Summer Investigation on Indoor Environment of Residential Buildings in Beijing and Other Four Cities

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Abstract
In order to understand the actual conditions of urban residential indoor environment, indoor thermal comfort and indoor air quality in Beijing during the summer season, the investigation of indoor environment was carried out in Beijing, from August 21 to August 25 of 2002. Results of this investigation were compared with the results in other cities, which was already reported.

The questionnaire revealed the life style within residences of summer season, the types of air-conditioners used etc. This field survey showed that the indoor thermal comfort during the mid-day, evening hours and sleeping time in Beijing felt outside the ASHRAE comfort zone and the concentrations of formaldehyde and VOCs were relatively high in some houses.

Keywords: China; indoor environment; residential building; questionnaire investigation; field measurement

1. Introduction
Energy consumption of China has been increasing rapidly due to the recent economic growth and development. This leads to serious environment problems such as global warming, air pollution and acid rains. In residential buildings of developed countries, energy consumption used for space heating and cooling plays an important role in the total residential energy consumption.

On the other hand, indoor air quality has caught attention of the public in China. Volatile organic compounds (VOCs) and carbonyl compounds are a group of major indoor air pollutants that has been associated with many health effects including cancer (WHO1987). It is suspected that VOCs and carbonyl compounds are the major factor for “sick building syndrome” (SBS) (Molhave et al. 1986).

In order to estimate the future trend of the residential energy consumption and indoor environment in China, it is necessary to understand the situation of the usage of facilities, the indoor thermal conditions and air quality.

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the summary of this survey. Figure 1 shows the location of Beijing and the cities for measurement. Figure 2 shows the climograph [3] of cities where we have investigated. For the climate in August, Beijing is very hot and humid.

2. Outline of Survey

2.1 Questionnaire and Temperature Measurement

In this study, an identical questionnaire and two liquid crystal thermometers [4] were distributed to the families or relatives of teacher, the old boys of local university. This method is the same as the previous investigation used [2]. The contents of the questionnaire are classified into six key elements and tabulated in Table 2. Each family was requested to fix two liquid crystal thermometers onto the wall at a height of 1.1m above the floor in the bedroom and living room of their houses. The measurement was carried out in three different sections of five consecutive days from 6a.m.-8a.m. (morning), 11a.m.-1p.m. (mid-day) and 7p.m.-9p.m. (evening). The family was required to record the temperature readings from the liquid crystal thermometer within the interval of each of the section. The questionnaire was also completed by the family.

2.2 Measurement Detail

In Beijing, several families within the distributed families were selected for further measurement. In this further measurement, three small data loggers with sensor were used to record the measurements of temperature and humidity for indoor and outdoor. Each sensor for the indoor measurement was mounted on supports at a height of 1.1m from the floor level in living room and bedroom. The sensor for the outdoor measurement was fixed inside an aluminum flexible duct in order to prevent solar and sky radiation.

Regarding the measurement of air quality, passive sampling was applied in order to investigate the indoor air concentration, the outdoor air concentration and the personal exposure of VOCs and carbonyl compounds.

Table 1. Summary of This Survey

| Subject city | Survey period | Distributing number | Number of respondents | Number of apartment houses under measurement | Outdoor conditions | Average of relative humidity |
|--------------|---------------|---------------------|-----------------------|--------------------------------------------|-------------------|---------------------------|
| Beijing      | 2002/8/21 ~ 8/25 | 101                 | 90                    | 9 (6\(^{1}\)) | 26.7°C | 34.1°C | 20.9°C | 66.6%RH |

\(^{1}\) Number of apartment houses under measurement of indoor air quality

\(^{2}\) Based on the measurement

Table 2. Contents of The Questionnaire Survey

| Building Characteristic | Construction year, Structure, Height of building, Architectural area, Condition of veranda, Windows |
|-------------------------|--------------------------------------------------------------------------------------------------|
| Housing Equipment       | Cooling system, Equipment of supplying hot-water                                             |
| Residential Characteristic | Number of residents, Income                                                                  |
| Life Style              | Cooling period, Cooling time, Number of staying persons, Garment insulation value, Windows opening |
| Satisfaction rating     | Sense of thermal comfort, Satisfaction of the residence environment                           |
| Energy Consumption      | Consumption of city gas and electricity                                                        |
| Indoor Thermal Environment | Temperature in the morning, mlday and evening                                               |

The passive sampler suspended on breast for measuring personal exposure is shown in Fig.3. The passive gas tubes (8015-066, Shibata Scientific Technology Ltd, Japan) for VOCs and the 2, 4-dinitrophenylyhydrazine (DNPH) cartridges (Xpsoure, Waters Ltd, USA) for carbonyl compounds were used in this study. These samplers for the indoor measurement were put in the living room. The samplers for the personal exposure were fixed at the breast of household. The samplers for the outdoor measurement were fixed inside an aluminum flexible duct for protecting against solar and sky radiation.

All these measurements were done in five consecutive days during the investigation period.

Fig.2. Comparison of the climographs of major cities in China.
3. Results of Questionnaire Survey

3.1 Characteristics of Buildings

Figure 4 shows the floor areas of apartment unit in Beijing. The floor areas range from 40 m$^2$ to 140 m$^2$, with average area of 99.8 m$^2$.

Figure 5 shows the height of building, in terms of number of stories in Beijing. Most buildings have the number of stories from 15 to 20, with average stories of 15.

Figure 6 shows the energy source for hot-water supply of apartment unit in Beijing. About 70% of the families use the town gas from natural gas, and 15% of the families use electricity for hot-water supply.

3.2 Lifestyle

Annual income is shown in figure 7. The number of effective replies is 49, that is 54% of collections. Many...
residence replies forty thousand to sixty thousand.

Figure 8 reveals that 70-82% of residents in Beijing remain at home during the weekday from 8 a.m. to 5 p.m.. During lunch hour from noon to 1 p.m., 82% of the members of family stayed at their residences because many residents prefer to return home for lunch. On the other hands, more than 90% of the residents remain at home during weekend.

The clothing worn by the occupants, male and female, in the evening is shown in Fig. 9, in terms of thermal resistance of clothing (clo) that was calculated by the questionnaire for clothing. The average clo values for male and female are 0.24 and 0.32 respectively. The clo values of male are lower than the female.

3.3 Air-conditioning and Its Usage [2]

(1) Possession ratio of air-conditioner

A comparison of the possession ratio of air-conditioner is given in Fig. 10 which includes the result in Beijing and other cities. About 80% of the families in Beijing have equipped air conditioners in both living room and bedroom, and most of them are split unit type. The type of air-conditioner equipped is shown in Fig.11. In Shanghai, investigation has been done in 1998. But, it is reported by Long et al. [5] that the saturation level of air-conditioner in 2002 is 96.8%.

(2) Cooling method

Figure 12 shows the ratio of cooling method. The air-conditioners are not used at about 36% of the families for a typical summer day. On the other hands, 61% of the families use the air-conditioners.

(3) Period of using air-conditioning

Among the five cities, the period of using air-conditioning in Beijing and Xi’an are the shortest, as shown in Fig. 13. Based on the 50% line in Fig. 13, the period of air-conditioning used in Beijing is 2 months, and shorter than in Hong Kong, Shanghai and Changsha. From this survey, it is found that the adoption of air-conditioning in the cities except Hong Kong commences in the same months, however, the ending time of using

![Fig.10. Ratio of air-conditioner equipped in Families.](image)

![Fig.11. Type of air-conditioner equipped.](image)

![Fig.12. Ratio of cooling method.](image)

![Fig.13. The period of using air-conditioning.](image)

![Fig.14. Ratio of air-conditioner used in Families for a typical summer day.](image)
air-conditioning in Beijing and Xi’an finishes half a month or a month earlier than in Changsha and Shanghai. This is due to the difference of the geographic location where Beijing and Xi’an belong to the cold region in China.

4) Ratio of air-conditioning used for a typical summer day

Figure 14 shows the rate of air-conditioning used in the five cities for a typical summer day. In comparison with Beijing, Xi’an, Changsha and Shanghai along, two peaks are seen in these cities during the daytime from noon to 3 p.m. of 50-70% and in the evening from 5 p.m. to 11 p.m. of 70-90%. Although the indoor temperature during the daytime is higher than in the evening, the usage of air conditioning is low. This is due to the fact that fewer residents stay at home during such time of the day. On the other hand, in the situation of Hong Kong the usage peak of air-conditioning is found throughout the night until morning. In comparison with the cities except Hong Kong, the lowest usage rate obtained in Hong Kong at 11 a.m. is lower than those observed in Beijing, Xi’an, Changsha and Shanghai at the same time on the day.

5) Operating time

Figure 15 shows the operating time of air-conditioner per a day in Beijing. Some houses do not use air-conditioner on one hand and some houses use nearly 20 hours. The average of operating time is 9.8 hours.

6) Predetermined temperature

Figure 16 shows the predetermined temperature of air-conditioner in Beijing. The predetermined temperature ranges from 20°C to 30°C, with average area of 25.2°C.

3.4 Results of Indoor Temperature Measurement by Liquid Crystal Thermometer

Figure 17 shows the average values and standard deviations of the temperatures in the living room, bedroom and outdoor of residents in the five cities of China in the evening. The temperatures of the living room in Beijing are almost the same as the bedroom, and the average is about 27°C, which is also higher than the outdoor. The situation of the indoor temperatures in Beijing is the similar to Xi’an. The temperatures of the living room in Shanghai are the highest in the five cities.

4. Results of Field Measurement

4.1 Indoor Temperature and Humidity

Measurements were taken in 5 consecutive days in Beijing from August 21 (0:00 hour) to August 25 (24:00 hour) in 2002.

Less families use air-conditioning during the measurement period in Beijing. However, some families are found using air-conditioning for a few hours during the measurement period. House-A is one of such houses and the result of the measurements at House-A is shown in Figure 18. House-A was built after 2000, and its outer wall is made of reinforced concrete with internal insulation of 50mm. Air-conditioners are set in the living room and bedroom. In both living room and bedroom, the temperatures are between 21.5°C - 30°C, and the changes are small in comparison to the outside temperature. From daytime to the evening,
indoor temperatures are lower than the outdoor temperature. This family uses the air-conditioners in living room during the evening but in the bedroom during the sleeping hours. Therefore, the temperature, relative humidity and absolute humidity are lower during these periods. The variations of indoor relative humidity are within the range of 38%RH - 80%RH in both rooms. The indoor absolute humidity shows almost the same value as the outdoor except the operating time of air-conditioner, and the difference is within the range of
4.2 Relationship Between Outdoor and Indoor Temperatures [2]

Figure 19 shows the relationship between indoor and outdoor temperatures in the five cities during the measurement period. The sleeping hours, daytime and evening are specified as 0:00-4:00, 12:00-16:00 and 18:00-22:00, respectively. Each plot means an average value during each period of each day.

In Beijing, the temperature in living rooms is lower than the outdoor temperature during daytime. However, it becomes the same in the evening as outside temperature. In bedrooms, the temperature during sleeping time is higher than the outdoor temperature, except a few families that used the air-conditioners.

4.3 Evaluation of the Indoor Thermal Environment Based on Comfort Index [2]

Figure 20 shows the comfort zone of ASHRAE [6] in summer and indoor thermal environment. Indoor temperature and humidity are in the ranges of 26°C - 30°C and 50%RH - 70%RH at daytime, night time and sleeping time. The indoor thermal condition of these three periods in the case of Beijing is outside the ASHRAE comfort zone. However, ASHRAE comfort zone is used under the situation that summer clothing is light slacks and a short-sleeved shirt or a comparable ensemble with an insulation value of 0.5 clo for air movements less than 0.25 m/s. The temperature boundaries of the comfort zone can be shifted -0.6°C per 0.1 clo for clothing levels other than 0.5. Accordingly, it can be shifted to 1°C - 2°C high temperature side, considering clothing levels, and the thermal condition of a few families can be included in the comfort zone. Many occupants evaluated that indoor thermal environment in summer was ‘neutral or slightly hot’ during daytime and night.

4.4 Indoor Air Quality

Figure 21 reveals that the indoor formaldehyde concentration is between 14 mg/m³ and 898 mg/m³. Formaldehyde concentration in four houses exceeds the standard, set as 80 mg/m³ by the National Standard of China. All of the personal exposures of formaldehyde are higher than 80 mg/m³. Figure 22 shows that the indoor toluene concentration is approximately between 25 mg/m³ and 405 mg/m³. The other compounds are shown in Table 3. The source of formaldehyde and VOCs are expected to be indoor because of indoor concentration/outdoor concentration ratios (I/O) are larger than 1. Most of indoor concentration/personal exposure ratios (I/P) are about 1. The concentrations of these chemical compounds were relatively higher in newly constructed houses.

![Fig.21. Formaldehyde concentration.](image)

![Fig.22. Toluene concentration.](image)

*The figure in parenthesis means the number of years after the decoration.

Table 3-1. Organic Compound concentration.

| Compounds       | BJ1   | BJ2   | BJ3   |
|-----------------|-------|-------|-------|
|                 | Living room | Personal | Living room | Personal | Living room | Personal |
| formaldehyde (µg/m³) | 26    | 14    | 156   | 202   | 24    | 136   | 410   | 24    | 431   |
| acetaldehyde (µg/m³)  | 42    | 11    | 59    | 46    | 33    | 46    | 62    | 43    | 71    |
| benzene         | 88    | 27    | 77    | 17    | 16    | 24    | 43    | 25    | 45    |
| butanol         | 46    | 5     | 39    | 3     | 3     | 3     | 13    | 6     | 9     |
| heptane         | 2     | 21    | 2     | 11    | 10    | 11    | 13    | 11    | 11    |
| toluene         | 405   | 45    | 303   | 57    | 42    | 63    | 166   | 56    | 130   |
| ethylbenzene    | 36    | 15    | 31    | 32    | 19    | 33    | 32    | 15    | 43    |
| m-xylene        | 68    | 22    | 52    | 46    | 17    | 42    | 61    | 10    | 47    |
| styrene         | 35    | 5     | 29    | 5     | 5     | 5     | 31    | 5     | 31    |
| p-xylene        | 39    | 14    | 28    | 29    | 18    | 25    | 37    | 6     | 28    |
| alpha-pinene    | 314   | 2     | 222   | 28    | 2     | 28    | 44    | 2     | 36    |
| 1,3,5-trimethylbenzene | 25    | 13    | 15    | 28    | 31    | 29    | 32    | 31    | 31    |
| 1,2,4-trimethylbenzene | 29    | 2     | 23    | 36    | 2     | 37    | 2     | 2     | 2     |
| p-dichlorobenzene| 2     | 2     | 2     | 182   | 2     | 165   | 2     | 2     | 2     |

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5. Conclusions

Questionnaire investigation for the indoor living conditions together with field measurement were carried out to the urban residents (family type) of Beijing in the summer of 2002. Based on the results from this study, the conclusions are drawn as follows:

1) Air conditioner type used in Beijing is mostly the split-unit type. About 80% of the households in Beijing have air conditioners equipped in living room and bedroom.

2) The air-conditioning operation period is from June to September. During the day, the peak period in operating the air-conditioning is in the daytime and evening.

3) Indoor temperature and humidity are in the ranges of 26-30°C and 50-70 %RH at daytime, night time and sleeping time. Many occupants evaluated that indoor thermal environment in summer was ‘neutral or slightly hot’ at daytime and night.

4) Formaldehyde concentration in four houses exceeds the criterion, set as 80 mg/m³ by the National Standard of China.

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Table 3-2. Organic Compound concentration.

| Compounds          | BJ4 Living room | BJ4 Outdoor | BJ4 personal | BJ5 Living room | BJ5 Outdoor | BJ5 personal | TOL (average) | UP (average) |
|--------------------|-----------------|-------------|-------------|-----------------|-------------|-------------|---------------|--------------|
| formaldehyde (µg/m³) | 38              | 38          | 84          | 898             | 24          | 113         | 96            | 14.12        |
| acetaldehyde (µg/m³) | 41              | 42          | 53          | 55              | 39          | 45          | 38            | 1.79         |
| benzene            | 18              | 21          | 16          | 65              | 23          | 50          | 17            | 1.96         |
| butanol            | 23              | 21          | 21          | 66              | 11          | 40          | 28            | 3.87         |
| heptane            | 2               | 14          | 2           | 27              | 11          | 2           | 2             | 3.52         |
| toluene            | 31              | 27          | 27          | 187             | 37          | 57          | 55            | 3.91         |
| ethylbenzene       | 21              | 21          | 19          | 38              | 18          | 27          | 28            | 2.13         |
| m,p-xylene         | 28              | 11          | 23          | 42              | 20          | 36          | 29            | 3.38         |
| styrene            | 5               | 5           | 5           | 29              | 5           | 5           | 5             | 4.41         |
| o-xylene           | 9               | 9           | 12          | 13              | 14          | 14          | 13            | 2.58         |
| alpha-pinene       | 33              | 2           | 29          | 11              | 2           | 2           | 2             | 37.4         |
| 1,3,5-trimethylbenzene | 2          | 31          | 2           | 36              | 31          | 2           | 2             | 10.3         |
| 1,2,4-trimethylbenzene | 2           | 2           | 2           | 2               | 2           | 2           | 2             | 6.46         |
| p-dichlorobenzene  | 2               | 2           | 2           | 2               | 2           | 2           | 2             | 19.93        |

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