New York State Energy Research and Development Authority

Air Cleaning Technologies for Indoor Air Quality (ACT-IAQ): Growing Fresh and Clean Air

Final Report

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Air Cleaning Technologies for Indoor Air Quality (ACT-IAQ): Growing Fresh and Clean Air

Final Report

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NOTICE

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EXECUTIVE SUMMARY

People on average spend about 90% of their time indoors. The quality of air in office, residential, school, and industrial buildings can significantly affect the health and productivity of building occupants. It has been estimated that the potential productivity gain through improved IAQ are over $40 billion to $250 billion per year in the U.S.

The Wolverton air filtration system is a NASA research based spinoff technology that uses a plant root bed of activated carbon, porous shale pebbles, microbes, and a wet scrubber to remove VOCs from the air in tightly sealed buildings. The VOCs removed are converted to a food source for indoor plants that offer a green and natural environment indoors. The microbes that are responsible for the conversion can quickly reactivate the carbon so that it does not need to be replaced, unlike the typical carbon filters used for air cleaning, which need to be replaced every 3-6 months.

A prototype device was developed by Phytofilter Technologies, Inc. and improved by BEESL based on the Wolverton filtration technology for use in residential or commercial HVAC systems. In the prototype, air is pumped through the plant root bed via three imbedded manifold tubes. The VOCs are trapped by the mixture of activated carbon and moist porous shale pebbles that also act as a wet scrubber for many light compounds such as formaldehyde, acetaldehyde, and other low molecular weight aldehydes and ketones. The microbes formed by the root system of Golden Pothos convert the adsorbed VOCs into a food source for the plants, and thus cleanse the filter bed. While the filtration technology has been proven for its principle, its successful engineering application requires testing, evaluation, and demonstration to answer several important questions including:

1) How much clean air can the device provide on a continuous base with its current design?

2) How does the cleaning performance vary with the airflow rate and humidity conditions in the plant root bed?

3) What is the long term performance of the device at typical indoor environmental applications?

4) How much energy can be saved in a typical office building while maintaining high indoor air quality?

5) How can the device be incorporated into existing HVAC system while achieving high system performance?

The objectives of this project were to: 1) determine the single pass efficiency of the filter in removing both water soluble and non-soluble VOCs and the equivalent clean air delivery rate (CADR) under a relatively

high pollutant level (full-scale test chamber), as well as at a typical room level (a newly constructed office room); 2) evaluate the long-term performance in the real-world environment by monitoring its single pass efficiency for 10 months; 3) investigate the effect of moisture content in the root bed on the toluene and formaldehyde removal performance, and determine the best moisture content range for removing both water soluble and insoluble compounds; 4) investigate the possible effect the DBAF may bring to the indoor air temperature and relative humidity (RH); 5) estimate the potential benefit in building energy saving due to the use of the botanical air filter; 6) develop a numerical model to improve the understanding of the mechanism of the DBAF and optimize the design.

These objectives were achieved through the following specific tasks:

1) Determination of the performance of the prototype device for its ability to remove toluene(a compound widely used as a reference for TVOC)and formaldehyde (an important indoor VOC pollutant) for different flow rates(300-600CFM), humidity in the plant root bed (20-52% volumetric water content), and carbon to shale pebble ratio of 50/50. This was performed by using the full-scale IEQ chamber of BEESL/SU (16 ft x 12 ft by 10 ft high).

2) Improvement of the design of the prototype system by introducing a new auto-irrigation system.

3) Integration of the improved prototype device in the HVAC system for performance demonstration in the new ICUBE (intelligent cubical environments) on the third floor of Link Hall.

4) Monitoring of the performance of the device for over ten months and disseminate the results so as to help with the adoption of this technology into the market place.

5) Conduction of whole building energy simulation to determine the energy saving that can be achieved by using the air filtration device for an office building at cold climate conditions ,such as Syracuse, N.Y. This was performed by using the DesignBuilder/EnergyPlus simulation software.

6) Improve the in-house CHAMPS-BES (a model for coupled heat, air, moisture, and pollutant simulation) to account for the effects of microbes in the bio-filter system.

The potential use of plants for removing indoor VOCs has been demonstrated. Although potted plants alone are not efficient in real-world condition, the dynamic botanical air filtration system (DBAF) studied is very promising based on the laboratory evaluation and real-field demonstration.

Major findings from this research project are:

1) The full-scale chamber experimental results indicated that the DBAF had high initial removal efficiency for formaldehyde and toluene even without plants in the bed. With the plants, the filter system had even higher initial removal efficiency (90% for formaldehyde in the first four days, and over 33% for toluene). Still, it was not clear if the microbes played any role in such a short term test period. The long-term performance test results indicated that the DBAF were effective over a test period of 300 days, and the same level of single pass removal efficiency was maintained at the end of the test. This indicated the possible consumption of the VOCs by the microbes as suggested by Wolverton et al. [20]. Nevertheless, further study is needed to investigate the type of microbes that are responsible for the VOCs removal/degradation, and the rate of degradation. More detailed and carefully controlled laboratory experiments are needed to separate the adsorption, absorption, and microbe degradation processes involved in the DBAF root bed to improve the understanding and to develop a simulation model that can be used to optimize the DBAF design.

2) The operation of the DBAF resulted in 1 ^{o}C temperature decrease and 9–13% RH increase in the chamber air. In the office experiments, the operation of DBAF resulted in 0.5 ^{o}C temperature decrease and 17.7% RH increase. The moisture production rate due to the use of DBAF was in the range of 0.81–1.89 kg/h. Such moisture generation would improve the thermal comfort condition in winter, while in summer it would contribute to negligible effects on thermal comfort and cooling load.

3) In the long-term field demonstration test, it was found that 5% outdoor air plus the operation of the biofilter could achieve the same room formaldehyde/toluene concentration as having ventilation with 25% outdoor air. In other words, with the use of the bio-filter, the ventilation rate can be reduced from 25% to 5% of total air supply without adversely affecting the indoor air quality if formaldehyde and toluene are the target pollutants that dictate the required ventilation rate.

4) It was also found that bed water content had a positive effect on formaldehyde removal while a negative effect on the toluene removal in the field test. The single pass removal efficiencies were approximately 70% for formaldehyde and 40% for toluene when the volumetric water content was within the range of 5% to 32% in the root bed (corresponding to air relative humidity from 74% to 82% RH). Note that since only part of the total supply air was directed through the filter bed, the effects of the bio-filter operation on the indoor relative humidity was not significant (<15 %RH increase).

5) The single pass efficiency for formaldehyde and toluene did not show any significant decrease over a period of 300 days of continuous operation, indicating good long-term performance of the bio-filter system, although the role of microbes in sustaining the performance is yet to be determined.

6) Whole building energy simulation results showed that using the DBAF to substitute 20% of the outdoor air supply without adversely affecting the IAQ could save 10–15% in annual energy consumption for Syracuse climate, including 26% saving in heating, 2% in cooling and 1% in ventilation energy consumption. It is expected that a higher percentage of energy savings would be achieved for climate zones where more heating is required than Syracuse climate. Further simulations for different U.S. climate zones are needed to provide more quantitative results on applicability and energy saving potentials for a wider range of climate and air quality conditions.

7) A numerical model has been developed and implemented using the CHAMPS-BES to improve the understanding of the transport and bio-degradation processes involved in the DBAF. Assumptions and mathematical equations used to model the processes involved in a botanical air filtration system are presented. The model was used to simulate a mixture of activated carbon and porous shale pebbles as root bed of selected plants (such as Golden Pothos). The method of implementation for the model was also described. Preliminary model verification results for airflow and moisture were reported as well. The simulation results showed that the model could describe the pressure drop and airflow relationship well by using the air permeability as a model parameter. The water source added in the model also leads to the similar bed moisture content and outlet air RH as that in real test case. The implemented model was capable of simulating all the processes in the DBAF. The simulation results improved the understanding of the real mechanisms involved in the filter system. The model can potentially be used to improve the design of dynamic botanical air filtration systems. Further experimental research, however, is needed to determine the VOC degradation rates by various microbes in the root system.

It is anticipated that the outcomes of this project will positively impact public health and comfort levels in homes and businesses. The device will be manufactured in New York State. Its adoption in the market place will also create jobs and contribute to New York's economic development.

1. INTRODUCTION

Indoor air quality (IAQ) remains a very important issue today because it can significantly affect people's health, comfort, satisfaction and productivity. U.S. Environmental Protection Agency (EPA) studies of human exposure to air pollutants indicated that indoor air levels of many pollutants may be two to five times, and occasionally, more than 100 times higher than outdoor level [1]. In recent years, comparative risk studies performed by the EPA and Science Advisory Board (SAB) have consistently ranked indoor air pollution among the top five environmental risks to public health. The importance of indoor air quality is also due to the absolute amount of time that people spend indoors. Most Americans spend up to 90% of their time indoors and many spend most of their working hours in an office environment [2]. It has been estimated that the potential productivity gain by providing better indoor environmental quality are over $40 billion to $200 billion per year in the U.S [3].

Indoor air quality can be improved by three ways: controlling source, designing ventilation systems to dilute and exhaust contaminated air, and cleaning air [4]. Nowadays, there is no single fully satisfactory method for volatile organic compounds (VOCs) removal from indoor air, due to the difficulties associated with the diversity and variability at which VOCs are typically found in the indoor environment. Several studies have demonstrated the potential of biological methods to remove indoor VOCs [5-14]. Common indoor plants may provide a valuable weapon in the fight against rising level of indoor air pollution. Those plants in your office or home are not only decorative, but a NASA scientist found them to be surprisingly useful in absorbing potentially harmful gases and cleaning the air inside modern buildings [6-7]. Still, there are very limited data demonstrating the effectiveness of botanical air filtration at realistic and full-scale ventilation conditions, and inadequate understanding of the true removal mechanisms in these systems [15].

How well do house plants perform when they are used as cleaner for improving indoor air quality? In the 1990s, a published research indicated that potted plant can remove 9.2–90% formaldehyde, benzene or xylene in a small-sealed-chamber [7]. The pollutant reduction by plant seems remarkable at first glance. Nevertheless, another study clearly explained that the pollutant reduction from above research was achieved by a high plant loading in chamber (approximately one plant per 0.5 m^3), which is far in excess of what would be reasonable for indoor environment [16]. To achieve the results equivalent to those of chamber studies, 680 plants would be needed for a 340 m^3 (1500 ft^3) resident house. Therefore, the authors' conclusion was that indoor plants have little benefit for removing indoor air VOCs in residential and commercial buildings.

Still, because all the studies reviewed by Girman et al.[16] were based on a single potted plant and most of these studies focused on the pollutant static removal by plant leaves, it is still too early to make the general statement that indoor plant is not efficient to remove indoor air VOCs. One study had shown that three

plants in a real office of average area 13 m^2 (volume 32.5 m^3) were more than enough reduce TVOC by up to over 75% (indoor 0-plant ambient level ranging from 80 to 450 ppb), maintaining level at below 100 ppb, with or without air-conditioning [11]. Studies have shown that VOCs could become the potential carbon source for microbial communities in soil from the rhizosphere of plant [17-20]. Moreover, assimilation and metabolism of formaldehyde by plant leaves appear unlikely to be of value for indoor air purification due to the low uptake rate [21]. Especially, studies have demonstrated that it was the microorganisms of the potting mix that were the primary removal agents, with the plant mainly being responsible for maintaining root-zone microbial community [12-13]. Therefore, if the polluted air also can be introduced into plant root system and degraded by the microorganisms there, the removal capacity of the plant would be higher than the potted plant with leaf effect only.

Test results from a previous NYSERDA, National Grid, NYIEQ, and SU-sponsored project on the performance evaluation of existing air cleaning technologies show that none of the currently available air cleaning products can effectively remove all types of volatile organic compounds typically found in office and residential buildings. Technologies used in these products included: sorption by activated carbon, ultraviolet photocatalytic oxidization or UV-PCO, plasma ionization, ozone ionization, and soil filtration. Failure of the existing products in removing the indoor pollutants include inadequate selection of filter media, poor airflow management inside the cleaning devices, insufficient catalytic reaction surface area, or poor distribution of UV light irradiation. Therefore, it is necessary to develop an integrated technology in which a combination of different filtration media or air cleaning technologies may be used for removing targeted contaminants for a given indoor environment.

The Wolverton air filtration system, a NASA based spinoff technology, presents a unique opportunity for developing and commercializing such an integrated air cleaning device. It uses a plant root bed of activated carbon, porous shale pebbles, microbes and a wet scrubber to remove VOCs and radon from the air in tightly sealed buildings. The VOCs removed are converted into a food source for the indoor plants that also offer a green and natural environment indoors. The microbes that are responsible for the conversion can quickly reactivate the carbon, eliminating the need for replacement, unlike the typical carbon filters used for air cleaning that need to be replaced every three-to-six months.

A prototype device has been developed by Dr. Wolverton and Hank Nordberg based on the Wolverton filtration technology for use in residential or commercial HVAC systems (**Figure 1-1**). In the prototype, air is pumped through the plant root bed via three imbedded manifold tubes. The VOCs are trapped by the mixture of activated carbon and moist porous shale pebbles that also act as a wet scrubber for many light compounds such as formaldehyde, acetaldehyde, and other low molecular weight aldehydes and ketones. The microbes formed by the root system of Golden Pothos (a candidate plant) convert the adsorbed VOCs into a food source for plants, and thus cleanse the filter. While the filtration technology has been proven for

its principle, its successful engineering application requires testing, evaluation and demonstration to answer several important questions including:

- How much clean air the device can provide continuously based upon current design
- How does the cleaning performance vary with the airflow rate and humidity conditions in the plant root bed
- What is the long term performance of the device at typical indoor environmental applications and are there opportunities to improve it
- How can the device be incorporated into HVAC system while achieving optimal system performance (e.g., the device would be an extra moisture source)
- What is the estimated energy savings that will be realized by incorporating such a system into a normal building

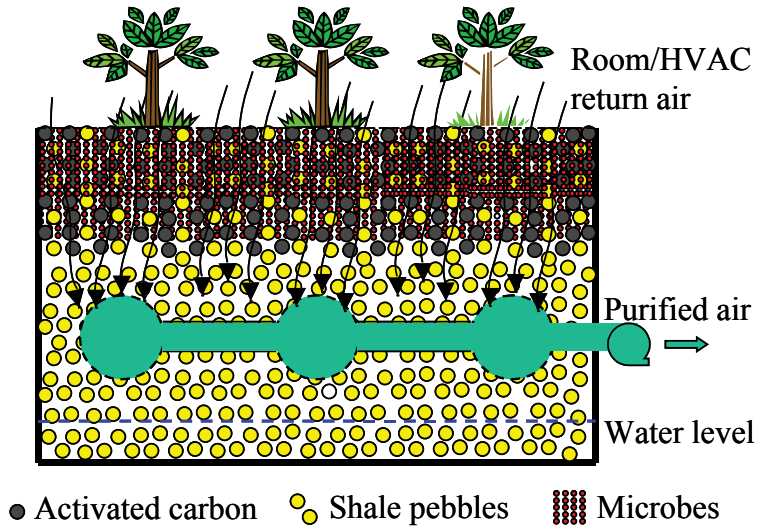

Figure 1-1. Principle of a Wolverton filtration system

The filtration bed is the plant's root and "soil" system consisting of activated carbon, special porous shale pebbles, plant's roots, microbes, and moisture transported via the porous shale pebbles. Room or HVAC return air is drawn through the filtration bed by the negative pressure created in three perforated tubes, which are manifolded and connected to a fan for air delivery. As air passes through the filtration bed, VOCs in the air are adsorbed by activated carbon and/or trapped in shale pebbles, and the microbes in the plant's root system convert the VOCs into food for the plant and regenerate the filtration bed for

adsorbing/trapping VOCs. The purified air can be delivered to occupied spaces directly or via the conventional/existing HVAC system.

The objectives of this study were to test, improve and demonstrate the bio-filtration device's performance for removing volatile organic compounds in indoor air and potential for saving energy while achieving good indoor air quality, and to improve the understanding of the combined heat, air, moisture and pollutant transport and bio-degradation processes involved in the botanical air cleaning system.

2. METHODS

To achieve the study objectives, we performed the following tasks:

1) Determination of the performance of the prototype device for its ability to remove toluene (a compound widely used as a reference for TVOC) and formaldehyde (an important indoor VOC pollutant) for different flow rates (300-600CFM), humidity in the plant root bed (20-52% volumetric water content), and carbon to shale pebble ratio of 50/50. This was performed by using the full-scale IEQ chamber of BEESL/SU (16 ft x 12 ft by 10 ft high)

2) Improvement of the design of the prototype system by introducing a new auto-irrigation system.

3) Integration of the improved prototype device in the HVAC system for performance demonstration in the new ICUBE (intelligent cubical environments) on the third floor of Link Hall

4) Monitoring of the performance of the device for over a month and disseminate the results so as to help with the adoption of this technology into the market place

5) Conduction of whole building energy simulation to determine the energy saving that can be achieved by using the air filtration device for an office building at cold climate conditions such as Syracuse, N.Y. This was performed by using the DesignBuilder/EnergyPlus simulation software

6) Improvement of an existing CHAMPS-BES (a model for coupled heat, air, moisture, and pollutant simulation) to simulate the processes involved in the filter

The study was focused on the removal of important volatile organic compounds that have most significant impact on IAQ including formaldehyde (a carcinogen) and toluene (that is typically used as a reference compound for VOCs found indoors when TVOC level is determined).

3. PROTOTYPE IMPROVEMENT AND LABORATORY EVALUATION

3.1 PROTOTYPE IMPROVEMENT

From the preliminary tests conducted in the full-scale IEQ chamber, it was found that with the original design, the plant in the bed could not obtain sufficient water from the bottom by "capillary effect" due to relatively strong air flow through the root bed, coming from the top. Modification was made on the prototype by adding irrigation water at the top, and the irrigation water was recirculated to avoid the loss of microbial in the root system. **Figure 3-1** shows the modified filter system.

Figure 3-1. Modified bio-filtration system

The modified dynamic botanical air filtration system (DBAF) prototype based on the principle of physical adsorption by activated carbon, absorption by water ("wet scrubber"), and VOCs degradation by microorganisms in the plant's root system was developed, as shown in **Figure 3-2(a)**[22]. The DBAF system used mixture of activated carbon and porous shale pebbles as root bed of selected plants (Golden Pothos (*Epipremnum aureum*)) with microorganisms growing in the root system. The filter bed was 1.8 m in length, 0.6 m in width and 0.2m in depth. The average diameter of the granular activated carbon and shale pebbles was 0.005 m, and the mixed ratio is 50/50 by volume. Eight Golden Pothos were evenly placed in the bed. The filtration system was operated with periodical irrigation and airflow passing-through. An axial flow fan was installed. The maximum air flow through the bed was 1014 m^3/h. Gas pollutants such as VOCs were adsorbed by the activated carbon sorbent, and the wet root bed also acted as a scrubber for formaldehyde and other water soluble compounds. The adsorbed and/or absorbed organic compounds

would be degraded by the microbes, regenerating the sorbent-based root bed. The purified air could be returned to indoor environment directly or fed to the supply air of an HVAC system to improve indoor air quality. The DBAF had a controller that automatically sequences the operation of the irrigation system and fan based on the signal from a moisture content sensor. The irrigation control sensor was buried in the center of the bed. When the moisture content was below the lower limit, the fan was stopped, and irrigation system triggered and operated until the moisture content was higher than the higher limit. Three minutes after the irrigation was stopped, the fan was triggered and operated until the moisture was below the lower level again. Three Campbell CS616-L water content reflectometers (M.C. Sensors) were buried inside the bed in sequence for accurate moisture content measurement in experiments conducted in a real-world condition (a newly constructed office building), as shown in **Figure 3-2(b)**.

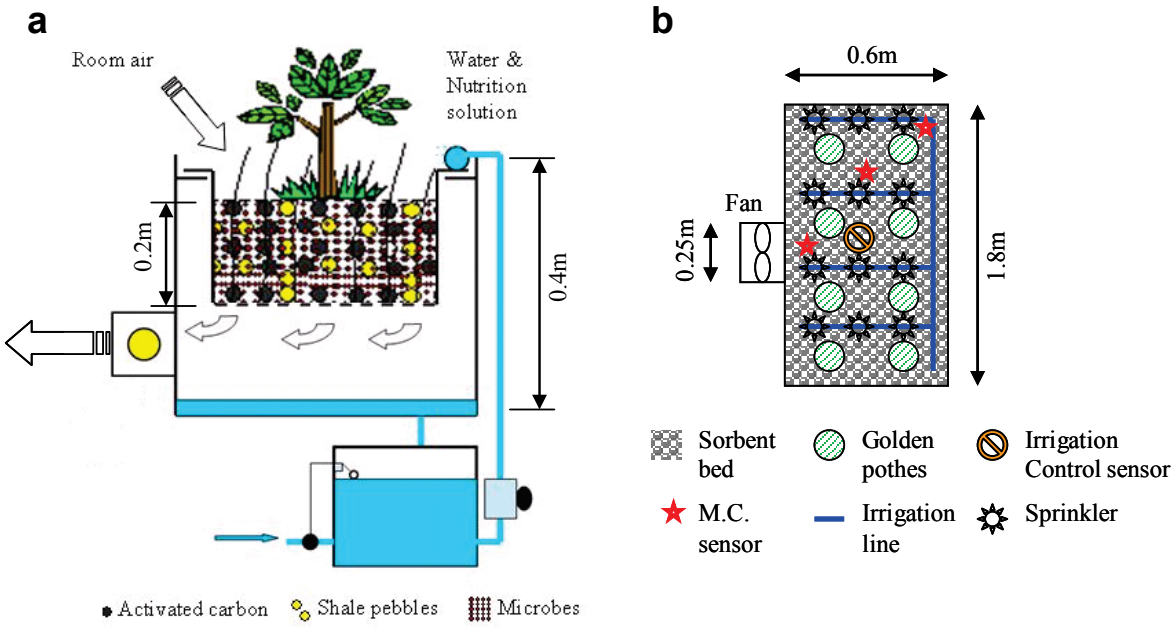

Figure 3-2. Schematic of dynamic botanical air filtration system: (a) side view, (b) top view. Moisture content sensor (M.C. sensor)[22].

3.2 LABORATORY EVALUATION

3.2.1 Test Method

The chamber used had interior dimensions of 4.84 m long x 3.63 m wide x 3.05 m high (54.4 m^3 in air volume), and was maintained at 23 ^oC and 60% RH. It was operated at full-recirculation mode with a total supply airflow rate of 680 m^3/h (12.5 air change per hour). The relatively high air change rate and use of a square air diffuser for space air distribution ensured complete air mixing inside the chamber [10].

Two sets of chamber tests were conducted to determine the initial (short-term) performance of the DBAF. In the first set of tests, the DBAF was evaluated by using the "pull-down" test procedure [10]. Formaldehyde and toluene were selected as target compounds. SF6 was used as tracer gas. They were injected into the chamber to achieve desired initial concentration levels, and their concentrations were continuously monitored before and after the DBAF was turned on. An INNOVA 1312 photoacoustic multi-gas monitor was used for measuring the concentrations of toluene ($C_{toluene}$), formaldehyde (C_{formal}), and the tracer gas (SF6) continuously until the concentrations of toluene and formaldehyde reached the background levels**. Figure 3-3** shows the schematic of the chamber test set-up. The VOCs removal performance of the DBAF was evaluated at six airflow rates through the DBAF (250 m^3/h, 600 m^3/h and 930 m^3/h) and two filter bed moisture content levels (30±2% for "high VWC" test and 15±1% for "low VWC" test).

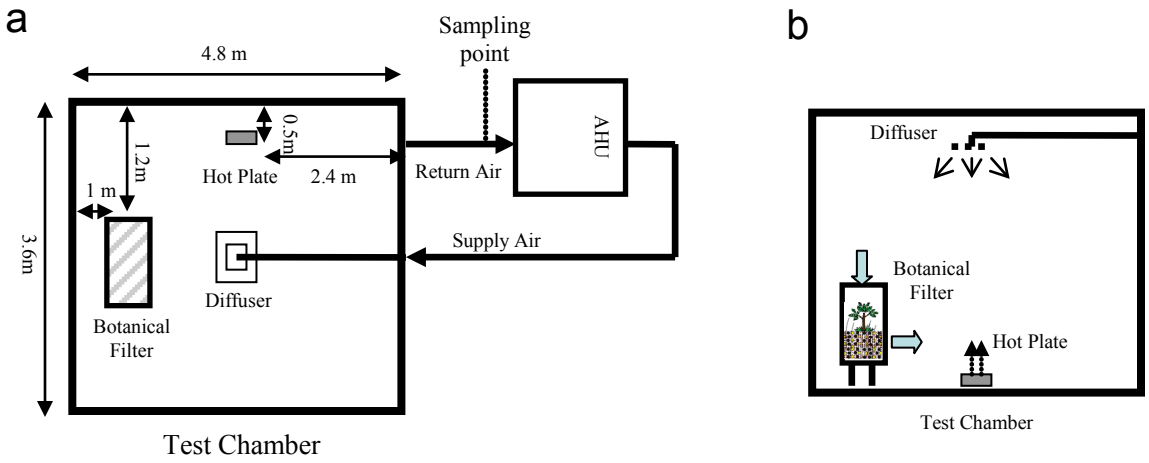

Figure 3-3. Schematic of the environmental chamber test setup: (a) top-view, (b) side-view. Air handling unit (AHU).

In the second set of chamber tests, a new working station made of particle board was placed inside the test chamber to simulate a typical emission source in an office environment. No clean air was supplied to the chamber and the VOCs concentrations were allowed to increase or decrease depending on the operation of the DBAF. The test lasted for four days, and the DBAF ran eight hours per day. The air flow rate passing through the filter bed was 510 m^3/h when the DBAF was turned on. The same INNOVA gas monitor was used to monitor formaldehyde and TVOC (quantified as toluene equivalent) concentrations.

Clean air delivery rate (CADR) represents the "effective" clean airflow rate delivered by the air cleaner [23]. The performance parameter measured directly by the "pull-down" test method was CADR. The analysis was based on the well-mixed single zone model. Assuming that: 1) the air was well mixed in chamber (as confirmed by tracer gas testing), and 2) the contaminant removal mechanisms other than air cleaning (e.g. surface adsorption effect and chamber leakage effect) were characterized by a first-order rate constant k_n, the mass conservation of contaminant in the "pull-down" test can be written as [24]:

$$V\frac{dC}{dt} = -\left(k_n V + CADR\right)\cdot C = -k_e V \cdot C \text{ , (C=C}_0 \text{ at t=0)} \quad (3\text{-}1)$$

then

$$CADR = \left(k_e - k_n\right)V \quad (3\text{-}2)$$

where, V is the testing chamber system volume, m^3; k_n is the exponential decay constant of the contaminant concentration without air cleaner operating (empty chamber effect), h^{-1}; k_e is exponential decay constant with air cleaner operating (that includes both the empty chamber and air cleaner effects), h^{-1}; C_0 is the initial contaminant concentration inside the chamber at t=0, mg/m^3; C is the contaminant concentration inside the chamber at time t, mg/m^3.

The decay rate constant of SF6 was 0.031 air change per hour (ACH) (corresponding to 1.68 m^3/h or 1.0 CFM), indicating that chamber leakage rate was acceptable. When there was no air cleaner in the chamber, the overall decay rate constant for each individual VOC ranged from 0.031 to 0.048 ACH---i.e., very close to that of SF6, indicating minimal surface adsorption effect of the chamber at the experimental conditions. Therefore, the chamber surface adsorption effect was neglected and only the chamber leakage rate (characterized by SF6 decay rate for each test) was used to determine k_n.

The equivalent single pass efficiency (SPE) can be calculated by following equation [24]:

$$\eta = \frac{CADR}{G \cdot E_d} \quad (3\text{-}3)$$

where, η is single pass efficiency of the air cleaner, %; G is the air flow rate through the air cleaner, m3/h; Ed is short-circuiting factor of the air cleaner, ($E_d = 1$ under well-mixed condition).

3.2.2 Results and Discussions

Pollutant removal performance. **Figure 3-4** presents the normalized formaldehyde concentration with three different air flow rates passing the filter bed: 250 m^3/h, 600 m^3/h and 930 m^3/h, obtained using the standard "pull-down" test procedure (i.e., 1st sets of chamber tests). Formaldehyde concentration at the time "0 hr" in the tests was 2 mg/m^3 (1.64 ppm). The background pollutant concentration in the chamber was measured for two hours before the test was started, and all the concentrations measured later were subtracted by the average background concentration. Then the concentrations were normalized by using the initial concentration at time t = 0 as reference) to facilitate the comparison. The negative concentration at the later period of the test means that the concentration achieved was lower than initial background level. Tracer gas (Sulfur hexafluoride (SF6)) concentration was also presented, and the chamber leakage rate from SF6 calculation was 0.031 ACH, which corresponded to 1.68 m^3/h and was excluded in the final CADR calculation for the DBAF. The formaldehyde concentration decreased quickly to the background

level after the fan was turned on. With higher airflow rate passing the sorbent bed, the formaldehyde concentration decreased faster. It means more clean air was delivered in a fixed time period.

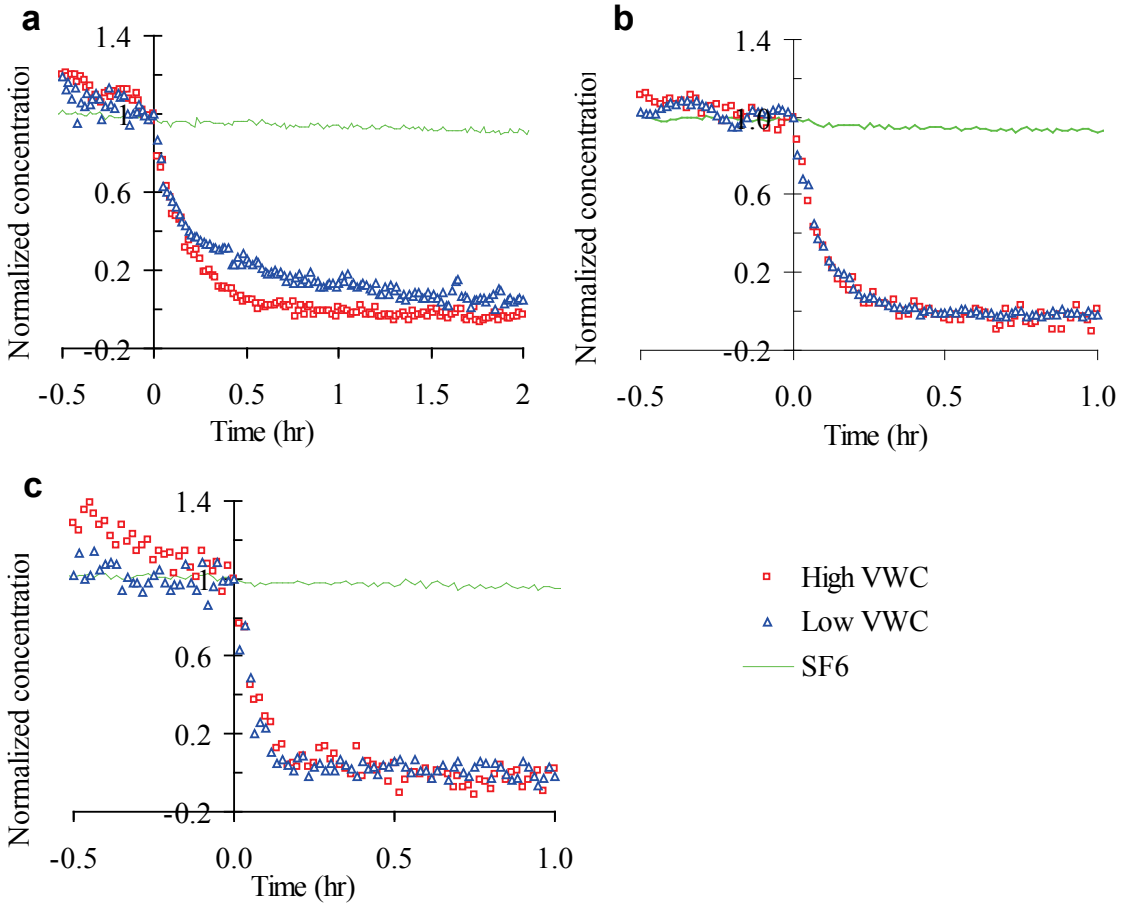

Figure 3-4. Normalized formaldehyde concentration at different air flow rate: (a) 250 m3/h airflow rate passing the bed, (b) 600 m3/h airflow rate, (c) 930 m3/h air flow rate. Volumetric water content (VWC) in the filter bed.

Toluene concentrations were also monitored at the same test conditions, as shown in **Figure 3-5**. Toluene concentration at the time "0 hr" in the tests was 8 mg/m^3 (2.16 ppm). Similar trend was observed for the effect of air flow rate, toluene concentration decreased faster at higher airflow rate test. Results also indicated that the SPE at higher air flow rate was less than that at lower air flow rate in general due to smaller residence time, but more clean air can be delivered during a fixed period of time at higher airflow rate test. That is why formaldehyde or toluene decreased faster at higher airflow rate test.

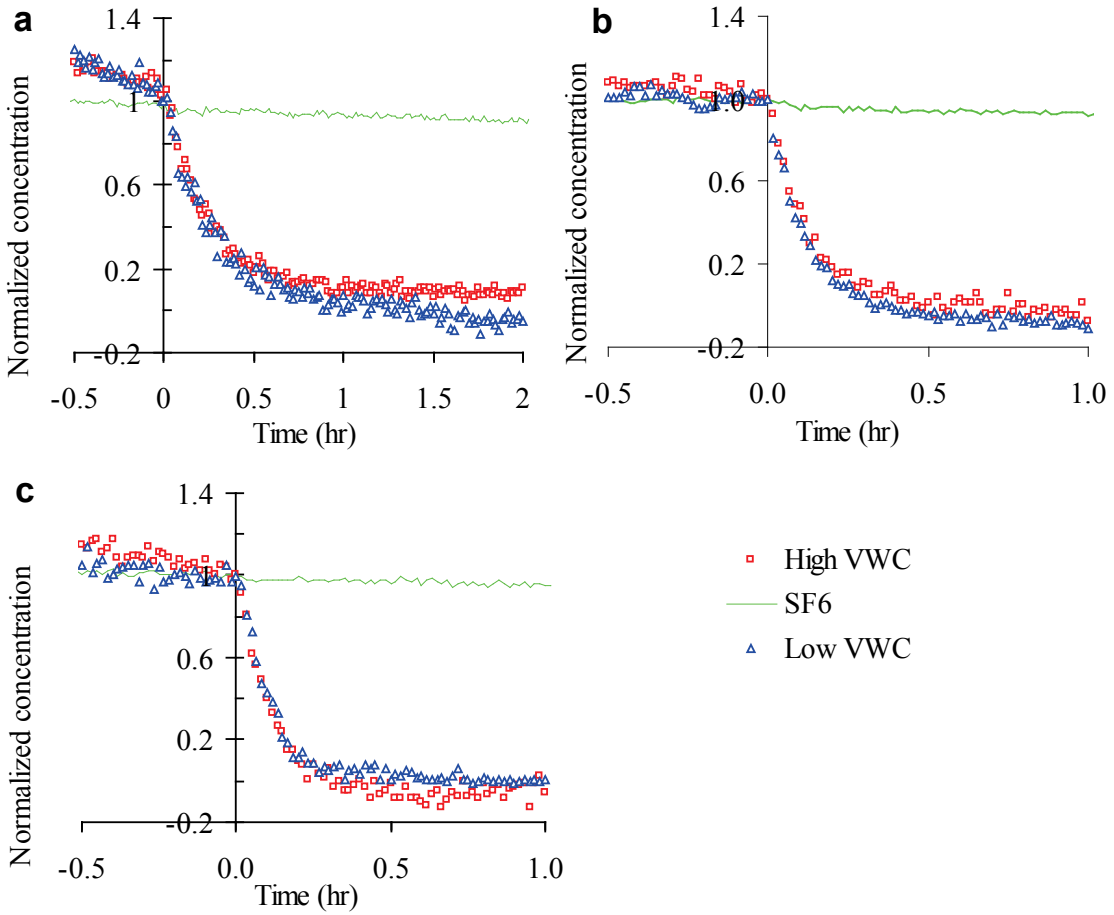

Figure 3-5. Normalized toluene concentration at different air flow rate: (a) 250 m3/h airflow rate passing the bed, (b) 600 m3/h airflow rate, (c) 930 m3/h air flow rate. Volumetric water content (VWC) in the filter bed.

Table 3-1 lists the CADR and SPE for formaldehyde and toluene in the first set of chamber tests. Overall, the CADR or SPE was not significantly affected by the test moisture condition because both high and low VWC conditions in the tests were well within the range of 5–32% bed water content, which is the range where the botanical filter worked well for both water soluble and insoluble compounds as to be further discussed later in this report.

Table 3-1 CADR and SPE for formaldehyde and toluene removal

Air flow (m^3/h)	Pollutant	Formaldehyde		Toluene	
	Moisture level (VWC)	High VWC (30±2%)	Low VWC (15±1%)	High VWC (30±2%)	Low VWC (15±1%)
250±10	CADR (m3/h)	266.9	253.7	247.9	232.4
	SPE (%)	98.7	93.8	91.7	85.9
600±15	CADR (m3/h)	582.4	581.7	529.1	436.7
	SPE (%)	94.4	94.3	85.8	70.7
930±20	CADR (m3/h)	698.1	731.8	759.7	492.0
	SPE (%)	69.0	73.2	77.2	50.1

ASHRAE 62.1-2010 specifies that the requirement of outdoor air for office buildings is 5 cfm (8.48 m^3/h) per person plus 0.06 cfm (1.02 m^3/h) per square foot floor area [25]. ASHRAE 62.1-2010 also specifies a maximum occupant density for office spaces of five people per 1000 ft^2 or per 100 m^2. Take this maximum value as example, the requirement of outdoor air for per 1000 ft^2 office building is 85 cfm (144 m^3/h). The maximum CADR of the filter for formaldehyde was 731.8 m^3/h. Therefore, the DBAF could serve an office building with 5000 ft^2 (465 m^2) floor area if formaldehyde is the target pollutant for air cleaning.

Effect of DBAF on the chamber air temperature and relative humidity. The test chamber air was maintained at 23 ^oC and 60% RH at the beginning of test, which is common in a conditioned office space for a hot and humid summer. **Table 3-2** lists the average temperature and relative humidity change in chamber return air with three different air flow rates passing through the filter bed: 250±10, 600±15 and 930±20 m^3/h. For the same air flow rate, tests were also conducted at two different volumetric water content (VWC) levels in the filter bed: High VWC (30±2%) and Low VWC (15±1%). The VWC level was measured by the filter bed moisture control sensor. The sensor was located in the center of the DBAF. Although it does not exactly represent the average moisture condition of the entire filter bed, the sensor represents relative levels of VWC in different tests. It can be found that the chamber air was cooled slightly at high VWC levels. With air flow rate of 250±10 m^3/h, temperature decreased by 0.2–0.5 ^oC while RH increased by 5.7–13.3%. For air flow rate of 600±15 and 930±20 m^3/h, temperature decreased by 0.6–1.1 ^oC and 0.8–1.0 ^oC while RH increased by 11.3–14.5% and 9.4%–13.5%, respectively. In summary, the chamber air temperature decreased by less than 1 ^oC and relative humidity increased by 10% to 15% RH in most tests.

Table 3-2 Average temperature and RH change "Δ" in chamber return air from the initial condition of 23 °C and 60% RH

Airflow rate (m3/h)	Bed moisture level (VWC)	High VWC (30±2%)	Low VWC (15±1%)	Moisture generation (kg/h)
250±10	Temperature Δ (°C)	-0.5	-0.2	0.81–1.14
	Relative humidity Δ (% RH)	13.3	5.7	
600±15	Temperature Δ (°C)	-1.1	-0.6	1.15–1.37
	Relative humidity Δ (% RH)	14.5	11.3	
930±20	Temperature Δ (°C)	-1.0	-0.8	1.23–1.89
	Relative humidity Δ (% RH)	13.5	9.4	

In this operation condition, the application of the DBAF will introduce additional humidity that needs to be removed by the HVAC during summer condition for thermal comfort, but would improve comfort during winter condition in which humidification is needed. The prototype DBAF tested produces approximately 0.81–1.89 kg/h of moisture based on the data in **Table 3-2**. It should be noted that the DBAF could serve a much larger building space than the chamber (465 m^2 versus 17.6 m^2 in floor area) per the outdoor airflow rate requirement recommended by ASHARE Standard 62.1-2010 [25]. The increase of relative humidity due to the operation of DBAF would be much smaller when it is used for a larger building space that matches its CADR capacity.

VOC removal performance for a simulated office environment with emissions from a wood-based workstation system

Figure 3-6(a) shows the test set-up with VOCs emissions from an office workstation system (i.e., the 2nd sets of chamber tests). **Figure 3-6(b)** shows the pollutant concentration in chamber varied with time. It decreased significantly after the DBAF began to work. Once the filter stopped running, the pollutant concentration in chamber began to increase due to sustained VOCs emissions from the furniture system. **Table 3-3** lists the CADR and SPE calculation for each running period. It was found that the filter also worked well at low concentration range tested (300–400 ppb). The single pass efficiency for formaldehyde was over 90% after the filter had been continuously running for four days, which might mainly be due to the absorption of the wet media bed, and meanwhile the SPE for TVOC (quantified as toluene equivalent) was 38%.

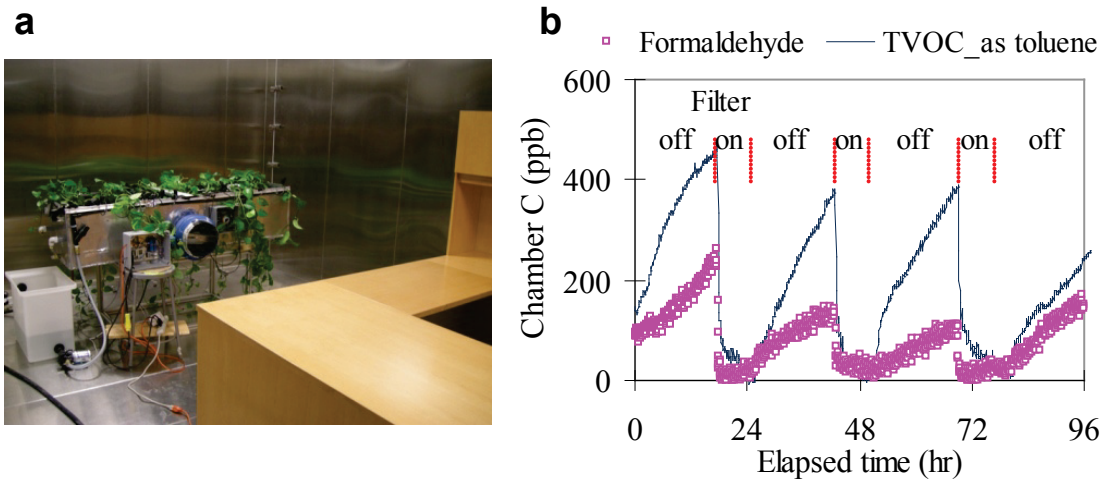

Figure 3-6. Test set-up and test chamber concentration vary with time: (a) test set-up (photo), (b) test results.

Table 3-3 CADR and SPE of BASF for VOCs Emitted from an Office Furniture During a 4-Day Test

VOC	Formaldehyde				TVOC as toluene equivalent			
Time (day)	1st	2nd	3rd	4th	1st	2nd	3rd	4th
Air leakage rate calculated by SF6 kn	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031
Decay rate calculated after turning on AC ke	16.27	14.83	8.71	8.59	4.86	5.72	3.14	3.63
CADR=V(ke -kn)/60 (m3/h)	510	510	470	465	260	310	169	195
Final single pass efficiency η (%)	100.0	100.0	92.6	91.3	51.5	60.7	33.1	38.4

4. FULL-SCALE FIELD PERFORMANCE DEMONSTRATION

4.1 TEST METHOD

Following the full-scale chamber tests, the botanical air filtration system was integrated into the HVAC system of a newly constructed office room in Syracuse, NY, as shown in **Figure 4-1**. The total volume of the test room was 265 m^3 (approximately 16.4 m long, 5.4 m wide and 3.0 m high). There were 16 work cubicles in the room. The botanical filter was connected with the supply air duct by steel pipes with diameter of 0.25 m. An independent fan was installed on the filter system, which provided an air flow rate of 815 m^3/h. The total amount of supply air for this room was 2378 m^3/h during the tests. The detailed test procedure can be found in Appendix B. Tests were started in the winter (December 2008 - March 2009). During this test period, the test room was maintained at 22 ^oC with a relative humidity of 15%. The effect to the room temperature and RH was investigated. The effect of filter bed moisture content to the single pass efficiency was also investigated. The improvement of the indoor air quality by using the botanical filter was evaluated as well. The single pass efficiency of the botanical in removing formaldehyde and toluene was kept on being monitored until October 2009, a ten-month-continuous monitoring period.

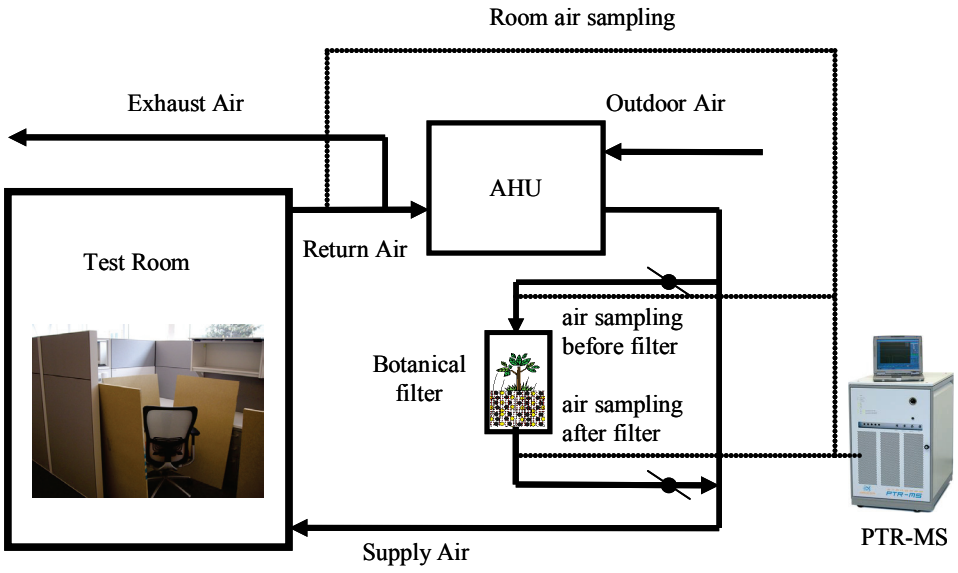

Figure 4-1. Integration of botanical filter into an HVAC system and setup for monitoring. Air handling unit (AHU). Proton Transfer Reaction Mass Spectrometer (PTR-MS).

Preliminary tests revealed that the test room had unusually low pollutant concentration due to the low emitting materials used. In order to simulate pollutant level under a more typical office conditions, 48 pieces of unused particleboard were placed in the test room. The size of each piece was 1.2 m by 0.8 m. After the particleboards were placed into the test room, an air sample was taken at the return air duct by

using a tenax sorbent tube, and analyzed by Gas chromatography-mass spectrometry (GC/MS). Pentanal, toluene, hexanal, xylene, α-pinene were found to have the highest concentrations. Toluene was selected as the target VOCs in current study since it is commonly used as calibration reference for the total volatile organic compounds (TVOC) [26]. Meanwhile, another air sample was taken at the same location by using 2,4-dinitrophenylhydrazine (DNPH) cartridge, and analyzed by high-performance liquid chromatography (HPLC). Formaldehyde and acetaldehyde were also detected. Formaldehyde was chosen as the other target compounds as they are typically identified as major compounds of concern in emission testing of composite wood materials and office furniture [27]. A Proton Transfer Reaction Mass Spectrometer (PTR-MS) was used to monitor these target compounds in real-time. The detection limits of PTR-MS are 0.06 ppb for toluene and 0.2 ppb for formaldehyde. The sampling inlet of PTR-MS was connected to the return air duct, as shown in **Figure 4-1**.

To study the effect of the filter bed on the air temperature and RH, air temperature and RH sensors were installed in four different locations: air right before entering DBAF, air immediately after DBAF, return air, and supply air of the test room. In the one-day test period, the DBAF was turned on for eight hours, from 12th hour to 20th hour, and was turned off during the rest of hours of the day.

To investigate the maximum clean air that the DBAF could provide, tests were conducted at four different HVAC system operation modes: 50% outdoor air (OA) (1138 m^3/h), 25% outdoor air, 10% outdoor air, and 5% outdoor air plus the DBAF (i.e., filter on). The room VOCs sampling location was in the return air duct. The 24-hour tests (three-hour-background measurement at 5% OA and the switch to the test ventilation mode) were conducted. The concentrations at the third hour (start point of ventilation mode change) were taken as the reference for normalization, 17 ppb for formaldehyde and 2 ppb for toluene, respectively.

To investigate the effect of filter bed moisture content on the toluene and formaldehyde removal performance, three Campbell CS 616-L water content reflectometers were used to measure the moisture content in the bed. Average of the readings from these three sensors was taken as the bed water content. The filter bed was saturated with water at the beginning of the test, and then the fan was kept on running until the bed water content decreased to less than 5% in VWC. The filter inlet and outlet contaminant concentrations were measured periodically, and then the single pass efficiency was calculated by using the following equation [24]:

$$\eta = \frac{G(C_{in} - C_{out})}{GC_{in}} = \frac{C_{in} - C_{out}}{C_{in}} \qquad (4\text{-}1)$$

where, G is the airflow rate through the air cleaner, m^3/h; C_{in} is the contaminant concentration at the inlet of air cleaner, mg/m^3; C_{out} is the contaminant concentration at the outlet of air cleaner, mg/m^3.

The filter was then kept on running for 10 months. The filter inlet and outlet contaminant concentrations were measured periodically. The calculated single pass efficiencies were used to study the long-term performance of the DBAF.

4.2 RESULTS AND DISCUSSIONS

4.2.1 Effect of DBAF on the Room Air Temperature and RH

Figure 4-2 shows the impact of DBAF on the test room air temperature and RH. **Table 4-1** lists the average temperature and RH at different test period. After the filter was turned on, the test room return air temperature decreased by 0.5 ^{o}C while return air RH increased by 17.7% RH. The moisture generation of DBAF was 2.54 kg/h under this test condition. Compared with the test results conducted in the test chamber, more moisture was generated due to test room low initial RH condition in the office room. The test room return air RH increased from 13.5–31.2%, which would improve the thermal comfort condition in dry winter climate.

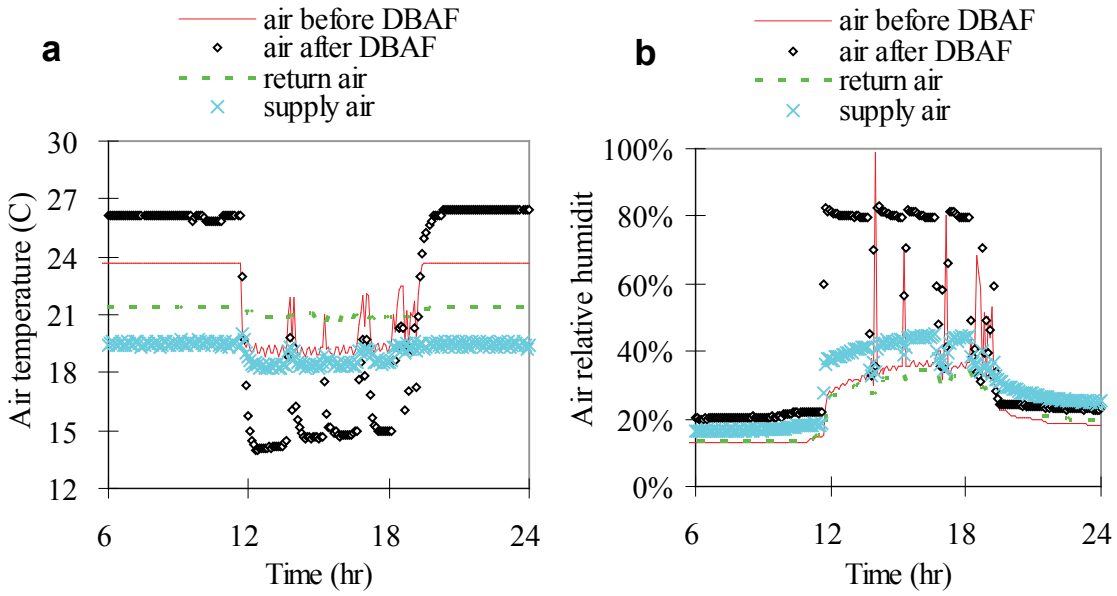

Figure 4-2 Effect of DBAF on room air temperature and RH: (a) Temperature, (b) RH.

Table 4-1 Average temperature and RH at different period in a 24-hr-test

Air parameter	Average Temperature (^{o}C)			Average RH (%)		
Test Period	1	2	3	1	2	3
	6-11hr	12-19hr	20-24hr	6-11hr	12-19hr	20-24hr
Air before filter	23.7	19.7	23.7	12.9	37.6	19.2
Air after filter	26.0	15.8	26.4	20.6	71.0	23.4
Return air	21.4	20.9	21.4	13.5	31.2	20.8
Supply air	19.5	18.6	19.5	16.9	40.5	26.3

4.2.2 Air-cleaning versus ventilation: How much clean air could the DBAF provide?

Figure 4-3 compares the normalized formaldehyde and toluene concentration in the office space among the four different operation modes. **Figure 4-3(a)** shows the normalized formaldehyde concentration (NFC) at different operation mode. The mode of 5% outdoor air plus filtration had the similar result as 25% outdoor air (560m^3/h) without filter. The botanical filter provided an equivalent clean air delivery rate of 476m^3/h for formaldehyde, which was within 10% of the value previously determined from a full-scale environmental chamber test (520m^3/h). **Figure 4-3 (b)** shows the normalized toluene concentration (NTC) at different operation mode. The operation mode with 5% outdoor air plus filtration resulted in a similar effect of 10–25% outdoor air ventilation for toluene removal.

In summary, the above results indicated that the DBAF was effective under very low pollutant concentration levels: 17 ppb for formaldehyde and 2 ppb for toluene. The botanical filter provided an equivalent clean air delivery rate of 476m^3/h for formaldehyde and toluene removal, which means the requirement for the amount of outdoor air could potentially be reduced by integrating the botanical air filtration system in the HVAC system of a commercial building, while achieving adequate indoor air quality if formaldehyde and toluene were the pollutants that dictated the required outdoor ventilation rate.

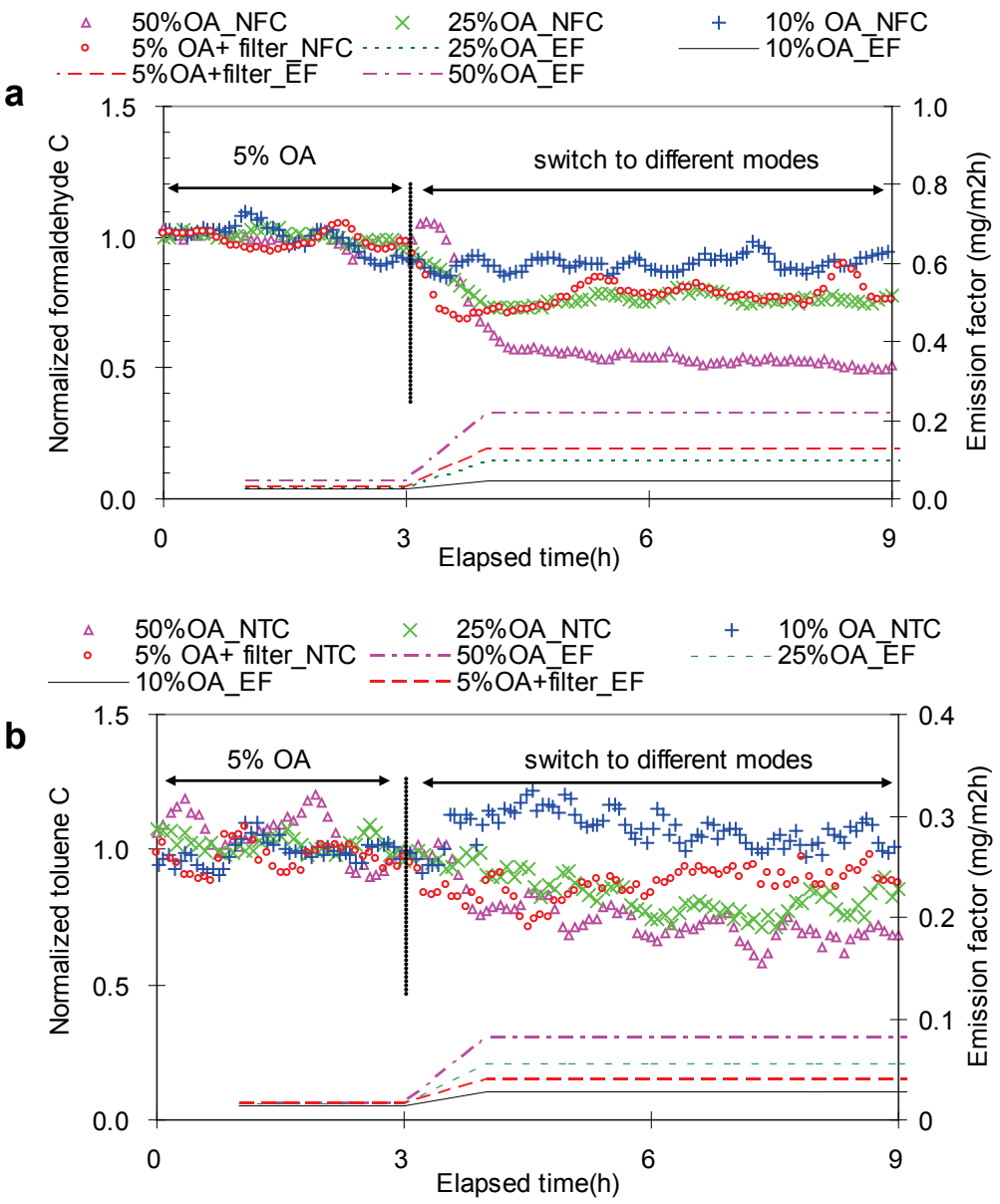

Figure 4-3. Comparison of room pollutants concentration: (a) Formaldehyde, (b) Toluene. Outdoor air (OA). Normalized formaldehyde concentration (NFC). Emission factor (EF). Normalized toluene concentration (NTC).

Figure 4-3 also shows the emission factors under different operating conditions, estimated based on the following mass balance equation for the room space, assuming that the air was well-mixed in the room:

$$V\frac{dC}{dt} = AE - QC - Q_f C\eta - \delta \qquad (4\text{-}2)$$

where, V is the room volume, m^3; A is the total surface area of emission source, m^2; E is the emission factor, mg/m^2h; Q is the outdoor air ventilation rate, m^3/h; C is the contaminant concentration inside the

chamber at time t, mg/m^3; Q_f is the air flow rate through the filter, m^3/h; η is the single pass efficiency of the filter, which was determined by measuring the concentrations right before and after the DBAF (η=0 when DBAF was completely bypassed); δ is the room sink effect, mg/h.

For the same outdoor air flow rate and operation mode of the DBAF, the concentrations of both compounds had a very slow decay rate so that a quasi-steady state assumption was adopted in estimating the emission factor, E, in Equation (4-2), i.e., neglecting the transient term on the left hand side of equation (4-2) and the sink effect term δ (which was also considered negligible, comparing to the other terms in the equation), we have:

$$E = \frac{1}{A}\left(QC + Q_f C\eta\right) \qquad (4\text{-}3)$$

During the field test, the initial emission factors of formaldehyde and toluene were 0.046 mg/m^{2}h and 0.015 mg/m^{2}h respectively at 5% outdoor air ventilation. **Figure 4-3** also shows that the emission factors increased with outdoor air ventilation or operation of botanical filter due to a higher concentration gradient between the source and the room air caused by the reduction of indoor concentration by ventilation or air cleaning.

4.2.3 Effect of Bed Water Content

The effect of bed water content on the single pass removal efficiency (SPE) was studied. Three Campbell CS 616-L water content reflectometers (**Figure 3-2(b)**) were used to measure the accurate moisture content in the bed. Average of the readings from these three sensors was taken as the bed water content in the following analysis. The filter bed was saturated with water at the beginning of the test, and then the fan of the filter was kept running until the bed water content decreased to less than 5% in VWC. The SPE was checked periodically, as shown in **Figure 4-4**.

The single pass efficiency for formaldehyde was maintained at over 70% when the bed water content was higher than 10%, then it decreased very fast when the water content of the bed was less than 5%. On the contrary, the SPE for toluene was almost zero when the bed water content was higher than 40%, then it increased significantly as the bed water content decreased. The SPE for toluene was maintained at over 40% when the water content was lower than 30%. The reason for this might be the different water solubility of these two compounds. Formaldehyde is water soluble, while Toluene is not. The results indicated that 5% to 32% bed water content is the best range where the botanical filter worked well for both water soluble and insoluble compounds. The SPEs were around 70% and 40% for formaldehyde and toluene, respectively in this range.

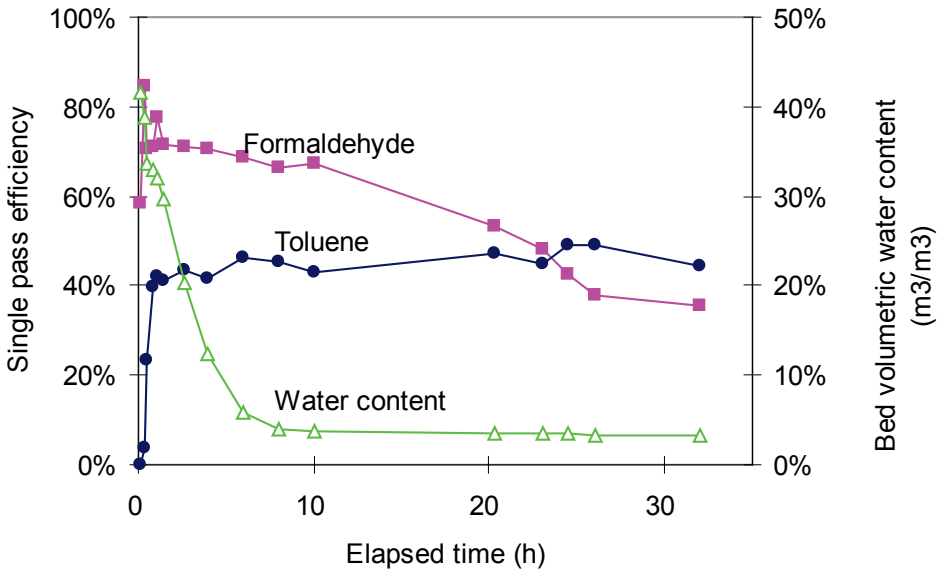

Figure 4-4. Effect of bed water content on removal of pollutants

Formaldehyde is very weakly adsorbed on activated carbon or any other untreated adsorbent, because the formaldehyde molecules are small and light so the Van der Waals force between formaldehyde and activated carbon is very weak [28]. It appears that the "wet film" formed in DBAF worked as an effective scrubber in removing formaldehyde of the air. Formaldehyde was first absorbed by the "wet film" formed in the sorbent bed, and then degradated by the microorganisms living in the "wet film" or the microbial communities in soil from the rhizosphere of plant.

4.2.4 Long-Term Performance

Long-term performance evaluation of the DBAF is needed to determine whether formaldehyde and toluene retained by the bed are consumed by the microorganisms in the root system so that the removal efficiency of the bed can be maintained. During a 300-day long performance test in which DBAF operated continuously in cycles plus 5% OA ventilation, the initial formaldehyde and toluene concentration increased to 17 ppb and 2 ppb, respectively, due to the emissions from the particleboards introduced into the office environment. After the filter was running for 10 days, the room formaldehyde and toluene concentration decreased to 10 ppb and 1 ppb, respectively, and then kept at a relatively constant level, meaning that the VOCs continuously emitted from the particleboards were removed by the 5% OA ventilation plus DBAF. **Figure 4-5** presents the SPE of the botanical filter on formaldehyde and toluene during the test period as well as the water content of the media bed. The SPE for formaldehyde almost stayed constant, around 60%. The SPE for toluene was negatively influenced by the water content in the bed, but was still kept at 20% 300 days later. Note that without the botanical filter, concentrations in the

spaces would have been 30% higher than current results, due to the continuous generation of toluene and formaldehyde by the sources.

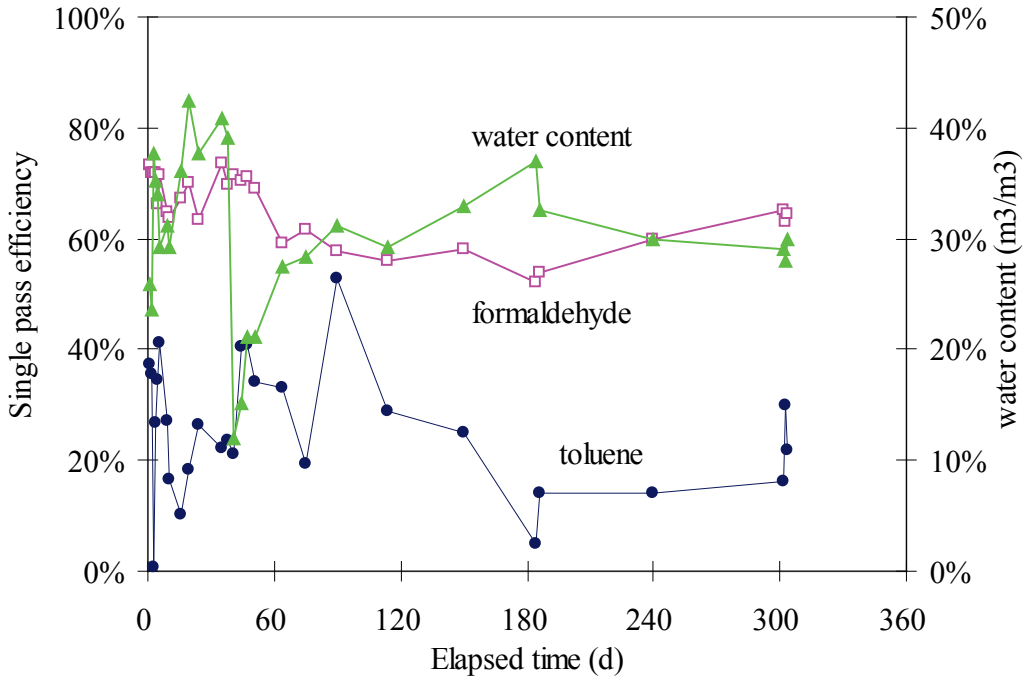

Figure 4-5. Botanical filter single pass efficiency (SPE) over 300 days

Seven (7) bacterial species from the botanical filter system using DNA sequencing were identified, including *Arthrobacter aurescens TC1*, *Arthrobacter oxydans*, *Leifsonia xyli subsp. xyli str. CTCB07*, *Bacillus cereus*, *A. aurescens*, *Pseudomonas putida*, and *Bacillus spp* [29]. Degradation of formaldehyde solution by individual species was conducted. According to Henry's law, the formaldehyde concentration in the water film around the sorbent particle was 0.001% by weight if the formaldehyde concentration in the air passing through the sorbent bed was 50 ppb. The initial liquid formaldehyde concentration in the test was 0.001% by weight. It was found that the maximum reduction rate was 86.2% after 24 hours, by *A. aurescens TC1* [29].

Therefore, as long as there are sufficient carbon sources (formaldehyde or VOCs) in the air passing through the bed, the microorganisms living in the sorbent bed will degrade them. Moreover, the microorganisms that are responsible for the degradation can quickly reactivate the carbon particle so that it need not be replaced, unlike the typical carbon filters used for air cleaning which need to be replaced every three-to-six months.

There is a concern whether this botanical filter would cause indoor microbial pollution. A pilot test was conducted to address this issue. Five liters of filter outlet air was sampled and bubbled through Luria-Bertani (LB) medium (containing 10 g/L tryptone, 5 g/L yeast extract, and 10 g/L sodium chloride) to observe any possible microbial growth. No colony was found on the LB agar plates (LB medium supplemented with 1.5% agar) during incubation for up to 120 h at 30 ºC, which means there was no microbial pollution in the sampled air. The potential release of microorganisms from indoor biological purifiers during long-term operation should be further studied and prevented.

Biofiltration system has been used for many years in the industrial setting as well as indoor air setting [8]. There are some significant differences between the DBAF and previous biofiltration system. The material used in the bioscrubber of previous biofiltration system was lava rock, while the bed of DBAF consisted of porous shale pebble and granular activated carbon. The BET (Brunauer, Emmett and Teller) Theory is commonly used to evaluate the gas adsorption data and generate a Specific Surface Area result expressed in units of area per mass of sample (m2/g). The activated carbon had a BET (Brunauer, Emmett and Teller) surface area of 900–1100 m^2/g and 80% of the pore size was less than 10 nanometers, which was highly effective for adsorbing VOCs. The plants used in the previous biofiltration system were over hundreds of species of plants typically used in indoor landscaping, while the plants used in the DBAF were more selective (e.g. Golden Pothos (*Epipremnum aureum*)) for ease of maintenance and more root-zone microbial community [30]. The previous biofiltration system has much lower face velocity than the current DBAF (0.01 m/s vs. 0.25 m/s), and delivers much less clean air airflow rate per unit surface area (360 m^3/h by a 10 m^2 bioscrubber compared to 970 m^3/h by a 1.08 m^2 DBAF root bed with an acceptable pressure drop of 73 Pa). As a result, the DBAF system developed in this study would be easier to be adopted for indoor air cleaning either as part of an HVAC system or operated as a standalone unit to provide the required clean airflow rate.

5. POTENTIAL ENERGY SAVING ESTIMATION

Buildings accounted for 38.9 percent of total U.S. energy consumption in 2005 [31]. Residential buildings accounted for 53.7 percent of that total, while commercial buildings accounted for the other 46.3 percent. There is a growing concern about energy consumption in buildings and its likely adverse impact on the environment. With economic growth, buildings, especially fully air conditioned offices, will continue to be a key energy end user. One way to alleviate the ever growing demand for energy is to have a more energy efficient building facility and unit.

5.1 ENERGY SIMULATION MODEL DESCRIPTION

Based on the performance test results conducted in the office field demonstration, the outdoor air could be reduced from 560–119 m^3/h with the DBAF integrated into the HVAC system. To estimate the potential benefit in building energy saving due to the use of the botanical air filter, the energy consumption of the building integrated with the DBAF prototype was simulated through EnergyPlus for an entire year using representative climate data for Syracuse, NY. The latitude and longitude are 43.12 º and -76.10 º, respectively. The elevation is 125 m.

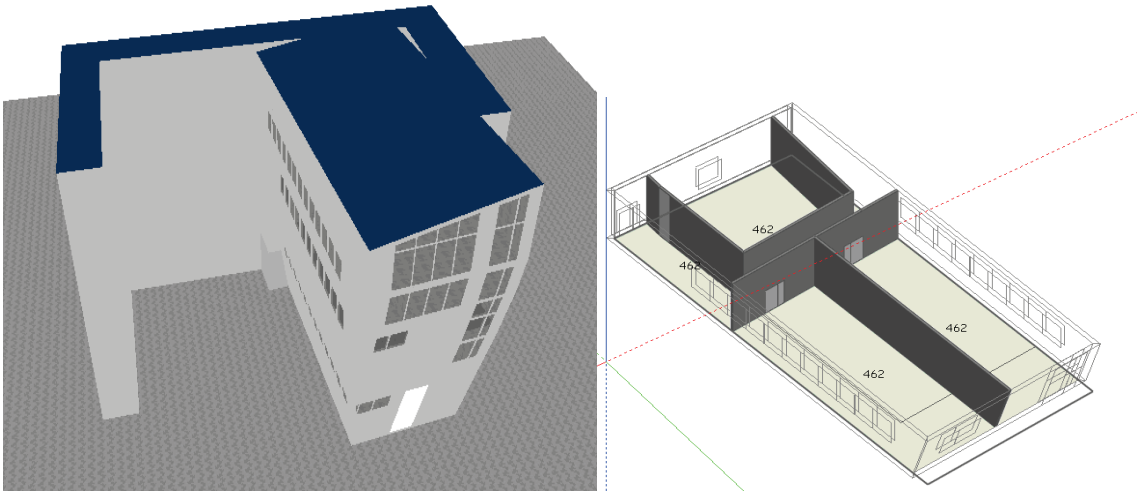

Figure 5-1. Schematic view of the building in simulation

The south side of the building was connected with another office building. There are four floors in the building. The first and second floors are laboratories. The third and fourth floors are air-conditioned office area. There are two large office rooms on third floor, with 16 work cubicles in each. The fourth floor consists of two conference rooms, eight work cubicles in the central open area, and 13 individual office rooms. The total area of the third and fourth floors was 438 m^2. Energy consumption simulation was only conducted for the office area (entire third and fourth floors). The DBAF required for third and fourth floors

would be 1.2 m in length and 0.8 m in width. The building window-wall ratio was shown as in **Table 5-1**, along with wall and window areas.

Table 5-1 Window-Wall ratio

	Total	North	East	South	West
Gross wall area (m2)	4248.59	863.47	1259.75	842.12	1283.26
Window opening area (m2)	277.93	85.28	106.01	0.00	86.65
Window-wall ratio (%)	6.54	9.88	8.41	0.00	6.75

The building structure was first generated in the DesignBuilder [32] and then uploaded into EnergyPlus. The zones control and HVAC system set-up were then finished step by step in EnergyPlus. The yearly energy consumption of the office area with 560 m^3/h outdoor air supply (0.5 ACH equivalent fresh air ventilation rate) was simulated as the baseline. Then, the outdoor air was reduced to 119 m^3/h, and the yearly energy consumption of the same building was simulated again. Comparison between above two simulated case was conducted. In terms of the simulation set-up, the ventilation schedule was on for 12 hours (7:00 AM-6:00 PM) during weekday and off during weekend and holidays. The boiler nominal efficiency for heating was assumed 0.8. The chiller nominal coefficient of performance for cooling was assumed to be 3.2. The fan total efficiency for ventilation was assumed 0.7(power transferred to the air in Watts/fan electricity consumption in Watts). The pump motor efficiency for hot/chilled water was assumed 0.9. The nominal power of the fan in the DBAF was 0.15 kW.

5.2 RESULTS AND DISCUSSIONS

Figure 5-2 shows the outdoor temperature in a year at Syracuse (left side) and normal HVAC system energy consumption for link hall additional building (right side). It can be seen that most of the energy consumption for such building comes from heating (Gas: Plant) at the location such as Syracuse.

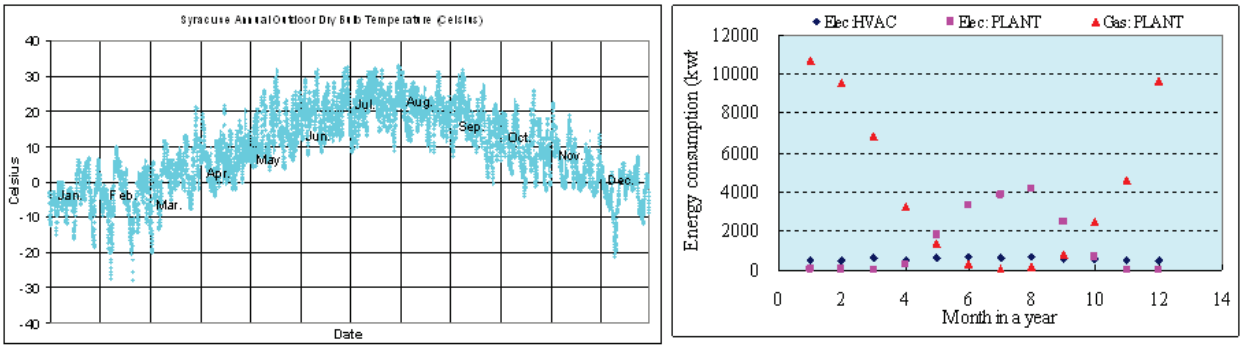

Figure 5-2. Yearly outdoor temperature at Syracuse and building HVAC energy consumption

With the phytofilter integrated into the HVAC system, the ourdoor air can be reduced by a certain part, such as from 25% OA (330 CFM outdoor air) to 5% OA (67 CFM outdoor air), which leads to change in the energy consumption. **Table 5-2** shows the monthly energy consumption and saving ratio at these two operation modes: 25% OA and 5% OA plus filter. At 5% outdoor air with filter on, the total energy saving for such building located at Syracuse is about 4152 kWh per year, which is 10%-15% saving compared with the entire energy consumption involved in the building HVAC system. Moreover, the energy saving listed in **Table 5-2** can be analyzed further in detail. The saving will be 26% if considering the heating part only, while only 2% for cooling. One percent more fan energy was consumed at the operation mode of 5% OA + DBAF due to the addition of the flow resistance through the filter bed.

Table 5-2 Monthly building energy consumption related to HVAC system

	Heating [KWh]		Cooling [KWh]		Fan energy consumption [KWh]			
	25%OA	5%OA+Filter	25%OA	5%OA+Filter	25%OA	5%OA	DBAF	5%OA+DBAF
January	4408	3196	10	9	579	536	25	561
February	2860	2107	6	6	565	510	24	534
March	1465	1003	3	3	690	645	28	673
April	610	522	565	571	593	586	24	610
May	154	154	2514	2514	678	678	28	705
June	23	23	3681	3605	725	725	26	751
July	4	4	4087	3991	710	710	24	734
August	19	19	4245	4113	764	764	28	792
September	161	161	2232	2225	615	615	25	640
October	732	663	523	526	597	595	26	621
November	1277	929	2	2	584	558	26	584
December	2861	1870	7	5	596	541	23	564
Yearly total	14574	10652	17875	17571	7696	7463	307	7770
Saving		3922		304				-74

The heating and cooling energy consumptions are for all the loads of the third and fourth floors, not just the ventilation loads. While expressed as kWh, the heating energy consumption is natural gas usage and can be converted to Btus using 1.0 kWh = 3,413 Btus. The fan energy consumptions are for all the air moving equipment needed to meet the heating and cooling loads and the ventilation requirements of the third and fourth floors.

Note 1: The fan energy consumption listed in Table 5-2 can be further analyzed. The fan energy consumption at operation mode of 25% OA and 5%OA was obtained from simulation when the outdoor ventilation ratio was changed from 25% to 5%. Overall, more fan energy was consumed in cooling season than that in heating season. The nominal power of the DBAF is 0.15KW. The DBAF was running for 10 hours during weekdays and turned off during weekend and holidays. The total fan energy consumption for the operation mode of 5%OA+DBAF was obtained by adding fan energy consumption of 5%OA and DBAF together.

Note 2: The above simulation was based on the premise that the requirement of outdoor air can be reduced from 560 m3/h to 119 m3/h after the DBAF was integrated in the building HVAC system. The energy consumption from the fan of DBAF was considered in the ventilation part. Still, the temperature and RH effect that the DBAF may bring to the HVAC system were not reflected in the simulation since there is no available botanical filter model in current EnergyPlus software. Furthermore, the climate zones also play an important role in the potential energy saving from the application of the DBAF. Further analysis on the energy saving potential of the DBAF for different climate zones will be needed. An analysis of the energy savings potential for the DBAF in New York City is included in Appendix C for reference.

Table 5-3 lists the monthly peak load demand for the climate of Syracuse, NY. It does follow the trend of monthly energy consumption.

Table 5-3 Monthly peak load demand for Syracuse, NY

	Heating				Cooling				Fan energy				
SYR	0.25OA		0.05OA		0.25OA		0.05OA		0.25OA		0.05OA		0.05OA+DBAF
Month	Time	kW	Time	kW	Time	kW	Time	kW	Time	kW	Time	kW	kW
Jan.	01/30 08:00:00	167.4	01/03 08:00:00	155.3	01/03 08:00:00	0.9	01/03 08:00:00	0.9	01/19 17:00:00	4.3	01/30 08:00:00	3.1	3.2
Feb.	02/13 08:00:00	151.9	02/13 08:00:00	137.1	02/13 08:00:00	0.7	02/13 08:00:00	0.6	02/23 14:00:00	4.4	02/16 12:00:00	3.0	3.2
Mar.	03/06 08:00:00	141.0	03/06 08:00:00	124.7	03/06 08:00:00	0.6	03/06 08:00:00	0.5	03/23 12:00:00	4.5	03/13 17:00:00	4.2	4.4
Apr.	04/10 07:00:00	83.2	04/10 07:00:00	71.1	04/24 16:00:00	17.8	04/24 16:00:00	18.3	04/03 13:00:00	4.5	04/05 12:00:00	3.8	3.9
May	05/09 07:00:00	20.7	05/09 07:00:00	20.7	05/11 15:00:00	20.9	05/11 15:00:00	20.0	05/11 15:00:00	3.5	05/11 15:00:00	3.5	3.6
Jun.	06/29 07:00:00	1.3	06/12 07:00:00	4.7	06/09 16:00:00	24.7	06/19 10:00:00	23.3	06/19 11:00:00	3.9	06/19 11:00:00	3.9	4.1
Jul.	07/13 07:00:00	1.1	07/14 07:00:00	0.8	07/31 07:00:00	34.7	07/31 07:00:00	33.7	07/31 08:00:00	4.0	07/31 08:00:00	4.0	4.2
Aug.	08/24 07:00:00	2.0	08/18 07:00:00	3.8	08/07 11:00:00	24.7	08/07 10:00:00	23.0	08/28 10:00:00	3.9	08/28 10:00:00	3.9	4.0
Sept.	09/29 07:00:00	34.2	09/29 07:00:00	34.3	09/11 07:00:00	24.6	09/11 07:00:00	24.5	09/11 08:00:00	3.8	09/11 08:00:00	3.8	3.9
Oct.	10/11 07:00:00	48.5	10/11 07:00:00	48.6	10/13 15:00:00	13.8	10/13 15:00:00	13.8	10/19 09:00:00	3.3	10/23 11:00:00	3.2	3.3
Nov.	11/27 08:00:00	98.8	11/27 08:00:00	88.0	11/27 08:00:00	0.3	11/27 08:00:00	0.3	11/09 17:00:00	4.5	11/17 15:00:00	4.0	4.2
Dec.	12/11 08:00:00	186.0	12/11 08:00:00	166.6	12/11 08:00:00	1.1	12/11 08:00:00	0.9	12/20 16:00:00	4.4	12/11 08:00:00	3.2	3.3

While expressed as kW, the heating energy consumption is natural gas usage and can be converted to Btu/hr using 1.0 kW = 3,413 Btu/hr.

6. MODELING AND SIMULATIONS

In order to improve the understanding of the transport and bio-degradation processes involved in the DBAF, a numerical model has been developed and implemented using the CHAMPS-BES, a model for coupled heat, air, moisture, and pollutant simulations [33].

6.1 MODEL DEVELOPMENT

6.1.1 Model Description and Assumption

The model represented in this study describes the VOCs transport and biological degradation processes. As air passes through the filter, the processes involved in the VOC transport, adsorption/absorption and decomposition mechanism in the whole bio-filtration system include:

1. **VOCs advection by airflow** The transport of gas phase VOCs by air flow through the filter bed.
2. **VOCs gas phase diffusion through bed void**
3. **VOCs convective mass transfer to sorbent** This is the adsorption process of adsorbable compounds from the bulk of the gas phase to the external surface of adsorbent pellets (activated carbon). Each sorbent pellet is assumed to be homogeneous and the VOC internal diffusion in the micropores is not described in detail in current the model.
4. **VOCs convective mass transfer to liquid** This is the absorption process, describing transport of gaseous pollutant from the air into contacting liquid, such as water film at the surface of sorbent/pebble. The liquid serves as a solvent for the pollutant. Water film formed in the surface of pebbles or activated carbon will become the wet scrubbers, where water soluble compounds such as formaldehyde in the indoor air can be absorbed on it.
5. **VOCs physical adsorption by activated carbon** After pollutant molecules transport from gas phase to solid phase by convective mass transfer at the surface of solid, instant equilibrium between gas phase and solid phase is assumed, which is described by a constant partition coefficient.
6. **VOCs absorption by liquid film** Henry's constant is the parameter to describe the instant equilibrium between gas phase and liquid phase.
7. **VOCs consumption by microorganisms** The microbes formed in the root system of a plant will consume the absorbed or adsorbed VOCs as a food source.

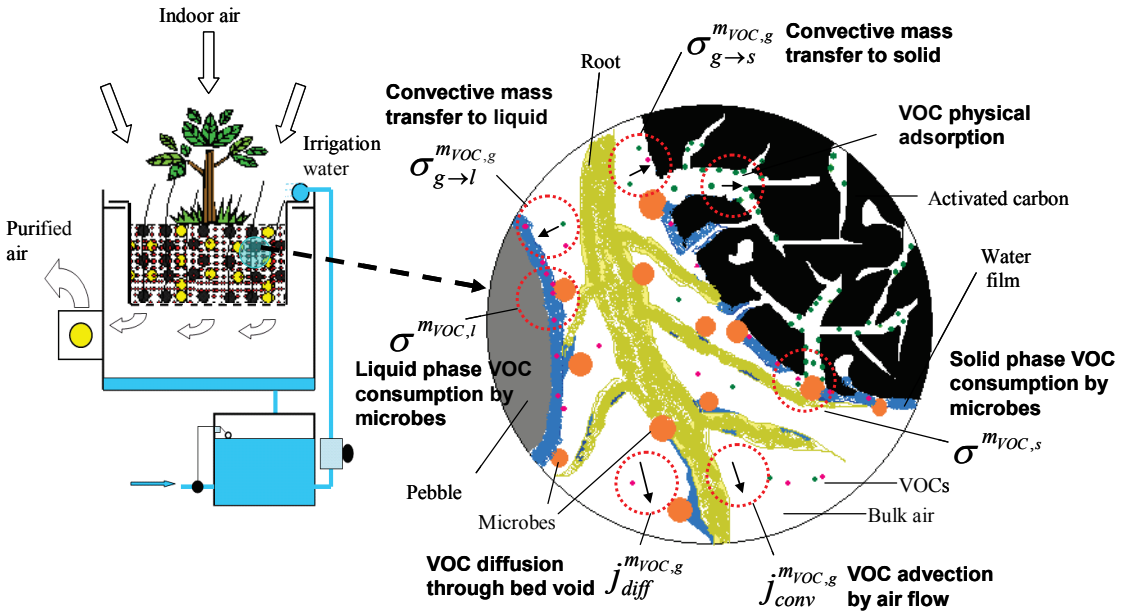

Figure 6-1. Physical process involved

The major assumptions in the model include:

1) The adsorption process is isothermal, and no temperature change

2) The axial dispersion in the sorbent bed is neglected due to dominating bulk flow effect (convection)

3) The air velocity through the sorbent bed is constant and even

4) The sorbent pellet has spherical shape

5) The partition coefficient is constant

6) Microbes grow by geometric series with enough carbon source or nutrient

7) The moisture content in the bed is even in the horizontal direction

Under the above assumptions, the equations in the following section can be used to describe the transport and degradation processes.

6.1.2 Governing Equations

VOCs in the filter bed are divided into three components: gas phase, adsorbed in solid, and absorbed in liquid. For each of them, the governing equation is described as follows:

VOC Mass Balance In Gas

Transport of gas phase VOCs can happen via convection with air, through diffusion, exchange between gas and solid, and exchange between gas and liquid.

$$\frac{\partial \rho^{m_{VOC,g}}}{\partial t} = -\frac{\partial}{\partial x}\left(j_{conv}^{m_{VOC,g}} + j_{diff}^{m_{VOC,g}}\right) - \sigma_{g\to s}^{m_{VOC,g}} - \sigma_{g\to l}^{m_{VOC,g}} + \sigma^{m_{VOC,g}}, \qquad (6\text{-}1)$$

Where $\rho^{m_{VOC,g}}$ is the VOC density in gas; $j_{conv}^{m_{VOC,g}}$ is VOC mass flux due to convection; $j_{diff}^{m_{VOC,g}}$ is VOC mass flux due to diffusion. The exchange between gas and solid is denoted by $\sigma_{g\to s}^{m_{VOC,g}}$, and the exchange between gas and liquid is denoted by $\sigma_{g\to l}^{m_{VOC,g}}$, whereas the arrow indicates positive transfer direction. The term $\sigma^{m_{VOC,g}}$ can be used to describe any source or sink of gas phase VOC components, such as a constant emission source. This term is zero in the current botanical filtration model.

Convective VOC transport happens through convective air flux.

$$j_{conv}^{m_{VOC,g}} = c_{gas}^{m_{VOC}} j^{m_g}, \qquad (6\text{-}2)$$

Where $c_{gas}^{m_{VOC}}$ is the gas phase VOC concentration (mass fraction) in ($kg_{(VOC)}/kg_{(gas)}$); j^{m_g} is gas mass flux density from the airflow calculation in ($kg_{(gas)}/m^2s$), determined by:

$$j^{m_g} = -K_g \frac{\partial p_g}{\partial x}, \qquad (6\text{-}3)$$

For the sorbent bed filter, the air flux can be determined by the air permeability of the bed and pressure drop across the filter as follows:

$$j^{m_g} = -K_g \frac{\Delta p}{\Delta x}, \qquad (6\text{-}3a)$$

Where K_g is gas permeability through the media, s; p_g is gas pressure, which equals to the sum of partial pressures of dry air and water vapor, Pa; ΔP is the pressure difference across the entire root bed, Pa; x is the coordinate in the bed flow direction, m; Δx is thickness of the bed, m.

The diffusion flux of gas phase VOC in the bed void is calculated by:

$$j_{diff}^{m_{VOC,g}} = -\frac{D_{VOC,mat}}{R_{VOC}T}\frac{\partial p_{VOC,g}}{\partial x}, \qquad (6\text{-}4)$$

$D_{VOC,mat}$ is the VOC diffusion coefficient in material, it is calculated by the VOC diffusion coefficient in air $D_{VOC,air}$ (given in m^2/s) and diffusion resistance factor μ_{voc} (dimensionless, which takes into account the tortuosity of bed-void).

$$D_{VOC,mat} = \frac{D_{VOC,air}}{\mu_{VOC}}, \qquad (6\text{-}5)$$

Adsorption Flux: Transfer From Gas To Solid Phase

When there is a concentration gradient between the gas phase concentration in the bulk air and at the surface of sorbent (gas phase at surface boundary layer, which is assumed to be in instantaneous equilibrium with the adsorbed VOCs at the surface with a partition coefficient K_{ma}), there will be an exchange flux into the direction of the lower concentration.

The mass transfer equation from gas phase to solid phase can now be given:

$$\sigma_{g\to s}^{m_{VOC}} = \frac{k_{m,g\to s} A_{tol}(1-w)}{V_{REV}}\left(\rho_{gas}^{m_{VOC,g}} - \rho_{gas}^{m_{VOC,s}}\right) = \frac{k_{m,g\to s} A_{tol}(1-w)}{V_{REV}}\left(\rho_{gas}^{m_{VOC,g}} - \frac{\rho^{m_{VOC,s}}}{K_{ma}}\right), \qquad (6\text{-}6)$$

Where $k_{m,g\to s}$ is the VOC mass transfer coefficient between gas and solid; A_{tol} is the total external surface area of the sorbent material that available for pollutant/VOC adsorption or absorption. w is the wetness ratio of the surface of the activated carbon pellet. It is a function of the bed volume water content. The wetness ratio equal to zero when the bed is absolutely dry and equal to one as the bed is total saturated with water. V_{REV} is the reference element volume. K_{ma} is the partition coefficient of the solid media.

The total surface area for spherical pellet sorbent bed can be calculated by equation (6-7). Where θ_{por} is the porosity of the sorbent bed. R is the radius of the sorbent particle/pellet.

$$A_{tol} = \frac{(1-\theta_{por})V_{REV}}{\frac{4}{3}\pi R^3} 4\pi R^2 = \frac{3V_{REV}(1-\theta_{por})}{R}, \qquad (6\text{-}7)$$

Absorption Flux: Transfer From Gas To Liquid Phase

For water soluble pollutant/VOC, such as formaldehyde, when there is a concentration gradient between the gas phase concentration in the bulk air and the surface of the liquid (gas phase at the surface boundary layer of liquid, which is also assumed to be in instantaneous equilibrium with the absorbed VOCs at the surface with a Henry's law constant H), there will be an exchange flux into the direction of the lower concentration.

The mass transfer equation from gas phase to liquid phase can now be given:

$$\sigma_{g\to l}^{m_{VOC}} = \frac{k_{m,g\to l} A_{tol} w}{V_{REV}}\left(\rho_{gas}^{m_{VOC,g}} - \rho_{gas}^{m_{VOC,l}}\right) = \frac{k_{m,g\to l} A_{tol} w}{V_{REV}}\left(\rho_{gas}^{m_{VOC,g}} - H\rho^{m_{VOC,l}}\right), \qquad (6\text{-}8)$$

With w as wetness ratio as described above, $A_{tol}w$ is the external surface area of the liquid film covering the sorbent material or pebble in filter bed.

VOC Mass Balance In Solid

$$\frac{\partial \rho^{m_{VOC,s}}}{\partial t} = \sigma_{g\to s}^{m_{VOC,g}} + \sigma^{m_{VOC,s}}, \qquad (6\text{-}9)$$

Where $\rho^{m_{VOC,g}}$ is the VOC density in solid; $\sigma_{g\to s}^{m_{VOC,g}}$ is the VOC transport from gas phase by convective mass transfer; $\sigma^{m_{VOC,s}}$ is considered as the common source/sink term. The consumption of adsorbed VOC by microbes is such a sink in the botanical filtration system. Another example is the chemi-sorption process (negative source term), and it is not available in the botanical air filtration system.

VOC Mass Balance In Liquid

$$\frac{\partial \rho^{m_{VOC,l}}}{\partial t} = \sigma_{g\to l}^{m_{VOC,g}} + \sigma^{m_{VOC,l}}, \qquad (6\text{-}10)$$

Where $\rho^{m_{VOC,l}}$ is the VOC density in liquid; $\sigma_{g\to l}^{m_{VOC,g}}$ is the VOC transport from gas phase by convective mass transfer; $\sigma^{m_{VOC,l}}$ is considered as the common source/sink term. An example for such a source/sink term in the botanical filtration system is the process of pollutant/VOC degradation by microbes in the root system (negative source term).

Source/Sink Flux For Solid/Liquid Phase VOC: Microbial Biodegradation

The absorbed or adsorbed VOCs will be served as carbon source for microorganisms. As long as there is carbon source in the liquid film or sorbent surface, the microbes will take them as food, therefore, the VOCs will be degraded. Basically, there are two main factors that affect the VOCs degradation by microbes. One is the available carbon source, the other is the number of microbes that will take charge of the degradation. So the biodegradation flux can be expressed as:

$$\sigma^{m_{VOC,l}} = \left(k_1 N_1 + k_2 N_2 + \cdots + k_n N_n\right)\rho^{m_{VOC,l}}, \qquad (6\text{-}11)$$

Where $N_1 \cdots N_n$ are the corresponding number of microbial species found in the root bed, with unit as Colony Forming Unit (CFU); $k_1 \cdots k_n$ are the biodegradation rate constants for each microbial species found in the root bed, with unit L·h/CFU. Here it is assumed that the activity of the pollutant/VOC degradation by each species is independent of each other. Experiments are underway to determine the degradation rate constants for major microbes species identified such as Arthrobacter aurescens TC1.

6.2 MODEL IMPLEMENTATION

The model was implemented in CHAMPS-BES as below:

1. VOC mass was considered existing in gas, solid and liquid phase.
2. VOC adsorption flux, absorption flux and bio-consumption flux were implemented as sink terms, which were applied as "Field Conditions".
3. Water source was enabled to simulate the irrigation of the DBAF.

6.3 RESULTS AND DISCUSIONS

6.3.1 Air Flow through the Bed

In current model, the pressure difference between the inlet and outlet of the filter is a direct input parameter, and is obtained from the measurement with 0.229 m^3/s air passing through the entire bed (cross-section area of 1.08 m^2 and thickness of 0.2 m), which is 73 Pa. According to equation (6-3a), the gas permeability can be calculated with airflow rate and pressure drop across the filter. The calculated air permeability was 0.00069 s, and was assigned to the material in the bed. Based on above parameter input to the model, the output air flux passing through the root-bed was 0.254 $kg/(m^2s)$, which was the same as the measured air flow rate considering air density of 1.2 kg/m3 at 20°C and bed cross-section area of 1.08 m^2.

6.3.2 Moisture in the Bed

The initial moisture content in the bed was set at 0.1 m^3(water)/m^3(bed). A water source term was assigned in the field condition to simulate the periodical irrigation. The water source was turned on for three minutes every hour. Water was added into the bed at a rate of 0.09 $kg/(m^3s)$, which means 0.09 kg water was added in per cubic meter bed per second. **Figure 6-2** shows the average bed moisture content and outlet air RH change over time from simulation. It is shown that due to the scheduled irrigation, the average bed moisture content was maintained at 0.08~0.1 m^3(water)/m^3(bed). Meanwhile, the bed outlet air RH was in the range of 60% to 95%. Previous field test showed the measured bed outlet air RH was between 74% and 82%. It is shown in **Figure 6-3** that bed moisture content changes over time by simulation.

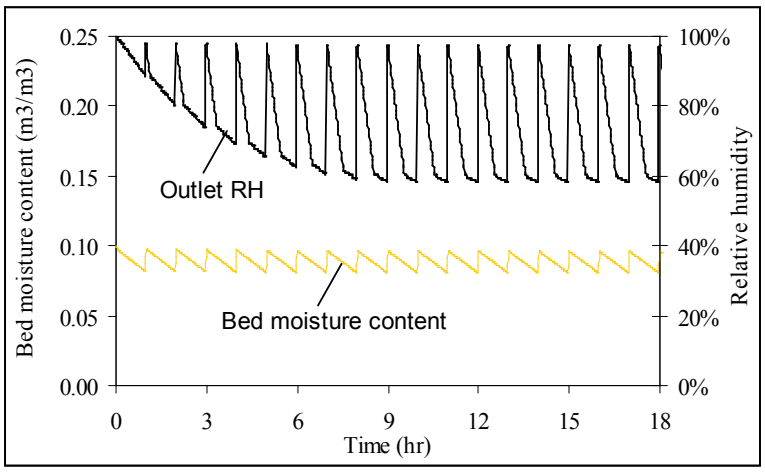

Figure 6-2. Bed average moisture content and outlet air relative humidity

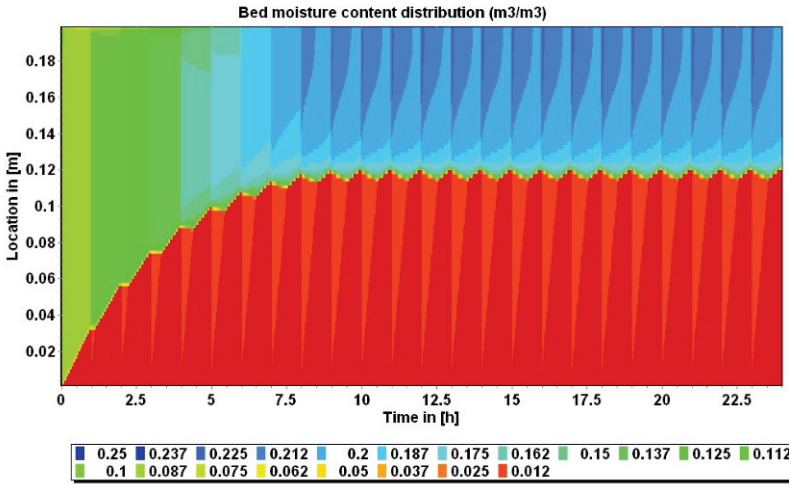

Figure 6-3 Bed moisture content distribution in real time

6.3.3 Modeling of Breakthrough Profiles

Breakthrough curve simulation was conducted to investigate the effect of the parameters involved in the filter model to the filter performance. There are two main factors during the physical adsorption process: one is the partition coefficient, and the other is the gas-to-solid mass transfer coefficient. Partition coefficient reflects the capacity of a material on adsorbing VOCs. Higher partition coefficient means bigger capability. The gas-to-solid mass transfer coefficient reflects the speed rate of mass transfer from gas phase to solid phase. Higher gas-to-solid mass transfer coefficient means faster mass transfer between gas and solid phase.

6.3.4 Effect of Partition Coefficient

In order to investigate the effect of partition coefficient, the gas-to-solid mass transfer coefficient was fixed at 5.67 m^3/s, which was for current five inches sorbent bed based on calculation. The partition coefficient of the sorbent material was set up at 1, 10, 100 and 1000, respectively. **Figure 6-4** shows the change of outlet VOC concentration at above four different partition coefficients. The inlet concentration was always maintained at 0.1 mg/m^3. The outlet concentration reached equilibrium in less than one minute when the partition coefficient was only one. Still, it took longer time to have the outlet concentration increased to the same value as the inlet as the partition coefficient increased from 1 to 1000.

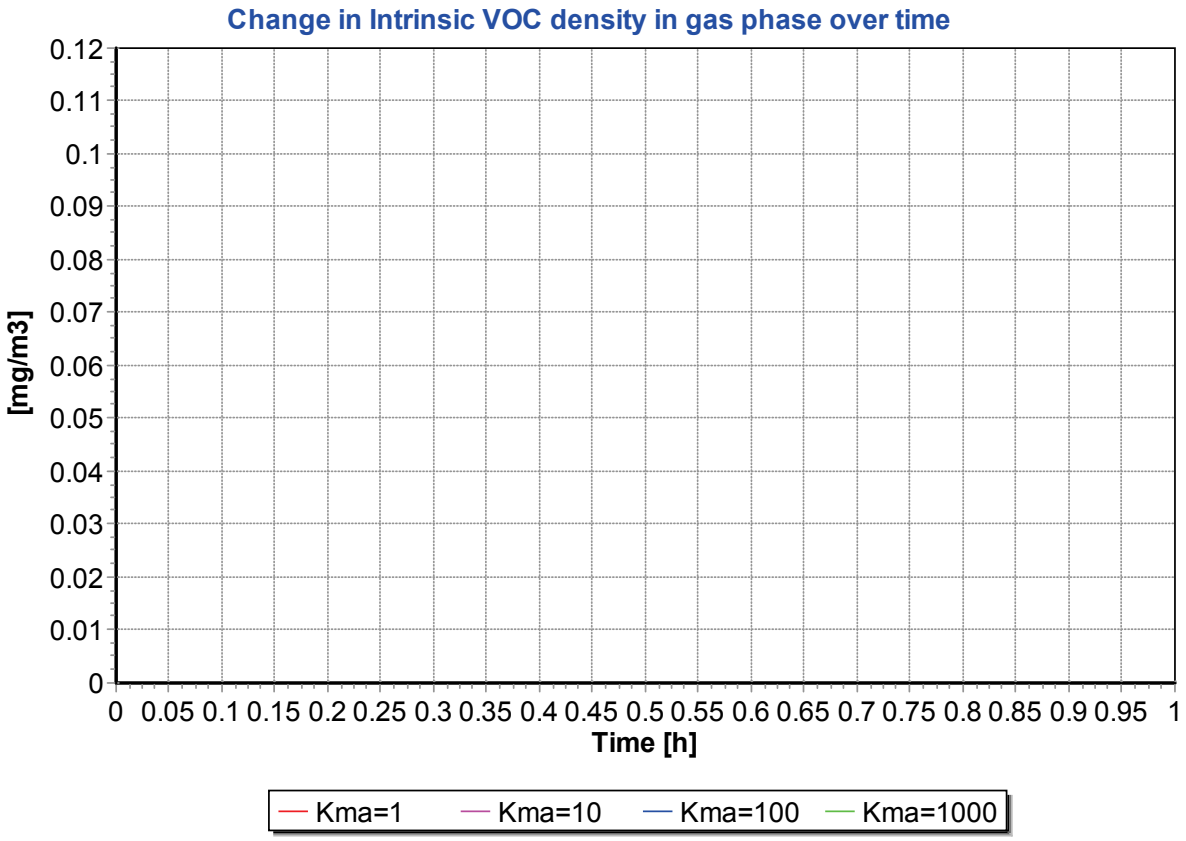

Figure 6-4. Effect of partition coefficient

6.3.5 Effect of Gas-to-Solid Mass Transfer Constant

When it comes to simulate the effect of gas-to-solid mass transfer constant, the partition coefficient was fixed at 1000, while the gas-to-solid mass transfer constant was set up at 0, 0.1, 1 and 10, respectively. The simulation result was as shown in **Figure 6-5**. For the gas-to-solid mass transfer constant of 0, it means that there was not any mass transfer occurred between gas phase and solid phase. The red curve in Figure 6-5 was for the mass transfer constant at 0, which was, as expected, that the outlet concentration increased to

the same value as the inlet concentration once the simulation started. Meanwhile, as the mass transfer constant increased, it took less time to have the outlet concentration become to the equilibrium concentration (same as inlet concentration), which indicated that the mass transfer process would become quicker as the transfer coefficient increased.

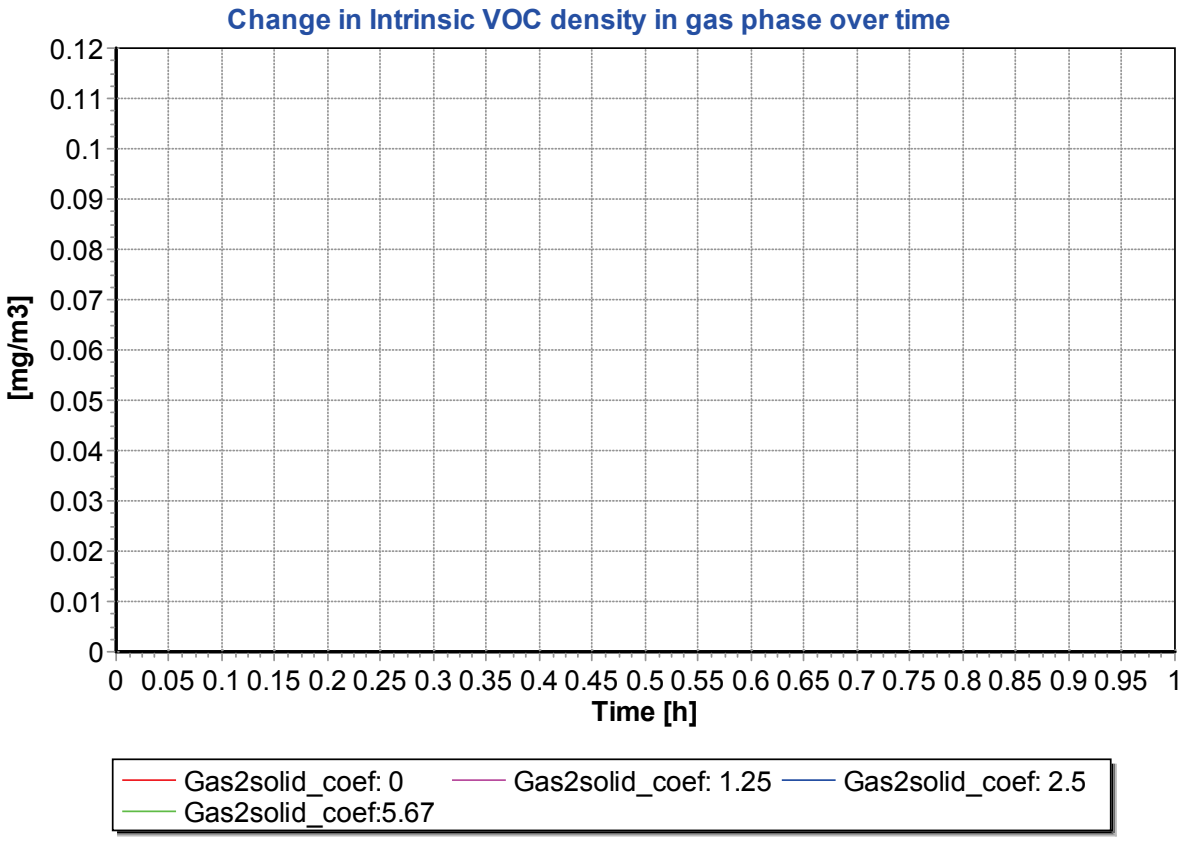

Figure 6-5. Effect of gas to solid coefficient constant

Effect of Gas-to-Liquid Mass Transfer Constant

The next step is to simulate the pollutant absorption by the wet surface of the sorbent particle. For the water soluble compounds, such as formaldehyde, the main principle of absorption is due to the presence of moisture (or water vapor). There are also two major impact factors in the absorption process, one is the Henry's Law constant, and the other is the gas-to-liquid mass transfer constant. At normal condition, the Henry's law constant is constant. For example, the Henry's law constant for formaldehyde is 1.33×10^{-5} m^3/m^3. The gas-to-liquid transfer constant reflects the speed rate of mass transfer between gas phase and liquid phase. Higher constant value means higher speed rate of mass transfer happened. **Figure 6-6** shows the effect of gas-to-liquid mass transfer constant to the breakthrough curve. There is no irrigation in this case. Initial water content of 0.2 (m^3/m^3) was assigned in the bed.. It can be seen that it took less time to

have the outlet concentration become to the equilibrium concentration (same as inlet concentration) as the mass transfer constant increase. **Figure 6-7** shows the breakthrough curve at different gas-to-liquid constant with the irrigation on for three minutes per hour. The fluctuation of the outlet concentration is due to the irrigation.

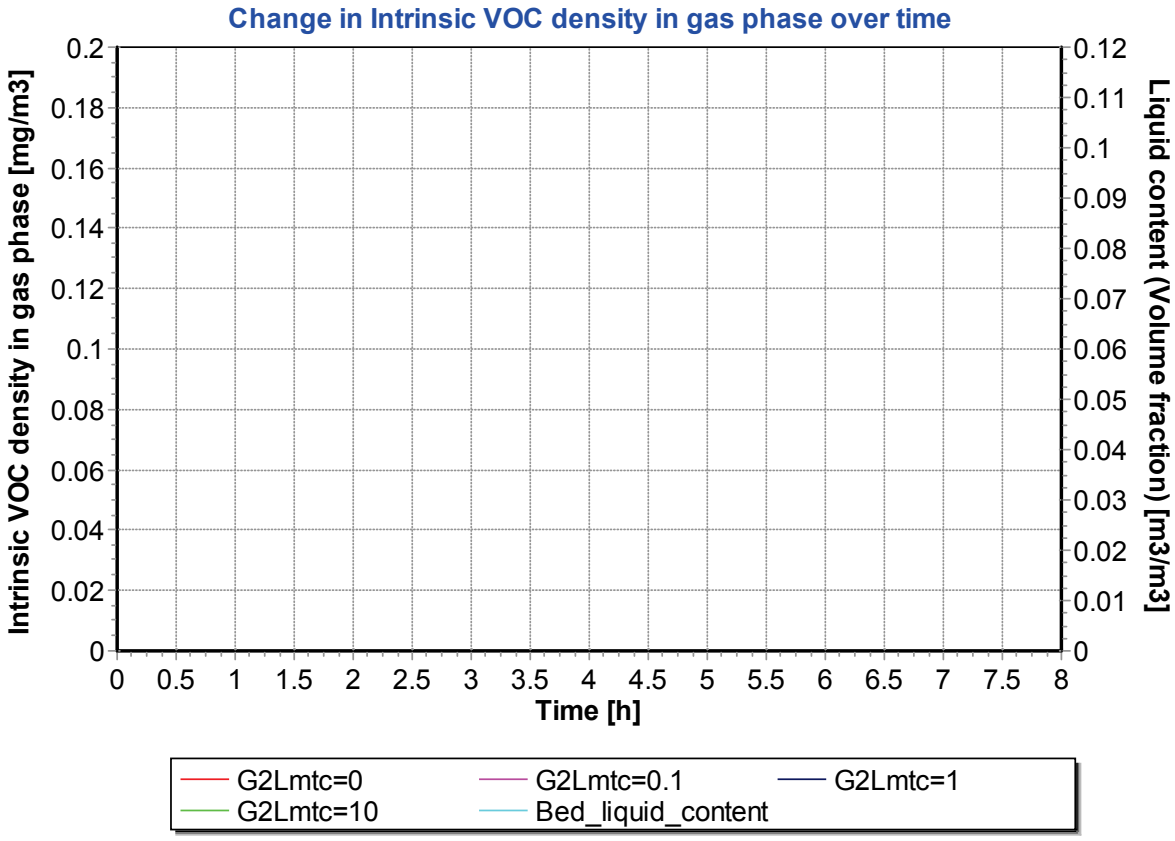

Figure 6-6. Effect of gas to liquid coefficient constant without irrigation

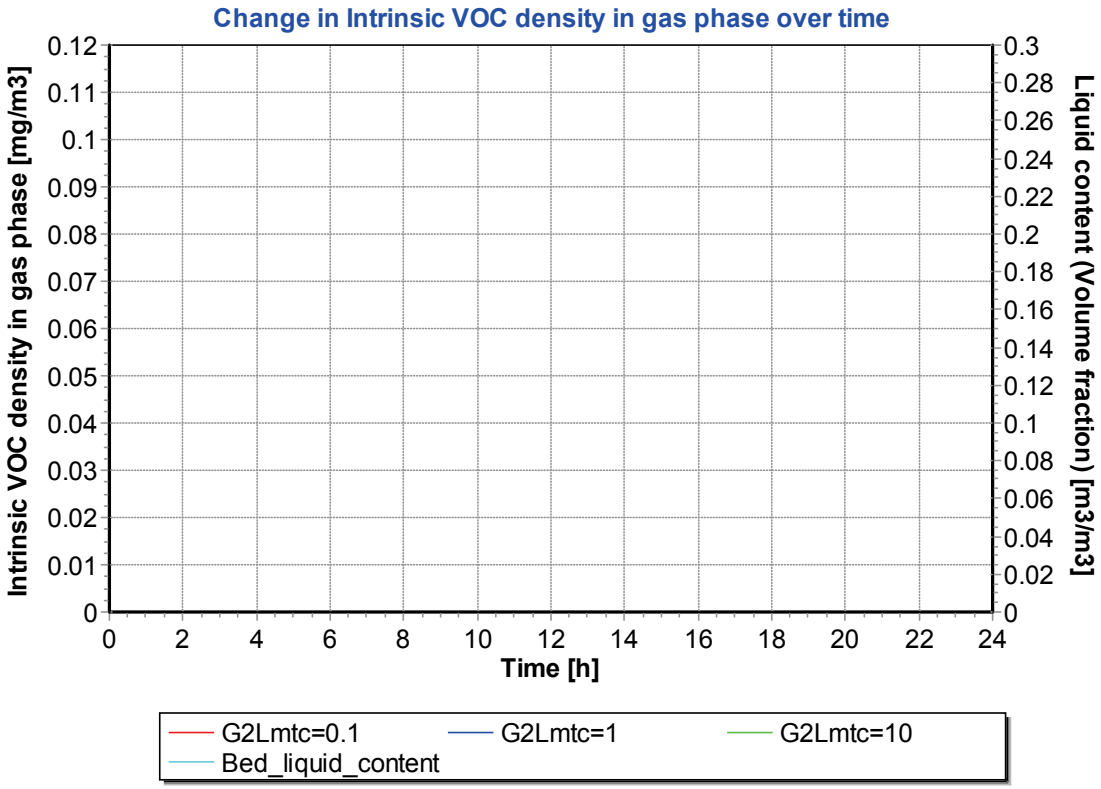

Figure 6-7. Effect of gas to liquid coefficient constant with irrigation

6.3.6 Effect of Bio-degradation Rate Constant by Microbes

As it mentioned in the model assumption, the pollutant bio-degradation follows the first-order kinetics. The bio-degradation rate constant reflects the pollutant removal due to the micro-organisms activities. **Figure 6-8** shows the outlet concentration reduction when the bio-degradation rate constant was increased from 1×10^{-7} s^{-1} to 5×10^{-4} s^{-1}. It can be seen that final outlet concentration was close to the inlet concentration when the rate constant was increased from 1×10^{-7} s^{-1} to 1×10^{-6} s^{-1}. The final outlet concentration began to become significantly lower than the inlet concentration when the rate concentration was increased from 1×10^{-6} s^{-1} to 1×10^{-5} s^{-1}. The final outlet concentration went down to half of inlet concentration when the rate increased to1×10^{-4} s^{-1}. Therefore, the critical bio-degradation rate constant is 1×10^{-5} s^{-1}, which means the bio-degradation rate of the DBAF has to be maintained above 1×10^{-5} s^{-1} to be effective in removing formaldehyde. **Figure 6-9** shows the breakthrough curve that has all the processes together. The simulation cases were conducted in this way: (1) adsorption only; (2) adsorption with irrigation; (3) absorption with irrigation; (4) adsorption and absorption with irrigation; (5) adsorption, absorption and bio-degradation with irrigation. It can be seen that the VOC removal capacity increased as more processes were added. These simulation results were only used to see how these removal processes were involved in the DBAF performance.

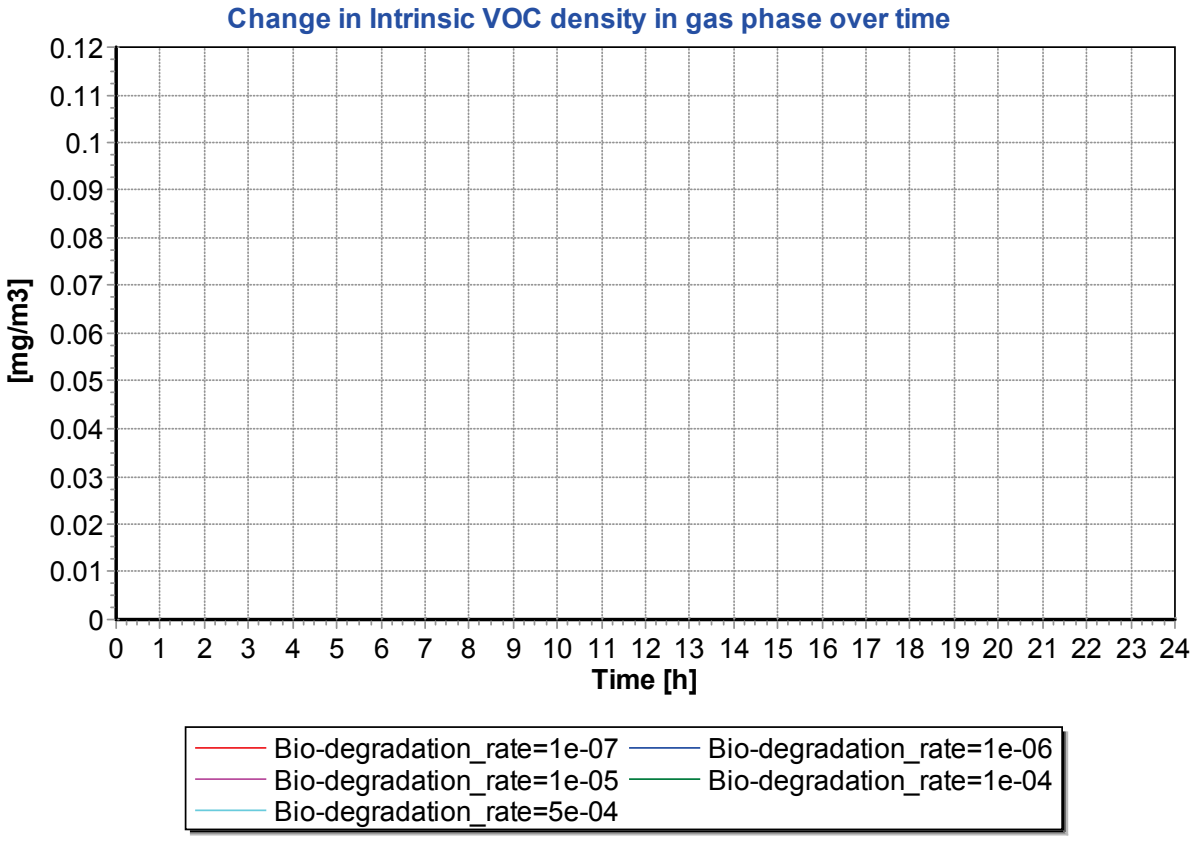

Figure 6-8. Effect of bio-degradation rate constant

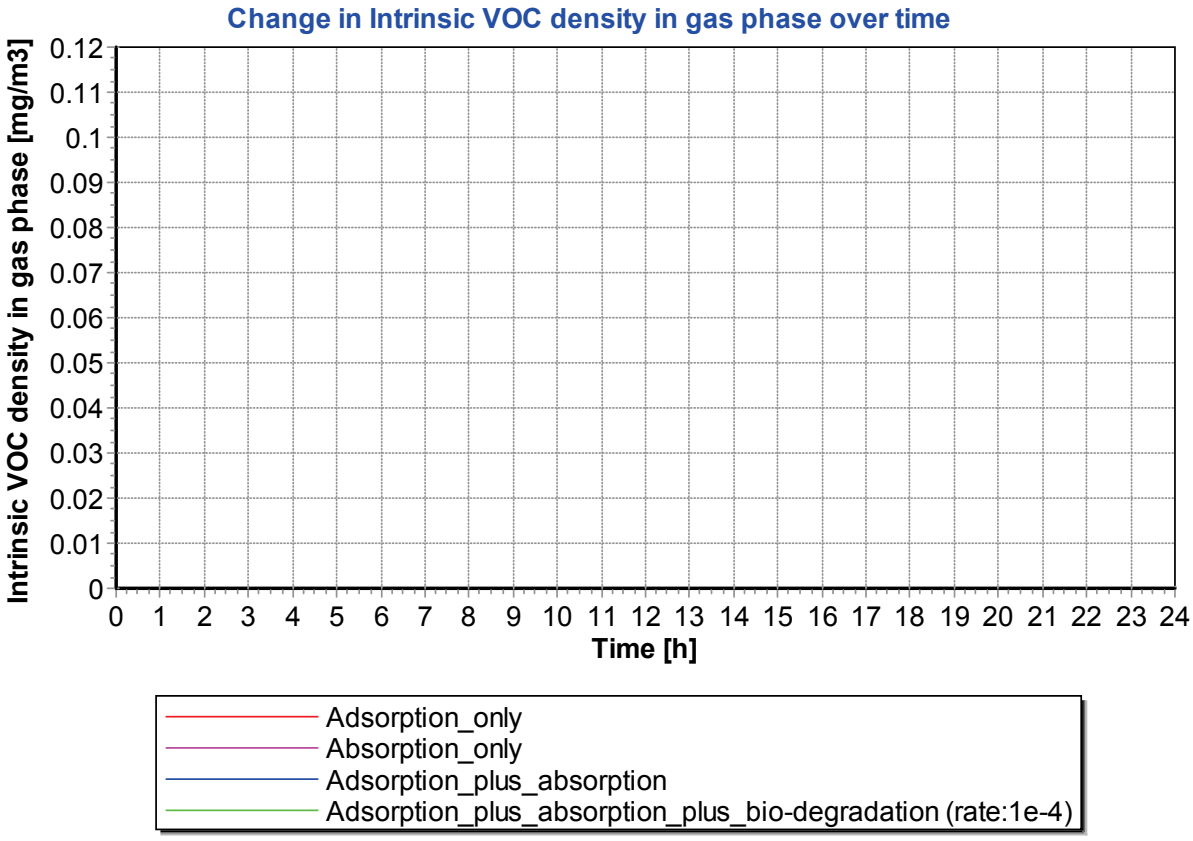

Figure 6-9. Simulation results with all the processes involved

7. SUMMARY AND CONCLUSIONS

In the full-scale chamber test, the filter system had fairly high initial removal efficiency for formaldehyde and toluene even without plants in the bed. With the plants, the filter system had even higher initial removal efficiency (90% for formaldehyde in the first three days, and over 50% for toluene). Still, it was not clear if the microbes played any role in such a short term test period.

In the long-term field demonstration test, it was found that 5% outdoor air plus the operation of the biofilter could achieve the same room formaldehyde/toluene concentration as having ventilation with 25% outdoor air. In other words, with the use of the bio-filter, the ventilation rate can be reduced from 25% to 5% of total air supply without adversely affecting the indoor air quality if formaldehyde and toluene are the target pollutants that dictate the required ventilation rate.

The effect of bed water content to the removal of formaldehyde/toluene was also studied in the field demonstration test. It was found that bed water content had positive effect on formaldehyde removal, while negative effect on the toluene removal. The single pass removal efficiencies were approximately 70% for formaldehyde and 40% for toluene when the volumetric water content was within the range of 5% to 32% in the root bed (corresponding to air relative humidity from 74% to 82% RH). Note that since only part of the total supply air was directed through the filter bed, the effects of the bio-filter operation on the indoor relative humidity was not significant (<15 %RH increase).

The single pass efficiency for formaldehyde and toluene did not show any significant decrease over a period of 300+ days of continuous operation, indicating good long-term performance of the bio-filter system, although the role of microbes in sustaining the performance is yet to be determined.

The energy consumption for the building that was integrated with such filter system was simulated by EnergyPlus. It was found that yearly energy saving potential for Syracuse climate was approximately 10 to 15% in average. The saving would be 26% if consider the heating part only, while 2% for cooling and 1% for ventilation.

Assumptions and mathematical equations used to model the processes involved in a botanical air filtration system are presented. The model was used to simulate a mixture of activated carbon and porous shale pebbles as root bed of selected plants (such as Golden Pothos). The method of implementation for the model was also described. Preliminary model verification results for airflow and moisture were reported as well. The simulation results showed that the model could describe the pressure drop and airflow relationship well by using the air permeability as a model parameter. The water source added in the model also led to the similar bed moisture content and outlet air RH as that in real test case. The implemented

model was capable of simulating all the processes in the DBAF. The simulation results improved the understanding of the real mechanisms involved in the filter system. The model can potentially be used to improve the design of dynamic botanical air filtration systems. Further experimental research is, however needed to determine the VOC degradation rates by various microbes in the root system.

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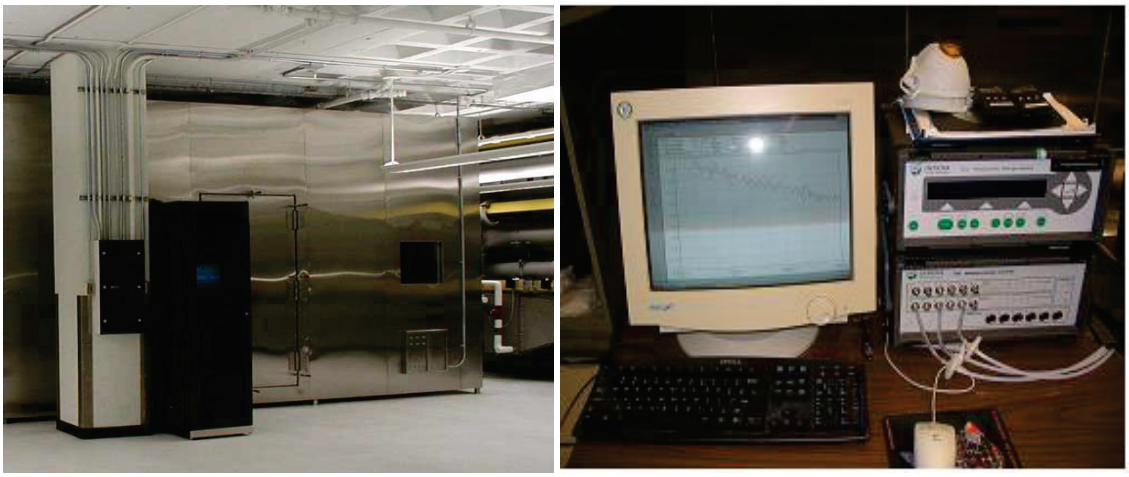
APPENDIX A FULL-SCALE CHAMBER PULL-DOWN TEST PROCEDURE

TEST FACILITY AND INSTRUMENT

The pilot/formal tests for characterizing the performance of the media filter in terms of VOC removal were carried out in a full-scale stainless steel environmental chamber depicted in **Figure A-1(a)**. The chamber has a dimension of 16 ft long x 12 ft wide x 10 ft high (4.84 m long x 3.63 m wide x 3.05 m high) and an interior volume of 1920 ft^3 (54.4 m^3).

INNOVA 1312 Photoacoustic Multi-gas Monitor was used for online measurements of the concentration of toluene equivalent ($TVOC_{toluene}$), the concentration of formaldehyde (C_{formal}), and the concentration of tracer gas (SF_6), as shown in **Figure A-1(b)**. The monitor was based on the photoacoustic infrared detection method. For $TVOC_{toluene}$, the sensitivity and response factor of the instrument for different compounds were different, so the readings from the gas monitor were only used as semi-quantitative measures to monitor the change of TVOC concentrations over time and how they differed for different operation conditions for the pilot tests.



(a) IEQ chamber **(b) INNOVA 1312 gas monitor**

Figure A-1. Test facility and instrument

TEST PROCEDURE

- Put the filter bed system into the chamber (as shown in **Figure A-2**)
- Flushed the chamber overnight then set the return air at 800 CFM to make the air in the chamber in well-mixed. The chamber was running at full-recirculation mode

- Injected SF6 to check the air tightness of the chamber system. The concentration was monitored continuously during the entire test period
- Set up 1312 photoacoustic multi-gas monitor to continuously monitor TVOC, formaldehyde and tracer gas concentration
- Preparation of tested VOCs. Weighed calculated amount of liquid toluene (target 300mg which equals to approximately 5mg/m^3 initial chamber concentration) to a glass bottle with septum; weighed calculated amount of paraformaldehyde (target 120mg which equals to approximately 2mg/m^3 initial chamber concentration) to a glass bottle with septum. The uncertainty related with injection amount would be determined from the accuracy and resolution of syringe
- Injection of tested VOCs. Quickly opened the chamber door and brought the two glass bottles (one for formaldehyde and one for liquid toluene) into the chamber. Poured the solid paraformaldehyde into one petri dish and the liquid toluene into the other petri dish on the hot plate, left the bottle (on hot plate to facilitate the evaporation of VOC residuals inside the bottle) and the cap inside the chamber. Then quickly stepped out of the chamber and closed the chamber door. The whole process was taken approximately 1 to 2 minutes
- Turned on the power of hot plate from chamber control panel. Recorded the time
- Turned off the power of hot plate after 1 h. The injection period for VOCs was one hour
- Turned on the fan power of the filter bed system to start the air filtration system. Recorded the time as the test start point.
- The test period lasted about 4 hours (The time depended on when the contaminant concentration decreased to the background level)
- Flushed the chamber once the test was done
- Downloaded test data and analyzed test results.

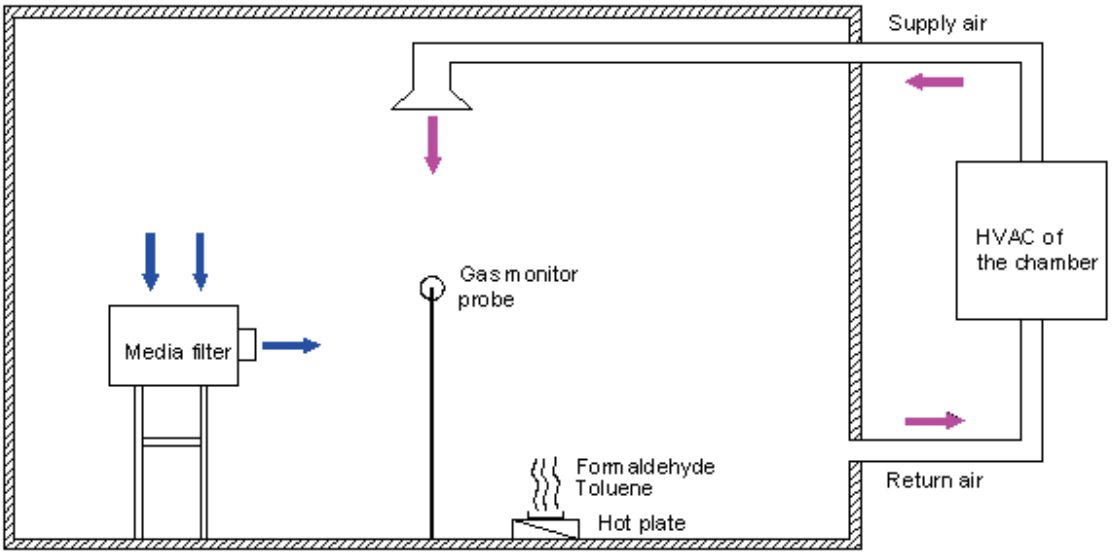


Figure A-2. Schematics of the test chamber

CALCULATION OF CADR AND REMOVAL EFFICIENCY

Three parameters had been commonly used to quantify the performance of air cleaning devices: single-pass efficiency (conversion), clean air delivery rate (CADR), and effectiveness of the device (Nazaroff, 2000). Single-pass efficiency and CADR were used here to evaluate the effectiveness of the filter bed.

Single-pass efficiency (η) represented the fraction of pollutants removed from the air stream as it passed through the device. It was defined as:

$$\eta = \frac{G(C_{in} - C_{out})}{GC_{in}} = \frac{C_{in} - C_{out}}{C_{in}} \qquad \text{(A-1)}$$

Where,

C_{in} = contaminant concentration at the inlet of air cleaner, mg/m^3 for VOC and number of particles/cm^3 for particulates.

C_{out} = contaminant concentration at the outlet of air cleaner, mg/m^3 for VOC and number of particles /cm^3 for particulates.

G = airflow rate through the air cleaner, CFM or m^3/h.

CADR represents the "effective" clean airflow rate delivered by the air cleaner. It is defined as:

$$CADR = \eta \cdot G \cdot E_d \quad \text{(A-2)}$$

Where, E_d = short-circuiting factor of the air cleaner, $Ed=C_{in}/C$, where C is average concentration in the test chamber (E_d = 1 at well-mixed condition).

CADR was calculated from the test results. The analysis was based on the well-mixed single zone model. Assuming that the air was well mixed in chamber and the contaminant removal mechanisms other than air cleaning (e.g. surface deposition effect and chamber leakage effect) were the same with and without air cleaner operating and can be characterized by a first-order rate constant k_n, the mass conservation of contaminant can be written as:

$$V\frac{dC}{dt} = -(k_n V + CADR)\cdot C, \quad (C=C_0 \text{ at } t=0) \quad \text{(A-3a)}$$

Or

$$\frac{dC}{dt} = -(k_n + \frac{CADR}{V})\cdot C = -k_e \cdot C \quad \text{(A-3b)}$$

Where,

V - volume of the testing chamber system, ft^3 or m^3,

k_n – contaminant concentration decay rate without air cleaner operating (chamber effects), min^{-1} or h^{-1},

k_e – total contaminant concentration decay rate with air cleaner operating, min^{-1} or h^{-1},

C_0 – Initial contaminant concentration inside the chamber, mg/m^3 for VOC and number of particles/cm^3 for particulates.

If CADR did not change during the test period, an analytical solution could be obtained from Equation (A-3) as:

$$C = C_0 \cdot e^{-(k_n+\frac{CADR}{V})t} = C_0 \cdot e^{-k_e t} \quad \text{(A-4)}$$

CADR was then determined by linear regression of *ln* (C/C_0) *vs. t* from the measured concentration decay curve:

$$CADR = V(k_e - k_n) \quad \text{(A-5)}$$

After the CADR was calculated, together with measured the airflow rate through the air cleaner, the removal efficiency could then be calculated by dividing the CADR by the airflow rate through the air cleaner. This calculated removal efficiency was the same as the single-pass efficiency defined in Equation (A-1) since the air in the chamber was well-mixed.

The step-by-step data analysis procedure for VOCs was summarized as follows:

1. Calculated k_n based on the measured tracer gas concentration decay or contaminant concentration decay before time zero (if the contaminant decay during the static period did not match the SF6 decay very well);

2. Calculated k_e by linear regression of $ln\ (C/C_0)$ *vs.* t from measured concentration decay curve after turning on the air cleaner (dynamic period);

3. Calculated CADR according to Equation (A-5);

4. Determined the removal efficiency by dividing the calculated CADR value by the measured airflow rate through the air cleaner.

APPENDIX B FULL-SCALE FIELD APPLICATION TEST PROCEDURE

SOURCE INTRODUCTION

In order to simulate contaminant source in the test room, 48 pieces of unused particle board were moved into the test room. The size of each piece was 48 by 32 inches. Three (3) pieces were used in each cubical, and there were totally 16 workstations in the test room. The test room was operated at 5% outdoor ventilation flow rate with 70 CFM outdoor air and 1400 CFM total supply air.

Figure B-1. Contaminant source introduced into the test room by using particleboards

VOCS IDENTIFICATION

After the particleboards were placed inside the test room, an air sample was taken at the return air duct by using a Tenax sorbent tube, and analyzed by GC/MS. **Table B-1** lists the detail the VOCs found in the room. Pentanal, Toluene, Hexanal, Xylene, Alpha-Pinene, (1s)-(b)-Pinene were selected as the target VOCs in the room. In addition, formaldehyde and acetaldehyde were also chosen as target compounds as they are typically identified as major compounds of concern in emission testing of composite wood materials.

Table B-1 Test room VOCs identification (By GC/MS)

RT	Response area	Est.Conc. (ug/m3)	VOC Name	M.W.	Formula	CAS#	Note
2.664	169,827,440	8.37	OXIRANE, TRIMETHYL-	86	C5H10O	5076-19-7	
5.059	86,847,696	4.28	MERCAPTAMINE	77	C2H7NS	60-23-1	
6.337	118,900,960	5.86	PENTANAL(Valeralde.)	86	C5H10O	110-62-3	
7.897	147,092,128	7.25	TOLUENE	92	C7H8	108-88-3	room bkgd
8.626	186,059,488	9.17	CYCLOTRISILOXANE, HEXAMETHYL-	222	C6H18O3Si3	541-05-9	tube bkgd
9.562	1,077,273,088	53.08	HEXANAL	100	C6H12O	66-25-1	
11.344	68,134,416	3.36	BENZENEETHANOL, .ALPHA.,.BETA.-DIMETHYL-	150	C10H14O	52089-32-4	
13.019	597,559,104	29.45	.ALPHA.-PINENE	136	C10H16	80-56-8	
13.714	50,035,800	2.47	CAMPHENE	136	C10H16	79-92-5	
14.348	51,328,636	2.53	CYCLOTETRASILOXANE, OCTAMETHYL-	296	C8H24O4Si4	556-67-2	
14.76	448,029,344	22.08	(1s)-(b)-pinene	136	C10H16	18172-67-3	
15.968	61,673,916	3.04	Benzaldehyde				
16.441	134,613,712	6.63	d-limonene				
16.592	88,311,400	4.35	Octanal	128	C8H16O	124-13-0	
17.88	56,756,684	2.80	Undecane				room bkgd
18.897	108,563,536	5.35	P-TRIMETHYLSILYLOXYPHENYL-BIS(TRIMETHYLS	370	C17H34O3Si3	1000079-08-1	
19.249	79,402,592	3.91	Nonanal	142	C9H18O	124-19-6	
21.382	95,913,080	4.73	PENTADECANAL-	226	C15H30O	2765-11-9	
21.518	240,076,816	11.83	2-PROPENOIC ACID, 6-METHYLHEPTYL ESTER	184	C11H20O2	54774-91-3	

Table B-2 lists the target compounds that were continuously monitored by PTR-MS. It also shows the solubility of these compounds in water, which would help to understand the filter bed performance in removing water soluble vs. non-soluble compounds.

Table B-2 Target compounds monitored by PTR-MS (Ion Mass of 21)

VOC Name	M.W.	Formula	CAS#	Solubility in water
Formaldehyde	31	CH2O	50-00-0	Soluble
Acetaldehyde	45	C2H4O	75-07-0	Soluble
Pentanal (Valeralde.)	86	C5H10O	110-62-3	Very slightly soluble
Toluene	92	C7H8	108-88-3	Insoluble
Hexanal	100	C6H12O	66-25-1	Insoluble
Xylene	106	C8H10	1330-20-7	Insoluble
Alpha-Pinene	136	C10H16	80-56-8	Insoluble

FILTER BED SINGLE PASS EFFICIENCY MEASUREMENT

The filter bed single pass efficiency (SPE) would help to understand the change of the test room contaminants concentration after the filter system was turned on. The single pass efficiency was measured as follows:

- The contaminants concentration of the filter upstream was measured for a number of five minute intervalsand the average of these five minutes data was taken as data 1;
- The sample system was switched to downstream. The contaminant concentration of the filter downstream was measured for five minute intervals and the average of these five minutes data was taken as data 2, and it was used as the downstream concentration;
- The monitor was switched back to measure the upstream concentration for the next five minutes and the average of these five minutes data was taken as data 3;
- The average of data 1 and data 3 was used as the upstream concentration;
- The filter single pass efficiency could be obtained as one minus downstream concentration divided by upstream concentration.

EFFECT OF BED WATER CONTENT TO THE SINGLE PASS EFFICIENCY

Test procedure

- The media bed was irrigated with water until it became saturated, which can be realized in this way: an automatic irrigation system was setup to achieve this. A moisture control sensor was used to continuously monitor the moisture content (M.C.) in the filter bed and it was set-up at the saturation level (50%). The irrigation was kept on running until the signal light of the moisture sensor was off, which means the media bed was saturated already
- The fan was kept running at its maximum flow rate(480cfm) until inlet air RH was close to the outlet RH: the moisture control sensor was set-up at its minimum level to avoid the fan stopping running during the test period, which means get the media bed dry gradually

- In the first half hour, PTR-MS was used to measure the contaminants concentration of upstream for five minutes, and the average was taken as data 1, and then it was switched to downstream for another 5-minute measurement and the average was taken as data 2, after that it was switched back to upstream for another fiveminute measurement, and the average was taken as data 3. The average of data 1 and data 3 was used as the upstream value, and data 2 was used as the downstream value. The single pass efficiency was obtained: one minus downstream value divided by upstream value
- After that, the test period was extended to 10 minutes for each side, then it took 30 minutes to get one single pass efficiency
- The procedure of measuring single pass efficiency was repeated every 30 minutes until the bed water content was lower than 5%, and then the filter bed single pass efficiency at different moisture level could be obtained.

TEST ROOM CONTAMINANTS CONCENTRATION MONITORING

Test Procedure

- On the first day, PTR-MS started to monitor the room concentration, and the first-two-hour test result was taken as room background, and a GC/MC sample was also taken at the same time
- After two hours, the particleboards were moved in, then four hours later, a GC/MS sample was taken to identify the VOCs existing in the room, and hexanal, pentanal, toluene, xylene, pinene, formaldehyde and acetaldehyde were selected as target compounds
- In the second day, the room ventilation was adjusted to 5% (70 CFM outdoor air) at first, then eight hours later, was increased to 50%(700 CFM outdoor air); 16 hours later, it was switched back to 5%
- Twenty four hours later, the filtration system was turned on and kept running for eight hours; then was shut off; and then the filter on/off cycle was repeated two more times
- In the second week, two more tests were done to monitor the room contaminant concentration change at ventilation of 25% and 10%.
- See **Table B-3** for the schedule for the two-week test

Table B-3 The schedule for the two-week test

Test period	Time (h)	Procedure
Week 1	0	Got PTR-MS started
	2	Moved particle board in
	24	Adjusted outdoor air to 5%
	32	Adjusted outdoor air to 50%
	45	Adjusted outdoor air back to 5%
	72	Turned on the filter
	78	Turned off the filter
	100	Turned on the filter
	108	Turned off the filter
	124	Turned on the filter
	132	Truned off the filer
Week 2	0	Got PTR-MS started (with 5% outdoor air)
	8	Adjusted ventilation to 25%
	24	Adjusted ventilation back to 5%
	32	Adjusted ventilation to 10%
	48	Adjusted ventilation back to 5%

Table B-4. Air change rate for different operation mode

Room Volume	Supply air	Operation mode	Air change rate (times/h)
9385 ft3	1400cfm	50% OA	4.5
		25% OA	2.2
		10% OA	0.9
		5% OA	0.4

APPENDIX C ENERGY ANALYSIS FOR THE NEW YORK CITY CLIMATE

Table C-1 Annual simulation result for New York city, NY

	Heating [KWh]		Cooling [KWh]		Fan energy consumption [KWh]			
	25%OA	5%OA+Filter	25%OA	5%OA+Filter	25%OA	5%OA	DBAF	5%OA+DBAF
January	4009	2807	10	8	563	536	25.2	561
February	1852	1278	4	4	588	517	24	541
March	819	602	2	1	748	671	27.6	699
April	321	301	748	740	608	601	24	625
May	145	145	2832	2752	684	684	27.6	712
June	8	8	4307	4208	756	756	26.4	782
July	1	1	4920	4570	742	743	24	767
August	7	7	4896	4626	797	797	27.6	824
September	27	27	3376	3301	645	645	25.2	670
October	355	354	753	753	648	617	26.4	643
November	760	635	2	1	604	580	26.4	607
December	1733	1086	4	3	620	545	22.8	568
Yearly total	10037	7250	21854	20966	8003	7692	307	7999
Saving		2788		888				4

Table C-2 Monthly peak load demand for New York city, NY

	Heating				Cooling				Fan energy				
NYC	0.25OA		0.05OA		0.25OA		0.05OA		0.25OA		0.05OA		0.05OA+DBAF
Month	Time	kW	Time	kW	Time	kW	Time	kW	Time	kW	Time	kW	kW
Jan.	01/23 08:00:00	168.3	01/23 08:00:00	151.1	01/23 08:00:00	0.8	01/23 08:00:00	0.7	01/12 16:00:00	3.5	01/26 13:00:00	3.0	3.1
Feb.	02/06 08:00:00	135.8	02/06 08:00:00	120.1	02/06 08:00:00	0.6	02/06 08:00:00	0.5	02/03 17:00:00	4.5	02/10 13:00:00	3.3	3.5
Mar.	03/06 08:00:00	98.0	03/06 08:00:00	87.6	03/06 08:00:00	0.3	03/06 08:00:00	0.3	03/01 14:00:00	4.5	03/17 15:00:00	4.3	4.4
Apr.	04/10 07:00:00	28.2	04/10 07:00:00	27.6	04/28 16:00:00	21.3	04/28 11:00:00	20.7	04/07 11:00:00	4.3	04/10 16:00:00	3.9	4.1
May	05/05 07:00:00	23.6	05/05 07:00:00	23.6	05/30 11:00:00	27.4	05/31 10:00:00	24.6	05/30 10:00:00	3.9	05/30 10:00:00	3.9	4.1
Jun.	06/16 07:00:00	1.1	06/16 07:00:00	1.1	06/19 07:00:00	29.7	06/19 07:00:00	29.5	06/26 08:00:00	4.1	06/26 08:00:00	4.1	4.2
Jul.	07/07 07:00:00	0.2	07/07 07:00:00	0.2	07/24 07:00:00	41.8	07/24 07:00:00	39.9	07/24 07:00:00	4.1	07/24 08:00:00	4.2	4.3
Aug.	08/31 07:00:00	1.0	08/31 07:00:00	1.0	08/07 07:00:00	29.9	08/07 07:00:00	29.9	08/21 08:00:00	4.1	08/21 08:00:00	4.1	4.2
Sept.	09/13 07:00:00	0.9	09/13 07:00:00	0.9	09/05 07:00:00	31.9	09/05 07:00:00	31.4	09/05 08:00:00	4.0	09/05 08:00:00	4.0	4.2
Oct.	10/30 08:00:00	60.8	10/30 08:00:00	60.7	10/02 16:00:00	17.4	10/02 16:00:00	17.1	10/17 15:00:00	4.4	10/19 14:00:00	4.3	4.4
Nov.	11/27 08:00:00	107.9	11/27 08:00:00	96.1	11/27 08:00:00	0.4	11/27 08:00:00	0.3	11/21 17:00:00	4.5	11/06 15:00:00	4.0	4.1
Dec.	12/11 08:00:00	143.4	12/11 08:00:00	126.4	12/11 08:00:00	0.6	12/11 08:00:00	0.6	12/22 17:00:00	4.5	12/14 15:00:00	3.3	3.4

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