Experimental study on the influence of ventilated window on indoor air quality and energy consumption

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Abstract

The ventilated window has great potential on improving indoor air quality, but it may increase energy consumption. This paper studies the influence of different running modes of ventilated window on indoor PM2.5 and CO\textsubscript{2} concentration and the overall energy consumption. When indoor PM2.5 concentration was more than 90ug/m\textsuperscript{3}, and outdoor PM2.5 concentration was less than 300ug/m\textsuperscript{3} after ventilated window operating for an hour, indoor PM2.5 concentration decreased for 9-16\%, it is appropriate to operating the ventilated window, but it was still 0.18-0.27 times more than the secondary standard. Operating the ventilated window for 55mins on mid-grade and high-grade respectively could reduce the increment of CO\textsubscript{2} concentration for 3.31\% and 22.19\% than that without ventilated window operating. When the ventilated window operating on low-grade, the increment of CO\textsubscript{2} concentration was 11.34\% larger than that without ventilated window operating. By increasing air volume and operating time of different modes, indoor air quality can be improved. Comparing with the condition with ventilated window off, the maximum energy consumption after ventilated window operating for 24 hours on high-grade was 2.462 kW·h\textsuperscript{-1} (2.054 kW·h\textsuperscript{-1} for air conditioning consumption). Appropriate operating mode and running time can be chosen to reduce energy consumption effectively.

Keywords: Indoor air quality, Energy consumption; Ventilated window; PM2.5, CO\textsubscript{2}.

1. Introduction

There are heavy hazy weathers in mid-eastern China since 2013. The concentration of PM2.5 in air exceeds the standard seriously\textsuperscript{[1]}. It not only influences city weather but also human health\textsuperscript{[2]}. In order to reduce energy
consumption\cite{3}, air tightness of the building structure is more and more high which leads to bad indoor air quality\cite{4}. It’s easy to get sick building syndrome(SBS) when ventilation is not enough\cite{5-6}. And it’s not suitable to open window at all on hazy weather. Ventilated window can not only send fresh air in, but also purify it. Thus it solves the window-open problem on hazy weather. Besides, it also solves the small range and limited function problem of Exhaust fan and air purifiers\cite{7}. Influence of nature ventilation and bidirectional ventilated window ventilation on indoor CO\textsubscript{2} concentration is analyzed\cite{8}. The results show that bidirectional ventilated window has an effective improvement on indoor air quality. Experimental study on the importance of bidirectional ventilated window parameters on energy saving is done\cite{9}. Two new types of solar ventilated window can reduce cooling load and energy consumption effectively\cite{10}. Thermal performance of bidirectional ventilated window is valued by experiment combined with simulation\cite{11}. Most of the ventilated windows above can reduce indoor CO\textsubscript{2} concentration and energy consumption but have no purifying function. This paper studied a new type of ventilated window with purifying function, which has a considerable filtering effect.

2. Method

The comprehensive laboratory is composed by the test room, outdoor environmental chamber, a new ventilated window and monitor room (Fig. 1-2). For convenient and accurate study, all walls, floors, ceilings and doors of the test room and outdoor environmental chamber are heat preservation and insulation.

![Fig 1. The comprehensive laboratory of building energy](image1)

![Fig 2. The new ventilated window](image2)

2.1. The new ventilated window

<table>
<thead>
<tr>
<th>Mode Parameters</th>
<th>Low-grade</th>
<th>Mid-grade</th>
<th>High-grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ventilation volume</td>
<td>0.54m\textsuperscript{3}/h</td>
<td>0.74m\textsuperscript{3}/h</td>
<td>0.95m\textsuperscript{3}/h</td>
</tr>
<tr>
<td>Filter efficiency</td>
<td>78.6%</td>
<td>77.4%</td>
<td>75.2%</td>
</tr>
</tbody>
</table>

The new ventilated window (Fig. 2) is installed in the partition of the test room and outdoor environmental chamber. It has lighting effect of the ordinary window, and it can purify the air through ventilator (Fig. 3) installed in the window frame. Using mechanical air supply, fresh air can be sent in after purification without opening the window (Fig. 4), and the filter efficiency of ventilator is medium efficiency. The new ventilated window has three operating modes, the performance parameters of each mode are shown in Table 1.
2.2. Test content and methods

The experiment studied the influence of different running modes of ventilated window on indoor air quality and overall energy consumption.

Consider PM2.5 and CO₂ concentration as the index of indoor air quality to analyze the influence on indoor PM2.5 and CO₂ concentration when the ventilated window was opened.

The main factors that affect indoor PM2.5 concentration are outdoor PM2.5 concentrations and ventilation modes. The outdoor environmental chamber uses burning cigarettes as pollution source, which generates flue gas of particulate matter < 2.5μm (mainly 0.7μm) to simulate different outdoor pollution concentrations. According to the concentration distribution of serious contamination of the northern Chinese city during the heating period[12-13], set PM2.5 concentration in outdoor environment simulation chamber as 200ug/m³, 300ug/m³, and initial indoor PM2.5 concentration as 105ug/m³, and analysis the change of PM2.5 concentrations of the main activity area, that is, measuring point C2 (Fig. 5) after operating the ventilated window. And the distance from concentration sensor to floor is 1.2m.

Through the preliminary monitoring of outdoor CO₂ concentration it can be found that variation range of outdoor CO₂ concentration in the daytime was little, about 200-300ppm. Open the south window in the outdoor environment chamber and bring outdoor air in directly in the experiment. The initial CO₂ concentration (C0) of the test room was set to 500 ppm, which was lower than most authorities standard value, 900 ppm[14-15]. The CO₂ liberation system can liberate CO₂ quantitatively. Normal person may exhale 25L CO₂ per hour[16], the test room area is 11.4 m² and set for 2-3 people, the liberation flow of CO₂ is 1L·min⁻¹ that is controlled by the flow meter. Measuring point arrangement is shown in Fig. 5.
Operating the ventilated window will consume electric power and have an impact on indoor air-conditioning system energy consumption at the same time due to the temperature difference of indoor and outdoor air. The experiments used a power meter to measure the power of the ventilated windows of different running modes. And indoor air conditioning energy consumption with the ventilated window on and off was calculated through the measured supply and return air temperature and volume of fan coil. During the experiment, the outdoor environment simulation chamber temperature was 6-7 °C, the indoor test room temperature was 20 °C.

3. Results and discussion

3.1. Influence of ventilated window on indoor concentration of PM2.5 particle

The experiment set no human activities or pollution source in the room, PM2.5 particle mostly came from the outdoor particulate penetration\(^{17-18}\), indoor concentration of PM2.5 was generally lower than the outdoor concentration\(^{19}\), the initial concentration was about 105ug/m\(^3\), indoor air quality was slightly polluted\(^{20}\). With the secondary standard of daily average concentration limits: 75ug/m\(^3\) in "Ambient air quality standard"\(^{21}\) as the standard to evaluate indoor and outdoor concentration of PM2.5. When outdoor concentration of PM2.5 was 300ug/m\(^3\), which would exceed the standard 3 times; When outdoor concentration of PM2.5 was 200ug/m\(^3\), which would exceed the standard 1.7 times, and indoor concentration of PM2.5 would exceed the standard 0.4 times.

Table 2  The concentration variation of indoor PM2.5

| Outdoor concentration | Mode  | Low-grade | | Mid-grade | | High-grade | |
|-----------------------|-------|-----------|--------|-----------|--------|-----------|
|                       | C0    | Ce        | η (%)  | C0        | Ce     | η (%)     | C0        | Ce     | η (%)  |
| 300ug/m\(^3\)         | 0.104 | 0.095     | 9%     | 0.106     | 0.093  | 12%       | 0.106     | 0.094  | 11%    |
| 200ug/m\(^3\)         | ——    | ——        | ——     | 0.106     | 0.089  | 16%       | ——        | ——     | ——     |

C0, the initial concentration. Ce, the end concentration. η, the decreasing concentration in an hour.

Fig. 6-7 and table 2 showed that: when the outdoor concentration of PM2.5 was 200-300ug/m\(^3\) and the indoor concentration of PM2.5 was 105ug/m\(^3\) about, after an hour of running the ventilated window, the indoor concentration of PM2.5 decreased by 9%-16%, but it still exceeded the standard 0.18-0.27 times. When the ventilated window was operating the same mode, the lower outdoor concentration of PM2.5 was, the lower PM2.5 concentration of fresh air through the ventilated window after purification was, and the better indoor air quality would be. When outdoor concentration of PM2.5 was 300ug/m\(^3\) and the ventilated window was set on high-grade, indoor concentration of PM2.5 had the maximum decrease. Therefore, the higher grade ventilated window is set, the bigger volume of air supply is, the larger indoor air change rate is, and the better indoor pollutant dilution will be. Pope\(^{22}\) had made a lot of researches and found that: total mortality of lung cancer, heart and lung diseased increased by 8%, 6% and 4%
when the concentration of PM2.5 increased by 10ug/m³. Therefore, when the outdoor concentration of PM2.5 is 200-300ug/m³ and the indoor concentration of PM2.5 is 105ug/m³, open the ventilated window can reduce the indoor concentration of PM2.5 and improve indoor air quality, which is beneficial to human health.

3.2. Effect of ventilated window on indoor CO₂ concentration

The experiment used CO₂ concentration as the parameter to evaluate the improvement of indoor air quality. The experiment mainly studied the effect of CO₂ concentration when the ventilated window was operating on different modes at the main activity area of point C2 (Fig. 8). And CO₂ concentrations of different points indoor with the ventilated window running the same modes was shown in figure 9.

![Fig 8. Different modes](image1)

![Fig 9. Different points](image2)

<table>
<thead>
<tr>
<th>Modes</th>
<th>Low-grade</th>
<th>Mid-grade</th>
<th>High-grade</th>
<th>Shut-down</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₀ (ppm)</td>
<td>546</td>
<td>524</td>
<td>540</td>
<td>520</td>
</tr>
<tr>
<td>Cₑ (ppm)</td>
<td>3206</td>
<td>2834</td>
<td>2399</td>
<td>2909</td>
</tr>
<tr>
<td>ΔC (ppm)</td>
<td>2660</td>
<td>2310</td>
<td>1859</td>
<td>2389</td>
</tr>
<tr>
<td>ζ</td>
<td>-11.3%</td>
<td>3.3%</td>
<td>22.2%</td>
<td>——</td>
</tr>
</tbody>
</table>

Table 3 The concentration variation of indoor CO₂

From figure. 8, it could be found that when the ventilated window was off, CO₂ concentration of point C2 increased gradually with CO₂ liberating equipment operating, and it increased to 2909 ppm in 55mins, so the indoor CO₂ concentration increased about 460% than initial CO₂ concentration (Table 3), and indoor air quality was poor. When use PD as the criterion to evaluate indoor air quality, PD increases 10% at least[23]. Under the same condition, the increment of indoor CO₂ concentration decreased by 3.3% and 22.2% with ventilated window operating on mid-grade and high-grade respectively. But the increment increased by 11.3% with ventilated window operating on low-grade. This mainly because the high-grade have the maximum amount of venting and higher wind speed than the other two modes, and outdoor CO₂ concentration is difficult to control. Operating the ventilated window on mid-grade and high-grade have better dilution effect of CO₂ concentration. When ventilated window operates on low-grade, the air volume and velocity are small, it is difficult to reach the area where CO₂ is liberated; Air supply function disturbed the airflow near the ventilated window and prevented the CO₂ diffusing from the generating source. And he ventilated window running time is short, which results in CO₂ aggregates in the region near point C2, and CO₂ concentration increasing. Therefore, air volume need to be increased of each operating mode of ventilated window. Compared with the condition that the ventilated window was off, CO₂ concentration of point C1, C3 and C4 reduced obviously. CO₂ concentration reduced 28.4% at most under conditions with the ventilated window open for 55 mins. Point C2 was close to the pollution-generating zone, CO₂ concentration minimum attenuation was 3.0%. So operating the ventilated window on
mid-grade and high-grade can effectively reduce indoor CO₂ concentration, ventilation effect is remarkable. The experimental select a slightly higher of CO₂ emission rate, and the testing room is small, so the CO₂ concentration will be relatively lower in real rooms.

### 3.3. Effect on energy consumption

The experiments used a power meter to measure the power of the ventilated window of different running modes. And calculating indoor air conditioning energy consumption with the ventilator on and off through the measured supply and return air temperature of fan coil and the amount of wind. The equation is as follows:

\[
Q = cM(t_r - t_s)
\]

Where Q is the heating load, c is the air specific heat capacity, M is the mass of fan coil supply air, ts is the supply air temperature of the fan coil, and tr is the return air temperature of the fan coil.

![Fig 10. The overall energy consumption of different modes](image)

The experiment compared the energy consumption between 3 modes with the condition with the ventilated window off for 24 hours. Overall energy consumption on different grades is shown in figure. 10, and it shows that operating the ventilated window will increase indoor heating load and electric energy. Compared with the condition with the ventilated window off, it increased 0.609kW·h⁻¹ of energy consumption (0.448kW·h⁻¹ for air conditioning) with the ventilated window operating on low-grade for 24 hours; 0.760kW·h⁻¹ on the mid-grade (0.520kW·h⁻¹ for air conditioning) and 2.462kW·h⁻¹ on the high-grade (2.054kW·h⁻¹ for air conditioning).

### 4. Conclusions

This paper studied the influence of ventilated window on indoor air quality and energy consumption. Conclusions are as follow:

When the concentration of indoor and outdoor PM2.5 is about 100 and 300ug/m³ respectively, PM2.5 concentration decreases for 16% after the ventilated window operating for 1 hour on mid-grade; When indoor and outdoor PM2.5 concentration is about 100 and 300ug/m³ respectively, after the ventilated window operating for an hour on low-grade, mid-grade and high grade respectively, indoor PM2.5 concentration decreases for 9%, 12% and 16%. Thus it is acceptable to operating the ventilated window. Though indoor air quality has been improved this way, it’s still 0.18-0.27times more than the secondary standard. Extend the running time of ventilated window can decrease PM2.5 concentration effectively.

When indoor CO₂ concentration is 200-300ppm and outdoor CO₂ concentration is about 500ppm, operating the ventilated window for 55mins on mid-grade and high-grade respectively can reduce the increment of CO₂ concentration for 3.31% and 22.19% than that without ventilated window operating. When the ventilated window operates on low-grade, the increment of CO₂ concentration is 11.34% larger than that without ventilated window operating. So increasing air volume and operating time of ventilated window can improve indoor air quality.
The electric consumption of ventilated window itself after operating for 24 hours is low and the energy consumption of air conditioning system increases with the ventilated window running. The overall energy consumption after the ventilated window operating for 24 hours on low-grade is 0.609 kW·h⁻¹ (0.448 kW·h⁻¹ for air conditioning consumption) more than that without ventilated window operating; Accordingly, 0.760 kW·h⁻¹ (0.520 kW·h⁻¹ for air conditioning consumption) on mid-grade and 2.462 kW·h⁻¹ (2.054 kW·h⁻¹ for air conditioning consumption) on high-grade. Thus, different running modes and time can be chosen to reduce energy consumption effectively.

Acknowledgements

This study was supported by the Innovation Team of Tianjin City (TD12-5048).

References