# Optimal window opening based on natural ventilation measurements

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## ABSTRACT

From the energy point of view, buildings should be as tight as possible. But lack of ventilation will result in high level of indoor pollutants, which is harmful for occupants. Numerous studies find that lack of ventilation could cause symptoms for occupants, which are characterized by World Health Organization as Sick Building Syndrome.

There are lots of real-time ventilation data and rational ventilation standards in the world. However, these kinds of measurements lacks in China, so more data is needed. In China, most public schools have neither air condition nor mechanical ventilation, so the main form of ventilation is natural ventilation. Thus, it is crucial to do research in measuring the natural ventilation rate in order to improve the indoor environment.

Natural ventilation is mainly driven by heat buoyancy and wind pressure. The lowest air change rate happens when the wind speeds and temperature differences are low. If the quantity of fresh air can satisfy the ventilation standard under these circumstances, the natural ventilation can satisfy most conditions.

According to climate data, the days in which wind speed is below 0.5m/s accounts for about 26%. Most of the school buildings aren't located in open areas. Furthermore, in consideration of the emergency evacuation for the children, the school buildings are built only with 1-3 floors. So, the disturbances of the surrounding buildings contribute to low wind speeds around the school building.

The time period between cooling and heating seasons usually comes with low indoor and outdoor temperature difference, where most classrooms have open windows for ventilation. It is therefore important to find out whether the ventilation rate is sufficient during this period of time.

The measuring method is based on the release of a stable rate of the tracer gas $CO_2$ given off by solid $CO_2$ (dry ice) in an insulated box. In theory, the dry ice will sublime at a constant rate as long as there is sufficient dry ice in the box. Thus, the dry ice sublimation rate should remain constant at any time once the steady state heat transfer condition has been reached.

The results of the measurement can enrich the database of the Chinese current ventilation situation. The early-design-stage predictions of natural ventilation performance in renovated buildings provide reference to the design of natural ventilation systems.

## KEYWORDS

Natural ventilation; Tracer gas; Constant injection; Optimal window opening; Energy saving

## 1 INTRODUCTION

Indoor environment is an integral part of people's lives as we spend most of our lifetime indoors, making ventilation an important role in built environment (Sundell 2004).

Also, ventilation affects heating and cooling seasons, which has a huge impact on energy loads of buildings. Nowadays, energy saving is becoming a priority in many countries, especially in China. In this case, tightening and insulating of a building envelope as well as ventilation reduction have been the main saving tendencies. Laws and standards on buildings' air-tightness are ratified, and people applied the approaches in most new and renovated buildings.

From the energy point of view, buildings should be as tight as possible. So, buildings have become significantly tighter. But the consequences of these steps, unfortunately, were not always thoroughly considered. For instance, low infiltration rate is a serious problem resulting from the relentless tightening of building envelopes.

On the other hand, the role of ventilation in school buildings plays an important role because the amount of supplied fresh air not only have a direct effect on health, but also indirectly influences the presence and concentrations of allergies' risk factors, such as dampness and mold, home dust mites, environmental tobacco smoke, etc. Young children are also more sensible to most indoor pollutants. (Bornehag, Sundell et al. 2005, Ridley, Pretlove et al. 2006, Kolarik, Naydenov et al. 2008)Furthermore, studies have confirmed that there's strong relationship between study efficiency and supply of fresh air. Thus, sufficient ventilation is essential to peoples' health as well as their study performance (Bakó-Biró, Clements-Croome et al. 2012).

In China, most public schools don't have mechanical ventilation, so the main form of ventilation is through natural ventilation, where people get fresh air from opening windows.

But according to questionnaires collected from primary school teachers, most teachers have the sense of ventilation, but they don't have fixed habits of opening windows, because they have no idea when and how much to open the windows to ensure proper amount of fresh air.

Therefore, a theoretical background for how many windows (based on window area) have to be opened during a natural ventilated classroom for a year is required, in order to maintain a healthy indoor environment. Only by this way, a balanced ventilation rate to ensure both energy saving and good indoor environment is ensured.

In order to know the amount of window openings required, the ventilation rate has to be measured. The minimum required ventilation rate is taken from the national standard. Thus, conducting quantitative analysis upon this indoor environment factor, ventilation rate is introduced. The usual ways to measure the natural ventilation rate includes blower door test、CFD simulation and tracer gas (TG) method. This paper uses field measurements by tracer gas (TG) method to get the ventilation data.

The TG methods can be classified based on the type of control and injection method. Three of the frequently used methods are: decay-, constant injection (emission)-, and long term average method – passive perfluorocarbon tracer gas (PFT) method.

The measurement is designed to find out the relationship between the temperature difference and ventilation rate for the specific classrooms, so plenty of ventilation data under different temperature differences are need. Thus, the decay method isn't a suitable for long-term measurements. Moreover, the low control of taking samples (the sampling time is chosen approximately according to the time of tracer gas injection) decreases the accuracy of the method rapidly during unsteady ventilation rate. In passive perfluorocarbon tracer gas (PFT) method, little amount of tracer gas is needed, the analyses procedure is complicated and recently there are only few laboratories in the world, which can perform PFT analyses.

So when measuring long-term unsteady ventilation rates, the only method possible method is the constant injection method (Sherman 1990, Roulet and Vandaele 1991, McWilliams 2002).

Unlike the heating and cooling season, where the indoor temperature is kept constant, the time period in-between usually comes with low indoor and outdoor temperature difference, where most classrooms have open windows for ventilation. It is therefore necessary to find out the indoor temperature for these periods of time. In order to get the whole years' data of indoor temperature, simulation is applied. The parameters are set based on the real conditions. The temperature difference and ACH relevance was measured during April, with no heating or cooling present. The results of this measurement give the minimum temperature difference for efficient natural ventilation driven by buoyancy.

The results contribute in enriching the database of the current Chinese ventilation situation. Furthermore, according to the results, under the present situation in renovated buildings, the paper provides a window opening guidance to rectify peoples' behaviour in natural ventilation

And the early-design-stage predictions of natural ventilation performance in renovated buildings could provide reference to the design of natural ventilation systems.

# 2 METHOD

## 2.1 Description of test site

One type of classroom, with a total of 4 classrooms, was measured in a primary school, the corridor outside and the inside picture of the classroom are showed in Fig.1 and Fig.2. The school is situated in Beijing, China. The dimensions of the classrooms are showed in Fig. 3, where the room volume is 17 $m^3$.

The heating season is from Nov.15 to Mar.15, with an indoor temperature about 18 °C; the cooling season is from June to August, where the indoor temperature is mostly maintained at 22-26 °C. The remaining days of the whole year are concluded in the transition season, during which there are no heating and cooling applied in the classrooms.

Classes last from 8:00 to17:00, Mon-Fri, and summer and winter vacation both lasts 7 weeks.

All field experiments were conducted during transition season with no heating or cooling approaches.

All classrooms have no mechanical ventilation, with windows facing both north and south direction. The field measurement was conducted with doors shut and 3 windows on one side widely open.

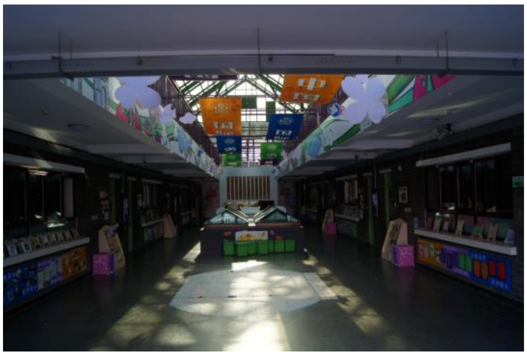

Figure 1: Corridor outside the classrooms.

Figure 2: Indoor picture of a classroom.

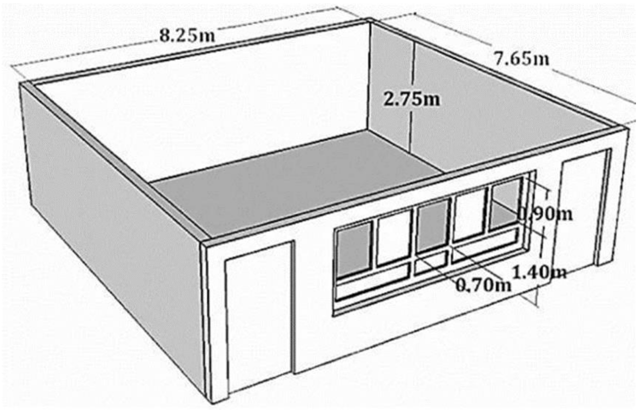


Figure 3: Classroom dimensions.

## 2.2 Calculation of ventilation rate

Based on the conservation of mass, the relationship can be presented as follows:

$$F + Q \times C_e = V_{zone} \times \frac{dc}{d\tau} + Q \times C \quad (1)$$

The ACH calculation process for the constant injection method is based on a parametric iteration technique, where the change in the tracer gas concentration between two measurements (indoor and outdoor concentrations) can be expressed as (Šťávová 2012)：

$$\Delta C = \frac{\Delta\tau}{V_{zone}} \times (F - N \times V_{zone} \times (C_1 - C_e)) \quad (2)$$

ΔC- change of tracer gas concentration
Δτ- time interval,
$V_{zone}$- zone volume,
F – constant tracer gas injection rate,

N- number of ACH,
$C_1$- indoor tracer gas concentration,
$C_e$- outdoor tracer gas concentration.

The unknown parameter is N, with all the rest as input values. The calculation was repeated for each consequent time interval to get a theoretical curve. The $C_1$ is the first concentration measured of the time interval, followed by a theoretical concentration $C_{2,t}$ at the end of the time interval calculated as a sum of the initial concentration ($C_1$) and the individual step increase ΔC. The calculation process is repeated for every single following time interval, giving a theoretical exponential curve of $C_{2,t}$.

At last, Eq. 2 was applied to calculate the difference between the measured and theoretical values. The Solver tool Add-in in Microsoft Excel was then used for the curve fit to minimize the sum of the errors between the measured and theoretical values, so that the value of N is found.

$$\min\left\{\sum_i Error(C_{i,t})\right\} \rightarrow min\left\{\sum_i (C_1 - C_{i,t})^2\right\} \quad (3)$$

Index i=0…k, where k is the number of measured concentrations

The ventilation rate, Q, was then calculated with Eq. 4.

$$Q = N \times V_{zone} \quad (4)$$

The measured indoor $CO_2$ concentration was divided up between step-up, constant and decay concentration in order to calculate the ventilation rate. The calculated sums of the errors were small due to this method, and varied between 1-5%, so the curve fit had an error of 1-5%. This calculation method is applicable with a variable indoor tracer gas concentration, when the ventilation rate is unsteady.

## 2.3 Tracer gas

The tracer chosen for the experiment was $CO_2$. The dry ice in an insulated box works as a constant injection tracer source, releasing a constant rate of $CO_2$ (Cheng and Li 2014). The box was rectangular shaped with 5 cm thick polyurethane insulation material, with exit hole at the top, as shown in Fig. 4.

Figure 4: Dry ice box.

Each classroom had one or two boxes with 15 kg dry ice, which was enough to satisfy the indoor tracer gas concentration for 2-3 days. Each box was refilled with dry ice when necessary. The weight loss of the dry ice box was used to calculate the emission rate of $CO_2$, $F_{CO2}$, with the following equation:

$$F_{CO_2} = \frac{m \times V_m}{M_m} \quad (5)$$

$CO_2$ concentrations were measured with *Telaire* 7001 sensors. The measuring range of the sensors is between 0-2500 ppm with an accuracy of ±5%. The $CO_2$ concentration was measured with a logging interval of 1 min. Four sensors were positioned inside each classroom at different positions in order to verify that the indoor concentration was uniform. The average was used between the four sensors. Two $CO_2$ sensors were used to measure the outdoor concentration, positioned in the corridor.

## 2.4 Temperature

The ventilation rates in the measurement are mainly influenced by the buoyancy effect only. In order to get the indoor and outdoor temperature difference, two temperature sensors were positioned in the centre of the room and one outdoors. The temperature was measured with *Air Temperature and Humidity Meter WSZY-1*, with an accuracy of ±0.1 °C.

## 2.5 Wind speed

To ensure that natural ventilation is driven by buoyancy pressure regardless of wind pressure, a wind sensor, *Wind Micrometer 5825* with an accuracy of ±0.1m/s, was used to measure the wind speed. The ACH data used are under the condition that the wind speed then is no more than 0.5 m/s. The sensor was positioned in the middle of the corridor, facing towards the outside.

## 2.6 Simulation of indoor temperatures

Since outdoor temperature can be known from climate data, simulation of indoor temperature is required, in order to get the buoyancy pressure conditions for the entire year.
The indoor temperature can be found through different ways. Due to limited time, this study used simulation. Regardless of the wind pressure, the simulation used a *Building Information Modeling* software named *DeST (Yan, Xia et al. 2008)*. The building envelope parameters are based on the real-time conditions. Parameters of heat generations are shown in Table 1.

Table 1: Heat generation parameters.

| Parameter | Heat generation [W] |
|---|---|
| People (36 total) | 62* |
| Lights | 360 |
| Equipment | 0 |

*Number indicates the heat generated per person.

# 3 RESULTS

This part shows the results from the field experiment in four classrooms using single-sided ventilation. There were no people, or equipment, nor other disturbances present during the measurements, except two times per day weighting the dry ice which only took half minute per room.

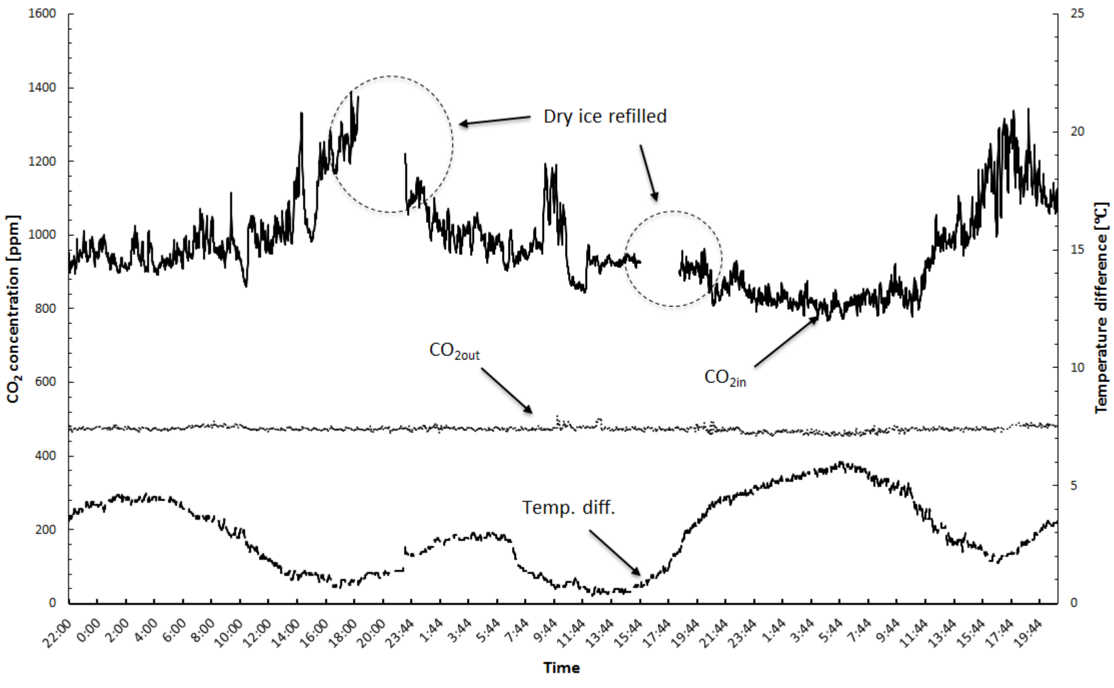


Figure 5: Indoor and outdoor $CO_2$ concentration and temperature difference.

Fig. 5 shows the data for the calculation part for 3 continuous days. The indoor $CO_2$ concentration was averaged, because the sensors had a position difference of less than 10 %. For the calculation of ventilation rate, the indoor $CO_2$ data was divided between: step-up, constant and decay. In order to calculate the ventilation rate with minimal curve fit errors, the time interval was set to 0.5h for the calculation part, which the temperature remains constant during the interval. So the temperature difference during the interval was averaged.

The calculation results are showed in Fig. 6, consisting of over 500 data points.

The horizontal axis represents the temperature gradient $\sqrt{\left(\frac{T_{\mathrm{i}}-T_{\mathrm{o}}}{T_{\mathrm{i}}}\right)}$ and the vertical axis represents the ventilation rate in the classroom.

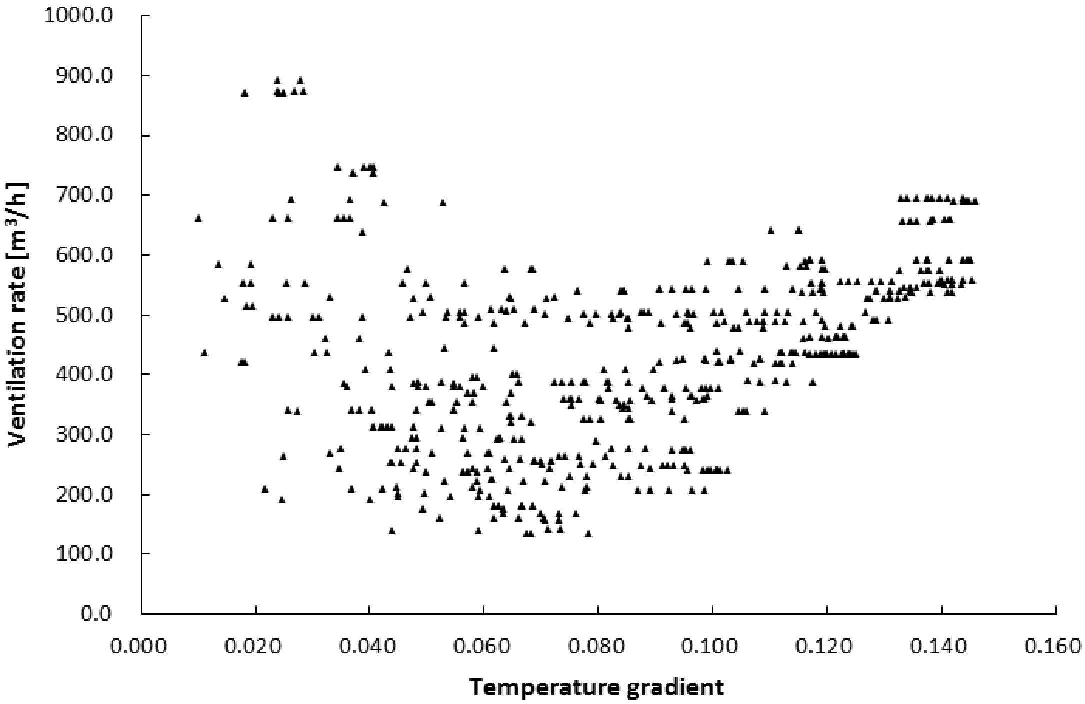


Figure 6: Ventilation rate and temperature gradient comparison.

After excluding the data for wind speeds over 0.5 m/s, the linear relationship is shown in Fig. 7, consisting of over 350 data points.

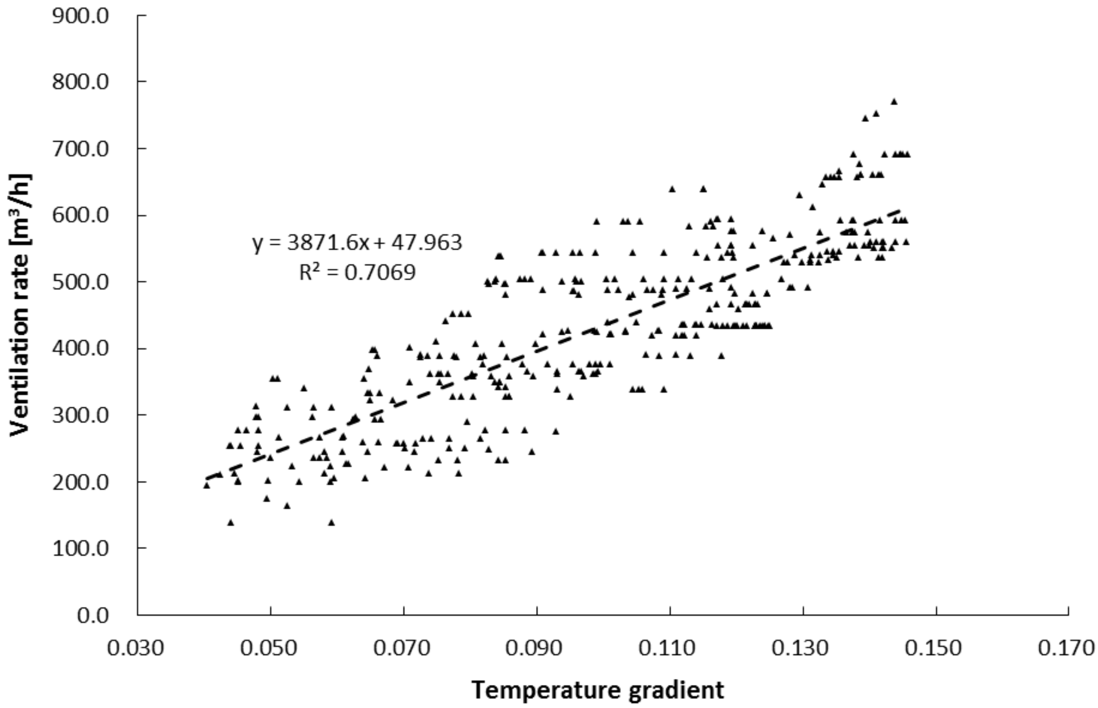


Figure 7: Ventilation rate and temperature gradient comparison.

Comparison of results between the tracer gas method and Bernoulli equation is showed in Fig. 8.

$$Q = \frac{1}{3} C_{\mathrm{D}} A \sqrt{g H \frac{T_{\mathrm{i}}-T_{\mathrm{o}}}{T_{\mathrm{i}}}} \tag{5}$$

Where discharge coefficient $C_D = 0.7$; area of the window is A=3*0.7*0.9; the height of the window is H=0.9
;
Since most of ventilation rates are between 0.75 and 1.25 theoretical values, the error ratio is considered less than 25%.

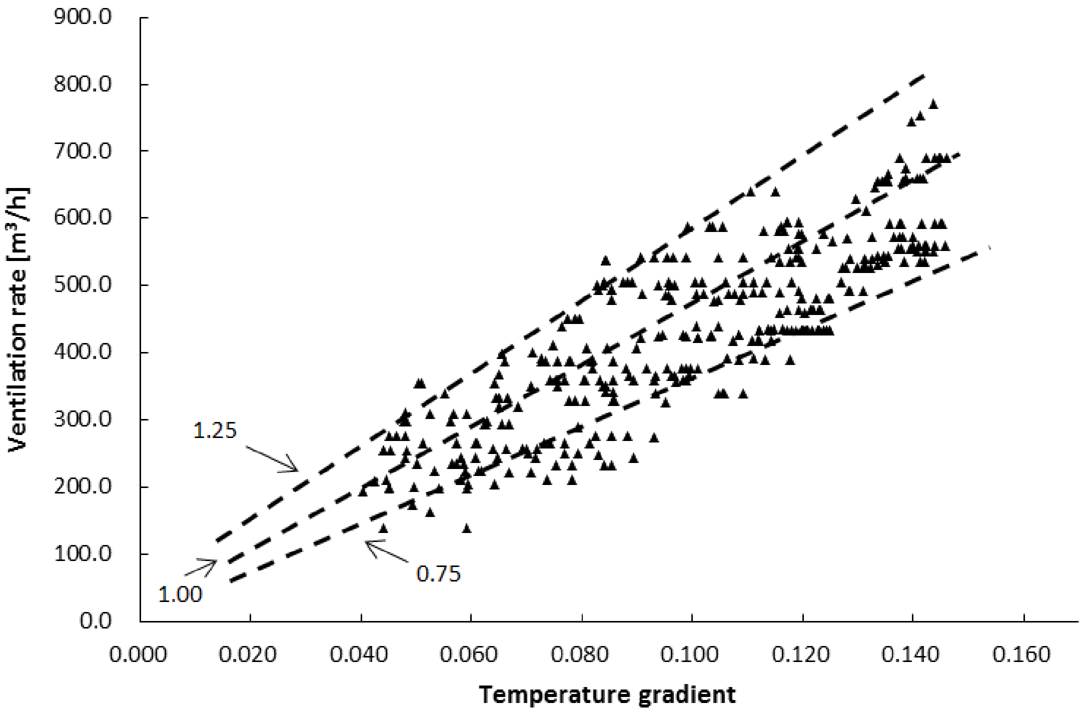


Figure 8: Comparison of measurement results and Bernoulli equation.

Based on an entire year temperature difference from the simulation results during day time, the proper window opening suggestions are given in Table 2.

Table 2: Open-window suggestions

| **temperature gradient** $\sqrt{\left(\frac{T_i - T_o}{T_i}\right)}$ | **Suggested number of opened windows** |
|---|---|
| >0.29 | 1 |
| 0.14-0.29 | 2 |
| 0.09-0.14 | 3 |

# 4 DISCUSSION

The field experiment of the ventilation rate measurement can have several deviations, since there was no artificial mixing. Thus, the uniformity of the tracer gas in the classrooms can’t be 100% ensured. Furthermore, the interval for the ventilation rate calculation is 0.5h, during which, the temperature may change. Lastly, the simulation model can’t represent the real-time indoor temperature of the classroom.

The results enrich the ventilation database in China, and could increase peoples’ attention to their own behavior in opening of windows. Also, the results are available in the early-design-stage of the building design. The predictions of natural ventilation performance in renovated buildings could provide reference to the design of natural ventilation systems.

Others can use the field measurement to obtain the relationship between ventilation rates and temperature under low wind speed. Then find out the temperature inside and out for several temperature differences, for example, 0-5, 10-15 and 20-25°C, where field measurement is also available: by measuring a day or two in typical months. At last, a window opening guide for the teachers can be given.

The measurements purely consider the effect of buoyancy pressure, regardless of the wind pressure. Future work can test cross-ventilation as well, since single-sided and cross ventilation is totally different. Cross ventilation is much more wind sensitive, making it hard to measure in real-time situations.

## 5 CONCLUSIONS

This paper measured ventilation rates with constant injection method to get natural ventilation rates driven by buoyancy pressure in classrooms in a Chinese primary school located in Beijing. Based on the data measured, the relationship between ventilation rate and temperature difference is found. Then, simulation is applied to find the indoor temperature in the classrooms for an entire year. Combined with the climate data of the outdoor temperature, the temperature difference of the whole year can be known. At last, a window opening strategy depending on the indoor and outdoor temperature difference for natural ventilation is provided, in order to save energy.

The results are also available in the early-design-stage of the building design. The predictions of natural ventilation performance in renovated buildings could provide reference to the design of natural ventilation systems.

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