Effect of variable ventilation modes on indoor thermal comfort and building energy consumption

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Abstract
This paper provides an insight into the impact of ventilation on building energy consumption and indoor thermal comfort. Four variable ventilation modes and one fixed ventilation mode were considered. Results show that variable ventilation modes bring a more comfortable indoor thermal environment than the fixed one, with a significant energy reduction ranging from 39.4 to 61.7%. Compared with other modes, the air change rate per hour of 0.5–15 is cost-effective and applicable in naturally ventilated buildings. An improvement of ventilation settings in the tradeoff simulations adopted by building energy codes is necessary to better predict building energy demands.

Keywords: building energy consumption; ventilation; indoor thermal comfort

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1 INTRODUCTION
Faced with increased building energy consumption and rising energy prices, China is trying to lower its energy demand in the building sector through several enforced building energy standards [1, 2]. In these standards, the energy efficiency design of the building envelope was emphasized. For example, the U-values of external walls, roof and windows are not allowed to be higher than certain values. But ventilation, a potential passive cooling strategy, for each room of a residential building is set to be a fixed value of 1 air change rate per hour (ACH) in building energy performance simulation, without considering occupants’ behavior of opening windows to increase natural ventilation to reduce discomfort and energy consumption. Thus, in the design stage, architects and engineers often focus on the thermal performance of the building envelope [3–5] and overlook the energy savings potential of ventilation, which is a significant measure in the reduction of energy consumption of the building and indoor thermal discomfort [6, 7]. Therefore, studies on the effect of variable ventilation modes on indoor thermal comfort and energy consumption are of great importance.

Numerous studies have been conducted on the effect of ventilation on building performance. Liping and Hien [8] studied the impacts of four ventilation strategies and facade designs on the indoor thermal environment for naturally ventilated residential buildings for hot-humid climate according to the number of thermal discomfort hours in a whole typical year on the basis of a series of TAS simulations. Geros et al. [9] carried out experiments for determining the cooling potential of night ventilation techniques in the urban environment. Santamouris et al. [10, 11] introduced a method to evaluate the energy efficiency of night ventilation on reducing the cooling load of a thermostatically controlled building. Givoni [12] examined the effectiveness of night ventilation in lowering the maximum indoor daytime temperature. Richard and Gail [13] reported a new adaptive comfort standard that allows warmer indoor temperatures for naturally ventilated buildings during summer and in warmer climate zones, adopted in ASHRAE Standard 55. Short et al. [7] presented a design strategy for low-energy ventilation and cooling within an urban heat island, and this low-energy technique enables cooled air to be distributed throughout the building without mechanical assistance. Nielsen and Drivsholm [14] investigated the energy-efficient demand-controlled ventilation in single family houses with the ventilation having two flow rates: a high rate and a low rate. These two mechanical ventilation modes can be switched based on sensing the CO2 concentration and moisture content in the outdoor air and exhaust air. A study on ventilation strategy and air change rates in idealized high-rise compact urban areas was conducted by Hang and Li [15]. They numerically studied the ventilation and air change rates in some aligned square building arrays.
However, these studies either focused on some fixed ventilation strategies or on the cooling energy consumption. Although ventilation-related indoor thermal comfort issues have been studied by these authors, these studies are based on different climatic regions. The situation in the hot summer and cold winter zone in China is different from that of other countries or regions. Because the hot summer and cold winter zone in China is sultry in summer and cold and wet in winter, and the mean temperature of July is \(\approx 28^\circ C\) higher than other places of the same latitude in the world, while the mean temperature of January is \(\approx 8–10^\circ C\) lower [16]. In addition, compared with developed countries, most residential buildings in China are not houses but apartment buildings, which may rise to 6–20 stories high, with each floor having 4–8 apartments. These two different characteristics lead to a great need for evaluating variable ventilation modes on the improvements of energy requirements and indoor thermal conditions. This paper uses degree hours [17] as an index to assess the indoor thermal comfort and gives a detailed analysis of the energy savings potential of variable ventilation, based on a number of building simulations by the program DeST-h.

2 METHODOLOGY

2.1 Building model
A representative residential building in Hangzhou in the hot summer and cold winter zone, with each household area of \(\approx 100 \text{ m}^2\), was modeled in this paper. The thermal design for the building envelope of this model, such as the \(U\)-values of walls (1.45 W/m\(^2\)K), roof (0.97 W/m\(^2\)K) and windows (3.2 W/m\(^2\)K), complies with the design standard for the energy efficiency of residential buildings in the hot summer and cold winter zone [2]. Energy and indoor thermal comfortable simulations were carried out with the program DeST-h, a dynamic thermal simulation program developed by Tsinghua University in China and validated by comparison with both well-known international thermal simulation programs and experimental results [18, 19]. The residential building model was illustrated in Figure 1. The window-to-wall ratio is 30% for windows facing east, west and north, and 50% for those facing south.

The indoor temperature is set at 26°C for cooling and 18°C for heating for air-conditioned rooms with different ACH modes. The air conditioner has an energy efficiency ratio of 2.3 when cooling and its performance coefficient is 1.9 when heating. The total power density of miscellaneous loads (including lighting systems and occupants) is 4.3 W/m\(^2\) for all air-conditioned rooms in accordance with the setting in Design standards for energy efficiency of residential buildings in the hot summer and cold winter zone [2].

2.2 Variable ventilation modes
To evaluate the energy savings potential and indoor thermal comfort improvement that can be achieved by ventilation, several possible dynamic ACHs in reality were considered, including a fixed ACH of 1 (according to the design standards [2]) and variable ACHs of 0.5–5, 0.5–15, 0.5–50 and 0.5–500. According to a study conducted by Bu [20], the natural ventilation availability in different areas of China is \(\approx 15 \text{ ACH}\). Hence, in this paper the first two variable ACH modes are considered as natural ventilation, while the latter two mean mechanical ventilation. Although these modes are different, these variable ACH modes are considered to be controlled ideally and thus ventilation can be automatically changed according...
to the difference of indoor and outdoor temperatures in building simulation, to minimize cooling and heating energy demands. The lower limit value of 0.5 indicates an average air infiltration [21] when occupants close all windows and doors in winter for avoiding heat loss.

3 RESULTS AND DISCUSSION

3.1 Indoor thermal comfort

Indoor relative humidity and air temperature are two key factors that influence indoor thermal comfort. Indoor relative humidity ranging from 40 to 60% is recommended as an index for a comfortable indoor environment in most regions [22]. Figure 2 presents the Hangzhou's monthly average outdoor relative humidity. It shows that the average outdoor relative humidity is more than 60% for each month and around 80% during summer in which natural ventilation is desirable for cooling. This means that natural ventilation in this area will bring the moisture indoors and may increase the indoor relative humidity to \( \sim 80\% \), an uncomfortable humidity condition according to Chang et al. [22]. However, a field survey on the thermal comfort in residential buildings conducted by Li [23] showed that occupants in this area have adapted to an average indoor relative humidity of as high as 76.4% with a thermal sensation vote of between \(-1\) and \(1\) (slightly cool to slightly warm) for 87% of occupants, due to frequently opened windows [22]. In other words, a high indoor relative humidity will not cause an uncomfortable indoor thermal condition in this area. Therefore, only indoor air temperature was considered to assess the indoor thermal comfort in this paper.

Room base temperature \( (T_b) \), which represents hourly indoor air temperature without the air-conditioner running all the year, is a key important factor to calculate indoor thermal environment [24]. Similar to the term—degree day, a degree hour \( (\text{De.H}) \) computed as the integral of \((T_b - T_c)\) \( (T_c \text{ denotes a comfortable indoor temperature in summer}) \) was used to assess indoor thermal comfort. Detailed information about this index is described by Satman and Yalcinkaya [17]. According to Jian and Jiang [24], \( T_c \) can be set at 29°C in China. Figures 3 and 4 show the cumulative hours of \( T_b \) in the comfortable range and the De.H for different ACHs.

It can be seen that the cumulative hours of \( T_b \) between 22 and 29°C increases by \(31 - 106\%\), depending on the ACH variation compared with the ACH of 1. According to Figure 3, the ACH of 0.5–15 shows a more comfortable indoor thermal environment than others. This may be attributed to the fact that a higher variation in ACH \((0.5 - 50 \text{ or } 0.5 - 500)\) decreases \( T_b \) to lower than \(22°C\) in the spring and autumn seasons. Figure 3 shows that De.H can be reduced by \(73 - 99\%\), depending on the ACH variation for different rooms. This means that variable ventilation plays a significant role in improving indoor thermal comfort. For the ACHs of \(0.5 - 50 \text{ and } 0.5 - 500\), the indoor thermal improvement is very close to that of \(0.5 - 15\), indicating that an increase in the higher limit value of variable ACH brings little contribution to the energy and indoor thermal performance. From Figure 3, it can be seen that there is little difference of the cumulative hours between the ACHs of \(0.5 - 5 \text{ and } 0.5 - 15\), and it seems that for \(R1 \) and \(R3 \) the ACH of \(0.5 - 5\) performs better than that of \(0.5 - 15\), which is unreasonable because a higher ventilation rate should lead to a lower \( T_b \). However, De.H (Figure 4) gives a reasonable result that for each room the ACH of \(0.5 - 15\) is more effective than that of \(0.5 - 5\), totally contrary to the former. Although the ACH of \(0.5 - 15\) does not have the best indoor thermal improvement, it achieves an over 86% reduction compared with the fixed ACH and a 65% reduction compared with the \(0.5 - 5\) ACH.
Figures 5–7 show the $T_b$ for the rooms R1, R2 and R3 with different ACHs on 4 typical summer days. This shows that the fixed ACH of 1 induces higher $T_b$s at every hour than others, with $T_b > 32^\circ$C (a highly uncomfortable indoor thermal condition) for each room. The $T_b$ variation for the ACHs of 0.5–15, 0.5–50 and 0.5–500 for these three rooms is similar, with a reduction ranging from 3 to 6°C for each hour compared with the ACH of 1, and the $T_b$s for these ACHs are close to each other, indicating that a higher ACH of more than 15 has little contribution to the reduction of $T_b$. The $T_b$ for the ACH of 0.5–500 is closest to the outdoor temperature, indicating that ventilation is an effective strategy to lower the indoor temperature. For the ACH of 0.5–15, a reduction of $\sim 5^\circ$C can be achieved for each hour compared with the ACH of 1. Although it is not as significant as the ACHs of 0.5–50 and 0.5–500, the indoor thermal improvement of this mode is obvious. For a residential building without mechanical ventilation systems, the ACH of 0.5–15 is a suitable variable ventilation mode in this area.

3.2 Energy performance

Figure 8 demonstrates the cooling, heating and total energy demands for different ACHs. The heating energy requirement is only around one-fifth of the cooling one for each ventilation mode, due to a large window-to-wall ratio and high solar radiation densities in summer. Compared with the fixed ACH mode, the variable ACH modes show great improvements of the heating energy requirement, with an $\sim 50\%$ reduction. This is due to the fact that these variable ACH modes have the lower limit value of ACH (0.5) that is half that of the fixed ACH mode, and thus automatically lower the ACH to 0.5 in winter to reduce the heating energy requirement.

The total energy savings of these variable ACHs are ranging from 39.4 to 61.7%, depending on the ACH variation range. It also shows that the ACH of 0.5–15 has a significant reduction of energy demand compared with the fixed ACH and the ACH of 0.5–5, with a total energy decrease of 52.9 and 39.4%, respectively. Although the ACHs of 0.5–50 and 0.5–500 have energy savings of $\sim 61\%$ compared with the fixed ACH mode, a higher ACH value needs more energy for mechanical ventilation systems. Moreover, the energy savings potential of increasing the higher limit value of a variable ACH mode to high above 15 becomes smaller and smaller, from 5.8% (0.5–15 to 0.5–50) to 1.2% (0.5–50 to 0.5–500). Hence, the ACH of 0.5–15, which merely relies on natural ventilation by opening windows and doors, is more cost-effective and applicable in residential buildings and should be paid more emphasis in design and operation stages.
4 CONCLUSIONS

This paper gives a simulation-based analysis of the impacts of variable ventilation modes on energy and indoor thermal performance. Results show that variable ventilation shows great advantages on the improvement of indoor thermal comfort and reductions of building energy consumption over the fixed ventilation rate of 1, and the ACH of 0.5–15 is cost-effective and applicable in naturally ventilated buildings. For a residential building with mechanical ventilation systems, an ACH of higher than 15 is available and can create a more comfortable indoor thermal environment in summer, but may increase the total energy requirement. Although the actual ACH will not reach the assumed ventilation rates in naturally ventilated buildings, this simulation study evaluates the potential of well-controlled natural ventilation in reducing energy demands and creating comfortable indoor conditions, and gives us some suggestions on how to improve the energy efficiency of buildings in design and operation stages by natural ventilation. In conclusion, to better predict the energy demand for residential buildings in China, an improvement of the ventilation setting (change a fixed ventilation rate to variable ones) in the tradeoff simulations adopted by building energy codes is necessary since occupants prefer to open windows in hot summer conditions to enhance ventilation, and this will bring a significant improvement in energy and indoor thermal comfort.

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