Exploration on The Characteristics of Natural Ventilation in Bedrooms and Its Determination Method

Chen Huang1, Jialing Zhang1*, Qinhou Zhang2, Zhijun Zou1, Lele Zhou1, Yufeng Miao1

1University of Shanghai for Science and Technology, China.
2Shanghai Pudong New Area Real Estate (Group) Co., Ltd. China.

Abstract: In this paper, the CO2 (carbon dioxide) exhaled by indoor occupants was used as the tracer gas, and the variation of indoor CO2 concentration in the whole day was observed. Among the 454 samples, 114 and 345 valid samples were screened out which can be used to calculate the daytime and night ventilation rate by the tracer gas method through the sectioning method. The results indicated that seasonal differences in daytime average ventilation are greater than night average ventilation. The highest daytime-average ventilation was found in autumn, next was summer, there was the lowest ventilation in winter. According to the necessary fresh air rate when sleeping at night, night average ventilation rate of 30.1% of samples met the standard. The ventilation rates of different building characteristics were analyzed, residential location, construction age, living floor, room size, window structure, indoor dampness, and window opening habits were all included. The results revealed that the window opening habits was the most significant factor for natural ventilation. Both daytime and night average ventilation rate are basically in the ratio of 2:1 when the windows are opened and closed. moreover, there was higher impact of outdoor climate on daytime average ventilation when window was closed. Significant impact of window structure and indoor dampness on night average ventilation was observed when window was opened. Present study proposed the measurement and determination methods of ventilation when daytime activities of occupants were happened indoors.

Ventilation in residences can partly reflect the design level of the house and the living environment of the occupants. The natural ventilation of an existing residence is closely related to different seasons, the location of the house, the building structure, and especially the opening characteristics of doors and windows. It’s very meaningful to determine the natural ventilation of an existing dwelling quantitatively.

The common method currently used for the determination of natural ventilation in dwellings is the tracer gas method [1,2], and simulation tools such as computational fluid dynamics (CFD) [3], or software [4] are also often used in the study of natural ventilation characteristics in dwellings. Due to the characteristics of the tracer gas method that can often use carbon dioxide exhaled by the human body as a tracer gas, this method has shown better superiority for building site measurements [5]. In recent years, many studies aimed at improving the testing accuracy of the tracer gas method [6,7]. However, all present measurement methods are performed in the actual buildings which were under strictly defined measurement conditions or laboratory. In the present paper, the daytime concentration variation of carbon dioxide, which was used as the tracer gas, was detected in 24 hours, the tracer gas method would be used to determine the daytime average ventilation and night average ventilation in the residential buildings in Shanghai area.

1. Principle of tracer gas method

According to the principle of mass conservation of tracer gas, ventilation volume was calculated by the tracer gas method, as shown in eq. 1.

\[ \frac{dC}{d\tau} = F(\tau) + N(\tau)(C_{out} - C(\tau)) \] (1)

Herein: \( \frac{dC}{d\tau} \): Indoor tracer gas concentration changes during test intervals, m³/m³; \( d\tau \): Test intervals, s; \( F(\tau) \): tracer gas released per unit time [8], m³/s; \( N(\tau) \): air exchange rate, h⁻¹; \( C_{out} \): tracer gas concentration outside the room, m³/m³; \( C(\tau) \): tracer gas concentration in testing room at \( \tau \) time, m³/m³.

CO2 released by the people was used as tracer gas in the calculation for ventilation in the children's bedrooms, the released CO2 could be calculated using the following equation based on the parameters of weight, height and activity status of the people in the room during testing periods in the questionnaire.
Herein, $RQ$: Dimensionless constant related to respiration, taken as 0.83 \cite{9}. $M$: Human metabolic rate, $W/m^2$, taken as 40 $W/m^2$ and 70 $W/m^2$ for adult \cite{10} and 75% of adult was applied in calculation of children. $H$: Height, m; $W$: Weight, kg.

Assuming that the indoor ventilation was stable, air exchange rate ($N$) could be calculated by eq.1 and related parameters. Calculating values of $CO_2$ concentration were also obtained from eq.1 using air exchange rate ($N$). The difference between Calculating values of $CO_2$ concentration and Testing values of $CO_2$ concentration were estimated by eq.2 in the present study. The sample would be treated as invalid sample if the difference values larger than specific values.

$$F = \frac{0.201RQ \cdot M \cdot H^{0.725} \cdot W^{0.425}}{21 \cdot (0.23RQ + 0.77)} \tag{2}$$

$$MAPE = \frac{1}{n} \sum_{i=1}^{n} \frac{|C_i - C_{ai}|}{C_{ai}} \times 100\% \tag{3}$$

Herein, $C_i$: Calculating values of $CO_2$ concentration through planning solutions, ppm; $C_{ai}$: Testing values of $CO_2$ concentration, ppm; $n$: The number of concentration measurements during the period.

2. The determination of daytime and night average ventilation in children’s bedroom

Present data were obtained from on-site inspection in CCHH (China, Children, Homes, Health) study conducted in Shanghai during 2013-2014 in 454 children’s homes. The $CO_2$ concentration in the children’s bedrooms was monitored for 24 hours on the testing day, and the data were recorded every 1 min and stored in the instrument by self-recording. One measurement point was arranged in the bedroom generally \cite{11}. Meanwhile, a questionnaire containing building characteristics, bedroom characteristics, activity status of the occupants, and information about windows were also conducted on the testing day.

The 24-hour period of one day can be divided into four periods according to the changes of indoor personnel activities and 24-hour carbon dioxide concentration. A: testing period, T_r\~16:00, B: night activity period: 16:00–22:00; C: sleeping period, 22:00–06:00; D: day activity period before testing, 06:00–T_r. Sleeping period were used as Calculation basis of night average ventilation because its stability. Detailed time may vary slightly in actual calculations. The average daytime ventilation was obtained using the time weighting of the four phases of ventilation.

The principles of nightly average ventilation sample screening: 1) take the time period with stable changes in $CO_2$ concentration in C period as the calculating basis, and the minimum time period was set to 6 hours; 2) calculated MAPE<10% within the time period. The principles of daytime average ventilation sample screening: 1) calculated MAPE<15% within four periods; 2) total discard time in four periods should lower than 20% of 24h, that was 4.8h. Air exchange rate ($N$) was calculated by planning solution and parts of samples were invalid. After screening, the valid samples of daytime and night average ventilation were 114 and 345, respectively.

3. Calculating results of daytime-average and night-average ventilation

The daytime and night average ventilation in children’s bedroom were shown in fig.1. Quartile and arithmetic mean were also indicated in fig.1. There was the highest daytime average ventilation in autumn, summer was the next, the smallest ventilation was found in winter. The daytime average ventilation rate in autumn, summer, and winter were 97.4, 67.9, 63.3, and 40.0 $m^3/h$, respectively, and night average ventilation were 51.1, 44.6, 51.1, and 44.9 $m^3/h$. The daytime and night average ventilation rates were in the range of 3–310 $m^3/h$ and 1–427 $m^3/h$. Among them, the average daytime ventilation rate varied greatly between different four seasons. According to the necessary fresh air rate when sleeping at night (25$m^3/h$), 75% of adult was applied in calculation of children, night average ventilation rate of 30.1% of samples met the standard.

Fig.1 Daytime and night average ventilation in different seasons

The present paper analyzed the ventilation of different building characteristics such as residential location, construction age, living floor, room size, window structure, indoor dampness, and window situation (opening or closing), etc. It was found that the most influential factor was window condition.

The natural ventilation was closely related with the window opening or closing. Assuming that there was only one window in children’s bedroom in general. Natural ventilation distribution in daytime and night was shown in figure (a), the sample sizes (open: close) were 89:12 and 122:203 in calculation of daytime and night average ventilation, respectively. From figure (a) we could know that the ventilation was 2:1 when the windows are opened and closed, and the difference in night average ventilation with different window situation was significant.

From figure (b), there was significant impact of material of window frame on night average ventilation, the night average ventilation in the room with window frame of other materials (wood and plastic steel) is 1.5 times higher than in the room bedroom with aluminum window frame and there was no significant difference of
the daytime average ventilation in bedroom with different materials of window frame. From figure (c), significant difference of night average ventilation was found in single and double window, ventilation in the bedroom with double windows was 72% of that with single window. No different of daytime average ventilation was found in single and double window, this was mainly due to the larger closed proportion of windows at night. According to questionnaire, 59% of windows closed at night, but only 12% at daytime, the impact of window structure on ventilation was elevated when the proportion of closed window was larger.

The distribution of the daytime and night average ventilation whether there was indoor dampness shown in figure (d). the figure shows that the night average ventilation in room without indoor dampness was significantly higher than room with dampness, which was also due to the fact that the proportion of closed windows at night (59%) was higher than the proportion of opened windows at daytime (12%).

To sum up the above factors affecting the ventilation of the children's bedroom, the most important is the opening and closing condition of the windows. When the window is closed, the window layers and indoor dampness would cause significant impact on ventilation. According to people's living habits, the higher proportion of windows closed was found. Therefore, the influence of building structure was significant at night. When the window is opened, ventilation was more affected by the outdoor environment, such as climate. High significance was found in daily-average ventilation rather than night-average ventilation when season is different.

4. Determination method of natural ventilation

The above study showed the importance of determination of natural ventilation on analyzing impact factor for ventilation. There was no clear quantitative method for determining the daytime natural ventilation in dwellings. In the present paper, the 25% and 76% of samples were selected by a series of condition settings and applied in calculation of daytime and night average ventilation, and the method for calculating the natural ventilation during general daytime activities in dwellings was determined.

It should be ensured that the dwelling is the most unfavorable state when ventilation measurement. In this paper, the minimum necessary opening of doors and
windows is used as the judgment condition, we defined that when minimum necessary opening of doors and windows was 15% or 20%, which have been verified by experts, the dwelling is the most unfavorable state. The tracer gas method could be applied in residential ventilation measurement, and CO2 exhaled by the occupants in the residences as the tracer gas. Tracer gas released manually could also applied to improve the accuracy of the field test. Testing should be based on the daytime activities of the people in the room and carried under the condition that stable outdoor wind speed, and testing was recommended to conduct below 3m/s. In this paper, passive measurement method without human intervention for natural ventilation was recommended to estimate the daytime average ventilation in children’s bedroom.

1) Before the field test, the testing instruments of CO2 should be calibrated. 2) Opening extent of the door and window should be set according to the minimum necessary opening (Once confirmed, no changes shall be made during testing periods). 3) The measurement points should be placed in the active area of the breathing height of the occupants [11]. 4) If the measurement starts at the T moment, the valid measurement periods ranged from T+1 hours to the end of the next day T+25, valid actual measurement time is 25 hours. 5) During the test, the personnel daytime activity in the room should be kept (drastic activity was not permitted), the daytime activity condition, amount, height and weight of the people in the room should be recorded. 6) After retrieving the instrument at the end of the test, obtained CO2 concentration should be calibrated according uniform deviation requirements. If the concentration deviation was not met the requirement, present sample was regard as invalid sample and should be abandoned.

According to the daytime activities of the people in the room, total valid measurement time was divided into 4 periods (A, B C, D). If the test began at 10 am, then the A period is 11:00 am-16:00 am, the B period is 16:00pm-22:00pm, the C period is 22:00pm-06:00pm, and the D period is 06:00am-11:00am the next day. The exact time could be determined according to the actual activity. In the 4 periods, night average ventilation was calculated by the concentration data in C period. If the measured indoor CO2 concentration is lower than outdoor, the data of the day was invalid. Possible reasons for the deviation were as following: 1) Instrument should be calibrated again. 2) There was CO2 emission source outside, the measured data is still available under this condition. 3) Others. Data should be measured again after the problems were solved. Ventilation in 4 periods were calculated according to uniform sample screening rules. and daytime average ventilation was calculated through the time-weighted method.

The current method may be imprecise. It is necessary to ensure that the rules for measuring the natural ventilation of all rooms should be uniform, and that the setting of deviation range should also be reasonable. The recommended division of time periods could be based on the actual measurement situation.

5. Conclusion

In summary, the most important impactor affecting ventilation in children’s bedroom was the opening and closing state of the windows. When windows were closed, windows structure and room size would cause a great impact on ventilation. Due to high rate of closing window in residences, the impact of building structure on ventilation become more significant at night. Once windows opened, outdoor environment, such as season, would cause the great impact on daytime average ventilation rather than night average ventilation.

Reference

[1] O. Leif, S. Hans, B. Carl-Axel, H. Vidar, The Ventilation Rate of 344 Oslo Residences[J]. Indoor Air, 1998, (8):190-196.
[2] Y. Li, X.F. Li, Field testing of natural ventilation of residential buildings in Beijing in summer[J]. Heating Ventilating & Air Conditioning. 2013, 43(12): 46-50.
[3] C.F. Gao, W.L. Lee, Evaluating the influence of openings configuration on natural ventilation performance of residential units in Hong Kong[J]. Building and Environment, 2011, 46(2011): 961-969.
[4] W. Peder, A. Kenichi, C. Paolo, Health, work performance, and risk of infection in office-like environments: The role of indoor temperature, air humidity, and ventilation[J]. International Journal of Hygiene and Environmental Health, 2021, 233(2021): 1-18.
[5] M.W. Qi, X.F. Li, He. H, Discussion on Measuring Ventilation Rates of Dorms through Tracer Gas Method with Human Body as CO2 Release Source[J]. building science, 2013, 29(6): 52-57.
[6] X.T. Li, X. Wang, X.F. Li, Investigation on air age in a ventilated room with tracer gas technique[J]. Heating Ventilating & Air Conditioning, 2001, 31(4): 79-81.
[7] G. Hong, B.S. Kim, Field measurements of infiltration rate in high rise residential buildings using the constant concentration method[J]. Building and Environment, 2016, 97(2016):48-54.
[8] A.K. Persily, Evaluating building IAQ and ventilation with indoor carbon dioxide[J]. Ashrae Transactions, 1997, (2):103-110.
[9] Quality A. Standard Guide for Using Indoor Carbon Dioxide Concentrations to Evaluate Indoor Air Quality and Ventilation[J]. Astm, 2012.
[10] ASHRAE. ASHRAE Handbook-Fundamentals[M]. Atlanta GA, American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2013.
[11] GB/T 18883-2002. Indoor air quality standard[S]. Beijing, Standards Press of China, 2002.