



Predicting gas-phase air-cleaning system efficiency at low concentration using high concentration results: Development of a framework



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ABSTRACT

Granular activated carbon filters (GAC) have been used for industrial air and water filtration for long time. This technology has recently been recommended for the design of energy-efficient and immune buildings. The existing standard recommends the test to be carried out at 100 ppm, which is for the accelerated tests but much higher than the actual contaminant concentrations in buildings. Therefore, there is a need to develop a framework to evaluate the performance of these technologies at low concentration using the available high concentration experimental data. This paper briefly reviews the existing methods for predicting the performance of granular activated carbon, and then suggests a procedure to estimate the performance of GAC for indoor air gas contaminants removal at low concentration using high concentration results. The method is based on the application of a set of isotherm and breakthrough models as a tool for extracting the data from higher concentrations and translating them into the low level concentrations. Results show that stoichiometric breakthrough times, the adsorption rate constants (in Wheeler–Jonas equation) and product constants (in Yoon–Nelson equation) do not strongly depend on concentration, demonstrating some indicators for simulating the experiments at indoor air level conditions.

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1. Introduction

The effectiveness of granular activated carbon filters (GAC) in air cleaners for the control of typical indoor concentrations of contaminants has been questioned for the past few years. The ASHRAE Standard 145.1 (2008) and ASHRAE Standard 145.2 (2010) specify a dynamic small-scale test method and full scale method for evaluating the performance of gaseous filters, respectively. The ASHRAE standard 145.1 is specified for loose granular media, and it is commonly used for testing and ranking different adsorbent media [1]. ASHRAE Standard 145.2 is proposed for the evaluation of the performance of full-scale in-duct gas-phase air cleaning device, can

be used to evaluate the impact of media, and medium holder designs, pleats or bypasses on the filter performance [2]. To reduce the experimental time, the ASHRAE Standards run at elevated concentrations. For example, ASHRAE Standard 145.1 recommends the test to be carried out at 100 ppm, which is ascribed to industrial emission concentrations but much higher than the actual contaminants concentration in buildings.

Quantification indexes of an activated carbon based filter (capacity, efficiency or breakthrough) depend on the filter features, such as the amount of carbon used and also the concentration of adsorbates. Both earlier laboratory and field measurements indicated that by increasing the level of concentration the time to reach the specific point of breakthrough (40%, 50% or 100% or saturated point) will decrease [3–11].

Table 1 lists the breakthrough times of VOC adsorption on activated carbon (AC). It is mentioned that the life spans of GAC adsorption devices range from a few month to several years, based on anecdotal field experience and extrapolations of laboratory studies. Conversely, the measured breakthrough times in accelerated tests (ppm levels) ranged from about 2 h to several hundred hours. Very limited information is available to assess the feasibility of a systematic method for estimating the useful life of

Abbreviations: ASHRAE, American Society of Heating, Refrigeration, and Air-Conditioning Engineers; VOC, Volatile Organic Compound; ppmv, Parts Per Million by Volume; ppbv, Parts Per Billion by Volume; GAC, Granular Activated Carbon; ACF, Activated Carbon Fiber; MEK, Methyl Ethyl Ketone; HVAC, Heat, Ventilation, and Air Conditioning; IAQ, Indoor Air Quality.

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Table 1
VOC adsorption tests in the literature.

Reference	Test method/Flow rate	Sorbent/Specification	Compound/Concentration	Lifetime/Breakthrough%
Graham et al., 1990 [3]	Full-scale/30000; 56000 (cfm)	GAC/1872; 3495 (lbs.)	Benzene/12.8; 45.5 (ppb)	>7months; 3years/100%
Liu 1990 [4]	Full-scale/2000 (cfm)	Coconut-based AC/ 90 (lbs.)	Decane/0.2; 15 (ppm)	30 (h)/3%; 100 (h)/100%
Foster 1992 [5]	Small-scale/60 (mL/min)	AC fiber-15/NR ^a	Heptane/0.5–118 (ppm)	20 (h)/4%; 7 (h)/100%
VanOsdell et al., 1996 [6]	Small-scale/25.6 (L/min)	GAC (VA)/25 (g)	Benzene/10.3 (ppmv)	75 (h)/100%
Huang et al., 2003 [7]	Small-scale/60 (mL/min)	AC fiber-14/0.2 (g)	Acetone/56.5 (ppmv)	100 (h)/100%
Cheng 2008 [8]	Small-scale/1.3 (L/min)	GAC/NR	Toluene/0.44–71.7 (ppm)	800–13 (h)/40%
Bastani et al., 2009 [9]	Full-scale/0.93 (m ³ /s)	GAC (VA)/NR	1,1-DCE/0.1–1000 (ppm)	73–2 (h)/50%
Shiue et al., 2010 [10]	Small-scale/0.076–0.152 (m/s)	GAC (IAA-VB)/NR	MEK/50; 250; 1000 (ppm)	20; 10; 2.7 (h)/100%
Safari 2011 [11]	Small-scale/30 (L/min)	Coconut shell AC/2 (g)	Benzene/50; 250; 1000 (ppm)	25; 9.2; 2.8 (h)/100%
		GAC/25 (g)	Toluene/102–2652 (ppm)	15–1 (h)/100%
			Toluene/4(ppm)	30 (h)/50%
			Toluene/10–70 (ppm)	95 (h)/50%
			MEK/100 (ppm)	15–3 (h)/100%
			n-hexane/100 (ppm)	12 (h)/100%
				15 (h)/100%

^a NR: not reported.

a gaseous filter in a large range of concentrations. These results also confirm that the proposed ASHRAE standards could be used for ranking the filters and/or investigating the impact of different design and/or media on the filter's performance, but they are not practical to be used to investigate the performance of filters when they are exposed to lower level of contaminant concentration that can be found in actual applications. Therefore, there is a need to develop a procedure to predict the performance of gas-phase filters when they are challenged with contaminant level that can actually be found in indoor environment using the ASHRAE standard methods.

This paper first gives a brief review of the fundamentals of mass transfer in porous media, the governing equations and the influential parameters involved in comparison of adsorption mechanism in terms of concentration level. It then, reports the outcomes of a comprehensive literature review of the existing analytical and empirical models to estimate the gas-phase filter breakthrough time, and it finally proposes a procedure to estimate the breakthrough time/performance of a filter at low concentration using the experimental results from high concentration.

2. Existing models

2.1. Mass transport modeling

As depicted in Fig. 1, the mass transfer between gas phase (bulk air) and solid phase (sorption filter media) in a bed containing porous material occurs at different stages [12]:

- 1 External diffusion of the contaminant through air-phase boundary layers separating the sorbent's exposed surface from the bulk air-phase. The total contaminant transfer through the filter and the convection from the bulk air to the adsorbent's boundary layer equals the rate of storage change

$$w_a C - w_a C_0 + K_h (C - C^*) = -M_a \frac{dC}{dt} \quad (1)$$

where C_0 , C and C^* are the air-phase concentrations at the filter's inlet, of the bulk and near-surface locations, respectively (g/m^3); w_a is the supply airflow rate (g air s^{-1}); M_a is the mass of air (g); $K_h = \rho_{air} A_s h_m$ represents the boundary layer mass transfer rate (g air/s); A_s is the exposed sorbent surface area (m^2); ρ_{air} is the air

phase density ($\text{g air}/\text{m}^3$), and h_m is the surface-average mass transfer coefficient (m s^{-1});

- 2 Internal diffusion of the contaminant molecules from hypothetical air layer into the active sites of the sorbents. This type of phenomenon can be described by Fick's law of diffusion within the granules of sorption filtration, or the linear driving force (LDF) model, which is simpler but less accurate [13,14]. The rate of contaminant concentration change in the pellets (the sorbed-phase) is equal to the rate of contaminant diffusion from the hypothetical layer to the pores:

$$K_D (C^* - C_p) = M_s \frac{dC_s}{dt} \quad (2)$$

where C_p is air-phase concentration within the pores ($\text{g}/\text{g air}$); C_s is adsorbate concentration in solid phase (sorbed-phase concentration) ($\text{g}/\text{g solid}$); M_s is the mass of sorbent available (g); r_p is the sorbent granule radius (m); D_e is the effective diffusivity (m^2/s), $K_D = 15M_s D_e K_T / r_p^2$ characterizes the pore diffusion rate (g air/s) and K_T is the tangent slope of adsorption isotherm ($\text{g air}/\text{g sorbate}$) [12].

As a boundary condition, the diffusion rate from the hypothetical air phase layer to the pores is equal to the convection from the bulk to the hypothetical air phase layer:

$$K_D (C^* - C_p) = K_h (C - C^*) \quad (3)$$

After substitution of C^* , the two basic mass balance equations for a gaseous filter are obtained:

$$w_a C - w_a C_0 + \frac{K_h \cdot K_D}{K_h + K_D} (C - C_p) = -M_a \frac{dC}{dt} \quad (4)$$

$$\frac{K_D K_h}{K_D + K_h} (C - C_p) = M_s \frac{dC_s}{dt} \quad (5)$$

- 3 Adsorption of the sorbate on specific active sites. The adsorption step is very rapid for physical adsorption, and as a result, one of the preceding diffusion steps controls the rate of adsorption to filter. Assuming equilibrium between the air phase and the sorbed phase at a constant temperature, the adsorption isotherm is considered between the sorbed-phase concentration and the air. After identifying an appropriate isotherm equation, the system of equations ((4) and (5)) can be

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