Experimental Study on Purification of Indoor Air Particulate Matter by Household Air Conditioner

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Abstract. The most common indoor air pollutants are particulate matter. However, existing indoor air purification techniques have many drawbacks. Admittedly, the low-temperature condensation method can be regarded as an effective method to remove particulate matter. In this paper, experiments are designed to examine the concentration reduction efficiency of PM2.5 and PM10 in the room by using air conditioner. The experimental results showed that household air conditioners have a purification effect on particulate matter. Under the refrigeration mode of maximum air volume, the concentration reduction efficiency of PM2.5 and PM10 reaches 60.99% and 57.47% respectively. The greater the volume of the air, the higher the concentration reduction efficiency of particulate matter. In the purification of PM2.5 and PM10 by household air conditioner, low-temperature condensation plays an important role. It can be suggested that the amount of condensed water affects the concentration reduction efficiency of PM2.5 and PM10 in the room.

1. Introduction

Currently, the most common indoor air pollutants are particulate matter, such as PM2.5 and PM10. Additionally, the particulate purification technology mainly includes HEPA and electrostatic dust removal technology [1]. However, the disadvantages of HEPA still abound, such as high resistance, low air-handling volume, large energy consumption and high cost. Electrostatic dust removal technology also has several shortcomings, such as poor efficiency and the generation of ozone [2].

Condensation of water vapor, working on particles to increase their sizes, is an effective way to purify particles. Fletcher [3] proposed the classical heterogeneous nucleation theory, in which the nucleation of water vapor on insoluble particles starts with a crystal embryo. On this basis, Yoshida [4] constructed a water vapor supersaturation field to promote the growth of fine particles, discovering that the removal efficiency can reach 80%-90%. Moreover, the cooling water of 20~30°C condensation, adding steam and mixed gas was chosen as their experimental methods. They believed that the water vapor phase transition has a good prospect for particle removal. Some scholars [5-6] discussed the effects of factors on the removal of flue gas particles, involving its residence time in supersaturated steam area, concentration of flue gas fine particles and concentration of supersaturated steam. What’s more, some scholars also enhance the removal efficiency of particulate matter in flue gas by combining water vapor phase change with condensation [7-8]. In order to further explore the purification effect of cryogenic condensation on particulate matter, Ying Tang and Gan pan used an
intelligent temperature control module to maintain the inner of the condenser at a given temperature (-60°C to 25°C) to analyze the effect of cryogenic condensation on the removal of particulate matter [9]. The results indicated that the mass concentration of PM2.5 has dropped below the national standard in China (0.075 mg/m³) when the condenser temperature decreased to -16.5°C. However, it’s too expensive to apply the cryogenic method into removing the particles, the most important reason of which lies in the large energy consumption required in a sub-zero temperature environment. In fact, the generation of condensed water can be observed in the experiments of Ying Tang. Moreover, temperatures above zero were not the focus of their research. Hence, we assume that the particulate matter can be condensed and eventually removed when the temperature of contaminated air is below the dew point temperature. In addition, the evaporation temperature of household air conditioners is 7-10°C, lower than the dew point temperature of indoor air. It can be implied that household air conditioners may be equipped with a bearing on the removal of particulate matter. This paper investigated the purification effect of household air conditioners on indoor particulate matter, and discussed the decisive factors of concentration reduction efficiency of particulate matter.

2. Materials and methods
The experiment was conducted in the room (the length of 7.2 m, the width of 3.2 m, the height of 3.6 m, the room area of 23.0 m² and a space volume of 83.0 m³). One wall-mounted split household air conditioner, KFR-35GW/S2F, was installed. Besides, the testing parameters involved indoor air temperature, indoor air relative humidity, PM2.5 and PM10 concentration and air supply speed of air conditioner. The testing instruments included the HT-853 relative humidity meter, the H3 particulate matter concentration tester and the 405-V1 anemometer. Totally, there were 5 measuring points in the room. After measuring the data of corresponding ones, the average calculation was based on the resulting data.

Particulate matter purification and particulate matter leakage experiments were designed under different air volumes and air conditioning modes. Among them, the maximum air volume is 426.8 m³/h; the medium air volume is 358.0 m³/h; the minimum air volume is 297.6 m³/h. There were two air conditioning modes including ventilation mode and refrigeration mode. Polluted air was produced by burning incense. The initial pollution concentration of particulate matter was controlled within 100-250 μg /m³ by controlling the burning time of incense, with the total test time of 3 hours per test. In each experiment, the particulate matter concentration was tested at 30-minutes interval. Before starting each experiment, the room was restored to initial state and air conditioner was washed by clean air.

3. Results and discussion

3.1. Particulate Matter Leakage Experiment
Particulate matter concentration of the room was affected by leakage and indoor deposition rate. In order to verify the main effect of air conditioner on the purification of particulate matter, the leakage experiments were carried out in the room. The results showed that PM2.5 leaked 6.3 μg /m³ per hour on average with a total leakage rate of 19 μg/m³. The average hourly leakage of PM10 is 9.9 μg /m³, and the total leakage rate is 28.7 μg /m³. What’s more, the effect of particulate matter concentration reduction caused by leakage and indoor deposition rate has been taken into account in other experimental results. It is worth noting that indoor deposition rate is strongly related to the air velocity in the room. As the air velocity increases, the deposition rate of particulate matter on interior surfaces of the room will decrease. In leakage experiment, air velocity was 0m/s, the deposition rate of particulate matter was the largest at this time [10-11]. Therefore, in other experiments, the effect of particulate matter deposition rate on the concentration of particulate matter will be less than that in leak experiments.
3.2. Purification of Particulate Matter in Ventilation Mode

When the air conditioner was set to ventilation mode, the compressor of the air conditioner stopped operating. The experimental data were obtained, as shown in Fig 1(a) and Fig 1(b):

Figure 1. Concentration variation curve of particulate matter with different air volumes in ventilation mode

The concentration reduction efficiency $\eta$ of particulate matter in the room was defined as the following formula:

$$
\eta = (1 - \frac{C_2}{C_1}) \times 100\% \quad (1)
$$

In the formula (1), $C_1$ is initial concentration of indoor air particles, $C_2$ is final concentration of indoor air particles. Different from the purification efficiency of particulate matter, the reduction efficiency of particle concentration refers to the reduction degree of indoor particulate matter concentration. What’s more, $C_1$、$C_2$ had been took account of the effect of indoor deposition rate and leakage.

The concentration reduction efficiency of PM2.5 and PM10 in ventilation mode can be calculated by formula (1). The concentration reduction efficiency of PM2.5 and PM10 under different air volumes is shown in Fig 2.

Figure 2. The concentration reduction efficiency of particulate matter in ventilation mode

In accordance with Fig 1 and Fig 2, it can be noticed that the household air conditioners in ventilation mode had a certain effect on the purification of particulate matter, and so was air volume: the greater the air volume, the higher the concentration reduction efficiency. Since the influence of leakage and particulate matter deposition was took into consideration, it can be considered that the particulate matter adheres to the surface of the evaporator or coarse filter. With the air volume increased, more particulate matter will adheres to the surface of the evaporator or coarse filter. Due to
the particle size of PM10 was larger than PM2.5, PM10 was easier to be intercepted on the surface of evaporator and coarse filter.

3.3. Purification of particulate matter in refrigeration mode

When the indoor air was treated through air conditioner, the indoor air was sent back to the room after passing through a coarse filter and an evaporator. In refrigeration mode, the room air temperature was set to 26°C, and the surface temperature of the evaporator was 8°C, with the dew point temperature of indoor air was about 21°C at this time. The variation of particulate matter concentration in refrigeration mode can be seen in Fig 3(a) and Fig 3(b).

![Figure 3](image)

**Figure 3.** Concentration variation curve of particulate matter with different air volume in refrigeration mode

According to equation (1), the concentration reduction efficiency of PM2.5 and PM10 in the refrigeration mode can be calculated, as is shown in Fig 4.

![Figure 4](image)

**Figure 4.** The concentration reduction efficiency of particulate matter in refrigeration mode

On the basis of Fig 3 and Fig 4, it can be noted that the household air conditioner in the refrigeration mode has a better purification effect on the particulate matter than that in ventilation mode. The larger the air volume, the higher the concentration reduction efficiency, which is in line with the experimental conclusion of the particulate matter purification. During the first hour, the concentration of particulate matter decreased rapidly, and after one hour, its purification speed gradually slowed down. With reference to Fig 1-4, compared with the efficiency of particulate matter purification in the ventilation mode, the PM2.5 concentration reduction efficiency in the refrigeration mode was increased by about 33.05%, and the PM10 concentration reduction efficiency was about 22.70% higher.
3.4. Purification of particulate matter under low-temperature condensation

The purification effect of particulate matter in refrigeration mode was considerably better than that in ventilation mode. Accordingly, it was crucial to consider other impacts in the experiment so as to further explore the process playing a major role in the removal of indoor particulate matter. After considering the influence of particulate matter removed by air conditioner in ventilation mode (the impact of collision interception between evaporator and coarse filter on particulate matter), it can be analyzed consequently that low-temperature condensation enables to purify particulate matter. The variation process of particulate matter concentration under low-temperature condensation are showed in Fig 5(a) and Fig 5(b).

![Figure 5. Concentration variation curve of particulate matter with different air volumes under low-temperature condensation](image)

The particulate matter concentration reduction efficiency under low-temperature condensation can be obtained in formula (1), which is shown in Fig 6:

![Figure 6. Comparison of low-temperature condensation particulate matter concentration reduction efficiency](image)

As is shown in Fig 5 and Fig 6, it can be found that the concentration of particulate matter decreased rapidly in the first 40 minutes, while the decline rate slowed down after 40 minutes. Given that the influence of particulate matter removed by air conditioner in ventilation mode, the average concentration reduction efficiency of PM2.5 and PM10 under three different air volumes was revised, which was decreased by 20.05% and 24.99% respectively, but low-temperature condensation still had a good removal effect on the particles, which accordingly indicated that the condensation played the main role in particulate matter purification.

The proportion of leakage, ventilation and condensation to total concentration reduction efficiency is shown in Fig. 7.
As is illustrated in Fig 7, the following conclusions can be drawn: under three kinds of air volumes, the loss of particulate matter caused by the loss of natural leakage accounted for almost equal proportion in the concentration reduction efficiency of total particulate matter (PM2.5 and PM10); the greater the air volume of the air conditioner, the higher the proportion of low-temperature condensation in the total particulate matter concentration reduction efficiency. On the contrary, its loss proportion caused by non-condensation in the concentration reduction efficiency of total particulate matter decreased with the increasing air volume.

Under three kinds of air volumes, the proportion of low-temperature condensation in the total concentration reduction efficiency of PM2.5 was higher than that of PM10. The increasing particle size provided a boost to the particulate matter concentration reduction efficiency of non-condensation. Undeniably, low-temperature condensation played an important part in the purification, which demonstrated that it had a certain relationship with particle size as well.

3.5. Condensed water quantity

After taking various influencing factors into account, the concentration of particulate matter still decreased. Where did PM2.5 and PM10 have gone? Due to the significance of the low-temperature condensation in purifying particulate matter, it could be considered that particulate matter was discharged along with condensed water. Therefore, the amount of condensed water was used as an indicator to directly quantify the low-temperature condensation.

The condensed water quantity $W$ was calculated according to the following formula [12]:

$$W = G_w(d_1 - d_2)$$  

(2)

In the formula (2), $d_1$ is initial air moisture content, $d_2$ is final air moisture content $G_w$ is mass air flow.

The other factors, such as temperature, relative humidity, moisture content change and condensed water quantity, were calculated according to formula (2), as shown in Table 1.

| Water content (g/kg) | Maximum air volume refrigeration | Medium air volume refrigeration | Minimum air volume refrigeration |
|---------------------|---------------------------------|---------------------------------|---------------------------------|
| Condensed water quantity (g) | 1545 | 879 | 461 |

On the basis of Fig 5-6 and Table 1, it can be noted that the quantity of condensed water was positively correlated with concentration reduction efficiency, which indicated that the amount of the condensed water quantity had a greater correlation with the particle removal.
3.6. Purification mechanism
Based on the conclusion of experiments, it can be believed that low-temperature condensation can reduce the concentration of indoor particulate matter. With the decreased air temperature in the evaporator, the temperature of evaporator surface will lower than the dew point temperature of indoor air. When the air was dehumidified, particulate matters will be removed by condensate water. Moreover, we also believe that the purification of particulate matters by condensed water was related to the growth of particle size. When the air was dehumidified, the water vapor in the air will condense on the surface of particulate matters. Then with the continuous condensation of water vapor, the size of particulate matters increases continuously, the larger particulate matters will be easier removed by condensate water, while the smaller particulate matters proceed to circulate during the process until completely removed. Most air-conditioning systems, such as household air conditioner, fan coil system and VRF air conditioning system, tend to apply condensation for dehumidification. Therefore, these systems play certain purification effects on particulate matter.

4. Conclusion
1) Household air conditioners have a purifying effect on the particulate matter. With regard to the efficiency of purifying particulate matter, the air conditioner in the refrigeration mode is superior to that in the ventilation mode. Furthermore, the greater the volume of the air, the higher the concentration reduction efficiency of particulate matter.

2) Under the refrigeration mode of maximum air volume, the concentration reduction efficiency of household air conditioner to PM2.5 and PM10 reaches 60.99% and 57.47% respectively. In the purification of PM2.5 and PM10 by household air conditioners, low-temperature condensation plays an important role. The amount of condensed water affects the concentration reduction efficiency of PM2.5 and PM10.

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