Field study on indoor air quality in a passive residential building in Chinese severe cold area

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Abstract. A field survey was conducted on indoor air quality in a passive low-energy residential building during the winter of 2017 to 2018 in Harbin. The results showed that the mean indoor air temperature was 25.5 °C, and the average relative humidity was 31.3%. The level of CO₂ in passive building (PB) was always lower than the limit of 1000 ppm, indicating a higher air exchange rate in PB. The indoor PM2.5 concentrations in passive households were significantly correlated with the outdoor PM2.5 concentrations but did not vary as much as outdoors. For the clean condition, indoor PM2.5 concentration in PB met the requirement of Chinese standard of no more than 75 µg/m³. For the severe haze polluted condition, the use of a ventilation system with HVAC-filter and enhanced air tightness in PB clearly contributed to lower levels of indoor PM2.5 concentration. Nevertheless, during the outside air polluted period, there was a significant proportion of time with indoor pollution levels exceeding the air quality standard. Therefore, the improvement of filter efficiency is warranted for mechanically ventilated PB.

1. Introduction
The technology and practice of passive house was derived in German. This kind of architecture is design and built with high envelope insulation, enhanced air tightness of doors and windows and some advanced passive technologies, such as heat recovery. Besides, making full use of renewable energy according to local conditions can release passive house from much depending on fossil energy. Extremely high airtight envelopes create the need for mechanical ventilation system to provide fresh air for occupants. While in a suitable design and construction, passive house can achieve both the major decrease in heating energy consumption and increase of indoor air quality (IAQ). Feist [1] reported that a passive houses consume about 80% less energy for heating than requested for a conventional new building. A passive residential building (PB) was constructed as the first demonstration project in Harbin, China, which was designed in cooperation between Chinese and German designers and erected by Chinese contractors.

Harbin, as a typical city of severe cold region of China, has an extremely cold climate during winter. The heating period lasts for 6 months. The heating energy consumption accounts for a large part of building consumption. Higher airtightness leads to a lower air leakage rate and save energy, which may cause IAQ problems and threatens health for occupants. Fine particular matter (PM2.5) is a major concern causing IAQ problems in China nowadays. Epidemiological studies show that the incidence and mortality of human beings are positively correlated with the concentration of indoor particles [2, 3]. Therefore, it is of great significance to study the IAQ of the passive building applied with German technology in Harbin. In order to evaluate the indoor air quality in a PB in Harbin, a continuous tracking investigation was conducted during the winter of 2017 to 2018. This paper presents the results from measurements in the monitored passive households.
2. Method
The PB was designed according to the German passive house criteria, which was equipped with a mechanical ventilation system with heat recovery, allowing for a good control of the air exchange rate. The environmental parameters were measured via air quality monitor called Ikair, which is an intelligent air comprehensive index monitor including temperature and humidity monitor, PM2.5 monitor and CO2 monitor. We placed air quality monitors in the living room, main bedroom and kitchen in each sample households. The test instruments and accuracy of Ikair are shown in Table 1.

| Name                  | Type           | Parameter    | Range       | Accuracy  | Notes       |
|-----------------------|----------------|--------------|-------------|-----------|-------------|
| Air quality monitor   | IKair          | Air temperature | -40~100°C  | ±0.3°C    | Continuous test |
|                       |                | Relative humidity | 0~100%     | ±3%       |             |
|                       |                | CO2          | 0~5000ppm   | ±75ppm    |             |
|                       |                | PM2.5        | 0~1000μg/m³ | ±10%      |             |

3. Results
3.1. Indoor climate
In winter, the mean indoor air temperature was 25.5°C, 1.5°C higher than the upper limit recommended by ASHRAE 55-2013 [4]. The average RH was close to the lower limit of the standard with an average of 31.3%. Indoor air temperature was high due to the high supply water temperature for radiant ceiling system. In the severe cold climate zone of China, the areas of residence are large, and the thermal inertia of building envelope is significant. It is difficult to regulate a huge heating system to achieve heating balance within different users. Although control valves were installed in the heating system for each room, residents seldom use them.

3.2. Indoor CO2 concentration
CO2 intensities can be employed to see indoor air quality and ventilation. For a residential household, an occupant spends more time in a bedroom than in the other rooms. Therefore, it is very important to sustain good indoor air quality in a bedroom for human health. The average CO2 concentrations were 594 ppm in the passive houses. The 1000 ppm limit was exceeded in PB during 4% of the measured time period. In this study, we select one main bedroom in a passive apartment. The selected bedroom was occupied with a young couple, and they usually stay at home at night between 20:00-7:00 (the next day). The PB occupants kept the mechanical ventilation system on all the time. Figure 1 shows the indoor CO2 concentration fluctuation during 24h of a day in December, 2017.

![Figure 1. Indoor CO2 concentration fluctuation of a day in December](image-url)
3.3. Indoor PM2.5 concentration

The average indoor PM2.5 concentration in December was 55 μg/m³ in the PB. The indoor concentration of PM2.5 was analyzed under good and severe polluted weather condition, respectively. One typical passive household was selected for detailed analysis.

![Figure 2. Indoor/outdoor PM2.5 concentrations under good weather condition](image1)

On December 11th, the concentration of outdoor PM2.5 ranged from 12 to 45 μg/m³, with an average of 24 μg/m³. This day was selected as a typical day of good weather. Figure 2 shows the fluctuation of measured PM2.5 concentration in both outdoor and indoor air over this example 24-hour period. Windows in the selected home were closed and the mechanical ventilation system remained open in the whole day.

The average concentration of indoor PM2.5 was 7 μg/m³ and ranged between 4~23 μg/m³ in the passive household. Indoor air PM2.5 concentrations was below 75 μg/m³ and lower than the ambient air PM2.5 concentrations. The results showed that indoor PM2.5 concentrations were significantly correlated with the outdoor PM2.5 concentrations. The indoor air PM2.5 concentrations of the passive household remained flat and did not vary as much in response to fluctuations of the ambient air PM2.5 concentrations.

On December 29th, 2017 the concentration of outdoor PM2.5 ranged from 31 to 442 μg/m³, with an average of 198 μg/m³. This day was selected as a typical day of severe polluted weather. Figure 3 shows the fluctuation of measured PM2.5 concentration in both outdoor and indoor air over this example 24-hour period at two type households. The windows were kept closed and the mechanical ventilation system remained open in the whole day.

![Figure 3. Indoor/outdoor PM2.5 concentrations under severe polluted weather condition](image2)
The results show that the average concentration of indoor PM2.5 was 87 μg/m³ and ranged between 27~166 μg/m³ in the passive household. Indoor air PM2.5 concentrations was lower than the ambient air PM2.5 concentrations but exceeded 75 μg/m³. As can be seen from Fig.5, the indoor PM2.5 concentrations followed the trends of outdoor concentrations, with the indoor variation lagging. Ambient air had the minima concentration at about 7:00 am and 15:00 pm, while the peak values occured at about 10:00 am and 21:00 pm. Indoor PM2.5 concentrations lagged behind those of ambient air about 30 minutes. However, the changes of the indoor air PM2.5 concentrations were smoother and did not vary as much in response to fluctuations in ambient concentrations especially in the passive household. More specifically, indoor PM2.5 concentration in the passive household appeared to be much lower when the outdoor PM2.5 concentration had the peak value between 9:00-11:00.

4. Discussion

4.1. Thermal environment
As a result, the passive building was supplied with more heat than its requirements due to inappropriate operations, leading to a higher indoor air temperature. The radiant ceiling heating system used in the building requires low temperature water, while in practice the heating system was connected to the urban centralized heating system with a high temperature of supply water. When the indoor air temperature was over high, most residents would feel uncomfortable and preferred a lower temperature. And according to subjective responses, most residents felt warm and dry in winter.

Therefore, a lower indoor temperature was recommended in design and operation. Not only could residents' thermal comfort be improved, but also the energy consumption was reduced.

4.2. Indoor CO2 concentration and air exchange rate
CO₂ is often used as an indicator of IAQ. CO₂ concentration is mainly released by occupants in bedrooms. It is not believed to directly pose any health risks; however, it is a proxy for unmeasured indoor-generated pollutants with emission rates linked to occupancy. High CO₂ intensities may show insufficient ventilation and high indoor contaminants intensities, resulting in the Sick Building Syndrome symptoms. Many practitioners assume ventilation rates are insufficient when indoor CO₂ concentrations exceed 1000 ppm.

The measured CO₂ concentrations in the passive far below 1000 ppm. Equipped with the mechanical ventilation system in the PB, there was a sufficient ventilation rate resulting in lower CO₂ level, which could also remove other indoor contaminants effectively. For many naturally ventilated building in severe cold area, in the absence of sufficient ventilation to reduce and eliminate the CO₂ that is consistently being thrown out by the occupants at night-sleep time, CO₂ can gather and its intensity becomes stronger.

Recently, an airtight envelope system has become popular in design of residential buildings to reduce heating loads. Residential building windows are kept closed frequently during cold winter in the severe cold area. Therefore, to maintain good IAQ in such airtight buildings depends on mechanical ventilation systems.

4.3. Indoor PM2.5 concentration
In fog-haze weather condition with high ambient PM2.5 concentration, the use of a ventilation system with HVAC-filter in the PB clearly contributed to lower levels of indoor PM2.5 concentration. On December 29th, the outdoor PM2.5 reached the peak value between 8:00-12:00, the indoor average PM2.5 concentrations were 86 μg/m³ and 122 μg/m³ in the passive and conventional household respectively for this period.

There are less uncontrolled air leaks through building structures in PB with extremely airtight envelopes and positive pressure indoors. The indoor particles are mainly derived from the fresh air sent into the room through mechanical systems. Obviously, a filter in the fresh air unit plays an important role to create a better indoor environment. Under highly polluted weather, the observation indicated that the improvement of air tightness and the use of filtered fresh air supply handling system could improve the indoor air quality significantly compared to CBs without the air cleaner in operation. Although
indoor PM2.5 concentration in the passive household was lower than that in the conventional household, the concentration was still higher than 75 μg/m³ in a severely polluted ambient environment. M5 medium filter was used in this fresh air unit, which is generally used for primary filtration in an air conditioning and ventilation system, and the filtration efficiency of PM2.5 is about 20%~30%. Therefore, improved filtration is warranted in mechanically ventilated buildings, particularly for ultrafine particles. Moreover, purifiers for indoor recirculated air are highly recommended for all buildings.

5. Conclusion
This study investigated the indoor air quality in mechanically ventilated PB. The conclusions are as follows:

- The mean indoor air temperature was 25.5°C, 1.5°C higher than the upper limit recommended by ASHRAE 55-2013. The average RH was 31.3%, close to the lower limit of the standard. A high temperature of supply water for the radiant ceiling heating system in practice resulted to overheating phenomenon in passive apartments.
- The indoor average CO₂ concentrations were 491ppm in the PB, far below the upper limit of 1000, indicating that the addition of mechanical ventilation system in the PB can provide sufficient fresh air required by occupants.
- Under good weather condition, indoor PM2.5 concentration remained flat and far below Chinese limit of 75 μg/m³. Under fog-haze condition, the use of HVAC-filter combined with enhanced air tightness in the passive household decreased the indoor PM2.5 significantly. However, indoor PM2.5 concentration exceed the standard of 75μg/m³ with high ambient PM2.5 concentration. Therefore, improved filtration is warranted in mechanically ventilated PB.

References
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