Indoor air quality investigation of a university library based on field measurement and questionnaire survey

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Abstract
This article presents field studies and questionnaire survey on the indoor air quality (IAQ) in library rooms in University of Science and Technology Beijing in April 2016, with no heating, to find out actual situation of IAQ in university library. Nine rooms equipped without centralized air-conditioning system were carefully selected for the test. Results showed that each room had diverse indoor thermal environment and concentrations of CO₂, PM2.5, formaldehyde and TVOC. The concentration of CO₂ ranged from 575 to 2400 ppm, PM2.5 concentration was 40–70% of the outdoor, the highest concentration of formaldehyde and TVOC was ~0.042 and 0.285 mg m−3, respectively with half of the upper limit. The concentrations of CO₂ and PM2.5 in the holding-reading rooms were higher than that in the rooms only holding books. The situation of formaldehyde and TVOC concentrations was just opposite. The correlations between satisfaction of IAQ and the concentrations of indoor air pollutants were not as a constant, but changing with different rooms. Based on gray system theory, satisfactions were affected seriously by CO₂ and PM2.5. One improving plan with the theme of ‘ventilating rapidly along with purifying’ was determined based on a general mass balance equation. In theory, IAQ can be improved <5 min for the most unfavorable condition. Through analysis, requirements of fresh air and functionality of the space usages should be considered in the ventilation or central air-conditioning system design.

Keywords: indoor air quality; university library; pollution evaluation; rapid ventilation; air purification

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1 INTRODUCTION
University students spend a lot of time in library. Due to the construction history gets several dozen years even much more, many university libraries are usually equipped without central air-conditioning systems for heating, cooling and ventilation, therefore, it might be much more difficult to provide students with comfort indoor thermal environment and indoor air quality [1]. Especially in transition season with windows and doors closed, IAQ will be deteriorated further because the fresh air only relies on air infiltration [2–4]. Therefore, the issue of indoor air pollution in university library has drawn more and more concerns.
emitted from paper and other cellulose-based materials during degradation [8, 9].

Formaldehyde and VOCs are regarded as highly toxic and carcinogens sources that can cause respiratory illness [10, 11]. Most VOCs are widely used in construction, furniture, textiles, carpentry and chemical industry [12, 13]. High levels of formaldehyde and TVOC are risk factors to asthma and rhinitis, and may even lead to skin, melanoma, lung and endocrine-related cancers [14–21]. Moreover, indoor CO2, formaldehyde and total VOC (TVOC) are risk factors of sick building syndrome (SBS) which have been regularly reported worldwide [22–25].

What’s more, emissions of formaldehyde and TVOC are influenced by many environment factors [26–31], such as temperature, humidity and air velocity. Numerous studies have reported that there are seasonal discrepancies of the IAQ. VOCs with high boiling point will only be detected under high indoor temperature, for example, more alkanes were detected in summer than in winter [32]. Formaldehyde concentrations in large departments reached peak in summer for almost the whole year [33]. Indoor concentration of particulate matter with aerodynamic diameter <2.5 μm (PM2.5, go directly to the alveoli of the lungs) changed with outdoor concentration, indoor PM2.5 concentration was much higher in winter than it in summer [34].

Beijing, the capital city of China located in the North China Plain (NCP), the region with the heaviest air pollution [35, 36], attracts the most attention of the government and the public since it has a population of 20.7 million in 2012 and 4.5 million foreign tourists. The annual average concentrations of PM2.5 were observed ~87 μg m⁻³ in 2013 [37], greatly exceeding the World Health Organization (WHO) guideline value of 10 μg m⁻³ [38]. Annual average concentrations of air pollutants in Beijing were given by Guo et al. [39], the data were 86 μg m⁻³ for PM2.5, 62 ppb for O3, 35 ppb for NO2, 9.5 ppb for SO2 and 1.1 ppm for CO, respectively.

Although IAQ and the emission sources of air pollutants were investigated in many office buildings, residential buildings and public buildings, the most of previous studies are conducted only for objective measurement while overlook the individual feelings in the environment. The aim of this research is to investigate IAQ in nine rooms of one university library in Beijing through onsite measurements (temperature, relative humidity, CO2, PM2.5, formaldehyde, TVOC) and questionnaire surveys. According to the finding [40], air infiltration rate in winter will be two to three times to it in transition seasons under the condition of doors and windows closed because of the temperature difference between indoor and outdoor. So the research was conducted in April based on the most disadvantageous situation.

2 MATERIALS AND METHODS

2.1 Site location and description
This study was conducted in the city of Beijing(northern China, 39°54′20″, N-116°25′29″E) during the sampling campaign for 5 weekdays. Nine rooms of the library in the University of Science and Technology Beijing (USTB) were selected which were donated as 1EE, 1EW, 1CL, 1CT, 1WS, 1WN, 3CT, 3WN, 3WS, respectively. The selection of nine rooms followed the way of controlling variables and considered factors of similar building scale, floor layout, HVAC systems, human behavior or function of rooms, the age of books and so on. For example, the influence of books at various times on IAQ can be acquired by dividing the rooms into two groups, the one is only to hold books (1EE, 1CL, 1CT, 3CT), the other one is holding-reading integration which provides a permanent place for reading or studying (1EW, 1WS, 1WN, 3WS, 3WN). This four-storey library building is constructed in brick-concrete. The layout and total area of each floor are similar. After several renovations, the library that built in 1952 covers an area of seven acres and a half, construction area of 20 000 m², includes more than 2000 seats for reading and learning. All the rooms are designed with double plastic steel windows. All of the rooms were decorated at least 5 years ago. As for ventilation, no mechanical ventilation system was installed in the library. The occupants relied on air infiltration in winter and transition season and natural ventilation by opening windows in summer. When the exterior windows are closed, ventilation is purely by air infiltration driven by indoor–outdoor temperature differences and wind pressure.

Beijing has a climate of cold winter and hot summer. The average outdoor temperatures in December, January and February are all below 0°C. There are centralized district heating systems in Beijing and they are generally operated from November 15 to March 15. In winter, occupants seldom open windows so as to assure thermal comfort and save energy. Consequently, the indoor temperature is almost constant during the entire heating season. For the library rooms, the indoor temperature varies within a small range; in spring and autumn, no heating or cooling is used and the room temperature varies but in general within the comfort range; in summer, the outdoor temperature can reach 35°C during daytime, so split-unit air conditioners will be run in the rooms.

These temperature differences were ~20°C in winter and 10°C in transition season. Thus, higher infiltration rate would be expected in winter. According to the equation regressed by Wallace et al. [41], the estimated infiltration rate of the library rooms in winter would be about two to three times that in transition season. The infiltration rate can hardly be larger than 0.5 h⁻¹ in urban area of northern China where the air tightness is rather good [40]. In the measurement conducted by Chen et al. [42] in northern China, the average infiltration rate of the buildings built in the 1990s was 0.24 h⁻¹. In conclusion, IAQ is much worse in transition season. This is why we decide to make this study in April, just ~2 weeks after the central heating stopped. We assumed that each room’s natural infiltration change rate was 0.5 h⁻¹ according to the study [43]. During measurement, the nine rooms of Heating, Ventilation, Windows options were the same, respectively ‘no heating’, ‘infiltration’ and ‘closed’. More details of nine rooms are listed in Table 1.

As shown in Figure 1, there are a lot of mountains in the northwest part of the Beijing so the city will not be influenced seriously by Siberian cold current. Thus, for wind condition,
Table 1. Library room characteristics overview during the measurement.

| Furniture/material | Floor covering | Total area (m²) | Age of books (years) | Type/function |
|--------------------|---------------|----------------|----------------------|---------------|
| Bookshelf, chair, desk | Marble         | 160            | <1                   | Hold books and read |
| Bookshelf          | Marble         | 80             | <1                   | Hold books   |
| Bookshelf          | Marble         | 350            | 1–60                 | Hold books   |
| Bookshelf          | Marble         | 350            | 1–60                 | Hold books   |
| Bookshelf, chair, desk | Synthetic rubber | 650          | 1–20                 | Hold books and read |
| Bookshelf, chair, desk | Synthetic rubber | 650          | 1–20                 | Hold books and read |
| Bookshelf, chair, desk | Marble         | 350            | 1–60                 | Hold books   |
| Bookshelf, chair, desk | Synthetic rubber | 650          | 1–20                 | Hold books and read |
| Bookshelf, chair, desk | Synthetic rubber | 650          | 1–20                 | Hold books and read |

Figure 1. Location of Beijing and location of USTB.

dominate wind direction is northeast wind of the year. The windows of selected rooms are open toward west, so the influence of wind direction or speed outdoor is ignored. The library building is far away industry area so the industry pollution could be disregarded. Outline of the library in USTB is shown in Figure 2.

2.2 Sampling and monitoring
Indoor and outdoor measurements were performed in each library room, reading and recording the data from equipment every 2 h at a time from 8:00 to 22:00 for 5 weekday.

The physical and chemical parameters assessed were temperature, relative humidity, CO₂, PM2.5, HCHO, TVOC. Temperature and relative humidity were continuously monitored with data loggers, CO₂ was monitored everyday with a portable IAQ analyzer (TSI-IAQ-CALC). An optical light scattering spectrometer (BGPM-02) was used for measuring simultaneously PM2.5 fractions. One portable detector with the function of automatic calibration based on electrochemical sensor, was used for measuring HCHO and TVOC (LZY-204). All the testing equipment was calibrated as per the manufacturers’ recommended calibration procedures to ensure accuracy and consistence of the measurements. Table 2 lists the equipment used in the test and theirs specifications.

2.3 Questionnaire survey
Field measurement is easily to be mastered and has good repeatability, but there will be a difficulty for measuring accurately once pollutant kinds are pretty or the concentrations of some pollutants are much lower [45]. Besides, the main evaluation of IAQ is people and there are huge differences in the feeling of people. For this, Prof. Fanger put the concept ‘perceived air quality’ to evaluate IAQ [46]. There is a leap in cognition that standards issued by American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) involved the principle both subjective and objective evaluation [47, 48].

The questionnaire was adopted from a Sweden study on health-relevant exposure and modified for the actual situation in China [49–51]. For the questionnaire survey, 270 valid questionnaires in total were collected, and the number of questionnaires from nine rooms was almost equal. The questionnaire includes ~30 questions on basic information, indoor environment evaluation, symptoms and perception when leave library rooms, which are summarized in Table 3.

There mainly focused on the two parts: indoor environment evaluation and symptoms. The quantification on indoor environment used a scale model ranging from 1 to 5, representing the salespersons perception levels from ‘very bad’ to ‘very well’; while for the SBS perception degree, 1–5 represented ‘never’ to ‘very serious’, details were shown as follows.

Satisfaction on indoor environment

| e.g. Temperature | Very bad | Bad | Neutral | Well | Very well |
|------------------|----------|-----|---------|------|----------|
| e.g. Fatigue     | Never    | □1  | □2      | □3   | □4       |
| If get following symptom? | Very serious | □1  | □2      | □3   | □4       |

The Chinese Standard for Technical specifications for monitoring of IAQ (JGJ.T 167-2004) [44] was used as a reference for the decision of the sampling points. Combined with the using function and structure of rooms, three sampling points are set up in accordance with the diagonal way in each room. Finally, we take an average. The height of each sampling point was consistent with the human respiratory zone, i.e. between 1.2 and 1.5 m above the floor level. The measurement points avoided interference from ventilation vents, human activities and interior walls. The distance between the wall and measurement points was >0.5 m. Outdoor measurements points were located ~30 m away from the entrance of the library.
The participants sat still indoors for at least 30 min, and completed the questionnaire while seated. The questionnaire was compiled by the surveyor independently. In satisfaction, except for ‘very bad’ and ‘bad’, others were all satisfied with the factor; in symptom, expect for ‘never’, others all have this kind of symptom.

Table 2. Detailed information of testing equipment.

| Parameters          | Instrument model | Measuring principle     | Measuring range     | Accuracy     | Distinguishability |
|---------------------|------------------|-------------------------|---------------------|--------------|------------------|
| Temperature         | WSZY-1           | Temperature sensor      | 40–100°C            | ±0.5°C       | 0.1°C            |
| Relative humidity   | WSZY-1           | Humidity sensor         | 0–100%              | ±3%          | 0.10%            |
| CO₂                 | TSI-IAQ-CALC     | NDIR                    | 0–5000 ppm          | ±3%/± 50 ppm | 1 ppm            |
| PM2.5               | BGPM-02          | Optical light scattering| 0–999 ug m⁻³        | ±5%          | 1 ug m⁻³         |
| Formaldehyde        | LZY-204          | Electrochemical sensor  | 0–3.000 mg m⁻³      | ±2%          | 0.001 mg m⁻³     |
| TVOC                | LZY-204          | Electrochemical sensor  | 0–9.999 mg m⁻³      | ±2%          | 0.001 mg m⁻³     |

Table 3. Summary of the subjective questionnaire.

| Questions                              |                                      |
|----------------------------------------|--------------------------------------|
| Basic information                      | Gender, age, daily studying hours, illness history |
| Evaluation of indoor environment       | Temperature, RH, indoor air quality, ventilation |
| Symptoms                               | Fatigue, dizziness, breathing difficulty, dust feeling, stuffy/pungent odor, efficiency decreasing, irritable feeling |
| Perception when leave library rooms    | When leaving malls, the symptom change (more severe, stay same, better, almost disappear) |

The participants sat still indoors for at least 30 min, and completed the questionnaire while seated. The questionnaire was compiled by the surveyor independently. In satisfaction, except for ‘very bad’ and ‘bad’, others were all satisfied with the factor; in symptom, expect for ‘never’, others all have this kind of symptom.
In order to show the statistic more intuitively, the number of people involved in the questionnaire survey was taken as the denominator, the number of people satisfied with the factor of indoor environment or the people with the symptom was taken as numerator. Thereby, the result expressed as a percentage was required in following charts.

2.4 Evaluation of IAQ
The evaluation of IAQ in buildings is complex because IAQ involves a broad spectrum of substances and agents that vary over time and space. To address this complexity, IAQ indices are used to describe, classify and improve IAQ by providing easy-to-understand and comprehensive rankings of IAQ levels in buildings. There are many IAQ indices that have been proposed all over the world [52]. We adopt the synthetical pollution index method set by Humphreys [53] to analyze and evaluate the level of air quality monitored in library rooms, the following equation gives the IAQ index (I):

\[
I = \left( \max \left( \frac{C_1}{S_1}, \frac{C_2}{S_2}, \ldots, \frac{C_n}{S_n} \right) \right) \cdot \left( \frac{1}{n} \sum_{i=1}^{n} \frac{C_i}{S_i} \right)
\]

(1)

\(C_i\) and \(S_i\) are the concentration of measurement and standard for the same air pollutant; \(n\) is the kind of measured air pollutants. \(C_i/S_i\) is called sub-index.

IAQ according to the calculating index (I) can be divided into five levels [35], as shown in Table 4.

2.5 Correlation analysis
To determine which indoor air pollutant has the most seriously influence on people’s feelings, we determine the correlation between satisfaction of IAQ and the concentrations of pollutants based on the gray system theory. The gray system theory is theorized by Deng [54] and developed by Liu [55]. It focuses on the study of problems involving small samples and poor information and deals with uncertain systems with partially known information through generating, excavating and extracting useful information from what is available. Grey incidence analysis based on the gray system theory, provides a new method to analyze which factors have primary influence, and which have less influence, on the development of the system. In this paper, the model of absolute degree of grey incidence is used for analysis. The definition of absolute degree of grey incidence is as follows.

Let \(X_i, i \in \mathbb{N}_2^n\) be two sequences with the same length that is defined as the sum of the distances between two consecutive time moments, shown as follows:

\[
s_i = \int_1^n (X_i - x_i(1)) dt
\]

\[
s_i - s_2 = \int_1^n \{[X_i - x_i(1)] - [X_2 - x_2(1)] \} dt
\]

Then

\[
X_{i-2} = \frac{1 + |s_i| + |s_j|}{1 + |s_i| + |s_j| + |s_2| - s_2}
\]

is referred to as the absolute degree of grey incidence between \(X_i\) and \(X_2\). For more details, please refer to the book by Liu et al. [56].

2.6 Measures to improve IAQ
Based on the result of the Section 2.4, we take ventilation and purification as the main idea to control or improve IAQ. The theory is based on conservation of mass.

3 RESULTS AND DISCUSSION

In this section, China Indoor Air Standard (GB/T 18 883-2002) [57] was used as reference mode to evaluate the thermal environment and IAQ, in which the range of temperature as well as relative humidity were 22–28°C and 40–80%, respectively. Besides, the upper limits of CO2, TVOC and formaldehyde concentrations were 1000 ppm (24 h), 0.6 mg m\(^{-3}\) (8 h) and 0.1 mg m\(^{-3}\) (1 h), respectively.

3.1 Comfort parameters (\(T, RH, CO_2\))
A summary of temperature and relative humidity is shown in Table 4. In the nine test rooms, 3WN has the greatest temperature fluctuating ranging from 18.0 to 30.0°C. 3CT and 1WS have the lowest 12.4% and highest 47.6% humidity, respectively and almost every room has excessively low humidity (<40%) but no one excessively high humidity (higher than 80%). Figures 3 and 4 show the number of people and indoor CO2 concentration respectively on a typical sampling day.

According to the stable daily routine for most students, the number of people had been a gradual increase during 9:00–10:00 and reached peak at 11:00 in the rooms (1EW, 1WS, 1WN, 3WS, 3WN). With the arrival of the lunch break, the number of people was falling rapidly during 11:00–13:00 and reached the lowest at 13:00. Then the number increased quickly again during 13:00–15:00 and remained stable until the library closed. During the same time period, the number of people in other rooms (1EE, 1CL, 1CT, 3CT) had been in a low level all the time.

As shown in Figure 4, indoor CO2 concentrations seem to be influenced by human occupancy. Indoor CO2 concentrations were excessive (except 1CL and 1CT) by the Chinese IAQ...
standard which the maximum value is 1000 ppm [57]. In most rooms, CO₂ was beginning to build up when the pupils start occupying the library rooms and then started declining slightly during the lunch break. The same upward trend was followed during 13:00–21:00. It was noteworthy that higher CO₂ concentration happened as the number of people declined during dinner. This might be explained for the following reasons: one, CO₂ was accumulated constantly with the doors and windows closed during measurement; the other, the emission of CO₂ by the remainder was still greater than wind seepage. By a simple estimation, there is a balance between CO₂ concentration produced and released based on the density of 0.1 per m⁻².

3.2 TVOC and formaldehyde concentration levels

Figure 5 shows the concentration of indoor formaldehyde varies during the daily testing period. From the figure we can see that indoor formaldehyde concentrations were all relatively stable and had similar trends except for 1EW. This trend can be explained by formaldehyde gathering due to the sources that are irrelevant for people. The volatile date in 1EW might be resulted by the operation. In 3CT and 1CT, formaldehyde concentrations are the highest, ~0.035–0.04 mg m⁻³. Among them, formaldehyde concentration in 3CT is ~60% higher than it in 3WS. The reason might be that the placed density of books in 1CL and 1CT is almost more than twice it in other rooms and lots of old books are hold in 1CL and 1CT.

As show in Figure 6, the change of TVOC concentration is more gently. TVOC concentration gets peak during 11:00–13:00 because of some factors such as people’s activities, temperature and relative humidity. In 1CT and 3CT, TVOC concentration is much higher than other rooms; the 3CT indoor concentration of TVOC is ~40% higher than 3WS indoor. The reason might be similar with the explanation of formaldehyde.

It is important that both the concentrations of formaldehyde and TVOC are under the levels of Chinese standard [57].

| Room   | 1EE  | 1EW  | 1CL  | 1CT  | 1WS  | 1WN  | 3WS  | 3WN  | 3CT  | Outdoor |
|--------|------|------|------|------|------|------|------|------|------|---------|
| Temperature (°C) | 21.4 | 20.3 | 19.7 | 15.4 | 20.2 | 19.9 | 20.4 | 18.0 | 16.4 | 9.8     |
| RH (%) | 22.4 | 22.4 | 29.7 | 18.2 | 19.4 | 22.4 | 18.7 | 19.3 | 12.4 | 31.5    |
3.3 Particulate matter concentrations (PM2.5)

Figure 7 shows that the concentration of indoor and outdoor PM2.5 distribution during one typical testing day. Significant strong correlation between indoor and outdoor PM2.5 concentrations is found. Outdoor concentration of PM2.5 is excessive seriously within the sampling periods, after the biggest growth of PM2.5 during 9:00–11:00, the growth begins slowing gradually and gets peak around 15:00, ~140 ug m$^{-3}$. However, the lowest indoor concentration measured is only ~55 ug m$^{-3}$ at the same time. The concentrations of PM2.5 are the lowest and relatively stable in 1CT and 3CT; the highest are in 1EE, 1WS, 1WN, 3WN, 3WS and similar with outdoor changes in general. The levels indoors are all lower than found outdoors. As shown in Figure 8, taken together, indoor PM2.5 concentration is ~40–70% to it outdoor. For the difference of PM2.5 concentration in each indoor room, there might be other indoor sources such as people’s activity [58, 59].

3.4 Feelings of people

The data of questionnaires are shown in Table 6 focused on people’s satisfactions and symptoms.

In order to facilitate the analysis, the data can be simplified into three categories according to statistical results above: 1EE and 1EW; 1WS, 1WN, 3WS and 3WN; 1CL, 1CT and 3CT. The results are shown in Table 7.
For people in different rooms, there may be a big difference on subjective feeling of the same parameter. A more intuitive comparison is shown in Figure 9a. The satisfactions of indoor temperature and relative humidity for people are almost 60–80%, similar and higher. It indicates that the satisfactions of ventilation and air quality are much more different, even <10% in 1CT, 1CL and 3CT. With doors and windows closed during the transition season, without air conditioning or ventilation system, the concentration of carbon dioxide is high, the ventilation rate is low, and the air is not fresh.

Figure 9b illustrates that people in the library rooms get noticeable dust feeling, breathing difficulty, stuffy/pungent odor and dizziness symptoms. This might be because people in the mall had long exposure time in the library rooms and automatically to maintain a stable position. SBS were associated with odors and environmental factors. Odors perception is an early predictor of SBS, and odors are caused by one or more VOCs. Thus, the overall odors perceptions are influenced by many kinds of individual odors, for example, the degradation of cellulose-based materials, mold of walls and emission from body [60].

3.5 The level of IAQ
The air quality levels in library rooms are calculated based on the data of field measurements, as shown in Figure 10. The levels of 'light pollution' and 'moderate pollution' occurred to the rooms, 1EW, 1WS, 1WN, 3WS, 3WN, with the holding-reading integration. In other library rooms that only hold books, the air quality levels are all 'no pollution'. This is easy to understand: the more seriously exceed the standard, the higher sub-index (C/Si) and the synthetical pollution index (I) are. In the holding-reading rooms, CO2 concentrations were exceeded very seriously, so the air quality levels in these rooms are 'pollution'. It is inferred that when outdoor air quality is worse (PM2.5 concentration is pretty high), the levels of IAQ will be 'moderate pollution' and even 'heavy pollution' because the sub-index of PM2.5 will be higher. The upper limit with indoor PM2.5 concentration is 75 ug m⁻³ [57], combining with the conclusion 'indoor PM2.5 concentration is ~40–70% to it outdoor' in Section 3.4, it can be concluded that PM2.5 and CO2 are both the primary affecting factors of IAQ when outdoor PM2.5 concentration is over 190 ug m⁻³.

3.6 The correlation between satisfaction of indoor air quality and the concentrations of pollutants
We analyze the correlation by the modeling software of grey system theory, downloaded from the web 'http://igss.nuaa.edu.cn' for free. According to the indoor air levels, 3WS and 3CT is taken as the representative of different type room respectively to determine the correlation. The satisfaction of IAQ by questionnaire and the concentrations of indoor pollutants by field measurement are shown in Tables 8 and 9.

After entering the data in Tables 8 and 9 into the software, we get the results. The correlations between satisfaction of IAQ and the concentrations of pollutants arranged from the largest to smallest, are in order, 0.88 (PM2.5), 0.61 (TVOC), 0.58
and 0.57 (CO₂) in 3WS, 0.73 (CO₂), 0.63 (PM2.5), 0.58 (formaldehyde), 0.58 (TVOC) in 3CT. It is no doubt that IAQ are affected seriously by CO₂ and PM2.5 according the field measurement, however, the strong correlation between indoor air satisfaction and the concentrations of formaldehyde and TVOC noteworthy, especially in the rooms only books.

It can be seen that the primary indoor air pollutant is not the same in different room. In order to build a more satisfactory indoor environment, the requirements of fresh air and the functionality of the space usages should be considered in the ventilation system or central air-conditioning system design.

3.7 The effect of IAQ improvement in theory

From Section 3.5, we get the conclusion: when outdoor air quality is good, CO₂ concentration is the primary factor affecting IAQ; when outdoor air quality is poor (outdoor PM2.5 concentration is over 190 μg m⁻³), IAQ is affected by the concentrations of PM2.5 and CO₂. According to research [61], the plan with the theme of ventilating rapidly in a short time to decrease CO₂ concentration and purifying to eliminate PM2.5 by ventilating is determined. While for mechanical ventilation, temperature difference between indoor and outdoor air was ignored based on the assumption that there was an electric heating or heat recovery unit at air inlet.
The calculation of required fresh air increment for the control of indoor CO₂ concentration is based on a general mass balance equation as shown in the following equation.

\[
\frac{dC_i}{d\tau} = N(C_o - C_i) + \frac{nQ}{V} \tag{2}
\]

Where, \( C_o \) is the concentration of outdoor CO₂; \( C_i \) is the concentration of indoor CO₂, ppm; \( \tau \) is the time period, \( s^{-1} \); \( N \) is the rate of indoor ventilation, \( h^{-1} \); \( n \) is the number of indoor people, per; \( Q \) is the releasing rate of CO₂ for human body, ml/(per s); \( V \) is the room volume, \( m^3 \).

The volume fraction of outdoor CO₂ is 0.03%, national standard of indoor CO₂ concentration is 1000 ppm and the corresponding volume fraction is 0.1%. The function is holding-reading in 3WS, CO₂ concentration is at much higher level, so choose 3WS as an example to calculate. When indoor CO₂ concentration is 1500 ppm, begin to ventilate mechanically to decrease indoor CO₂ concentration to the national standard of 80% or 800 ppm. The time interval of iterating calculation is 1 min, indoor ventilating rate (N) is 10 times/h, indoor CO₂ concentration can be reduced to 781 ppm ~5 min. Because the CO₂ concentration in 3WS is much higher, the calculating results can be applied in other holding-reading rooms. The results of calculating are shown in Figure 11.

In the rooms only holding books, CO₂ concentration gets beyond the national standard until 15:00 but excessive rarely, so ventilating naturally can decrease obviously CO₂ concentration.

For PM2.5, we established equation (3) based on a general mass balance equation:

\[
\frac{dC_i}{d\tau} = N_nC_o - N_nC_i + N_iPC_o - N_iC_i - N_p\eta_pC_i - K\tau \tag{3}
\]

where, \( C_i \) is the indoor PM2.5 concentration, \( ug/m^3 \); \( C_o \) is the outdoor PM2.5 concentration, \( ug/m^3 \); \( \tau \) is the time period, \( s^{-1} \); \( N_n, N_i, N_p \) are the air changing rate respectively for ventilation and infiltration wind and air purifier, \( h^{-1} \). \( N_i \) is the 0.5 times \( h^{-1} \) [43], \( N_i \) is the 0 when the window is open; \( P \) is the penetration coefficient, \( P \) is 1 when the window is open, \( P \) is 0.8 [62] when the window is closed; \( \eta_p \) is the filter efficiency of air purifier for first time; \( K \) is the sedimentary rate of indoor particles, is always 0.000025 \( s^{-1} \); the secondary suspension has little effect, therefore, ignored.

Taking 1WS as a represent for it is one of the rooms that PM2.5 pollution is the most serious. The area is 650 \( m^2 \) in 1WS and the processing size of the air purifier is 30~50 \( m^2 \), so 10 air purifiers are set averagely. Beginning to calculate when PM2.5 concentration is 180 \( ug/m^3 \). \( N_i \) is ~5 times \( h^{-1} \), \( \eta_p \) is 90%. During ventilating, \( N_i \) is 0, so equation (3) can be simplified into following equation.

\[
\frac{dC_i}{d\tau} = N_nC_o - N_nC_i - N_p\eta_pC_i - K\tau \tag{4}
\]

Table 8. The data of satisfaction and measured concentrations in 3WS.

| Time    | 9:00 | 11:00 | 13:00 | 15:00 | 17:00 | 19:00 | 21:00 |
|---------|------|-------|-------|-------|-------|-------|-------|
| Satisfaction of indoor air quality (%) | 95   | 77    | 72    | 56    | 61    | 69    | 55    |
| CO₂ (ppm) | 715  | 1469  | 1414  | 1744  | 1880  | 2180  | 2422  |
| PM2.5 (ug m⁻³) | 46   | 53    | 69    | 80    | 87    | 81    | 80    |
| Formaldehyde (mg m⁻³) | 0.025| 0.027 | 0.026 | 0.021 | 0.027 | 0.028 | 0.026 |
| TVOC (mg m⁻³) | 0.178| 0.192 | 0.193 | 0.198 | 0.189 | 0.197 | 0.189 |

Table 9. The data of satisfaction and measured concentrations in 3CT.

| Time    | 9:00 | 11:00 | 13:00 | 15:00 | 17:00 | 19:00 | 21:00 |
|---------|------|-------|-------|-------|-------|-------|-------|
| Satisfaction of indoor air quality (%) | 3    | 5     | 6     | 5     | 4     | 4     | 2     |
| CO₂ (ppm) | 633  | 873   | 892   | 950   | 1060  | 1084  | 1170  |
| PM2.5 (ug m⁻³) | 88   | 92    | 106   | 100   | 104   | 112   | 100   |
| Formaldehyde (mg m⁻³) | 0.037| 0.041 | 0.039 | 0.042 | 0.039 | 0.038 | 0.038 |
| TVOC (mg m⁻³) | 0.262| 0.284 | 0.27  | 0.278 | 0.281 | 0.274 | 0.272 |

Figure 11. CO₂ concentration variation in 3WS in mechanical ventilation.

Formaldehyde (mg m⁻³) 0.025 0.027 0.026 0.021 0.027 0.028 0.026
TVOC (mg m⁻³) 0.178 0.192 0.193 0.198 0.189 0.197 0.189

Table 8. The data of satisfaction and measured concentrations in 3WS.

Table 9. The data of satisfaction and measured concentrations in 3CT.
During calculating, $N_n$ is 10 times $h^{-1}$, indoor and outdoor PM2.5 concentrations are 60 $\mu g\ m^{-3}$ and 270 $\mu g\ m^{-3}$.

If air purifiers are no working during ventilating, so $N_p$ is 0. By calculating, indoor PM2.5 concentration increases to 184.91 $\mu g\ m^{-3}$ after ventilating for 5 min. Indoor PM2.5 concentration decreases to 56.72 $\mu g\ m^{-3}$ after air purifier working for 2 min. The calculating results are as shown in Figure 12.

Synthesize the above results, the preliminary plan of improving IAQ with the theme ‘ventilating rapidly in a short time and along with purifying’ is feasible.

4 CONCLUSIONS

This article presents the onsite measurement of nine library rooms without central HVAC systems in the University of Science and Technology Beijing during non-heating period (April in 2016). The field measurements including indoor and outdoor air temperature, relative humidity and the concentrations of CO2, PM2.5, formaldehyde, TVOC and questionnaire surveys are measured and analyzed. Results show that each library room has diverse IAQ. One improving plan is made based on the results. The main findings are summarized as follows:

- Various indoor air pollutants with varying concentrations were detected in the library rooms in USTB, in terms of the high CO2 concentration of 575–2400 ppm, the changing PM2.5 concentration (40–70% of the outdoor), the highest concentration of formaldehyde and TVOC is ~0.042 and 0.285 mg/m$^3$, respectively, with half of the upper limit.
- CO2, PM2.5, formaldehyde, TVOC concentrations are different in different library rooms. The concentrations of CO2 and PM2.5 in the holding-reading rooms are higher than that in the rooms only holding books. The situation of formaldehyde and TVOC concentrations is just opposite.
- The correlations between satisfaction of IAQ and the concentrations of indoor air pollutants are not as a constant, but changing with different rooms. So the requirements of fresh air and the functionality of the space usages should be considered in the ventilation system or central air-conditioning system design.
- One simple plan of improving IAQ with the theme of ‘ventilating rapidly in a short time along with purifying’ is determined based on a general mass balance equation. In theory, for the most unfavorable condition, CO2 concentration can be decreased from 1500 to 800 ppm <5 min by ventilating mechanically with 10 times h$^{-1}$ ventilating rate, PM2.5 concentration can be decreased from 180 to 75 $\mu g\ m^{-3}$ ~2–3 min by setting air purifiers averagely for area.

In this research, only four types of air pollutants were measured namely CO2, PM2.5, formaldehyde and TVOC. More detailed and comprehensive survey is recommended to include other pollutants such as benzene, mould and Radon. The impacts of formaldehyde and TVOC on the health of people studying and working in library rooms should be highly considered. The measurement of a Long term and wide range is vital and should be carried out in the future.

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REFERENCES

[1] Guy Robertson. Robertson on Library Security and Disaster Planning: [M]. Elsevier, 2016, 41–4.
[2] Li N, Li J, Fan R et al. Probability of occupant operation of windows during transition seasons in office buildings [J]. Renew Energy 2015;73:84–91.
[3] Mihucz VG, Záray G. The quality of air [J]. Compr Anal Chem 2016;73:45–71.
[4] Shi S, Chen C, Zhao B. Air infiltration rate distributions of residences in Beijing [J]. Build Environ 2015;92:528–37.
[5] Fenech A, Strlic M, Kralj Cigic I et al. Volatile aldehydes in libraries and archives [J]. Atmos Environ 2010;44:2067–73.
[6] Marchand C, Bulliot B, Lecalve S et al. Aldehyde measurements in indoor environments in Strasbourg (France). Atmos Environ 2006;40:1336–45.
[7] Kim J, Kim S, Lee K et al. Indoor aldehydes concentration and emission rate of formaldehyde in libraries and private reading rooms. Atmos Environ 2013;71:1–6.
[8] Strict M. Material demographics: on the smell of old books. Anal Chem 2009;81:8617–22.
[9] Radiello. The Radial Diffusive Sampler, Fondazione Salvatore Maugeri IRCCS. Retrieved from: http://www.radiello.com/english/ald_en.htm on 1 September 2009.
[56] Liu S, Yang Y, Wu L. *The Grey System Theory and its Application [M]*. 7th ed. Science Press, 2014.

[57] GB/T 18883–2002. Indoor Air Quality Standard. Ministry of Health, Beijing (2000) [in Chinese].

[58] Ramos CA, Reis JF, Almeida T et al. Estimating the inhaled dose of pollutants during indoor physical activity [J]. *Sci Total Environ* 2015;527–528:111–8.

[59] Zhang M, Zhang S, Feng G et al. Indoor airborne particle sources and outdoor haze days effect in urban office areas in Guangzhou [J]. *Environ Res* 2017;154:60–5.

[60] Yang S, Gao K, Yang X. Volatile organic compounds (VOCs) formation due to interactions between ozone and skin-oiled clothing: measurements by extraction-analysis-reaction method [J]. *Build Environ* 2016;103:146–54.

[61] Ma H, Shao X, Li X. Feasibility analysis on combination strategies of window ventilation and air cleaners in residential buildings under haze weather. *J HV&AC* 2016;46:18–23.

[62] Chen C. Effect of outdoor inhaled particles on indoor air quality and its control. *Ph.D. Thesis*. Tsinghua University, Beijing, 2012.