Building and Environment 75 (2014) 1–10

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Gas-phase filters breakthrough models at low concentration – Effect of relative humidity

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ARTICLE INFO

Article history:
Received 31 October 2013
Received in revised form
30 December 2013
Accepted 17 January 2014

Keywords:
Relative humidity
Breakthrough
VOC
Model
Gas-phase filter

ABSTRACT

Indoor air quality (IAQ) is a major concern in non-industrial buildings since it influences occupants' health, comfort and productivity. Adsorption-based granular activated carbon (GAC) filters are commonly being used to purify indoor air by removing indoor air pollutants. Predicting the breakthrough time of filters is necessary for scheduling their maintenance and/or regeneration. However, the pollutants' concentrations that typically encounter in indoor environment are very low thus increasing the influence of humidity on the filter performance. Also, the existing standard recommends the test to be carried out at 100 ppm, which is much higher than the actual volatile organic compounds (VOC) concentration in buildings. This paper reports the development of a framework for predicting the breakthrough curve of activated carbon filters at low concentration and different levels of relative humidity applying accelerated test data. The procedure is based on two well-known empirical models: Wheeler–Jonas and Yoon–Nelson equations. The overall mass transfer coefficient in the Wheeler–Jonas equation and the proportionality constant in the Yoon–Nelson equation (both as a function of adsorption capacity) are a function of humidity level. Results show that the proposed framework allows the breakthrough time at humid condition and low contaminant concentration to be estimated using the data obtained from the existing standard test procedure.

1. Introduction

Predicting the breakthrough time (BT) of filters is necessary for scheduling their maintenance, regenerating and/or replacement. One approach to predict the breakthrough time is to develop correlation among the influential parameters using the experimental data taking into consideration the effect of environmental parameters. In this way, the developed model can be applied to provide the user with the information for estimating the filter performance under conditions of actual use. Recently, a framework was proposed for predicting the dynamic performance of granular activated carbon (GAC) filters at dry conditions; see Fig. 1 [1]. Two approaches were proposed where in the first approach the value of 50% breakthrough time (τ) corresponding to the Yoon–Nelson equation was estimated from either the linear function of inlet concentration (Method 1) or the 10% breakthrough time ($t_{b,10\%}$) (Method 2); and in the second approach the value of adsorption capacity corresponding to the Wheeler–Jonas equation was obtained from the extrapolated value of validated adsorption isotherm fitted to the experimental data (Method 3). Both parameters were later used to predict the breakthrough curve at low levels of concentration. It was demonstrated that the proposed framework can predict with a good accuracy in the range of 15–300 ppm concentration. However, further research is needed to verify the applicability of the proposed model in the lower range of concentration where relative humidity could play an important role on the filter performance.

Although the air containing the organic vapor is seldom free of water vapor, most of the earlier studies on the development of predictive breakthrough models focused on dry air conditions [1–6]. Therefore, in order to generalize the methodology there is a need to study the effects of humidity on the influencing parameters. Previous experimental studies show that adsorption capacity decreases with increasing relative humidity (RH) particularly at higher range of RH [7–10]. This can be explained by the capillary condensation effect of water vapor, at the active sites, on the surface of the micropore in view of Kelvin equation [11]. Further, it was reported that adsorption of organic vapors, water-soluble and insoluble compounds, behave differently under humid conditions

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http://dx.doi.org/10.1016/j.buildenv.2014.01.010

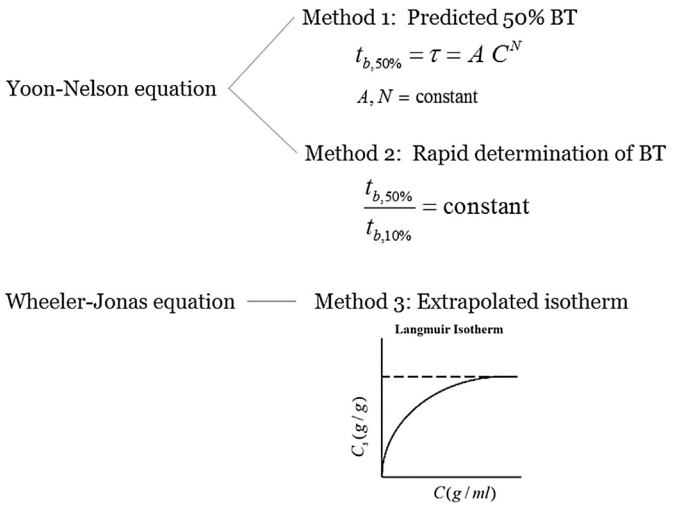

Fig. 1. Different pathways for quantification of breakthrough time at low concentrations using Wheeler–Jonas and Yoon–Nelson equation.

[12,13]. Cooperative adsorption takes place between hydrophilic volatile organic compounds (VOCs) and water vapor up to certain humidity levels while there is always competitive adsorption for hydrophobic ones [14].

However, few studies considered the effect of VOCs concentration level in their studies. Some studies mentioned that the RH effect is more pronounced at the lower adsorbate concentrations than at the higher concentrations [15–18] while they did not suggest any practical and/or procedure to demonstrate the effect of concentration change at different RH levels.

This paper first gives a brief review of adsorption isotherms, breakthrough predictors, their parameters and the effect of environmental conditions on each term. It then, reports the outcomes of a series of experiments which were carried out on a small-scale setup for a large range of concentrations, and finally proposes a procedure to estimate the filter breakthrough time/performance at low concentration using the experimental results from high concentration and different relative humidity levels.

2. Models

2.1. Isotherm models

Adsorption isotherm relates the sorbed-phase concentration (capacity) to the air-phase concentration. There are various models to describe this relation (type I to V based on Brunauer's classification). Axley [19] stated that for sorption of air pollutant in building materials, Langmuir and Linear models are the most appropriate choices. For sorption of any gas phase pollutants, if its concentration is within one order of magnitude of its saturated value, the BET model should be used. D–R and Freundlich models are used for industrial sorbents which show nonlinear equilibrium behavior [1,19]. Table 1 summarizes the linearized form of aforementioned isotherms and their parameters.

2.2. Breakthrough models

The three methods mentioned in the framework integrate the application of two well-known empirical equations, see Fig. 1. A careful examination of these methods shows that each equation may be expressed as $t = X + YZ$. The corresponding terms are presented in Table 2.

X and Z terms are the same in both Yoon–Nelson and Wheeler–Jones equations while Y term is defined as $M/k'Q$ in the Yoon's equation and as ρ_b/k_v in the Wheeler's equation. Consistent with the preceding discussion, the only difference observed in the theoretical breakthrough models is attributed to the Y terms.

2.3. Investigation of parameters

From the earlier developed framework (Fig. 1), it can be seen that there are four criteria which indicate the independency or weak dependency of the breakthrough time with the concentration. Detailed information of these indicators is necessary in order to generalize the application of the developed framework.

1) Mass transfer coefficient (K_v and k)

It was experimentally explored that K_v in the Wheeler–Jonas equation and k ($k = k'\tau$) in the Yoon–Nelson equation, are weak function of inlet concentration [1]. This conclusion is in conformity with Lodewyckx and Vansant's developed equation for K_v in which it is a function of both adsorbent (size and capacity) and adsorbate (molecular weight and similarity coefficient) characteristics [20]:

$$K_v = \frac{800\beta^{0.33}u^{0.75}}{d_p^{1.5}}\sqrt{\frac{C_{se}}{MW}} \quad (1)$$

where d_p is the mean adsorbent size, u is the linear velocity, and β is the similarity coefficient in the D–R equation. As long as the same medium is used as sorbent and the same compound is used as adsorbate, these properties remain constant. Also it is reported that [5]:

Table 1
Representative adsorption isotherm models.

Model	$C_{se} = f(C_e)$	Model parameters[a]
Linear	$C_{se} = K_p C_e$	K_p is the partition or distribution coefficient or Henry's constant
Langmuir	$\frac{C_e}{C_{se}} = \frac{1}{C_{s_0}K_L} + \left(\frac{1}{C_{s_0}}\right)C_e$	C_{s_0} is the maximum adsorption capacity (mg/g) and K_L is the affinity constant (m^3/mg)
Freundlich	$\ln C_{se} = \ln K_f + \frac{1}{n}C_e$	n is Freundlich exponent and K_f is Freundlich constant.
Dubinin–Radushkevich (D–R)	$C_{se} = C'_{s_0}\exp^{-D\left[\left(RT\ln\left(\frac{P_0}{P}\right)\right)^2\right]}$	C'_{s_0} is the maximum capacity available for the adsorbate (mg/g); D is the microporosity constant (mL/J)
Brunauer, Emmett, and Teller (BET)	$\frac{(P/P_0)}{C_{se}(1-P/P_0)} = \frac{1}{cC''_{s_0}} + \frac{c-1}{cC''_{s_0}}(P/P_0)$	c is a dimensionless constant; C''_{s_0} is the amount of sorbent (capacity) required to form a monolayer of the adsorbate (mg/g)

[a] C_e is the equilibrium air-phase concentration within the pores (mg/m^3_{air}), C_{se} is the equilibrium adsorbate concentration in solid phase (adsorption capacity or sorbed-phase concentration) (mg/g_{solid}), R is the universal gas constant (8.314 J/(mole K)); T is the absolute temperature of the system; P_0 is the sorbate saturation vapor pressure at temperature T, and P is the partial pressure of the sorbate in the gas.