FIELD TESTING OF NATURAL VENTILATION IN TYPICAL COLLEGE STUDENT DORMITORIES IN BEIJING

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ABSTRACT

In Beijing, China, most student dormitories have no individual fresh air systems. Therefore, the dorms can only use natural ventilation to gain fresh outdoor air. In order to evaluate indoor air quality of college dorms in China, it is necessary to measure air exchange rate. However, the existing softwares to simulate single-sided natural ventilation cannot analyze air exchange rate accurately. Therefore, field testing is necessary in order to calculate air exchange rate. This paper uses carbon dioxide exhaled by people as tracer gas to measure air exchange rate. From the measurement results with this method, different field influence factors are discussed. Then, the new modified testing method is applied in the large-scale field testing. Finally, a more convenient and reliable empirical equation to estimate air exchange rate is put forward.

KEY WORDS

Natural ventilation, carbon dioxide, tracer gas, human emission, empirical equation

INTRODUCTION

In China, most student dorms use natural ventilation, instead of mechanical ventilation. Thus, in order to improve the indoor air quality, fresh outdoor air is necessary from natural ventilation.

In recent years, with the increasing enrolment expansion of universities, China has 22.3 million undergraduates in 2010, which is four times of the number (5.6 million) in 2001[1]. The huge number of undergraduates caused growing concerns about the indoor air quality of Chinese undergraduates' dorms, a type of buildings with highest residential density. The undergraduates' dorms usually have four to eight students per dorm with only natural ventilation. Insufficient fresh air causes poor indoor air quality and consequently influences students' health and learning efficiency. Therefore, it is vital to find out the natural ventilation rate in Chinese undergraduates' dorms.

Although the simulation method has a lot of advantages, e.g. flexibility in shaping the house layout and setting the exact parameters (K.A. Papakonstantinou et al., 2000), the simulation results must be verified by the measurement results. Therefore, since most student dorms in Beijing have a similar dorm type, the empirical equation based on the measuared results is widely useful.

In order to reduce the cost of the large-scale field testing, carbon dioxide (CO_2) exhaled from people is used as tracer gas to measure air exchange rate. This tracer gas method is improved to get accurate results. Different influence factors of the method and field-testing are analysed. Finally, an empirical equation to estimate ventilation rate is put forward based on the large-scale field-testing results.

LITERATURE REVIEW

CO_2-method using human expiration

The tracer gas method using CO_2 produced by people as tracer gas has already been applied in several studies worldwide. Stavova did deep research on the method in Denmark(Stavova.P et al.,2011). Fujikawa M applied the method to measure air exchange rate in multizones in Japan (Fujikawa M et al., 2010). Detlef Laussmann made a large-scale field testing using the method in Germany (Laussmann D et al., 2011). However, due to variations and differences in human expiration intensity, ventilation conditions and usage between foreigners and Chinese, the applicability of the method remains confirmed. In China, Sun Yuexian applied the method to measure air exchange rates in college dorms in Tianjing University (Sun Yuexian, 2010), but she didn't verify the applicability of the method. Considering that CO_2 expiration rate is also an important factor, studies on calculation of CO_2 production has been reviewed. In China, Wang Jun pointed out that human CO_2 expiration rate was related with age, gender, metabolism, body surface area, etc (Wang Jun et al., 2010). As for another related factor——body surface area, Hu Yongmei put forward a more suitable surface area calculation for Chinese people (Hu Hongmei et al., 1999). Overall, there are very a few studies related with the CO_2-method in China.

Simulation and empirical equations

Computational Fluid Dynamics (CFD) is often used to research on detailed information about indoor airflow. Numerical simulation research on contamination distribution in college dorms was analyzed by Ma Ronghua (Ma Ronghua et al., 2008). Different ways of opening windows in student dorms were simulated by Feng Zhiping (Feng Zhiping et al., 2008). Weng Jinping also discussed about open-window locations based on simulation results (Weng Jinping et al., 2009). Most studies using CFD methods focuses on detailed information about indoor airflow and strongly depend on boundary conditions, which may be more complex and not necessary for estimating ventilation rate. With respect to empirical equations, De Gids and Phaff concluded the following empirical equation based on 33 experimental conditions (De Gids et al., 1982):

$$U_m = \sqrt{C_1 U_{10}^2 + C_2 h \Delta T + C_3} \qquad (1)$$

where U_m is average airspeed through the window (m/s), U_{10} is average wind speed measured at the local weather station at referenced altitude of 10 meters above (m/s), C_1 is wind coefficient (without dimension), C_2 is stack coefficient ($m.K^{-1}.s^{-2}$), h window height (m), ΔT is temperature difference (K), C_3 is turbulent coefficient (m^2/s^2). In Equation (1), the airflow rate is proportional to the square root of the temperature difference. Furthermore, DeST Vent, a thermal simulation software developed by Tsinghua University, used Equation (1) as one of the empirical models in the software (Zhang Mingrui, 2011). In other words, empirical equations contribute to improve software simulation and building design.

To sum up, it is both necessary and significant that research on the CO_2-method using CO_2 produced by human as tracer gas to measure ventilation rate in China. By applying the method, an empirical equation for calculating ventilation rate of student dorms is put forward. Therefore, current ventilation of student dorms is evaluated and suggestions for window design are discussed.

EXPERIMENTAL PRINCIPLE

Calculation for air exchange rate

The principle of the tracer gas method to measure ventilation is based on mass balance in a single zone. When people are the only indoor source of CO_2, the equation of mass balance can be expressed by the following eq. (Heidt & Werner, 1986):

$$V\frac{dC_{in}}{d\tau} = Q\left(C_{out} - C_{in}\right) + F \qquad (2)$$

where C_{in} is indoor tracer gas concentration (mg/m^3), C_{out} is outdoor tracer gas concentration (mg/m^3), Q is ventilation rate (m^3/s), τ is time (s), F is volumetric flow rate of tracer gas emission (m^3/s), V is volume of the zone (m^3).

The differential equation can also be described with the following eq:

$$\Delta c = \frac{\Delta\tau}{V}\left[F - nV(C_{in,0} - C_{out})\right] \qquad (3)$$

where $C_{in,0}$ is indoor concentration at the initial moment, C_{out} is outdoor concentration, $\Delta\tau$ is time intervel, Δc is concentration change corresponding to the time period.

Therefore, tracer gas concentration relationship between the moment τ_k and the anterior moment τ_{k-1} is established:

$$C_{in}(k) = \frac{\Delta\tau}{V}\{F - nV[C_{in}(k-1) - C_{out}]\} + C_{in}(k-1) \qquad (4)$$

where $C_{in}(k)$ is tracer gas concentration at the moment τ_k, $C_{in}(k-1)$ is tracer gas concentration at the anterior moment τ_{k-1}.

Because air exchange rate often fluctuates and are easily influenced by weather conditions or indoor people disturbance, the Least Square Method (LSM) is applied to reduce the influence of fluctiations. At one moment, actual indoor concentration is $C_{in}(k)$, and the predicted indoor concentration is $C'_{in}(k)$. The relationship between predicted concentration at the moment τ_k and predicted concentration at the moment τ_{k-1} is

$$C'_{in}(k) = \frac{\Delta\tau}{V}\{F - nV[C'_{in}(k-1) - C_{out}]\} + C'_{in}(k-1) \qquad (5)$$

The relationship between actual and predicted concentration can be found:

$$\min \sum_{k=0}^{k=m} [C_{in}(k) - C'_{in}(k)]^2 \qquad (6)$$

Therefore, air exchange rate is solved by the combination of Equation (5) and Equation (6).

Human emission rate of carbon dioxide

According to ASHRAE Handbook Fundamentals, (2009), an empirical equation for metabolic rate is (Nishi, 1981)：

$$M = \frac{21(0.23RQ + 0.77)Q_{o_2}}{A_D} \qquad (7)$$

where M is metabolic rate (W/m^2), RQ is respiratory quotient (molar ratio of Q_{CO_2} exhaled to Q_{O_2} inhaled, dimensionless), Q_{O_2} is volumetric rate of oxygen consumption (mL/s), A_D is DuBois surface area (m^2).

The measurement of the nude body surface area, originally proposed by DuBois and DuBois(1916) is described by:

$$A_D = 0.202 H^{0.725} W^{0.425} \qquad (8)$$

where W is mass (kg), H is height (m).

Using the calculation model of DuBois surface area into Equation (7) and replacing the met for the unit of metabolism (1 met=$58.1W/m^2$), the human CO_2-emission is well defined as a function of humans weight W[kg], height H [m] and activity level[met] :

$$F = RQ\frac{0.00056028 H^{0.725} W^{0.425} M}{0.23RQ + 0.77} \qquad (9)$$

where F is volumetric rate of CO_2 emission (m^3/s).

The empirical equation proposed by Nishi(1981) was established basing on westerners. Because of the differences in surface area, metabolism and components of diet between westerners and Chinese, the applicability of Equation (9) remains doubtful. As Hu Yongmei researched and Chen Zhiqiang verified, a suitable surface area calculation for Chinese is defined with following model (Hu Yongmei, 1999) :

$$S=0.71H+0.0133W-0.1971 \qquad (10)$$

Thus, a new equation to calculate CO_2 emission is

$$F=RQ\frac{(0.001917H+0.0003456W-0.005321)M}{0.23RQ+0.77} \qquad (11)$$

Both of Eq(9) and Eq(11) for CO_2-emission calculation remain researched and verified.

METHODS RESEARCH

Uniformity verification of indoor CO_2-distribution

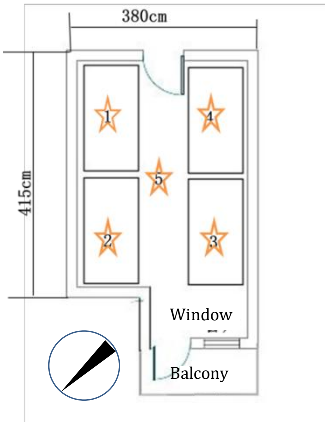

Figure 1 Student dorm plan

There are four students each room with a volume of 51.3m^3 and four beds. Each room has two doors on both sides of the room, with one facing balcony and another facing the corridor. The plastic steel window faces northwest and is located 1.1m high above ground. The window is sliding type and maximum opening area is 0.4m^2. During all the experiments in this paper, doors of both sides are closed and only the window could be opened. None of the dorms have mechanical ventilation system. Therefore, the ventilation of the dorms are considered as single-sided natural ventilation. Besides, human behaviours, such as reading and sleeping, were recorded in order to evaluate metabolism.

To verify the uniformity of indoor CO_2-distribution, five CO_2 measurement locations were tested in the room. The locations are marked as star symbols in Figure 1. Location 1,2,3,4 are located below each bed respectively and location 5 is in the center of the dorm. The locations were 1.5m above the ground, and the total height of the room is 3m. Lack of enough sensors to measure all the locations simultaneously, the uniformity was verified by a series of experiments, with three or four locations tested each time.

As for the data processing, firstly, air exchange rate n(i) can be solved by a single point respectively. Secondly, average concentration of the dorm can be obtained by the mean concentration of the locations, thus, average air exchange rate is solved. Relative error of a single point is judged by the following equation:

$$\text{Relative error}=\frac{\left|n(i)-\bar{n}\right|}{\bar{n}}100\% \qquad (12)$$

- Verification of location points 1, 2, 3, 4

Set up the CO_2-sensors on the location 1,2,3,4 and CO_2-concentration trends were recorded:

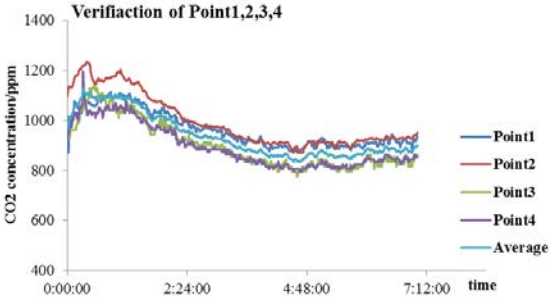

Figure 2 Verification of location point 1,2,3,4

According to human behavior recorded, after 1:30am, students in the dorm were all asleep and the CO_2 emission rate decreased gradually and became stable. At the same time, the indoor CO_2-concentration reduced correspondingly. From 2:30am to 5:30am, the CO_2 emission rate and indoor CO_2-concentration were relatively steady. The air exchange rate also had a relatively less fluctuation. So the period from 2:30am to 5:30am was suitable for calculating air exchange rate. During this period, the average outdoor wind speed was less than 0.2m/s, dominant wind direction was southwest, the outdoor temperature was 23℃ and the indoor temperature was 26 ℃ . The window size was 0.4 m^2.

The calculation results of air exchange rates are shown in Table 1.

Table 1
Results of uniformity experiment 1

	AIR EXCHANGE RATE (h^{-1})	**RELATIVE ERROR**
Point 1	1.4	1.7%
Point 2	1.4	0.2%
Point 3	1.3	4.2%
Point 4	1.4	2.4%
Average	1.4	

- Verification of location points 1, 3, 5

Set up CO_2-sensors at location 1, 3, 5 and the CO_2-concentration trend is shown in Figure 3. The period from 3:30am to 5:30am was chosen to be calculated. During this period, average outdoor wind speed was 0.2m/s, dominant wind direction was northwest. The outdoor temperature was 13℃ and the indoor temperature was 18℃ . The window size was 0.2 m^2.

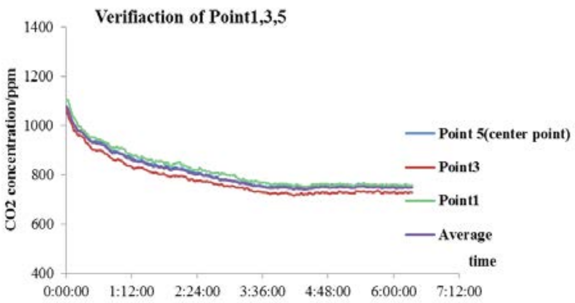

Figure 3 Verification of Point 1,3,5

The calculation results of air exchange rate is shown in table 2.

Table 2

Results of uniformity experiment 2

	AIR EXCHANGE RATE (h^{-1})	**RELATIVE ERROR**
Point 5 (center point)	2.1	2.9%
Point 2	2.3	7.5%
Point 4	2.0	5.0%
Average	2.1	

- Verification of location points 2, 4, 5

CO_2-sensors were set up at location 2, 4, 5 and the CO_2-concentration trend is shown in Figure 4. The period from 3:30am to 5:30am was chosen to be calculated. Average outdoor wind speed was 0.3m/s, dominant wind direction was northeast. The outdoor temperature was 13℃ and the indoor temperature was 18℃ . The window size was 0.2 m^2.

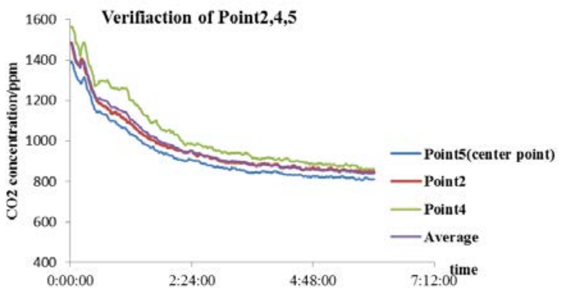

Figure 4 Verification of Point 2,4,5

The calculation results of air exchange rates are shown in Table 3.

Table 3

Results of uniformity experiment 3

	AIR EXCHANGE RATE (h^{-1})	**RELATIVE ERROR**
Point 5 (center point)	1.6	7.3%
Point 1	1.5	1.3%
Point 3	1.4	6.3%
Average	1.5	

According to the uniformity experiments, a single measurement location can represent the average concentration of a dorm, on the condition that outdoor weather fluctuates little and all the students fall into deep sleep with a stable emission rate of CO_2. Less measurement locations are necessary in the large-scale experiment, because it contributes to save a number of CO_2-sensors per dorm.

Verification of calculation equation of human CO_2-emission rate

The experiments were conducted in two individual dorms during the deep sleep state at night. Each dorm had 4 Chinese young females. While the experiments were conducted, all the windows and doors gaps were sealed by adhesive tapes, and the dorms could be regarded as air-tight rooms. Hence, the increasing of indoor CO_2-concentration was affected only by human expiration. An example of the indoor CO_2-concentration trend for a dorm is shown in Figure 5.

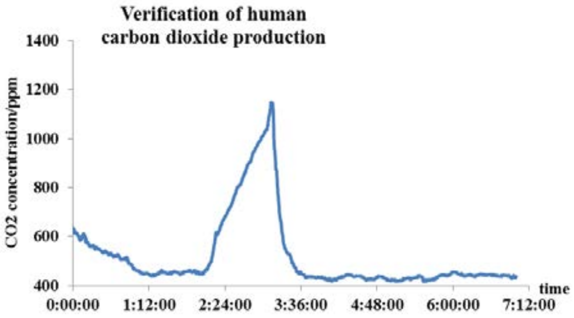

Figure 5 Verification of human CO_2-production

As Figure 5 shows, from 1:30am to 2:30am, the indoor CO_2-concentration was about 430ppm, close to the outdoor concentration. Then from 2:30am to 3:00am, while the room was sealed with tape, there was an obvious increase in the indoor CO_2-concentration. This part was the human CO_2-production rate ($mg.s^{-1}.m^{-6}$). After the experiment, the window was opened again and the indoor concentration decreased fast.

The experimental and theoretical results are compared in Table 4.

Table 4

Comparison results of human CO_2-emission

	DORM A	**DORM B**
The experimental result L/h	28.4	28.6

The theoretical result of Equation (9) L/h	38.9	38.2
Relative error between calculation results by Equation (9) and the experimental result	27.2%	25.1%
The theoretical result of Equation (11) L/h	38.3	37.1
Relative error between calculation results by Equation (11) and the experimental result	25.6%	22.9%

As is shown, the theoretical results calculated by Equation (9) and Equation (11) are obviously larger than the experimental result. The R-squared of CO_2 curve fitting is 0.998, which verified tightness of the dorm and reliability of the results. The result shows that both Equation (9) and Equation (11) are less effective for Chinese, and the modified equation for calculating Chinese human body surface area doesn't contribute much to decrease the errors. A revised factor can be put forward for Equation (9):

$$F^{*} = \varepsilon \cdot RQ \frac{0.00056028 H^{0.725} W^{0.425} M}{0.23RQ + 0.77} \qquad (13)$$

where ε is a recommended revised factor (equal to 0.75) for CO_2-emission calculation of Chinese young females.

Influenced by different diet structure and metabolism, Chinese has a different CO_2 emission rate from westerners, therefore, it is of great significance for further research on Chinese CO_2-emission rate considering ages and genders.

Verification of reliability of the CO_2-method

In order to verify the reliability of using CO_2 expirated by human to measure air exchange rates, the article used sulfur hexafluoride (SF_6) as a second tracer gas for comparison.

At one night from 3:00am to 5:00am, all the students in the dorm fell asleep. The measure locations of SF_6 and CO_2 are both settled in the center of the dorm. The total CO_2-emission rate of students in the dorm was revised as 28.6m^3/h. The average wind speed was 0.3m/s, dominant wind direction was northwest, the indoor temperature was 18℃ and the outdoor temperature was 5℃ ; the window size was 0.1m^2.

The decay trend of the SF_6-concentration in the dorm is shown in Figure 6.

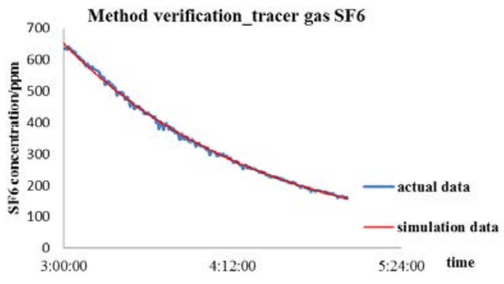

Figure 6 Method verification using SF_6

The CO_2-concentration trend in the dorm is shown in Figure 7.

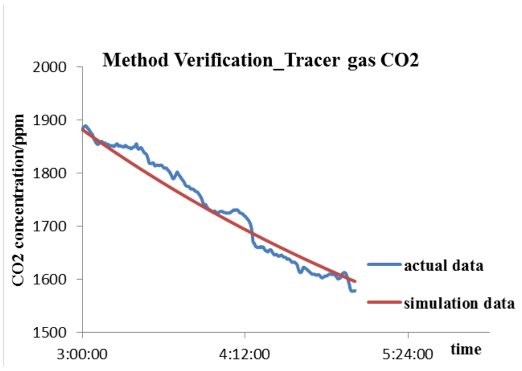

Figure 7 Method verification using CO_2

The results of air exchange rates calculated by the two tracer gases are shown in Table 5.

Table 5

Results of the method verification

TRACER GAS	AIR EXCHANGE RATE (h^{-1})
SF_6	0.71
CO_2	0.78

The air exchange rates solved by the two tracer gases are similar and the relative error was smaller than 10%, which verified the reliability of the CO_2-method.

LARGE-SCALE FIELD TESTING

The large-scale field testing was carried out in a girl's dormitory building in Tsinghua University. The building have six floors, located in the red wireframes marked in Figure 8. The location points in Figure 1, numbered 1,2,3,4, represents northern, southern, eastern and western rooms respectively.

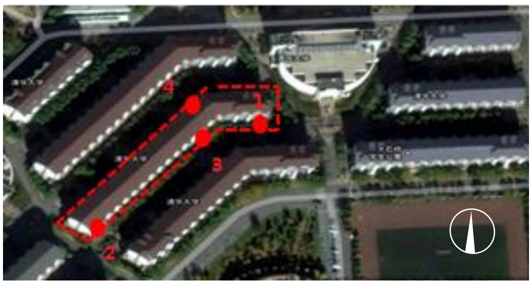

Figure 8 Sketch map of dorm locations

Each room has four students living there, with a room height of 3 meters and a floor area of 17.1 m^2, which is a typical student dorm in China. None of the dorms have mechanical ventilation system, and main ventilated pattern of dorms is single-sided natural ventilation. During the testings, all the doors were closed and only window could be opened. The dorm plan is the same as Figure 1 or symmetrical to it. According to the results conducted from method research, during the experiments, students CO_2-

emission rate was calculated by Equation (13) and the CO_2-measurement location was chosen in the center of room. The testing time was selected at night while the students were considered asleep and the metabolic rate was relatively stable, equal to 0.7met. For another important reason, it is at night that most students go back to the dorms for sleeping, and thus, the dorms has a higher residential density. Also, students spend relatively longer time at night than in the daytime in the dorms.

- Difference on positions

The CO_2-concentration trends in four rooms, one from each location for a night are shown in Figure 9.

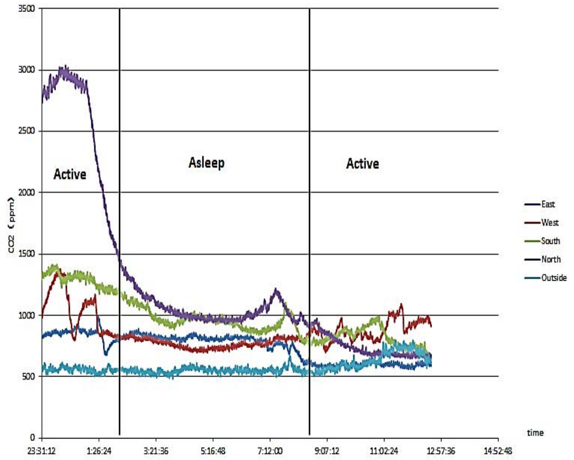

Figure 9 CO_2-concentration trends in different locations

As Figure 9 shows, the outdoor CO_2-concentration of the building remained almost steady, around 500ppm, but in the four rooms it varied. In Table 6, the difference in temperature between indoor and outdoor ranged within 5.4±0.5℃ , wind speed was below 0.4m/s, the dominant wind direction was southwest. The air exchange rates from four rooms are shown in Table 6.

Table 6

Measure results in different positions I

POSITIONS	**AIR EXCHANGE RATE (h^{-1})**
East	1.2
West	1.6
South	1.2
North	1.2

Table 6 shows that air exchange rates measured at the four rooms had some differences. Compared to rooms located northwards, eastwards and southwards that were more likely to be influenced by the surrounding buildings, the western room was less impacted by shelterings and thus had a relatively higher air exchange rate. However, when the wind speed was slower, the differences in the four locations were even smaller. For example, in Table 7, the difference in temperature between indoor and outdoor ranged within 2.5±0.5℃ , wind speed outside was 0.1m/s, and dominant wind direction was southeast. The air exchange rates of dormitories located on different locations are shown in Table7.

Table 7

Measure results in different positions II

POSITIONS	**AIR EXCHANGE RATE (h^{-1})**
East	1.2
West	0.94
South	1.2
North	0.93

Because of the very low wind speed, wind pressure contributed only a little to the air exchange rate of the dorms, and correspondingly, the differences impacted by shelterings were smaller.

In conclusion, the slower outside wind speed is, the less differences of air exchange rates caused by different locations were. When the wind speed was less than 0.5m/s, the differences were very slight.

- Fitted empirical equation

According to the data recorded by meteorological observatory in Tsinghua University, average wind speeds during the summer nights (from May 23rd to August 30th) is shown in Figure 10.

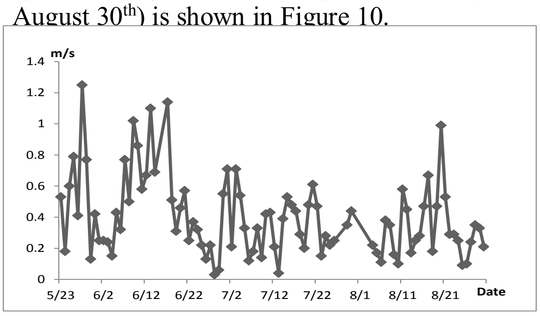

Figure 10 Average wind speeds in summer nights

As Figure 10 shows, about 73% of the nights during summer in Beijing had a wind speed slower than 0.5 m/s. Actually, the low wind speed contributes little to air exchange rate. Eg. Equation (1) (De Gids et al., 1982):

$$U_m = \sqrt{C_1 U_{10}^2 + C_2 h \Delta T + C_3} \tag{1}$$

The best fitted coefficients for Equation (1) based on the experiments De Gids and Phaff conducted are : C_1 equals to 0.001, C_2 equals to 0.0035 and C_3 equals to 0.01. When the wind speed is below 0.5m/s, the value of outside wind speed(U^2_{10}) multiplied by wind coefficient(C_1) is dozens of times smaller than the value of height(h) multiplied by temperature difference(ΔT) and stack coefficient (C_2). Besides, the wind effect in single-sided ventilation is more difficult and complex to analyze, because of the rapid fluctuations of wind speed and direction (turbulent diffusion) (Haghighat F et al., 1991). Therefore, the model suitable for student dorms in Beijing could be simplified to only establish the relationship between air exchange rate and temperature difference between indoor and outdoor. Thus, in following discussions, only the cases where the wind speeds less than 0.5m/s were chosen to be analyzed. The relationship between air exchange rate and square root of temperature difference was fitted in Figure 11.

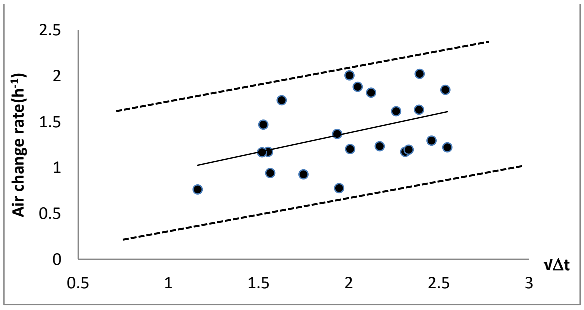

Figure 11 Relationships between air exchange rate and corresponding temperature difference

According to Figure 11, an empirical equation for calculating air exchange rate of student dorms can be described as the following linear equation:

$$N=0.42\sqrt{\Delta T}+x \qquad (14)$$

where N is air exchange rate (h^{-1}), ΔT is temperature difference between indoor and outdoor (℃), C_n is a coefficient(equals to 0.42), and x is a correction factor (ranging from 0 to 1.15 h^{-1}).

Table 8

Correction factor for the Equation (14)

SHELTERING DESCRIPTION	**CORRECTION FACTOR X**
No shieldings around	1.15
Partly-sheltered by buildings	0.55
Sheltered by buildings all around	0

For the large intentional openings, the ventilation rate Q is directly proportional to the area of opening. Thus, air exchange rate per opening area $N_{pa}(h^{-1}m^{-2})$ equals to $N(h^{-1})$ divided by the area of opening $A_w(m^2)$. In the field testing, the volume of the student dorms is $51.3m^3$ and the area of opening is $0.4m^2$. The general form that includes the temperature difference, the volume of room, the area of opening and correction factor is

$$Q=N_{pa}A_wV=(1.1\sqrt{\Delta T}+2.5x)\ A_w\ V \qquad (15)$$

where Q is ventilation rate(m^3/h), ΔT is the temperature difference, V is the volume of room, A_w is area of opening(m^2), and x is a correction factor (ranging from 0 to 1.15h^{-1}).

DISCUSSION

According to *Indoor Air Quality Standard(GB/T 18883-2002)*, the acceptable quantity of fresh air is 120m^3/h for 4 occupants living in a dorm, in other words, the air exchange rate is 2.3h^{-1}.

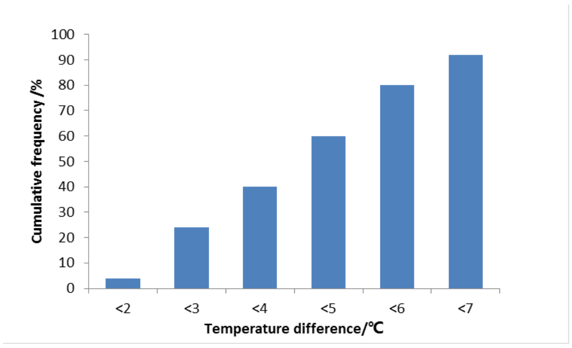

Figure 11 The cumulative frequency of temperature difference in summer nights

As shown in the Figure 11, temperature difference is usually less than 6°C and the air exchange rate is usually less than 1.5h^{-1} in most of the time during the summer nights. Most dorms failed to meet the ventilation standard. Therefore, additional ventilation methods such as adding mechanical ventilation system or enlarging the opening area of the windows should be considered. In order to reach air quantity 30m^3/h per capita, the area of opening that corresponds to temperature difference is shown in the following table.

Table 9

Opening area A_w corresponding to temperature difference ΔT for partly-sheltered dorms(x=0.55)

ΔT(℃)	2	3	4	5	6	7
$A_w(m^2)$	0.80	0.71	0.65	0.61	0.57	0.55

In order to meet the ventilation standard in 90% of the time, the temperature difference should be no less than 2℃ , and the opening area of window should be 0.8m^2. However, the maximum opening area of window in the student dorms is 0.4m^2. Therefore, the current window needs to be redesigned. For example, sliding window may be changed by casement window or the design of window size may be increased.

CONCLUSION

This paper focuses on field testing to obtain an suitable empirical equation for evaluating air exchange rate more convenient and reliable in student dorms in Beijing, China. This paper analyzed the experimental method, using CO_2 exhaled by humans as tracer gas, in order to calculate air change rate accurately. According to the results from the method research, the uniformity of CO_2-distribution and the reliability of the method are well verified. Besides, for a single measurement location, the average air exchange rate can be estimated accurately, which increases the feasibility of the method applied in large-scale field testing.

A recommended revised factor (equal to 0.75) for Chinese young females CO_2-emission calculations is put forward. Further research is needed to confirm the conclusion and more revised factors for various age and genders, are of great importance to study on.

An empirical equation to estimate ventilation rate conveniently and reliably is put forward:

$$Q= (1.1\sqrt{\Delta T}+2.5x)\ VA_w \qquad (15)$$

where Q is ventilation rate(m^3/h), ΔT is the temperature difference(℃), V is the volume of room(m^3), A_w is area of opening(m^2), and x is a correction factor (ranging from 0 to $1.15h^{-1}$).

The current window should be redesigned such as changing sliding window by casement window or increasing the design of window size to enlarge the area of opening.

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