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A study on variation laws of infiltration rate with mechanical ventilation rate in a room

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ABSTRACT

Mechanical ventilation system is commonly used or recommended to supply the outdoor fresh air for both centralized and non-centralized air-conditioning buildings. ASHRAE requires a positive pressure (i.e., zero infiltration rate) for mechanically ventilated rooms. In fact, positive pressure is difficult to be maintained under poor building airtightness or low mechanical ventilation rates. When the positive pressure is not achieved, the existence of air infiltration brings two problems—the outdoor air pollutants infiltrating indoors and the excessive fresh air cooling/heating load. In order to solve the above problems, air purifiers can be used to remove the indoor pollutants, and the mechanical ventilation rate should be reduced to prevent the excessive ventilation. Therefore, in order to determine the Clean Air Delivery Rate (CADR) for the air purifier and to calculate the amount of mechanical ventilation that should be reduced, the influence of mechanical ventilation on the room infiltration rates must be figured out. This study investigates the variation laws of the infiltration rate with the mechanical ventilation rate, and then theoretically deduces the relational expressions between the two rates for stack effect and wind dominant ventilation models. The theoretical derivations were validated by tests in actual rooms. From a practical perspective, this study can be used to improve the indoor environment and ventilation rates for mechanically ventilated rooms, demonstrated by the case study.

1. Introduction

Nowadays, people spend 85 to 90% of their time in the indoor environment [1,2]. The exposure to indoor air pollutants has significant negative effects on the occupants' health and can even cause sick building syndrome (SBS) [3–5]. To maintain a satisfying indoor air quality and prevent SBS, sufficient fresh outdoor air for building occupants is vital [6,7].

Buildings with centralized air-conditioning systems are ventilated by the mechanical ventilation systems. However, buildings without centralized air-conditioning systems (especially the most common ones such as residential buildings) do not have the mechanical ventilation systems. Accordingly, their fresh air ventilation depends on the infiltration and natural ventilation [8–10]. In general, infiltration is not enough to guarantee an adequate ventilation rate [11–13]. Natural ventilation occurs by opening windows or doors, which brings about an uncontrolled ventilation rate and directly introduces the outdoor pollutants into an indoor environment [14–16]. Thus, ASHRAE Standard 62.2 suggests using the dwelling-unit mechanical ventilation systems to guarantee the ventilation rate and the indoor air quality in the residential buildings [17]. Therefore, for both centralized and non-centralized air-conditioning buildings, mechanical ventilation is commonly used or recommended for fresh air supply.

In order to limit the infiltration of outdoor air pollutants and high dew point air, the mechanically ventilated rooms are required to keep a positive pressure [7,8]. Based on that, some researches have assumed a zero infiltration rate (i.e., a positive room pressure) when the mechanical ventilation system is on [18–20]. However, other studies have indicated that rooms at positive air pressure are difficult to be achieved if the building airtightness is poor or the mechanical ventilation rate is low [12,13,21–23]. From a previous study, Shi & Li [24] found that a mechanical ventilation rate of up to 3.2 times the initial infiltration rate is required to maintain a positive room pressure. Many centralized air-conditioning buildings such as offices are high-rise buildings with glass facades, which have poor airtightness and infiltration rates up to 0.70 h^{-1} [25,26]. According to the relevant standards, the ventilation requirements for office buildings range from 1.25 to 2.50 h^{-1} [7,27], and thus the mechanical ventilation rate may not be enough to keep the positive pressure for some office rooms. The infiltration rate for residential buildings is averagely 0.34 h^{-1} in Beijing, Shanghai, and Xi'an

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[28], 0.41 h^{-1} in Guangzhou [29], and 0.60 h^{-1} in US (single family) [30]. As a result of low occupant density in the residential buildings, the ventilation requirements are within the range of 0.45–0.70 h^{-1} in Chinese standard [31], and 0.60–1.10 h^{-1} in ASHRAE Standard [17], which are too low to achieve a positive room pressure. Therefore, although ASHARE requires a positive pressure for mechanically ventilated rooms, it commonly occurs that the positive pressure is unable to be achieved under the actual building airtightness and ventilation rates.

When a positive room pressure is not achieved, the outdoor air pollutants get into the indoor environment along with the infiltrated air [13,16]. Two ways can be used to solve this problem: one is increasing the mechanical ventilation rate to achieve a positive room pressure, and the other is using the indoor air purifiers to remove the pollutants. Increasing the mechanical ventilation rate is not recommended, as it enhances the air conditioning loads, and causes the energy loss [32,33]. Thus, using air purifiers is a more suitable choice. In order to determine the Clean Air Delivery Rate (CADR) for the air purifier in a mechanically ventilated room, the infiltration rate under the given mechanical ventilation rate must be identified. Hence, it is essential to figure out the relationship between the infiltration and mechanical ventilation rates.

In addition, considering that the mechanical ventilation rate of a room is designed according to the building occupants and indoor air quality, when the mechanical ventilation rate is not enough to keep the positive room pressure, the excessive ventilation will occur due to the existence of air infiltration [34], which also causes the loss of energy. To avoid the above problem, ASHRAE Standard 62.2 proposes an infiltration credit method which allows to reduce the mechanical ventilation rate for buildings with poor airtightness [12,17]. The required mechanical ventilation rate is calculated by the following equation [17]:

$$Q_{fan} = Q_{tot} - Q_{\text{inf},e} \tag{1}$$

where Q_{fan} is the required mechanical ventilation rate, m^3/h; Q_{tot} is the total required ventilation rate, m^3/h; $Q_{\text{inf},e}$ is the effective annual average infiltration rate which is dependent on the effective leakage area as well as the weather and shielding factors, and has a constant value during the whole year, m^3/h. However, based on our previous research, the mechanical ventilation causes changes in the room pressure, resulting in decreasing infiltration rate [24]. Thus, the total ventilation rate will be lower than the requirement if the mechanical ventilation rate is determined using the constant infiltration rate in Eq. (1). Therefore, to calculate the required mechanical ventilation rate, the influence of mechanical ventilation on room infiltration rates needs to be figured out.

Numerous researches have ignored the variation of infiltration rate with the mechanical ventilation rate and assumed an unchanged infiltration rate in their calculations and simulations, which are the same as what ASHRAE Standard 62.2 does [25,26,35–38]. Other researches have focused on determining the mechanical ventilation rates needed to keep the positive pressure for rooms with cleanliness requirements, such as the operation rooms and clean rooms [39–41]. To date, the researches related to the relationship between the infiltration and mechanical ventilation rates have mainly focused on the superposition methods of the two rates. Nolwenn and et al.'s study [42] summarized various superposition methods investigated since 1980s and found that the most historically used ones are the Quadrature and Half-fan models. Their study simultaneously put forward a new model named Sub-additivity. Besides, another widely used model is the Power Law model [43]. The above mentioned models are listed in Table 1, where $Q_{\text{inf},0}$ is the initial infiltration rate when the room is not mechanically ventilated, m^3/h; Q_{mv} is the mechanical ventilation rate (i.e., the mechanical fresh air supply rate), m^3/h; and Q_{inf} is the infiltration rate when the room is mechanically ventilated, m^3/h. As shown in Table 1, in each model, due to the room pressure changes when mechanically ventilated, the infiltration rate decreases with the increase of the mechanical ventilation rate. In the Quadrature, Power Law and Sub-additivity models, a zero infiltration rate is achieved only when the mechanical ventilation rate is infinitely great, which does not conform to the reality. Actually, the validation results of these models in the references were sometimes contradictory. The Half-fan model supposes that the infiltration rate decreases to zero when the mechanical ventilation rate is over two times the initial infiltration rate, which is similar to what we have found in the previous work [24]. However, the model is derived from empirical tests and lack of theoretical explanations.

Table 1
Summary of superposition models.

Name	Model	Ref.
Quadrature	$Q_{\text{inf}} = \sqrt{Q_{\text{inf},0}^2 + Q_{mv}^2} - Q_{mv}$	[8,44–46]
Half-fan[a]	$Q_{\text{inf}} = \begin{cases} Q_{\text{inf},0} - \frac{1}{2}Q_{mv}\ (\text{for } Q_{mv} < 2Q_{\text{inf},0}) \\ 0\ (\text{for } Q_{mv} \geq 2Q_{\text{inf},0}) \end{cases}$	[44,47–49]
Sub-additivity	$Q_{\text{inf}} = Q_{\text{inf},0} \times \exp\left(-\frac{2}{3}\frac{Q_{mv}}{Q_{\text{inf},0}}\right)$	[42,50]
Power Law	$Q_{\text{inf}} = \left(Q_{\text{inf},0}^{\frac{1}{n}} + Q_{mv}^{\frac{1}{n}}\right)^n - Q_{mv}$	[43,45,51]

[a] Only applicable for infiltration caused by stack effect.

This study aims to investigate the variation laws of the infiltration rate with the mechanical ventilation rate by theoretical derivation based on the power law equation of crack flows [8,52,53]. The relational expressions between the two rates were derived, then tests were conducted in actual rooms to validate the theoretical derivations. The results of this study can be used as a guidance for optimizing the ventilation rates and for selection of air purifiers in rooms with mechanical ventilation systems.

2. Methodology

The main factors causing air infiltration in buildings are stack effect and wind pressure [8,54,55]. In this study, the influence of mechanical ventilation on the room infiltration rates was investigated under two ventilation models: stack-effect-induced single-sided ventilation (hereinafter, stack effect model), and wind-pressure-induced cross ventilation (hereinafter, wind dominant model). For the two models, the relational expressions between the infiltration and mechanical ventilation rates were deduced.

2.1. Relational expression of stack effect model

Fig. 1 shows the stack effect model in a situation when the outdoor temperature is higher than the indoor temperature. The stack-effect-induced single-sided ventilation takes place in a room with exterior windows or doors positioned only on one side, when the indoor-outdoor temperature difference is significant and the wind speed outdoor is low. The air infiltrates and discharges the room via the cracks around the external windows.

The theoretical derivation of the stack effect model is based on the following assumptions: a) infiltration and exfiltration occur through the cracks around the openable exterior windows or doors, and there is no other crack on the building envelop [56]; b) temperature difference between the adjacent rooms is so small that there is no air exchange through inner doors [29].

In Fig. 1, H is half the total window height, m; H_1 is window height of the negative pressure where outdoor air penetrates into indoors, m; and H_2 is window height of the positive pressure where indoor air discharges into outdoors, m.

Fig. 2 illustrates the frontal view of the exterior window in the stack effect model, where W is the width of window, m. In addition, the width of the window crack at each location is supposed to be δ (mm)