EFFECT OF WINDOW FILTRATION VENTILATOR ON INDOOR THERMAL COMFORT AND AIR QUALITY

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ABSTRACT

Providing an adequate quantity of fresh, clean air to occupied areas of residential and public buildings is necessary for diluting indoor CO2, airborne particles and other gas pollutant, especially for overpopulated buildings like school. The window filtration ventilator is a new idea which replacing one part of the window frame by a ventilator with filter, and it is considered suitable to improve on air quality in the classroom. However, the practical use of the new kind of ventilator in an actual room is still needed to be verified. This paper aimed at investigating thermal comfort and air quality in rooms by both experimental and numerical methods, both before and after window filtration ventilator had been installed.

INTRODUCTION

Indoor air quality influences the people's health and thermal comfort, because about 85% of the lifetime of a person are in the indoor environment (Klepeis et al. 2001). Providing an adequate quantity of fresh air to occupied areas are necessary for dilution of indoor CO_2, airborne particles and other gas pollutant (Awbi 2003). However, the outdoor air quality becoming worse and worse in recent years (van Donkelaar et al. 2010), especially in developing countries. Moreover, many articles indicated that outdoor particles contribute to indoor particle pollution significantly (Abt et al. 2000; Kopperud et al. 2004; Turpin et al. 2007; Chen and Zhao 2011). For classrooms, inadequate ventilation was considered the main cause of health symptoms (Clements-Croome et al. 2008, Bakó-Biró et al. 2012) In order to cope with this situation, supplying purified fresh air is needed instead of simply delivering outdoor air into the room without any control. The window filtration ventilator is a brand new ventilation device which replacing one part of the window by a mechanical ventilator. Fig 1 showed the design sketch and the original designed model. The ventilator is the positive pressure source in positive pressure fresh air supply system, which is designed to have the air filtration capability.

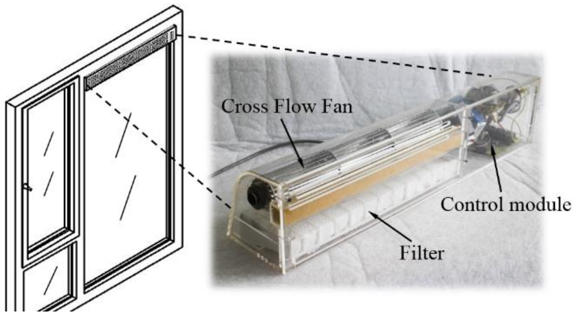


Figure 1 Window Filtration Ventilator

To evaluate the thermal comfort in the room, air velocity and temperature was the most influencing parameters (Fanger 1970). To evaluate the air quality, the concentration of CO_2, local mean age (LMA) and local mean residual lifetime (LMR) were involved in the analysis. As shown in Figure 2, LMA and LMR are defined based on the concept of "age of air" (Sandberg 1981), which were to examine ventilation efficiency. As air can reach the point through various paths, the mean value of the ages at the point is called the local mean age (LMA) of the air at P. Likewise, the length of time required for the contaminant located at P to reach an exhaust is called the residual lifetime of the contaminant at P. The mean value through various paths is the local mean residual lifetime (LMR).

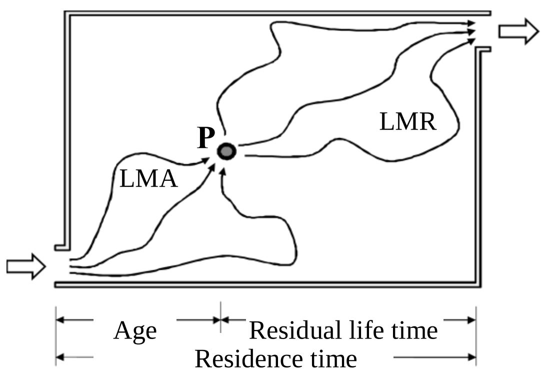


Figure 2 Concept of age and residual lifetime of indoor air. (Hwataik Han 2012)

Currently, these parameters mentioned above are typically obtained by two main methods: experimental measurements and numerical simulations, predominantly computational fluid dynamics (CFD) simulations. Since Nielsen 1974, who was the first one to apply CFD to room airflow prediction, applications of CFD for airflow predictions in enclosed spaces have become popular (Chen 2009). Compared with experimental study, CFD simulation is less expensive and more efficient. However, since the turbulence models in CFD used approximations, the simulation results may contain uncertainties. Therefore, the CFD results need to be validated by corresponding experimental data before CFD can be used for further studies. (Chen and Srebric 2002)

In this study, the research object is a typical classroom of a primary school in Beijing, China. The window filtration ventilator is considered to supply purified fresh air into the classroom. Before the large scale application of the ventilator, its effects on thermal comfort and air quality must be investigated in advance, especially in winter, which probably have bigger thermal comfort risk using the new kind of ventilator.

METHODS

Boundary conditions

The object of our study was a typical classroom of a primary school in Beijing, China, in winter, as shown in Figure 3, which was very likely to have big problems with fresh air, both because of the overcrowded of people and polluted outdoor air. The size of the classroom was 8.5 m × 6 m × 3 m. The room had three windows in the middle of the south wall, and two doors in the both sides of the north wall. All the sizes of the windows were 1.7 m × 1.4 m and 1 m above the floor. Under the windows, there were three heaters inside the wall. During the class hours, there were always 30 children in the classroom.

Figure 3 The photograph of the classroom.

To obtain the thermal boundary condition of the classroom, an infrared camera (InfraTec VarioCAM® hr research, Dresden, Germany) was used to measure the temperature of each wall, window, heater and pupil. The thermography of a window and a heater was shown in Figure 4, and the detailed thermal boundary condition was given in Table 1.

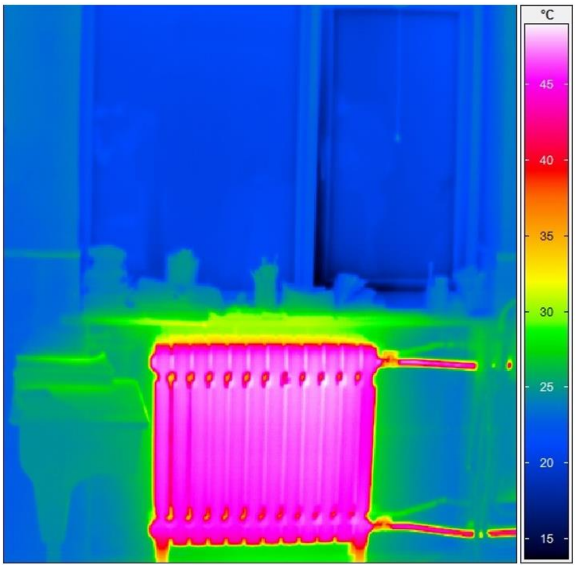


Figure 4 The thermography of a window and a heater.

Objects	Temperature (℃)
Pupils	30
Heaters	46
Windows	16
Desk	23
Wall (front)	20
Wall (back)	20
Wall (left)	19
Wall (right)	21
Wall (ceiling)	22
Wall (ground)	19.5

Table 1 The surface temperature in the classroom

The ventilation rate was calculated by the tracer gas method with human body released CO_2 (Sandberg and Sjöberg 1983, Sherman 1990). The instantaneous concentration of CO_2 was monitored by two 1% CO2 + RH/T Environmental Data Logger (CO2 Meter Inc., Ormond Beach, USA) in the classroom during a typical school day. Assuming that the air in the room was fully mixed, due to the conservation of air and CO_2, Equation (1) was given:

$$V\frac{dC_{in}}{d\tau}=Q\left(C_{out}-C_{in}\right)+S \qquad (1)$$

where, C_{in} was indoor CO_2 concentration, mL/m³; C_{out} was outdoor CO_2 concentration, mL/m³; Q was the ventilation rate, m³/s; τ was the time, s; V was the volume of the classroom, m³; S was the CO_2 emission rate of inner source, mL/s.

Integrating τ of Equition (1), we can obtain Equition (2):

$$(C_{in} - C_{out}) = (C_{in,0} - C_{out})e^{-\frac{Q}{V}\tau} + \frac{S}{Q}(1 - e^{-\frac{Q}{V}\tau}) \quad (2)$$

The measured real-time concentration data could calculate air-leakage rate of the classroom and CO_2 release rate by pupils: when no people in the classroom (just after class), the decay of CO_2 concentration was all caused by the air-leakage of the classroom, which calculated the air-leakage rate; during the class, the concentration of CO_2 would step up, and the CO_2 release rate could by calculated from the data in this period. Moreover, with the emission rate of the CO_2 calculated, we can calculate the fresh air volume needed by the classroom.

Computational Models

Simulation of the distribution of airflow and CO_2 concentration in the classroom uses a commercial CFD software ANSYS Fluent v.15.0 (ANSYS Inc. 2013a), which based upon the numerical model of "Finite Volume Method" (Versteeg and Malalasekera 2007). This software solved the transient, three-dimensional, viscous, incompressible unsteady Reynold-Averaged Navier-Stokes (RANS) equations. These conservation equations describing these transport phenomena were of the general form as Equation (3):

$$\frac{\partial \rho \phi}{\partial t} + \vec{\nabla} \cdot \left(\rho \phi \vec{V} \right) = \vec{\nabla} \cdot \left(\Gamma_{\varphi} \vec{\nabla} \phi \right) + S_{\varphi} \quad (3)$$

where: $\vec{\nabla}$ is the velocity vector; Γ_{φ} is the diffusion coefficient and S_{φ} is the source term. The symbol φ represents the concentration of the transported quantity.

For a relatively low Reynolds number flow in a room, RNG k - ε turbulence model (Choudhury 1993) is recommended by Zhang et al. 2007. A detailed discussion of the RNG k - ε model can be found in ANSYS Inc. 2013b. This research simulates the air flows by RNG k - ε model. The calculations are isothermal so buoyancy and thermal effects are neglected and the ideal gas law is used. The solutions are considered converged when the normalized residuals are less than 10^{-3}.

According to (Sandberg 1981), we compiled the UDFs (user-defined functions) to obtain the LMA value in computational domain. As the calculated flow pattern has been fixed, the air age from inlet to P point and from P point to outlet was determined, as shows in Figure 2. Hence, we use another UDF to reverse the whole flow pattern, and assign the air age of outlet is zero, so that we could use the same UDF compiled for LMA to obtain the value of LMR.

RESULTS AND DISCUSSIONS

Air-leakage rate

The air-leakage rate of the classroom was calculated by the CO_2 concentration data after class, shown in Figure 5. In this figure, the relative concentration of CO_2 was calculated by the difference between the indoor and outdoor concentration that was assumed to be 400 ppm. During this period, there were no people in the classroom and the windows and doors were force to be closed, and the decay of the relative CO_2 concentration was all caused by the leakage of air through the slots of doors and windows. By curve fitting and comparing to Equation (2), the air change rate was 0.00827 1/min (0.48 1/h), and then the air-leakage rate of the classroom was calculated as 74.9 m^3/h.

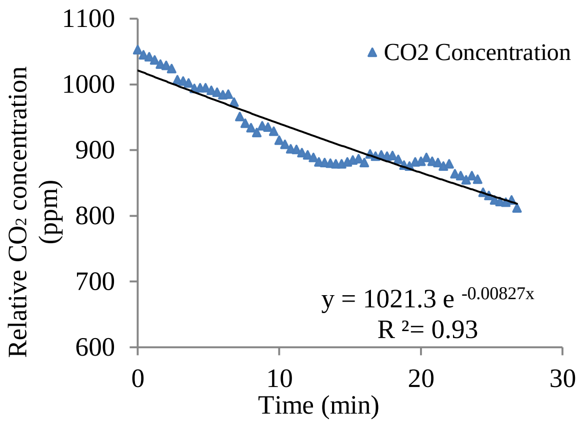


Figure 5 The decay of CO2 concentration after class and the fitting curve.

CO_2 emission rate

During the class, all the students and teacher were in the classroom. In a period of class hour, the windows and doors were forced to be closed in order to calculate the emission rate of people in the classroom. In the Equation (2) this time, Q is the air-leakage rate calculated in the last section, and the emission rate is calculated by curve fitting as shown in Figure 6, e.i., the CO_2 emission rate of inner source is 1701 ppm/h. To simplify the boundary conditions of simulation, the emision rate was averaged by 30 children. To control the concentration of CO_2 not exceeding 1000 ppm, the needed fresh air was calculated by mass conservation, and the total needed airflow rate of window filtration ventilator was 442.6 m^3/h

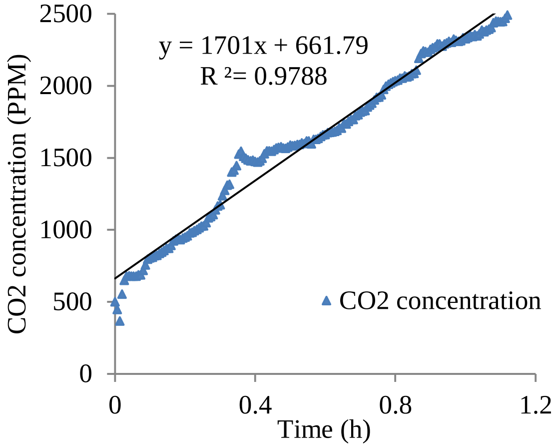
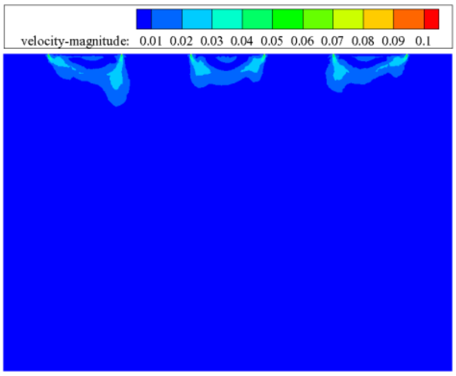


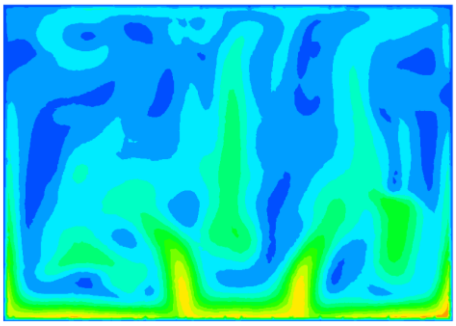
Figure 6 The step-up CO_2 concentration during class time and the fitting curve

Thermal comfort

The distribution of airflow and temperature in the classroom was shown in Figure 7. The contour maps were all at 1.2 m high from the ground, which were considered to be the “breathing zone” of pupils. Figure 7 (a) and (b) shows the distribution of velocity From the figure, we can find that the airflow distribution in the occupied area was relatively small (below 0.1 m/s) and uniform, which thought to have good contribution to thermal comfort. Figure 7 (c) and (d) shows the distribution of temperature before and after using the ventilator. When using the ventilator, although the average temperature would drop 2.3 ℃ in the occupied zone, the distribution of temperature would be more uniform due to the airflow mixing effect.



(a)



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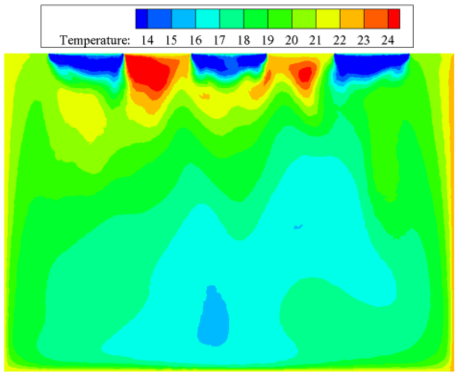

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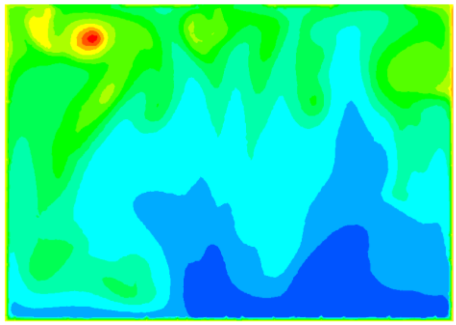
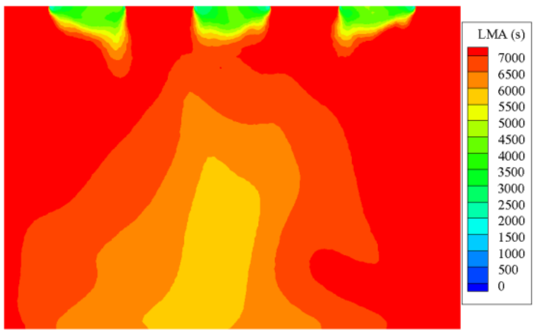


(d)

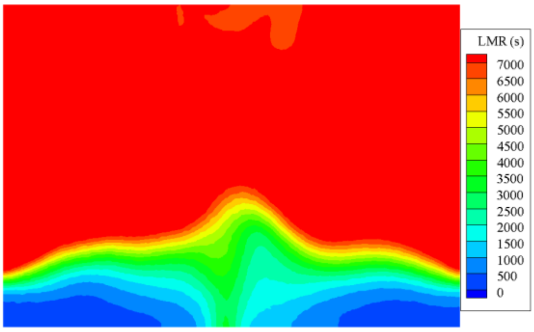
Figure 7 The distributions of velocity and temperature before and after using the ventilator.

Air quality

The air quality was evaluated by LMA and LMR in this study. Before using of window filtration ventilator, the distributions of LMA and LMR were shown in Figure 8 (a) and (b), and the mean value of them is up to 6720 s and 6588 s, which showed a bad ventilation effectiveness in the classroom. That is to say, when the windows and doors closed, the CO_2 released from people would be accumulated very fast. After using the ventilator, the two distributions were in Figure 8 (c) and (d). By comparing the distribution of LMA and LMR before and after using the ventilator, and the mean of them were 1344 s and 1334 s. By comparing LMA and LMR before and after using the ventilator, we can find that there was a significant improvement on air quality of the classroom.



(a)



(b)

(c)

(d)

Figure 8 The distribution of LMA and LMR before and after using the ventilator.

CONCLUSIONS

In this study, thermal boundary conditions were obtained by a thermography, and velocity boundary conditions (ventilation rate) were calculated by the measured varying curves of CO_2 concentration. Then the parameters, which determined thermal comfort and air quality in the classroom, were investigated through a RNG k - ε turbulence model. By comparing the distribution of temperature before and after using the ventilator, we can find that using the new kind of window filtration ventilator would not lead to thermal comfort problems due to the temperature drop was acceptable. Moreover, from the distribution of LMA and LMR, we can find that the classroom would have a substantial improvement in air quality using the ventilator. Hence, this study proved the feasibility of the new kind of ventilator.

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