Indoor Thermal Environment of Residential Buildings in Three Cities of China

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Abstract
This paper deals with the space heating and indoor thermal environment of residential buildings in three large cities in China; Shanghai, Beijing and Harbin. The investigation was carried out for 240 houses during the winter from 1998 to 2000 by means of questionnaire and liquid crystal thermometers. Also, the temperature and humidity of 20 houses were measured by small data loggers with temperature and humidity sensors. The findings are as follows: 1) In Shanghai, air conditioning units are popularly used for space heating in 45% of houses. One or two rooms of the house are heated for only about 4 hours in the evening. The indoor temperature of the houses is around 15°C and is stable during the measurement period due to the thermal capacity of the concrete structure. The occupants wore relatively heavy clothes in the low temperature indoor environment. 2) In Beijing, central space heating is popular and all rooms are heated throughout the entire day. The room temperature is around 20°C. 3) In Harbin, the heating system is not operated all day long in some cases although central space heating is popular. The indoor temperature of these apartments is 5°C lower than others that are heated all day.

Keywords: China; Indoor thermal environment; Residential building; Questionnaire survey; Field measurement

1. Introduction
Energy consumption in China increases rapidly due to the recent economic development. That is one major reason for the air pollution problem in large cities of China. Energy use in the residential sector amounts to 40% of the total energy share that include biomass (Liu, 1993) and is increasing. In residential buildings of developed countries, energy consumption used for space heating plays an important role in total residential energy consumption.

In order to estimate the future trend of residential energy consumption in China, it is necessary to understand the saturation level of space heating equipment and the indoor thermal environment. However, there is no data available of these. Shanghai belongs to the translation-heating zone, Beijing and Harbin belong to the central heating zone, respectively, which are classified by the Chinese government. We selected multi-family houses of these three cities and investigated the indoor temperature and humidity in the winter from 1998 to 2000. The investigation consisted of a questionnaire survey (100 apartments in Shanghai, 40 in Beijing and 100 in Harbin) and field measurements (six apartments in Shanghai, three in Beijing and five in Harbin). This paper shows the results of investigation and analyzes the difference between Shanghai, Beijing and Harbin.

2. Questionnaire Survey
2.1 Outline of Questionnaire Survey
The name of cities, investigating period, number of respondents and outdoor environment during the investigation are shown in Table 1. The indoor temperature is read and recorded using liquid crystal thermometers during a period of one week continuously. Data of the outdoor environment comes from the nearest meteorological observatory. The average temperature during the period of investigation is 9.2°C in Shanghai, -3.6°C in Beijing and -5.9°C in Harbin.

2.2 Method and Content of Questionnaire
In this investigation, we distributed questionnaire and liquid crystal thermometers to pupils in an elementary school or junior high school. Pupils recorded the indoor temperature and their parents answered the questionnaire. Two liquid crystal thermometers, each attached 5mm thickness polystyrene foam board were distributed to each house, and the wall one meter above the floor in a bedroom and living room. The room temperature in the morning (6:30 ~ 8:30), midday (11:30 ~ 13:30) and evening (18:00 ~ 20:00) for a one week period were recorded. The period of recording the in-
Table 1. Outline of the Questionnaire Survey

| Subject city | Survey period | Subject for distribution | Distributing number | Number of respondents | Number with temperature data | Outdoor conditions |
|--------------|---------------|--------------------------|---------------------|-----------------------|-----------------------------|--------------------|
| Shanghai     | From 12/1997 to 1/1998 | An elementary school and a junior high school | 100 | 74 | 68 | 9.2°C, 76% RH |
| Beijing      | 1/1999        | A junior high school     | 40 | 36 | 36 | −3.4°C, 39% RH |
| Harbin       | From 2/2000 to 3/2000 | A junior high school     | 100 | 99 | 99 | −5.9°C, 65.4% RH |

Table 2. Contents of Questionnaire Survey

| Category                        | Details                                                                                     |
|---------------------------------|---------------------------------------------------------------------------------------------|
| Thermal environment             | Temperature of living room and bedroom in morning, midday and evening                      |
| Housing equipment               | Space heating & cooling systems, household equipment                                        |
| Life style                      | Period of heating, kind of clothing, methods for prevention of indoor air pollution and condensation, retrofitting of rooms |
| Building performance            | Construction year, height of building, floor space, composition of rooms                    |
| Energy consumption              | Consumption of city gas and electricity on December                                          |
| Occupant characteristics        | Family structure, age of householder                                                        |

door temperature was from Dec. 27th, 1997 to Jan. 2nd, 1998 in Shanghai, from Jan. 12th to Jan. 18th, 1999 in Beijing, and from Mar. 5th to Mar. 12th, 2000 in Harbin. The contents of the questionnaire are shown in Table 2.

3. Results of Questionnaire Survey

3.1 Characteristics of Occupants

The ratio of households composed of one couple and one child is 80%. The number of apartments with two households is small. The age of householder is between 40 and 50 years in most cases.

3.2 Description of Residential Buildings

Figure 1 shows the view of apartments measured in Shanghai and Beijing. Residential buildings constructed during the past five years amount to 50% in Shanghai, 18% in Beijing and 26% in Harbin. While buildings over 15 years of age in Beijing and Harbin are about 40% and 49%, respectively. Windows have a single sash and an insulation material is not used in construction. In Beijing, one half of the apartments are equipped with double sashes, while in Harbin all apartments are equipped with double sashes. The floor area of apartments differs from 16m² to 88m² in Shanghai, 15m² to 98m² in Beijing and 15m² to 200m² in Harbin. The average is 37.9m², 44.3m² and 46m², respectively.

Apartments with one or two bedrooms and one living room are 60% in Shanghai, 80% in Beijing and 56% in Harbin. In some apartments, the bedroom is used as a living room. Forty percent of apartments in Shanghai consist of just one or two rooms. Even if there are both a bedroom and a living room, the bedroom is used as a living space in many cases because the living room is small and a television set is placed in the bedroom.

3.3 Saturation Level of Household Equipment Ex-
cept for Space Heating

Figure 2 shows the saturation level of household equipment except for space heating. Air cleaner, exhaust fan, kitchen hood with a fan and a hot-water heater are popular. The saturation level of air cleaners in Shanghai is about 27%, higher than Beijing and Harbin. The saturation level of gas hot-water heaters is about 82% and 68% in Shanghai and Beijing, and is lower than 10% in Harbin. Although the questionnaire did not include the question regarding the use of a gas range, it is used in almost all apartments. The saturation level of kitchen hood with a fan is 90%, 65% and 95% in Shanghai, Beijing and Harbin, respectively, while the exhaust fan is found in 42% of apartments in Shanghai, 38% in Beijing and 43% in Harbin, and is mainly installed in the bathroom.

3.4 Use of Space Heating

The space heating equipment used in apartments is shown in Fig. 3. Air conditioning units for both space heating and cooling and electric infrared heaters are popular in Shanghai. But electric panel heaters, electric warm-air heaters, electric foot heaters and gas heaters are used in some apartments. In most cases, air-conditioning units are installed in the bedroom. The electric portable infrared heater is used in different rooms. Electric warm-air heaters are always hung on the wall in bathroom. On the other hand, in Beijing and Harbin, heating equipment used in Shanghai is not popular because radiators connected with district heating system are installed in each apartment. The electric infrared heater and the electric warm-air heater are also used for space heating if there is no radiator in a room or district-heating system is not operated.

The heating period is shown in Fig. 4. In Shanghai, the heating period is mainly from December to February. In Beijing and Harbin, the district-heating system is operated during four months from November to March, and during six months from October to April respectively. The energy source is coal. In the mean time, it shows the high frequency of use of auxiliary heating equipment in Harbin. The reason is that the district heating system was not operated all day in many apartments this year, while in Beijing hot water for space heating is supplied all day.

Figure 5 shows the heating hours during the day in Shanghai and Harbin. The heating time is only from 6:00 to 10:00 in the evening in Shanghai, and there are not many apartments that use space heating for more than five hours. The reasons for this are such as ‘the room is warm’ and ‘to save fuel expenses’. In Harbin 26% of the apartments investigated, hot water heating hours were limited. The heating time during the day was only two hours, and the average time is less than seven hours in these cases. So 10% of apartments use auxiliary heating all day, and 50% use it from 6:00 to 9:00 in the evening.

3.5 Indoor Humidity Sensation

Indoor humidity sensation is shown in Fig. 6. The ratio of response of ‘neutral’ is nearly 70% and 50%, ‘feeling humid’ is about 28% and 30% in Shanghai and Harbin, respectively. The response of ‘feeling dry’ is more than 60% in Beijing, and about 22% in Harbin. In field measurements in Shanghai and Harbin, we found vapor condensation on the windows and walls in many cases.

According to the questionnaire, mold growth appears in 2% of apartments in Shanghai and 30% in Harbin. There is no mold growth in Beijing.
3.6 Indoor Temperature Measured by Liquid Crystal Thermometer

(1) Bedroom temperature in the evening
In Shanghai, the data of 41 apartments where the temperature of the living room and bedroom were recorded separately and the other 16 apartments where the bedroom is used as a living space were used for analysis. In Beijing and Harbin, the data of bedroom temperatures was collected from 36 apartments and 99 apartments, respectively. Bedroom temperatures of each apartment in the evening were averaged for a period of one week.

Figure 7 shows the frequency distribution. Room temperature distributes from 14°C to 26°C in Harbin, from 18°C to 24°C in Beijing and from 10°C to 25°C in Shanghai. There are two increases which appear between 14°C and 18°C and between 22°C and 26°C in Shanghai. It is estimated that apartments with temperature between 14°C and 18°C were not heated, and the apartments between 22°C and 25°C were heated. According to the questionnaire, most apartments maintain a low temperature without space heating during this period in Shanghai. In 20% of the apartments in which the indoor temperature is lower than 18°C. This is due to the limited heating hours and inefficient heating system.

(2) Temperature of bedroom and living room
The average temperature and the standard deviation of bedrooms and living rooms in the morning, midday and evening are shown in Fig. 8. The temperature in Beijing is 3°C to 7°C higher than that of Shanghai and 2°C higher than that of Harbin. The difference between the three cities results from the different type of space heating, efficiency of the heating system and heating hours. The bedroom temperature is higher than the living room temperature in three cities. This is because families spend a lot of time in the bedroom.
3.7 Occupant’s Clothing

Figure 9 shows the relationship between the indoor temperature and thermal insulation value of the occupant’s clothing (clo value), that was obtained by response to the question regarding kind of clothing. In the case of Shanghai, when the indoor temperature is 14°C, the average of clo insulation value is about 1.4. According to the standard of ASHRAE55 (1992), when clo insulation value is 1.4, the operative temperature for thermal comfort is 18°C. The actual room temperature is about 4°C lower than this standard. In Harbin, when the temperature is 18°C, the average insulation clo value is about 1.3clo. In Beijing, the average clothing insulation value is about 1clo. when the temperature is around 20°C. Due to the response regarding thermal comfort, ‘feeling cold’ is about 30% in Harbin, while the total account of ‘not cold’ and ‘comfortable’ in Beijing is over 90%.

4. Results of Field Measurement
4.1 Description of Apartments Measured

Table 3 shows the summary of apartments and houses regarding measurement. The multi-family houses investigated in Shanghai were built from the 1960s to 1990s, and are less than six stories. Thickness of the outside and inside walls is 35cm and 25cm, respectively. The windows have a single sash. The houses investigated in Beijing are all high-rise buildings constructed after the 1980s. The widow has double sashes, which were retrofitted by the occupants. The apartment in Harbin were built from the 1980s to 1990s. The windows have double sashes as in Beijing, all apartments have two-frame doors, and the outside wall is 49cm, thicker than Beijing.

Table 3. Summary of Houses Measured

| Subject Houses | Structure of Housing | Floor Space [m²] | Family Structure | Space Heating Equipment | Outdoor Environment |
|----------------|---------------------|-----------------|-----------------|------------------------|---------------------|
| SHANGHAI       |                     |                 |                 |                        |                     |
| A              | Thickness of outside wall : 35cm, Inside wall : 25cm | 23.8 | Middle-aged couple + daughter | Air-conditioning | * Average temperature: 10°C |
| B              |                     | 27.7 | Middle-aged couple | Living room: air-conditioning | * Average relative humidity: 60% |
| C              |                     | 23.3 | Old-aged couple | Electric stove | * Raining days: 12/31,1/2,1/4 |
| D              |                     | 41.2 | Middle-aged couple | Bedroom: air-conditioning |                     |
| E              |                     | 56 | Old-aged woman + daughter | Bedroom: air-conditioning |                     |
| F              |                     | 50.8 | Old-aged man + young couple + child | Living room: air-conditioning |                     |
| BEIJING        |                     |                 |                 |                        |                     |
| M              | Window of bedroom : double sashes | 74 | Old-aged couple + young couple | District heating system | * Average temperature: -2.8°C |
| O              |                     | 98 | Middle-aged couple + son | Bedroom and Living room: air-conditioning | * Average relative humidity: 38% |
| P              | Window of bedroom and kitchen : double sashes | 45 | Middle-aged couple + daughter | Lavatory and kitchen: radiators | * Clear weather |
| H              | Thickness of outside wall : 49cm, | 32 | Old-aged couple | District heating system |                     |
| L              | Window of bedroom : double sashes | 200 | Middle-aged couple + young couple | All day | * Average temperature: -3.9°C |
| Q              |                     | 41 | Old-aged man + young couple | Intermittent heating | * Average relative humidity: 47% |
| Y              |                     | 49 | Old-aged couple + Daughter | All day | * Clear weather |
| J              |                     | 120 | Middle-aged couple |                     |                     |

Fig. 9. Relationship between Indoor Temperature and Thermal Insulation Value of Occupant’s Clothing
The family structure is composed of one couple and one child or one couple with their parents. As floor space per person is very small, in some cases, there is a bedroom shared by one middle-aged couple and a mature child in Shanghai. Even though space heating apparatus is found in each apartment in Shanghai, it hadn't been used during the investigating period except in Houses B, E and F in which occupants used space heating when feeling cold at one time. In Beijing and Harbin, all apartments use district hot water heating. In some cases in Harbin, the heating hours are limited like House Q. Hot water was supplied for five hours from 6 to 9 o’clock in the morning and from 5 to 8 o’clock in the evening during the measurement period. House plans of three apartments investigated are shown in Fig. 10. In House C in Shanghai, the kitchen is shared with the adjacent apartment. The toilet is for common use in one story and there is no bathroom. In Beijing and Harbin, a radiator connected to the district heating system is installed in all apartment houses including all investigated apartments. But in most cases, there is no radiator in the toilet.

Fig. 10. House Plans of Three apartments

Fig. 11. Profiles of Temperature and Humidity of about Houses C, P and Q
4.2 Method of Measurement

The period of measurement is from Dec. 28th, 1997 to Jan. 6th, 1998 in Shanghai, from Jan. 14th to Jan. 19th, 1999 in Beijing, and from Feb. 28th to Mar. 5th, 2000 in Harbin. Compact data loggers with temperature and humidity sensors are fixed on the wall one meter above the floor in two rooms such as bedroom and living room. Data is recorded every five minutes in Shanghai and 30 minutes in Beijing and Harbin.

4.3 Results of Measurement

(1) Profile of temperature and humidity during one day

Figure 11 shows the profiles of temperature and humidity, which were averaged at each hour during the measurement period. The room temperature of House C in Shanghai is stable between 12°C and 14°C even if the outdoor temperature changes. The temperature of living-bedroom is 14°C and the temperature of dining room is low between 12°C and 13°C because the room faces the northern corridor which is open to the outside. The relative humidity is about 75%. The temperature of House P in Beijing is about 18°C all day. The relative humidity is low between 10% and 30%. The temperature of House Q in Harbin is about 16°C all day. The relative humidity is about 70%. The reason why the temperature of the two apartments doesn’t change is due to the thermal capacity of reinforced concrete.

(2) Relationship between indoor and outdoor temperatures

Using the average data during a half an hour period, the relationship between indoor and outdoor temperatures of Houses C, P and Q is shown in Fig. 12. The change of indoor temperature is small compared with the outdoor temperature. It is clear that the indoor temperature of Houses P and Q in Beijing and Harbin is higher than that of House C in Shanghai.

Figure 13 shows the regression lines between bedroom and outdoor temperature of all houses investigated. In Shanghai, the temperature of Houses A, D and C with no heating, is lower than Houses B and E with space heating. The temperature of Houses A and D especially falls at 8°C to 11°C. The temperature of Houses M, O and P in Beijing that use the district heating system are 5°C to 10°C higher than those in Shanghai. The temperature of Houses J, L, Y and H that were heated all day is about 5°C higher than that of House Q the heating of which was limited.

(3) Indoor Humidity

Measurement results show that indoor relative humidity is different between apartments in Shanghai and distributes from 55% to 85%. The absolute humidity is from 5g/kg to 8g/kg and a little higher than that of the outdoors. Figure 11 shows that the absolute humidity of House C is about 8g/kg. As the dew point temperature is estimated to be 10.5°C, there is a possibility of vapor condensation on the window surface and outside concrete wall surface without insulation. In fact, condensation was found in most cases during visits to the apartments. The relative humidity of houses measured in Beijing is low and distributes from 10% to 35% like House P. In Harbin, indoor relative humidity distributes from 15% to 70%. That of House Q is the highest, and the absolute humidity is about 9kg/kg. Although the occupants use insulation materials on the northern wall and window frames, vapor condensation occurred heavily. The reason is that insulation is insufficient on the structure and the heating time is limited.
5. Conclusions
1) In Shanghai, the air conditioning units are popularly used for space heating in 45% of houses. One or two rooms of the house are only heated for about four hours in the evening. The indoor temperature of the houses is around 15°C and is stable during the measurement period due to the thermal capacity of the concrete structure. The occupants wore relatively heavy clothes in the low temperature indoor environment. In Shanghai, energy consumption will increase in the future due to the need for comfortable thermal environment.

2) In Beijing, central space heating is popular and all rooms are heated throughout the whole day. The room temperature is around 20°C, and the energy source is coal.

3) In Harbin, although central space heating is popular, the heating system is not operated all day long in some cases, and the indoor temperature of these apartments is 5°C lower than others which are heated all day.

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