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Impact of various ventilation modes on IAQ and energy consumption in Chinese dwellings: First long-term monitoring study in Tianjin, China

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ABSTRACT

People typically spend many hours a day inside their homes. Outdoor PM2.5, indoor décor, and the activities of residents worsen indoor air quality. Natural ventilation, natural ventilation with a portable air cleaner (PAC), and mechanical ventilation are some of the main ventilation modes. However, limited data are available on the actual performance of different ventilation modes. We conducted a one-year on-site program of measurement in six apartments in Tianjin, China. The results showed that indoor air quality was affected by both outdoor particle concentration and indoor activities (walking, cooking, etc.). Natural ventilation alone cannot guarantee indoor air quality. A mechanical ventilation system could reduce the duration of high indoor particulate pollution periods to some extent; however, whole year monitoring revealed that it was not effective in increasing healthy time ratios. Reduction in CO_2 concentrations above the standard levels through mechanical ventilation is 22.3% more than that through natural ventilation dwellings. Natural ventilation with a portable air cleaner can remove mass particulate pollution rapidly and maintain good indoor air quality with long-time operation. This study is expected to contribute towards the improvement of indoor air quality and the health of residents.

1. Introduction

Buildings create an indoor microenvironment, in which people participate in indoor activities and generally spend 90% of their lives [1]. In this microenvironment, the activities of the occupants (cooking, furnishings, smoking, etc.) are the main factors influencing indoor air quality (IAQ). Odor causing compounds, carbon dioxide, tobacco smoke, formaldehyde, and volatile organic compounds (VOCs) are the most common indoor air pollutants. Airtight buildings are prevalent [2,3], and inefficient and uncontrolled window ventilation gives rise to poor indoor air quality in dwellings [4]. Long exposure to poor indoor air quality can have an adverse effect on the health of occupants [5].

Although ventilation is an effective means of improving indoor air quality, people cannot obtain enough outdoor air using only natural ventilation. As outdoor pollution becomes increasingly severe, especially in northern China, people are paying more attention to various ventilation modes for the improvement of indoor air quality. In their current state, there are three methods for moving outdoor air into city residences: (1) natural ventilation, (2) natural ventilation with indoor purifying units, and (3) mechanical ventilation.

Outdoor PM2.5 level has an impact on natural ventilation, and it is critical to understand how particulate matter is transported from outdoors to the indoor environment through natural ventilation. Many studies have focused on the I/O ratio [6,7], which is the ratio of indoor particle concentration to outdoor particle concentration. For residential buildings in China, the I/O ratios reported in the literature vary within a wide range (0–5) [8]. Under various measurement conditions, natural ventilation can draw outdoor particles into the indoor environment, or it can dilute indoor particulate pollution if the outdoor air is clean. Residents who are concerned about PM2.5 pollution are paying increasing attention to air purifiers and mechanical ventilation systems for regulating indoor air quality. Table 1 presents a comparison of different ventilation modes.

Although numerous reports on IAQ and ventilation in residential buildings exist, a universal conclusion has not been reached about the appropriate modes of ventilation, especially for Chinese buildings. Building IAQ data and simulation results from other countries are not directly applicable for China because the differences between the lifestyle and environmental conditions of China and developed countries may mean that the appropriate ventilation modes are different. Meanwhile, the sources of the particles that affect indoor air quality differ in Chinese and foreign buildings. The research results of foreign scholars are based on a relatively clean outdoor environment, and the ventilation purification strategy focuses on indoor particle sources (such as smoking, cleaning, and personal activities [18]). In residential buildings in China, however, in addition to indoor particle sources,

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Table 1
Comparison of the advantages and disadvantages of three ventilation modes.

Ventilation mode	Advantages	Disadvantages
Natural ventilation	• Convenient • Economical [9]	• Insufficient outdoor air • PM2.5 penetration [10] • Low level of thermal comfort
Natural ventilation with air purifier	• Effective in removing particles [11] • Flexible in use	• Energy consumption • Performance influenced by physical characteristics of particles [12], purification technology [13], position [14,15], usage habits
Mechanical ventilation	• Outdoor air • PM2.5 obstruction	• Energy consumption [16] • Performance influenced by system maintenance [17], operation mode, filters

outdoor particles accounts for a large proportion of particulate matter pollutants. Smoke from cooking [19] also complicates the particle pollution situation in Chinese residential buildings.

A number of studies have reported severe levels of indoor particulate matter pollution, but the standard measurement method has limited applicability for long-term particle analysis and traceability analysis. The test results in most studies have been obtained by field sampling, which reflects the average particle concentration over a period of time, but it is difficult to obtain long-term field data. Furthermore, field tests tend to disrupt the field conditions, so that the results do not accurately reflect the situation. It is important to collect accurate long-term indoor air quality data and to understand the effects of different ventilation modes on indoor air quality in residential buildings.

The objectives of this study were (1) to obtain real data on the performance of various ventilation modes in terms of indoor air quality in the cold zone of China; (2) to propose a method for comparing the performance of various ventilation modes in particle pollutant removal; and (3) to compare indoor air quality with the natural ventilation mode, natural ventilation with air purifier mode, and mechanical ventilation with filter mode, based on long-term data and energy consumption analysis. These results were analyzed to allow more informed decision-making about the impacts of each ventilation mode on IAQ and energy consumption in residential buildings in China.

2. Methods

2.1. Experimental design

In a previous investigation, 200 naturally ventilated apartments and 60 mechanically ventilated occupied residential dwellings in five climatic regions were monitored during the period from 2017 to 2018. Taking into account the conflict between severe outdoor air pollution and thermal comfort regarding IAQ and ventilation in cold zones, we chose Tianjin as a typical city to evaluate the IAQ and ventilation scenarios and compare the performance of various ventilation modes.

Currently, because of rapid economic development, industrial expansion, and urbanization in China, haze and smog events occur frequently. Air pollution is shifting from local to regional scale. The Beijing-Tianjin-Hebei (BTH) region is the largest and most dynamic economic region in northern China, accounting for 9.7% of national GDP and 8.1% of the country's population in 2014 [20]. It also accounted for 9.0% of national coal consumption and 22.6% of national steel production in 2013 [21]. PM2.5 pollution was found to be severe in the BTH region, with average annual concentrations ranging from 126 to 180 $\mu g/m^3$ [22]. PM2.5 concentrations, on more than 95% of sampling days, exceeded 35 $\mu g/m^3$ [23]. As a typical city in the BTH region, Tianjin has severe air pollution and its average PM2.5 concentration was ranked 99th out of 113 cities in China in 2014 [24]. Meanwhile, Tianjin is a windy city, and natural ventilation can generally meet the requirements of indoor air exchange and remove indoor particulate pollutants. With the frequent occurrence of haze or smog episodes, however, air purifiers and mechanical ventilation have become increasingly popular in residential buildings.

Six dwellings in Tianjin, in the cold zone of China, were randomly selected and were monitored for one year from 2017 to 2018. They are all located in downtown area. Three of them have mechanical ventilation system, and the others had natural ventilation. A questionnaire survey of mechanical ventilation system and air purifier usage in Tianjin has been conducted before the dwellings selection. We consider information of retention ratio, system brand and model, usage intention in the selection work. In each dwelling, we placed indoor IAQ online data-loggers (Ikair sensors) in the bedroom to collect data of indoor temperature, relative humidity, and PM2.5 and CO_2 concentrations. Sensor's location is near the bed to collect data in respiratory area. The Ikair sensor at each sampling point took measurements continuously for periods of at least 1 min every day. Some of the characteristics of the buildings and individual ventilation modes are listed in Table 2.

PM2.5 is the main particle pollutant in residential buildings in China. It is appropriate to use PM2.5 as an indicator of the long-term effects of different ventilation modes. Meanwhile, CO_2 concentration is closely related to mechanical system performance. It is a key factor in the evaluation of new air volume, airflow organization, and performance of mechanical ventilation systems in residential buildings. CO_2 also serves as a comprehensive indicator of indoor air quality, and it is the key to a relevant standard compilation. Therefore, long-term PM2.5 and CO_2 concentrations data for each dwelling were collected to evaluate the performance of the various ventilation modes.

Two of the mechanically ventilated dwellings had a bidirectional flow system (with a heat recovery unit), while the other one had a single flow system (without a recovery unit) to introduce outdoor air into the room. A set of online data-loggers were used in the mechanical system to determine the operating parameters, such as supply air and exhaust air temperature and humidity, supply air pressure, PM2.5 concentration, and operating power. For naturally ventilated residential dwellings, we installed window sensors to record signals for open and closed windows.

Using the long-term data from the six dwellings, we analyzed the performance of the natural ventilation mode, the natural ventilation

Table 2
Characteristics of monitored buildings and individual ventilation modes.

Site	Construction time	Floor area (m^2)	Ventilation mode	No. of occupants	Cooking times per week	Smoking	Types of sensors	Total monitored hours
N1	2010s	94.2	NV	3	8–14	F	T/RH/W/PM2.5/CO_2	5960.5
N2	2010s	68.5	NV + PAC	3	21	F	T/RH/W/PM2.5/CO_2/E	6841.0
N3	1980s	57.0	NV + PAC	6	13–19	F	T/RH/W/PM2.5/CO_2/E	6174.3
M1	2010s	104.2	BF-MV	5	15–21	T	T/RH/W/PM2.5/CO_2/P/E	6859.4
M2	2000s	89.5	BF-MV	4	15–21	F	T/RH/W/PM2.5/CO_2/P/E	6131.4
M3	2000s	66.4	SF-MV	4	15–21	F	T/RH/W/PM2.5/CO_2/P/E	6811.3

Note: NV means natural ventilation; MV means mechanical ventilation; BF means bidirectional flow; SF means single directional flow. T means temperature sensor; RH means relative humidify sensor; W means windows state sensor; E means energy sensor; P means pressure sensor.