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A Review of High-Rise Ventilation for Energy Efficiency and Safety

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ABSTRACT

With rapid economic growth, the number of high-rise buildings increases significantly due to land shortage in highly populated cities. Compared with other types of buildings, high-rise buildings have a higher cooling load and are more energy intensive, leading to huge cooling energy consumption and peak electricity demand. Ventilation has proved to be an effective approach to reduce cooling load and thereby save cooling-related energy and reduce peak electricity demand for high-rise buildings, which is important for achieving sustainable development of cities and society. Building safety is a challenge in high-rise ventilation. Fires and the resultant air pollution in high-rise buildings are often disastrous and cause huge losses if the high-rise ventilation system is not designed and operated well. This paper presents a review of previous studies on energy efficiency and building safety for high-rise ventilation, including natural ventilation, mechanical ventilation and hybrid ventilation. Statistical analysis was conducted on the research methods, number of literature review sources, and topics. The research gap was also discussed. Through the review, it was found that increasing research has been conducted on high-rise ventilation, especially on the topic of building safety. It was also recommended to consider both safety and energy simultaneously, in order to achieve energy efficiency and safety in high-rise ventilation and therefore to promote the application of ventilation in high-rise buildings.

1. Introduction

As one of the main energy consumers, buildings consume 20% ~ 40% of total global energy use (IEA, 2018b). Compared with other types of buildings, high-rise buildings have a higher cooling load and are more energy intensive (Walker, 2017). Electricity use, per square meter of floor area, is nearly two and a half times greater in high-rise office buildings of 20 or more storeys than in low-rise buildings of six storeys or less (Walker, 2017). The high cooling load of high-rise buildings is due to high internal heat gain (lights, equipment, etc.) and wide use of huge glazed façades (Yuan, Vallianos, Athienitis, & Rao, 2018). On the other hand, due to population growth and limited land in cities, numerous high-rise buildings have been constructed. It was reported that there are 142 cities that have erected over 100 high-rise buildings, and New York City possesses the most high-rise buildings: 6034 high-rise buildings in 2019 (SkyscraperPage.com, 2019). In addition, the number of high-rise buildings keeps growing rapidly, especially in cities with fast economic growth. For example, at its peak, there were 150 high-rise buildings under construction in recent years in Toronto (Staff, 2018). Therefore, reducing the cooling load of high-rise buildings is critical to energy savings.

Building ventilation, including natural ventilation (NV), mechanical ventilation (MV), and hybrid ventilation (HV), has proved to be an effective solution not only for improving air quality (Cao, 2019; Deng, Feng, & Cao, 2018), and thermal comfort (Y. Deng, Feng, Fang, & Cao, 2018; Liu, Huangfu, Xiong, & Deng, 2014) but also for cooling indoor spaces and reducing building cooling load (Ren & Cao, 2019a; Wang, Olesen, & Kazanci, 2019), i.e., ventilative cooling (IEA, 2018a). Driven by stack effect, outdoor air can pass through horizontal floors, remove indoor heat, and exit through vertical spaces, such as atria, stairwells, double-skin façades (DSF) and elevator shafts during NV and HV. The stack effect refers to buoyancy-driven airflow due to a difference in indoor and outdoor air densities, which often occurs in large vertical spaces. Building ventilation could reduce cooling-related energy consumption from 56% to 86% (Hu & Karava, 2014; Malkawi, Yan, Chen, & Tong, 2016). The energy performance of ventilative cooling highly depends on the local climates, and it was reported that over 50 world's largest cities in different regions and climates were found with great potential of ventilative for more than 2000 hours each year (Chen, Tong, & Malkawi, 2017). Due to their cold climates, high-rise ventilative cooling is available for a long time throughout the year in Canada and Northern Europe, not only during shoulder seasons but also in summer periods (Artmann, Manz, & Heiselberg, 2007). Cold climates are featured by large diurnal temperature variations and relatively low

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night-time temperatures even in the summer. A high-rise building structure can be cooled during the night and provide a huge heat sink during the daytime, which significantly reduces cooling loads and thus peak electricity demands.

However, one of the major roadblocks to adopting high-rise ventilation is the fire safety concern associated with the stack effect in large vertical spaces. During regular operations, many existing features and functions of these large spaces can contribute to the stack effect and high-rise ventilation for a potential maximum level of energy savings. However, during fire outbreaks, they could become major spreading routes for fire-generated smoke laden with toxic gases to spread far from the fire origins deep throughout the buildings, endangering people's lives, causing property damage and generating obstacles for firefighters, e.g., the Joelma Building, Brazil (189 deaths, 1974); the Dupont Plaza Hotel Fire, US (97 deaths, 1986); and the most recent Grenfell Tower fire in London, UK (80 deaths, 2017) (Wikipedia, 2018). It was reported that around 145000 reported structure fires in high-rise buildings occured per year from 2009 to 2013 in U.S., causing an average of 40 deaths, 520 injuries and $154 million in property damage per year (Ahrens, 2016). The problem can be further complicated by interactions with dynamic weather conditions, including variable winds, temperatures and building ventilation system operations.

Considering that energy efficient and safe high-rise buildings are essential for the sustainable development of cities and society, this paper reviews the previous studies that tackle energy efficiency and building safety issues in high-rise ventilation, including NV, MV, and HV. The reviewed studies are from internationally recognized journals, relevant conference proceedings and study reports through search engines including Google Scholar, ScienceDirect and SpringerLink. The research methods, research gaps, and recommended future research are also discussed.

2. Energy efficiency and safety in natural ventilation

NV refers to the flow of air through open windows, doors, grilles, and other planned building envelope penetrations (ASHRAE, 2017). It is driven by pressure differences across the building envelope caused by wind, stack effect or both, which can be categorized as wind-driven NV, buoyancy-driven NV, and wind & buoyancy-driven NV. The wind-driven NV can be further classified as single-side ventilation (fresh air enters the room and exhausted air leaves the room through the same side due to the effects of wind coinciding with buoyancy) and cross ventilation (air flow moves between the two sides (windward and leeward) of a building's envelope driven by wind and/or stack effect.

The two driven forces, wind and buoyancy, bring challenges to the design and control of high-rise NV. One of the challenges is the variation of wind conditions from the ground floor to the top floor of a high-rise building (Omrani, Garcia-Hansen, Capra, & Drogemuller, 2017a). The relationship between wind pressure and wind speed is given by Eq. (1) (ASHRAE, 2017).

$$p_w = C_p \rho \frac{U^2}{2} \tag{1}$$

Where p_w is the windward pressure relative to outdoor static pressure, Pa; ρ is outdoor air density, kg/m^3; U is wind speed, m/s; C_p is the wind surface pressure coefficient, dimensionless. As building height increases, the wind speed increases parabolically (Günel & Ilgin, 2014), creating large wind pressure difference on the building façade according to the Eq. (1). Hence, the design and control of NV in high-rise buildings must consider the wind variation from the ground floor to upper floors. For example, the too high wind speed at upper floors may result in uncomfortable indoor air velocity and unacceptable wind-induced noise. It was revealed that the wind-driven NV potential reduced vertically along the high-rise building with the same opening design from ground to top floor (Tong, Chen, & Malkawi, 2017).

Another challenge of NV design is airflow movement driven by buoyancy, i.e. stack effect, in high-rise buildings, which is caused by the density difference due to the temperature difference between the inside and the outside (Wood & Salib, 2013). Neglecting vertical density gradient, the stack pressure difference for a horizontal hole at any vertical location can be expressed as Eq. (2).

$$p_s = \rho\left(\frac{T_i - T_0}{T_i}\right) g (H_{NPL} - H) \tag{2}$$

Where p_s is the stack pressure difference, Pa; ρ is outdoor air density, kg/m^3; T_i and T_0 are absolute indoor and outdoor temperature, K; g is gravitational acceleration, m/s^2; H_{NPL} *and* H are the height of neutral pressure level (NPL) and height above reference plane respectively, m.

The variation of wind pressure at different height can also result in serious fire safety issues. Since smoke readily response to small pressure difference, the complex wind conditions of high-rise buildings make the smoke movement difficult to be predicted and thus cannot have a sound smoke control strategy (Black, 2010). The problem worsens when cross-ventilation is applied, which requires airflow paths for wind passing through the building. These airflow paths will become routes for smoke and fire spreading far away from the origin when fire incident occurs (Chen, Liu, Zhang, Deng, & Huang, 2008).

NV is a complex heat and mass transfer process. Empirical equations are often used to calculate the ventilation rate, Q, m^3/s, which is listed in Eqs. (3) ~ (4):

Single-sided ventilation:

$$Q = \pm \frac{1}{2} f C_D A \sqrt{|U^2 - (\frac{2\gamma P_a}{\rho V})\nu|} \tag{3}$$

Cross ventilation:

$$Q = \sqrt{\frac{Cp_1 - Cp_2}{\frac{1}{A_1^2 C_{D1}^2} + \frac{1}{A_2^2 C_{D2}^2}}}\, U = \sqrt{\frac{\Delta C_p}{\frac{1}{A_1^2 C_{D1}^2} + \frac{1}{A_2^2 C_{D2}^2}}}\, U \tag{4}$$

where V is total volume of the building, m^3; ν is change of air volume inside the building, m^3; γ is the specific heat ratio of air which equals to 1.4 for adiabatic flows and 1.0 for isothermal flows (Haghighat, Brohus, & Rao, 2000); ρ is the air density, kg/m^3; A is opening area, m^2; C_p is pressure coefficient, dimensionless; f is mixing effectiveness, dimensionless; and P_a is the atmospheric pressure, Pa. U is wind velocity and is calculated by Eq. (5), where the wind velocity coefficients, K and α, are for wind profile, and discharge coefficients, C_D, for window type selection are considered as constants. Cp_1 C_{D_1} and Cp_2 C_{D_2} refer to the pressure coefficients and discharge coefficients of the inlet and outlet openings of cross-ventilation. The values of K and α can refer to the reference (Andersen, Heiselberg, & Aggerholm, 2002), and the value of C_D can refer to the reference (Long Wang, Pan, & Huang, 2012).

$$U = U_r \cdot K \cdot Z^{\alpha} \tag{5}$$

The following sections will review the previous research on energy efficiency and building safety for these three types of NV.

2.1. Influencing factors of different types of natural ventilation on energy efficiency

2.1.1. Wind-driven natural ventilation

The parameters of wind-induced ventilation, including building positioning, floor planning, building façade, and roof, have a significant influence on the indoor airflow and airflow patterns, and therefore impact NV performance in terms of removing indoor heat.

(A) Building positioning

Building positioning refers to the arrangement of buildings on the ground surface according to their locations and dimensions. Previous studies demonstrated that the surrounding buildings or structures affect the wind pressure distribution on a building significantly, which is