Evaluation of the performance of ventilative cooling systems with different control parameters

Yan Hu1, 2, Zhengtao Ai1, 3, and Guoqiang Zhang1, 3
1 Department of Building Environment and Energy, College of Civil Engineering, Hunan University, Changsha, Hunan, China
2 Department of Building Environment and Energy, College of Civil Engineering, University of South China, Hunan, China
3 National Center for International Research Collaboration in Building Safety and Environment, Hunan University, Changsha, Hunan, China

Abstract: To evaluate the performance and energy savings of different ventilative cooling systems, three mixed forms of ventilative cooling were described and the most promising rule-based heuristic control criteria were used as applicable control strategies based on various control parameters. Parametric analyses including the ventilative cooling set-points and control frequencies have been conducted. EnergyPlus was used to perform the aforementioned analyses based on a typical office building. Case studies verified that the use of different control parameters led to different indoor air environment and energy performance in a certain climatic zone. Then, the percentages outside the range indexes (POR) of the three mixed forms of ventilative cooling with various control parameters in five representative climatic zones in China were calculated, the results demonstrated that the ventilative cooling performance was mainly related to the ventilative cooling form in HSCW, HSWW, and temperate climatic zones. While in cold and severe cold climatic zones, it was mainly affected by selection of control parameters and its corresponding set-points. It can provide guidance for the selection of ventilative cooling scheme capable of maintaining indoor environment level with a low energy consumption in different climatic zones of China.

1 Introduction

Ventilative cooling system may not only largely diminishes the thermal discomfort and overheating risk of buildings during cooling periods, but also contribute to achieve high indoor air quality (IAQ) level. The appropriate forms of ventilative cooling systems and their control strategies are the two main factors that affect cooling effect. Different ways of fresh air introduction will result in different levels of energy consumption and indoor air environment. Some studies showed that complex algorithms and control strategies for ventilation do not perform better than simple ones [1], and the settings of the parameters of the strategies are more important than the control strategy itself [2].

Motivated by the common energy consumption and indoor air environment troubles in public buildings, a simple rule-based heuristic control strategy was proposed to maximize the exploitation of the cooling potential of outdoor air. Performance and energy savings were evaluated through numerical simulation based on an office building in hot summer and cold winter climate. We further examined adaptive ventilative cooling forms and control parameters for office buildings in different climatic zones in China.

2 Method

2.1 Building model

A typical office building, with the dimensions of 6 m (length) × 4 m (width) × 3.8 m (height), was numerically constructed. The office is a room on the fourth floor of
an office building located in Changsha (Fig.1). The enclosed space is assembled with a 3.25 m² window in the north wall, and the minimum office space per capita is 6 m².

![Fig. 1. The office room model.](image)

This study investigated, in a variety of fresh air supply, the effect of different ventilative cooling systems: (1) AC+Win: automatic window control for natural ventilation and air conditioning (AC) (the area of the openable window is 1.2 m²), (2) AC+Fan: constant air volume mechanical ventilation (5 air changes per hour (ACH)) and AC, and (3) AC+BV: balanced heat recovery ventilation system (5 ACH) with a summer bypass and AC. EnergyPlus was adopted to model the influence of building envelope, mixed-mode ventilative cooling system, and control strategies.

### 2.2 Control strategies for ventilative cooling

![Fig. 2. Block-schematic diagram of ventilative cooling control.](image)

(\(T_{in}\) : represents indoor air temperature, \(T_{out}\) : represents outdoor air temperature, \(T_{set}\) : represents ventilative cooling set-point, 0: means that window is closed or AC is off, 1: means that window is opened or AC is on.)

The control block schematic diagram of the first ventilative cooling form (AC+Win) can be seen in Fig.2. The other two ventilative cooling forms based on different control parameters have the same control frameworks.

The widely used control parameters of thermal comfort of a space created by a ventilative cooling system, namely, indoor dry bulb air temperature \(T_d\) [3], operative temperature \(T_{op}\) [4] and Predicted Mean Vote (PMV) [5] mainly affect thermal sensation. The carbon dioxide (CO₂) concentration level was regarded as the most important index to represent IAQ level in spaces where occupants are major pollutant source.

A series of scenarios with diverse control parameters were created as reported in Table 1. There were 9 scenarios for each form of ventilative cooling system.

<table>
<thead>
<tr>
<th>IAQ</th>
<th>Thermal comfort</th>
<th>Ventilative cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂=1000 ppm= (1)</td>
<td>(T_{d}=24, 25, 26°C= (3) scenarios)</td>
<td>AC+Win</td>
</tr>
<tr>
<td>PMV=0, 0.3, 0.5= (3 scenarios)</td>
<td>(T_{op}=24, 25, 26°C= (3) scenarios)</td>
<td>AC+Fan</td>
</tr>
<tr>
<td>(3 scenarios)</td>
<td>AC+BV</td>
<td></td>
</tr>
</tbody>
</table>

### 3 Results and Discussion

An indicator of performance was analyzed in this study: percentage outside the range index (POR). For example, \(POR_{Td}\) can evaluate the frequency of overheating occurrences, representing the sum of hours with occupation in which the air temperatures exceed a set temperature value, divided by the sum of hours in which occupation of the rooms is considered during cooling periods, as presented in Eq.(1).

\[
PO_{Td} = \frac{\sum_{\text{times} \in \text{occ}} T_{ah} > Td}{\sum_{\text{times} \in \text{occ}}} (1)
\]

### 3.1 Automatic ventilative cooling control frequency

The minimum duration of sampling time was set as 5 min, and the sampling times of 10 min, 20 min, 30 min, and 1 h were also conducted. The PORs of \(T_d\), \(T_{op}\), PMV, CO₂, and energy consumption under different scenarios at different control frequencies were calculated. Standard deviation (SD) can be utilized to indicate the volatility of the data over the control frequency. Only the standard deviation of \(POR_{Td}\) was less than 2, it can be considered independent of the control frequency. Other data suggested that the control frequency should be reduced as much as possible. In addition, the constraints in the response time of a monitoring instrument and the
actuation time of a ventilative cooling system shall be taken into consideration. Eventually, 5 min was selected as the control time-step in these cases.

3.2 Thermal comfort and IAQ performance

According to the standard for indoor environment of buildings in China, the indoor air temperature was set to be less than 26 °C, CO₂ below 1000 ppm, and the PMV in the range of ±0.5. Fig. 3 indicates PORs of different scenarios.

This study demonstrated that all the daily-averaged CO₂ met the requirements. According to the 5-minute time-step statistics, all the $\text{POR}_{\text{CO}_2}$ were controlled within 9%, and SD was 1.9%. This indicated that the ventilative cooling form, thermal comfort parameters, and the corresponding set-points had little influence on indoor CO₂ concentration. This was mainly because the control parameters of IAQ maintained the same, and the ventilation rate was greater than that required to maintain indoor IAQ level.

If PMV was used as evaluation index of thermal comfort, the lowest $\text{POR}_{\text{PMV}=±0.5}$ in all cases was about 15%, which means only 76.5% (=90% × (1-15%)) occupants were satisfied with the thermal environment at most. A probable reason was that PMV model that was suitable for steady state environment would overestimate dissatisfaction. Maintaining consistent thermal comfort, the amount of energy consumption in PMV-based control at a set-point of 0.5 allowed about 9% reduction of energy consumed compared to that with $T_{op}$-based control at a set-point of 26 in the AW and AF systems. These results indicated that PMV-based control was a reasonable solution to obtain better thermal comfort and energy savings. But for the AB system, the energy consumption of PMV-based control was higher than that of $T_{op}$-based control.

If $T_d$ was used as evaluation index of thermal comfort, the dry bulb air temperature setting was very sensitive to POR results. When the temperature setting values of $T_d$ and $T_{op}$ remained the same, the $T_{op}$-based control offered better PORs, but the consumed energy was much higher (32-50%) than that of $T_d$-based control. It can be seen from Fig. 3 (c) that their energy consumed were approximate when $T = 24°C$ and $T_{op} = 26°C$ with different $\text{POR}_{T_d}$. It suggested that the selection of control parameters and its corresponding set-points should be determined carefully.

![Fig. 3. PORs of thermal comfort and IAQ performance.](image)

(The abscissa represents different control parameters)

If $T_{op}$ was used as evaluation index of thermal comfort, the $T_{op}$-based control still offered better PORs, and other control parameters were unsatisfactory. It can be seen that their $\text{POR}_{T_{op}}$ were approximate when $T = 24°C$ and $T_{op} = 26°C$ with the almost same energy

3
consumption. It shows that selecting appropriate air temperature parameters can obtain consistent cooling effect and energy consumption of $T_{op}$ based control. The influences of control parameters and its corresponding set-points on thermal comfort were greater than that of ventilative cooling forms. From thermal comfort perspective, the optimal controlled parameter was $T_{op}$ because of the relatively low PORs. Though the POR values of different ventilative forms of the same control parameters differed little relatively, the difference of the energy consumption was great. The optimal ventilative cooling form was the AC+BV system with the lowest PORs of thermal comfort and energy consumption in Changsha. When the PORs of thermal comfort performance indexes was within a certain range, the worst was the AC+Win system with the highest energy consumption, which was because that the uncontrolled fresh air increased energy consumption of AC.

3.3 Meteorological considerations

The utilization potential of natural ventilation varies significantly from climate to climate. Five cities with typical climate representation were selected for the analysis, i.e., Harbin, Beijing, Changsha, Guangzhou, and Kunming, which are the representatives of severe cold zone, cold zone, hot summer and cold winter zone (HSCW), hot summer and warm winter zone (HSWW) and temperate zone respectively. The cooling period was set from May 1 to October 8 (8 a.m.-6 p.m.), 1610 hours in total (except Harbin: May 22 to August 31).

Fig. 4 shows that all the scenarios where $POR_{T_{d}} < 10\%$ . It was found that there was an optimal combination of control parameters and the corresponding set-points, as well as ventilative cooling forms in diverse climatic zones. In HSWW and HSCW climates, the AC+BV was the optimal solution whatever the value of POR is. In temperate climate, the AC+Win was the best choice for ventilative cooling. Whereas, in cold and severe cold climates, it was not appropriate to determine which ventilative cooling form was optimal, and the ventilative cooling effect was mainly affected by the selection of control parameters and the corresponding set-points.

4 Conclusions

The ventilative cooling form, control parameters related to thermal comfort and its corresponding set-points had little influence on CO$_2$ concentration based on this rule-based heuristic control criteria. From thermal comfort perspective, the optimal control parameter was $T_{op}$, then the $T_{d}$, and the last PMV, in hot summer and cold winter climatic zone.

The main factors affecting thermal comfort of ventilative cooling system in different climatic zones were different. In HSCW, HSWW, and temperate climatic zones, the ventilative cooling effect was mainly related to the ventilative cooling form. While, in cold and severe cold climatic zones, it was mainly affected by selection of control parameters and its corresponding set-points. This also shows that different ventilative cooling forms have certain climatic adaptability.

Reference


