Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 146 (2016) 296 – 302

Procedia Engineering

www.elsevier.com/locate/procedia

8th International Cold Climate HVAC 2015 Conference, CCHVAC 2015

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

Ningning Zhang[a], Wufeng Jin[a], Junwei He[a,*]

[a]*Tianjin University of Commerce, Tianjin, China*

**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 $CO_2$ concentration and the overall energy consumption. When indoor PM2.5 concentration was more than 90ug/$m^3$, and outdoor PM2.5 concentration was less than 300ug/$m^3$ 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 $CO_2$ concentration for 3.31% and 22.19% than that without ventilated window operating. When the ventilated window operateing on low-grade, the increment of $CO_2$ 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 $kW \cdot h^{-1}$ (2.054 $kW \cdot h^{-1}$ for air conditioning consumption). Appropriate operating mode and running time can be chosen to reduce energy consumption effectively.



Peer-review under responsibility of the organizing committee of CCHVAC 2015

*Keywords:* Indoor air quality, Energy consumption; Ventilated window; PM2.5, $CO_2$;

## 1. Introduction

There are heavy hazy weathers in mid-eastern China since 2013. The concentration of PM2.5 in air exceeds the standard seriously[1]. It not only influences city weather but also human health[2]. In order to reduce energy

* Corresponding author. Tel.: +86 13802186472; fax: +86 022 26667502.
*E-mail address:* kob@tjcu.edu.cn



Peer-review under responsibility of the organizing committee of CCHVAC 2015
doi:10.1016/j.proeng.2016.06.394

consumption[3], air tightness of the building structure is more and more high which leads to bad indoor air quality[4]. It's easy to get sick building syndrome(SBS) when ventilation is not enough[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[7]. Influence of nature ventilation and bidirectional ventilated window ventilation on indoor $CO_2$ concentration is analyzed[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[9]. Two new types of solar ventilated window can reduce cooling load and energy consumption effectively[10]. Thermal performance of bidirectional ventilated window is valued by experiment combined with simulation[11]. Most of the ventilated windows above can reduce indoor $CO_2$ 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.

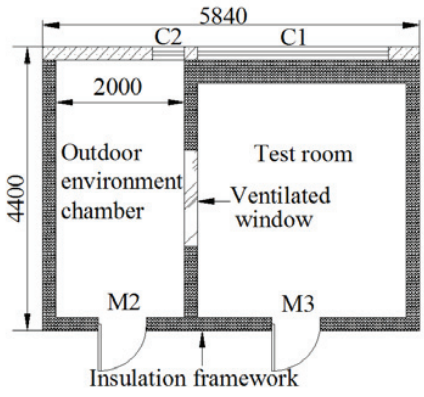


Fig 1. The comprehensive laboratory of building energy

Fig 2. The new ventilated window

### 2.1. The new ventilated window

Table 1 Performance parameters of the new pattern ventilated window

| Mode / Parameters | Low-grade | Mid-grade | High-grade |
|---|---|---|---|
| Ventilation volume | 0.54m$^3$/h | 0.74m$^3$/h | 0.95m$^3$/h |
| Filter efficiency | 78.6% | 77.4% | 75.2% |

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.

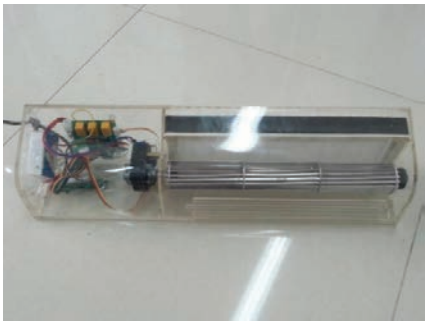

Fig 3. The ventilator

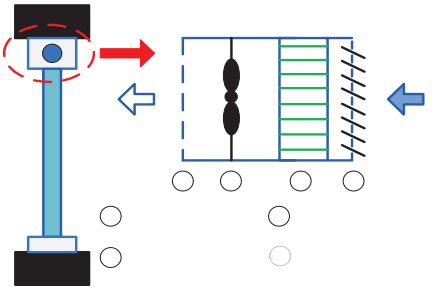

Fig 4. The schematic diagram

*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 $CO_2$ concentration as the index of indoor air quality to analyze the influence on indoor PM2.5 and $CO_2$ concentration when the ventilated window was opened.

The mainly 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/m$^3$, 300ug/m$^3$, and initial indoor PM2.5 concentration as 105ug/m$^3$, 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.

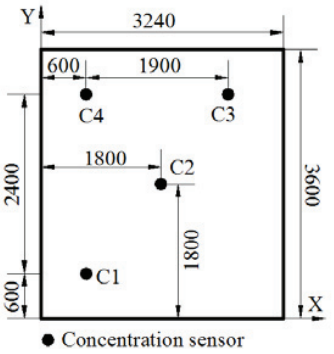


Fig 5. Measuring points roo*m*

Through the preliminary monitoring of outdoor $CO_2$ concentration it can be found that variation range of outdoor $CO_2$ 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 $CO_2$ concentration (C0) of the test room was set to 500 ppm, which was lower than most authorities standard value, 900 ppm[14-15]. The $CO_2$ liberation system can liberate $CO_2$ quantitatively. Normal person may exhale 25L $CO_2$ per hour[16], the test room area is 11.4 m$^2$ and set for 2-3 people, the liberation flow of $CO_2$ 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 ℃, the indoor test room temperature was 20℃.

## 3. Results and discussion

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

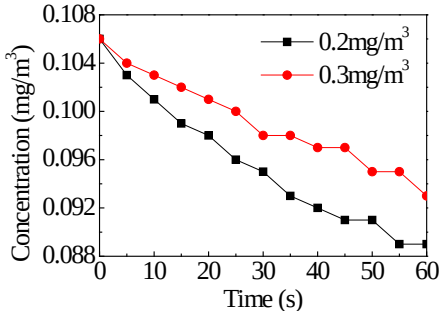


Fig 6. Different concentrations of outdoor

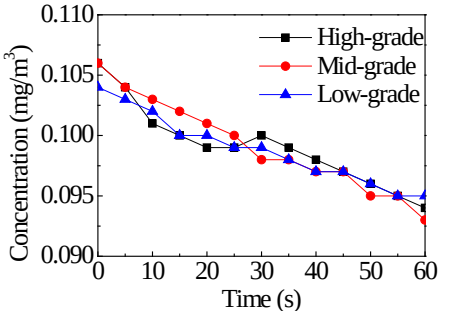


Fig 7. Different modes

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

| Mode / Outdoor concentration | 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/m$^3$. Therefore, when the outdoor concentration of PM2.5 is 200-300ug/m$^3$ and the indoor concentration of PM2.5 is 105ug/m$^3$, 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 $CO_2$ concentration*

The experiment used $CO_2$ concentration as the parameter to evaluate the improvement of indoor air quality. The experiment mainly studied the effect of $CO_2$ concentration when the ventilated window was operating on different modes at the main activity area of point C2 (Fig. 8). And $CO_2$ concentrations of different points indoor with the ventilated window running the same modes was shown in figure 9.

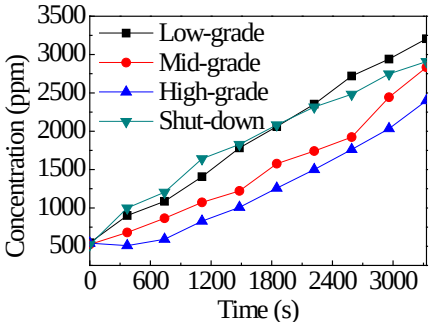


Fig 8. Different modes

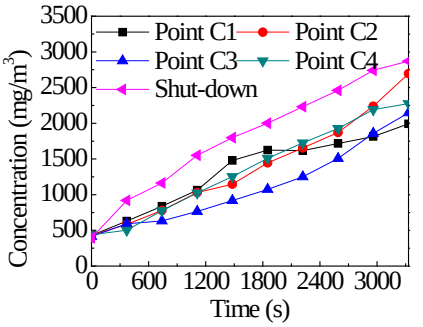


Fig 9. Different points

Table 3 The concentration variation of indoor $CO_2$

| Modes | Low-grade | Mid-grade | High-grade | Shut-down |
|---|---|---|---|---|
| C0 (ppm) | 546 | 524 | 540 | 520 |
| Ce (ppm) | 3206 | 2834 | 2399 | 2909 |
| △C (ppm) | 2660 | 2310 | 1859 | 2389 |
| ξ | -11.3% | 3.3% | 22.2% | —— |

ξ, the decay in each mode that compared with the shut-down respectively.

From figure. 8, it could be found that when the ventilated window was off, $CO_2$ concentration of point C2 increased gradually with $CO_2$ liberating equipment operating, and it increased to 2909 ppm in 55mins, so the indoor $CO_2$ concentration increased about 460% than initial $CO_2$ 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 $CO_2$ 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 $CO_2$ concentration is difficult to control. Operating the ventilated window on mid-grade and high-grade have better dilution effect of $CO_2$ concentration. When ventilated window operates on low-grade, the air volume and velocity are small, it is difficult to reach the area where $CO_2$ is liberated; Air supply function disturbed the airflow near the ventilated window and prevented the $CO_2$ diffusing from the generating source. And he ventilated window running time is short, which results in $CO_2$ aggregates in the region near point C2, and $CO_2$ 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, $CO_2$ concentration of point C1, C3 and C4 reduced obviously. $CO_2$ 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, $CO_2$ concentration minimum attenuation was 3.0%. So operating the ventilated window on

mid-grade and high-grade can effectively reduce indoor $CO_2$ concentration, ventilation effect is remarkable. The experimental select a slightly higher of $CO_2$ emission rate, and the testing room is small, so the $CO_2$ 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:

$$Q = cM(t_r - t_s) \tag{1}$$

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.

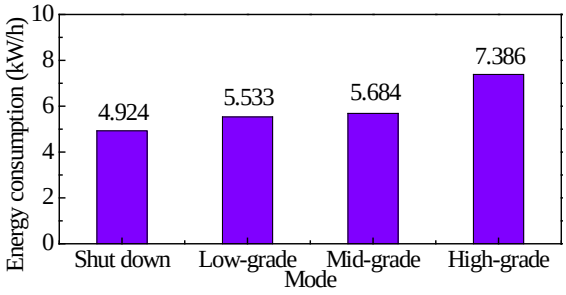


Fig 10. The overall energy consumption of different modes

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/$m^3$ respectively, PM2.5 concentration decreases for 16% after the ventilated window operating for 1hour on mid-grade; When indoor and outdoor PM2.5 concentration is about 100 and 300ug/$m^3$ 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 $CO_2$ concentration is 200-300ppm and outdoor $CO_2$ concentration is about 500ppm, operating the ventilated window for 55mins on mid-grade and high-grade respectively can reduce the increment of $CO_2$ concentration for 3.31% and 22.19% than that without ventilated window operating. When the ventilated window operates on low-grade, the increment of $CO_2$ 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 24hours 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 24hours 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

[1] Pui David Y.H., Chen S., and Zuo Z.L. 2014. PM2.5 in China: Measurements, sources, visibility and health effects, and mitigation. Particuology, 13, 1–26.
[2] Qian J., Ferro A. and Fowler K. 2008. Estimating the resuspension rate and residence time of indoor particles. Journal of the Air & Waste Management Association, 58(4), 502-516.
[3] David A. and Svend S. 2011. Experimental analysis of energy performance of a ventilated window for heat recovery under controlled conditions. Energy and Buildings, 43, 3200-3207.
[4] Wei J.S., Zhao J.N., and Chen Q.Y. 2010. Energy performance of a dual airflow window under different climates. Energy and Buildings, 42, 111-122.
[5] Wargocki P., Sundell J., and Bischof W. 2002. Ventilation and health in non-industrial indoor environments: report from a European multidisciplinary scientific consensus meeting (EUROVEN). Indoor Air, 12(2), 113-128.
[6] World Health Organization. 1983. Indoor air pollutants exposure and health effects. Copenhagen: EURO Reports and Studies No. 78.
[7] Wei J.S., Zhao J.N., and Chen Q.Y. 2011. Applicability study of dual-airflow for different climatic zones. Journal of HV&AC, 41(4), 69-72.
[8] Wei J.S., Zhao J.N., and Chen Q.Y. 2011. Improvement of indoor air quality through dual- airflow window ventilation. Building Science, 27(2), 69-72.
[9] Wei J.S., Zhao J.N., and Chen Q.Y. 2010. Optimal design for a dual-air flow window for different climate regions in China. Energy and Buildings, 42, 2200-2205.
[10] Pei G., Zhou T.T., Ji J., et al. 2009. Experimental study of two novel ventilated solar screen windows in Hong Kong. Acta Energiae Solaris Sinica, 30(3), 282-286.
[11] Jorge S.C. and Helena C. 2014. Evaluation of the thermal performance indices of a ventilated double window through experimental and analytical procedures: Uw-values. Renewable Energy, 63, 747-754.
[12] Wang S.Y, Yao L., Wang L.L., et al. 2014. Mechanism for the formation of the January 2013 heavy haze pollution episode over central and eastern China.Science China: Earth Sciences, 57, 14-25.
[13]Xie Dongdong. 2013. Study on indoor air quality at rural houses in severe cold region. Master. Thesis, Harbin Institute of Technology, The Haerbin, 20-25.
[14] World Health Organization Regional Office for Europe. 2000. Air quality guidelines for Europe. WHO Regional Office Europe.
[15] Standard A. 1989. Standard 62-1989, Ventilation for acceptable indoor air quality. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.
[16] Wei Jingshu. 2011. Performance evaluation and optimazation of a dual-airflow window. Ph.D. Thesis, Harbin Institute of Technology, The Haerbin, 11-72.
[17] Abt E., Suh H.H., Allen G., et al. 2000. Characterization of indoor particle sources: A study conducted in the metropolitan Boston area. Environ Health Perspect, 108, 35-44.
[18] Allen R., Larson T., Sheppard L., et al. 2003. Use of real time light scattering data to estimate the contribution of infiltrated and indoor generated particles to indoor air . Environ Sci Technol, 37, 3484-3492.
[19] Cheng H., Hu M., Zhang L.W., et al. 2009. PM2.5 concentrations in indoor and outdoor air and their relationship in the fall of Beijing. Journal of Environment and Health, 26(9), 787-789.
[20] HJ 633-2012. 2012. Technical regulation on ambient air quality index (on trial). Ministry of environmental protection of the people's republic of China, Beijing.
[21] GB 3095-2012, 2012. Ambient air quality standards. Ministry of environmental protection of the people's republic of China, Beijing.
[22] Pope C.A., Burnett R.T., Thurston G.D., et al. 2004. Cardiovascular mortality and long-term exposure to particulate air pollution: epidemiological evidence of general pathophysiological pathways of disease. Circulation, 109(1), 71-77.
[23] Jokl M.V. 2000. Evaluation of indoor air quality using the decibel concept based on carbon dioxide and TVOC. Building and Environment. 35, 677□ 697.