Experimental Analysis of Residential Ventilation and Dehumidification Strategies in Chongqing

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Abstract. As a typical representative city of China's hot and humid climate zone, Chongqing has an average annual relative humidity of 70% - 80%. Continuous online monitoring of indoor air quality (IAQ) were conducted in more than 20 residents of Chongqing city. It was found that the apartments in the area had excessive indoor absolute humidity in summer (far exceed the ASHRAE recommended comfort limit—12g/kg) and excessive indoor relative humidity in winter and transitional seasons. It is necessary to dehumidify the outdoor intake air during the summer and decrease the indoor related humidity during the winter and transition seasons. Based on the above two points, it is proposed to adopt a fresh air system with dehumidification function in Chongqing, which can remove excessive absolute humidity caused by outdoor air in high humidity month. The fresh air system, which changes natural ventilation to mechanical ventilation, increase indoor insulation effect and reduce relative humidity.

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. The high-humidity environment is very suitable for the growth of microorganisms such as mold, mites etc. [1], and has a great impact on the thermal comfort and health of the human body. [2, 3] Sichuan-Chongqing area belongs to subtropical monsoon humid climate, and the typical city-Chongqing has an average annual relative humidity of 70% - 80%. It is especially important to understand the wet pollution situation in the residences in order to develop a HVAC system suitable for high temperature and high humidity climate.

1 METHODS

1.1 Sampling methods

In order to investigate the air quality in Chongqing apartments, 20 households in different districts were selected randomly as experimental households. The investigation lasted for one year (2017). In addition, two research methods were used for this study. For temperature, humidity and carbon dioxide, which reflects indoor odor pollution, were monitored by an on-line monitoring system. As for formaldehyde, which is a representative pollutant for indoor air, were measured by on-site measurement.

1.1.1 Long-term monitoring system

An indoor-air-quality test sensor is used for the collection of indoor environmental parameters. This sensor is an integrated system that simultaneously detects temperature, humidity, CO2, etc. And the detected data can be transmitted to the network platform through WIFI in real time. The long-term monitoring data of this survey are all from the network platform. The long-term monitoring system for indoor air quality testing is described in detail by Junjie Liu et al. [4] Long-term monitoring sensors are placed in the living room and bedroom of the household, and a set of data is uploaded every minute. For some of the households, MIJIA window state sensors were selected to monitor occupants' window-opening and closing behavior.

1.1.2 On-site measurement

Indoor formaldehyde concentrations were measured by the spectrophotometry using MBTH hydrochloride as the adsorbent, which is a standard method of measuring indoor formaldehyde concentration recommended in the Chinese national standard [5]. According to the standard, the sample flow rate was set at 0.5L/min, and the sampling time was 20 min. The detection limit of this method was 10 $\mu g/m^3$, and has been used in many studies. [6, 7] Formaldehyde concentration is calculated according to the standard recommended formula.

Two sets of conditions were used for the measurement, normal conditions and closed conditions. The closed state refers to the concentration of formaldehyde measured after closing the doors and windows more than 12h. The formaldehyde concentration in the normal condition was taken as the initial concentration, and the formaldehyde

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concentration measured in the closed condition was taken as the termination concentration.

The infiltration rate was measured by CO2 decay method. Before measurement, CO2 was injected into rooms with closed windows and doors until the concentration was higher than 2500 ppm. A fan was operated in each room to ensure a uniform CO2 concentration. After that, the CO2 concentration was continuously measured at an interval of 1 min. The infiltration rate can be calculated as follows:

$$n'=(ln(C_1-C_0)-ln(C_t-C_0))/t \qquad (1)$$

where n' = the infiltration rate of the room, h^{-1},
C_1 = the initial CO2 concentration, ppm,
C_t = the final CO2 concentration after t time, ppm,
C_0 = the outdoor CO2 concentration, ppm,
t = the duration of the measurement, h.

1.2 Data processing method

Parameters used for indoor air quality assessment, in addition to directly obtaining parameters such as: temperature, relative humidity (RH), CO2 concentration, as well as indirect parameters such as absolute humidity (AH) and ventilation rate. These parameters need to be obtained by calculation. The calculation method is as follows.

1.2.1 Absolute humidity

According to ASHRAE handbook [8], Indoor absolute humidity is calculated according to the following equation:

$$W=0.621945\, p_w/(p-p_w) \qquad (2)$$

Where W = absolute humidity, g/kg
p= local atmospheric pressure, Pa, (for Chongqing, the indoor atmospheric pressure in summer is about 97kPa, and in winter it is about 99kPa)
p_w = water vapor partial pressure, Pa

1.2.2 Indoor ventilation rate

The concentration of pollutants in the room can be expressed by the following mass conservation equation:

$$V\, dC/d\tau = Q\, C_s + m\, Q\, C \qquad (3)$$

Where V = Room volume
C= Contaminant concentration in the room
τ= Contaminant purification time
Q = Room ventilation
Cs = Concentration of pollutants in the air supply
m = Pollutant emission rate in the room

In order to reduce the indoor pollutants below the recommended value, assume that the indoor pollutant concentration is in a steady state. A simple integral calculation is performed on the mass conservation equation, and the calculation equation of the ventilation rate required for the room is as follows:

$$n=m/(V(C_2-C_s)) \qquad (4)$$

Where n = Room ventilation rate
V = Room volume
m = Pollutant emission rate in the room
C_2= Pollutant concentration of steady state
C_s = Concentration of pollutants in the air supply

2 Results

2.1 Measurement of indoor air quality

Since the size of the bedroom is suitable for the study of the infiltration rate, the bedroom is selected as the room for the study of the ventilation rate in the room. The formaldehyde concentration data obtained from the household test is shown in the fig. 1. WHO [9] and Chinese national indoor air quality standard [10] recommended a guideline of 0.1mg/m³ of formaldehyde exposure concentration, which is marked with black line in the figure. It indicates that the concentration of formaldehyde of closed condition is higher than the normal condition, and the highest in summer. In closed condition, the average concentration of formaldehyde in bedroom reached 0.095 mg/m³ in summer.

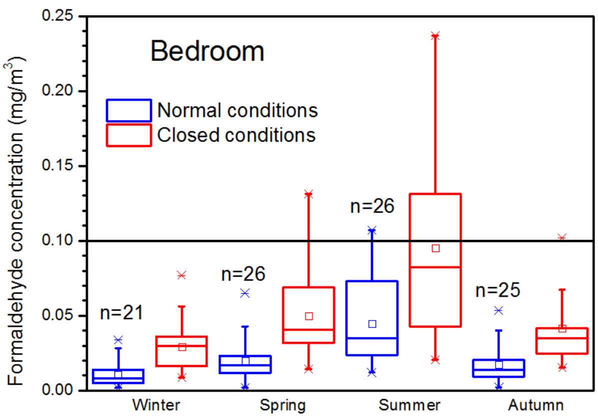

Fig. 1. Statistical data of formaldehyde concentration in four seasons of residential buildings in Chongqing

2.2 The required ventilation rate

In order to remove indoor air pollutants, the room needs a certain ventilation rate. VOCs contamination of interior finishing materials can be indicated by formaldehyde concentration, while indoor air odor can be indicated by carbon dioxide concentration. Substituting the test data into equation (4), the ventilation rates required to eliminate indoor formaldehyde and CO2 can be calculated respectively (table 1). The maximum ventilation rate is taken as the required ventilation rate, which is 0.82 h^{-1}.

Table 1. Ventilation rate required to remove pollutants in Chongqing's residential bedrooms

pollutantants	Season	Ventilation Rate(h^{-1})

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CO_2	——	0.82
formaldehyde	winter	0.08
	spring	0.4
	summer	0.82
	autumn	0.21
Maximum Ventilation Rate(h^{-1})	——	0.82

2.2.1 Ventilation rate required to remove odor

The ventilation rates required to remove CO2 is calculated according to equation (4). The source of indoor CO2 is mainly the human body. The CO2 exhalation rate of human body is calculated by the method recommended in ASTM D6245 [11]. The intensity of activity in the bedroom is low, and the activity intensity during lying down (0.8 met) is accepted.

According to ASTM D6245, the outdoor air carbon dioxide concentration is defined as 350 ppm, and the indoor and outdoor difference is set to 650 ppm. The volume of each bedroom is substituted to determine the required ventilation rate, which is shown in table 1.

2.2.1 Ventilation rate required to remove formaldehyde

Same with CO2, the ventilation rate required to remove formaldehyde in the room is calculated by equation (4). The indoor formaldehyde source intensity is obtained by the on-site test data.

To prevent adverse health effects from formaldehyde exposure, the WHO and Chinese national indoor air quality standard recommended a guideline of 0.1 mg/m3. [9, 10] The concentration of formaldehyde in the atmosphere is set to 0.01 mg/m^3. The results calculated by equation (4) are show in table 1.

2.3 Indoor thermal comfort and ventilation strategy suggestion

2.3.1 Overall temperature and humidity in bedroom

The first two sections examined common indoor contaminants — formaldehyde and CO2 and gave reasonable ventilation rate for the removal of contaminants. In addition, the indoor thermal comfort is also worthy of attention. The monthly mean temperature and humidity of bedroom are used to evaluate indoor thermal comfort. Overall temperature and humidity of bedroom are show in Fig. 2.

The indoor temperature is between 5 °C and 30 °C throughout the year. The temperature is the highest during July and August. The quartile value falls between 23-29 °C, and the individual value exceeds 30 °C, which is caused by the unopened air-conditioner during the daytime. According to GB 50736-2012 [12], the indoor thermal comfort level is divided into two levels. The first level comfort zone is 22-24 °C in winter and 24-26 °C in summer. The secondary comfort zone is 18-22°C in winter and 26-28°C in summer. Considering the temperature comfort zone is 22-26 °C, for Chongqing city, the upper quartile of the indoor temperature is lower than

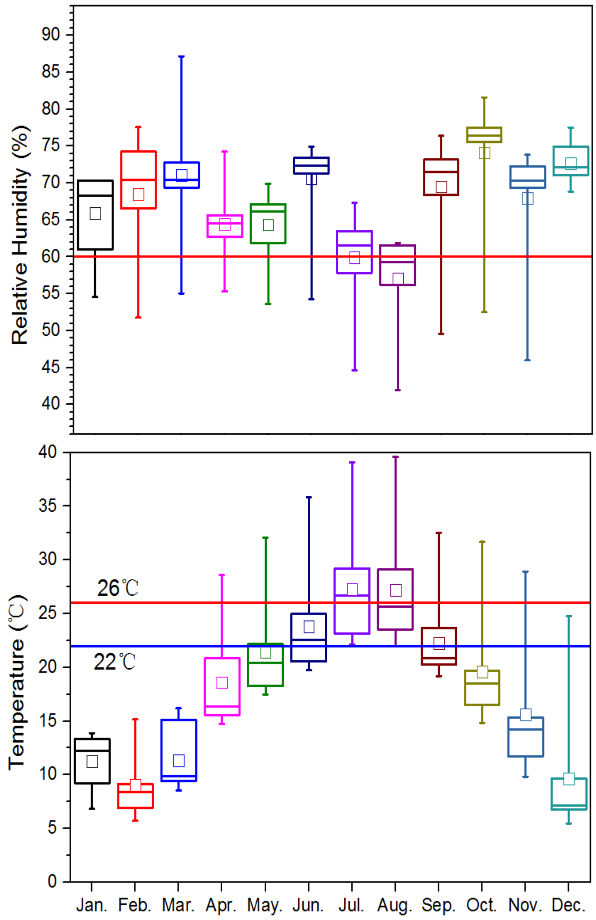

Fig. 2. Statistical Analysis of Temperature and Humidity of Chongqing Residential Houses throughout 2017

18 °C in the spring, autumn and winter. Especially in February and December, the quartile interval between 5-10 °C, it is a very uncomfortable low temperature range for the human body.

As for the relative humidity, the quartile value is above 60% except July and August. The highest RH appeared in October, reaching more than 75%. The comfort relative humidity of the human body ranges from 40-60%. For Chongqing city, it is clear that the RH is too high throughout the year.

2.3.2 Humidity trend throughout the year

In addition to the relative humidity (RH), the absolute humidity (AH) is also calculated by Equation (2) to evaluate the indoor humidity. The annual trend of RH and AH are shown in the fig. 3. The trend of outdoor precipitation and temperature are also shown in the fig. 3.

The ASHRAE Handbook gives an acceptable upper limit of AH of 12 g/kg without giving the lower limit. From the average value of each month, the indoor absolute humidity in June, July and August exceeded the upper limit of 12g/kg. In contrast, indoor and outdoor RH

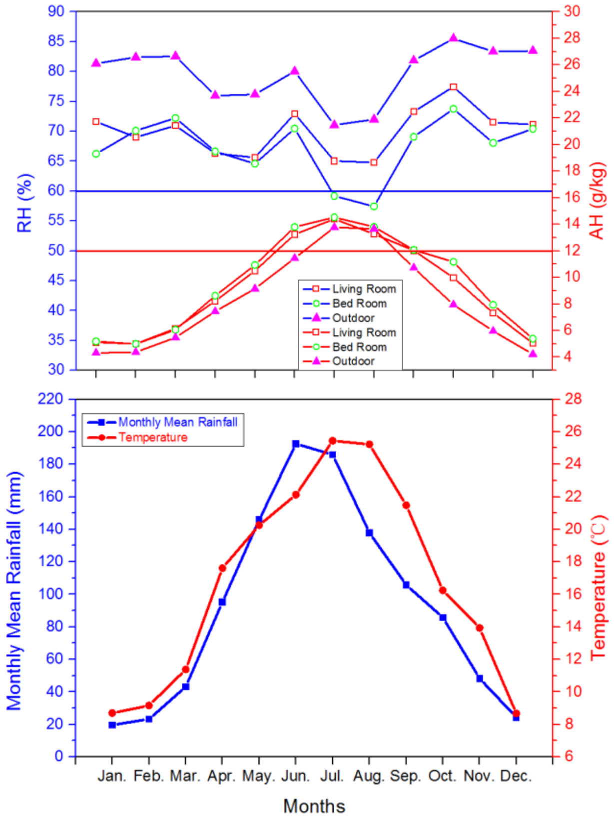

Fig. 3. Monthly average humidity trend of residential rooms in Chongqing and monthly average trend of outdoor temperature and rainfall (2017)

reached the lowest value of the year in July and August. This should be due to the increase in outdoor temperature while the precipitation rises at the same time, which resulting in an increase in the saturated water vapor partial pressure. It can be seen that temperature also has a greater impact on relative humidity.

In the context of this rain and heat climate, summer dehumidification is especially important. The AH data of July and August was compared with that of June. Under the same high AH, the difference between indoor and

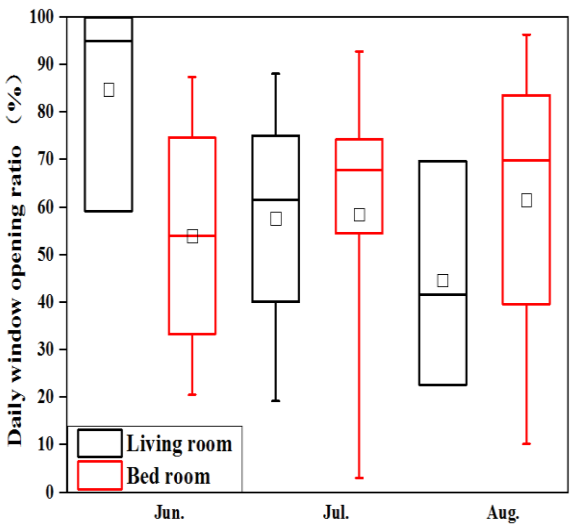

Fig. 6. Statistics on the daily window opening radio of some residents in Chongqing during the summer of 2017

outdoor AH in June is greater than that in July and August, which is the result of dehumidification of indoor air conditioners. Because of indoor wet source, the indoor air AH is higher than the outdoor. The dehumidification effect of the air conditioner can control the indoor AH at a level comparable to that of the outdoor. That is to say, the air conditioner has a better dehumidification effect on the indoor wet source.

From the same trend both indoors and outdoors, it can be inferred that residents in Chongqing have a good window opening habit (Fig. 6), which causes the indoor hot and humid environment to be greatly affected by the outdoor. Therefore, the higher ratio of window opening time is the reason for the same trend of indoor and outdoor heat and humidity conditions, and is also the main reason for the high indoor air AH in summer.

2.3.3 Ventilation strategy recommendations

As mentioned above, residential buildings in Chongqing need to increase dehumidification in the summer to reduce excessive AH, while increasing indoor temperature during winter and transitional seasons to reduce excessive RH. At the same time, residents in Chongqing have good habits of switching windows, and have a higher demand for fresh air. In combination with the above conditions, a fresh air system with dehumidification and auxiliary heat function can be used to assist the split air conditioner in summer to remove the outdoor wet load. On the other hand, in the winter and transition season, the fresh air can be adjusted by introducing fresh air through the fresh air system. Thereby improving the temperature condition and reducing the relative humidity in the room.

3 Discussion

In this paper, formaldehyde is used as the main indoor air pollutant to calculate the ventilation. In fact, due to the particularity of Chinese cooking methods, indoor VOCs are quite complex and require more comprehensive analysis.

The article mainly considers the bedroom and living room. The kitchen and bathroom, which are the high pollution areas in the house, are not considered. These two areas are generally equipped with a negative pressure exhaust system, and the fresh air system should be designed in conjunction with it to achieve the overall optimal effect. Meanwhile, Chinese kitchens are one of the main sources of indoor VOCs, PM2.5 and other pollutants, and it is worthy of further research.

The article proposes to use mechanical ventilation instead of natural ventilation, and the energy consumption caused by this strategy has not been discussed. Comparing the operating energy consumption of the mechanical fresh air system with the energy consumption of the dehumidification and heating equipment under natural ventilation can be a direction for future research.

4 Conclusions

1. In the summer of Chongqing, air conditioning can only effectively remove indoor wet source. It is necessary to increase the auxiliary dehumidification means to reduce the excessive moisture content of the outdoor fresh air.
2. Residential buildings in Chongqing have problems of excessive relative humidity and low temperature during the winter and transition seasons. It is necessary to increase the indoor temperature to meet the needs of thermal comfort and to reduce the relative humidity.
3. By using a fresh air system with dehumidification and heating functions, it can simultaneously meet the purpose of increasing indoor temperature during winter and transition seasons, and dehumidification during summer. It is a ventilation strategy suitable for the Chongqing area.

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