marine (4C)	2000 < HDD18 °C ≤ 3000
5A, 5B, and 5C	Cool-humid (5A) dry (5B) marine (5C)	3000 < HDD18 °C ≤ 4000
6A and 6B	Cold – humid (6A) dry (6B)	4000 < HDD18 °C ≤ 5000
7	Very cold	5000 < HDD18 °C ≤ 7000
8	Subarctic	7000 < HDD18 °C