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Analysis of indoor humidity environment in Chinese residential buildings

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ABSTRACT

A high or low humidity environment is related closely to not only many health problems, but also has great influence on the construction durability and energy consumption. It is very important to control humidity level, in order to achieve a healthy and comfortable indoor environment. However, various problems of the air humidity in inhabited dwellings are not yet taken serious consideration in China. Moreover, there is hardly any information available regarding the actual humidity environment in Chinese residential houses. For this reason, it is difficult to select appropriate moderate moisture strategies to maintain a harmonious indoor humidity level.

The current authors carried out a field measurement survey on indoor thermal environment in nine Chinese cities. Based on this investigation, the purpose of this present study is to develop a database of actual indoor humidity conditions for moisture moderate design, through which the characteristics of indoor humidity environment in Chinese residential houses can be identified and clarified.

The results demonstrated that the indoor humidity level is too low with the relative humidity falls below 20% in some cities where residences equipped with central heating system in winter. On the other hand, indoor humidity is very high with the relative humidity beyond 80% in some cities where residences have inadequate heating and high outside humidity ratio in winter. The severe indoor humidity environment indicated that the moisture level in the residential houses of China should be mitigated and controlled in order to achieve a sustainable and healthy indoor environment.

1. Introduction

Many evidences have indicated that indoor humidity environment is closely related to health problems and it also affects energy consumption and the durability of the building envelope.

Low humidity environment (RH $<$ 30%) is associated with dryness of skin and throats, mucous membrane, sensory irritation of eyes [1–4], as well as static electricity [5]. Sunwoo [6] proposed that it is necessary to maintain the relative humidity greater than 10% and 30% to avoid the dryness of mucous membrane and the dryness of eyes and skin respectively.

On the other hand, high humidity environment may affect the perceptibility of air quality [7], and also induce the growth of mold leading to respiratory discomfort and allergies [8,9]. Fisk [10] suggested by using meta-analyses, that building dampness and mold are associated with increases of 30–50% in a variety of respiratory and asthma-related health outcomes, and also pointed out the importance of prevention against moisture accumulation. Kishi [11] did a questionnaire survey in six different locations in Japan and found that an increased risk of Sick House Syndrome (SHS) when several dampness indicators, 'condensation'; 'visual mold growth'; 'moldy odor'; 'slow drying wet towels in the bathroom' and 'water leakage' appeared simultaneously.

In addition, moisture contributes to the deterioration of building materials [12], and has an impact on the building energy performance [13,14]. Mendes [15] found that the conduction loads simulation models, which ignore moisture, might overestimate the conduction peak loads up to 210% and underestimated the yearly integrated heat flux up to 59%. And these can lead to oversize the HVAC equipments (especially in dry climates) and underestimate the energy consumption (primarily in humid climates).

For these reasons, keeping indoor humidity environment steady at the correct level is very important for ensuring the sustainability and health of buildings. It is known that the control of moisture is of prime importance to moderate the indoor humidity level. However, the indoor humidity environment is complicated and is influenced by many factors such as moisture sources (human presence and activity, equipment, plants), ventilation and infiltration of building envelope, air flow and temperature distributions in rooms, moisture adsorption and desorption from surrounding surfaces (interior

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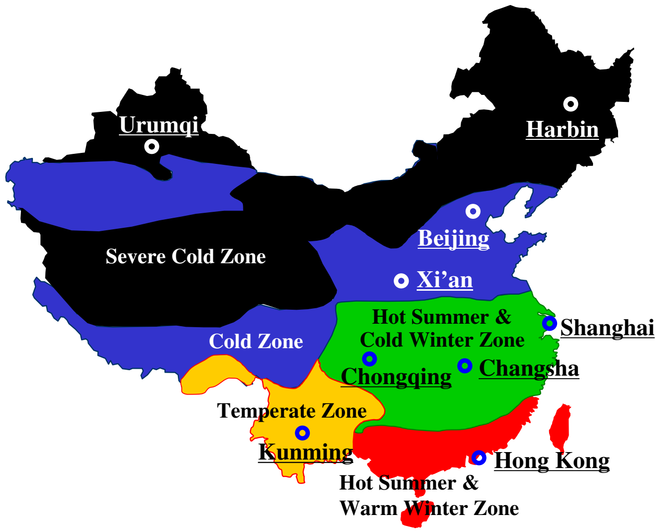

Fig. 1. Location of 9 cities and climate zones in China.

walls, floor, carpet, furniture, futon and books, etc.), as well as the absolute humidity of the outdoor air. It is rather difficult to do realistic predictions of these factors. Therefore, in order to make moisture mitigating strategies and to reduce moisture related damage, large-scale field measurement is necessary and this approach is valuable as it makes possible to clarify the actual humidity conditions thoroughly.

In USA, Japan, and European countries, the research studies on moisture control strategies have been positively advanced and received better understanding. Rudd [16] measured and analyzed indoor moisture and temperature conditions and equipment operation for 43 houses in warm-humid and mixed-humid climate regions of the United States. Kalamees [17] carried out long-term field measurements of indoor climate in 170 detached houses in Finland. Temperature and relative and absolute humidities were analyzed in subgroups of houses according to their ventilation systems and the hygroscopic materials used. Zhang [18,19] analyzed the indoor humidity environment for 72 houses in six regions of Japan and examined the relations between the indoor humidity environment and the level of thermal insulation (or air-tightness), as well as the possibility of fungal damage, based on long-term field measurements.

In China, humidity related problems have become increasingly serious, especially in the situation where high and low humidity environments are formed easily by the spread of artificial materials with poor moisture buffering performance. There is growing concern about moisture damage, such as shrink, crack, deterioration and mold. However, there is hardly any information available regarding the actual humidity environment in Chinese residential houses. Brockett [20] investigated and reported the results of energy consumption of the residential houses in five Chinese cities. Jian [21] studied the indoor thermal environment of apartment units in Beijing during a summer season. Yoshino [22] carried out a large-scale field measurement of indoor thermal environment in nine major Chinese cities and predicted the energy conservation feasibility for space heating and cooling. All of these studies are essentially done for the thermal environment and energy consumption. The research work that focuses on moisture related problem is scarcely found.

In this paper, based on the current author's previous study [22], the indoor humidity environment of the residential houses in China was analyzed. The aim of this work is to develop a database of actual indoor humidity conditions for moisture moderate design, through which the characteristics of indoor humidity environment in Chinese residential houses can be identified and clarified.

2. Methods

2.1. Selection of houses

The large-scale field measurement survey was done in residential houses of 9 major cities of China. These cities are Harbin, Urumqi, Beijing, Xi'an, Shanghai, Changsha, Chongqing, Kunming and Hong Kong, and they are located in different climatic zones of China, as shown in Fig. 1. The characteristics of these cities are as follows: Harbin is the most northerly major city in China, which has a very cold and dry winter; Urumqi is located on the western side of China with very dry outdoor climate; Beijing is the capital and it is situated in the cold climate zone; Xi'an has continental climate; Shanghai is the biggest city of China with high outdoor humidity; Changsha has a monsoon climate within the sub-tropical zone, thus the summers are long and hot as well as high humidity in outdoor; Chongqing is a major city in central-western China with high humidity in outdoor; Kunming belongs to a low-latitude monsoon climate, does not have bitter cold in winter or extreme heat in summer, thus the change in outdoor temperature and humidity is minimal; Hong Kong is located on China's south coast belonging to humid sub-tropical climate, the summer is hot and humid with occasional showers and thunderstorms. In each city, 3–12 houses were selected. These 9 cities gathered large population of China.

Table 1
Details of the winter measurement survey.

City	Survey period	Number of houses for measurement	Heating system	Average outdoor conditions during investigation
Harbin	2000.2.28–3.5	5	Central heating	−5.9 °C, 65.4%RH[b]
Urumqi	2004.1.2–1.6	10	Central heating	−12.1 °C, 66.8%RH[a]
Beijing	1999.1.14–1.19	3	Central heating	−1.1 °C, 38%RH[a]
Xi'an	2002.1.13–1.17	10	Central heating	5.1 °C, 72%RH[a]
Shanghai	1997.12.31–1998.1.5	6	Individual space heating	9.2 °C, 76%RH[b]
Changsha	2003.1.8–1.12	10	Individual space heating	4.0 °C, 81.6%RH[a]
Chongqing	2003.1.17–1.21	10	Individual space heating	10.1 °C, 87.6%RH[a]
Kunming	2004.1.11–1.15	10	Individual space heating	11.0 °C, 56.3%RH[a]
HongKong	2002.1.5–1.9	12	Individual space heating	19.1 °C, 54%RH[b]
Total		76		

[a] Based on the measurement.
[b] Based on local meteorological data.

Table 2
Details of the summer measurement survey.

City	Survey period	Number of houses for measurement	Cooling system	Average outdoor conditions during investigation
Harbin	2003.8.12–8.16	10	–	23.6 °C, 65.7%RH[a]
Urumqi	2004.8.6–8.10	10	–	22.4 °C, 44.2%RH[a]
Beijing	2002.8.21–8.25	9	Air-conditioner	26.7 °C, 66.6%RH[a]
Xi'an	2001.8.17–8.21	10	Air-conditioner	24.7 °C, 69.7%RH[a]
Shanghai	2003.8.1–2003.8.5	10	Air-conditioner	32.3 °C, 64.1%RH[a]
Changsha	2002.8.22–8.26	5	Air-conditioner	30.4 °C, 71.2%RH[a]
Chongqing	2002.8.9–8.13	10	Air-conditioner	33.9 °C, 49.2%RH[a]
Kunming	2002.8.15–8.19	10	–	21.2 °C, 71.3%RH[a]
Hong Kong	2001.8.8–8.12	12	Air-conditioner	29.4 °C, 79%RH[b]

[a] Based on the measurement.
[b] Based on local meteorological data.

Therefore, the houses investigated in this survey represent the typical Chinese urban residential houses.

2.2. Outline of the field investigation

The measurement was carried out in a period of 5–6 days, with the sampling interval of 30 min, during winter and summer seasons. The outline of the measurement survey in winter and summer are shown in Tables 1 and 2 respectively. The investigated houses of the winter survey totalled 76. It should be noted that the measurement for the month of January was conducted in all houses of the 9 cities, except those in Harbin. Measurement survey in Harbin in winter was done at the beginning of March, so the investigated outdoor temperature and absolute humidity were slightly higher than general winter level. For the summer study, there were in total 86 houses investigated.

The air temperature and humidity were measured by using temperature/humidity data loggers with small sensors, which were placed in 3 different locations; bedroom and living room (both at a height of 1.1 m above ground floor level), and outdoor (sited on the north side of the house). The houses in Harbin, Urumqi, Beijing and Xi'an were used central heating system in winter. On the other hand, in summer the houses in Harbin, Urumqi and Kunming did not use air-conditioner as cooling system.

3. Results

3.1. Examples of temperature and humidity profiles

An example of temperature and humidity profiles (Urumqi 07: Urumqi 07 means house number 07 in Urumqi) in winter is shown in Fig. 2. The temperatures of the living room and the bedroom were stable at around 21 °C during the measurement period. The relative humidity in the living room was found very low between 11 and 33%, while the relative humidity in the bedroom held steady around 40%. The latter was due to the artificial regulation of humidity in the bedroom via placing some trays filled with water during the measurement period.

An example of the summer temperature and humidity profiles (Shanghai 10: Shanghai 10 means house number 10 in Shanghai) is shown in Fig. 3. Indoor temperatures were remarkably lower than that of outdoor temperatures except during the sleeping hours. Also absolute humidity was sharply reduced from morning to evening and was obviously lower than outdoor. It might be of the reason that the air-conditioner was continually used in this house. Temperature and humidity variations in this house showed typical characteristics in the house where air-conditioner was frequently used in summer.

3.2. Climate of living room in winter season

3.2.1. Statistical results of each house in winter

The winter measurement results, with statistical values (average, standard deviation, maximum and minimum) of living room are shown in Fig. 4. Those data in rectangle are mean value of each city. The mean room temperatures in Harbin, Urumqi, Beijing and Xi'an where central heating were used, were comparatively high in the range from 17 to 22 °C. In the case of Hong Kong, located in the hot summer and warm winter zone, the room temperatures were stable at around 20 °C. But the room temperatures in Shanghai, Changsha, Chongqing and Kunming where individual heating were used, were all below 15 °C for the reason of inadequate heating or unused heating.

The mean relative humidity was found below 30% in Urumqi and Beijing, while in Shanghai, Changsha and Chongqing, the indoor relative humidities were comparatively high. Especially in the houses of Chongqing, the indoor temperatures were low, but the

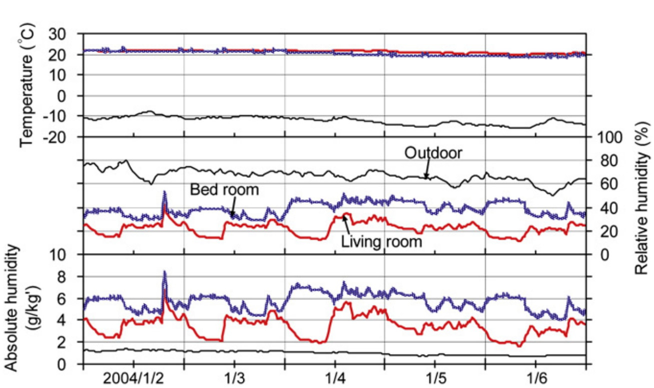

Fig. 2. Temperature and humidity profiles in house of Urumqi 07 in winter.

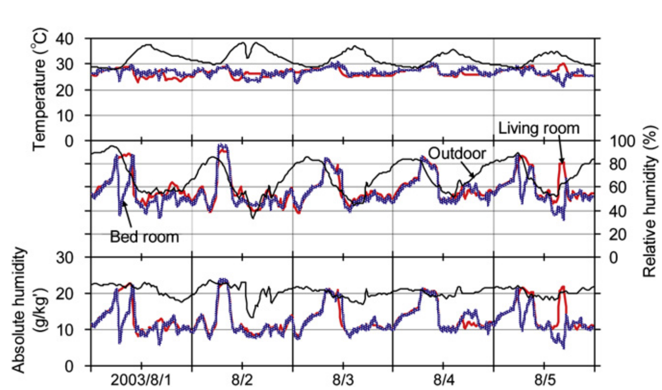

Fig. 3. Temperature and humidity profiles in house of Shanghai 10 in summer.

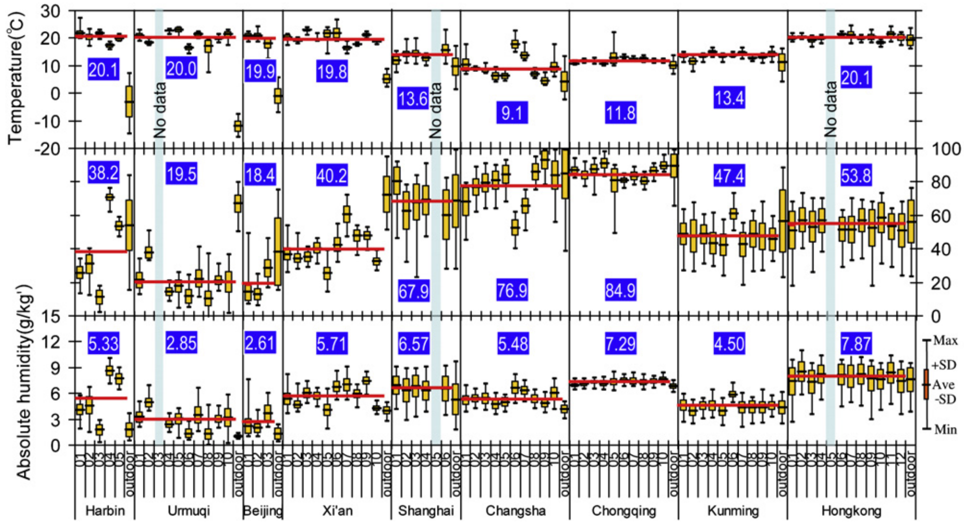

Fig. 4. Temperature and humidity in the living room of each house in winter.

absolute humidity was stable and high. That is the reason why the indoor relative humidity of these houses was very high, over 80%.

The indoor absolute humidity in Chongqing and Hong Kong was comparatively high between 7 and 8 g/kg'. The obtained absolute humidity, in half of the investigated houses, of Harbin, Urumqi and Beijing, was lower than 3 g/kg'. The standard deviations of indoor and outdoor absolute humidity in Shanghai and Hong Kong, were found larger than all other cities.

3.2.2. Frequency distribution for relative humidity of each house in winter

The relative humidity of living room in each house measured over a period of 5–6 days was analyzed and its frequency distribution of each house is shown in Fig. 5. In Harbin, the frequency distribution of indoor relative humidity had a big difference between each house. It might be due to the fact that some overdry strategies were executed in some of houses. In other cities, there was no significant difference between the houses. In Chongqing, particularly, the relative humidity of all the houses distributed in a narrow range of 80–100%. In a majority of houses in Harbin, Urumqi, Beijing and Xi'an, where central heating was used, the relative humidity was mainly below 40%. In the houses of Kunming and Hong Kong, the relative humidity was found distributing in a medium humidity range from 30 to 70%. In the houses of Shanghai, Changsha and Chongqing, the relative humidity was observed in a high humidity range between 60% and 100%.

3.3. Climate of living room in summer season

3.3.1. Statistical results of each house in summer

The measurement results in summer, with statistical values (average, standard deviation, maximum and minimum) of the living rooms are shown in Fig. 6. The mean room temperature in

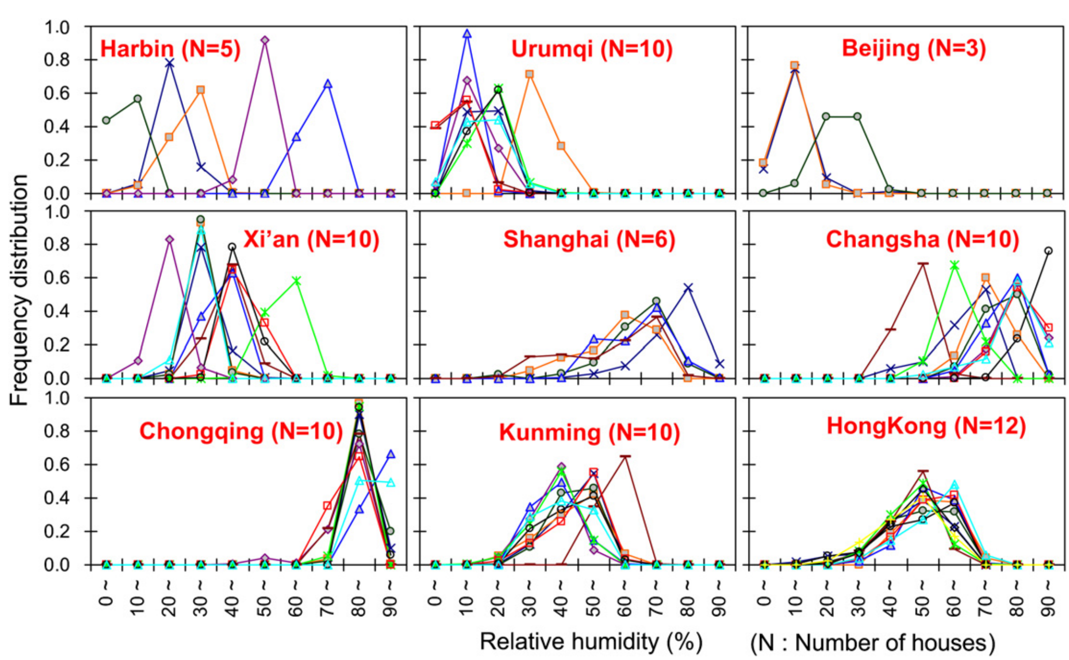

Fig. 5. Frequency distribution for relative humidity in the living room of each house in winter.

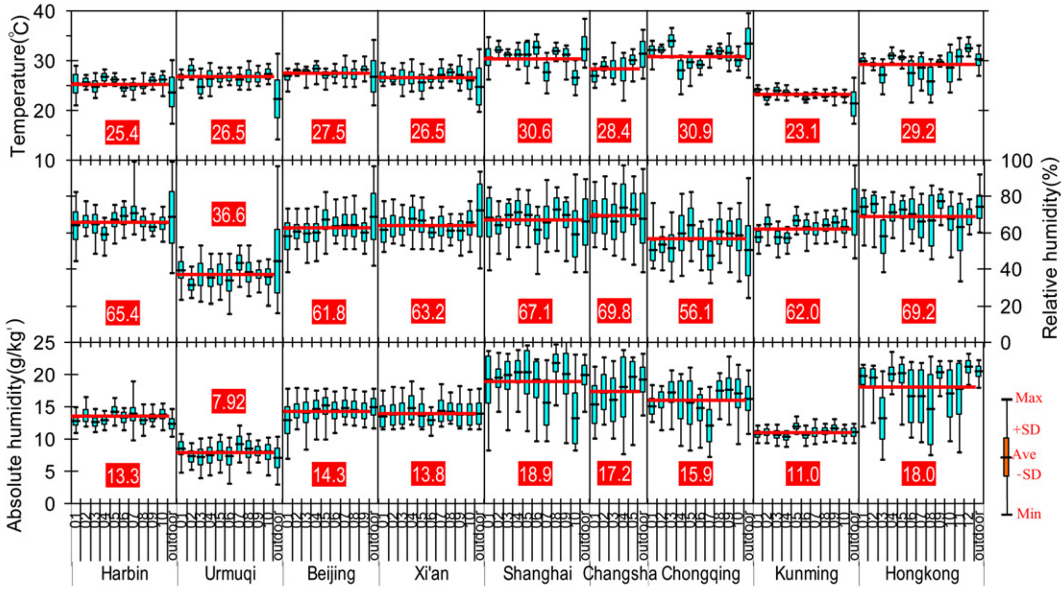

Fig. 6. Temperature and humidity in the living room of each house in summer.

Kunming was found the lowest with 23 °C, while in Shanghai and Chongqing, the mean room temperatures in most of the houses were higher than 30 °C.

Indoor relative humidities varied between 50% and 80% in almost all of the measured houses, except in Urumqi where the indoor relative humidities were found between 30% and 50%. In Chongqing, indoor relative humidity was recorded below 70% and was about 20% lower than that of winter. It is attributed to the cause of the high room temperature in summer.

For the case of Urumqi, the indoor absolute humidity was the lowest within the 9 cities of this study, with the mean value of 7.9 g/kg'. In Kunming, the indoor and outdoor absolute humidities were stable around 11 g/kg'. In Shanghai, Changsha and Hong Kong, the average indoor absolute humidities were high between 17 and 19 g/kg'. In some houses of these three cities, such as Shanghai 07, 10, Changsha 01, 03, Hong Kong 03, 06, 07, 08, 10 and Hong Kong 11 (numbers are the house number in each city), the indoor absolute humidities were lower than the outdoor absolute humidity with large variations. As described for the example of Shanghai 10 in 3.1, the reason may be due to long hours operation of cooling system in these houses.

3.3.2. Frequency distribution for relative humidity of each house in summer

The relative humidity of living room in each house over a period of 5–6 days in summer was analyzed and the frequency distribution of each house is shown in Fig. 7. For the frequency distribution of indoor relative humidity, there was no big difference between the houses in each city. Most of them were found in the range from 30 to 80%.

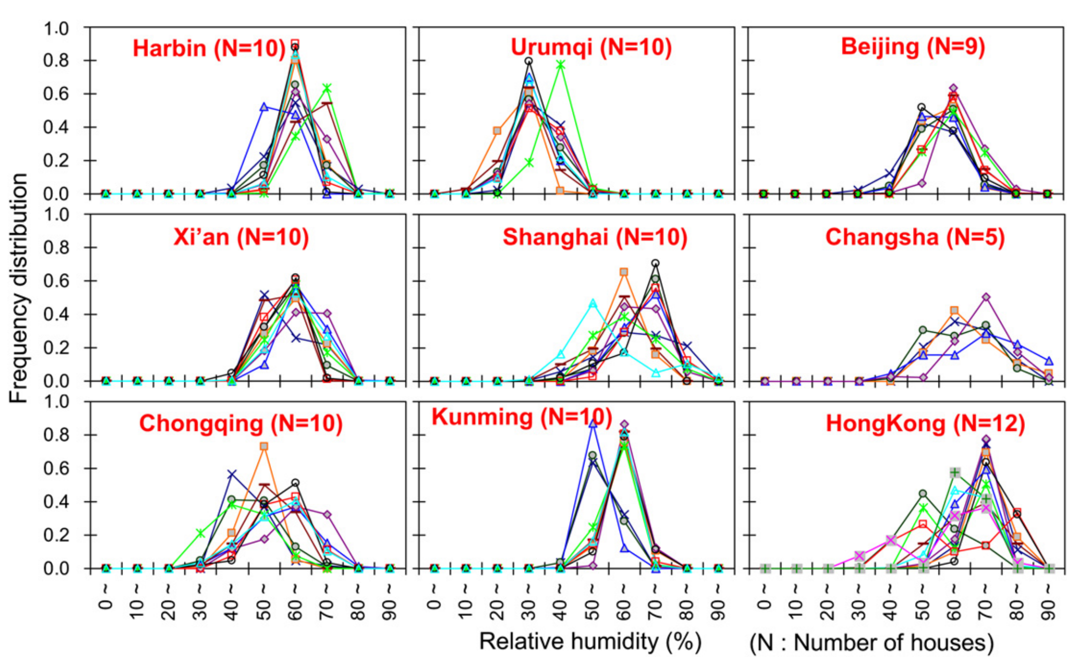

Fig. 7. Frequency distribution of relative humidity in the houses during 5–6 days of summer.

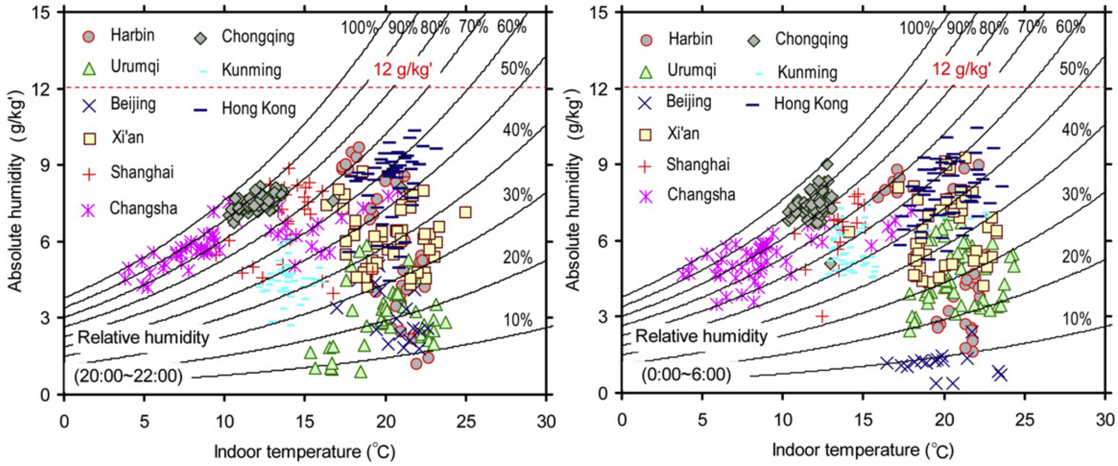

Fig. 8. Temperature and humidity conditions in living room during the time of family gathering (20:00–22:00) (left) and in bedroom during sleeping time (0:00–6:00) (right) in winter.

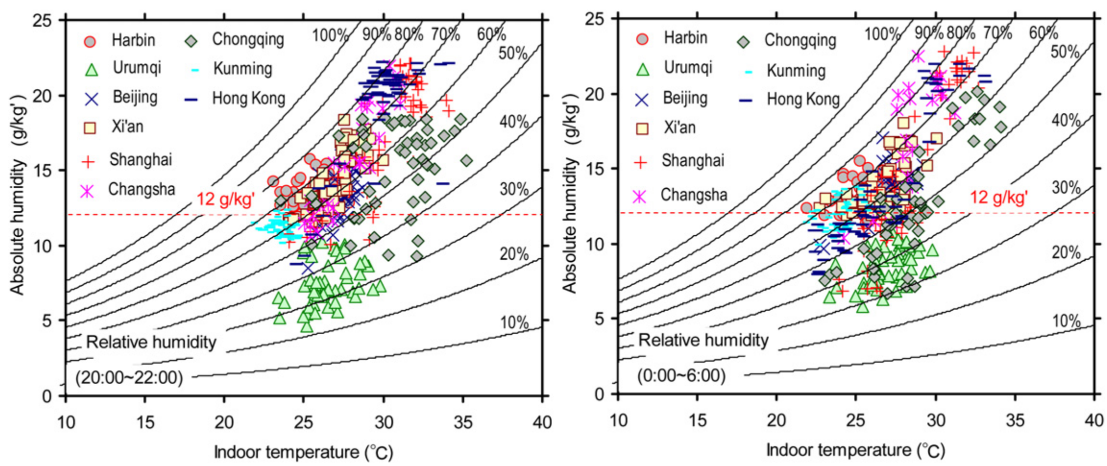

Fig. 9. Temperature and humidity conditions in living room during time of family gathering (20:00–22:00) (left) and in bedroom during sleeping time (0:00–6:00) (right) in summer.

3.4. *Evaluation on humidity environment from directions of thermal comfort and health*

In terms of thermal comfort, ASHRAE Standard 55-2004 [23,24] regulated a highest acceptable humidity value (absolute humidity: 12 g/kg'), and have no lowest acceptable humidity value. In regard to health effects, however, Arundel [25] proposed that the optimum relative humidity range for minimizing adverse health effects is between 40% and 60%. As above-mentioned, low humidity or high humidity may cause adverse health effects. Therefore, the humidity environment in the living room when all family members are together, and also in the bedroom during sleeping time is very important.

Temperature and humidity conditions of each house in winter and in summer are shown in Figs. 8 and 9 respectively. In winter, the absolute humidities in all of the investigated houses fell below the ASHRAE maximum acceptable humidity value of 12 g/kg' [23,24], both in the living room and bedroom. Nevertheless, the situation of the houses of Changsha, Shanghai and Chongqing which are considered as low temperature and high humidity environment should be mitigated in order to ensure achieving a healthy indoor humidity environment. This concept should also apply to the houses of Beijing, Harbin and Urumqi which are considered as low humidity environment. On the other hand, in summer, there are many houses in the cities of Shanghai, Changsha, Chongqing and Hong Kong, where absolute humidities were far above 12 g/kg'. Thus, the majority of the investigated houses in these 4 cities could not achieve the thermal comfort environment in the summer period during the investigation due to high humidity.

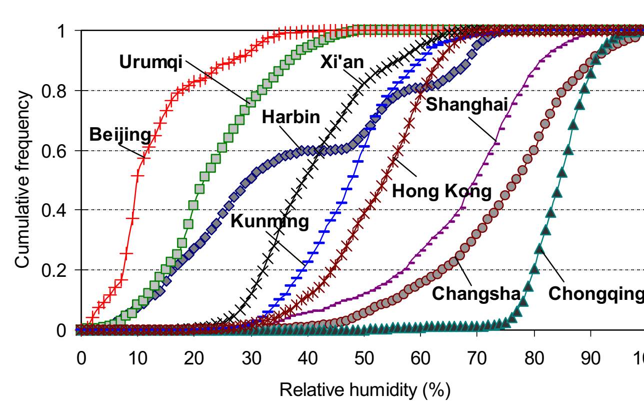

Fig. 10. Cumulative frequency of indoor relative humidity in the houses of 9 cities during winter season.

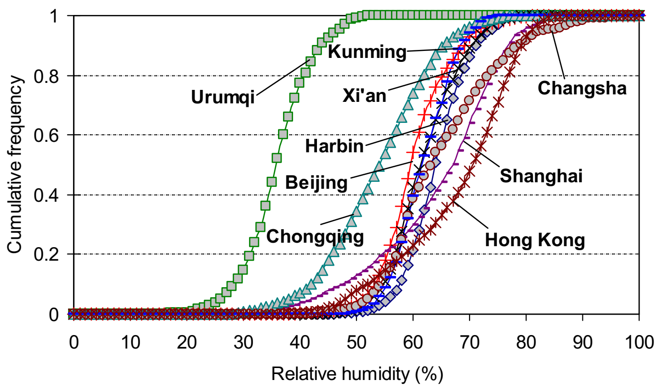

Fig. 11. Cumulative frequency of indoor relative humidity in the houses of 9 cities during summer season.

3.5. Overall humidity environment in 9 cities

3.5.1. Cumulative frequency of indoor relative humidity

The cumulative frequency of the winter indoor relative humidity (including living room and bedroom) in the houses of each city is shown in Fig. 10. It was found that approximately 80% of the measurement results for indoor relative humidity were below 30% in Urumqi and Beijing. For the case in Chongqing, nearly 80% of the indoor relative humidity was above 80%. Also, the cumulative frequency of relative humidity that exceeded 70% covered more than half of the houses in Shanghai and Changsha. A severe humidity environment such as low humidity or high humidity in winter should be mitigated.

The cumulative frequency of the summer indoor relative humidity (including living room and bedroom) in the houses of each city is shown in Fig. 11. In the houses of Urumqi, the indoor relative humidity almost occurred only in the low humidity range of 20–50%. In the houses of Hong Kong, the cumulative frequency of relative humidity that exceeded 70% covered half of the measurement results.

3.5.2. Correlations between indoor absolute humidity and outdoor absolute humidity

The average indoor absolute humidity in all the houses of each city was calculated and analyzed based on its dependency on outdoor absolute humidity. The analysis results for the winter and summer cases are given in Figs. 12 and 13 respectively.

In the case of winter, the statistical correlations between indoor and outdoor absolute humidities in Harbin and Urumqi were found low. Moreover, indoor absolute humidities in Harbin and Urumqi were obviously higher than that of outdoor. Considering the building envelop in these two cities with thick wall and double window, it can be inferred that the houses in Harbin and Urumqi are comparatively well airtight, which makes indoor water vapour difficult to be exhausted. On the other hand, the correlations between indoor and outdoor absolute humidities were strong in Kunming and Hong Kong, with the correlation coefficient over 0.95. It is considered that natural ventilation or opening windows are usually/frequently applied in most houses in Kunming and Hong Kong, which make indoor humidity change by the fluctuating outdoor humidity.

In the case of summer, the statistical correlations between indoor and outdoor absolute humidities in Urumqi, Xi'an and Kunming were shown strong, with the correlation coefficient over

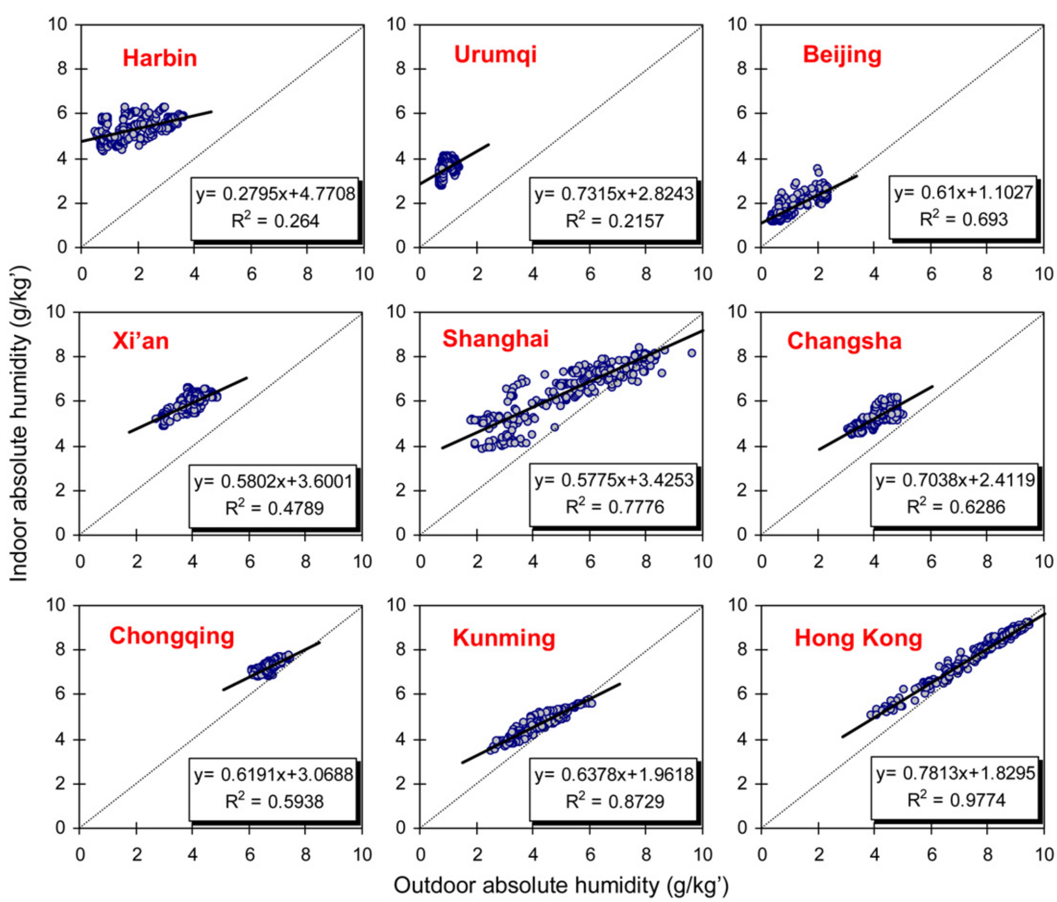

Fig. 12. Correlations between indoor absolute humidity and outdoor absolute humidity in winter.

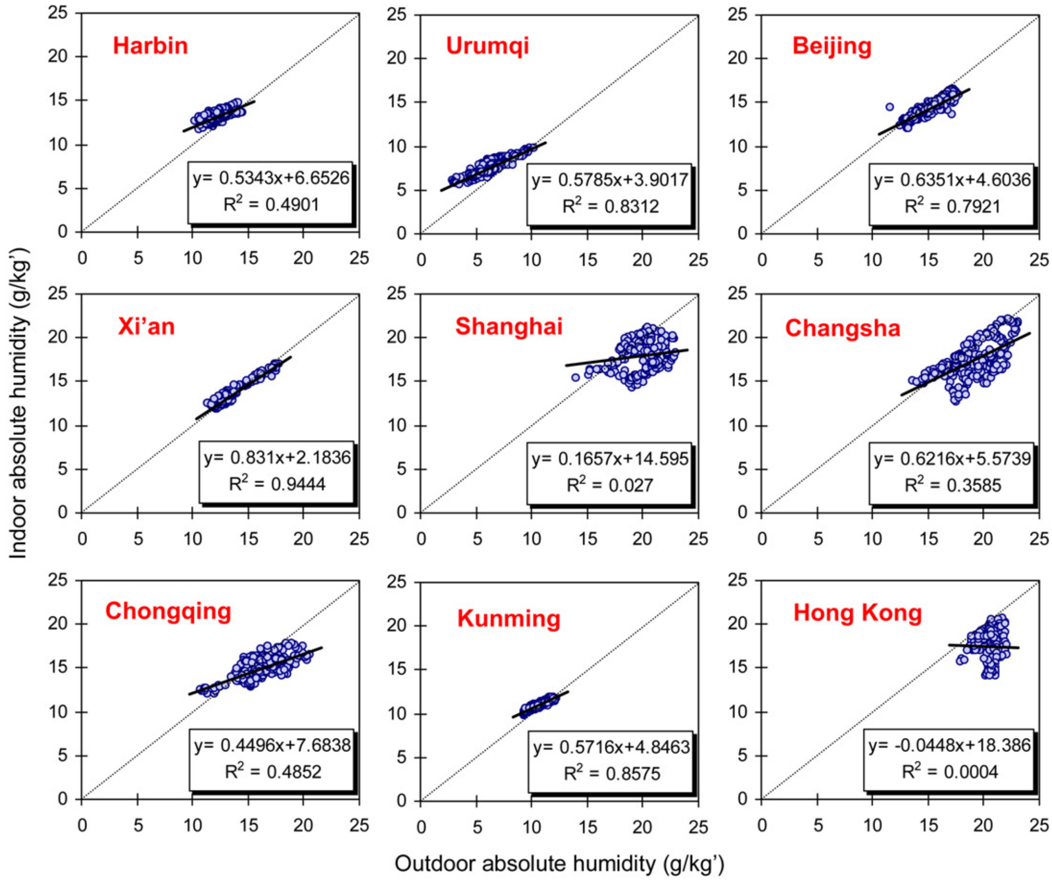

Fig. 13. Correlations between indoor absolute humidity and outdoor absolute humidity in summer.

0.9. It is speculated that natural ventilation was mostly welcomed by the inhabitants to adopt in these 3 cities. On the other hand, the correlations were low in Shanghai and Hong Kong, and the indoor absolute humidities often fell below the outdoor absolute humidity. It is believed that air-conditioners in the houses of these two cities were usually used.

3.5.3. Daily amplitude of indoor climate

With regard to residential houses, there are no criteria for acceptable fluctuations of temperature and humidity. However, some guidelines are available for commercial and institutional buildings. Large daily fluctuations of temperature and relative humidity should be avoided for museums, in order to prevent big surface pressure for exhibits [26]. Moreover, it has been shown that organic materials are naturally acclimatized to a mid-range relative humidity of around 50% and the relative humidity varied on a daily basis of: 10% represents a low risk to most organic materials; 20% is dangerous to some composite objects; 40% is destructive to most organic objects [27].

In order to study the variability of the indoor climate in Chinese residential houses, daily amplitudes of temperature, relative humidity and absolute humidity in the living room and bedroom of each house, i.e. the differences between daily maximum and minimum values, were calculated. The average values of these daily values over the winter and summer periods in each city are shown in Table 3. In winter, the large amplitude of temperature in Changsha showed that some problems existed with the temperature control systems. While in summer, the daily amplitudes of temperature in the living room and bedroom in Shanghai, Changsha, Chongqing and Hong Kong were comparatively high with over 3 °C. The variations of temperature and absolute humidity

Table 3
Average daily amplitude of indoor temperature (ΔT), relative humidity (ΔRH) and absolute humidity (ΔAH) during winter and summer.

	Winter						Summer					
	Living room			Bedroom			Living room			Bedroom		
	ΔT	ΔRH	ΔAH	ΔT	ΔRH	ΔAH	ΔT	ΔRH	ΔAH	ΔT	ΔRH	ΔAH
Harbin	2.5	9.8	1.7	3.0	10.4	1.9	1.9	13.2	2.6	1.9	12.1	2.5
Urumqi	2.1	13.8	2.1	2.0	13.2	2.1	1.9	13.6	2.9	1.8	12.9	2.9
Beijing	2.2	16.1	2.5	3.2	6.2	0.9	2.9	19.6	5.2	2.8	17.7	4.9
Xi'an	2.6	11.2	1.9	2.8	11.2	2.0	2.4	14.0	2.9	2.5	14.0	2.9
Shanghai	3.7	23.3	2.5	2.9	20.4	2.4	4.3	26.5	8.7	4.8	34.4	11.3
Changsha	3.4	16.6	1.5	4.6	19.9	1.5	5.0	29.2	9.7	4.3	17.4	8.8
Chongqing	1.3	8.4	0.8	1.7	11.1	1.0	3.3	22.1	6.2	5.6	25.0	8.4
Kunming	2.3	21.1	1.9	2.1	21.7	2.2	1.4	11.7	2.0	1.2	11.6	2.2
Hong Kong	2.0	18.3	2.7	2.7	18.1	2.7	4.1	23.1	7.7	5.1	28.1	9.4

influence the relative humidity changes. In this study, the average amplitude of the relative humidity was above 10% in all of the 9 cities. The average amplitude of the relative humidity was above 20% in Shanghai and Kunming in winter season, and in the other 4 cities of Shanghai, Changsha, Chongqing and Hong Kong in summer season. Based on the current investigation, it is deemed that some strategies for humidity moderation are necessary in all of the investigated cities.

4. Conclusions

In this study, in order to make clear the characteristics of humidity environment in Chinese residential houses, indoor humidity environment was analyzed across 9 cities of China, based on the one-week period of measurement results during winter and summer seasons.

The analysis results demonstrated that during winter seasons, indoor humidity was too low with the relative humidity fell below 20% in Urumqi and Beijing where houses were equipped with central heating system. The main reason, which caused the over-dry indoor environment, can be attributed to high room temperature and low outdoor absolute humidity. On the other hand, indoor humidity was very high with the relative humidity fell beyond 80% in Chongqing for the reason of inadequate heating and high outside absolute humidity. Health problems affected by low humidity or high humidity are thus required serious attention.

In the case of summer, in many houses of Shanghai, Changsha, Chongqing and Hong Kong, the absolute humidity was found higher than the maximum acceptable humidity value (absolute humidity: 12 g/kg') by ASHRAE. The majority of investigated houses could not achieve the thermal comfort environment due to high humidity.

Furthermore, indoor humidity environment in the investigated houses has strong correlations with outdoor humidity level, heating and cooling system (type and operation hours), human behavior, as well as building airtight performance. Compared with outdoor humidity level, indoor humidity increases by artificial humidifying or in airtight house, while indoor humidity decreases by operating air-conditioner for long time or opening window.

The current state of indoor humidity environment in the houses of 9 Chinese cities indicated that serious problems of high or low humidity generally exist in Chinese residential houses. The severe indoor humidity environment in the residential houses of China should be mitigated and controlled. Furthermore, this study provided a valuable database on indoor humidity control design with building envelope (furnishing material, airtight performance) and building equipment (air-conditioner, mechanical ventilation, humidifier and dehumidifier), as well as occupant's behavior (opening window, using frequency for air-conditioner), so as to achieve a sustainable and healthy indoor environment for Chinese residential building.

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