CHEMICAL ENGINEERING TRANSACTIONS
VOL. 71, 2018

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Xiantang Zhang, Songrong Qian, Jianmin Xu
Copyright © 2018, AIDIC Servizi S.r.l.
ISBN 978-88-95608-68-6; **ISSN** 2283-9216

DOI: 10.3303/CET1871137

Performance Test and Structural Analysis of Indoor Air Purifier

Zhihui Deng [a,b], Xiliang Zhang [a]

[a] School of Mechanical Engineering, Jiangsu University, Zhenjiang 212013, China
[b] School of Machinery and Electron Engineering, Changzhou College of Information Technology, Changzhou 213164, China
dengzhihui9012@163.com

The purpose of this study is to improve the performance of indoor air purifiers. To this end, the performance and structure of indoor air purifiers were analysed in this paper. Simple background reduction method and the natural attenuation deduction method were used to analyse the performance test and structure of indoor air purifier. The study found that the purifier A has the best ability to remove formaldehyde, which can remove 80% of formaldehyde within half an hour; purifier B can remove 70% of formaldehyde within half an hour. Therefore, the structure of purifiers affects the purification efficiency, and in the design of the purifier structure, more attention should be paid to the reasonable ratio of radiation field, concentration field and flow field.

1. Introduction

China produces a large amount of waste and atmospheric pollutants every year. However, because of the imperfect treatment mechanism of environmental pollutants in China, many pollutants have not been treated in time, seriously damaging the ecological environment. In most first- and second-tier cities of China, the phenomenon of disorderly emissions is more serious, lacking of relevant processing equipment, which seriously threatens the health of urban and rural residents. According to relevant data provided by China's environmental sector, China's industrial waste gas emissions have increased year by year, with an increase of more than 20%. Thus, the situation of air pollution in China is more severe, and it is of great significance to study the performance of indoor air purifiers.

2. Literature review

Research scholars at home and abroad have done a lot of research. Nowadays, indoor air purification technology is mainly divided into two types: capture type and reactive type. The capture type separates the contaminants from the air fluid by filtration or adsorption, leaving the contaminants in the air purifier. The reaction type principle mainly removes gaseous pollutants (molecular type pollutants) in the air by chemical reaction or ionization. Common reaction mechanisms are UV sterilization, photocatalysis and chemical catalysis, room temperature thermal catalysis, plasma and ozone oxidation. However, this purification method is easy to cause secondary pollution. There are three common capture air cleaning systems: mechanical filtration, electrostatic precipitator (ESP), and hybrid air purifiers (Chan et al., 2015).

In 1963, the German Hammer brothers developed the first indoor mechanical filter to remove soot from indoor air. The main components of mechanical filtration (also known as fiber filtration) are fans and filter dust collectors (Klepeis et al., 2017). The built-in fan draws indoor air into the purifier. The particulate pollutants in the air are filtered by diffusion, interception, impact or inertial force. Its filtration efficiency is affected by the structure of the air purifier, the nature of the filter material and the power of the fan. This type of purifier uses a wide variety of filter materials, and the filtration function depends mainly on the nature of the material. Porous filter materials such as nonwovens, filter paper and fibrous materials are most commonly used. The air filter for filtering PM2.5 is usually made of high-efficiency air filter material (HEPA: High Efficiency Particulate Air), and the material is ultra-fine glass fiber or synthetic fiber, which is often processed into paper. As early as the 1940s, the United States developed the earliest HEPA filter in the Manhattan project, which was used to prevent the spread of radioactive pollutants in the air. Nowadays, it has been widely used in the nuclear

Please cite this article as: Deng Z., Zhang X., 2018, Performance test and structural analysis of indoor air purifier, Chemical Engineering Transactions, 71, 817-822 DOI:10.3303/CET1871137

industry, pharmaceutical industry, food industry and semiconductor industry (Oh et al., 2014). The main components of HEPA are mostly glass fiber or quartz fiber. The efficiency of good HEPA material to remove particulate pollutants in the air can be as high as 99.97%. The most important feature of this material is the high efficiency of particle collection, but the resistance is very large. These two parameters depend on the fiber structure (bulk density, fiber diameter and thickness), operating conditions (filtration rate and temperature), and the characteristics of the trapped aerosol (density, particle size, and particle size distribution). The particulate contaminants are first deposited in the filter bed and deposited on the surface of the filter (Park et al., 2017). This process does not affect the apparent filtration rate. After that, a filter cake is formed on the surface of the filter. As the particulate matter continues to deposit, the resistance increases exponentially. Therefore, the requirements and energy consumption of the wind turbines are getting higher. In order to reduce energy consumption, such air purifiers have to periodically replace the filter media material. Moreover, the filter material is a one-time consumable, which is not economical. In addition, long-term use of this filter can cause contaminants to escape from the filter, producing human-perceivable contaminants. Therefore, the mechanical filter air purifier has a lower market share (Rice et al., 2018). However, primary filtration and intermediate filtration are still widely used in the pre-stage protection of high efficiency filters.

The electrostatic precipitator can use either high-voltage positive electrode discharge or high-voltage negative electrode discharge, but they all use corona discharge. It is mainly composed of a discharge electrode and a collecting electrode, and the discharge electrode is connected to the first stage of the DC high voltage power supply. Two prerequisites for corona discharge are high voltage power supplies and electrodes with very small radii. The mechanism of action is to generate static electricity by the corona discharge principle while generating an electrostatic field. Very small particulate contaminants are ionized into positive ions and electrons as they flow through the high voltage electric field. These particles can collide with other particles or air molecules to charge the latter, and the electrons and positive ions move to the positive and negative electrodes, respectively, to form an electric field across the gas between the two plates. Then, under the action of the electric field force, the charged particles are orientated in the electric field along the direction of the power line to be captured on the collecting electrode, and this process generates a minute current. The electrostatic air purifier does not need to replace the filter material regularly like a mechanical air purifier. After the power is turned off, the filter can be removed and cleaned for recycling (Shao et al., 2017). Compared with the mechanical filter, the electrostatic precipitator air purifier is economical and environmentally friendly. Therefore, it is attracting more and more people's attention, becoming the mainstream trend of indoor dust collector research, and at the same time, it is increasingly occupying the dominant market. With the development of this technology, the electrostatic precipitator purifier has higher and higher dust removal efficiency and lower energy consumption. However, during operation, the electrostatic precipitator air purifier generates secondary pollutants, that is, ozone, due to high-voltage electricity ionizing oxygen in the air. Moreover, the ozone concentration generated easily exceeds the indoor average of 0.16 mg/m^3 for one hour as stipulated by the National Indoor Air Quality Standard (GB/T18883-2015), which is also the biggest drawback of this type of air purifier. The filtration efficiency of such an air purifier is affected by a number of factors. The flow of air can affect the electrostatic field, which in turn affects the charging and motion of particulate contaminants. At the same time, if the concentration of particulate matter is high, it will also affect the electrostatic field, air flow field and particle motion.

Common electrostatic air purifiers are mainly divided into the following types: the conventional electrostatic air purifier consists of an electrode and a trap plate. The electrodes are placed in a central position. The electric field lines are perpendicular to the direction of air flow. The two-electrode plate electrostatic air purifier can change the voltage. It removes particulate and gaseous contaminants such as NO_x. The hybrid air purifier combines the principle of static electricity with other filtration mechanisms to improve its filtration efficiency and economy. After passing through the electrostatic field, a portion of the particles are captured by the collecting electrode and a portion is captured by the fibrous material. These fiber materials do not require the use of HEPA (HEPA resistance is too high, energy consumption is high) because charged particles charge the fiber filter material, which increases the filtration performance of the fiber material (Wongaree et al., 2016). The electrostatic precipitator system is designed with a water mist curtain at the front end of the electrostatic precipitator system. On the one hand, it can cool down and lower the high temperature gas to room temperature. On the other hand, the increase of humidity will cause the condensation of some small particles (especially nanoparticles), thereby increasing the particle size of the particle contaminants and improving the filtration efficiency. The experimental results show that the filtration efficiency of the nano-particles with water mist curtain and water mist curtain is 67.9%~92.9% and 99.2%~99.7%, respectively. The wet electrostatic precipitator system has high filtration efficiency. However, the humidity of the gas is greatly increased, causing discomfort to the human body. Therefore, it is not suitable for use in indoor environments. The first stage of the dual zone electrostatic precipitator system is the particulate pollutant charging area. There is a high voltage electric field in this area, and the particles are charged under the action of a high voltage electric field.

The second stage is the settling area. The particles settle to the collecting plate under the action of an electric field. Such a dust removing device is often used in the field of indoor air purification because of its small size. Today, most of the air-based electrostatic precipitators are used in the market. The main structures include electrostatic precipitators, pre-filters, fiber composite layers, fans and negative ion generators.
Physical and chemical adsorption is the main mechanism of action of adsorption air purifiers. The adsorption carriers commonly used in the two are activated carbon, silica gel, molecular sieves or fibers. Physical adsorption often requires that the adsorbent support be porous and have a large specific surface area. The principle is to use the intermolecular force to adsorb the pollutants on the adsorption carrier to achieve the effect of removing pollutants. Today, mainstream air purifiers on the market often use adsorption methods to remove harmful gases or volatile organic compounds, such as sulfur dioxide, hydrogen sulfide, nitrogen oxides, benzene, formaldehyde and toluene in the air (Xiao et al., 2018). The advantage is that no matter the concentration of the pollutants, the adsorption effect can be good, and the adsorption speed is fast. The chemical adsorption relies on the above-mentioned materials as a carrier, coating a layer of active chemical substance on the surface thereof as needed, or merging with these chemicals to form a novel purification medium. Then, the pollutants in the air are removed by a chemical reaction method. Through catalysis, decomposition, oxidation and neutralization, a variety of harmful substances in the air are adsorbed, thereby achieving the purpose of eliminating pollutants. However, once the adsorption carrier is saturated, it needs to be replaced and cannot be recycled.

3. Principles and methods

This experiment was carried out in a sealed chamber of 2m × 2m × 1m, as shown in Figure 1. The sealing chamber was mainly composed of double-layer glass, the joint was connected by aluminium alloy material, and the sampling hole was arranged on the left side.

Figure 1: Nano Ti02 particle TEM photo zoomed

During the experiment, 8 glass plates were placed on the shelf, and the black light lamps were fixed on the shelves. Each of the glass plates was illuminated by a lamp on average, and the surface light intensity was 150 uw/mz measured by an ultraviolet radiation meter. After the contaminated gas was generated, two fans were turned on to mix the polluted gas in the sealed chamber. Then, the changes of the concentration values of the pollution gas in the natural decay experiment and the photocatalytic degradation experiment were observed.

Table 1: Types of air cleaners

Types of	Main component
Electrostatic air purifier	Negative ion generator， high voltage electrostatic precipitator， etc.
Mechanical air purifier	Negative ion generator， filter dust removal device， blower， etc.
Negative ion air purifier	Negative ion generator
High pressure water pressure air purifier	The use of waterfalls is the principle of generating negative ions
Dust removal adsorption air purifier	Negative ion generator， activated carbon fiber and molecular sieve
	Carrier dust removal adsorption device and blower， etc.
Special purpose air purifier	Device for removing certain or certain gas pathogens

At present, there are many types of air purifiers. According to the dust removal method, it can be divided into electrostatic and mechanical air purifiers; according to the object to be removed, it be divided into dust-removing and dust-removing harmful gas types; according to the method of removing harmful gases, it be divided into physical adsorption, chemical adsorption and ionization. Table 1 lists the types of purifiers. The photocatalytic air purifier this study focuses on is a special-purpose air purifier. Now the functions of air purifiers are more diverse. The single dust removal function can no longer meet the requirements of modern living. Many purifiers have the functions of both dust removal and indoor pollutants removal, such as formaldehyde and cigarette gas.

Simple background reduction method: After pollutants are released in a relatively clean environment, the concentration of pollutants is tested before the purifier starts, and then the concentration of pollutants at different times is determined when the purifier is started. According to the formula, the purification effect can be determined when air purifier is turned on for i-hour. The formula is: purification rate i(%)=(contaminant concentration before start-up. Contaminant concentration after start-up)/pollutant concentration before start-up × 100%. This method hasn't taken the natural attenuation characteristics of pollutants and the effects of temperature and humidity during testing into consideration, with large limitation, although it is relatively simple in use.

Natural attenuation deduction method: for the experimental group, the determination of the purification efficiency, the occurrence, measurement methods of the pollutants, and the calculation of the purification efficiency are the same as the method above. The measurement of the natural attenuation rate occurs in the same environment as above, in the same measurement method, but the purifier is not started up.

Natural attenuation rate (%) = (initial equilibrium concentration of pollutants after pollutants occurrence-contaminant concentration after start-up for i-hour)/initial equilibrium concentration of pollutants×100%; purification rate I= experimental group purification rate-natural attenuation rate. This method takes into account the influence factor of the pollutant's natural attenuation, but in most cases the natural attenuation simulation conditions do not agree with the experimental conditions. In addition, the results of the same set of data processed by different formulas are different, so it is difficult to accurately evaluate the purification efficiency of the purifier.

Clean air delivery rate method: The function of the air purifier is to remove one or more pollutants in the air. The ability to remove certain air pollutants is expressed by the clean air delivery rate (CADR).

$$CADR=V(Ke - Kn)$$

where:
CADR- Clean air delivery rate;
V- Lab volume;
Ke- Total attenuation constant;
Kn- Natural attenuation coefficient.

4. Results and analysis

The experimental gas for testing the air purifier performance is currently the most polluted formaldehyde indoor. Formaldehyde is a common air pollutant, mainly from the manufacturing industries of resins, plastics, leather, and paper etc. In addition, when used as an edible disinfectant, antiseptic and fumigant, it can pollute the air. The carrier of the photocatalyst is a honeycomb paper product, as shown in Figure2.

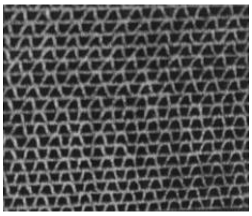

Figure 2: Photocatalyst layer of air cleaner A

During the experiment, the purifier A was placed in the sealed chamber, formaldehyde gas was generated, and the fan was opened to make the formaldehyde gas evenly mixed in the sealed chamber. When the concentration value was stable, the purifier was started through remote control and timed, and the data was recorded every 2 minutes. The photocatalytic layer was taken out, and only the coarse filter layer and the high-voltage electrostatic layer were retained. When, the purifier A was started as usual, the non-photocatalytic layer experiment was carried out, and also compared with the experiment of the photocatalyst layer with the purifier A (incl. the wrong filter layer and high-voltage electrostatic layer). In addition, in order to determine whether the coarse filter layer and the high-voltage electrostatic layer are degraded, a natural attenuation experiment was performed (that is, formaldehyde gas is generated only in the sealed chamber, and the purifier is not placed in the sealed chamber). The experimental results are shown in Figure 3.

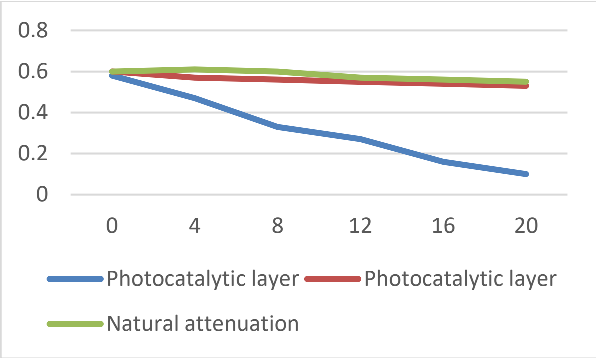

Figure 3: Comparison of the effects of air cleaner A (with and without photocatalystlayer) on purifying formaldehyde

The experiments show that the coarse filter layer of the purifier A and the high-voltage electrostatic precipitating layer only function to filter dust. With photocatalytic layer in the purifier A, its concentration of formaldehyde has a rapid decrease, from the initial concentration of 0.6ppm to 0.12 ppm after 30 minutes, with the formaldehyde degradation rate of 48%; whereas, without photocatalytic layer, the formaldehyde concentration reduced from the initial concentration of 0.6ppm to 0.54ppm, with degradation rate of 10%. Therefore, the photocatalytic layer of the purifier A has a significant degradation effect on formaldehyde. During the natural attenuation process, the concentration of formaldehyde also decreased after 30 minutes, which is the same as the non-photocatalytic process. This can confirm our inference that the coarse filter layer and the high-voltage electrostatic layer do not degrade formaldehyde.
Table 2 clearly lists the performance indices. Next, the structure and performance of the purifier B were studied.

Table 2: Performance indicators of air cleaner A purifying formaldehyde under three different conditions

	Natural attenuation	Photocatalytic layer	Photocatalytic layer
Attenuation index	0.0034	0.0543	0.0035
Half life	203.87	12.77	198.04

Figure 4 that the purifier B only with photocatalytic layer has no photodegradation effect on formaldehyde, and the initial concentration of formaldehyde is 0.6 ppm; after 30 minutes, it's still 0.6 ppm, with degradation rate of 0. When the overall performance (that is, the photocatalytic layer and the activated carbon adsorption layer) was tested, the concentration of formaldehyde decreased from the initial concentration of 0.66ppm to 0.17ppm after 30 minutes, with the concentration decrease rate of 71.7%. When the purifier B has only the activated carbon adsorption layer, the rate of decrease in formaldehyde concentration is also 71.7%. It can be concluded that the adsorption of formaldehyde by activated carbon is very large, and the photocatalytic layer does not work at all.

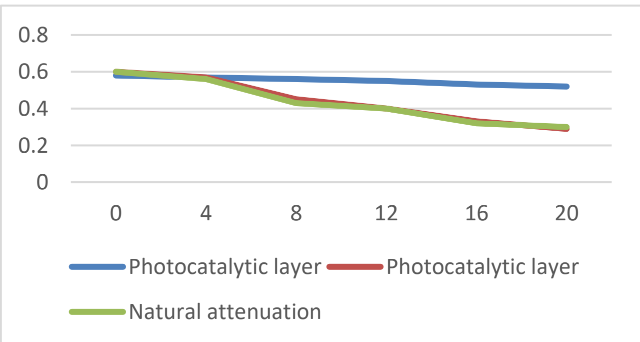

Figure 4: Comparison of the effects of air cleaner B (with photocatalyst and active carbon layer) on purifying formaldehyde

The reason why the activated carbon layer reduces the concentration of formaldehyde is mainly that the activated carbon is a special carbonaceous material, and an amorphous carbon containing graphite crystallites. It has a developed void structure, and a large specific surface area, with the total specific surface area per up to 1500m2 per gram of activated carbon. This characteristic endows it with a strong adsorption capacity. It is because of the activated carbon that many purifiers use it for air purification. However, activated carbon, as an adsorbent, cannot eliminate harmful substances fundamentally. After a period of use, the adsorption saturation occurs and its activity shall lose.

5. Conclusions

In this paper, the formaldehyde purification performance of two air purifiers was tested by experiments. It states the advantages and disadvantages of the two air purifiers, as well as the effect of the number of photocatalytic layers and the amount of air on the purification of formaldehyde by purifier A. Through experimental analysis, it is concluded that Purifier A has the best removal ability of formaldehyde, which can remove 80% of formaldehyde in half an hour; its photocatalytic layer has good performance, but certain loss of the nano-material on the photocatalytic layer was found during the experiment. Purifier B can remove 70% of formaldehyde within half an hour, because of the activated carbon adsorption layer rather than its photocatalytic layer. Combined with theoretical research, it’s also concluded that the photocatalytic layer is the core part of the purifier. The photocatalyst, the carrier and the immobilization method of the catalyst are the key factors affecting the performance of the purifier. In addition, the structure of the purifier also affects the purification efficiency. For the design of the purifier structure, more attention should be paid to the reasonable ratio of radiation field, concentration field and flow field.

In the future development and research of indoor air purifiers, it is necessary to pay attention to the influence of the flow field, concentration field and radiation field.

Reference

Chan W., Lee S.C., Hon A., Liu L., Li D., Zhu N., 2015, Management learning from air purifier tests in hotels: Experiment and action research, International journal of hospitality management, 44, 70-76, DOI: 10.1016/j.ijhm.2014.10.007

Hao Z.G., Su X.M., 2018, Determination and Distribution of Indoor Off-odor Pollutants, Chemical Engineering Transactions, 68, 475-480, DOI: 10.3303/CET1868080

Klepeis N.E., Bellettiere J., Hughes S.C., Nguyen B., Berardi V., Liles S., Hovell M.F., 2017, Fine particles in homes of predominantly low-income families with children and smokers: Key physical and behavioral determinants to inform indoor-air-quality interventions, PloS one, 12(5), e0177718, DOI: 10.1371/journal.pone.0177718

Oh H.J., Nam I.S., Yun H., Kim J., Yang J., Sohn J.R., 2014, Characterization of indoor air quality and efficiency of air purifier in childcare centers, Korea, Building and Environment, 82, 203-214, DOI: 10.1016/j.buildenv.2014.08.019

Park H.K., Cheng K.C., Tetteh A.O., Hildemann L.M., Nadeau K.C., 2017, Effectiveness of air purifier on health outcomes and indoor particles in homes of children with allergic diseases in Fresno, California: A pilot study, Journal of Asthma, 54(4), 341-346, DOI: 10.1080/02770903.2016.1218011

Rice J.L., Brigham E., Dineen R., Muqueeth S., O’keefe G., Regenold S., Diette G.B., 2018, The feasibility of an air purifier and secondhand smoke education intervention in homes of inner city pregnant women and infants living with a smoker, Environmental research, 160, 524-530, DOI: 10.1016/j.envres.2017.10.020

Shao D., Du Y., Liu S., Brunekreef B., Meliefste K., Zhao Q., Xu H., 2017, Cardiorespiratory responses of air filtration: A randomized crossover intervention trial in seniors living in Beijing: Beijing indoor air purifier study, biapsy, Science of the Total Environment, 603, 541-549, DOI: 10.1016/j.scitotenv.2017.06.095

Wongaree M., Chiarakorn S., Chuangchote S., Sagawa T., 2016, Photocatalytic performance of electrospun CNT/TiO 2 nanofibers in a simulated air purifier under visible light irradiation, Environmental Science and Pollution Research, 23(21), 21395-21406, DOI: 10.1007/s11356-016-7348-z

Xiao R., Mo J., Zhang Y., Gao D., 2018, An in-situ thermally regenerated air purifier for indoor formaldehyde removal, Indoor air, 28(2), 266-275, DOI: 10.1111/ina.12441