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Field study on indoor air quality of urban apartments in severe cold region in China

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ABSTRACT

An investigation on indoor air quality was carried out in urban apartments in Harbin, China. The indoor and outdoor concentrations of $PM_{2.5}$, PM_{10}, CO, CO_2, SO_2, NO_X, TVOC, HCHO and NH_3 were monitored. Simultaneously, questionnaire surveys on the indoor perception of air quality among occupants were conducted. In addition, a continuous measure on indoor air pollutants was performed during cooking period and the indoor air quality in newly-decorated urban apartments was also studied.

The results showed that the indoor $PM_{2.5}$ and PM_{10} during the space heating period, especially the haze weather period caused by heavy smog, were polluted seriously. Good linear relationships between indoor and outdoor concentrations of PM were identified in the condition of terrible outdoor air quality. In contrast, the concentrations of HCHO, CO, CO_2, NO_X and SO_2 approximately satisfied the requirements of national standard unless the serious haze weather occurred. According to the subjective surveys, occupants could evaluate the indoor ventilation correctly, but the indoor air quality was always overestimated. Moreover, the factor of illness history of the occupants had an obvious influence on the evaluation of indoor air quality. Furthermore, cooking increased the indoor concentrations of HCHO, CO and TVOC significantly, and the indoor air quality in newly-decorated urban apartments was heavily polluted by HCHO, NH_3 and TVOC.

1. Introduction

1.1. Research background

Indoor air quality (IAQ) has attracted increasing attentions and concerns recently since the living standard is improved obviously. Hundreds of indoor pollutants from various indoor and outdoor sources have been identified in indoor environments, which are associated with seriously adverse effects on human health (Jones, 1999; Tang et al., 2016). Undoubtedly, living and working in a poor indoor environment would make occupants uncomfortable and even lead to some sick building syndromes (SBS), such as sneezing, coughing, eye irritation and skin irritation (Massey et al., 2016). For example, particulate matter (PM) is likely to induce heart, lung disease and even lung cancer (Begum et al., 2009).

People spend most of time indoors and therefore healthy indoor environments can reduce the unhealthy risks and achieve a good living style accordingly. Many field studies on indoor air quality both at urban and rural houses are conducted in recent years (Deng et al., 2017; Fan et al., 2017; Kalimeri et al., 2016; Mainka et al., 2015). Wal et al. (1991) conducted a field study in urban houses in Netherlands and pointed out that ventilation could effectively reduce the indoor concentrations of CO, CO_2, NO, NO_2, PM and HCHO. Molloy et al. (2012) carried out a field study in urban houses in Australia and indicated that a reverse relationship was identified between the indoor concentrations of air pollutants and building construction time. Pereira et al. (2014) found that the concentration of CO_2 in Portuguese secondary classrooms frequently exceeded the national and international limits based on field studies. Branco et al. (2014) pointed out that the concentrations of PM were often higher than the corresponding limits in study rooms of urban nurseries at Porto city because of the poor ventilation. Wang et al. (2014) carried out a field study on indoor air quality of rural houses in winter in severe cold region in China. The indoor pollutants of PM, CO, NO_X and SO_2, which were mainly emitted by Chinese Kang, always exceeded the national standard values seriously. Zhang et al. (2015) investigated the indoor air quality during the heating and cooking periods in rural areas and pointed out that the influences of CO, NOx and inhalable particles polluted from rural areas on the air quality of the urban areas could not be overlooked. Jiang and Bell (2008) investigated the indoor air quality at rural and urban areas in northeast

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China and found that the indoor air quality at rural areas, which widely used the biomass, was worse than that at urban areas.

1.2. Motivation and challenge

For the severe cold region in China, the winter is very long and cold, and the space heating period lasts for around six months. In winter, coal is widely used in the centralized heating system in the urban area and straw is the main material for cooking and heating at the rural houses (Mestl et al., 2007). Due to the air pollutants released by the coal and straw (Wang et al., 2004; Zhang and Smith, 2007), the air pollution of urban area in winter in the severe cold region of China are always serious. What's worse, the haze weather with severe smog has occurred frequently in winter in China recently and the air quality issue is becoming a big challenge. For example, in October 2013, the heaviest haze weather caused by severe smog throughout history attacked Harbin, one of the biggest cities in the northeast of China. The terrible weather lasted for several days and the visibility was less than 10 meters, which resulted in serious inconveniences to citizens' living and health. In fact, many reasons lead to such poor air quality of urban areas in winter. The first and direct factor is that the continuous inversion and weak wind weather occurs frequently in winter. It is difficult for the air pollutant diffusion and raises the possibility of air pollution. Secondly, large amounts of straws are burnt by peasants for heating and cooking in winter at suburb. Combustion products of straws including many kinds of air pollutants would release into the environment. As a result, the urban areas will be influenced by serious air pollution coming from surrounded rural areas. Finally, widely using the coal boilers and furnaces for space heating in urban areas generates large amounts of air pollutants and causes the air pollution in winter.

Facing the above challenges, it is meaningful and necessary to investigate the indoor air quality of urban apartments in winter in the severe cold region, especially under the heavy haze weather caused by severe smog. However, limited researches were conducted to investigate the indoor air quality in the severe cold region of China under aforementioned weather conditions. Therefore, field studies on indoor air quality were carried out in urban apartments in Harbin, a typical city located in the severe cold region in China. The studies were conducted between September 2013 and May 2014. During the test period, serious haze weather with heavy smog pollution occurred. .

In each field study, the indoor and outdoor air pollutants of $PM_{2.5}$, PM_{10}, CO, CO_2, SO_2, NO_X, TVOC, HCHO and NH_3 were monitored. In addition, the influences of cooking and decorating on indoor air quality were also investigated and studied. According to the field measurements and questionnaires, the indoor air quality in urban apartments was analyzed. Also, the relationships between the indoor and outdoor PM were identified.

2. Methodology

The objective test and questionnaire survey were conducted simultaneously for the field studies.

2.1. Sampling sites and sampling events

Harbin, with a quite long and cold winter, is a typical city located in the severe cold region in China. The space heating period lasts for around six months in winter. To investigate the indoor air quality of urban apartments in the severe cold region of China (especially in winter), the field studies were selected to be carried out in Harbin. The field tests were carried out about every two weeks between September 2013 and May 2014. The sites for the study were ten apartments from nine residential buildings in five residence communities in Harbin. The appearances of these five residence communities are shown in Fig. 1 and the basic information of the selected ten apartments is shown in Table 1.

In Table 1, these ten apartments were with relatively long construction time so as to remove the influence of decorating on indoor air quality. Among these ten apartments, apartment 1 was chosen to conduct a continuous test to study the influence of cooking on indoor air quality. In addition, another six apartments, which experienced repair or decoration within six months, were selected to investigate the indoor air quality in newly-decorated apartments. These two studies were carried out in November 2013.

The indoor pollutants were measured between 19:30pm and 21:30pm every field study except the study of cooking. This period was the main time that the occupants stayed at home after work and could also ensure a sufficient time interval after cooking activities which may potentially influence the accuracy of measurements.

The indoor and outdoor concentrations of nine air pollutants were measured on sites simultaneously, including $PM_{2.5}$, PM_{10}, CO, CO_2, SO_2, NO_X, TVOC, HCHO and NH_3. The information of instruments for tested parameters is shown in Table 2. $PM_{2.5}$ and PM_{10} were monitored by a portable instrument (TSI 8532), with an accuracy of $\pm 5\%$ within the range of 0.001–150 mg/m^3. CO_2 was measured by a portable instrument (Tal 7001), with a resolution of 1 ppm within the range of 20–10000 ppm. CO, SO_2, NO_X, TVOC and HCHO were measured by portable instruments (GT901 series) with a resolution of 0.01 ppm within the range of 0–100 ppm. NH_3 was measured by a portable instrument (MIC) with a resolution of 0.01 ppm within the range of 0–100 ppm. The instruments for the measured pollutants are shown in Fig. 2. To guarantee the accuracy of the measurement, the calibration of each instrument was conducted for the field study. Normally, the calibration of each instrument was needed every twelve months using either a zero concentration gas or with a gas with a specific concentration. In this study, all the instruments were factory calibrated prior to the field tests. Considering the harsh conditions for outdoor measurements, another calibration of each instrument was carried out with the help of each instrument's factory during the field study. In addition, the PM portable instruments performed zero calibration with a zero filter prior to every use.

Fig. 3 shows the indoor location of the sampling site in one of the field-study urban apartments. The sampling site in each apartment was located in the central of the living room, which was the main activity place for the occupants. Considering human respiratory zone introduced in the indoor air quality standard, the height of each sampling site was set as about 1.0 m above floor level (ASHRAE Standard 62.1-2007). The concentration of each indoor pollutant was recorded as the average value measured within one hour. In addition, the outdoor concentration of each air pollutant was measured for each apartment. The outdoor measuring site was located about 30 m in front of each residential building. Due to the seriously cold weather of Harbin in winter (i.e., the temperatures always kept at $-20\sim$-30 °C), effective methods were necessarily adopted in case the instruments were failure caused by the very low temperature. According to the operational condition of each instrument shown in Table 2, the instruments of PM and CO_2 were beyond the acceptable working conditions for the outdoor measurements. In such a case, thermal insulation packages were equipped with the instruments and the sampling time was set to be shorter than that for the indoor tests, i.e., the average values measured within half an hour.

2.2. Questionnaire survey

Questionnaire surveys were carried out in each field study, simultaneously with the objective investigation. 20 subjects stayed at 10 apartments with long construction time participated in the questionnaire surveys every time. The questionnaire contained objective and subjective questions, as presented in Table 3. The objective questions included the gender and age of occupants, the frequency of cleaning and the time interval after cooking, etc. The subjective questions included the evaluations on air ventilation and perceived indoor

Fig. 1. Appearances of five residence communities.

Table 1
Basic information of sampling apartments in Harbin.

Number of apartment	Construction time	Floor level	Floor area	Number of Occupant
1	2001	7	34.4	2
2	2001	7	15.1	2
3	1999	4	36.2	2
4	1999	3	23.6	2
5	1996	5	14.1	1
6	1996	5	11.1	2
7	1993	7	32.4	2
8	2000	7	34.6	2
9	2001	4	41	3
10	2001	7	32	2

air quality, the indoor sensations (in terms of dust, odor and foul air), the acceptance of current indoor air quality, etc. 276 questionnaires were collected in total during the entire test period.

3. Results and analyses

This section presents the objective and subjective results of field studies conducted in the apartments with long construction time, which reflects the normal indoor condition of urban apartments in winter in the severe cold region of China. The results measured in newly-decorated apartments as well as the continuous test for studying the influence of cooking are discussed in section 4.

3.1. Objective analyses

3.1.1. Indoor and outdoor concentrations of air pollutants

The Chinese national standard of each indoor air pollutant is defined with the mass units except CO_2, as shown in Table 4. The standard values except $PM_{2.5}$, PM_{10}, HCHO and CO_2 should be converted into volume units in order to be compatible with the units of measurements by the instruments.

For the field studies of the sites with long construction time, the monthly average indoor and outdoor concentrations of measured air pollutants from September to May in the coming year are shown in Fig. 4. The dash lines in the figure denote the national standard limit values of individual indoor pollutants. In this study, the space heating period is from November to next April and the non-heating period refers to September and May. In general, the indoor and outdoor air quality of non-heating period was obviously better than that of the heating period. The monthly average concentrations of $PM_{2.5}$ and PM_{10} almost exceeded the corresponding standard values during the entire space heating period. The indoor concentrations of PM were polluted seriously by the higher outdoor PM concentrations during the relatively colder months from October to next February. In October, because of the heavy smog in the outdoor environment, the indoor concentration of $PM_{2.5}$ reached about 0.6 mg/m^3, over 7 times higher than its standard value. As the serious haze weather alleviated, the indoor air quality experienced an obvious improvement but was still very bad from November to next February. After the weather changed to be warm, the indoor concentration of $PM_{2.5}$ was decreased and fluctuated around its standard value. On the contrary, during the non-heating period, indoor $PM_{2.5}$ could satisfy its standard requirement and outdoor concentrations were lower than indoor concentrations. In fact, the mass concentration of particle matter with the aerodynamic diameter less than 2.5 μm (i.e., $PM_{2.5}$) always accounts for more than 80% of that of the particle matter with the aerodynamic diameter less than 10 μm (i.e., PM_{10}) (Massey et al., 2012). Hence, a similar changing trend with that of $PM_{2.5}$ was occurred on PM_{10} during the test period.

Moreover, the indoor and outdoor concentrations of the other seven air pollutants were shown in Fig. 4. Except the period with heaviest haze weather (i.e., October), these seven indoor pollutants were almost below their national standard limits. When the very bad outdoor weather occurred, the occupants reduced the indoor ventilation to

Table 2
Instruments for tested parameters.

Tested parameter	Instrument	Resolution	Measuring range	Accuracy	Operational Temp.
PM	TSI 8532	0.001 mg/m^3	0.001–150 mg/m^3	±5%	0–50 °C
CO_2	Tal 7001	1 ppm	20–10000 ppm	-±50 ppm	0–50 °C
CO, SO_2, NO_X, TVOC, HCHO	GT901	0.01 ppm	0–100 ppm	±3%	−40–70 °C
NH_3	MIC	0.01 ppm	0–100 ppm	±3%	−40–70 °C

Fig. 2. Instruments for measured air pollutants.

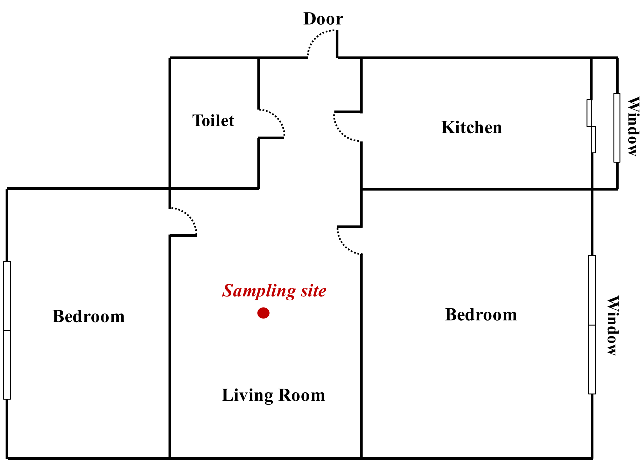

Fig. 3. Indoor sampling site in one of the field-study urban apartments.

Table 3
Summary of subjective questionnaire.

	Questions
Basic information	Gender, age, daily working hours, work pressure, satisfaction level about work, illness history, frequency of cleaning
Indoor air sensations	dust, odor, foul air and air ventilation
Perceived indoor air quality	evaluation, acceptance

avoid the air pollutants coming indoors and hence the pollutants emitted from indoor sources could not be released to the outsides effectively. Therefore, the indoor concentrations of HCHO, CO, CO_2, NO_X and SO_2 were notably exceeded the standard values in October. In addition, CO, NO_X and SO_2 were the air pollutants in haze weather and their indoor concentrations followed the changing trends of PM because of the infiltration. During the test period, the maximum concentrations of NH_3 and TVOC appeared in October but were below the standard limits.

3.1.2. Air exchange rate

The air exchange rate (AER) of each measured site was also studied, as calculated by Eqs. (1) and (2).

$$V\frac{dC_{in}}{d\tau} = Q(C_{out} - C_{in}) + Q_{CO_2} \tag{1}$$

$$n = \frac{Q}{V} \tag{2}$$

where, Q is the ventilation rate per second, m^3/s; C_{in} and C_{out} are the indoor and outdoor CO_2 concentrations, mL/m^3; Q_{CO_2} is the volumetric rate of carbon dioxide produced in liters per second, m^3/s; V is the volume of the site; τ is the time, s; n is the air exchange rate.

According to *ASHRAE fundamental handbook*, Eqs. (3) and (4) are used to describe the carbon dioxide generation rate as a function of the physical activity level of occupants and the body surface area in square meters of the average individual. Physical activity is expressed in terms of metabolic rate per unit of surface area (mets) with one met being equivalent to 58.2 Watts per square meter.

$$Q_{CO_2} = \frac{RQ \times A_D \times M}{21 \times [0.23RQ + 0.77]} \tag{3}$$

$$A_D = 0.202 \times (H)^{0.725} \times (w)^{0.425} \tag{4}$$

where, RQ is the respiratory quotient (and set as 0.83 in this study), which is the relative volumetric rate of carbon dioxide produced to oxygen consumed; M is the level of physical activity or the metabolic rate per unit of surface area in mets (which is estimated to be a moderate 1.4 mets of activity); A_D is the body surface area of the occupants, m^2; H is the height of the occupant, m; w is the weight of the occupant, kg.

Fig. 5 presents the average air exchange rate in each tested month. The dash line was the required air exchange rate to meet the national standard requirement. The determination of required air exchange rate was based on the minimum fresh air per occupant and the number of occupants. In Fig. 5, a significant difference of air exchange rate between the heating and non-heating periods can be found. It meant that the condition of outdoor air quality had an obvious influence on occupants' ventilation activities. Due to good outdoor air quality of the non-heating period, the occupants conducted ventilation frequently and hence the indoor air quality was good. But in the heating period, the air exchange rates marginally satisfied the requirement except October. Although the outdoor temperature in winter was very low in Harbin, the indoor ventilation was not avoided completely by the occupants and even could be marginally meet the requirement. This was because the indoor temperatures of measured sites were maintained over 28 °C contributed by the sufficient heating supply.

Table 4
National standard values of indoor pollutants (G.T.18883-2002, 2002).

	$PM_{2.5}$	PM_{10}	HCHO	CO	CO_2	NO_X	SO_2	NH_3	TVOC
Standard Value	0.075 mg/m^3 0.075 mg/m^3	0.15 mg/m^3 0.15 mg/m^3	0.10 mg/m^3 0.10 mg/m^3	10 mg/m^3 8ppm	0.1% 1000 ppm	0.30 mg/m^3 0.15 ppm	0.50 mg/m^3 0.18 ppm	0.20 mg/m^3 0.26 ppm	0.60 mg/m^3 0.50 ppm

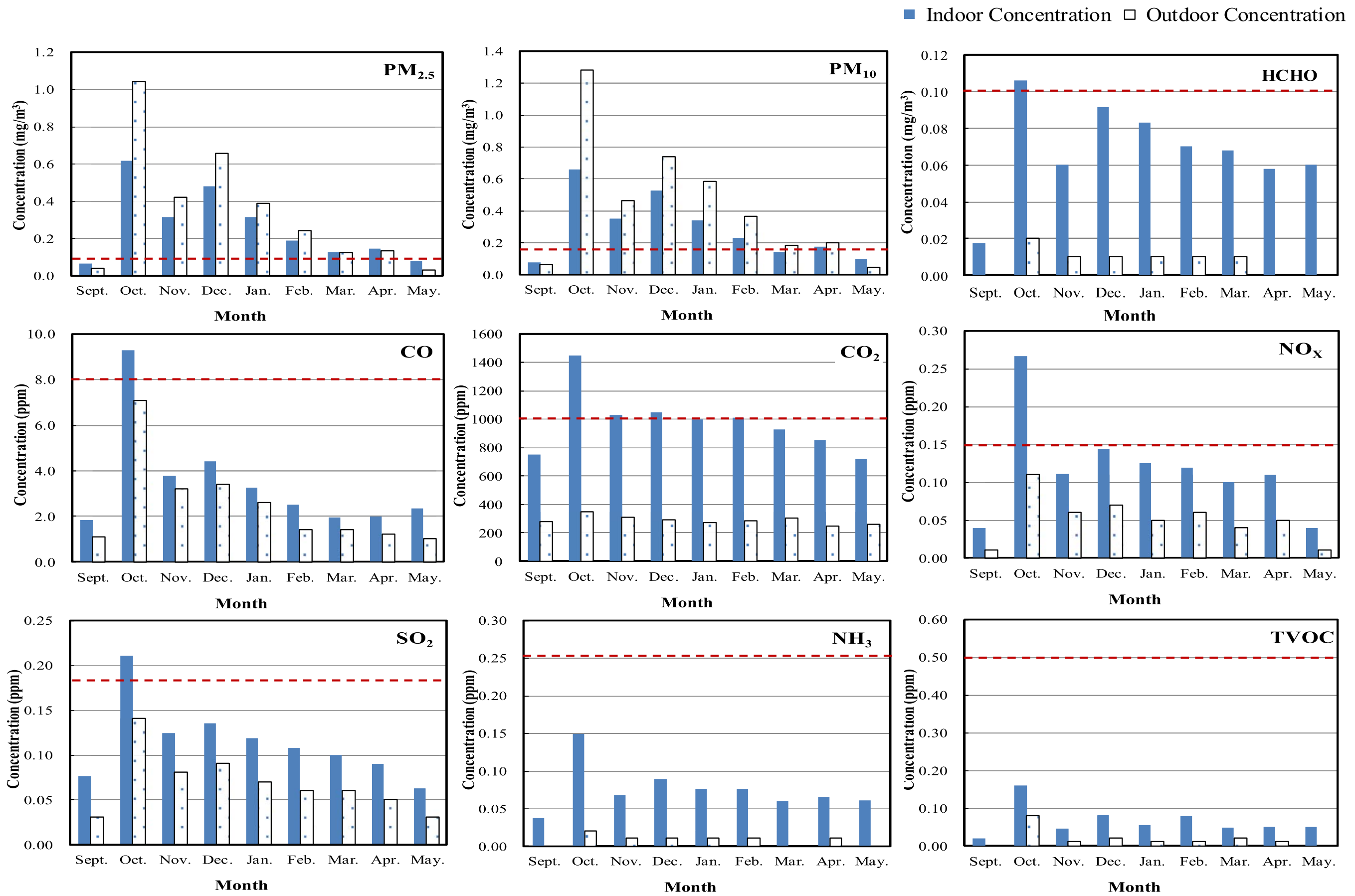

Fig. 4. Monthly indoor and outdoor concentrations of air pollutants in the sites with long construction time: *the red dash lines represent the national standard limits of individual indoor air pollutants.*

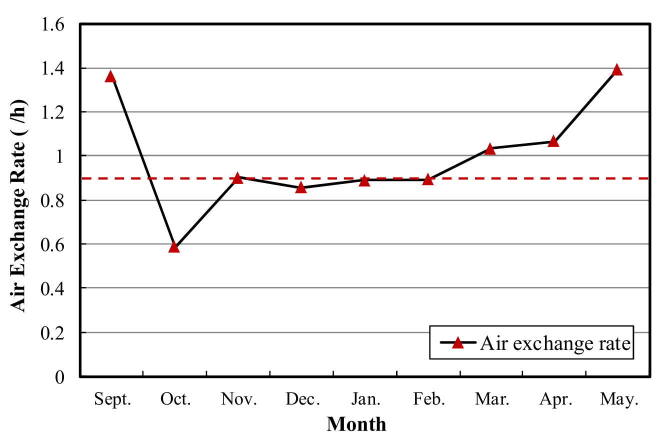

Fig. 5. Monthly air exchange rates in the sites with long construction time: *the red dash line represents the national standard of air exchange rate.*

3.2. Subjective analyses

The questionnaire surveys were conducted, simultaneously with the objective tests. The subjective questions covered the evaluation on indoor ventilation and perceived indoor air quality as well as the acceptance of current indoor air quality. Meanwhile, the interval from last cooking time was also surveyed to make sure a sufficient time experienced for avoiding the influence of cooking on objective measurements.

3.2.1. Evaluation on indoor ventilation

Table 5 shows the distribution of occupants' evaluation on indoor air ventilation. Five grades were used for the evaluation, i.e., “very good”, “good”, “general”, “bad” and “very bad”, and assigned with corresponding scores from 2 to −2 respectively. Generally, the monthly average scores on indoor air ventilation were over zero except October, which meant that the evaluations were better than the grade of general. During the space heating period except October, the perceptions of indoor air ventilation were at the grade between “Good” and “General”, and no occupant thought indoor ventilation very bad. This was mainly because the sufficient heating was provided in winter in Harbin. Although the outdoor temperature was very low and ventilation was conducted by the occupants, the sufficient heating supply could ensure the indoor air temperatures within the comfortable range. In October, less indoor ventilation was undertaken by the occupants because of the serious haze weather. Undoubtedly, the score on indoor ventilation in

Table 5
Evaluation on indoor air ventilation.

	Very good	Good	General	Bad	Very bad	Score
Sept.	38.9%	33.3%	27.8%	0.0%	0.0%	1.11
Oct.	0.0%	5.9%	47.1%	41.2%	5.9%	−0.47
Nov.	12.5%	25.0%	56.3%	6.3%	0.0%	0.44
Dec.	3.2%	38.7%	48.4%	9.7%	0.0%	0.35
Jan.	0.0%	15.4%	76.9%	7.7%	0.0%	0.08
Feb.	11.8%	35.3%	47.1%	5.9%	0.0%	0.53
Mar.	12.5%	56.3%	31.3%	0.0%	0.0%	0.81
Apr.	20.0%	53.3%	26.7%	0.0%	0.0%	0.93
May.	26.7%	60.0%	13.3%	0.0%	0.0%	1.13
Heating	8.0%	33.6%	47.2%	10.4%	0.8%	0.38
Non-heating	33.3%	45.5%	21.2%	0.0%	0.0%	1.12

Table 6
Evaluation on perceived indoor air quality.

	Very good	Good	General	Bad	Very bad	Score
Sept.	5.6%	72.2%	22.2%	0.0%	0.0%	0.83
Oct.	0.0%	17.6%	47.1%	35.3%	0.0%	−0.18
Nov.	6.3%	37.5%	50.0%	6.3%	0.0%	0.44
Dec.	6.3%	40.6%	43.8%	9.4%	0.0%	0.44
Jan.	0.0%	38.5%	46.2%	15.4%	0.0%	0.23
Feb.	6.3%	50.0%	43.8%	0.0%	0.0%	0.63
Mar.	6.3%	62.5%	31.3%	0.0%	0.0%	0.75
Apr.	6.7%	73.3%	20.0%	0.0%	0.0%	0.87
May.	8.3%	83.3%	8.3%	0.0%	0.0%	1.00
Heating	4.8%	44.8%	40.8%	9.6%	0.0%	0.45
Non-heating	6.7%	76.7%	16.7%	0.0%	0.0%	0.90

this month would decreased and fell in the range between "bad" and "very bad". Overall, the score of indoor ventilation during the non-heating period were obviously higher than that during the space heating period. Compared with the results of air exchange rate (shown in Fig. 5), the evaluation on indoor ventilation was almost consistent with the real conditions.

3.2.2. Evaluation on indoor air quality

Table 6 presents the results of occupants' evaluation on perceived indoor air quality. The evaluation was also classified into five grades, "very good", "good", "general", "bad" and "very bad", assigned with corresponding scores respectively (i.e., 2, 1, 0, −1, −2). The score of non-heating period was slightly better than the value of space heating period, and both were scored in the range between "good" and "general". During the space heating period, approximately 90% of the occupants thought the indoor air quality higher than "general" and even 4.8% of occupants gave a "very good" evaluation. In October, although the indoor concentrations of PM exceeded the acceptable standard values many times and HCHO, CO, CO_2, NO_X and SO_2 were also polluted seriously, the score was a little lower than the grade of "general" and no occupants felt the indoor air quality very bad. Therefore, the seriousness of living environment could not be felt and realized effectively and correctly by the occupants. Furthermore, the subjective survey on the acceptance of current indoor air quality was also included in the questionnaire surveys. According to the results, nearly 95% of occupants could accept the current indoor air quality during space heating period, and only 5% thought the current indoor air quality unacceptable and intolerable.

3.2.3. Different factors on the evaluation of indoor air quality

The influences of gender, age, illness history and frequency of cleaning on the perceived indoor air quality are shown in Table 7. In general, the factors, gender, age and frequency of cleaning, had a very limited influence on the evaluation of perceived indoor air quality. During the entire test period, the male's evaluation on indoor air quality was a little higher than that of female but not obvious. To investigate the influence of age on perceived indoor air quality, two groups were divided and young occupants thought the air quality a little better than that of old occupants (e.g., their parents). In addition, the occupants with more times of room cleaning had relatively higher scores on the indoor air quality. In contrast, the illness history impacted the evaluation of perceived indoor air quality significantly. During the heating period, the score of the occupants with illness history was two times lower than that without any illness history.

Table 7
Evaluation on perceived indoor air quality considering different factors.

Scores of perceived indoor air quality			
		Heating	Non-heating
Gender	Male	0.49	0.93
	Female	0.41	0.88
Age	20–30 years old	0.51	0.95
	45–55 years old	0.42	0.87
Frequency of cleaning	1–2 times per day	0.47	0.93
	Below 1 time per day	0.44	0.88
Illness history	With	0.21	0.84
	Without	0.64	0.97

4. Discussion

4.1. Comparison of objective and subjective results

Considering the fact that the measured indoor concentration of CO_2 was capable to reflect the indoor ventilation effectively, the subjective surveys on indoor ventilation and the measured indoor concentrations of CO_2 were combined together to be analyzed. Under bad outdoor weather conditions, the ventilation time was likely to be reduced and even avoided by the occupants. Then, the indoor concentration of CO_2 would increase and relatively bad indoor ventilation was perceived by the occupants accordingly. Based on a comparison between the results shown in Fig. 4 and Table 6, it was concluded that the occupants' evaluation on indoor ventilation was almost accurate and consistent with the actual measurements. High indoor concentration of CO_2 always accompanied with a relatively bad evaluation on indoor ventilation. In addition, air exchange rate could effectively reflect the indoor ventilation. Compared the results in Fig. 5 with Table 6, it was found that the scores of evaluation on indoor ventilation were in line with the air exchange rates.

On the contrary, it was worthy of noticing that the evaluations on perceived indoor air quality were inconsistent with that of the objective results. Although the indoor concentrations of $PM_{2.5}$ and PM_{10} were rather high and sometimes exceeded the standard limits seriously, most people could not feel and realize the seriousness of their living environment. In October, the indoor air quality was terrible because of the heavy haze weather and the indoor concentrations of measured pollutants exceeded the limits significantly. But the score in October was not very low and still near to the grade of "general". A good score for space heating period was evaluated by the occupants although some of indoor pollutants were higher than permitted limits. Therefore, low attention was paid by the occupants on indoor air quality, which may induce adverse effects on human health.

In summary, occupants could correctly feel and evaluate indoor ventilation. But occupants could not effectively and correctly evaluate the perceived indoor air quality of their living environment although the current indoor condition was rather poor. It is suggested that occupants should pay more attention on the indoor air quality and effective methods would be adopted in the future. For example, detectors of indoor air pollutants are recommended to be installed indoors, particularly for the PM detectors during space heating periods. Thus, the occupants can know when the indoor pollutants are higher than the limits and take measures to ensure their living environment healthy.

4.2. Influence of decoration on indoor air quality

The field tests for the newly-decorated urban apartments were carried out on the day in November 2013, which were selected for field studies on apartments with long construction time (namely normal apartments). This ensured that the comparison between the normal apartments and newly-decorated apartments was under a similar outdoor weather condition and the influence of decoration on indoor air quality was clearly presented accordingly. The comparison of indoor pollution between newly-decorated apartments and normal apartments was shown in Table 8.

Obvious differences of indoor concentrations of pollutants were existed between these two kinds of urban apartments. Due to finishing

Table 8
Indoor concentrations of pollutants in new-decorated urban apartments.

	$PM_{2.5}$ (mg/m^3)	PM_{10} (mg/m^3)	HCHO (mg/m^3)	CO (ppm)	CO_2 (ppm)	SO_2 (ppm)	NO_X (ppm)	NH_3 (ppm)	TVOC (ppm)
New-decorated	0.337	0.364	0.21	1.2	645	0.114	0.122	0.45	0.34
Normal	0.313	0.347	0.06	3.8	1029	0.111	0.128	0.07	0.05

materials used in newly-decorated apartments, the concentrations of HCHO, NH_3 and TVOC went up significantly, and 2 times, 6 times and 6 times were higher than the values in normal apartments, respectively. These three indoor pollutants (i.e., HCHO, NH_3 and TVOC) were much higher than their acceptable standard values. Moreover, the indoor concentrations of $PM_{2.5}$ and PM_{10} also increased about 10% in newly-decorated apartments. By contrast, the indoor concentrations of CO and CO_2 were decreased notably in comparison to the values in the normal apartments. This was mainly because the occupants deliberately reduced the staying time in newly-decorated apartments to avoid adverse effects on their health. As a result, the reduced staying time decreased the concentration of CO_2, and CO emitted by incomplete combustion was also reduced evidently because of fewer activities taken in the apartments such as cooking and smoking.

4.3. Influence of cooking on indoor air quality

In order to study the influence of cooking on the indoor air quality, apartment 1 was selected to conduct a continuous test during a cooking period. The test was carried out in the living room where most of activities were taken place in. The measured pollutants were $PM_{2.5}$, PM_{10}, HCHO, CO, TVOC and CO_2. The measuring started at five minutes before the cooking and the data were recorded every two minutes. The test lasted 110 min and the profiles of individual indoor pollutants were shown in Fig. 6.

Generally, cooking in the kitchen had an obvious influence on the air quality of living room. The indoor concentrations of $PM_{2.5}$ and PM_{10} were not obviously affected by the cooking, which may be caused by the extractor hood used in the kitchen. The changing profiles of HCHO, CO and TVOC were almost similar during the test period. Before the cooking, the concentrations of HCHO and TVOC were rather low (i.e., near to zero). At the start of cooking, the concentrations of these three indoor pollutants were increased significantly. After about 50 min, the concentrations of HCHO and TVOC reached about 0.7 mg/m^3 and 2 ppm, which severely exceeded the national standard values many times. Meanwhile, the maximum indoor concentration of CO was about two times higher than that before the cooking. These three indoor pollutants seriously increased mainly because they were the main ingredients of cooking fume and combustion products of liquefied natural gas used for cooking. Therefore, effective methods such as ventilation would be adopted and strengthened during cooking periods in order to guarantee the indoor air quality. In addition, the concentration of CO_2 experienced a slight increase during the cooking period because CO_2 was the pollutants of cooking and occupants begun to concentrated in the living room for dining.

4.4. I/O ratios of $PM_{2.5}$ and PM_{10}

The indoor concentrations of PM were always rather high in winter, especially during the haze weather period. To identify the sources of indoor PM, the I/O ratios of PM in each month were calculated and analyzed. During every field study for each apartment with long construction time, the indoor and outdoor concentrations of PM were measured as a pair for calculating the I/O ratios to find out their relationships.

Fig. 7 shows box-plots of the I/O ratios of $PM_{2.5}$ in different months. The I/O ratios of $PM_{2.5}$ during the space heating period were obviously lower than the values of non-heating period. From October to next January, the ratios of the measured sites were below unity and fluctuated over a small range. It indicated that the outdoor air quality was serious and the outdoor $PM_{2.5}$ was the main source for indoor pollution. The influence of indoor sources such as human's activity was very small and even could be ignored. Hence, avoiding the outdoor $PM_{2.5}$ into indoors would be an effective way to guarantee the indoor air quality in such periods (Guo et al., 2010). As the outdoor air quality improved, the outdoor concentration of $PM_{2.5}$ decreased and the indoor sources of $PM_{2.5}$ would not be ignorable. From February to April in the space heating period, the I/O ratios in the apartments with more indoor $PM_{2.5}$ sources were likely to be higher than one. Due to the different levels of indoor sources in each apartment, the I/O ratios of $PM_{2.5}$ in individual apartments fluctuated in a bigger range when the outdoor air quality was not so bad. During non-heating period (i.e., Sept. and May), the I/O ratios of $PM_{2.5}$ of individual apartments were very different, which revealed that the indoor pollution of PM was the primarily caused by the indoor sources. Therefore, under a good outdoor air quality, to control the indoor sources of $PM_{2.5}$ would be reasonable and effective to reduce the indoor concentration of $PM_{2.5}$.

Fig. 8 shows box-plots of the I/O ratios of PM_{10} in different months. According to the fact that $PM_{2.5}$ accounted for large part of PM_{10}, a similar changing trend of I/O ratios of PM_{10} was occurred during the test months.

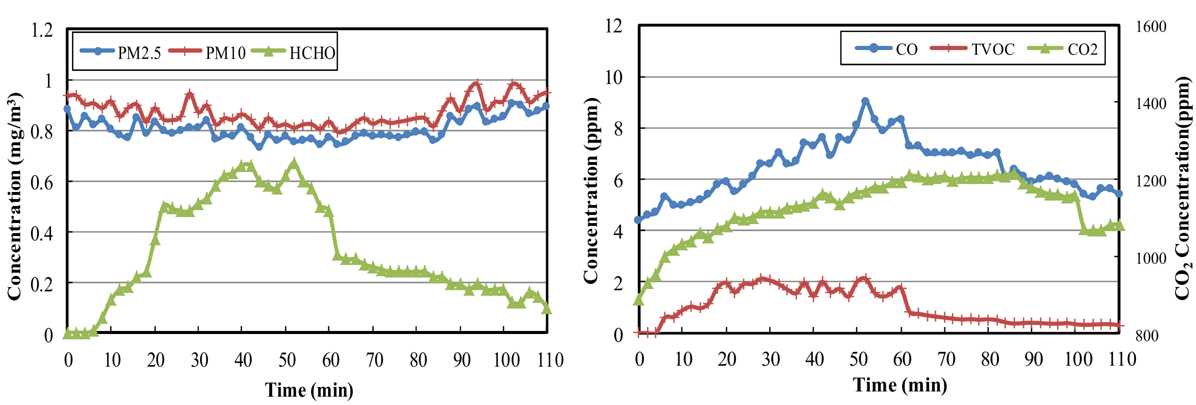

Fig. 6. Concentrations of measured indoor pollutants during cooking period.

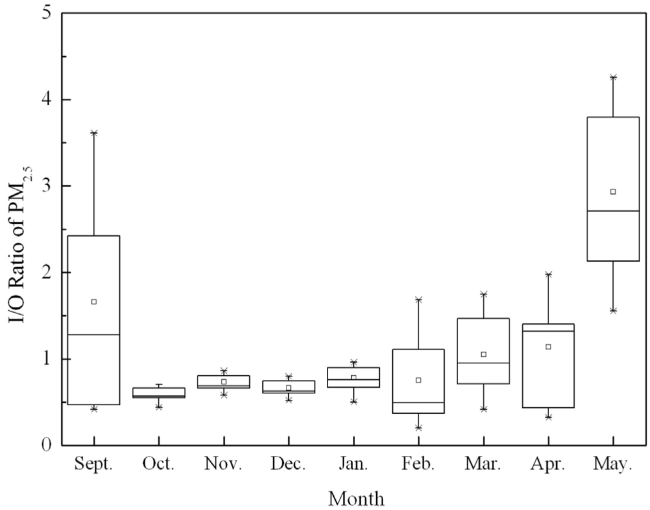

Fig. 7. I/O ratios of $PM_{2.5}$ in different months.

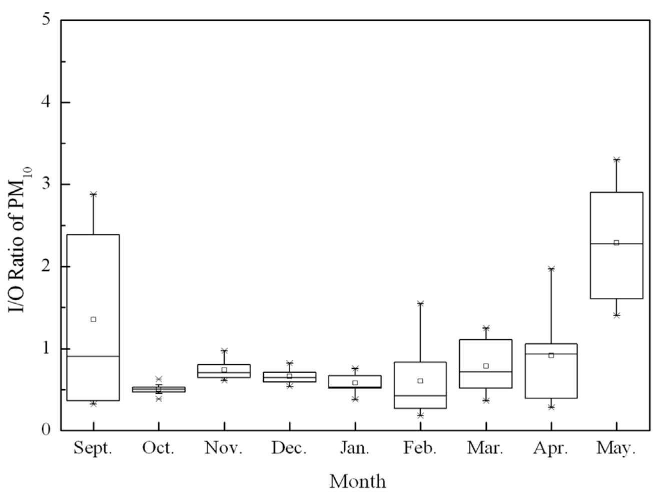

Fig. 8. I/O ratios of PM_{10} in different months.

4.5. Correlation between indoor and outdoor PM

As discussed in section 4.4, the indoor concentrations of $PM_{2.5}$ and PM_{10} were mainly influenced by the outdoor condition when the serious haze weather with severe smog was occurred. So the data measured from October to next February were selected to identify the relations between indoor and outdoor concentrations of PM.

The correlation between indoor and outdoor concentrations of $PM_{2.5}$ was shown in Fig. 9. A good linear relationship was obtained, as shown in Eq. (5) (Deng et al., 2015).

$$y = 0.577x - 0.069 \quad R^2 = 0.88 \tag{5}$$

where, y is the indoor concentration of $PM_{2.5}$, mg/m^3; x is the outdoor concentration of $PM_{2.5}$, mg/m^3.

Also, the correlation between indoor and outdoor concentrations of PM_{10} was shown in Fig. 10. A good linear relationship was obtained, as shown in Eq. (6).

$$y = 0.511x - 0.087 \quad R^2 = 0.85 \tag{6}$$

where, y is the indoor concentration of PM_{10}, mg/m^3; x is the outdoor concentration of PM_{10}, mg/m^3.

5. Conclusions

To investigate the indoor air quality of urban apartments in the severe cold region (especially in winter) of China, field studies were carried out in residential buildings in Harbin. Based on the objective measurements of indoor pollutants and subjective surveys, the results were concluded as follows:

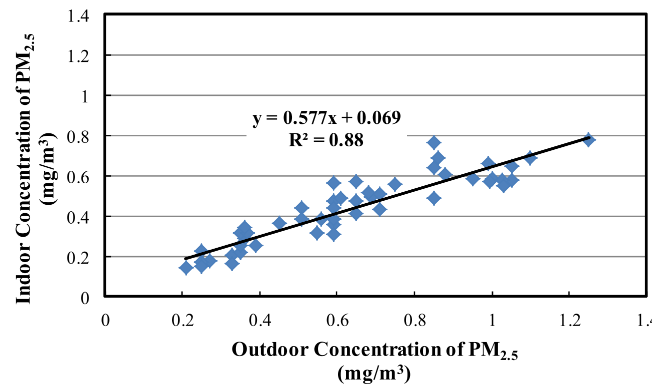

Fig. 9. Correlation between indoor and outdoor $PM_{2.5}$.

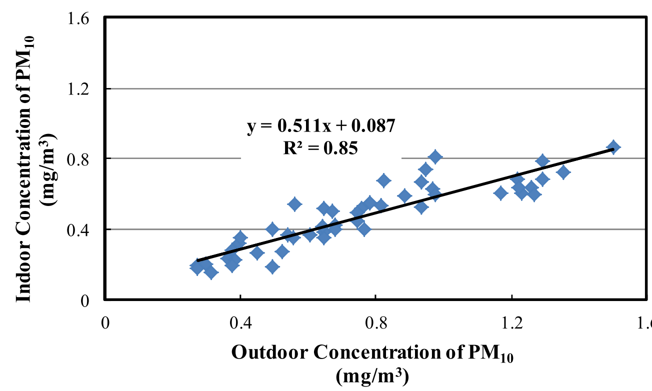

Fig. 10. Correlation between indoor and outdoor PM_{10}.

(1) For the apartments with long construction time, the indoor concentrations of $PM_{2.5}$ and PM_{10} were seriously exceeded the Chinese national standard during space heating period. Under heavy haze weather in October, the indoor concentrations of $PM_{2.5}$, PM_{10}, HCHO, CO, CO_2, NO_X and SO_2 were quite high. Particularly, the indoor concentrations of PM were many times higher than their corresponding standard values.
(2) According to the subjective surveys, the occupants' evaluation on indoor ventilation was almost accurate and consistent with the objective results. However, the occupants always overestimated the indoor air quality although the current indoor condition was rather poor. In addition, the illness history of the occupants had a significant influence on the evaluation of perceived indoor air quality.
(3) In the newly-decorated urban apartments, the indoor concentrations of HCHO, NH_3 and TVOC were 2 times, 6 times and 6 times higher than the measured values in the urban apartments with long construction time. But the concentrations of CO and CO_2 were lower notably in newly-decorated urban apartments.
(4) When cooking in the kitchen, the concentrations of HCHO, CO and TVOC in the living room were increased significantly and their peak values were many times higher than their corresponding standard limits.
(5) I/O ratios of $PM_{2.5}$ and PM_{10} were below unity in the condition of terrible outdoor weather and the outdoor pollution was the main source for indoor PM. As the outdoor condition improved, the I/O ratios of $PM_{2.5}$ and PM_{10} increased and fluctuated in bigger ranges so that the indoor sources would not be ignorable. In addition, good linear relationships between the indoor and outdoor concentrations

of PM were obtained when the outdoor air quality was bad during the space heating period.

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