Revista Română de Inginerie Civilă, Volumul 10 (2019), Numărul 3 

# Synthesis of knowledge on utilization of adsorption filters for healthy indoor environments

*Ayse Fidan Altun*, *Muhsin Kilic**

Bursa Uludag University, Department of Mechanical Engineering, Bursa, Turkey

**Abstract.** Building occupants are exposed to many different kinds of pollutants in indoor environments. A healthy and comfortable indoor environment is an essential need for humans. Air pollution is related to many deadly diseases such as cancer, respiratory and cardiac diseases. As a result, control of hazardous gases in the indoor air is crucial. The utilization of sorbent filters is a promising technology in reducing the level of pollutants from indoor air. This study presents a comprehensive review of adsorption filtering technology. The article discusses factors that influence filter performance, recent technological developments, advantages, limitations and challenges.

## 1. Introduction

People spend most of their time inside buildings. As a result, problems related to indoor air quality are more crucial than ever. Human beings are in need of fresh air supply continuously. Free access to air and water of acceptable quality is a fundamental human right [1]. There are different types of air pollutants, and air pollutants in the indoor environment must be kept under control, and concentration levels of the air pollutants should not exceed threshold values that are addressed in the related standards. If the sources of the air pollutants are not controlled, indoor air quality problems may occur, even if the ventilation and air conditioning system works correctly. Among the air pollutants, volatile organic compounds (VOCs) have been classified as an important indoor air pollutant type in buildings [2]. In the outdoor environments, industrial and vehicular emissions are major sources of VOCs, and in the indoor environment, inner building materials, furniture, perfumes, paints are the most common sources of VOCs [3]. In Table 1, the health effects of some of the major VOCs are presented.
Control of VOC levels inside the building environments is crucial as exposure to VOC emissions might cause severe health problems on humans. They cause acute symptoms such as irritations of the nose, throat and eyes, headaches, nausea, dizziness and also damage the internal organs such as kidneys and liver [4]. Exposure to some of the VOCs such as benzene can even lead several diseases such as leukemia, immune system abnormalities, neurological disorders, respiratory illnesses, etc. [5]. In addition to being harmful to human health, VOCs are also major contributors to stratospheric ozone depletion [6]. For these reasons, it is vital to develop air filters for the removal of gaseous contaminants. Since the concentration level of VOCs is very low inside the buildings, there are only a few technologies that can be applied for removing VOCs, which are oxidation technique such as photo-catalysis and cold plasma and adsorption systems [7]. In photo-catalysis, VOCs destruction is conducted by using photo-catalysts such as $TiO_2$ and UV light at ambient temperature [8]. Pollutant molecules come into contact with produced reactive species and break down to lower molecular weight products and eventually to $CO_2$, water and other by-products [9]. While the adsorption process is a surface phenomenon which involves the transfer of a gas phase material (adsorbate) to the surface of a solid (adsorbent) [10], a photo-catalysis unit would have an installation cost more than ten times greater and annual operation cost seven times greater when compared to sorbent filters [11]. In addition to having lower initial and operation costs, sorbent filters have another advantage of producing no harmful by-products, while oxidation techniques can generate harmful secondary chemicals such as $NO_x$, $O_3$, OH* radicals [12], [7]. As a result, most commonly used air purification technique for harmful gases is adsorption.

**Table 1.** Health effects of some of the significant VOCs [6]

| Classification | Representatives | Health effects |
|---|---|---|
| Alcohols | Methanol<br>Ethyl alcohol<br>Isopropyl alcohol | Throat irritation<br>Eye irritation<br>Nasal tumors<br>Central nervous system depression |
| Aldehydes | Formaldehyde<br>Acetaldehyde | |
| Alkenes | Propylene<br>Ethylene | Carcinogenic effects |
| Aromatic compounds | Benzene<br>Toluene<br>Ethylbenzene | Carcinogen<br>Produce photochemical smog |
| Ketones | Acetone<br>Ethyl butyl ketone | Central nervous system depression<br>Carcinogen<br>Headache and nausea |

The goal of this study is to provide a review of the critical factors governing VOC adsorption onto adsorbents. In this work, the impact of characteristics of VOCs, adsorbent properties, as well as adsorption conditions on adsorption performance is discussed.

* Corresponding author: mkilic@uludag.edu.tr

## 2. Sorbent Filters

Physical properties of adsorbents and adsorbates and environmental conditions profoundly affect the removal efficiency of sorbent filters. There are many different kinds of adsorbent/filtration media. Among them, activated carbon, activated carbon fiber, silica gel, and zeolite are the most commons [13]. Due to its low cost and large surface area activated carbon is the most extensively used adsorbent media. Activated carbon is developed by thermal decomposition of a carbonaceous material (coal, coconut shell, wood, etc.) and is activated with steam or carbon dioxide at high temperatures (700-1100˚C) [14]. Activated carbon can be found in different forms such as powders, micro-porous, granulated, molecular sieves and carbon fibers [15]. The structure of pores can be classified as macro pores (>50 nm), micro pores (<2nm), meso pores (2-50 nm) and represented in figure 1 [7], [14]. Silica gel and alumina have less surface area than activated carbon, but they are preferred to use for trapping polar compounds such as formaldehyde and sulfur-based contaminants [16].

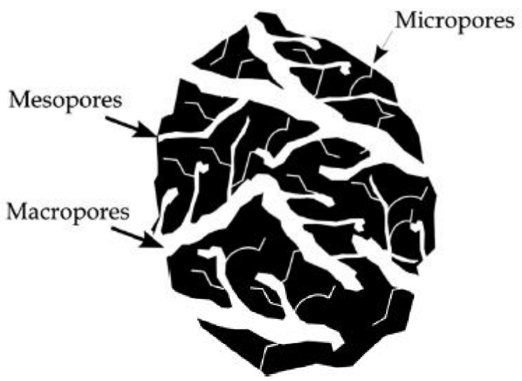


**Fig. 1.** Schematic representation of adsorbent pore structure [14]

### 2.1. Mechanism of adsorption

Adsorption is a reversible physical phenomenon that occurs between adsorbent surfaces (solid) and an adsorbate (fluid vapor) driven by cohesive forces [17]. Adsorption process of the contaminant gas occurs mainly within the pores and surface of the solid adsorbent [18]. To maximize the adsorbed amount of the pollutant gas, it is essential to know about adsorption characteristics of the adsorbate-adsorbent pair [19]. Sorbent air filters consist of fixed adsorption beds. VOC removal by the adsorption bed is a dynamic process. The area where adsorption takes place is called mass transfer zone. In the beginning, the bed adsorbs all of the pollutants, however, when the gaseous pollutants saturate bed's first layers, mass transfer zone moves through and finally leaves the bed [10]. The fraction of gas concentration passes the bed unadsorbed is called "breakthrough rate". This parameter is shown in Eq. 1.

$$BT(t)=(C_0(t))/(C_i(t))\ x100=1-EF(t)(\%) \qquad (1)$$

In this equation, $C_o(t)$ shows the downstream concentration of the contaminant gas, at the end of time t; $C_i(t)$ represents the upstream concentration of the contaminant gas [19]. EF(t) refers to single-pass efficiency of the filter. The time from the beginning of the adsorption process until the filter reaches a specific breakthrough rate is called breakthrough time. The main drawback of sorbent filters is that adsorbent material becomes saturated after a while. Therefore, adsorbent material should be regenerated periodically.

### 2.2 Related Studies

It is crucial to know which adsorbent material can adsorb most of the target gaseous contaminant for a given time [20]. It will enable potential users to make better decisions taking into account the function of the building. As a result, there are many experimental studies to understand the adsorption performance of different sorbent materials. Owen et al. [21], tested the efficiency of five different sorbent air filters following the ASHRAE 145.2 test standard. In their study, they selected three different VOCs (toluene, sulfur dioxide, ozone) and five different commercial and residential sorbent air cleaner with different media blend. Contaminant air stream was sent to the test air ducts and upstream, downstream concentration of pollutants were measured. As a result, they found out that, adsorption efficiency of the air cleaner varies according to the contaminant gas that is used. It was emphasized that testing with a single pollutant might not give similar results for a mixture containing that particular contaminant. Additionally, it was shown that a sorbent filter may show high efficiency for a particular gaseous contaminant and may show a lower efficiency for another. As a result, it was highlighted that users should select adsorbent material relevant to their gas contaminant removal needs.

Before ASHRAE 145.2 test standard, there was not any standard for measuring the efficiency of sorbent filters. As a result, Lee et al. [22], conducted a study to propose an experimental method for evaluating sorbent filters' efficiency in VOC removal. A closed-loop test system was used to investigate the performance of four different fibrous activated carbon filters (A,B,C,D) in toluene removal. The breakthrough time until 80% breakthrough rate was determined for each filter type. According to the results, 80% breakthrough time was 121.2 minutes for filter A, 61.97 minutes for filter B, 160.6 minutes for filter C and 358.8 minutes for filter D. As a result, compared to the other filters, filter D showed the best performance in toluene removal due to its highest specific surface area.

Often in experimental studies, the concentration of the contaminant gas is much higher (ppm) than in the real indoor air environment conditions (ppb). Since it is complicated and costly to conduct experimental studies with lower concentrations, researchers often prefer to use higher contaminant gas concentrations during their experiments. Since it is difficult and expensive to do experiments under low concentration levels, Pei et al. [23], developed a mathematical model to investigate the performance of the sorbent bed even under relatively low concentration levels.

**Table 2.** Sum. of experimental conditions of previous studies

| Literature | VOC | Concentration | Adsorbent |
|---|---|---|---|
| Lee et al. [22] | Toluene | 4.32 µl/min | Fibrous activated carbon types |
| Owen et al. [21] | Toluene<br>Sulfur Dioxide<br>Ozone | 50 ppm<br>35 ppm<br>0.5 ppm | Granular activated carbon types |
| Pei et al. [23] | Toluene<br>Decane<br>Hexane<br>Butanone<br>Iso-butonal<br>Tetrachlorothylene<br>D-limonene | 32 ppm<br>34 ppm<br>40 ppm<br>78 ppm<br>58 ppm<br>43 ppm<br>17 ppm | Pellet and granular activated carbon types. Activated alumina with potassium permanganate |
| Safari [7] | Methyl-ethyl ketone<br>N-hexane | 100 ppm<br>100 ppm | Granular activated carbon |
| Han et al. [20] | Ozone<br>Nitrogen Dioxide | 50ppb-1ppm<br>55ppb-100 ppm | Virgin AC types<br>Treated AC types<br>Activated alumina<br>Zeolite |
| Kholafei [10] | Toluene<br>Toluene, p-xylene, n-hexane,2-butanone mixture | 10 ppm<br>5 ppm of each | Granular activated carbon |
| Haghighat et al. [28] | Toluene | 4.32 µl/min | Fibrous activated carbon types<br>Granular activated carbon types |
| Haghighat et al. [29] | Toluene<br>Cyclohexane<br>Ethyl acetate | 50 µl/min<br>50 µl/min<br>50 µl/min | Granular activated carbon types |

They also validated the proposed model with laboratory test data for toluene, decane, hexane, butanone, iso-butonal, tetracholorothylene and d-limonene. Foster et al. [24], examined the VOC (n-butane, acetone, benzene) adsorption performance of various activated carbon filters with different specific surface areas (900, 1610, 2420 $m^2/g$) with the aim of optimizing adsorption of VOCs on activated carbon. According to the test results, as the specific surface area of the activated carbon fiber increased, the amount of adsorbed contaminant gas was also increased. In contrast, at low concentrations, activated carbon with smaller pore volume adsorbed the greatest amount of contaminant gas. It was emphasized that micropores rather than the larger macro and mezo pores are preferentially filled at low relative pressures. As a result, micropores are responsible for adsorption low contaminant concentrations. The change in adsorption capacity of the adsorbent with pore size was further demonstrated with Dubinin-Radushkevich equation.

$$W=W_0.\exp[-(A/\beta E_0^2)] \quad (2)$$

$$A=-\Delta G=RT \times \ln(P_0/P) \quad (3)$$

This equation was developed to describe the adsorption characteristics of carbon originated, microporous materials [25]. In equation 2, W is the volume of adsorbed gas for per gram carbon, $W_0$ is the micropore volume ($cm^3/g$), β is the similarity coefficient, $E_0$ defined as characteristic adsorption energy for a standard adsorbate. In Eq. 3, $P_0$ is the adsorption saturation pressure, P is the desired pressure value, and R is the universal gas constant. Safari [7], investigated the lifetime of a granular activated carbon sorbent filter in her study. An experimental study was conducted in four stages. First, n-hexane was added to the dry air, and the mixture was sent to the sorbent filter. In the second case, methyl-ethyl-ketone and dry air mixture was sent to the sorbent filter, and the adsorption performance was examined. In the third case, both of the contaminant gases were added to the dry air, and the mixture was passed through the sorbent filter. In the last case, the performance of the filter was examined by adding both contaminant gases to the moist air. For those four different cases, the lifetime of the filter was determined both experimentally and with the help of an appropriate mathematical model. According to the results of the study, it was observed that contaminant gases with higher molecular weight (such as n-hexane) were adsorbed more in the filter than the gases with lower molecular weight (such as methyl-ethyl-ketone). The lifetime of the filter calculated with the selected mathematical model is very consistent with the test results for single contaminant gas cases, and the relative error is calculated less than 10%. However, for case 3 and 4, relative error between selected mathematical model and the experimental results is calculated approximately 25%.

Although low cost and high adsorption capability make activated carbon one of the most preferred adsorbent material, micropore structure (<2 nm) of activated carbon may slow the transport velocity of VOC molecules in some cases. Wang et al. [26], investigated VOC adsorption performance (benzene and hexane) of mesoporous activated carbon with larger pore volume and higher specific surface area. They concluded that, since that large pore volume can be used entirely, high adsorption amounts were achieved for different VOCs despite their molecular size differences. They highlighted the superior adsorption capacity of mesoporous adsorbent materials.

Zhang et al. [5] conducted a literature review on the latest technological developments related to VOC adsorption. It was emphasized that VOC adsorption is very complicated and depended on many different factors. According to this study, the most important factors controlling VOC adsorption onto carbon materials are;

- **Structure of the adsorbent material:** Structural factors of the adsorbent material that impact VOC adsorption are the specific surface area, pore size, and bulk density. It was emphasized that the larger specific surface usually means greater adsorption capability. There are also some modification methods for enlargement the surface area of adsorbent materials. However, some of them might destruct surface form and decrease adsorption performance. It was also highlighted that in case of pore size, it is better to conclude as optimal adsorption occurs where pore size fits the adsorbate size; as a result, in some cases, mesopores are more advantageous for VOC adsorption, in others micropores are much better especially for small molecule VOCs.

- **Structure of the adsorbate gas:** The structure of the adsorbate gas is also crucial for adsorption performance. In the article, it was emphasized that contaminant gases with larger molecules have a better adsorption performance with adsorbent materials with larger pore volume. A similar tendency can be observed for VOCs with smaller molecules and adsorbent materials with smaller pore volumes. The boiling point is another critical parameter for adsorbate gases. In the article, it was highlighted that contaminant gases with higher boiling points would be preferentially adsorbed more than those with lower boiling point. Additionally, the molecular weight is another important parameter for adsorbates. Adsorbates with heavier molecular weight are more competitive than adsorbates with lighter ones.

- **Adsorption conditions:** Temperature, relative humidity, the concentration of the contaminant gas and air velocity play crucial roles in adsorption. In general, temperature and adsorption efficiency are inversely proportional, where temperature increases, adsorption capacity decreases. However, this is not always the same. VOC concentration and gas velocity are other important factors. Higher concentration of pollutants may shorten the breakthrough time. Reducing the air velocity increases the breakthrough time, in many cases.

Since there are different VOC removing methods from indoor, it is essential to choose the most suitable one for the application. Henschel [11], conducted a study to make a cost comparison between granule activated carbon (GAC) filter and photocatalytic oxidation (PCO) method. In this study, it was assumed that VOC generation rate inside a building zone is 5 mg/VOC/hr/$m^2$ floor area, and the air cleaner must reduce indoor pollutant concentration by 85% to 0.3 mg/$m^3$. First, granular activated carbon unit is designed and equipped, laboring and disposal cost is estimated with the use of related vendor literature and quotes. It was assumed that granular activated carbon should be replaced at every 3.7 months, at 30% breakthrough in order to achieve the target of elimination of 85% of the gaseous pollutant concentration. The increase in fan energy because of the pressure drop across the granular activated filter is also considered. Similarly, with the goal of decreasing indoor gaseous contaminants concentration to 85%, 2-cm thick, $TiO_2$ coated ceramic foam photo-catalytic oxidation reactors were designed and initial and labour costs were estimated with the use of related literature. According to the results of the article, it was emphasized that the installation and annual cost of the photocatalytic reactor is 10 times and 7 times higher than that of the activated carbon sorbent filter, respectively. In the article, it was emphasized that massive UV power consumption and cooling unit that removes heat from the UV bulb heat from the air stream are significant contributors to initial and annual costs of the PCO and even in most optimistic scenarios, it is impossible PCO reactors to compete with GAC filters.

Since breakthrough time of the adsorbent depends on many parameters such as environmental conditions, air flow rate etc., it is not sufficient enough to decide the most suitable adsorbent material for an application. As a result, Xu et al. [19], developed an approach to select the most suitable adsorbent material to adsorb contaminant gases with considering external diffusion, inner diffusion and inner surface sorption. With the new parameter designated as $V^*_{a,c}$, they defined the volume of purified air divided by the volume of adsorbent material. Sorbent filter with the highest $V^*_{a,c}$ value has the best performance to remove VOCs. Han et al. [20], conducted an experimental study to investigate whether sorbent filters which exhibit good adsorption performance with high contaminant gas concentrations also perform efficiently at low contaminant gas concentrations. They selected ozone and nitrogen dioxide as contaminant gases. They kept the ambient temperature constant at 23+1 ˚C and performed the measurements of 12 air ducts simultaneously. Both low and high concentration contaminant gasses passed through sorbent filters inside the air ducts, and concentration measurements were made inlet and outlet of the air filter with the help of multi-gas monitors. According to the results of the experiments, activated carbon filters adsorbed ozone better than non-carbon filters. Similar results were obtained in experiments with nitrogen dioxide gas. Activated carbon sorbent filters have a much better adsorption capability than non-carbon filters. Based on the results of the experiments, low concentration and high concentration adsorption performance of sorbent filters were consistent. Kabrein et al. [27], investigated the application of a combined filter in office buildings to eliminate both dust and particles and contaminant gases. In their work, they used a combined filter, which consisted of a sorbent filter with activated carbon material for VOC removal and particulate filter for dust removal with the aim of increasing air quality and decreasing energy consumption for ventilation. Experiments were conducted in a space that represents a typical office room. In accordance with ASHRAE 62, the exhaust air taken from the office unit is passed through the combined filter, and sent to the mixing chamber, and mixed with fresh air and then sent back to the indoor environment. With the help of particle measurement device and gas monitor, the contaminant concentrations at the inlet and outlet of the filter were measured, and filter efficiency was determined 3 months and 6 months after the application (Eq. 4).

$$EF=(C_{in}-C_{out})/C_{in} \quad (4)$$

The filter efficiency is calculated as in equation (4), where $C_{in}$ and $C_{out}$ are the contaminant concentrations at the input and the output of the filter respectively. According to the results of the article, filter efficiency of capturing $PM_{10}$ particulates was 90.76%, while 89.25% was found for the $PM_{2.5}$ particulates. It was also emphasized that the measured pressure drops of the combined filters are quite low compared to the conventional air filters. However, in this study, there are not any statements regarding VOC concentration measurements and sorbent filter efficiency.

Haghighat et al. [28], examined the adsorption performance of 12 different, fibrous and granulated activated carbon filters with the help of an experimental setup. Experimental setup was made of galvanized steel and consisted of a closed loop circular air channel of 0.1 diameter, a fan that circulates air flow, sorbent filter bed, an anemometer to measure the air velocity, injector pump for the addition of toluene gas to the air flow, gas sampler and multigas monitor. The experiment continued until the filter reached 80% breakthrough rate. Four different fibrous filters were tested and breakthrough time, in order to reach 80% breakthrough rate, was compared. According to the results, the filter with the largest specific area gave the best performance since the breakthrough time is the longest when compared to the other filter types. Accordingly, it was concluded that sorbent filters with high specific area perform better. In the 3rd stage of the experiment, adsorption performance of the different type of granular activated carbon filters was examined. Results of the experiments showed that 100% activated carbon filters perform best. For the case of activated carbon filters impregnated with potassium hydroxide, as the content of potassium hydroxide increases, toluene gas adsorption performance of the filter decreases.

Haghighat et al. [29], also examined the VOC (toluene, cyclohexane and ethyl acetate) removal performance of various activated carbon filters (three virgins and five impregnated) at different relative humidity values (30%, 50%, 70%) experimentally. Experimental results showed the adsorption performance variation depends on the type of granular activated carbon type, VOC type and different relative humidity levels. For the case of granular activated carbon (GAC) type, test results highlighted that virgin GAC filters have better adsorption performance than impregnated GAC filters. For the case of the effect of type of VOC on adsorption performance, test results showed that filters adsorbed toluene almost 2-3 times more than ethyl acetate and cyclohexane. Moreover, for the last case, it was concluded as adsorption filters perform better at low humidity levels. However, it was also highlighted that increasing humidity levels might result in favorable effects on hydrophilic and adverse effects on hydrophobic volatile organic compounds. As a result, removal efficiency dropped with increasing relative humidity for toluene and cyclohexane, and removal efficiency increased with increasing relative humidity levels for ethyl acetate.

Kholafei [10], examined the performance of activated carbon filters in the granular form. He conducted experiments in two stages. In the first stage, he changed the depth of the adsorbent bed and measured the toluene adsorption performance of the filter. In the second stage of the experiments, he kept the depth of the bed as constant (5 cm) and passed a mixture of contaminant gases, through the filter. The test results showed that gases with higher molecular weight could be easily attached to the adsorbent surface. As a result, it can be concluded that heavier gases can be adsorbed more. The breakthrough time of toluene is much higher in the first set of experiments when compared to the second set. This shows that toluene adsorption performance of the filter is better when a single gas is passed through. When a gas mixture passed through the filter, adsorption performance of toluene worsens. Lastly, he compared the test results with the analytical results he found with the Wheeler-Jonas Model and the results were consistent. Wheener–Jonas model offers the estimation of breakthrough time in a simple correlation.

$$t_b = \frac{M.W_e}{Q.C_{in}} - \frac{W_e.\rho_b}{K_v.C_{in}} In\left(\frac{C_{in}-C_{out}}{C_{out}}\right) \quad (5)$$

In this equation, $t_b$ refers to breakthrough time (minute), M is the weight of the carbon material in the bed (gram), $W_e$ refer to adsorption capacity ($g_{voc}/g_{carbon}$), $C_{in,out}$ refers to upstream and downstream concentration of the contaminant, Q is the volumetric air flow ($cm^3$/min), $\rho_b$ is the carbon density ($g/cm^3$), and $K_v$ is the adsorption rate constant ($min^{-1}$), respectively.

## 3. General Evaluation and further research directions

In order to fully understand the performance of sorbent filters, conducting field testing is inevitable. However, most studies in the literature were conducted for a single contaminant gas. Since there are numerous VOCs can be found in indoor air, further researches should be conducted to investigate the performance of sorbent filters on capturing VOC mixtures. In addition, there are not enough studies regarding magnitude of pressure drop occurred in the system after applying sorbent filters. Further researches should be conducted on the subjects as follow:

- Since there is more than one pollutant in the air, more field testing should be conducted for gas mixtures.
- More experiments should be conducted regarding real indoor concentration (ppb) levels.
- New carbon materials should be developed for better adsorption capacities.
- More studies should be focused on decreasing the pressure drop through the filters and decreasing the initial cost of the sorbent materials.

## 4. Conclusions

VOCs exist everywhere especially in the indoor environment and they are extremely hazardous and directly affect the health of building occupants. Exposure to various VOCs may cause eye, nose, throat irritation, leukemia, immune system abnormalities, neurological disorders, respiratory illnesses etc. As a result, air purification systems are getting more attention every day. Between all VOC removal technologies, sorbent filters are the most popular and common ones. In this study, the most critical factors that effects sorbent filters' efficiency are discussed. The results of this article are summarized below:

- Between all adsorbent materials, carbon originated adsorbent materials are the most effective ones due to their larger specific surface area. As a result, activated carbon filters adsorb better than non-carbon filters.
- At low concentration experiments, adsorbent media with micropore structure have better adsorption capacity whereas, at high concentration experiments, adsorbent media with mezo porous or macroporous structure have better adsorption efficiency.
- A sorbent filter may show high adsorption efficiency for a particular contaminant and may show a lower efficiency for another. Adsorption efficiency depends on many different parameters.
- Testing for a single contaminant would not give the same results as a mixture of gases also containing that particular contaminant.
- Contaminants with higher molecular weight are adsorbed more in the filters. Also, they are more competitive than gases with lower molecular weight.
- With the existing mathematical models, it is easy to estimate efficiency or breakthrough time of a single contaminant. However, gas mixtures are more complicated, and in most studies, mathematical modeling results and experimental results of the gas mixtures are not very consistent.
- Adsorbates with high boiling points are more competitive than adsorbates with low boiling points.
- With increasing relative humidity levels, adsorption efficiency of hydrophilic VOCs also increases, while adsorption efficiency of hydrophobic VOCs decreases.

**Acknowledgements**

The authors would like to acknowledge their appreciation for the support from TUBITAK-COST (Project no: 218M604).

## References

1. World Health Organization, "WHO Guidelines for Indoor Air Quality", 4 (2010).
2. Z. Shayegan, F. Haghighat, C.S., Lee, "Photocatalytic oxidation of volatile organic compounds for indoor environment applications: Three different scaled setups", CEJ, **357,** 533-546 (2019).
3. M.F., Yassin, A.M., Pillai, "Monitoring of volatile organic compounds in different schools: a determinant of the indoor air quality", IJEST, (2018).
4. S. Porkavosh, H. Marioryad, A. Jamshidi, S. A. Sadat, M.M. Baneshi, A. Mousavizadeh, World Family Medicine, **16,** 254-259. (2018).
5. X. Zhang, B. Gao, A.E. Creamer, C. Cao, Y., Li, "Adsorption of VOCs onto engineered carbon materials: A review", Jor. Haz. Mat. , **338,** 102-123 (2017)
6. J. Shuai, S. Kim, H. Ryu, J. Park, C.K. Lee, G. Kim, V. U. Ultra Jr., W. Yang, "Health risk assessment of volatile organic compounds exposure near Daegu dyeing industrial complex in South Korea", BMC Public Health., (2018).
7. V. Safari, "A Systematic Approach to Evaluating Gaseous Filter Models", Concordia University, M.Sc Thesis, (2011).
8. Z. Shayegan, C-S Lee, F.Haghighat, "$TiO_2$ photocatalyst for removal of volatile organic compounds in gas phase –A review" Chem. Eng. Jor. **334,** 2408-2439. (2018).
9. A.H.Mamaghani, F. Haghighat, C-S Lee, "Photocatalytic oxidation technology for indoor environment air purification: The state-of-the-art", Applied Catalysis B: Environment, **203,** 247-269. (2017).
10. H. Kholafei, "Indoor Air Contaminant Removal: Full-Scale Testing of In-duct Filters", M.Sc. Thesis, Concordia University (2009).
11. D.B. Henschel, "Cost Analysis of Activated Carbon Versus Photocatalytic Oxidation for Removing Organic Compounds from Indoor Air", J.A&W Man., (1998).
12. National Institute of Standards and Technology, NISTIR 7525, October, 2008.
13. L.W. Wang, R.Z. Wang, R.G. Oliveria, "A review on adsorption working pairs for refrigeration" Ren. & Sus. Rev., **13,** 518-534. (2009).
14. M.M. Younes, I.I. El-Sharkawy, A.E. Kabeel, B. B. Saha. "A review on adsorbent-adsorbate pairs for cooling applications", App. Ther. Eng. **114,** 394-414. (2017).

15. N.C. Sristava, I.W. Eames. “A review of adsorbents and adsorbates in solid–vapour adsorption heat pump systems”, App. Ther. Eng. **18,** 707-714. (1998)
16. A. Persily, C.Howard-Reed, S.Watson, N.Martys, E.Garboczi, H.Davis, NISTIR 7525: Standarts Development for Gas Phase Air Cleaning Equipment in Buildings, NIST, U.S. Deparment of Commerce (2008).
17. B.B. Saha, S. Koyama, I.I. El-Sharkawy, K. Habib, K. Srinivasan, P. Dutta, “Evaluation of adsorption parameters and heats of adsorption through desorption measurements”, Jor. Chem. and Eng. Data, **52,** 2419-2424. (2007).
18. M. Kılıç, E. Gönül, “Adsorption characteristics evaluation of R134A and R404A on different adsorbents.” Bulg. Jor. Chm. Com. **48,** 306-311. (2016).
19. Q.Xu, Y. Zhang, J., M., X., Li, “How to Select Adsorption Material for Removing Gas Phase Indoor Air Pollutants: A New Parameter and Approach”, Ind. Built Env. **22,** 30-38, (2013).
20. K. Han, J. S. Zhang, B. Guo, C. He, “Laboratory Comparison of Relative Performance of Gas Phase Filtration Media at High and Low $O_3$/$NO_2$ Challenge Concentrations (ASHRAE RP-1557)”, HVAC&R Research, 20, 522-531, (2014).
21. K., Owen, R. Pope, J. Hanley, “ASHRAE 145.2 Efficiency and Capacity Test Results for Five Gas-Phase Air Cleaners” ASHRAE Transactions, NY-14-C005. (2014).
22. C. Lee, J. Farant, F. Haghighat, B.Y.Talab, “Experimental Evaluation of the Performance of Gas-Phase Air Filters Using a Dynamic Closed-Loop Test System” ASHRAE Transactions, QC-06-040. (2006)
23. J. Pei, J. Zhang, W. Chen, B. Guo, “Modeling of sorbent-based gas filters: Development, verification and experimental validation”, ASHRAE Transactions. SL-08-046. (2008).
24. K.L. Foster, R.G. Fuerman, J. Economy, S.M. Larson, M.J. Rood, “Adsorption Characteristics of Trace Volatile Organic Compounds in Gas Streams onto Activated Carbon Fibers”, Chem. Mater. **4**, 1068-1073. (1992)
25. C.Nguyen, D.D. Do, “The Dubinin–Radushkevich equation and the underlying microscopic adsorption description”, Carbon. **39,** 1327-1336. (2001).
26. G. Wang, B. Dou, Z. Zhang, J. Wang, H. Liu, Z. Hao, “Adsorption of benzene, cyclohexane and hexane on ordered mesoporous carbon”, Jor. Env. Sciences. **30,** 65-73. (2015).
27. H. Kabrein, A. Hariri, A.M. Leman, N.M.R. Noraini, M.Z.M. Yusof, A. Afandi, “Impact of the air filtration on indoor particle concentration by using combination filters in offices building”, IOP Conference Series: Mat.Sc.Eng. 243 (2017).
28. F. Haghighat, C.S. Lee, G. Bolourani, “Improving HVAC system performance: towards the design of sustainable and dimmune buildings”, WIT Transactions on the Built Env. 94, 139-148. (2007).
29. F. Haghighat, C.s. Lee, B. Pant, G. Bolourani, N. Lakdawala, A. Bastani, “Evaluation of various activated carbons for air cleaning – Towards design of immune and sustainable buildings” Atmospheric Env. **42,** 8176-8184. (2008).