

ACTIVATED CARBON FILTERS USED IN RESIDENTIAL AND OFFICE BUILDINGS APPLICATIONS

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ABSTRACT

During the past half century, filtration techniques based on the use of activated carbons have been widely used in industrial applications, and considerable knowledge about the mass transfer processes involved has been developed. Surprisingly, the use of activated carbon filters in building applications has remained marginal, and one reason is probably the lack of information on the actual efficiency of such systems in realistic configurations of building operation. In the present paper, models combining advection, sorption and diffusion in a porous medium were implemented in the Matlab/Simulink environment to simulate the dynamic behavior of an integrated building/HVAC with activated-carbon filter system. Another application concerns in the implementation of the activated carbon in a portable air cleaning device. The aim of the simulations was to study the ability of the filter to improve the indoor air quality of the residential and office-like buildings located in urban areas. Several configurations were tested with real weather data taking into account the effect of humidity on the adsorption process and also the variation of exterior temperature. The simulations show good results only

when the filter is purged during the night, when it is introduced in a HVAC system. The other configurations show little interest compared to the case when there's no activated carbon filter in use.

1.INTRODUCTION

The past decades of indoor air quality research has placed a central emphasis on source-control, ventilation (dilution), and particle-filtration control strategies to mitigate indoor air problems. Multizone contaminant dispersal and airflow analysis tools have been developed to evaluate the efficiency of these strategies and, thereby, help designers attempting to implement them. In recent years, attention has turned to the possibility of using sorption filtration devices, specifically, activated carbon air cleaning systems to improve IAQ.

Modelling has the advantage to provide a large number of results within a short-time, as well as to propose an explanation to the phenomena observed. Yu and Neretnieks (1993) and Axley (1994) first proposed this method; they modelled the sorption dynamics of contaminants from the assembly of elemental models

representing 1) advection through the filter, 2) boundary layer diffusion at the surface of the activated-carbon grains, 3) diffusion through the macro-pores of the adsorbent, and finally 4) adsorption / desorption processes within the micro-pores. These models were first extended by adding low-concentration multicomponent sorption capacities, and subsequently validated from experimental data (Blondeau et al, 2005; Popescu et al, 2007). Then, simulations considering the real pollution and weather data of Rome (Italy) were carried out to analyse the benefits of using activated-carbon filters in office-like buildings (discontinuous occupancy) located in heavily-polluted urban areas. The emphasis was put on analysing the influence of 1) the location of the filter in the HVAC system, 2) a night purge of the filter, 3) the competition between species for the sorption sites, on the efficiency of the system and 4) relative humidity influence.

2.MODELS

The model used in this paper takes into account the elemental models for the activated carbon filter, the building and the mixing box of the HVAC system. These models were implemented in the Matlab/Simulink environment to simulate the behaviour of the integrated building, HVAC and activated-carbon filter system.

3.FILTER MODEL

The adsorption model for the filter has been developed based on the works of Axley (1994) and Yu and Neretnieks (1993). These studies consider that sorption dynamics in the activated carbon filter is governed by the following elemental transport phenomena: advective transports (pollutant carried by the air through the filter), boundary layer diffusion, porous diffusion and adsorption / desorption in the pore surface. These low concentration models as well as their validation are described in detail by Popescu et al. 2007, for dry isothermal conditions. In the present paper the humidity is modelled using cooperative multimolecular

sorption (CMMS) which is using in fact a pseudo Langmuir model (more details in Popescu et al. 2008).

Using the models presented by Axley (1994) and adding a new parameter ε_r which takes into account the recirculation flow between the filter cells (instead of the axial turbulent diffusion), the equations can be described as following:

$$\begin{cases} M_{a1} \frac{dC_1}{dt} = w_a C_0 - w_d (1 + \varepsilon_r) C_1 + w_a \varepsilon_r C_2 - \frac{K_d K_h}{K_d + K_h} [C_1 - f^{-1}(C_{s1})] \\ M_{ai} \frac{dC_i}{dt} = w_a (1 + \varepsilon_r) C_{i-1} - w_d (1 + 2\varepsilon_r) C_i + w_a \varepsilon_r C_{i+1} - \frac{K_d K_h}{K_d + K_h} [C_i - f^{-1}(C_{si})] \\ M_{an} \frac{dC_n}{dt} = w_a (1 + \varepsilon_r) C_{n-1} - w_d (1 + \varepsilon_r) C_n - \frac{K_d K_h}{K_d + K_h} [C_n - f^{-1}(C_{sn})] \end{cases}$$

for $i=2, n-1$

(1)

$$M_{si} \frac{dC_{si}}{dt} = \frac{K_d K_h}{K_d + K_h} [C_i - f^{-1}(C_{si})],$$

For the bulk air phase, the first three equations describe the mass balance for the first, intermediary and last cell of the discretized activated carbon filter. To correctly account for the concentration gradients in the direction of the airflow the filter is decomposed into n elementary cells connected in series (Figure 1). In these equations the unknown parameters are C_i (kg/kgair) the inter-pellet concentration and C_{si} (kg/kgair) sorbed phase concentration, C_i^* (kg/kgair) being boundary layer concentration and C_{pi} (kg/kgair) pore air phase concentration. All these concentrations are assumed to be uniform within the elementary cell but different from one cell to another. M_{si} (kg) and M_{ai} (kg) represents the mass of activated carbon and the inter-pellet mass of air within the filter respectively; w_a (kg_{air}/s) air flow rate through the filter, C_0 (kg/kg_{air}) the inlet concentration of the filter; $K_h = \rho_{air} A_s h_m$ and $K_d = 15 M_s D_p \sigma / R^2$, with σ being the slope of the adsorption isotherm at concentration C_p , , represent the boundary layer diffusion rate and the diffusion rate in the pores of the pellets, respectively. Each of the filter cells described by equations (1) was implemented as a mass transport component using the dynamic system simulation environment Matlab/Simulink.

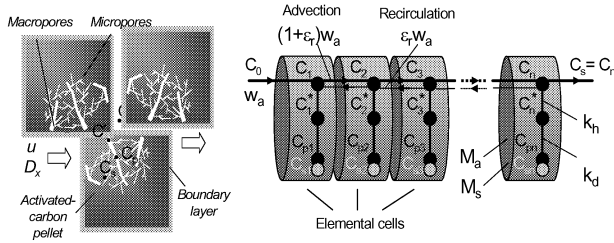


Figure 1. Schematic representation of the discrete filtering medium

Dubinin / Radushkevitch isotherm is widely used in industrial applications because of its predictive capacities (the gas parameters are easily predicted using a reference compound), but for many indoor air studies is not suitable because of failing to describe the behavior of the filter at concentrations close to zero. To solve this problem, the simulations presented hereafter were carried out using an extended Langmuir isotherm coupled with «cooperative multimolecular sorption» CMMS model for the humidity (see Popescu et al. 2008).

4. CMMS THEORY

The CMMS theory applied for activated carbons is based on the assumption that water vapors is behaving like the other contaminants within the adsorbent, meaning that is competing with the other species at the pore surfaces of the adsorbent.

For every species in the mixture, the transport equations are represented by equation (1) and coupled to each other by the extended Langmuir isotherm that relates the sorbed-phase concentration of a given species i to the air-phase concentrations of all components n in the contaminant mixture through the relation:

$$C_{si} = f(C_{pk,k=1,n}) = \frac{C_{si}^0 K_{Li} C_{pi}}{1 + \sum_{k=1}^n K_{Lk} C_{pk}} \quad \text{for } i = 1, n \quad (2)$$

where C_{si}^0 ($\text{kg} \cdot \text{kg}^{-1}$) and K_{Li} ($\text{kg}_{\text{air}} \cdot \text{kg}^{-1}$) are the Langmuir equation parameters for the individual species.

Water vapor unlike VOCs do not follow a Langmuir behavior concerning the inflections of the isotherm (usually having a type V isotherm according to BET classification compared to type I like VOCs). Using CMMS theory which is able to describe most of the isotherm types, a type V isotherm is described with the relation:

$$C_s = C_{sat} \frac{K_L \cdot x}{1 + K_L \cdot x} \quad (3)$$

where C_{sat} ($\text{kg}/\text{kg}_{\text{air}}$) is the air-phase concentration at saturation, and K_L depends on relative humidity, $x = C_p/C_{sat}$, as well as dimensionless constants K_0 , K_1 through the equations:

$$K_L = \frac{K_0}{w^2} \quad (4)$$

and

$$w = \frac{1}{2} \left(1 - K_1 \cdot x + \sqrt{(1 - K_1 \cdot x)^2 + 4 \cdot K_0 \cdot x} \right), \quad (5)$$

The parameters needed by CMMS model K_0 , K_1 and C_{sat} are determined by fitting the model with the experimental data of water vapor on the studied activated carbon called NC35.

When dealing with mixtures of n compounds in the air the same transport equations were used (equations 1), resulting $2n$ differential equations to solve. These equations are coupled by extended Langmuir isotherm for all the contaminants, only the humidity having the particular case of a Langmuir constant variable, K_L (equation 3) as a function of relative humidity.

In all cases the concentration gradient in the flow direction is modeled used so-called tanks in series method: if the filter length is l (m) and section A_{filter} , the serial connected cells are represented by 50 cells with $l/50$ length of same section.

5. ROOM MODEL

The whole building is modelled as a well-mixed single zone. The contribution of possible chemical reactions is not considered and the sorption processes at the wall surfaces are assumed to follow a linear behaviour. If assuming furthermore that the sorbed-phase concentration is always in equilibrium with the room bulk air-phase concentration (no boundary layer resistance), the mass conservation equation of the contaminant investigated may be described by the following equation:

$$(\rho V + A_{wall} K_p) \frac{dC_{build}}{dt} = w_{sup} (C_{sup} - C_{build}) + S \quad (6)$$

where V (m^3) is the building volume, A_{wall} (m^2) the total surface area of the walls, K_p (kg_{air}/m^2) the partition coefficient of the wall/contaminant system, C_{build} (kg/kg_{air}) the indoor contaminant concentration, S (kg/s) the internal emission rate of the contaminant, and w_{sup} (kg_{air}/s) and C_{sup} (kg/kg_{air}) the supply airflow rate (air intake) and concentration, respectively.

6. SIMULATIONS

The simulated office-like building is a virtual one with a volume of $3600 m^3$ located in Rome. The hourly-averaged outdoor concentrations of toluene, benzene and o-xylene measured by Brocco et al (1997) were used as inputs of the models. Typical outdoor temperature and relative humidity profiles for summer in Rome were generated using the TRNSYS-type 54 weather data generator. The outdoor concentration, temperature and humidity data were repeated several times to initialise the model. The results are presented using two time scales: indoor concentrations presented in steady state conditions during a day and the transitory one till saturation for each compound modelled. The airchange rate and supply airflow rate of the rooms are $w_{out} = 1800 m^3/h$ and $w_{sup} = 9000 m^3/h$, respectively. The granular activated-carbon filter considered is made up of

1,1 mm spherical grains (type CECA named NC35).

Table 1 : Model parameters for studied compounds

Species	M [g/mol]	$K_p^{(2)}$ [kg/m ²]	Ms [g]	Ma [g]	$h^{(1)}$ [m/s]	A_{wall} [m ²]
Toluene	92	3.45	7000	18	0.040	1500
Benzene	78	2.26			0.045	
o-xylene	106	4.63			0.038	
Water vapour	18	1.1			0.093	

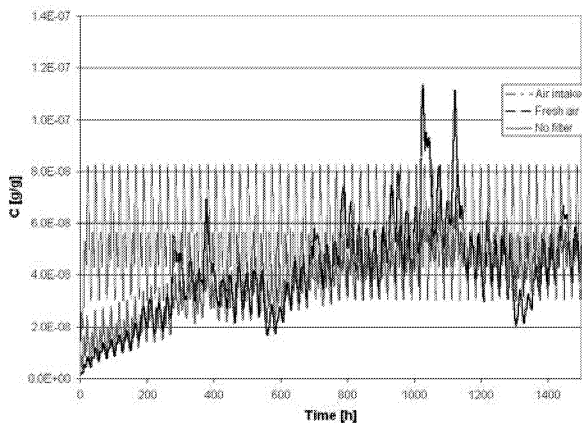
⁽¹⁾ The surface mass transfer coefficient is determined using Ranz- Marschall (after Yang 1987) equation, having the same value for the air flows of $9000 m^3/h$ and $1800 m^3/h$ by varying the cross section from $2.5 m^2$ to $0.5 m^2$.

⁽²⁾ Extrapolated from data of Tiffonnet et al (2002) by considering a linear correlation between partition coefficient and molecular weight.

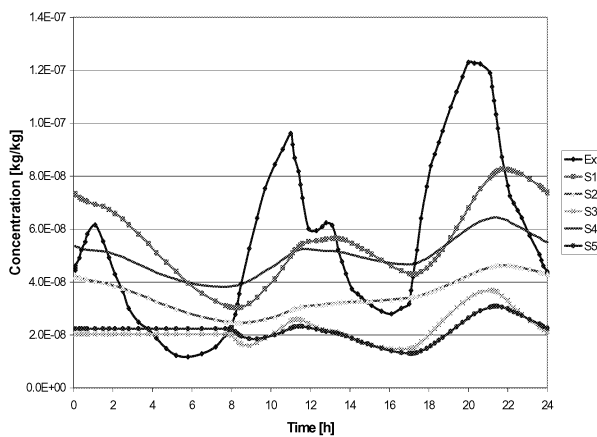
The simulations take into account different locations of the filter in the HVAC system and in some cases night purge of the filter (from 0 to 8am if it's the case). The inlet temperatures and relative humidities are either exterior ones when it's placed on the fresh air intake or constant when placed on air intake according to table 2.

Table 2: Description of the simulations

Simulation	Location of the filter (w_a)	Temperature	Night purge
S1	No filter	Outdoor summer	No
S2	Fresh air (1800 m ³ /h)	Outdoor summer	No
S3	Fresh air (1800 m ³ /h)	Outdoor summer	Yes
S4	Air intake (9000 m ³ /h)	15°C constant	No
S5	Air intake (9000 m ³ /h)	15°C constant	Yes



a)



b)

Figure 2: a) Evolution of interior concentrations of toluene as a function of filter placement;
b) Interior concentrations of toluene in steady state conditions

In figure 2a it can be observed in the case of toluene that only in about 1000 hours the filter is reaching saturation (same case for benzene but not for o-xylene which doesn't reach saturation during that period of time). If it's placed on fresh air, sometimes the concentrations show to be higher when using the filter than without one because of a possible desorption caused by summer time temperatures. The profiles from figure 2b have the lowest values as expected for the two investigated cases with night purge (case S3 and S5) compared to the reference case S1 (without filter). Whatever the location of the filter, supply temperature and relative humidity, the

result is a delay and a damping of the concentration profiles indoors (see S1 vs S2 or S4).

The comparison of mean concentrations (see figure 3) considered for S1 and S3 or S5 show that using the filter with night purge can reduce by 58%, 45% and 56% maximum concentrations and 52%, 44% and 51% the mean concentrations of toluene, benzene and o-xylene.

It should be mentioned concerning the purge that during the night, between 0-8h when the office is not occupied, the activated carbon filter is purged at a temperature of 50°C. This purge is done by desorbing the filter without introducing the air inside the building, that's why the inside concentrations shown in figure 1b are constant in that interval of time.

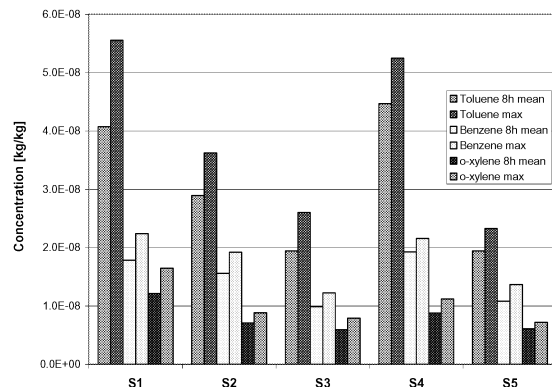


Figure 3: Maximum and mean concentrations during the 8h working period

7.CONCLUSION

The objective of the paper was to investigate the ability of an activated carbon filters to reduce outdoor concentrations from an urban polluted city. The models include the multicomponent implementation as well as the influence of humidity, using variable temperatures, humidities and concentrations. The results show that the activated carbon filter is able to improve significantly the IAQ if it is thermally purged during the night, involving additional energy into the system or operation cost for the building. An interesting post study for the paper might be a night purge using solar pannels for such an application. Also the results prove a

different behavior of the filter while operating on fresh air or intake air, that's why an optimal configuration is needed (mass of adsorbent, cross section flow, desorption temperatures,...).

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