Indoor Air Contaminant Removal: Full-Scale Testing of In-duct Filters

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ABSTRACT

Indoor Air Contaminant Removal: Full-Scale Testing of In-duct Filters

Hamid Kholafaei

Buildings occupants are exposed to several hundreds of pollutants in indoor environments. The utilization of in-duct ventilation filters is a promising technology in reducing the level of pollutants from indoor air. As of today, the removal performance of these filters is not clearly known. The major goal of this study is to develop an experimental method to measure the performance and service-life of full-scale in-duct Granular Activated Carbon (GAC) ventilation filters for the removal of multiple Volatile Organic Compounds (VOCs).

In this study, two sets of experiments were carried out. In the first set, the removal performance of four full-scale GAC filters with various media bed depths was measured for toluene removal. From obtained data, the applicability of the Wheeler-Jonas model in predicting the service life of full-scale GAC filters was studied and limitations were discussed.

In the second set of experiments, a 5cm-filter was tested with a mixture of representative VOCs consisting of toluene, p-xylene, n-hexane and 2-butanone. The objective was to improve understanding of the behavior of full-scale GAC filters in the adsorption of multiple VOCs. The results showed the removal performance is influenced by the physical properties of VOCs. The filter showed the highest performance in removing the p-xylene followed by toluene, n-hexane and 2-butanone. This ranking is positively

correlated to the molecular weight of VOCs. VOCs competed for adsorption on the carbon surface where lighter VOCs were displaced by heavier compounds. The results showed due to the competitive adsorption, the breakthrough time of toluene in the mixture gas test had significantly decreased in comparison to the toluene breakthrough time in the single gas test.

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I would like to express a heartfelt thank you to my parents and brothers who throughout my life always encouraged and supported my educational and personal dreams.

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LIST OF ABBREVIATIONS

ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
ASME	American Society of Mechanical Engineers
ATSDR	Agency for Toxic Substances and Disease Registry
BOCA	Building Officials and Code Administrators
CCOHS	Canadian Centre for Occupational Health and Safety
Cfm	Cubic Feet per Minute
CNS	Central Nervous System
DAS	Data Acquisition System
D-R	Dubinin-Radushkevich
EPA	Environmental Protection Agency
GAC	Granular Activated Carbon
GC/MS	Gas Chromatograph/Mass Spectrometer
HEPA	High Efficiency Particular Air
HVAC	Heating, Ventilating and Air-Conditioning
IUPAC	International Union of Pure and Applied Chemistry
MEK	Methyl Ethyl Ketone
MTZ	Mass Transfer Zone
NIOSH	National Institute for Occupational Safety and Health
IAQ	Indoor Air Quality
PERK	Perchloroethylene
ppb	Parts per Billion

ppm	Parts per Million
ppmv	Parts per Million by Volume
PTFE	Polytetrafluoroethylene
SEM	Scanning Electron Microscope
TVOC	Total Volatile Organic Compound
VOC	Volatile Organic Compound
UHP	Ultra High Performance

LIST OF SYMBOLS

English Symbols	**Description**
A	Cross Section Area of the Media Bed
C	Concentration
$C_{adsorption}$	Total Computed Capacity
C_{dc}	Discharge Coefficient of Nozzle
$C_{down,\ t}$	Downstream Concentration at Time t
$C_{up,\ t}$	Upstream Concentration at Time t
C_{R_t}	Filter Capacity at a Specific Elapsed Time
D	Nozzle Throat Diameter
d	Media Depth
E_t	Efficiency at Time t
K_v	Adsorption Rate Constant
M	Weight of Carbon Media Bed
N_U	Unit Coefficient
P_t	Contaminant Penetration at Time t
Q	Airflow Rate
R_e	Reynolds Number
$Rc_{t'}$	Retentivity at Elapsed Time t'
T_{ads}	Elapsed Time of Adsorption Test
t_b	Breakthrough Time
t'	Elapsed Time of Desorption Test

t_r	Residence Time
v	Face Velocity
W	Pore Size
W_d	Duct Width, (min)
W_e	Equilibrium Adsorption Capacity ($g_{\text{VOC}}/g_{\text{Carbon}}$)

Greek Symbols	**Description**
ρ	Density
ΔP	Pressure Difference

CHAPTER 1 INTRODUCTION

1.1 BACKGROUND

Indoor air quality (IAQ) is a serious concern since it can remarkably influence one's personal health, comfort and productivity. Indoor air is defined as "air from a non-industrial indoor environment such as dwellings, offices, schools and hospitals" (Brown *et al.* 1994). The United States Environmental Protection Agency studies show that most people spend about 90% of their time in indoor environments (EPA 2007-b).Their studies also indicate that indoor air pollutant levels can be higher than outdoor levels especially in the largest and most industrialized cities. Therefore, controlling indoor air pollutants has become an important research area in recent years.

In addition to its negative effect on health, poor air quality also adversely affects the economy. It was estimated in 1992 that poor indoor air quality costs over $1 billion/year in direct medical expenses and approximately $60 billion/year due to lost productivity in the workplace (Hennessey 1992). Reports by Romm (1998) indicate that the net dollar benefit of improving indoor air in office buildings is estimated to be around 8 to 17 times above the costs of improving indoor air quality.

Generally, indoor air pollutants can be divided into two major groups:

1. Particles (dust, mist, pollen, bioaersols, etc.)
2. Gasous contaminants (volatile organic compounds, combustion gases, etc.)

Volatile organic compounds (VOCs) comprise the majority of indoor contaminants. Hundreds of VOCs are identified in indoor environments. Their physical properties include boiling points in the range of approximately 50 to 250°C, and vapor pressures above 10^{-3} to 10^{-4} mm Hg (ASHRAE 2001).

VOCs originate from various sources such as new building materials and furnishings, consumer products, office equipment, tobacco smoke and polluted outdoor air. VOC contaminants may cause acute problems including skin or eye irritations, allergic reactions, offensive odors and chronic effects including cancer. Health effects caused by exposure to VOCs vary and depend upon the types and concentration of VOCs, the frequency and duration of exposure and individual sensitivity (Thad 2001).

In general, there are three strategies to improve indoor air quality in buildings:

1. Source control: This strategy is the most effective and economical. Removing the source of contaminants prevent them from generating and spreading contaminants. However, the source of contaminants in a building cannot always be identified easily and source removal is not always practical. For example, the building materials themselves can be the prominent source of gasous contaminants (Muller and England 1995).

2. General ventilation control: When source control is not practical, ventilation control is the next option. This strategy involves the introduction of diluted air into the building. However, like source control this method has some limitations. This method increases the energy consumption which may not be economical. Furthermore, most ventilation air used for dilution originates from outside the

building and in many urban environments the outside air contains strong outdoor pollution sources such as CO, NO_X, SO2, and O_3. Therefore, applying this air in ventilation might replace one group of contaminants by another and even possibly increase the total contaminant concentration in the building.

3. Control by filtration and purification: When the above methods are not sufficient and gas contaminants are fully dispersed indoors at a low concentration, filtration should be applied. This technique is a key strategy in improving IAQ while reducing significantly the ventilation load. Application of air cleaning devices has grown significantly as new building structures are designed to be airtight due to energy efficiency measures. In this strategy, air filters are installed in the heating, ventilation and air-conditioning (HVAC) system. Therefore, gasous contaminants are effectively removed by increasing the recirculation rate of the air through the gas-phase filtration system.

To decrease the level of indoor pollutants, both particles and gasous contaminants need to be removed. Filtration of airborne particles has been widely studied and different control devices are available in the market. Standards for evaluation of the performance of particulate filters have been extensively established (ASHRAE Standards 52.1-1991, 52.2 -1999). However, limited studies have been conducted on the filtration of gaseous contaminants from air obtained from indoor environments. Currently, there is a lack of standards for determining the performance of gaseous air cleaning systems. Standards provide the necessary information for HVAC designers in order to determine the appropriate gaseous air cleaning system. Standards also assist designers in creating suitable air cleaners for all types of building structures and determine a proper maintenance schedule for the air cleaners.

As mentioned previously, VOCs are the main type of gaseous contaminant found to reduce the quality of indoor air. Different technologies are used in air cleaning devices to remove indoor VOC pollutants. Sorption filtration is the most widely used gaseous air cleaning mechanism in non-industrial buildings (VanOsdell 1996). Depending on the application of air cleaners, different adsorbent/filtration media such as activated carbon, activated alumina and zeolite are used (Guo *et al.* 1996). According to Zhao *et al.* (1998), an ideal adsorbent should have a large pore volume, hydrophobic properties, no catalysis effect, high thermal stability and, ease of regeneration. In some cases, adsorbents can be impregnated with selected chemicals (chemisorption) to enhance its performance in removing target contaminants (ASHRAE 1999). For example, activated aluminum impregnated with potassium permanganate ($KMnO_4$) can be used to remove low molecular weight compounds such as formaldehyde (Thad 2001). Activated carbon, especially granular activated carbon (GAC), is the most common media in removing gas contaminants in indoor air (VanOsdell and Sparks 1995). Although activated carbon is increasingly used to remove indoor gasous contaminants, filter performance data is not well documented due to limited studies. Currently, there are no standards for ranking the performance of air cleaners that remove VOCs from indoor air.

Furthermore, the development and application of standard methods will provide better protection of building occupants against the hazardous chemical threats which in recent years has become an important concern in building design. With this threat, HVAC systems in buildings can be used as a potential targets to inject and distribute hazardous contaminants into buildings.

1.2 OBJECTIVES

The objectives of this study are:

- To develop an experimental methodology to simulate the removal performance and service-life of full-scale GAC in-duct ventilation filters under controlled conditions.
- To study the applicability of the Wheeler-Jonas model to predict the breakthrough time of full-scale gasous air filters.
- To design and develop an experimental set-up including a full-scale chemical generation system and an on-line gas sampling and analysis system.
- To apply the new experimental set-up and the developed experimental method to study the impact of multiple pollutants on the service life of full-scale GAC filters.

1.3 THESIS OUTLINE

Chapter 2 explains the fundamentals of adsorption and mass transfer in activated carbon filters and provides critical reviews of previous research on the relationship between VOC characteristics and removal performance of GAC filters. Chapter 3 describes the experimental set-up and details of designing the chemical generation system and on-line gas sampling and analysis system specifically designed to assess the impact of multiple pollutants on the performance of full-scale gasous air filters. Chapter 4 illustrates the test procedure and developed analysis methods to study the performance of GAC filters. Also, quantification methods applied to determine the removal efficiency, capacity and retentivity of GAC filters are explained. Chapter 5 presents and discusses the experimental results stemming from this research. Moreover, it investigates the applicability of the Wheeler-Jonas model for full-scale gas-phase filters. Finally, Chapter 6 provides the conclusions and recommendations for future work.

CHAPTER 2 LITERATURE REVIEW

2.1 INTRODUCTION

In recent years, society has recognized the importance of reducing building energy consumption while maintaining acceptable indoor air quality and thermal comfort. This preference emphasizes the need for economical solutions that utilize effective methods to remove gaseous pollutants from indoor environments. The high cost of conditioning outdoor air encourages HVAC designers to focus on increasing the amount of recirculated air in buildings. Sorption filtration is one of the common methods used in removing gaseous contaminants from indoor environments. It is a practical method in decreasing energy consumption. In this method, recirculated air is cleaned without the need to condition extreme outdoor air (ASHRAE 62-1989). Section M-1603.1.1 of the Building Office and Code Administrators (BOCA) allows up to 85% air to be re-circulated when the HVAC system is equipped with efficient air cleaners. Therefore, effective filtration and purification can be a solution for improving IAQ while reducing energy consumption.

In today's market, the most commonly used filters for air cleaning are designed to capture particles while being ineffective in removing gas-phase pollutants, such as VOCs. However, gasous air cleaner technology has not been widely accepted in the market because there are no standards in this field. ASHRAE has supported several research projects to study practical test methods for measuring the performance and capacity of gas-phase air filter devices for indoor air application (VanOsdell 1994). A standard (Standard 145.1 P) has been proposed by ASHRAE. However, it focuses mainly on the media performance and consequently can not be used for ranking the overall performance of air cleaners in typical-use conditions. Therefore, for the purpose of this study, a methodology has been developed to investigate the performance and service life of gasous air filters in the application of mechanical ventilation system.

In this chapter, the fundamentals of the adsorption process and mass transfer in activated carbon filters are explained. A review of tests methods in evaluating the performance of GAC filters is covered. And finally, previous research on the relationship between VOC characteristics and breakthrough time of GAC filters is explained along with the limitations of these studies.

2.2 ADSORPTION PROCESS

The adsorption process is a surface phenomenon which involves the transfer of a material from the gas phase (adsorbate) to a solid or liquid surface (adsorbent). Depending on the nature of the forces involved, the adsorption process may be classified as physical or chemical. Physical adsorption is caused by relatively weak intermolecular forces termed van der Waals (Ruthven 1984). On the other hand, chemical adsorption which usually abbreviated to chemisorption, involves essentially the formation of chemical bond between the surface of adsorbent and adsorbate (Ruthven 1984).

Physical adsorption can be distinguished by chemisorption according to some general features. During adsorption, a quantity of heat, described as heat of adsorption, is released. The heat of adsorption in physical adsorption is low compared to that of chemisorption. In chemisorption, the chemical bonds which are approached by large interaction potential, lead to high heats of adsorption. While the heat of physical adsorption is usually of the same order of magnitude as the latent heat of evaporation of the adsorbate, the heat of chemisorption is more than two or three times of latent heat of evaporation (Young 1962, Ruthven 1984). Physical adsorption is a general phenomenon and does not involve the sharing or transfer of electrons. It will occur with any gas-solid system that has appropriate temperature and pressure conditions. However, chemisorption will take place only if it involves the formation of chemical bonding between the adsorbate and the solid surface (Koltuniac 1986).

The interactions in physical adsorption are fully reversible and enables desorption at the same temperature. However, chemisorption involves chemical bonding and is irreversible. In physical adsorption, adsorbed molecules are free to cover the entire surface. Chemisorption, in contrast, is highly site specific and adsorbed molecules are fixed at particular sites. As result of sharing electrons with the surface, chemisorbed materials are limited to the formation of a monolayer on the surface of adsorbent (Noll 1992). However, physical adsorption can occur either as monolayer or multilayer adsorption and the adsorbed layer is always in equilibrium with the compound molecules in the gas phase (Attard and Barnes 1998).

2.3 ACTIVATED CARBON

Activated carbon is a solid and porous material and it is the most common adsorbent in HVAC systems (VanOsdell and Sparks 1995, Henschel 1998, ASHRAE 2007.a). It is commonly made in a two-step process. First, carbonaceous material is decomposed by heating until all organic compounds except the carbon are volatized. Then, the carbon is activated with steam or carbon dioxide at high temperature of 700-1100°C (Amundson and Kasten 1952).

Activated carbon can originate from different sources such as wood, coconut, peat, coal, sawdust and cellulose residues (Lambiotte 1942). Activated carbon has large surface area and pore volume which makes it a suitable media for the removal of VOCs. Generally, activated carbon is produced in different forms including powders, cylindrical, spherical beads, fibres and granules that can be used in air cleaning systems (Henschel 1998). In this study, the performance of air cleaners filled with the granular activated carbon (GAC) has been studied.

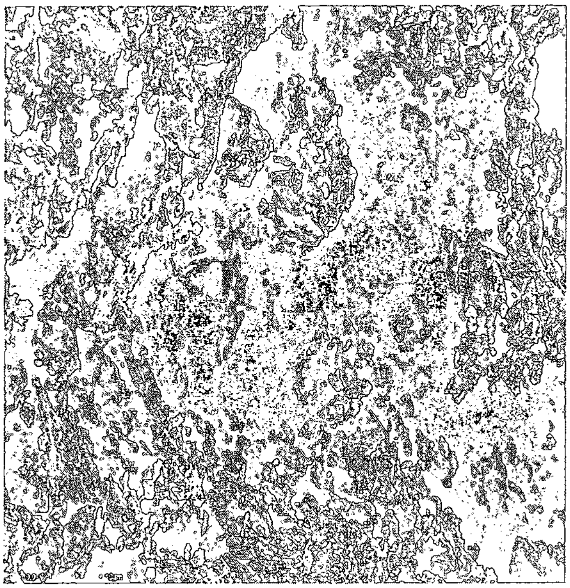

Figure 2-1: SEM photograph of activated carbon (Adapted from Haghighat *et al.* 2008)

Figure 2-2: The surface of granular activated carbon (Adapted from Novak 2007)

Activated carbon is hydrophobic and organophilic. It is composed mostly of neutral carbon atoms with no electrical gradient between molecules. Therefore, due to non activated with steam or carbon dioxide at high temperature of 700-1100°C (Amundson and Kasten 1952).

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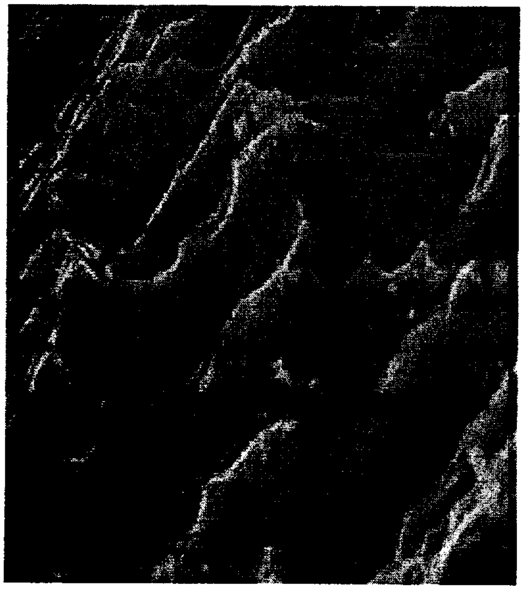


Figure 2-2: The surface of granular activated carbon (Adapted from Novak 2007)

Activated carbon is hydrophobic and organophilic. It is composed mostly of neutral carbon atoms with no electrical gradient between molecules. Therefore, due to non polarity of carbon surface, carbon adsorbents tend to adsorb nonpolar compounds rather than polar (Hines *et al.* 1993).

The porous structure is the most important property of activated carbon. Figure 2-1 demonstrates the scanning electron microscope (SEM) of activated carbon. Adsorption capacity and dynamic adsorption rate of activated carbon depends on the total volume, size and shape of the pores. According to the International Union of Pure and Applied Chemistry (IUPAC 1972), pores are classified as follows:

- Micropores: $W < 20$ Å
- Mesopores: 20 Å $< W < 500$ Å
- Macropores: $W > 500$ Å

W is the pore size which is defined by the diameter of a cylindrical pore or the distance between two sides of a slit-shaped pore.

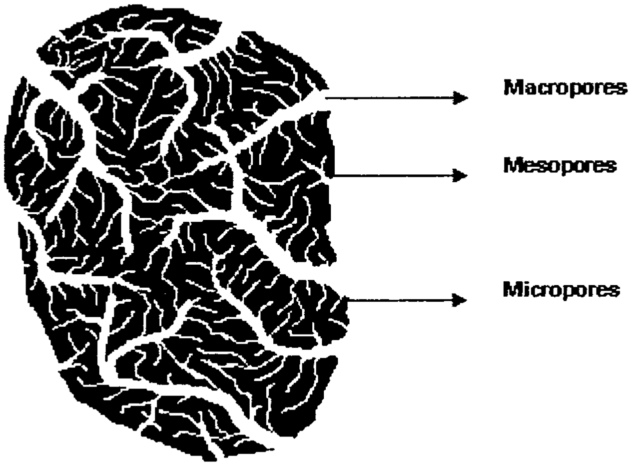


Figure 2-3: Structure of different types of pores in the activated carbon particle
Adapted from: www.roplex.co.uk/images/ActCbn3.gif

This classification is according to the influence of each pore size on the adsorption forces in the adsorbate molecule (Lee 2003). Adsorption forces are the highest in the micropores because micropores comprise the largest proportion of internal surface of activated carbon. Furthermore, the pore walls in micropores are closer together which creates a greater amount of adsorption force. Therefore, adsorption first takes place at micropores and progressively fills the lower energy sites. Micropores play a significant role in the removal of indoor VOCs (Foster *et al.* 1992). However, very large molecules may not be adsorbed on some sizes of micropores because of molecular sieve effects (Bansal and Goyal 2005). Thus, other pores of activated carbon with larger width adsorb the larger molecules if adsorption energy is adequate to hold the compounds.

2.4 MASS TRANSFER STAGES IN ACTIVATED CARBON

Mass transfer between activated carbon and gasous contaminant includes the following steps (ASHRAE 2007.a):

1. External diffusion: the gasous contaminant molecule diffuses through the boundary layer surrounding the adsorbent granule and transfers from bulk fluid to the external surface of the carbon. The external film mass transfer coefficient and the transferred compound concentration gradient between the bulk of the gas and solid surface determine the external diffusion rate (Noll *et al.* 1992). Hence, the diffusion rate decreases as contaminant load increases on the carbon surface. The net flow of gasous contaminant is toward the carbon surface as long as the concentration of contaminant in gas is higher than granular surface. Moreover, the diffusion rate is reduced in very low gas stream concentrations (ASHRAE 2007-a).

2. Internal diffusion: the contaminant molecules which penetrate the pore network inside the carbon diffuse into the pores and occupy a portion of the surface. Adsorption rate is higher and diffusion distances are lower for micropores.

3. Surface adsorption: the molecules of the contaminant are attached to the carbon surface and result in releasing adsorption energy. This step is relatively faster than other steps and controls the equilibrium between two phases (Noll 1992). Adsorbed molecules can be desorbed when either pure air moves through the bed or when replaced by another compound that has a stronger bond to the adsorbent surface or a much higher concentration.

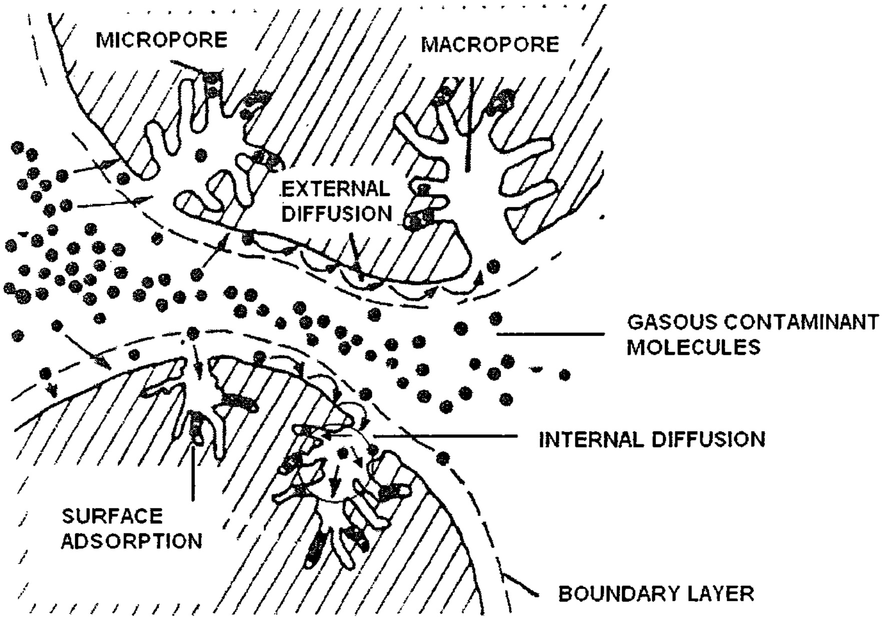


Figure 2-4: Mass transfer stages in the activated carbon (adapted from ASHRAE 2007-a)

2.5 FUNDAMENTALS OF DYNAMIC ADSORPTION

The concept of the adsorption process is useful to know how the GAC bed is capable of removing VOCs. Adsorption of gasous contaminants by the GAC media is a dynamic process. Adsorption in GAC is illustrated by movement of a concentration wave through the media bed, as shown in Figure 2-5. At the beginning, the media removes all of the inlet contaminants and the clean air leaves the media. The area in which transfer of contaminants from the gas to GAC takes place is known as the mass transfer zone (MTZ) (Noll *et al. 1992*).

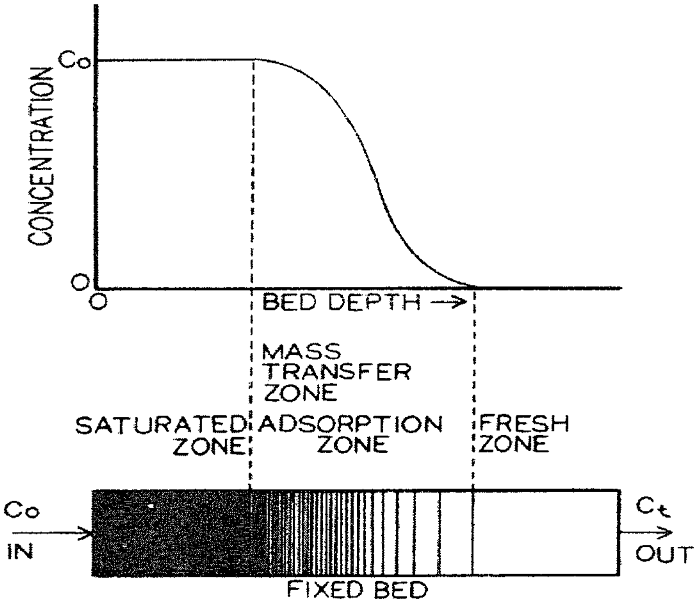


Figure 2-5: Development of contaminant gas concentration profile in packed bed of GAC (adapted from Noll *et al.* 1992)

The length of MTZ depends on the contaminant characteristics, air velocity through the media bed, inlet concentration and environmental conditions (Hunter and Oyama 2000). As the gas flow continues, the MTZ gradually moves through the bed and first layers of carbon are saturated by contaminants. As the saturated part of the bed increases, the MTZ gradually leaves the bed. The fraction of the inlet concentration which passes untreated through the bed is called the breakthrough. Over time, the contaminant load in the bed increases and the breakthrough rises and the outlet concentration eventually reaches the inlet concentration. At this point, the media bed is saturated and there is no more adsorption.

The time between the beginning of adsorption and the time in which effluent concentration reaches a specific breakthrough fraction is known as breakthrough time (t_b). The plot of breakthrough versus time profile is defined as breakthrough curve. The efficiency of GAC decreases while the breakthrough increases until the media bed is completely saturated and the breakthrough reaches unity.

2.6 THE WHEELER-JONAS MODEL

The dynamic performance of an adsorbent bed challenged with a constant concentration of adsorbate has been modeled by various kinetic reaction equations. Among them, the Wheeler-Jonas model can be used as a simple equation in predicting the breakthrough times of filters filled with GAC to remove organic compounds (Wu *et al.* 2005):

$$t_b = \frac{M.W_e}{Q.c_{up}} - \frac{W_{e}.\rho_b}{K_v.c_{up}} \ln\left(\frac{C_{up} - C_{down}}{C_{down}}\right), \qquad \text{Equation 2-1}$$

where

t_b= the breakthrough time (min)

M= the weight of carbon media bed (gram)

W_e= the equilibrium adsorption capacity (g_{voc}/g_{carbon})

$C_{up,\,down}$= the upstream (inlet) and downstream (outlet) concentration (g/cm^3)

Q= the volumetric flow rate through the bed (cm^3/min)

ρ_b= the bulk density of carbon (g/cm^3)

K_v= the adsorption rate constant (min^{-1})

The equation has been commonly used to predict the service life of carbon cartridges in removing organic compounds. However, research is required to investigate the application of this model in full-scale GAC in-duct ventilation filters; one of the objectives of this study.

2.7 APPLICATION OF GAC IN THE HVAC SYSTEM

As noted earlier, GAC is the most commonly used media for general indoor gasous contaminant removal purposes. This media is held in retaining structures such as panels, media trays and modules. These containers are perforated structures that allow air to pass through the removal media for treatment.

Depending on the application in buildings, granular activated media are available in two classes: total (full)-detention and partial-detention units (ASHRAE 2007.a). Full-detention units are suitable when an air filter with a high performance is required. For instance, GAC filters in total-detention units are necessary in protection of buildings against the industrial accidents such as the spilling of chemical agents or terrorist attacks. Commonly, a filter with a deep media bed is used in the total-detention units to provide sufficient contact time between the sorbent media and gasous contaminants. The filter with a deep media bed has a high removal performance but this high media thickness causes high pressure drop and results in increasing the energy use of the HVAC fan.

On the other hand, partial-detention units are useful when 100% removal collection of contaminants is not necessary. They have lower pressure drop and therefore less energy use. Unlike the full-detention units, 50% of the air or more may bypass the media bed and remain untreated (ASHRAE 2007.a). Furthermore, the filter sealing mechanism is different in a partial-detention unit than a full-detention unit. In a partial-detention unit, no special effort is required to seal the filter to the duct. However, in a full-detention unit, a great sealing mechanism is required to ensure that air is fully treated by the sorbent media bed (ASHRAE 2007.a).

2.8 TEST METHODS

Test methods for the gasous contaminant removal media are classified as static and dynamic (Rivers 1988). In a static test, the adsorbent is brought into equilibrium with certain contaminant(s). The purpose is to investigate the adsorbent/adsorbate interactions to obtain an adsorption isotherm. Adsorption isotherm shows the equilibrium capacity of adsorption media for a contaminant (adsorbate) as a function of either adsorbate concentration or partial pressure in gas phase, at a constant temperature. Adsorption isotherms such as Dubinin-Radushkevich (D-R) equation obtained from static tests can be combined into mass transfer models to predict the dynamic performance of an adsorbent. Dynamic (non-equilibrium) tests can be conducted in a wide range of conditions of adsorbate/adsorbent interactions as well as gas flow, particle size of contaminant, media packing and pore size distribution (VanOsdell 1994). Dynamic test methods can provide useful information such as removal performance and service-life of gasous air filters for the HVAC designers.

Dynamic tests can be carried out in an open loop, a closed-loop, or a partially closed-loop system. In an open loop system, it is easy to control the upstream concentration and humidity at desired constants levels. In a closed-loop or a partially closed-loop system, it is not simple to have a constant upstream concentration. This is because all or a part of the downstream air (the air that has passed through the filter) would return to the system as the inlet air (Lee *et al.* 2006). Most of the past experiments utilized open loop systems to study the removal performance of gas filters in removing VOC.

Normally, experiments for evaluating the performance of sorbent media such as GAC have been conducted on a small scale media (Mahajan 1987, Liu 1990, VanOsdell *et al.* 1996, Angelsio *et al.* 1998 and Guo *et al.* 2006). In fact, full-scale experiments to study gasous air filters in removing VOCs have been rarely conducted. Therefore, the performance of full-scale GAC in-duct ventilation filters in removing VOCs is not clear and more research is needed in this area. Generally, results from full-scale tests are more realistic, because some challenges such as air leakage around the filter holder or non-uniform distribution of sorbent media in the filter which may occur in a real HVAC system can be studied only in a full-scale system. Bastani *et al.* (2009) developed a full-scale test facility to investigate the removal efficiency of commercial gas-phase air cleaning devices. However, the developed system was not capable of measuring the removal performance of air cleaning devices exposed to a mixture of contaminants.

Therefore, as the major goal of this study, the experimental method is improved to overcome the limitations of the previous method.

2.9 EFFECTIVE PARAMETERS ON THE REMOVAL PERFORMANCE OF GAC FILTERS

Generally, the performance of adsorbent-based air cleaners depends on different parameters such as the properties and amount of sorbent media, the properties of VOCs, the velocity and flow rate of air passing the filter and environmental conditions such as relative humidity and temperature (Guo *et al.* 2006).

In this section, the impact of characteristics of VOC contaminant including the VOC type, VOC concentration and multiple VOCs on the service life a GAC filter is discussed. Previous research on these parameters is reviewed and the limitations of these studies critiqued.

2.9.1 Physical/Chemical Properties

Different studies have been conducted on the influence of gas contaminant on the removal performance of activated carbon filters. It is generally accepted that removal adsorption of carbon filters depends on the molecular weight, polarity, boiling point and vapor pressure of VOCs (Thad 2001). The overall review on different studies describes a common statement; the performance of a GAC filter improves as the molecular weight and boiling point of VOC increases and the vapor pressure and polarity of organic compounds decrease. Also, based on the boiling points of chemical compounds, the quality of adsorbed gas is categorized by (VanOsdell *et al.* 1996):

- Well adsorbed in boiling points above 0° C
- Moderately adsorbed in gases with boiling points between -100° C to 0° C and critical temperatures between 0° C and 150° C such as formaldehyde and ethylene
- Not easily adsorbed in lighter gases (e.g., oxygen, nitrogen and methane)

Therefore, GAC filters expect to show extremely low adsorption performance in removing light molecular weight and polar VOCs with relatively low boiling points (e.g., formaldehyde, vinyl chloride and methylene chloride). In fact, the MTZ of these compounds, especially in a low concentration, moves quickly through the carbon bed resulting in an accelerated breakthrough.

Chen *et al.* (2005) investigated the initial performance of fifteen commercial air cleaners tested in a full-scale chamber. The chemical components introduced to filters include a mixture of 16 VOCs chosen among different chemical categories in low concentration (1 mg/m^3 each). Their results show that for sorbent-based products including activated carbon filters, the efficiency increased with the increase of boiling point and molecular weight, and decreased as the vapor pressure of VOC compound increased. However, activated carbon was not sufficient for removing very volatile organic compounds such as formaldehyde, acetaldehyde, and dichloromethane and specific sorbent materials (e.g., activated alumina impregnated with potassium permanganate) was required to improve the removal efficiency.

Nelson and Harder (1976) studies shows the similar findings; more volatile VOCs have shorter breakthrough time. They studied the service life of the organic respirator cartridges filled with granular activated carbon. They passed individually a wide group of VOCs in high concentration of 1000 ppm through the cartridges. Results show that generally activated carbon can not effectively remove highly volatile compounds and the service life of the cartridge was short in removing VOCs with low molecular weights, boiling points and high vapor pressures. However, within each class of solvent, a linear relationship between solvent boiling points and breakthrough times was not observed.

The performance of three different types of GAC when challenged individually with toluene, ethyl acetate and cyclohexane was examined by Haghighat *et al.* (2008). Tests were conducted in a closed-loop dynamic system. Their results show that in all tests, the filter had better performance in removing toluene as compared to ethyl acetate and cyclohexane. The reason stems from the fact that toluene has stronger bonds with the carbon surface due to higher values of boiling point and molecular weight than ethyl acetate and cyclohexane.

2.9.2 Inlet Concentration

Levels of contaminants in the indoor environment are different and depend on the source of the contaminants. VanOsdell and Sparks (1995) inspected three emission scenarios that introduce VOC contaminants in indoor air:

- High concentration and short time incident such as spilling of a VOC material
- A medium emission and medium duration event such as painting a room
- Low-emission and long duration sources of VOC such as building materials

The VOC concentration affects the removal performance of an air cleaning system. Therefore, depending on each scenario, different filters can be applied to improve air quality. The first scenario requires a system with a high capacity as well as high efficiency but for a short duration. In low emission rate events, a system with low capacity with the moderate efficiency would be sufficient to reduce the contaminant concentration. However, the service life time and removal capacity of GAC filters for different concentrations of VOCs are not clear in the application of in-duct air cleaners, resulting in the need for more research regarding this issue.

Choosing the level of inlet challenge gas concentration is one of the factors in activated carbon filter tests. There can be a compromise between test concentration level and test duration. Tests in real indoor air concentrations require too much time, are more expensive and use more energy. Therefore, most tests have been done in higher concentrations related to indoor air and little information is available about the performance of GAC in actual field setting.

Graham and Bayati (1990) conducted the field experience with full-scale panel filters of GAC. Their result shows depending the location of building and relative humidity, breakthrough times differs from seven months to three years. Generally, evaluating field experience is difficult because GAC is exposed to multiple contaminants and the concentration varies with compounds and time.

Although accelerating the time of tests by increasing the inlet concentration is beneficial, studying air concentrations similar to those found in indoor air is necessary to obtain a more thorough profile of the efficiency of GAC filters. Most studies show that activated carbon effectively adsorbs VOCs contaminants in indoor air level. However, the required time to reach a certain percent of breakthrough is too long. Results by Liu (1990) show that 10% breakthrough time for heptane and decane in various concentrations ranging from 200 ppb to 118 ppm takes between 500 and 2000 hours.

One effective solution to significantly reduce the required test time is to conduct tests at constant concentration of challenge contaminants at ppm levels and the results extrapolated to estimate breakthrough times at ppb levels. Nelson and Harder (1976) studied the influence of concentration on the lifetime of cartridges. They conducted tests to measure the breakthrough time at 100 ppm and estimated the breakthrough time at low concentration. According to their results, breakthrough time is a function of concentration and longer breakthrough times are observed at lower concentrations. From their experimental data for various compounds as a function of concentration, Nelson and Harder proposed an empirical expression as follows:

$$\frac{t_{b,low\,conc}}{t_{b,high\,conc}} = \left(\frac{low\,concentration}{high\,concentration} \right)^{0.67} \qquad \text{Equation 2-2}$$

The exponent 0.67 is the average slope of tests with several compounds on a plot of breakthrough time versus concentration. Therefore, if the breakthrough time at a high concentration is known, breakthrough times at low concentration can be calculated.

VanOsdell *et al.* (1996) studied the performance of GAC in small-scale beds for five single-components VOC at concentration ranging 1000 to 0.1 ppm. The contaminants included 1,1-dichloroethane (1,1-DCE), hexane, methylethylketone (MEK), toluene, and decane. Their result shows that GAC performance measurements in high concentration can be used with caution to predict the performance for a single component VOC with an indoor concentration level.

2.9.3 VOCs Mixture

One of the challenges in designing indoor air cleaners is the diversity of VOCs existing in indoor air. Several hundreds of gases have been found in indoor environments in various concentrations. Data reported by Brown *et al.* (1994) shows that the mean concentration of different individual compounds in office buildings was 0.05 mg/m3 (0.013 ppm as toluene), while the mean concentration of total VOC varies between 0.180 to 4.15 mg/m3 (0.048 to 1.1 ppm as toluene).

In most tests, only a single gas contaminant has been used to measure the performance of gasous air filters. The information generated from these tests can not used to estimate properly the service life of air filters because only one compound has been considered. In fact, indoor air presents more than one compound and performance of gas removal devices may vary for different VOCs (Nelson and Harder 1974).

The literature often lacks experimental data in evaluating the performance of GAC filters in removing a mixture of gas contaminants. Mixture gas studies have been mostly conducted on organic-vapor cartridges (Vahdat *et al.* 1994, Lara *et al.* 1995, and Rodenas *et al.* 2006). Furthermore, the challenge gas concentration used in their studies was very high, whereas the typical indoor concentration is less than 2 ppm. Therefore, service life of GAC filters is not clear in the application of HVAC system in buildings. A methodology is required to investigate the behavior of full-scale in-duct GAC filters in adsorption of mixture VOCs representing major gasous contaminants in indoor air, which is a major objective of this study.

Adsorption competition and displacement phenomena are two important characteristics in the mixture gas adsorption on activated carbon. VOC contaminants compete for free space in adsorption media. Therefore, the presence of other organic compounds reduces the performance and service life of carbon filter for each individual component compared to adsorption individually (Kingsley 2004, and Lu 2005). The competition causes less volatile components which have stronger-bonds with carbon to be partially displaced with previously adsorbed light molecules of the mixture gas. This displacement may lead to the outlet concentration of the light adsorbed component to exceed the inlet concentration (Lara *et al.* 1995, Yoon *et al.* 1996, Wood 2002, and Lillo-Rodenas *et al.* 2006).

Generally, the impact of multiple pollutants on the performance of carbon filters have a common characteristic; the presence of heavy and less volatile compounds significantly decreases the adsorption properties of activated carbon in adsorbing more volatile compounds.

Lillo-Rodenas *et al.* (2006) investigated the behavior of different types of activated carbon including bituminous granular activated carbon in removing the binary mixtures of benzene and toluene with the concentration of each 200 ppmv. Their result showed that in all tests, both compounds were adsorbed initially on the carbon surface. However, over time, as the activated carbon sites were fully filled, the previously adsorbed benzene was displaced by more strongly adsorbed toluene and lead to the outlet concentration of the benzene to exceed the inlet concentration. Displacement of benzene by toluene proves that activated carbon has more affinity in the adsorption of toluene rather than benzene due to the lower volatility of toluene. Toluene with molecular weight of 96 and boiling point of 110°C has stronger bonds with carbon than benzene with molecular weight of 78 and boiling point of 80°C. Displacement phenomenon was observed for all types of activated carbon. The major differences among different activated carbons were the value of initial breakthrough time for benzene (67 minutes for Bituminous GAC), the maximum outlet concentration for benzene when benzene was displaced by toluene (310 ppmv for Bituminous GAC) and also the time difference between initial breakthrough time of benzene and toluene (63 minutes for Bituminous GAC) .

Lara *et al.* (1995) evaluated the service life of organic-vapor cartridges with the binary mixtures of acetone/m-xylene, acetone/styrene and toluene/m-xylene. The total concentration was maintained in 1000 ppm with the concentration ratio range from 0.1 to 0.75. Their results show that the more volatile compound penetrates first, independent of the concentration ratio, and its outlet concentration exceeds the inlet concentration.

As explained earlier, this behavior is interpreted in terms of displacement of adsorbed volatile compound by the less volatile one at the carbon surface. For example, in the acetone/m-xylene system, both compounds were adsorbed simultaneously on the carbon surface at the beginning of the adsorption. When the activated carbon was saturated, acetone penetrated the carbon. At the same time, m-xylene must displace the acetone to be adsorbed on the carbon. Therefore, the acetone concentrations in the outlet exceed the concentration in the inlet. The presence of acetone as a light compound had no significant effect on the removal capacity and 10% breakthrough time of m-xylene or styrene (heavier compounds). However, the removal capacity and 10% breakthrough time of acetone was lower than that observed with pure acetone. In the binary mixture of toluene/m-xylene, since toluene was the more volatile solvent, it penetrated first and was partially displaced by m-xylene. The service life with m-xylene was greatly reduced by the presence of toluene. The 10% breakthrough time for toluene remained almost constant at all concentration ratios. However, the 10% breakthrough time for m-xylene increased when its concentration decreased.

VanOsdell *et al.* (2006) studied the removal performance of three full-scale GAC filters. The challenge gas was a mixture of five compounds; hexane, MEK, toluene and PERK at concentration of 0.2 ppm each. For a carbon/fiber matrix composite filter, an immediate 10% breakthrough was observed. The relatively low initial performance might be the result of the leakage around the filter or the misdistribution of carbon in the fiber matrix. After 24 hours, the penetration of greater than 100% was observed for MEK and to approximately 35% for toluene. Results clearly show displacement of MEK by other heavier compounds. However, no interpretation was done by the author to explain the displacement of MEK by heavier compounds such as toluene and PERK. In fact, the reason for the penetration of greater than 100% for MEK interpreted by an error in upstream challenge concentration of MEK during that period.

Overall, a full-scale method assessing the characteristics of full-scale GAC filters in removing a mixture of pollutants has yet to be developed. Since, full-scale tests usually last for a long period, developing a feasible method is confronted with two major challenges. First, a new chemical generation system is needed to provide the continuous injection of VOCs mixture during the test. Second, a gas sampling system to continuously collect gas samples and transfer to the GC analysis apparatus must be developed.

CHAPTER 3 EXPERIMENTAL SETUP

3.1 INTRODUCTION

As mentioned earlier, one of the main objectives of this research study was to develop an experimental methodology to examine the effectiveness of full-scale GAC filters in the adsorption of a VOCs mixture. In this study, a full-scale system was utilized to simulate a building HVAC system. In addition, a chemical generation system along with an on-line gas sampling and analysis unit was designed and implemented. This set-up provides the ability to explore the impact of multiple VOCs on the service life of full-scale GAC filters as well as characteristics of mixture gas adsorption. The experimental design for these systems and details of the experimental set-up are described in this chapter.

3.2 TEST DUCT

3.2.1 Test Duct Description

The schematic of the full-scale test apparatus is shown in Figure 3-1. The test apparatus was designed according to ASHRAE standard 52.2 (1999). The cross section area of the duct is 0.61m x 0.61m and the total length of system is approximately 23 meters. The duct material is made of a stainless steel with a smooth interior finish that does not react or retain contaminants.

The rig has the ability to mount and support various full size commercial in-duct air cleaning devices. In addition, the rig has a variable-speed blower capable of providing an air flow rate up to 1.00m^3/s.

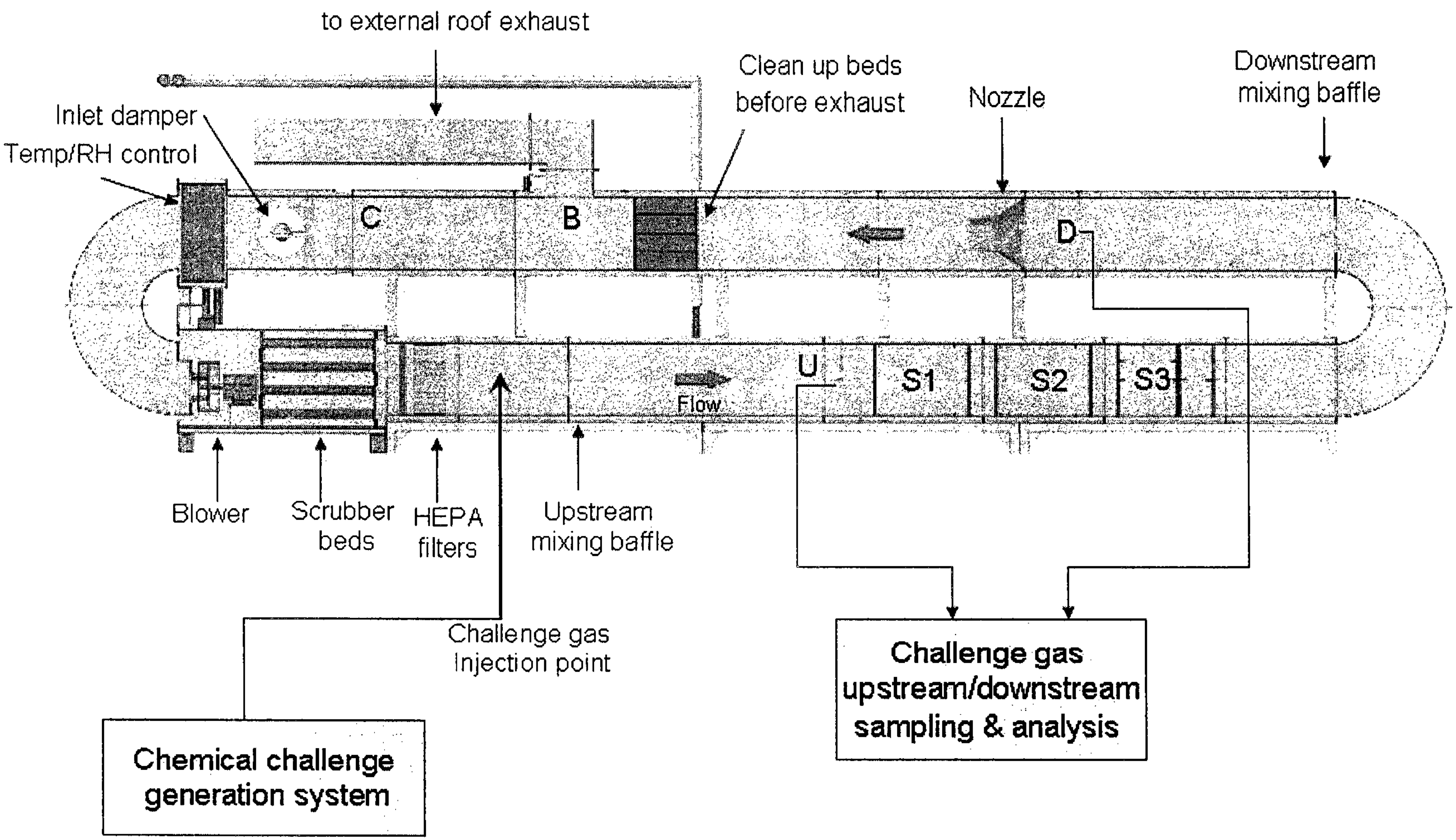


Figure 3-1: Schematic diagram of the test duct

Air enters the inlet damper and is conditioned using a humidifier (Nortec, MES-U Electrode Stem Humidifiers) coupled with a cooling coil to adjust the air temperature before being introduced into the blower. The conditions of the air before and after the filter are measured at time intervals determined during experiment by temperature and relative humidity transmitters (Vaisala HUMICAP® series MT100). The transmitters' sensors are aligned with the upstream and downstream sampling zones located before the filter and after the filter near the nozzle (see U and D in Figure 3-1).Transmitters are connected to a data acquisition system (DAS) (Agilent 34970A Data Acquisition/Switch Unit) which is plugged to a laboratory computer.

Cleanup beds and HEPA filters are positioned after the blower to clean the air and remove particulate pollutants prior to injecting the contaminant gases. In fact, these clean up beds protect test gas filters against dust deposits. Diffusing particles inside gas filters can block pores and dramatically decrease their life time.

In order to have uniformity in air velocity and dispersion of contaminants in the system, an orifice plate and a mixing baffle are installed downstream of the contaminant injection point. Furthermore, another identical orifice plate/mixing baffle are located after the bend at the downstream of the test device and allow sampling at a single-point downstream. The challenge contaminant(s) is injected to the duct between the inlet clean up beds and the upstream mixing orifice.

In this particular rig, different sections have been created to install various types of air filters with different media bed depth (S1, S2 and S3 in Figure 3-1). Panel filters filled with granular activated carbon with 5, 10, 15 and 30 cm bed depths were used in this study and installed separately.

The test duct can process the air flow with a once-through (open loop) mode or an air recirculation mode (closed-loop) by adjusting the dampers located before the duct exhaust and inlet opening (dampers B, C in Figure 3-1). All experiments have been conducted in open loop mode and exhaust air is removed through the laboratory's exhaust duct. Cleanup charcoal beds are installed before the outlet of the system to reduce exhaust contaminant concentration to environmentally acceptable levels.

This system was setup and calibrated and all qualification tests were conducted and passed the requirements of ASHRAE testing standard 52.2 (Bastani *et al.* 2009).

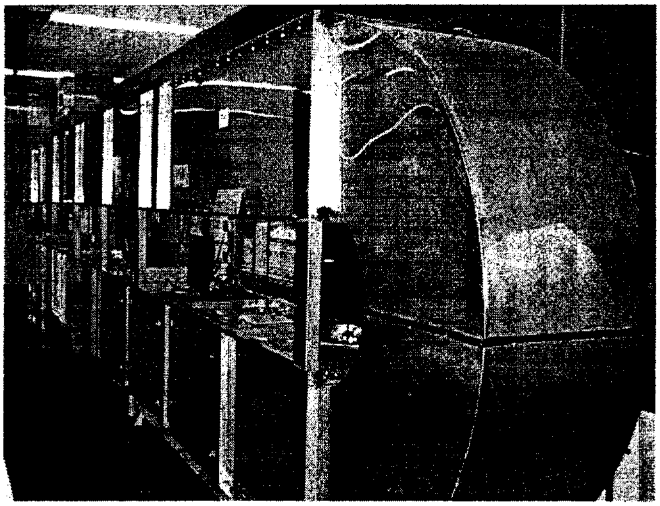


Figure 3-2: Test facility

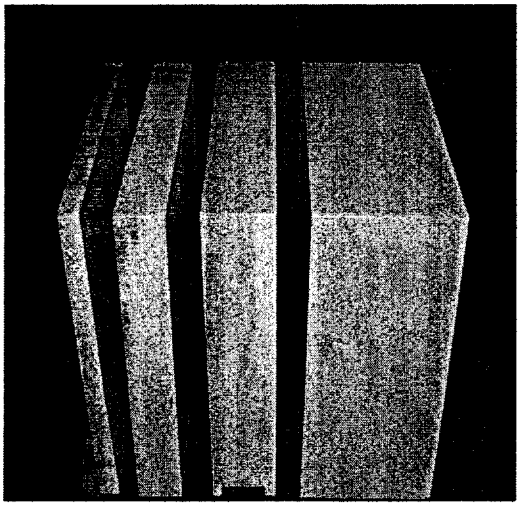


Figure 3-3: Panel filters used in this study

3.2.2 Duct Air Flow Measurement

The air flow of the duct was measured using a 17.8 cm (7'') diameter ASME long- radius flow nozzle according to ASHRAE standard 52.2. The following equation was applied and solved by Newton's equation to calculate the air flow rate in the duct. (ASME Standard1990):

$$Q = N_U * C_{dc} * D^2 * \left[\frac{\Delta P}{\rho * \left(1-\beta^4\right)}\right]^{0.5}, \qquad \text{Equation 3-1}$$

where

Q = air flow rate, m^3/s, (m^3/s, cfm)

N_U = the unit coefficient and equal to 1.1107x10^{-6} (SI) and 5.9863 (I-P)

C_{dc} = discharge coefficient of nozzle= $0.9975 - 6.53 * R_e^{-0.5}$

D= the nozzle throat diameter, (mm, in)

ΔP= nozzle pressure drop, (Pa, in. of water)

ρ = the air density in the nozzle inlet, (kg/m^3, lb/ft^3)

$\beta = \frac{D}{W_d}$ where W_d is the duct width, (mm)

R_e = Reynolds number= $\frac{K_R * \rho * Q}{D}$ where K$_R$ = 5.504x10^{-7} (SI) and 16,393 (I-P)

The nozzle is located after the downstream mixing baffle and near the temperature and relative humidity transmitter sensor. Pressure difference of the nozzle is measured by connecting two static taps mounted before and after the nozzle to a pressure transmitter (Cuba Control pressure difference transmitter type-694). The pressure transmitter is connected to the DAC. The pressure difference was measured in voltage units by the DAC and converted to inches of water. The values of the pressure drop of the nozzle and downstream air conditions (temperature and relative humidity of air passing through the nozzle) are used to calculate the air flow rate.

3.3 CHEMICAL GENERATION SYSTEMS

Two different gasous contaminant generation systems were utilized in this study. The first system was a bubbling generation system, typically used when only one gas contaminant is used as the challenge gas. The second system was a new chemical generation system that was specifically designed to generate a mixture of gasous contaminants.

3.3.1 Bubbling System

In the first set of experiments, toluene was used as the single gas and injected into the duct by a bubbling generation system. The schematic of this system is shown in Figure 3-4. The laboratory compressed air, adjusted by a pressure regulator, is used as a carrier gas and its flow rate is controlled by a mass flow controller (Omega FMA 5400/FMA 5500). The air is injected into the toluene bottles through a Teflon tube with the diameter of 0.64 cm. Next, air containing the evaporated toluene is passed into an empty bottle to collect possible droplets of toluene resulting from condensation and then moves to the injection port of the test duct. The injection port of the test duct is positioned after the clean up bed and before upstream mixing baffle. To prevent condensation of the contaminant on the interior surface area and to distribute the contaminant uniformly in the cross section area of the test duct, a perforated stainless steel tube with the diameter of 0.64 cm is installed inside the duct and connects to the carrier gas line.

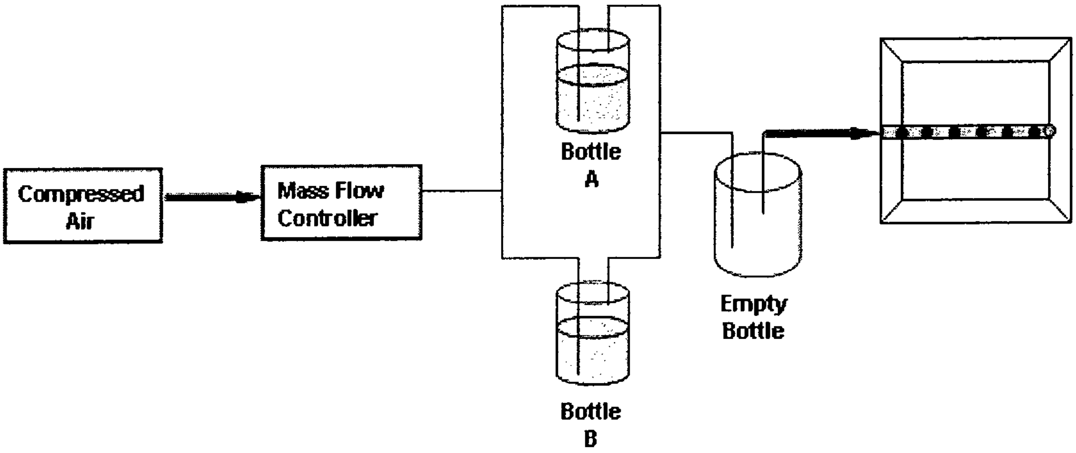


Figure 3-4: Single gas contaminant generation system (developed by Bastani *et al.* 2009)

3.3.2 Designing a New System for the Generation of Multi-Gas Contaminants

A new generation system was designed to generate multiple gas containments because the bubbling generation system used for the single gas tests had limitations. First, the bubbling system was unable to generate a mixture of chemical compounds with different physical properties. Furthermore, this system was not able to produce the gas contaminant in high concentration such as 100 ppm, because the maximum air flow rate of gas contaminant injection system was limited to 1% of the total test air flow (ASHRAE Standard 145.2, 2007-c) to make sure that contaminant has sufficient transport and mixing. This range of air flow rate will not generate a high concentration of saturated gas stream specifically for VOCs with high boiling point and molecular weigh. Lastly, the bubbling system lacked a heating system to prevent heavy VOCs from condensing in the gas line. Therefore, as a progressive step, a new generation system was developed to overcome these limitations.

3.3.2.1 Generation System Requirements

In order to design the new chemical generation system the following factors were considered as recommended by VanOsdell *et al.* (2006):

- To provide continuous generation of test VOCs at a constant concentration for the duration of the test
- To avoid operation of the generation system in conditions that would allow formation of aerosol. Liquid aerosol droplets might form due to incomplete vaporization of VOC liquid. The droplets can easily penetrate GAC media and may vaporize in the downstream of a filter. Therefore, the droplets increase the downstream concentration creating error in test results.
- To minimize safety hazards including explosions and fire
- To minimize personal exposure hazards from VOC liquids by including proper instruction for filling chemical containers and handling liquids

Designing a system with the above characteristics required the following units:

Chemical Container: A pressure vessel (Spraying System Co, 75 liter unit capacity) was used as the container to continuously provide liquid chemical during the operation of the generation system. This stainless steel pressure vessel equipped with the safety relief valve conforms to the ASME Code and is designed with the diameter of 22.86 cm and the length of 35.56 cm. The inlet pressure of vessel is controlled by a pressure regulator (0-413.7 kPa)

Mixing Chamber: A customized chamber was designed to provide an environment for chemicals to be fully mixed, vaporized and transferred to the test duct. The chamber was made of stainless steel to minimize the wall adsorption effects and prevent possible chemical reactions. The chamber is dimple jacked for hot water to circulate in order to prevent any condensation on the wall surfaces. For cleaning purposes, a perforated spray ball is used to scatter the cleaning solvents into the chamber.

Spraying Nozzle: A specific type of nozzle was used to atomize the liquid chemicals into the mixing chamber (1/4 JN-SS, Spraying System Co). This nozzle has an internal mixing set-up which means that the mixing process of the liquid and compressed air occurs inside the nozzle. In the internal set-up, liquid and compressed air streams are not independent and a change in air flow will affect the liquid flow. Therefore, by varying the pressure of liquid and compressed air, full atomized chemicals are sprayed into the chamber in a desired concentration.

Process Control Instruments and Transfer Lines: PTFE tubes were used to transfer the compressed air and pressurized liquid chemicals to the nozzle. The pressure of air and liquid lines were set and controlled by the pressure regulators installed before the nozzle.

Heating System: Applying continuous heat at a constant temperature to the mixing chamber during the chemical generation process improves the contact between the atomized chemicals and air. This heat will also prevent possible condensation of vaporized chemicals on the wall surface of the mixing chamber and the carrier gas tubes/fittings. Different heating devices such as heat tapes or heating blankets exist in the market. However, they are not safe enough to provide sufficient heat for a large chamber containing flammable gases. To achieve continuous and safe heating during the operation of generation system, a closed hot water system was designed.

3.3.2.2 System Description

Figure 3-5 shows the schematic diagram of the chemical generation system. The laboratory compressed air moves through a pressure vessel which contains liquid chemicals. Chemicals are transferred from the pressure vessel to a Teflon tube with the diameter of 0.64 cm. The pressure of the chemicals are adjusted by a liquid pressure regulator (0-206 kPa) connected to the Teflon tube (L in Figure 3-5). By controlling the pressure of liquid line, chemicals are moved through the nozzle (located at the top of the mixing chamber). The nozzle is configured to spray fine particles of chemicals in the mixing chamber.

Another Teflon tube with the diameter of 0.64 cm transfers compressed air controlled by a pressure regulator (0-413.7 kPa) to the nozzle (A in Figure 3-5). Then in the nozzle, liquid chemicals and compressed air are mixed and completely atomized particles are dispersed in the mixing chamber. The injection rate can be changed by varying the pressure of air and liquid lines.

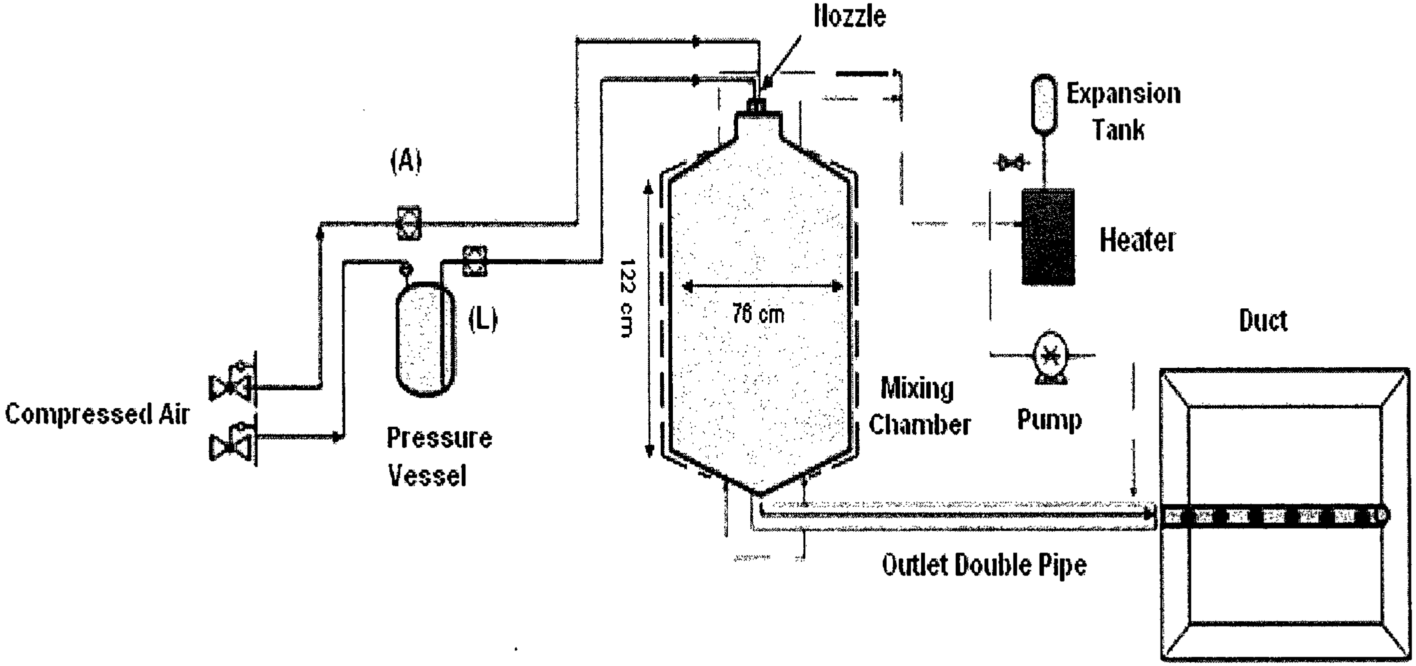


Figure 3-5: Schematic diagram of the chemical generation system

The mixing chamber is made of stainless steel with the diameter of 76 cm and the height of 130 cm. To ensure that atomized particles do not come into contact with the wall surface, the size of the chamber is designed to be larger than the total distance of the spray projection from the nozzle to the maximum dispersal point. Vaporized chemicals are produced in the mixing chamber by the combining of the atomized chemicals with the air. The mixing chamber is equipped with a vacuum breaker and pressure relief valve as a safety precaution. This chamber is capable of consistently and fully vaporizing chemical particles and transferring them to the test rig. Also, two sight glasses are housed on the wall chamber to monitor the spray distribution of chemicals injected by the nozzle.

The carrier gas is transferred from the mixing chamber to the duct by means of a doubled pipe. The double pipe consists of a tube-in-tube construction with a 1.90 cm (id) stainless steel tube for the gas transport and a 3.81 cm (id) stainless steel tube for heating of the inner tube.

Hot water from a heater (Model GE Series, 9 liter capacity, 1440 watts) with a controlled temperature is pumped by a circulator (Armstrong's Model ASTRO 3-Speed circulators) through the double pipe and then to the dimple jacket that surrounds the wall surface of the mixing chamber (dashed lines in Figure 2-5). An expansion tank (Amtrol EXTROL expansion tank, 7.57 liter unit capacity) is installed on top of the heater to remove excess water pressure which could be created by thermal expansion as the water is heated. The heating system provides a recirculation of hot water that is safe and maintains consistent heat during the injection process.

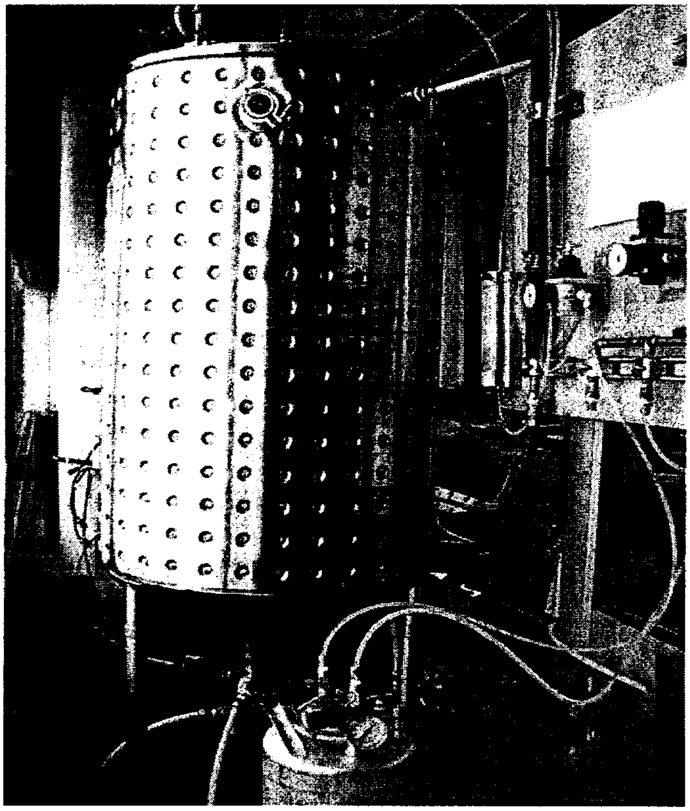


Figure 3-6: Test facility for the generation of mixture gas

3.4 GAS SAMPLING AND ANALYZING

Gas samples before and after the filters are obtained in order to determine the performance of the filters. Gas samples are taken by two stainless steel probes with diameters of 0.64 mounted after the mixing baffles. The probes are situated perpendicular to the air flow and select samples from the center of duct's cross section. Two different gas sampling and analysis systems are used in this study, one for the single gas tests and the other one is specifically designed for the multi-gas analysis.

3.4.1 Single Gas Analysis Set-up

For the single gas analysis in which toluene was used as the challenge gas, a photo-acoustic multi-gas analyzer detector (INNOVA Air Tech Instrument 1312) coupled with an automatic multi-channel sampler (CAI Intelligent Sampling System MK2) was utilized. Gas samples were collected and transferred to the multi-channel sampler. PTFE tubes were used to minimize the possible loss of the chemical compound due to adsorption on the tube wall. The auto sampler was programmed to take alternating samples from both the upstream and downstream sampling points at interval time periods that were determined by the gas detector.

The gas detector measured and monitored the concentration of total hydrocarbons as the toluene equivalent ($TVOC_{toluene}$). However, the system was not applicable for the multiple VOC analysis in which the concentration of each individual compound was required. Therefore, a Gas chromatograph/Mass spectrometer (GC/MS) coupled with a Thermal Desorber (Perkin Elmer model TurboMatrix 350) were used for the mixture gas analysis.

3.4.2 Designing an On-line Gas Sampling System for the Mixture Gas Analysis

Generally, there are two methods to collect gas samples before and after a filter: manual and on-line. In the manual sampling, gas samples are taken manually from the upstream and downstream sampling ports. An air pump with an adjusted flow rate is required to adsorb gas samples in a sampling tube. Then, the sample tube is placed in the Thermal Desorber for analysis.

This approach has some limitations. The process is time consuming and requires effort to manually collect the samples. Since, labor is involved in the sampling process; the number of samples taken is limited. Therefore, less data is collected for analysis. Also, there is a great potential for human error in the manual sampling method.

On the other hand, the gas sampling can be more productive by an on-line sampling system. In the on-line sampling system, the Thermal Desorber-GC/MS is connected on-line to the test duct and continuously monitors the upstream and downstream concentration of each individual VOC under real time conditions.

3.4.2.1 System Description:

Figure 3-7 shows the schematic plot of the on-line gas sampling and analysis system specifically designed for the mixture gas. The system consists of several components: an analysis apparatus, a multichannel valve, gas transfer lines and an air sampling pump.

The following describes the function of each component:

Analysis Apparatus: Gas samples are collected using a Thermal Desorber (Perkin Elmer model Turbo Matrix 350) and analyzed by a GC/MS analyzer (Perkin Elmer model Turbo Matrix 350). The GC/MS system is controlled by Turbo Mass software installed on a laboratory personal computer (PC).

A method was developed for the Thermal Desorber (TD) to continuously collect upstream and downstream samples at a predetermined sampling time. Then, samples were analyzed by GC/MS to determine the concentration of each individual VOC. Details for the GC/MS methodology are described in the next chapter.

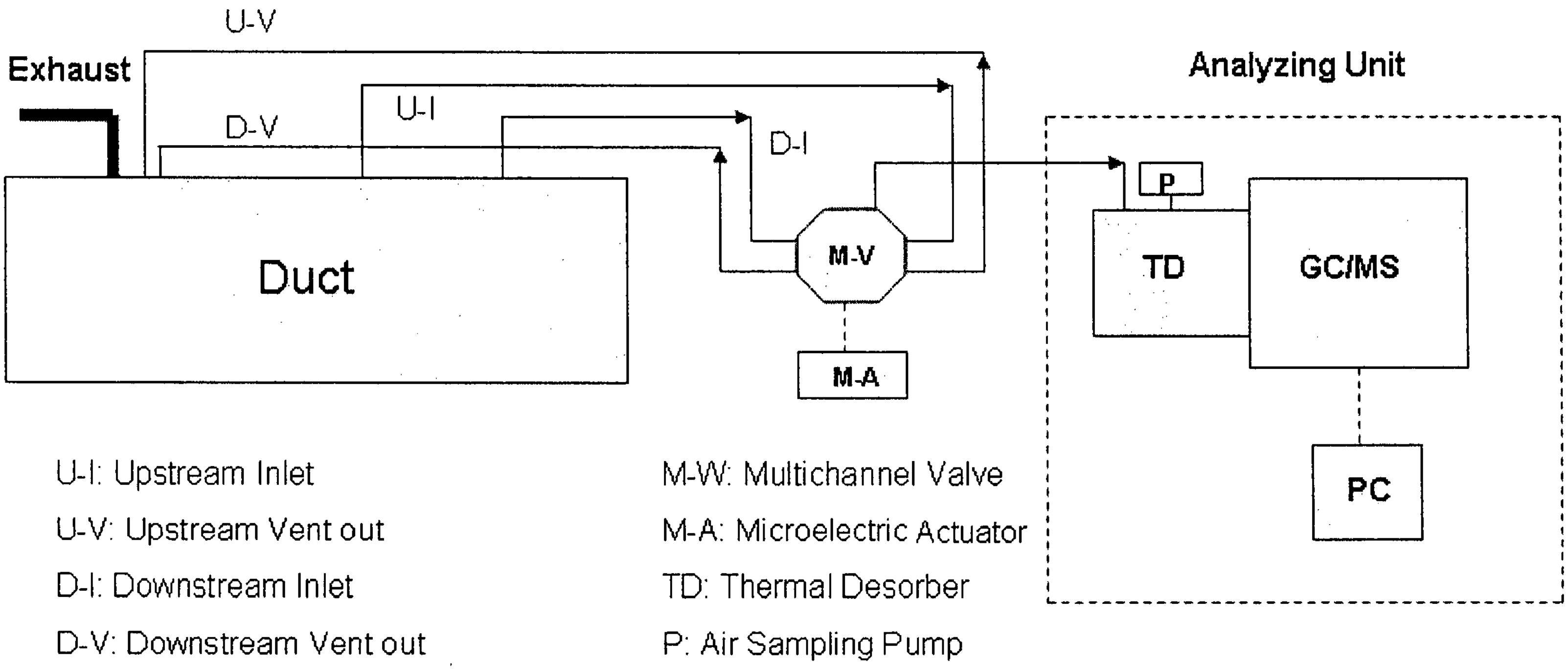


Figure 3-7: Experimental set-up for the mixture gas analysis

Multichannel Valve: A multichannel valve (8 position valve, Model SF, flow-through flow-path, VICI Valco Instruments Co) coupled with a multiposition microelectric valve actuator (VICI Valco Instruments Co) is used to automatically select air from the upstream or downstream or the laboratory. In this specific type of valve, when one air stream is selected, the other non-selected streams flow out through their individual outlets. The microelectric valve actuator is programmed to switch the valve to the desired position. The time needed to switch a valve from one position to another position is set by the program. The actuator utilizes four positions and alternates between channels in the following modes:

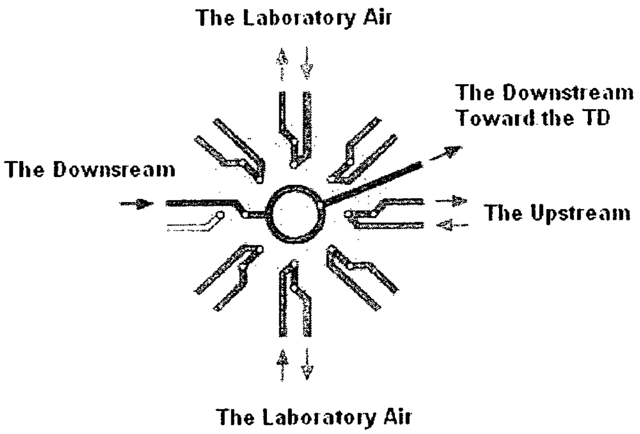
Position 1: selects the upstream

Position 2: selects the laboratory air stream

Position 3: selects the downstream

Position 4: selects the laboratory air stream

After each upstream and downstream flow, filtered laboratory air is introduced to purge the surface of the tube and/or fittings. Figure 3-8 shows the diagram of multichannel valve in the position 3, when the downstream is selected. The downstream is transferred from a common outlet port shown in Figure 3-9 to the Thermal Desorber. Simultaneously, other streams are vented to their own outlets.



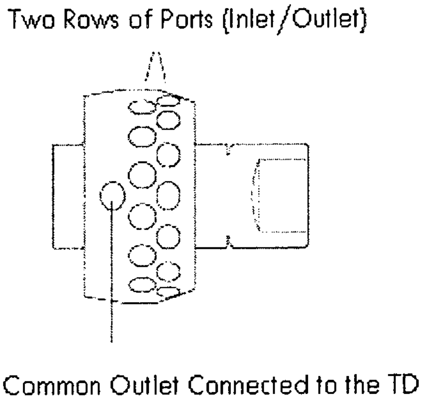


Figure 3-8: Multichannel valve in the position 3*
*(Modified from www.vici.com)

Figure 3-9: Ports of the multichannel valve*

Gas Transfer Lines: Upstream and downstream samples are transferred from sampling points to the multichannel valve by means of two individual stainless steel tubes with the diameter of 0.635 cm. As shown in Figure 3-7, the upstream and downstream flows continuously pass into the multichannel valve; one flow is selected by the valve and the other flow is vented out to the exhaust opening of the duct. Then, the selected flow is transferred to the Thermal Desorber using a stainless steel tube with the diameter of 0.32 cm.

Air Sampling Pump: An air sampling pump (oil free diaphragm pump, Charles Austin Pumps Ltd) is used to provide continuous vacuum and pressure source for the Thermal Desorber during the gas sampling. This pump is connected to the online sampling section of the Thermal Desorber by a stainless steel tube with the diameter of 0.32 cm.

CHAPTER 4 EXPERIMENTAL METHOD

4.1 INTRODUCTION

This chapter describes the experimental methodology developed to examine the performance of full-scale GAC filters.

4.2 TEST PROCEDURE

The following steps explain the testing procedure used in each experiment:

1) Each media container was filled with granular activated carbon (GAC). To decrease the chance of excess air space between the GAC media, the container was manually shook throughout the filling process. After the filling process, the filter was weighed by a balance (with ±5 gram accuracy) and the data was recorded.

2) The filter was properly installed in the corresponding filter slots. To reduce the chance of contaminant air bypassing the filter without contacting the media, all free space between the filter and the duct was sealed with gasket and aluminum foil tape.

3) After the test filter was installed, the temperature and relative humidity controller was adjusted to 23° C and 50% relative humidity and the humidifier functions were checked. Next, the pressure drop (resistance) of the filter against the conditioned air flow rate was measured and recorded in four different flow rates of $0.141 m^3/s$, $0.188 m^3/s$, $0.235\ m^3/s$, $0.353 m^3/s$. Information about the pressure

drop assists designers in determining suitable air filters for a HVAC system. To measure the pressure drop, two static taps were mounted before and after the filter and were connected to a pressure transmitter (Cuba control pressure difference transmitter type-694). Data from the pressure transmitter was transferred to the DAC and recorded every five seconds. The pressure drop values for tested filters are shown in Appendix A.

4) Before starting the injection process, the pressure regulators, tubes and all fittings of the generation system were checked to ensure no leakage. The flow rate of the duct was set at $0.187 m^3/s$ which resulted in the face velocity of 0.519 m/s in the system. Next, the background concentration of the duct was measured for minimum 30 minutes. This time was required to stabilize the test conditions of the duct.

5) Adsorption stage was started by injecting the challenge gas contaminant(s) into the duct. Since all tests lasted from a few days to a couple of weeks, a continuous control was necessary to ensure that all set points for both chemical generation system and analysis system were stable.

6) The generation system was turned off and the clean air passed through the filter to desorb chemicals from the filter. For analysis purposes, upstream and downstream concentration levels of air were measured during both the adsorption and desorption phases. After desorption stage was terminated, the duct blower was turned off and filter was removed and weighed.

4.3 TEST VOCs

4.3.1 Selection of the Test VOCS

In the first set of experiments, the filter was challenged with toluene, as a representative of indoor VOCs with a concentration of 10 ppm. However, the performance of a GAC filter in removing gasous contaminants varies for different chemical compounds. A study by Berglund *et al.* 1986 found that over 300 different VOCs have been detected in indoor environment. Therefore, performance of GAC filters should be investigated for a mixture of VOCs along with finding appropriate compounds which represent the major groups of indoor contaminants. For this study, the challenge mixture compounds were chosen based on the following factors recommended by VanOsdell (1994):

- The test VOCs should be chosen from a wide group of chemical classes and have different boiling points, polarities, solubilities and vapor pressures.
- The test VOCs should be frequently found in indoor environments and represent a majority of indoor air contaminants.
- The test VOCs should not have any serious health risks and not require any extraordinary safety precautions.
- The analysis of VOCs should be simple.
- The cost of test VOCs should be reasonable.

Toluene, p-xylene, n-hexane, and 2-butanone (MEK) with the concentration of each 5 ppm were chosen for the mixture gas experiments. As shown in Table 4-1, the tested compounds represent aromatics, alkanes and ketenes with different physical properties.

According to the published data by Brown *et al.* (1999), toluene, n-hexane, p-xylene and 2-butanone were among the predominant VOCs found in the indoor air of established buildings (greater than 3 months old). Also, in a study conducted at 56 randomly selected public and private office buildings across the USA, toluene, p-xylene and n-hexane were among the VOCs with the highest median concentrations (German *et al.* 1999). Studies in Danish residences and office buildings reported that toluene, n-hexane and p-xylene are among 10 contaminants with the highest steady-state concentrations (Thad 2003). Toluene, hexane and 2-butanone were included in the VOC challenge gas list of ASHRAE standard of 145.1P which was developed by the ASHRAE committee in order to test full-scale gasous contaminant air cleaning devices for removal performances.

Table 4-1: Physical properties of the target VOCs

Chemical Name	**Chemical Category**	**Molecular Formula**	**MW**	**BP (C°)**	**VP (mmHg) at 20°C**	**Solubility in water (g/l) at 20°C**	**Polarity**	**ASHRE Std 145. 1P**
n-Hexane	Alcane	C_6H_{14}	86.2	69	132	Insoluble	Non-Polar	X
Toluene	Aromatic	C_7H_8	92.1	111	22	0.47	Non-Polar	X
p-Xylene		C_8H_{10}	106.2	138	9	Insoluble	Non-Polar	
2-Butanone	Ketene	C_4H_8O	72.1	80	78	290	Polar	X

4.3.2 Health Effects and Common Sources of Tested Chemicals

According to EPA classification, all target compounds used in this study are in group D; not classifiable as carcinogenic (EPA 2007-a). Toluene has been recommended by several researchers as a representative VOC (VanOsdell and Sparks 1995, Liu 1996, Lee *et al.* 2006). According to ATSDR (1994), average concentration of toluene in indoor air is 31.5$\mu g/m^3$. The same study reports that using the common household products (paints, paint thinners, adhesives and nail polish) and cigarette smoke cause usually the highest concentrations of toluene in indoor air. People who work in occupations such as printing or painting are exposed to toluene since toluene is usually used as a solvent (ATSDR 1994). Exposure to toluene has both acute (short term) and chronic (long term) health effects. Exposure to low levels of toluene can have small narcotic effects in the central nervous system (Habrison 1998), while higher levels can cause headache, dizziness, fatigue, sore throat, mucous membrane irritation and nausea (EPA 2007-a).

N-hexane is an Alkane hydrocarbon with a low boiling point. N-hexane is used as a cleaning agent in the printing, textile, furniture, and shoe manufacturing. Acute exposure to n-hexane may cause dizziness, nausea, headache and irritation of eyes, nose, throat and skin. Chronic exposure to n-hexane includes disturbances in sensation, muscle weakness, distal symmetric pain in the legs and changes in vision (Hathaway *et al.* 1991).

P-xylene is used as a pesticide, a thinner for paint and varnishes. Common sources of p-xylene in indoor air are adhesives, floor/wall coverings, degreaser, tobacco smoke and kerosene heaters (Emil *et al.* 1997). According to Canadian Centre for Occupational Health and Safety (CCOHS), the main health effect from the inhalation of xylene vapors is depression of the central nervous system (CNS), with symptoms such as headache, dizziness, nausea and vomiting. Long term exposure effects of xylene include skin sensitization, harmful effects on the nervous system, blood effects and kidney and liver damages. Study by ATSDR (1994) reports that the concentration of p-xylene in indoor air is in the range of 0.010 to 0.047 mg/m^3 (ATSDR 1994).

2-butanone or methylethylketone (MEK) is used as a solvent. Short term inhalation exposure to 2-butanone may cause eyes, nose, skin and throat irritation. Limited information is available about the chronic effects of 2-butanone in humans. MEK is used in the production of paraffin wax and household products such as glues, lacquer and varnishes and paint remover.

4.4 PREPARATION OF VOC STANDARD SOLVENT MIXTURES, SAMPLING TUBES AND GC/MS APPARATUS

4.4.1 Standard Solvent Mixture

A standard solvent mixture with an equal partial concentration of each compound (2000 µg/ml) was prepared. In order to prepare the solution, the pure compounds were mixed together at a specific volume ratio (based on their density) in a volumetric flask and then diluted to the desired level (25 ml) with methanol as solvent. Standard mixtures of 1000, 500, 250, 100 and 50µg/ml were also prepared by diluting the standard solvent mixture of 2000µg/ml with methanol. The procedure of calculation is explained in Appendix B.

4.4.2 Sampling Tubes

Before staring the calibration, sampling tubes (Supelco Air Toxics stainless steel sampling tubes) were preconditioned by passing a flow of 50 ml/min compressed helium (UHP 5.0) through the tubes for 30 minutes at 300°. In order to prevent any contamination, conditioned tubes were wrapped with aluminum foil and then stored in a container.

4.4.3 GC/MS Calibration and Method Development

The GC/MS apparatus was calibrated for each compound in concentrations between 0-1000 µg/ml. As shown in Figure 4-1, a Hamilton syringe was used to inject the solution of the standard mixture into a flow of pure nitrogen with a constant rate of 75 ml/min.

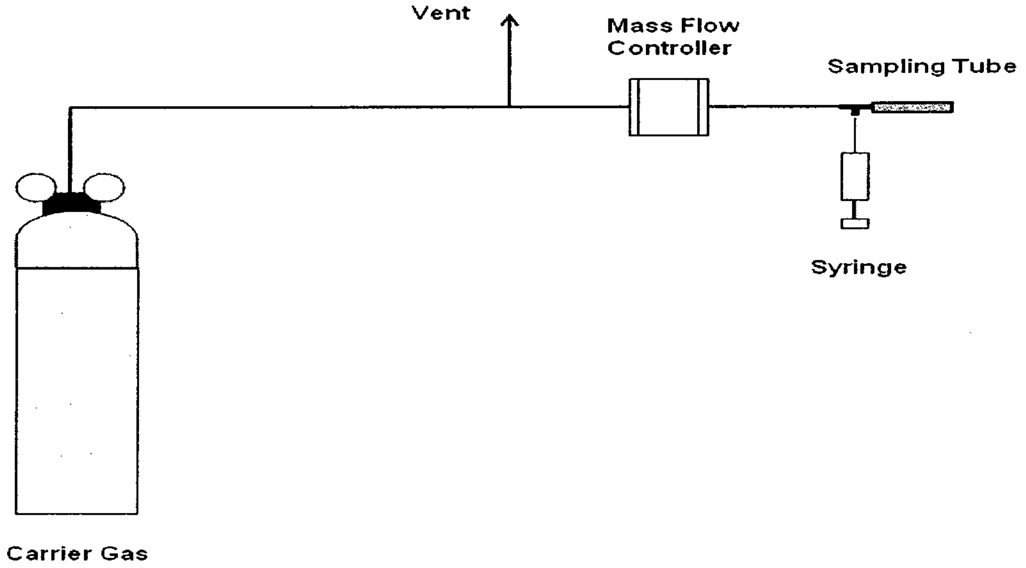


Figure 4-1: Schematic figure of the sample collecting set-up for the GC/MS calibration

Following the injection, the nitrogen flow continuously passed through the sampling tube via a T-joint for approximately 6 minutes. The injection was repeated three times for each concentration to minimize the possibility of injection error. Also, the injection was conducted in ascending order of concentration due to possible adsorption/desorption in the T-joint surface. Then, sampling tubes were analyzed by using the TD-GC/MS. The calibration was carried out in six different concentrations; 0, 50, 100, 250, 500 and 1000 μg/ml. A method was developed for the TD-GC/MS as following: first, in the thermal desorber, VOC samples were desorbed from the tube with 50 ml/min helium at 300° C for 8 minutes into a trap at temperature of 20° C and inlet split rate of 20 ml/min. Subsequently the trap desorption was followed at 300° C for 5 minutes and outlet split rate of 3 ml/min. Then, the VOC samples were transferred to the GC column at 200° C and flow rate of 2 ml/min. The GC method initiated at 50° C and was held for 5 minutes. Then, it was increased to 180° C with a heating rate of 10° C/min.

Table 4-2 shows the response of GC/MS apparatus to different level of injected VOCs. Figures 4-2 to 4-5 demonstrate calibration curves of each VOC.

Table 4-2: GC/MS response to different concentrations of injected VOCs

	Concentration (μg/ml)					
VOC	**0**	**50**	**100**	**250**	**500**	**1000**
n-Hexane	0	95517.34	232254.7	682727.5	1361757	2819390
p-Xylene	0	160064.9	357640.8	1281883	2479822	5447441
Toluene	0	1444891	2495513	8812585	14567407	30541664
2-Butanone	0	76428.76	169271.7	553439.3	1077109	2305718

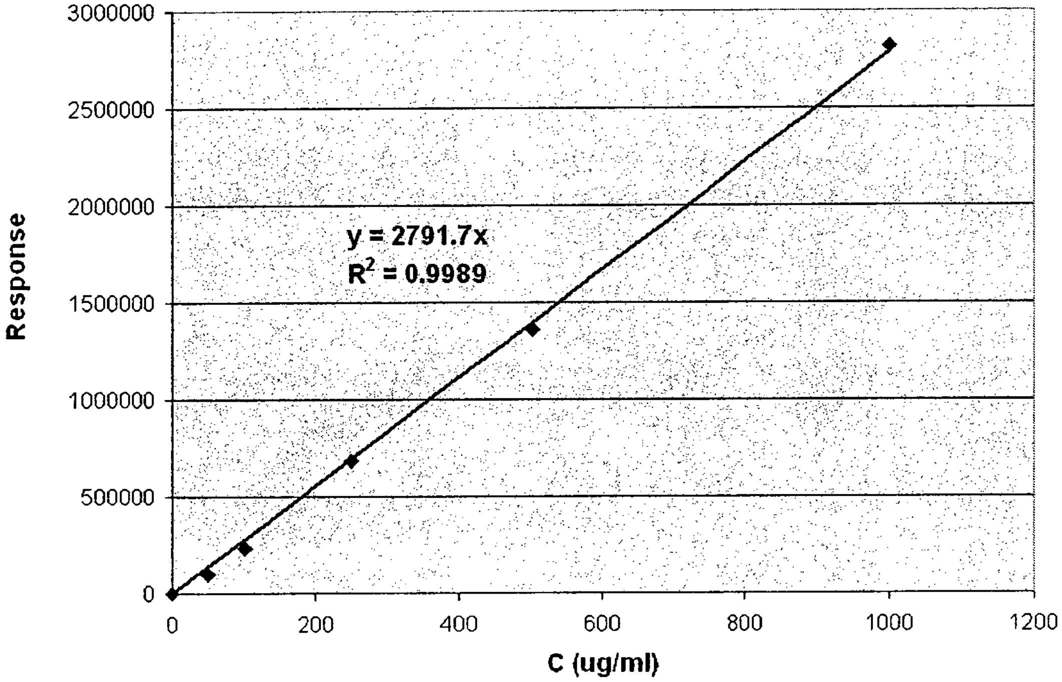


Figure 4-2: n-Hexane calibration curve

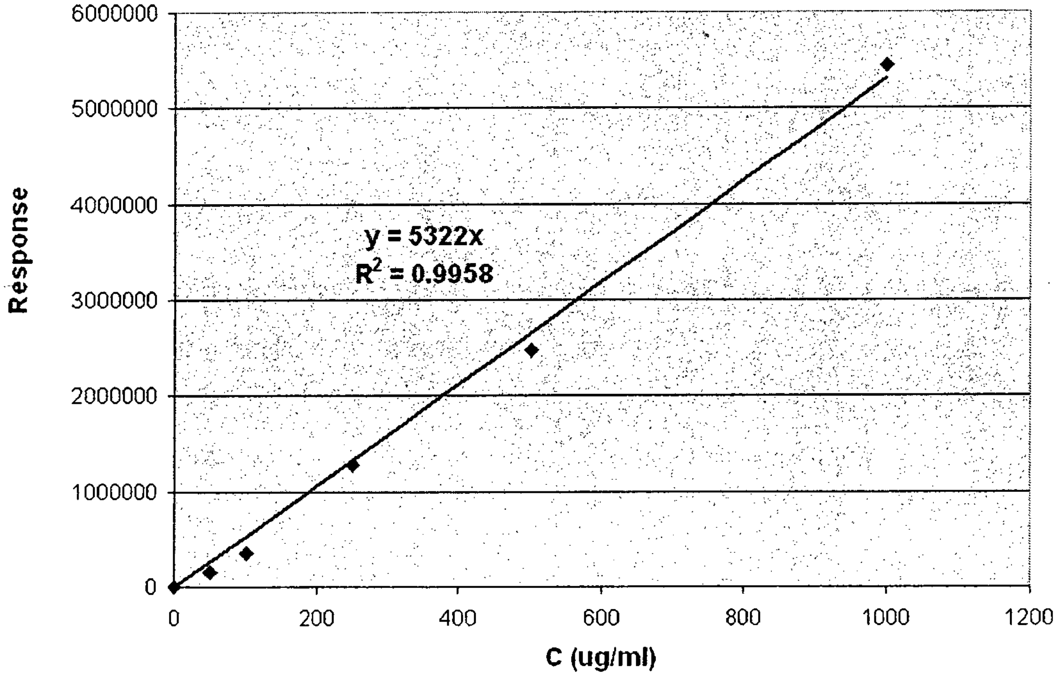


Figure 4-3: p-Xylene calibration curve

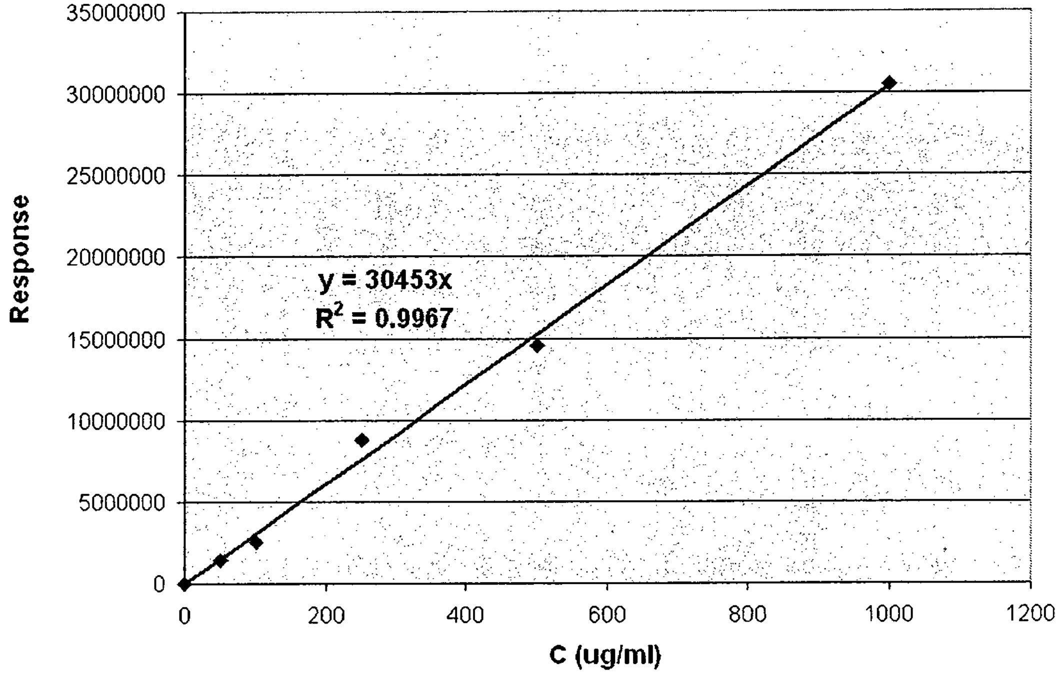


Figure 4-4: Toluene calibration curve

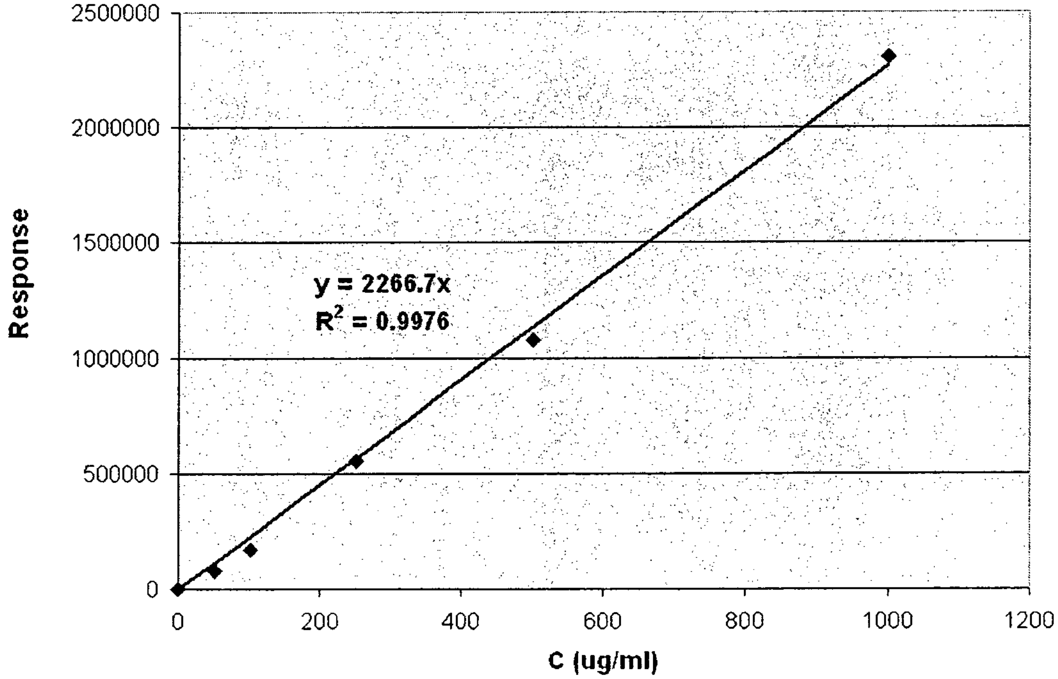


Figure 4-5: 2-butanone calibration curve

4.4.4 ANALYSIS METHODS

4.4.4.1 Single Gas Analysis Method:

To determine the adsorption efficiency of each filter, the concentration of toluene in upstream and downstream air of the filter was measured and recorded continuously every three minutes by the gas detector (photo-acoustic multi-gas analyzer detector). Since only one gas detector was applied, upstream and downstream air concentrations could not be measured simultaneously. Therefore, linear interpolation was applied to calculate the time-wise identical upstream air concentration.

4.4.4.2 Mixture Gas Analysis Method

Upstream and downstream multigas samples were collected continuously every 30 minutes by the Thermal Desorber and then analyzed by the GC/MS. To measure the individual concentration of each VOC, a method was developed for the TD-GC/MS as follows:

First, the Thermal Desorber collected VOCs for two minutes with a flow rate of 50 ml/min. The flow rate was controlled by a mass flow controller located at the online sampling section of the Thermal Desorber. Then, VOCs were transferred to an empty sampling tube placed inside the Thermal Desorber and desorbed from the tube with 25 ml/min helium at a temperature of 300° C for 8 minutes into a trap with a temperature of 20° C. Afterwards, the trap was desorbed at 300° C for 5 minutes. A transfer line moved VOC samples at 200° C and flow rate of 2 ml/min from the Thermal Desorber to the GC column (60 m, 0.32 mm i.d., 1.8 μm film thicknesses).

The GC method began at 50° C, and its temperature was held steady for 5 minutes. Subsequently, it was increased to 180° C with the heating rate of 10° C/min. VOCs were separated in the analytical column and were identified, quantified and analyzed under full scan detection mode in the MS. The mass spectrum of each VOC peak and the quantification ion were used for the identification and the quantification, respectively.

4.4.5 ENVIRONMENTAL CONDITIONS

During each experiment, temperature and relative humidity at both upstream and downstream points as well as the pressure difference were measured and monitored in a time interval of five minutes. Air conditions were checked regularly to ensure that the temperature and relative humidity were stable in 23°C ± 2°C and 50% ± 5%, respectively. Relative humidity was set on 50% because of two reasons. First, it represents typical conditioned indoor environment. Secondly, relative humidity above 50% has a negative effect on the GAC filter performance (Nelson and Harder 1976).

4-4-6 QUANTIFICATION METHODS

Based on the experimental data obtained from both upstream and downstream air concentrations, important parameters of a GAC filter such as removal efficiency, penetration, removal capacity and retentivity were computed.

4.4.6.1 Removal Efficiency

In this research study, the performance of a filter was quantified by its removal efficiency. The removal efficiency was calculated from data of both upstream and downstream concentrations during the adsorption time as follows (Haghighat *et al.* 2008):

Removal Efficiency, $E_t(\%) = \frac{C_{up,t} - C_{down,t}}{C_{up,t}} \times 100$, Equation 4- 1

where

$C_{up,t}$ = the upstream challenge gas concentration (ppm) as a function of time

$C_{down,t}$ = the downstream challenge gas concentration (ppm) as a function of time

E_t= the removal efficiency as a function of time

t= the elapsed time (hour)

The efficiency curve, which is the plot of the contaminant removal efficiency versus the adsorption elapsed time, is shown in Figure 4-6. This figure shows that the removal efficiency drops as time passes because more contaminants occupy the active sites on the media. Basically, in the adsorption process of gas contaminants, VOC molecules first move from the air to the boundary layer surrounding the adsorbent granule and then diffuse into pores towards the internal surface of the adsorbent. Therefore, if the media filter provides more surface area and better contact between contaminated air flow and the adsorbent granule, the removal efficiency will be higher.

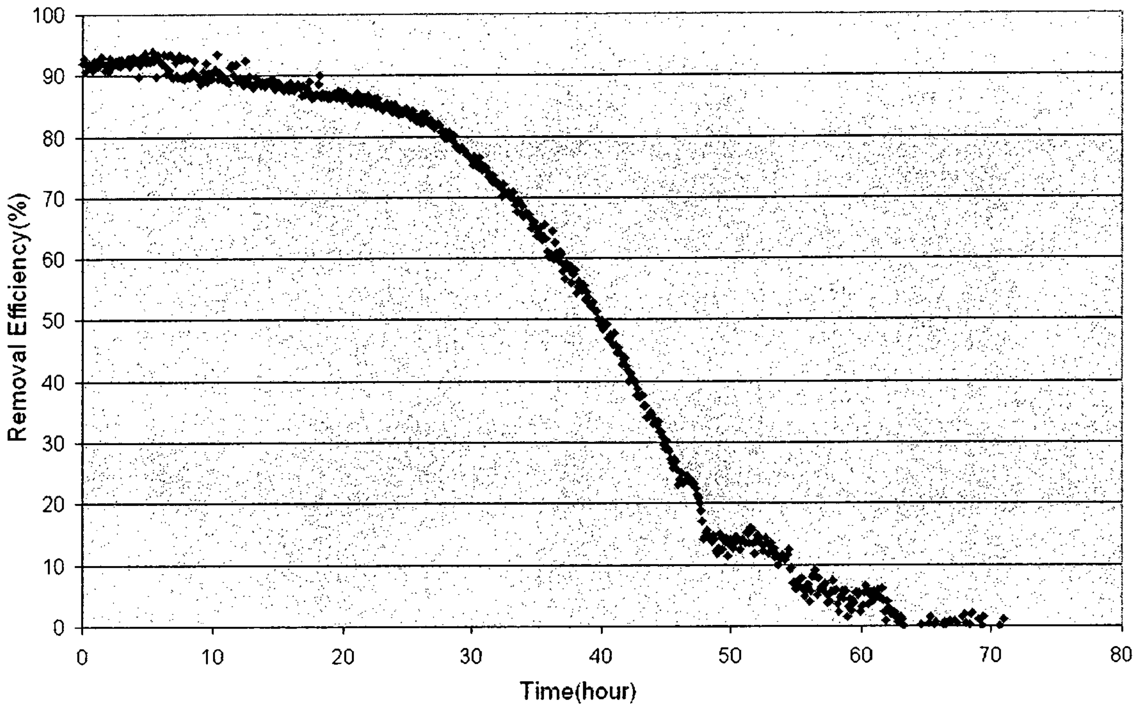


Figure 4-6: Efficiency profile for 5cm-filter challenged with toluene

4.4.6.2 Penetration

Contaminant penetration (breakthrough) is the point at which downstream concentration is measurable and increases over time, and it is calculated by the ratio of downstream concentration to the upstream concentration (ASHRAE standard 145-1 P 2008):

$$P_t = \frac{C_{down,t}}{C_{up,t}}, \qquad \text{Equation 4-2}$$

where

P_t = the contaminant penetration as function of time

$C_{up,t}$ = the upstream challenge gas concentration (ppm) as a function of time

$C_{down,t}$ = the downstream challenge gas concentration (ppm) as a function of time

The plot of the breakthrough of the gas contaminant in the bed versus the test duration has a specific sigmoid shape and is known as a breakthrough curve. This curve is presented based on the upstream and downstream concentration data for both the adsorption and desorption phases. Because penetration is meaningless with no challenge gas, the desorption side of the breakthrough curve shows a pseudo-penetration computed by dividing the downstream concentration and average upstream concentration (during the adsorption process). Figure 4-7 demonstrates the breakthrough curve for 5 cm-filter challenged with toluene during the adsorption and desorption process. The breakthrough increases in the adsorption phase and it reaches to one when the filter is fully saturated.

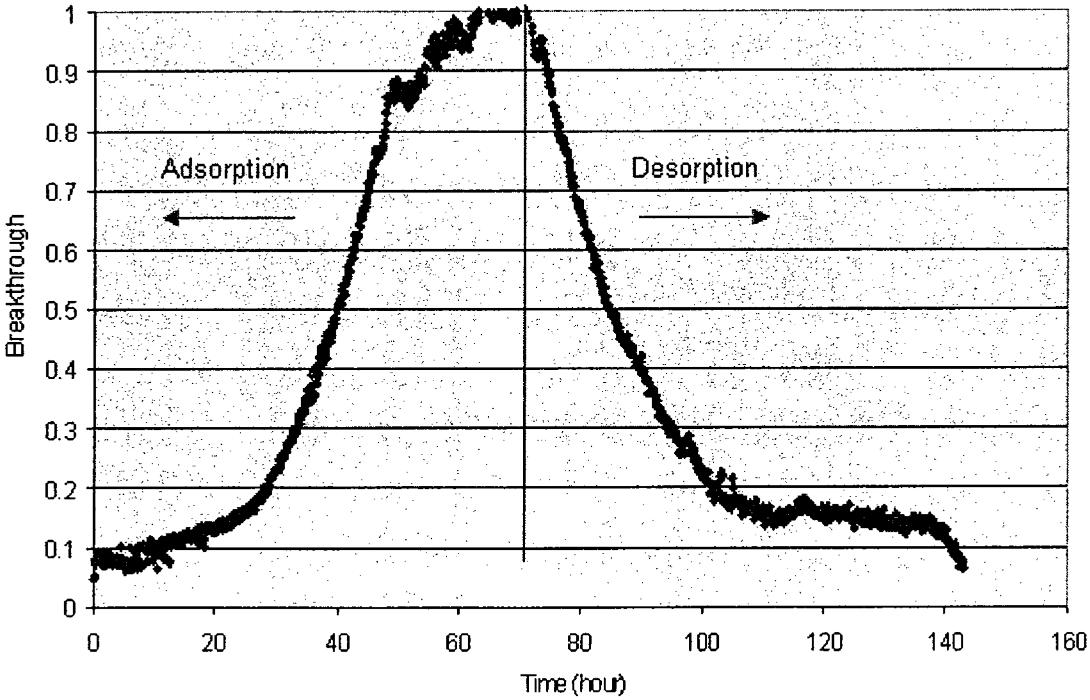


Figure 4-7: Breakthrough curve for 5cm-filter

Breakthrough time (t_b) is defined as the time between the beginning of the test and the time at which the outlet concentration reaches the specified breakthrough fraction. In this study, relevant breakthrough times at penetration percentages of 50% and 90% ($t_{b50\%}$ and $t_{b90\%}$) were used to analyze the removal performance of the filters. A 50% breakthrough time, $t_{b50\%}$, has been reported as a recommended percentage to evaluate gasous air filters (VanOsdell *et al.* 1996). The breakthrough time of 90%, ($t_{b90\%}$), is optional and studied less due to lengthy experimental time required.

4.4.6.3 Removal Capacity, C_R (weight %)

Another parameter for evaluating the effectiveness of gasous filters is the gas removal capacity. This capacity is expressed as the percentile fraction of the adsorbed mass of contaminant gas over the removal media weight (Haghighat *et al.* 2008):

$$C_{R_t} = \frac{\int_0^{T_{ads}} Q\left(C_{up}(t) - C_{down}(t)\right) dt}{M_{media}} \times 100\%, \qquad \text{Equation 4-3}$$

where

C_{R_t} = the filter capacity at a specific elapsed time (weight %)

T_{ads} = the elapsed time of adsorption test (min)

Q = the air flow rate in the duct (m^3/min)

$C_{up}(t)$ and $C_{down}(t)$ = the upstream and downstream concentration (kg/m^3) as a function of elapsed time

M_{media} = the mass of removal media (kg)

To analyze removal capacity of filters, specified elapsed times of 50% breakthrough time ($t_{b50\%}$) (A recommended percentage of the ASHRAE standard 145.1 P 2008) and 90% breakthrough time ($t_{b90\%}$) were used.

Removal capacity of a filter is the lowest at the beginning of the test and gradually rises with increasing amounts of collected gas contaminant on media bed. The maximum amount of capacity occurs at saturation (equilibrium), in which the media cannot collect any further contaminant. Generally, removal capacity of a gasous filter depends on the challenge gas contaminant (adsorbate), type of media (adsorbent) and environmental conditions such as temperature and relative humidity (Graham and Bayati 1990).

4.4.6.4 Desorption and Retentivity, Rc (weight %)

The desorption process was started once the contaminant injection process was finished and clean and conditioned air was used to purge the filter of the adsorbed contaminant(s). Desorption is the reverse process of adsorption in which the tested filter is the source of contaminant and sorbate molecules leave the surface of the media.

In each experiment, all conditions of desorption process such as duration, condition of the air and the flow rate were the same as adsorption. Similarly, the upstream and the downstream air concentrations and the pressure drop were measured at the same time intervals as in the adsorption process.

Retentivity shows the resistant ability of an adsorbent against the unloading of contaminant molecules. Retentivity represents the proportion of total capacity (weight %) that is retained on the media during desorption process (Bastani *et al.* 2009) :

$$Rc_{t'} = C_{adsorption} + \left(\frac{\int_0^{t'} Q\left(C_{up}(t) - C_{down}(t)\right) dt}{M_{media}} \right) \times 100\%, \qquad \text{Equation 4-4}$$

where

$Rc_{t'}$= retentivity (weight %)

$C_{adsorption}$= total computed capacity of the media after adsorption phase, (weight %)

M_{media}= Mass of the media (kg)

Q=the air flow rate (m^3/min)

t'= the elapsed time of desorption test

$C_{up}(t)$ and $C_{down}(t)$ = the upstream and downstream concentration (kg/m^3) for the desorption phase as function of elapsed time

Figure 4-8 shows the capacity and retentivity profile of 5 cm-filter. The filter was full-saturated by toluene in the challenge concentration of 10 ppm after approximately 70 hours. As soon as desorption started, the clean air unloaded the toluene molecules from the carbon media. The analysis of capacity and retentivity profile for tested filters will be described in chapter 5.

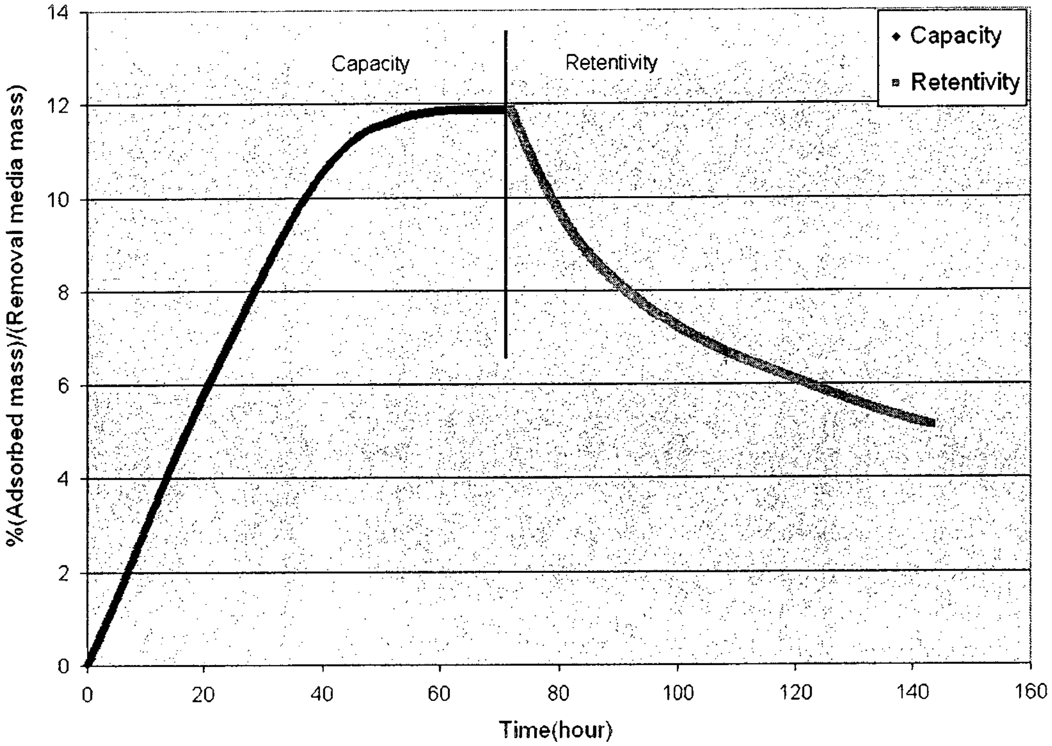


Figure 4-8: Capacity and Retentivity profile for 5cm-filter

CHAPTER 5 RESULTS AND DISCUSSION

5.1 INTRODUCTION

Two sets of experiments were carried out in this study; in the first set, panel filters filled with GAC with 5, 10, 15 and 30 cm bed depths were tested for toluene removal. In the second set, the new chemical generation system and the on-line gas sampling and analysis system were used to measure the GAC filter removal efficiency against a mixture of VOCs. The experiment was conducted and replicated with a 5 cm-filter in similar air flow rate and environmental conditions as the first set.

This chapter describes the outcomes of each experiment, the effect of media bed depth on the removal performance and how applicable the Wheeler-Jonas model (Wheeler 1969) is on the full-scale activated carbon filters. Moreover, the results of the mixture gas tests are used to assess the impact of multiple pollutants on the service life of full-scale GAC filters.

5.2 PHASE 1: SINGLE GAS TESTS ANALYSIS

5.2.1 Residence Time and Face Velocity Determination

Depending on the media bed depth, the air residence time and face velocity of each filter were determined based on the following equations:

$$t_r = d / v, \qquad \text{Equation 5-1}$$

$$v = \frac{Q}{A}, \qquad \text{Equation 5-2}$$

where

t_r = the residence time (s)

d = the media depth (m)

v = the face velocity (m/s)

Q = the volumetric flow rate (m^3/s)

A = the cross section area of the media bed (0.6 m x 0.6 m)

Table 5-1 presents the information for tested GAC filters challenged with toluene. The challenge gas must have sufficient contact time in a gas adsorption filter to ensure that it will be effectively adsorbed by the filter media. Usual residence times range between 0.02 and 0.2 seconds (Holmberg *et al.* 1993).

Table 5-1: Summary of information for tested filters

Test Name	Media Depth (cm)	Total Carbon Weight (Kg)	Face Velocity (m/s)	Residence Time (s)	Pressure Drop (Pa)
A1	5	7.8	0.525	0.097	205
A2	5	7.5	0.519	0.098	177
B	10	16.5	0.519	0.198	359
C	15	25.1	0.511	0.298	508
D	30	44.1	0.516	0.590	805

5.2.2 Test Conditions

Table 5-2 presents the environmental conditions of each test. Also included are the values of the challenge air flow rate and the average upstream concentration of each test. As the data shows, the test conditions are flow rate of 0.187 ± 0.002m^3/s, challenge gas contaminant concentration of 9.9± 0.3 ppm, relative humidity of 48± 2% and temperature of 23± 1°C.

Table 5-2: Summary of test conditions

Test Name **Conditions**	**A-1**	**A-2**	**B**	**C**	**D**
AVG Flow rate (m^3/s)	0.189	0.187	0.187	0.184	0.186
STDEV *	0.004	0.004	0.007	0.006	0.006
95% Confidence	1.73 e^{-4}	1.9e^{-4}	2.43 e^{-4}	1.9 e^{-4}	1.96 e^{-4}
CV ** (%)	2.11	2.13	3.74	3.26	3.22
AVG Upstream Concentration (ppm)	9.73	9.77	9.65	10.21	10.20
STDEV *	0.24	0.28	0.25	0.32	0.34
95% Confidence	0.02	0.02	0.01	0.01	0.01
CV ** (%)	2.46	2.86	2.59	3.13	3.33
AVG Upstream RH (%)	48.40	45.40	50.25	47.69	46.99
STDEV *	4.98	3.90	3.79	4.42	3.69
95% Confidence	0.39	0.26	0.13	0.15	0.12
CV ** (%)	10.22	8.59	7.54	9.21	7.85
AVG Downstream RH (%)	48.46	46.09	49.72	48.39	47.05
STDEV *	4.87	3.93	4.68	4.79	4.12
% 95 Confidence	0.35	0.26	0.16	0.23	0.23
CV ** (%)	10.04	8.52	9.4	9.89	8.75
AVG Upstream Temperature (°C)	23.00	22.02	23.77	23.17	23.10
STDEV *	0.54	0.57	0.63	0.77	0.57
95% Confidence	0.02	0.04	0.02	0.02	0.01
CV ** (%)	2.34	2.59	2.65	3.32	2.46
AVG Downstream Temperature (°C)	23.15	21.9	24.12	23.29	23.33
STDEV *	0.63	0.70	0.76	0.79	0.70
95% Confidence	0.02	0.04	0.02	0.02	0.02
CV ** (%)	2.72	3.19	3.15	3.39	3.00

* STDEV= Standard Deviation

** CV= Coefficient of Variation= (STDEV/Mean Average) x 100%

5.2.3 Repeatability Test

Test A1 was repeated to examine how reliable the results were for 5 cm-filter. For test A2, the environmental conditions were identical to test A1 with the only difference being that the media weight was 2.98% less than test A1 (7.54 kg vs. 7.765 kg). This second test supported the reliability of Test A1.

Figure 5-1 demonstrates the similarity in the efficiency profiles of both tests. The breakthrough curves for the adsorption and desorption processes are indicated in Figure 5-2. The 50% breakthrough time which is required to reach penetration of 0.5 was 39.97 hours for test A-1 and 40.57 hours for test A-2. The difference in breakthrough time is less than 1.5% showing that both tests have similar 50% breakthrough times.

Furthermore, the removal capacity profiles of both filters are shown in Figure 5-3. The 50% capacity (capacity in $t_{b50\%}$) of tests A-1 and A-2 are 10.52% and 10.53%, respectively. The difference in the 50% capacity is less than 0.1%: this meets the ASHRAE criteria which require no more that a 10% difference in the 50% capacity (ASHRAE standard145.2 P, 2007-c).

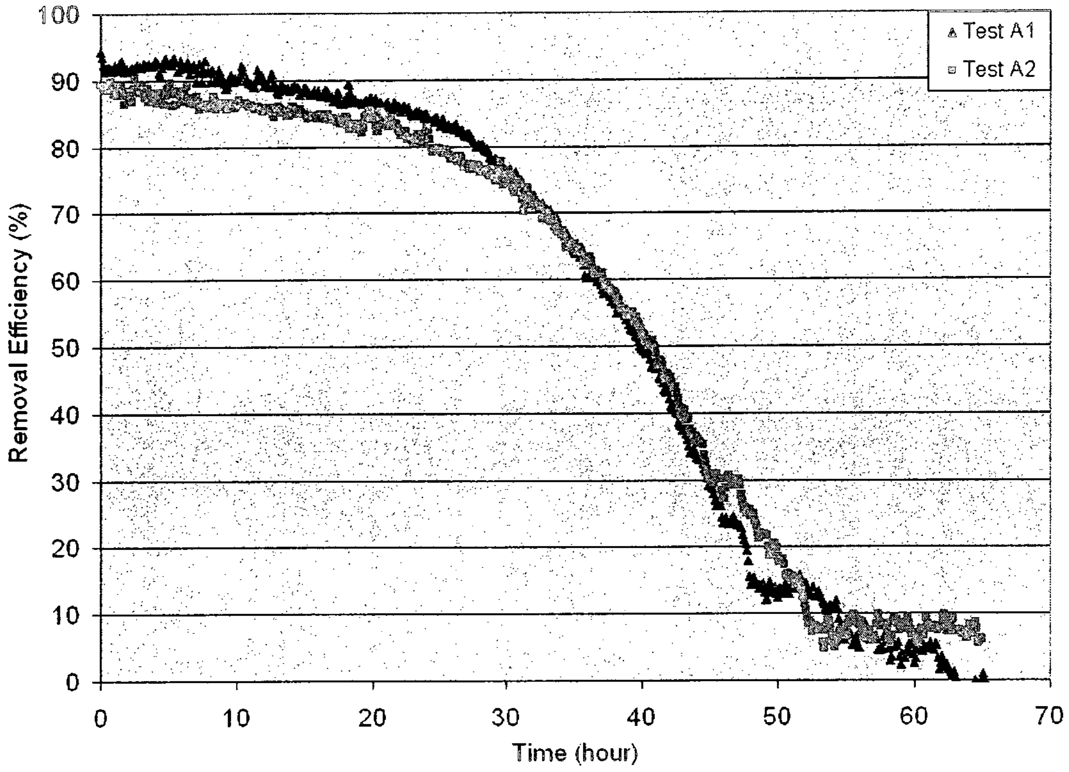


Figure 5-1: Efficiency profiles for Tests A1 and A2

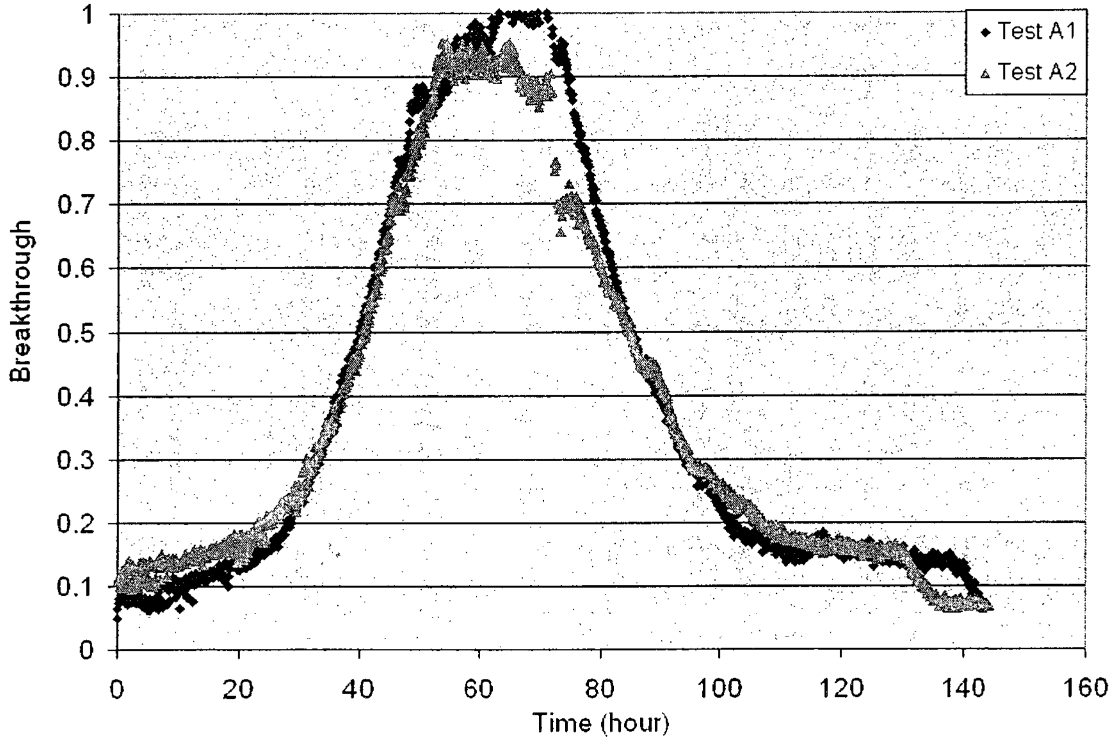


Figure 5-2: Breakthrough profiles for Tests A1 and A2

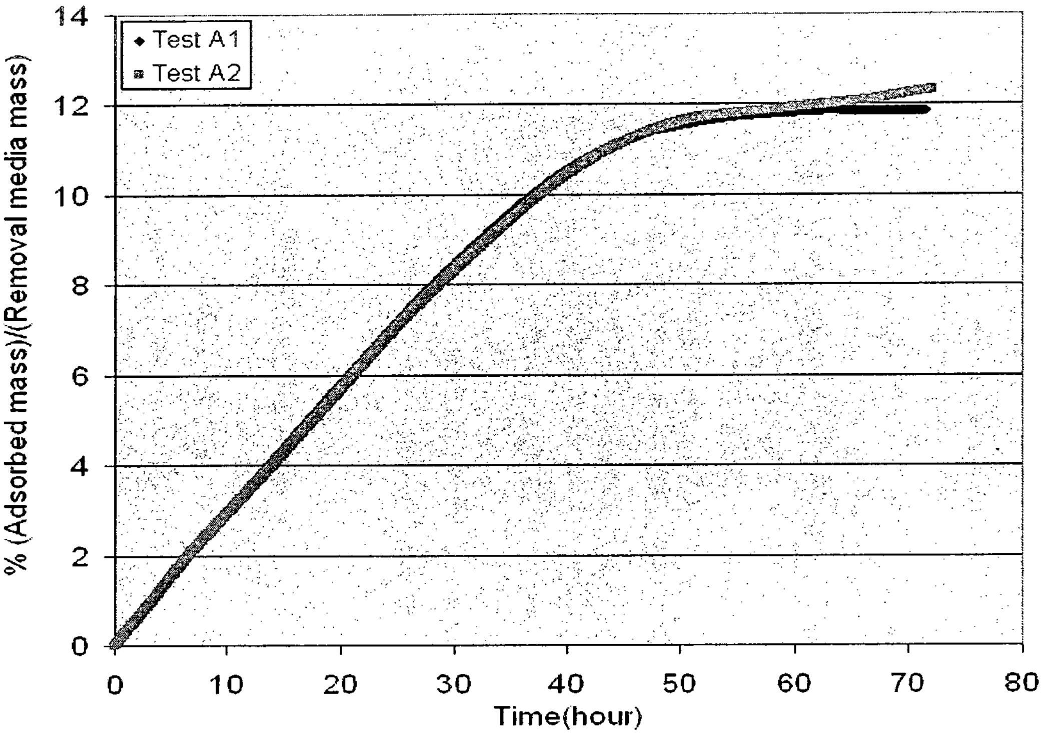


Figure 5-3: Removal capacity profiles for Tests A1 and A2

5.2.4 Test Results and Discussion

Performance of tested filters for removing toluene is determined from the calculated removal efficiencies and removal capacities over time. Figure 5-4 shows the efficiency profile of each GAC filter. The results clearly show the thicker the media bed depth, the better the performance. The extension of the bed depth results in increasing the residence time and allows the gas contaminant to have more contact with activated carbon surface, and consequently more removal of toluene.

However, while the initial efficiency of 5 cm-filter was the highest, 30 cm-filter had the lowest amount of initial efficiency. The initial efficiency was not as high as expected and by increasing the media bed thickness, the amount of initial efficiency dropped. The possible reason for this could be attributed to the negative influence of the high pressure drop values in these types of filters.

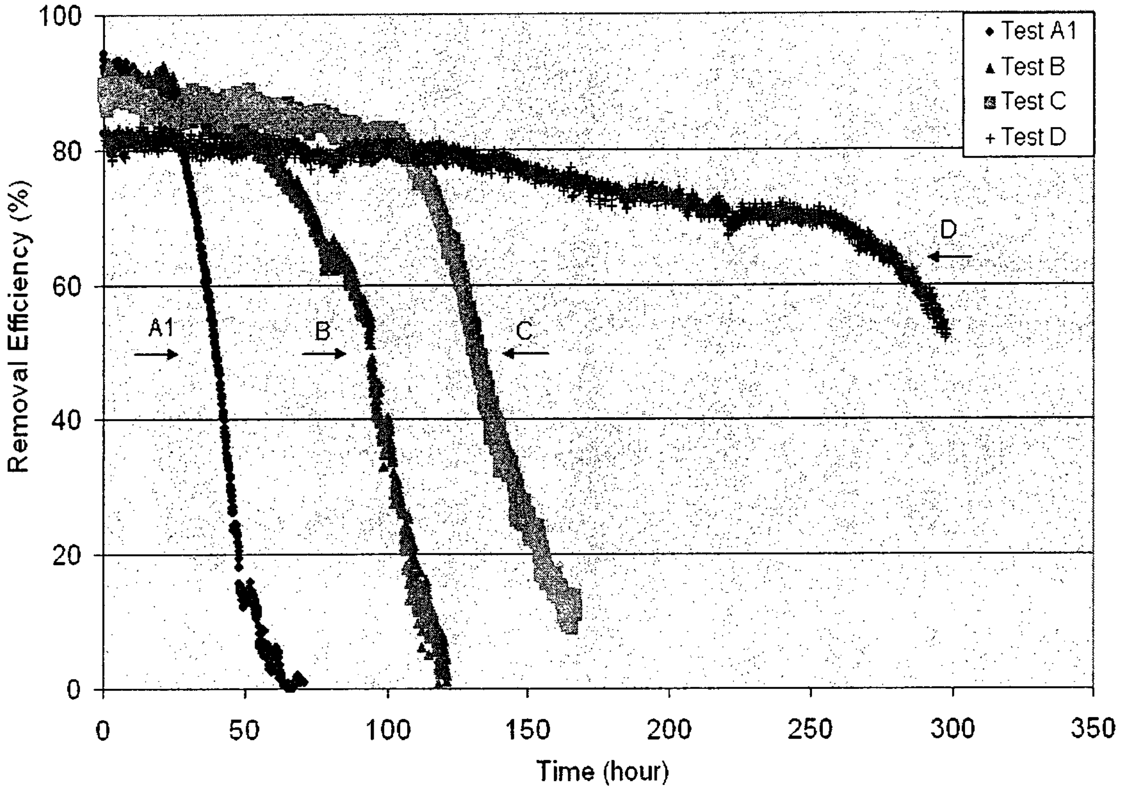


Figure 5-4: Efficiency profiles of different filters

Increasing the media bed thickness causes an increase in the pressure drop. Having a high pressure drop can cause an uneven air flow through the passages of lower resistance within the filter or bypass. Because of this, a fraction of the air passes untreated through the free space in the media bed resulting in a decrease of a filter's performance. Therefore, the initial efficiency is affected by the amount of bypass air flow in the filter (Kjaerboe and Peterson 1993). Bypass is a common problem in air cleaners resulting in a decrease of the performance of GAC media. Generally, this decrease in the filter performance can be due to leakage from filter gasket leaks (bypass) or internal GAC filter leaks (channeling) (NIOSH 2003, VanOsdell 2006).

Manually packaging media into a full-scale gasous air filter increases the chance of bypass and leaks that reduce the performance of sorptive media (VanOsdell 2006). Building air filters will generally have air leakage unlike respirator cartridges that have activated carbon homogenously packed in the bed which results in an initial efficiency of 100% for a short time period (Nelson and Correia 1976).

Figure 5-5 shows the breakthrough time of filters at the penetration of 50 % ($t_{b50\%}$) and 90% ($t_{b90\%}$), respectively. Since, the test for 30 cm-filters was terminated when downstream concentration reached half of the upstream concentration (50% breakthrough); data for breakthrough time at 10% removal efficiency is not available. As shown in Figure 5-5, the breakthrough time has increased with the increase in bed depth. Also, the time required for breakthrough to reach 90% from 50% is much less than the time to reach 50% breakthrough time ($t_{b50\%}$). For example, while the breakthrough time for 10 cm-filter and 15 cm-filter took 94.34 hours and 131.6 hours to reach their 50% efficiency; their removal efficiency dropped from 50% to 10% after 21.88 hours and 35.1 hours, respectively.

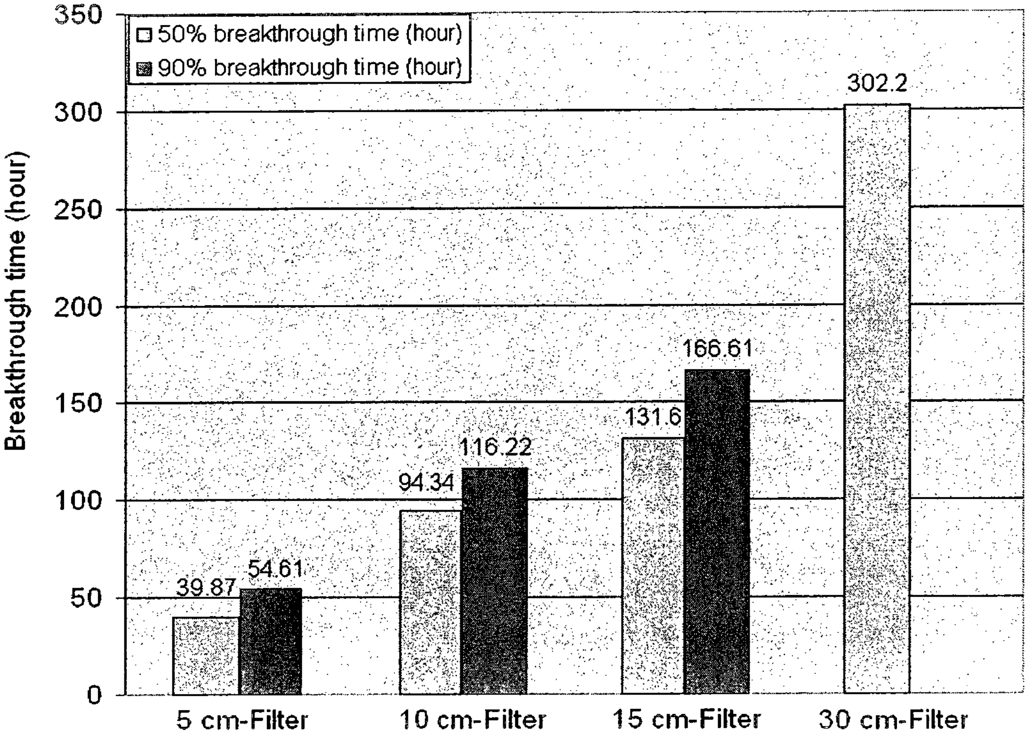


Figure 5-5: 50% and 90% breakthrough time for the tested filters

Figure 5-6 demonstrates the breakthrough profiles of tested filters. The average upstream air concentration was considered for calculation of the penetration in the desorption process. The figure above shows a general trend of the breakthrough times increasing as the media bed depth increases.

Figure 5-7 demonstrates the removal capacity of GAC filters at the 50% and 90% breakthrough times. Since, parameters which influence capacity such as adsorbent media, challenge contaminant and air conditions are kept constant, removal capacity values are approximately similar. Result shows that most surface sites in the activated carbon were blocked when removal efficiency reached 50% and the amount of removal capacity has not changed significantly from 50% breakthrough time to 90%.

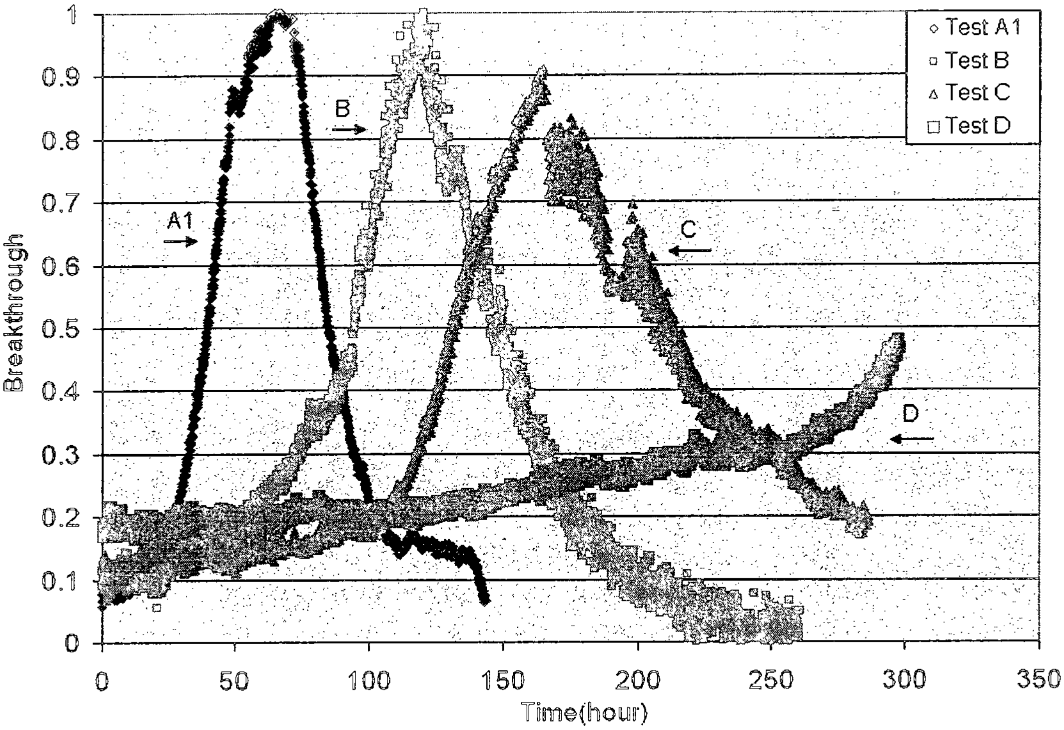


Figure 5-6: Breakthrough profiles of tested filters

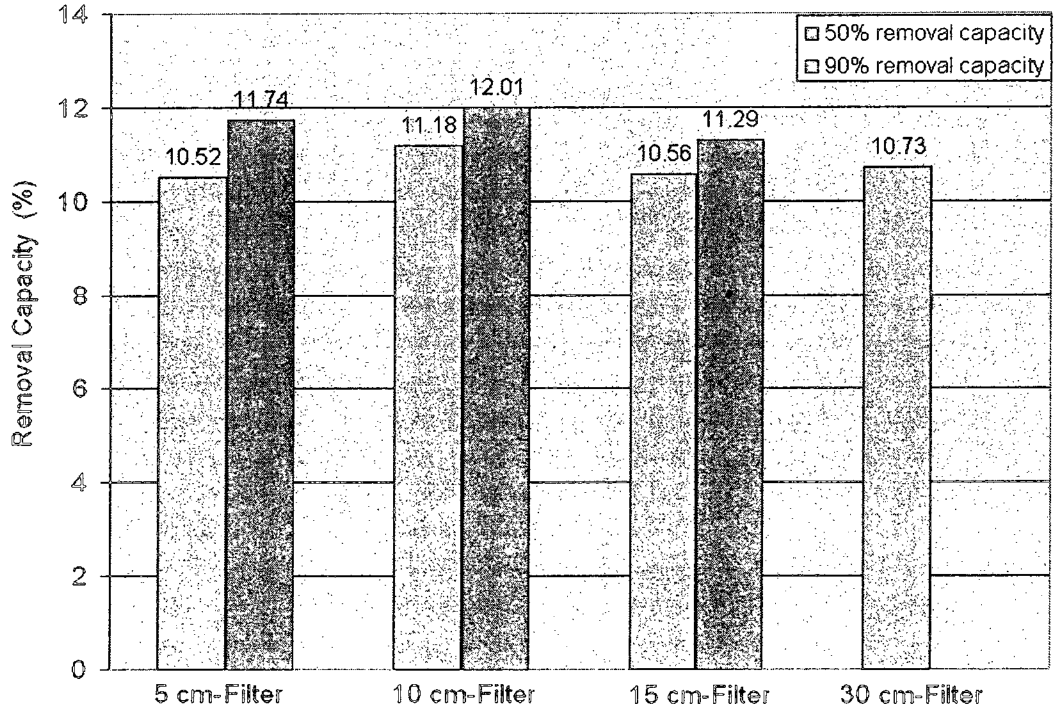


Figure 5-7: 50% and 90% removal capacity of filters with various media bed depths

Once desorption process started, downstream air concentration was measured for a period of more than 90% of total adsorption time. Retentivity of the media bed was calculated according to Equation 4-4. The retentivity of each filter is shown at different periods of time in Table 5-3. Toluene showed the resistibility against the desorption process because of the Van der Waals attraction forces holding toluene to the GAC. To remove at least 50% of the adsorbed toluene for 5 cm-filter and 10 cm-filter, the desorption period utilized the same amount of time required for the adsorption process.

Table 5-3: Data for removal capacity and retentivity

Media Thickness	5 cm	10 cm	15 cm	30 cm
Total Adsorption Time Duration (hour)	63.26	120.74	166.57	297.78
50% of Total Adsorption Time Duration (hour)	31.63	60.37	83.285	148.89
Total Computed Capacity (%)	11.88	12.03	11.29	10.73
Capacity after 50% of Total Adsorption Time Duration (%)	8.84	7.77	7.06	5.63
Retentivity after Total Adsorption Time Duration (%)	5.78	5.93	N/A	N/A
Retentivity after 50% of Total Adsorption Time Duration (%)	7.62	7.42	7.2	N/A

5.2.5 Applicability of Wheeler-Jonas Equation for Full-Scale Gas-phase Filters

Experimental data for tested filters are used to study the validity of Wheeler -Jonas model in the prediction of the breakthrough time of full-scale activated carbon filters (Kholafaei *et al.* 2009). Predicting the breakthrough time of filters is necessary for scheduling their maintenance. While Wheeler-Jonas model has been used previously to predict the service life of respirator cartridges, limited information exists about its performance for application in gas-phase filters used in HVAC system.

To predict the breakthrough time, parameters of W_e and K_v of the adsorbate-adsorbent system should be known. W_e is usually calculated by an adsorption isotherm equation (Wood and Moyer 1991), such as the Dubinin-Radushkevich (DR) equation (Dubinin 1989). Past research has noted that a small difference between the calculated adsorption capacity from isotherm equations and the measured capacity required for the Wheeler-Jonas equation may cause a large error in predicting the breakthrough time. Therefore, as a safety precaution, it is recommended to decrease the value of W_e calculated by D-R equation by 5% to prevent overestimation of the breakthrough time (Jufang *et al.* 2004). The estimation of the second parameter, K_v representing the effect of adsorption dynamics on breakthrough time, is more complicated. Several models are proposed to predict the value of K_v (Jonas and Rehrmann 1974, Wood and Estampfer 1993, Lodewyckx and Vansant 2000).

Furthermore, different approaches can be applied to calculate K_v from experimental breakthrough data and they have been summarized in a review by Wood (2001). In this study, two methods are used to estimate parameters of K_v and W_e based on the experimental data for all panel filters filled with GAC. Based on the results, the reliability of the Wheeler-Jonas equation used to predict the breakthrough time of full-scale carbon filters is investigated:

Method A: Breakthrough time (t_b) is plotted against the bed weight at fixed breakthrough values for tested GAC filters. The benefit of this method is that the results of several experiments with various amounts of activated carbon are considered. According to the Wheeler-Jonas equation, the plot of breakthrough time against the bed weight is expected to be a straight line. The regression line of the breakthrough time versus the media weight in breakthrough values of 0.2, 0.3, 0.4 and 0.5 is demonstrated in Figure 5-8. A reasonable linear regression is obtained with the excellent R^2 values. In addition, K_v and W_e are calculated from the intercept and slope of the regression line. As demonstrated in Table 5-4, the results show the dependency of the parameter of K_v to the breakthrough value. As discussed by Wood (2002), the reason for the error is that the extrapolated intercept of the lines is close to zero. Possible error in the calculation of K_v is one of the disadvantages of this method. However, the average value of W_e obtained from the slope of the regression lines is 0.127 (g_{VOC}/g_{carbon}) which is close to the value shown in Table 5-3.

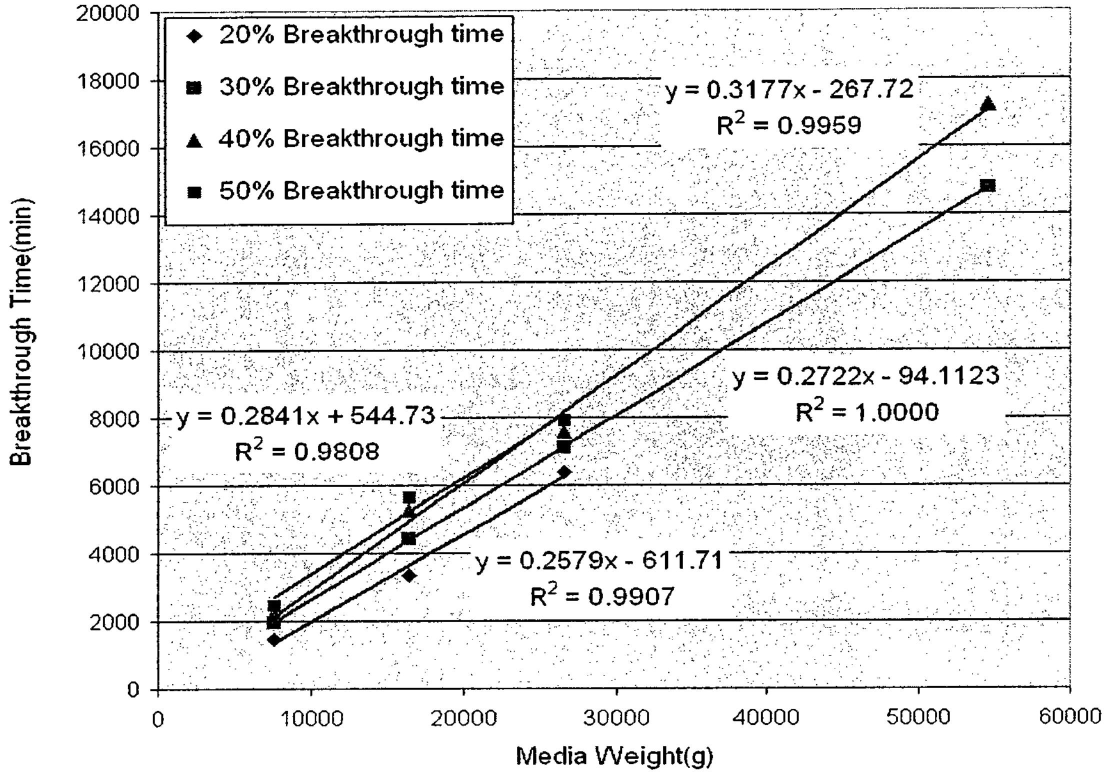


Figure 5-8: Breakthrough time versus media weight- method A

Table 5-4: Calculated values of W_e and K_v from methods A and B

	Method A				Method B		
Parameter	P_t=0.2	P_t=0.3	P_t=0.4	P_t=0.5	Test A1	Test B	Test C
W_e (gvoc/g$_c$)	0.109	0.118	0.135	0.121	0.130	0.148	0.131
K_v (min^{-1})	3256	13721	2838	88	3280	1067	1372

Method B: In the second method, a plot of the breakthrough time (t_b) against ln [(C_{up}-C_{down})/C_{down}] is derived for all filters in the breakthrough range of $0.2<P_t<0.5$. According to the Wheeler-Jonas equation, the plot is expected to yield a straight line. The plot for 5 cm-filter, 10 cm-filter and 15 cm-filter is illustrated in Figure 5-9. A small division in the regression lines is observed. This deviation in the regression line is found when the values of the breakthrough are not small. For example, while achieving 100% efficiency in gas masks is required (breakthrough values are small), in ventilation filters due to the fact the indoor contaminant concentration is commonly low, immediate and complete removal is not a major design goal (Kjaerboe and Peterson 1993, VanOsdell *et al.* 2006).

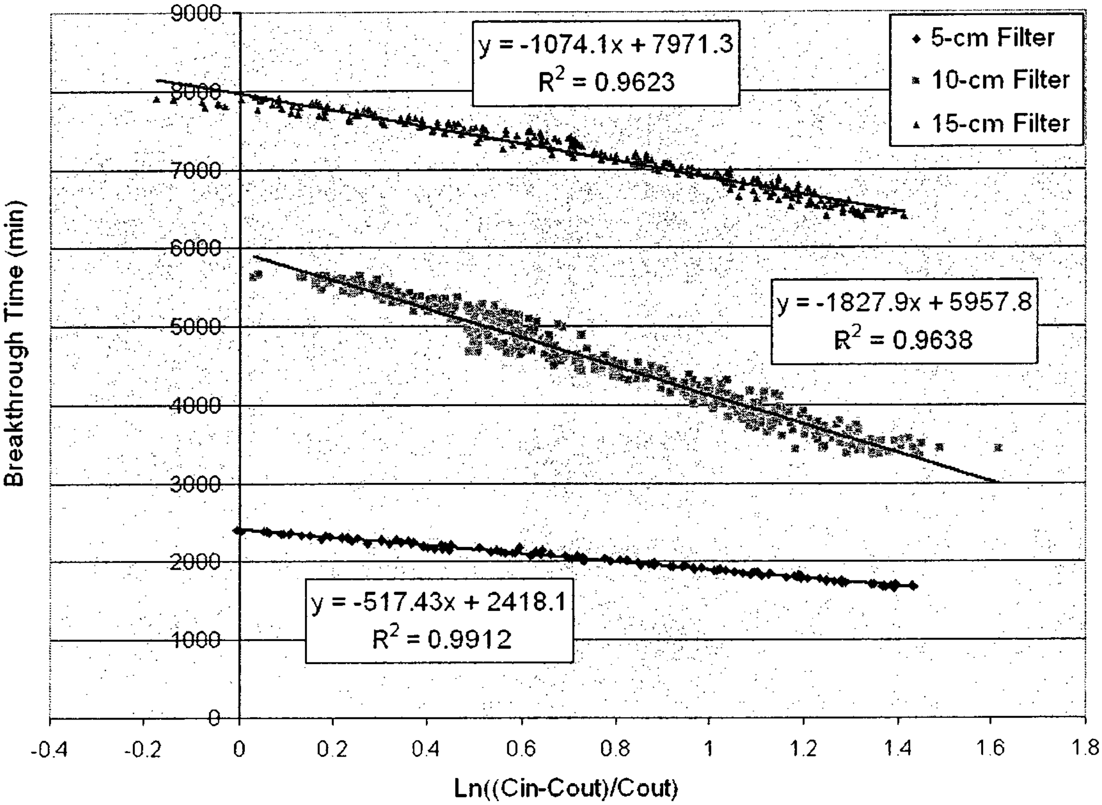


Figure 5-9: Validity of the Wheeler-Jonas equation- method B

Lodewyckx (2004) examined the validity of the Wheeler-Jonas equation by method B on their experimental data. As shown in Figure 5-10, the plot for very low values of the breakthrough (high values of ln [(C_{up}-C_{down})/C_{down}] shows straight trend, while increasing the breakthrough value resulted in a deviation of the extrapolated line.

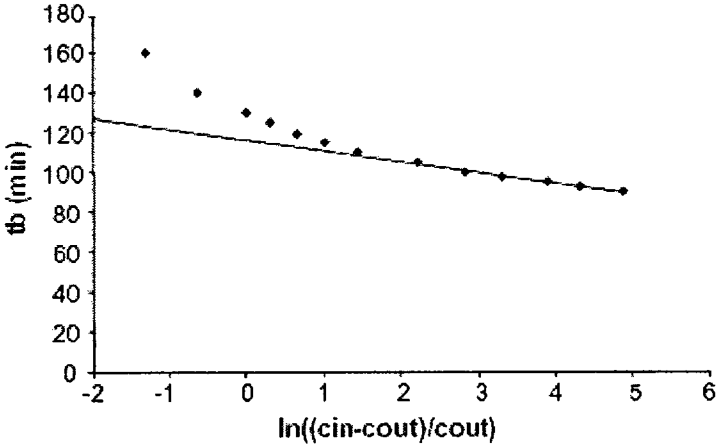


Figure 5-10: Regression line obtained from experimental data (Lodewyckx 2004)

Again, K_v and W_e can be obtained from the slope and intercept of the regression line. Table 5-4 shows the parameters for Tests A1, B and C. Although these values were based on a plot of many points, a high uncertainty in the calculated values was observed. First, the extrapolated line in each filter had a curvature which makes a larger error in calculation of K_v and W_e. Secondly, as a limitation of this method, all evidence was based on only one breakthrough curve.

In conclusion, applying the Wheeler-Jonas equation on the experimental data achieved a reasonable regression. But there are some limitations in application of this model to predict the breakthrough time of full-scale carbon filters for building applications. There is an uncertainty in the calculation of required parameters (K_v and W_e) in the Wheeler-Jonas equation when the 100% filter removal efficiency is not required. It is highly valuable to thoroughly examine new methods of calculating the required parameters for the Wheeler-Jonas equation and a standard method considering common challenges in air-handling units such as bypass air be developed in the future.

5.3 MIXTURE GAS TESTS ANALYSIS

5.3.1 Introduction

As noted earlier, an experimental method was developed to study the characteristics of GAC in-duct ventilation filters on the adsorption of multiple VOCs. The developed method was evaluated by conducting an experiment for 5 cm-filter. The test was carried out with approximately the same air flow rate and environmental conditions as the single gas tests; the air flow rate of 0.188± 0.004m^3/s, relative humidity of 50± 5% and the temperature of 22± 0.5°C. The mixture challenge gas consisted of toluene, n-hexane, p-xylene and 2-butanone with a concentration of 5 ppm each. The test was replicated in identical conditions to examine the reliability of the developed method.

5.3.2 Relationship between Removal Efficiency and VOC Properties

Figure 5-11 presents the removal efficiency curves of the filter in removing the VOCs mixture. The removal performance was highest for p-xylene, following by toluene, n-hexane and 2-butanone. This result is supportive of the fact that the performance of GAC filters is influenced by the physical properties of the gas contaminants it is exposed to. In general, less volatile compounds such as p-xylene and toluene with a higher molecular weights and boiling points are adsorbed better on the carbon surface than light and very volatile compounds like 2-butanone and n-hexane. 2-butanone had the lowest molecular weight in the VOCs mixture. Moreover, 2-butanone was the only polar compound in the VOCs mixture. GAC is hydrophobic and non-polar. Hence, 2-butanone had a weaker attraction to the adsorption sites of the carbon resulting in not being effectively removed by the GAC filter.

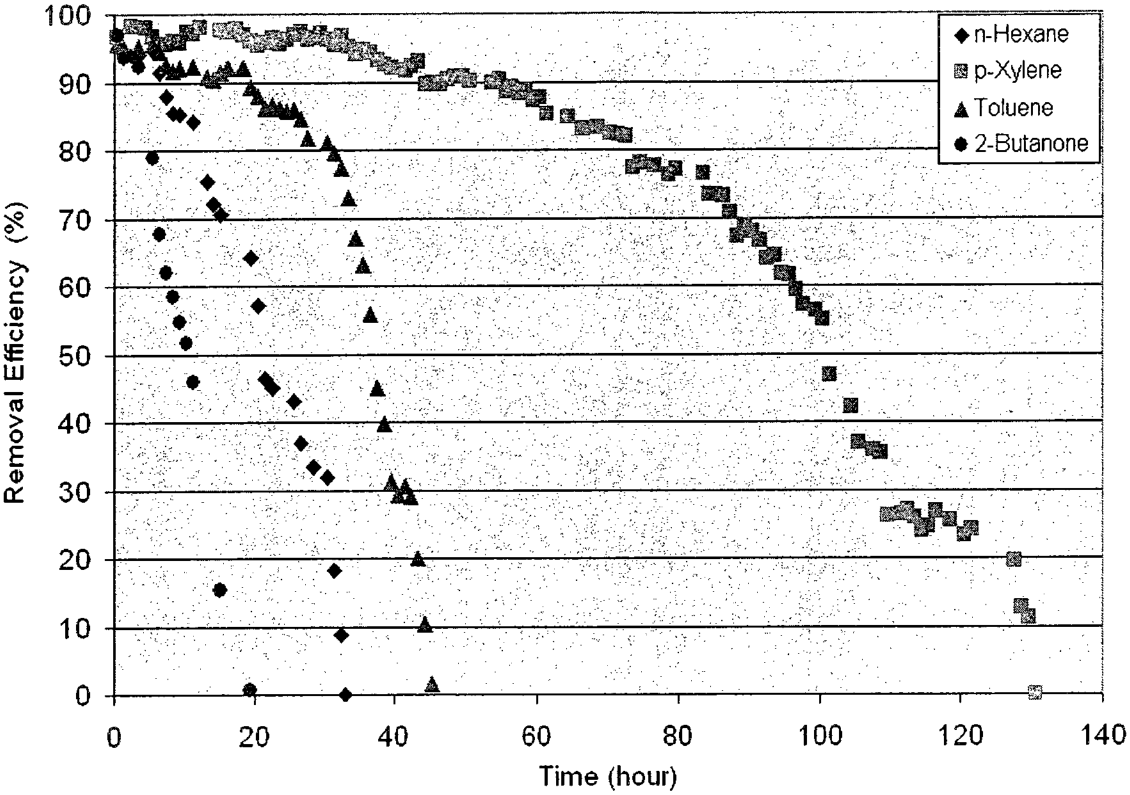


Figure 5-11: Removal efficiency profiles for the VOCs mixture

5.3.3 Breakthrough Time Analysis

Figure 5-12 presents the 50% and 90% breakthrough time values (the time in which the removal efficiency of the filter is 50% and 10%, respectively) of the VOCs mixture. The results showed that the largest breakthrough time was for p-xylene, followed by toluene, n-hexane and 2-butanone. This descending order is correlated with each compound's molecular weight. Also, no significant difference was seen between the 50% and 90% breakthrough time values of each VOC which means that the removal efficiency dropped very quickly from 50% to 10%.

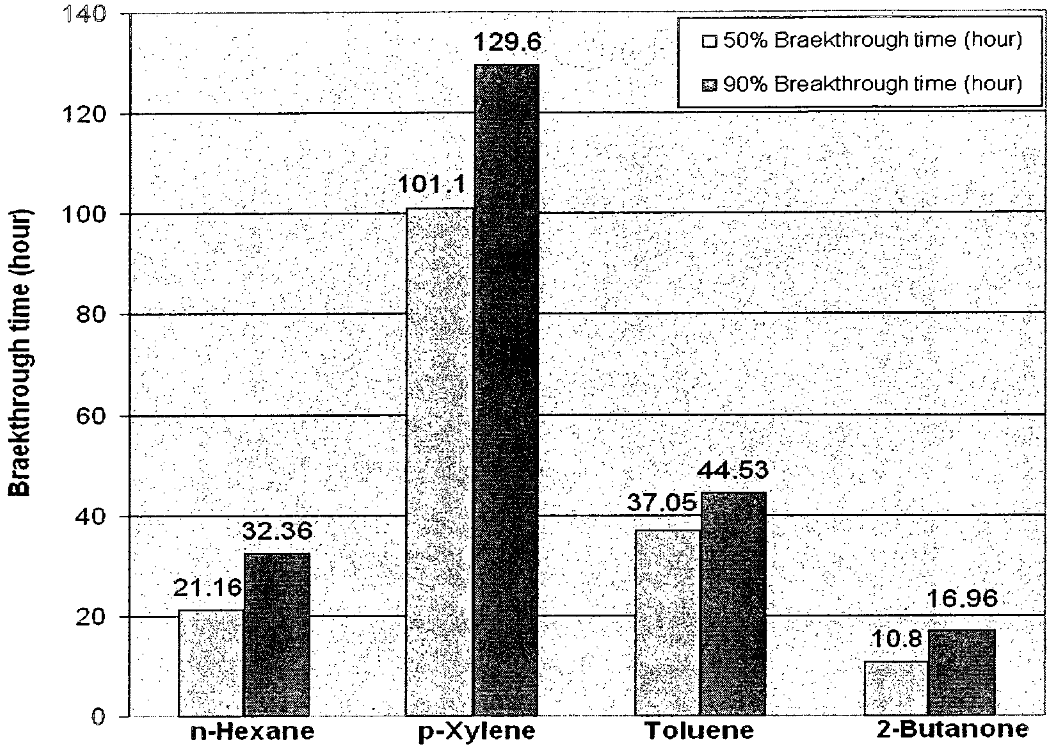


Figure 5-12: 50% and 90% breakthrough times for the VOCs mixture

5.3.4 Penetration Profiles

Figure 5-13 represents the breakthrough curves of the VOCs mixture. The curve shows that the most volatile VOC, 2-butanone, broke through first. The downstream concentration of 2-butanone increased quickly and exceeded the upstream concentration. The maximum downstream concentration of 2-butanone reached around 7 ppm which was 1.4 times of its upstream concentration. The same behavior occurred for n-hexane and toluene where their maximum downstream concentration reached to the maximum at a concentration equivalent to approximately 1.7 times of the inlet concentration.

After approximately 40 hours, the downstream concentration of 2-butanone and n-hexane fell. At the same time, the breakthrough of p-xylene slowly increased. Afterward, the downstream concentration of n-hexane and 2-butanone reached the same amount as the upstream concentration and remained stable until the end of the adsorption experiment. This phenomenon showed that there was no further adsorption of n-hexane and 2-butanone on the carbon surface. The maximum downstream concentration for toluene was 8.5 ppm and decreased to 6 ppm by the end of adsorption. The adsorption stopped when the downstream concentration of p-xylene reached the upstream concentration (100% breakthrough).

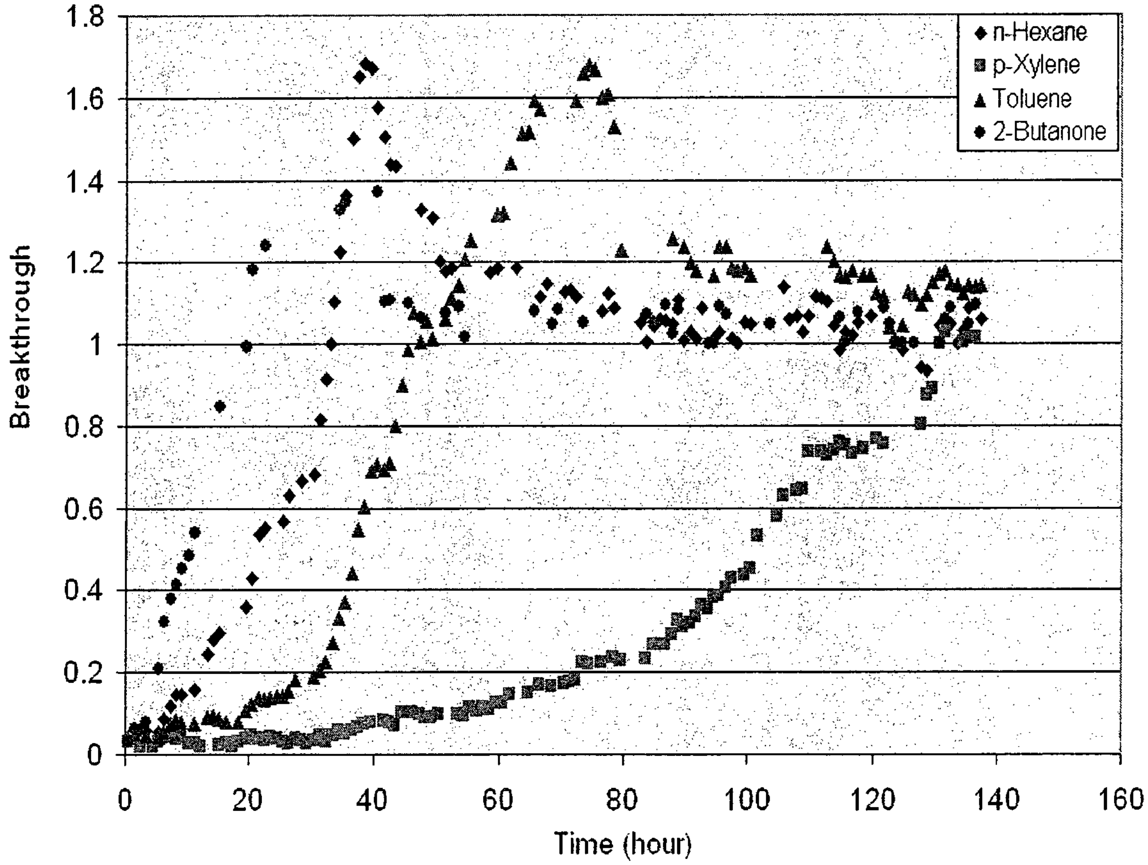


Figure 5-13: Penetration profiles for the VOCs mixture

5.3.5 Mixture Gas Adsorption Description

The behavior of the GAC in the adsorption of the VOCs mixture can be explained as the following: As soon as the challenge mixture gas was introduced to the GAC filter, VOCs competed for the smaller microporous which have a higher adsorption potential. 2-butanone was the most volatile compound and had a low attraction to the adsorption sites. Thus, 2-butanone broke through first and its downstream concentration increased very rapidly. After 19.5 hours, 2-butanone was displaced by other heavier compounds which caused the downstream concentration of 2-butanone to become higher than its upstream concentration. The downstream concentration of 2-butanone during the displacement was equal to the sum of the 2-butanone in the upstream plus the 2-butanone displaced from the surface of the carbon by other stronger VOCs. The same interpretation can be given for the n-hexane and toluene. Toluene was the last compound to be displaced by p-xylene after 47 hours.

5.3.6 Desorption

Once the p-xylene breakthrough value reached one, after approximately 140 hours, the chemical generation system was turned off. To begin the desorption process, clean air passed through the filter. P-xylene showed the strongest resistance against desorption followed by toluene, n-hexane and 2-butanone. This ranking is directly related to the strength of the bond between the adsorbate and GAC media. P-xylene is the less volatile compound (Table 4-1) and therefore has the strongest bond with the carbon. Desorption of p-xylene from the carbon surface was not completed by the end of desorption phase (i.e. after 48 hours). Desorption of toluene was completed after approximately 48 hours. Desorption of n-hexane was very fast and finished after around 11 hours. It is interesting to note, that no 2-butanone was detected on the downstream of the filter during the desorption process. This was due to the fact that the adsorbed molecules of 2-butanone were already completely displaced by the heavier compounds used during the adsorption test period.

5.3.7 The Effect of Multiple VOCs on Individual Component Breakthrough Times

The effect of the VOCs mixture on the breakthrough time of the GAC filter in removing the toluene was investigated. The breakthrough times of toluene in the mixture test was compared with the breakthrough times of toluene in the single gas test, test A1. This comparison shows how the presence of other compounds in the mixture influences the breakthrough time of toluene.

Test A1 was conducted in the toluene concentration of 10 ppm. The Wheeler-Jonas equation was applied to extrapolate the breakthrough times of toluene in the concentration of 5 ppm which was the same concentration in the mixture test. The experimental parameters of test A1 (Table 5-5) were inputted into in the Wheeler-Jonas equation to extrapolate the breakthrough times of toluene at the penetration values of 0.2, 0.3, 0.4 and 0.5.

Table 5-5: Experimental parameters of Test A1

M (g)	Q(cm^3)/min	ρ_b (g $_{carbon}$/cm^3)	W_e (g $_{voc}$/g $_{carbon}$)	K_v (min^{-1})
7765	1.14e^7	0.480	0.130	3280

Figure 5-14 demonstrates that the breakthrough times of toluene in the mixture test were significantly reduced compared to those in the single gas test. The breakthrough times of toluene in mixture test with the breakthrough values of 0.2, 0.3, 0.4 and 0.5 were reduced by 42.7%, 46.5%, 49.3% and 52.3%, respectively. This means that in mixture gas adsorption, the presence of other compounds will decrease the breakthrough time of each individual VOC.

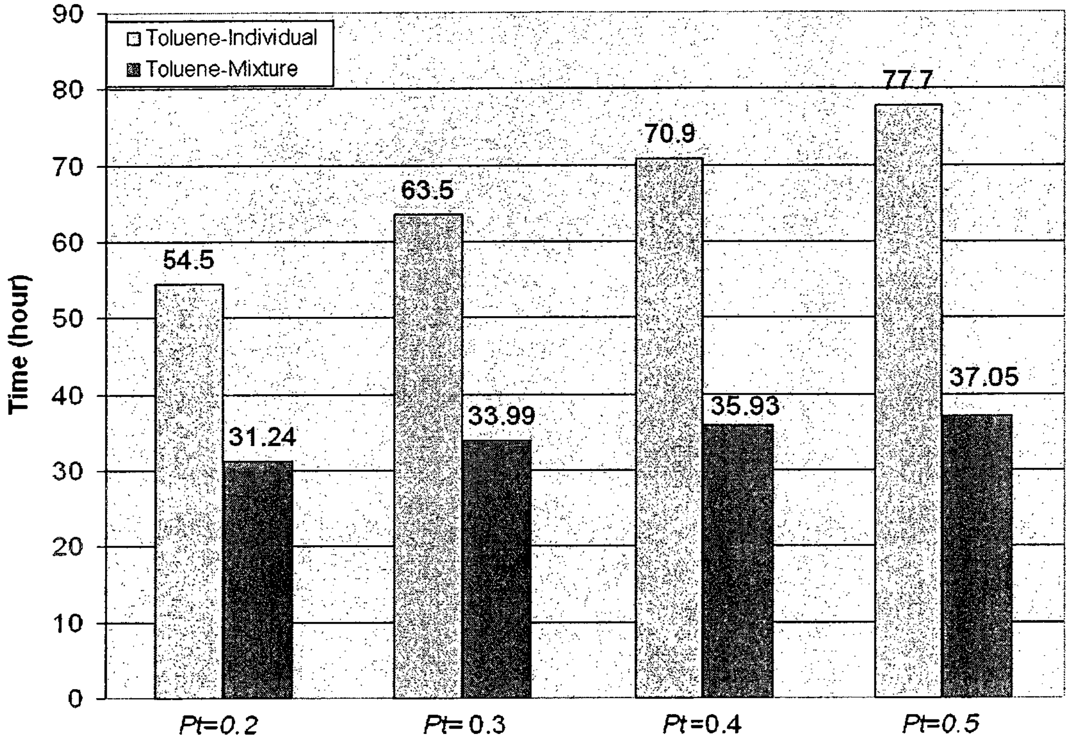


Figure 5-14: Breakthrough time values of the single gas test (Test A1) and the mixture test (Test 1) for Toluene

5.3.8 Repeatability Test

In order to examine how repeatable the results are for the mixture test, it was replicated in identical conditions. Figure 5-15 shows the 50% breakthrough time of test 1 and test 2. Results demonstrate that the 50% breakthrough times are similar for both tests. The maximum variation observed for toluene had a difference of less than 8%.

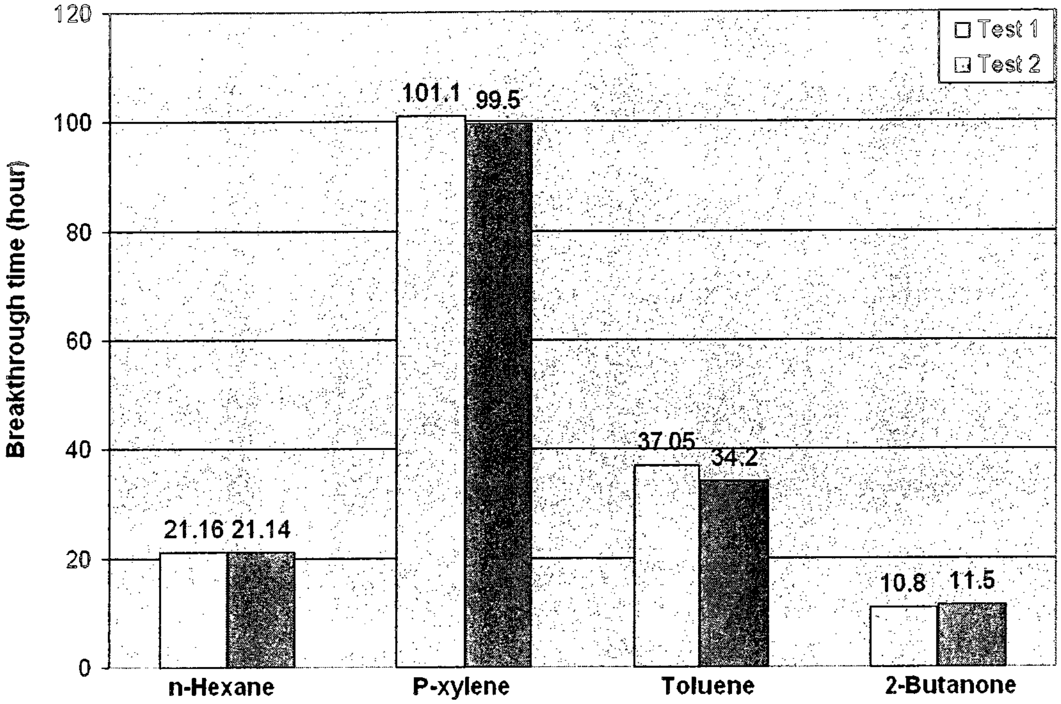


Figure 5-15: 50% breakthrough time for Test 1 and Test 2

Figures 5-16 to 5-19 compare the breakthrough curves of n-hexane, 2-butanone, toluene and p-xylene in test 1 and test 2. The breakthrough profiles of both tests verified the repeatability of experimental method used during both adsorption and desorption stages.

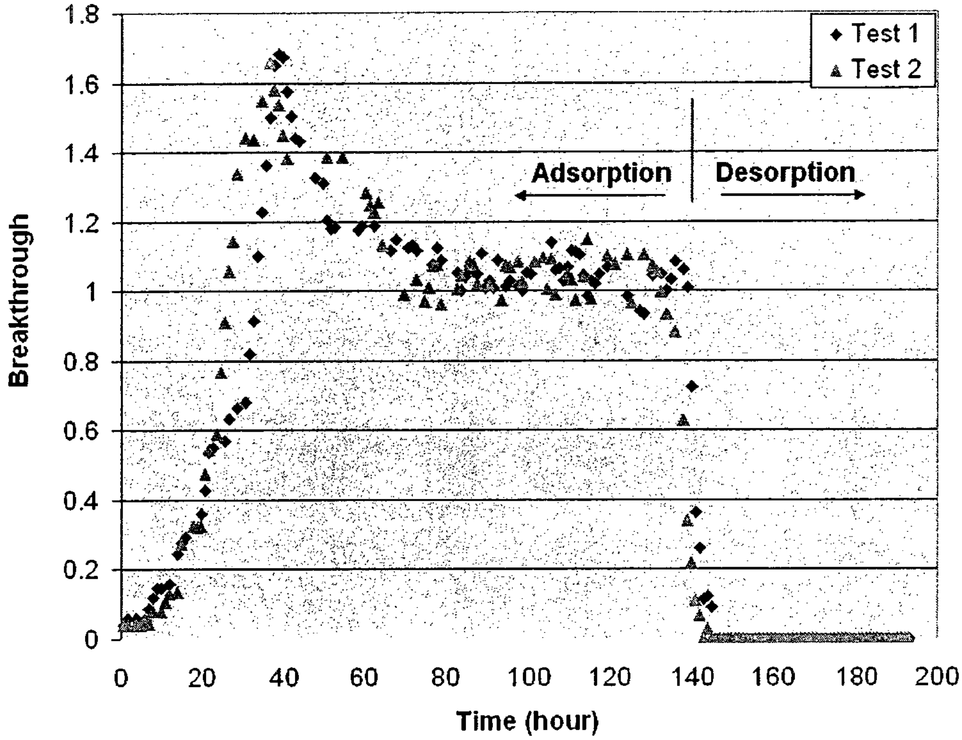


Figure 5-16: Repeatability evaluation, n-Hexane Breakthrough profile

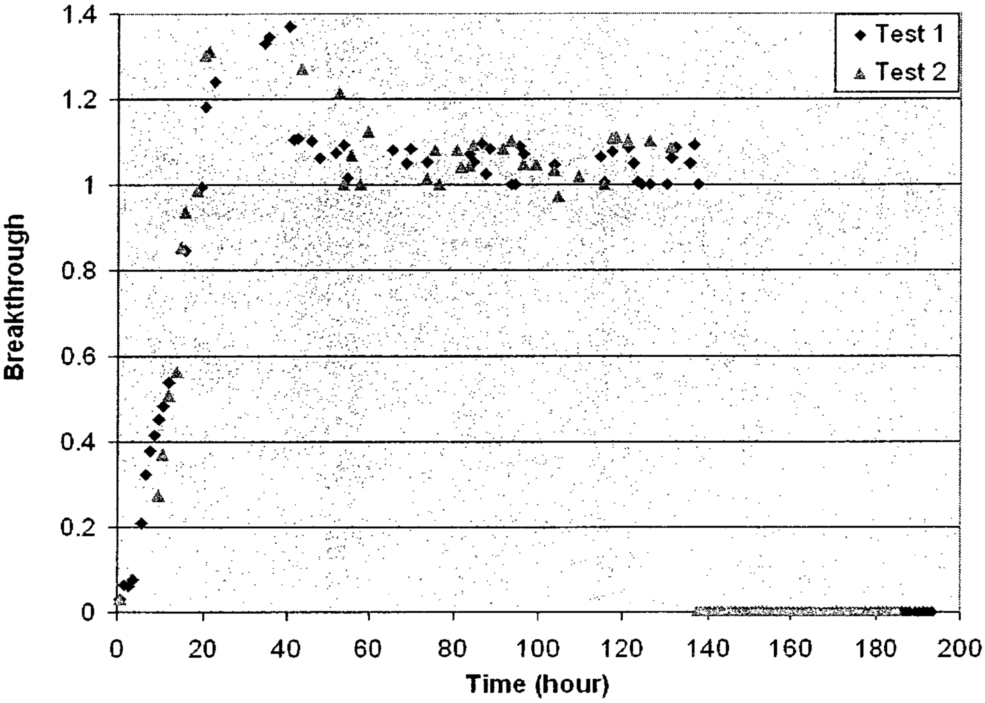


Figure 5-17: Repeatability evaluation, 2-Butanone breakthrough profile

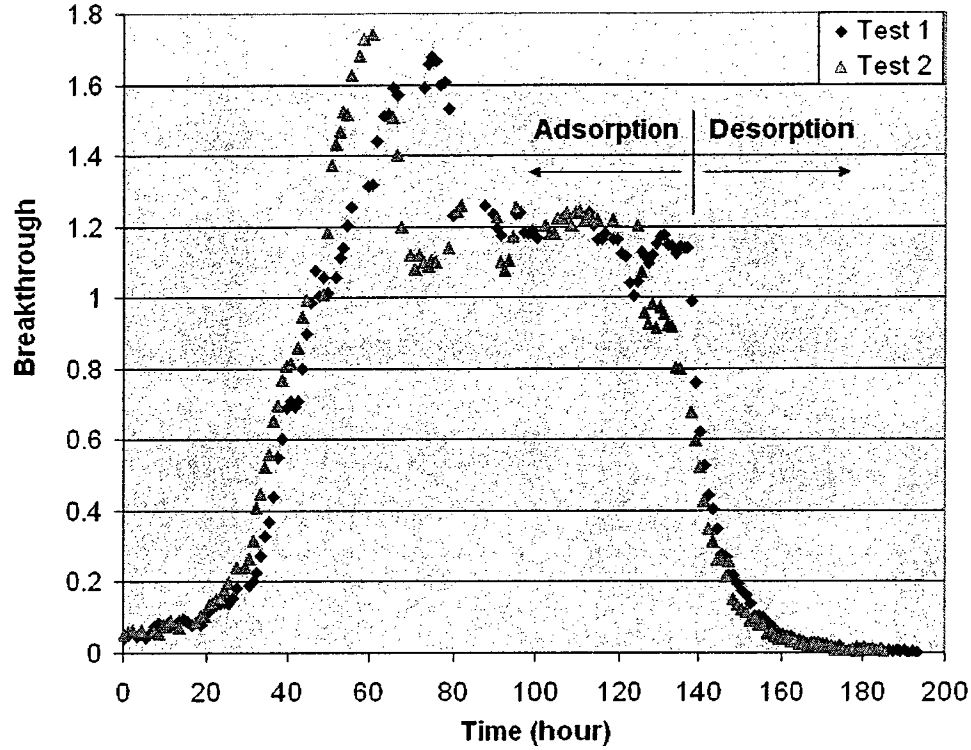


Figure 5-18: Repeatability evaluation, Toluene breakthrough profile

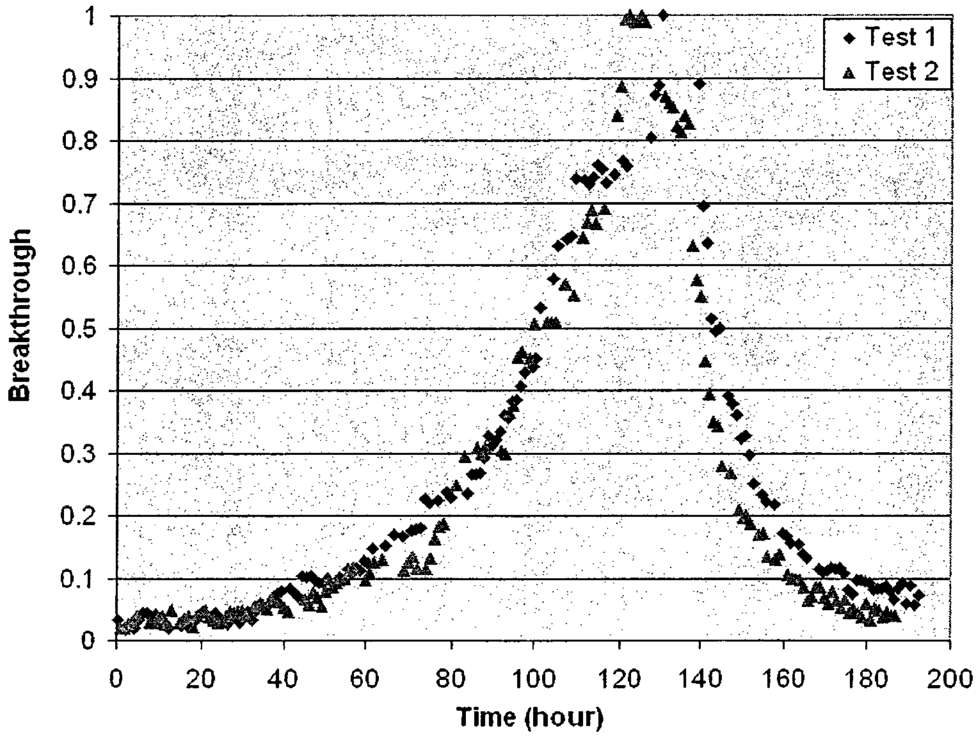


Figure 5-19: Repeatability evaluation, p-Xylene breakthrough profile

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

6-1 SUMMARY

The main objective of this study was to develop a test procedure to evaluate the removal performance of full-scale gasous air filters in building HVAC systems. Moreover, the impact of multiple VOCs on the removal efficiency and service life of full-scale GAC filters were investigated. To fully investigate the removal efficiency of VOCs, a chemical generation and a gas sampling and analysis system were designed and implemented. Both objectives were achieved in this study.

A full-scale test duct was utilized to study the removal performance of GAC filters with the nominal cross sectional area of 61cm x 61cm in an open loop mode. Each experiment was carried out in three phases: measuring filter pressure drop in different air flow rates, adsorption phase and desorption phase. During each experiment the relative humidity, temperature and air flow rate were set at 50%, 23° C and $0.187m^3/s$, respectively.

This study was carried out in two parts. In the first part, the removal performance of four GAC panel filters with different media depth was determined; toluene was used as the challenge gas. Based on collected data, the applicability of the Wheeler-Jonas equation for such applications was investigated and its limitations were discussed. The second part of the study was enhanced through the use of a new chemical generation system along with an on-line gas sampling and analysis unit. The purpose of the new systems' design was to examine the impact of multiple VOCs on the removal efficiency and service-life of GAC filters as well as studying the characteristics of mixture gas adsorption. A 5-cm filter was challenged against a mixture of four VOCs, toluene, p-xylene, n-hexane and 2-butanone, representing a majority of contaminants found in indoor air. Repeatability tests for each set of the experiments were conducted to examine the reliability of the developed method.

6.2 CONCLUSIONS

The conclusions of this study are as follows:

- The repeatability of the developed method was verified for both single and mixture gas tests. The results obtained from the repeatability tests with identical conditions were in agreement.
- The extension of the media bed depth increased the residence time and consequently improved the removal performance of the tested GAC filters. However, the pressure drop of filter increased significantly with the increase of the media bed depth.
- Although a great effort was made to seal the filter, air leakage or bypass was a common problem in the tested GAC filters. High pressure drop and media packaging methods caused the bypass and leaks, therefore reducing the initial performance of GAC media. Moreover, the data showed that as the media bed depth and pressure drop increased, the initial efficiency was reduced.
- The removal capacity of the tested filters in adsorbing toluene was similar since the factors which affect the removal capacity were constant. All tested filters

showed resistance against desorption due to the Vander Walls attraction forces between GAC and toluene molecules.

- Based on the experimental data from this study, the Wheeler-Jonas model has limitations in predicting the service-life of full-scale carbon filters. There was an error in the calculation of parameters of K_v and W_e when the initial breakthrough values were not close to zero.

- Removal efficiency of a 5-cm filter in removing the multiple VOCs with various physical properties (i.e. molecular weight, boiling point, vapor pressure) ranks as follows: p-xylene> toluene> n-hexane> 2-butanone. It shows the fact that the removal performance is affected by the physical properties of VOCs.

- It was found that among the different physical properties of VOCs, removal performance and service life of the tested GAC filters are positively correlated to the VOCs molecular weight. This conclusion is in agreement with results reported in previous studies.

- 2-butanone, n-hexane and toluene had a common behaviors; their downstream concentration increased and exceeded their upstream concentration during the adsorption phase. This phenomenon was due to the fact that each compound was displaced by other heavier compounds. P-xylene was the last compound which its breakthrough value reached one.

- VOCs were not removed from the carbon surface at the same desorption rate. The strongest resistance against desorption was observed for p-xylene followed by toluene, n-hexane and 2-butanone. The resistance was directly proportional to the strength of bonding between GAC media and VOC contaminant.

- Significant difference was found between the breakthrough time of toluene in the single gas test and the mixture test. The competitive adsorption in the mixture gas test significantly reduced the toluene breakthrough time compared to the toluene breakthrough time in the single gas test.

6.3 LIMITATIONS OF THE PRESENT STUDY

The air flow rate introduced to the tested filters was approximately 0.187 m^3 /s (400 cfm) which is less than the typical air flow rate found in a building HVAC system which is around 1 m^3/s. This is due to the fact that the tested GAC panel filters were designed for an air flow rate up to 0.187m^3/s and a higher air flow rate may result in fluidization of the sorbent media.

Among the VOCs chosen in the preliminary list, isobutanol which represents the category of alcohols found in indoor air was excluded because it did not meet the sensitivity requirements of the GC/MS detection instruments for the developed method.

One of the difficulties of the new chemical mixture generation system was to generate a constant injection rate of the challenge concentrations. The system was sensitive to the variation in air or liquid pressure therefore even a slight variation in the pressure influenced the injection rate.

6.4 RECOMMENDATIONS FOR FUTURE WORK

Based on the findings of this study, recommendations for future research on the application of full-scale GAC filters for the removal of indoor VOCs are as follows:

- A mathematical model is needed to investigate whether the test results obtained at the ppm-level concentration can be applied to predict the performance of GAC filters at the ppb level, which is more typical of an indoor air environment.

- To better understand the performance of indoor air filters in buildings, field test on GAC filters are required and the data should be compared to GAC filter performance data obtained from these laboratory full-scale tests.

- The developed method has the ability to assess the removal performance of other types of gasous air filters with different structure and sorbent media. Therefore, this method should be applied to investigate the removal performance of other types of filters.

- Investigation on the impact of inlet concentration of multiple VOCs on the removal performance of GAC filters is needed. Moreover, examining the effect of changing the concentration level of one compound on the breakthrough time of other compounds would be of value.

- There are more VOCs frequently found in indoor air than ones utilized in this study. Further research should investigate the impact of various VOCs mixtures on the performance of GAC filters. Also, a database that provides this valuable information to researchers, HVAC designers, manufactures and building owners should be created.

- Research is required to examine the effect/s of the air flow rate as well as environmental parameters like temperature and relative humidity on the removal performance of GAC filters.

- The new chemical generation system should be optimized by designing a pressure control system to automatically regulate the pressure of the air and liquid during chemical injection.

- Finally, more research is needed to examine the adsorption of multiple VOCs on the full-scale gasous air filters in indoor air environments. The experiments carried out in this study are a starting point, however more research is needed to investigate the characteristics of VOCs mixtures both with and without inorganic compounds that are commonly found in indoor air. Data from these experiments can be used to verify the models of adsorption of multiple gases.

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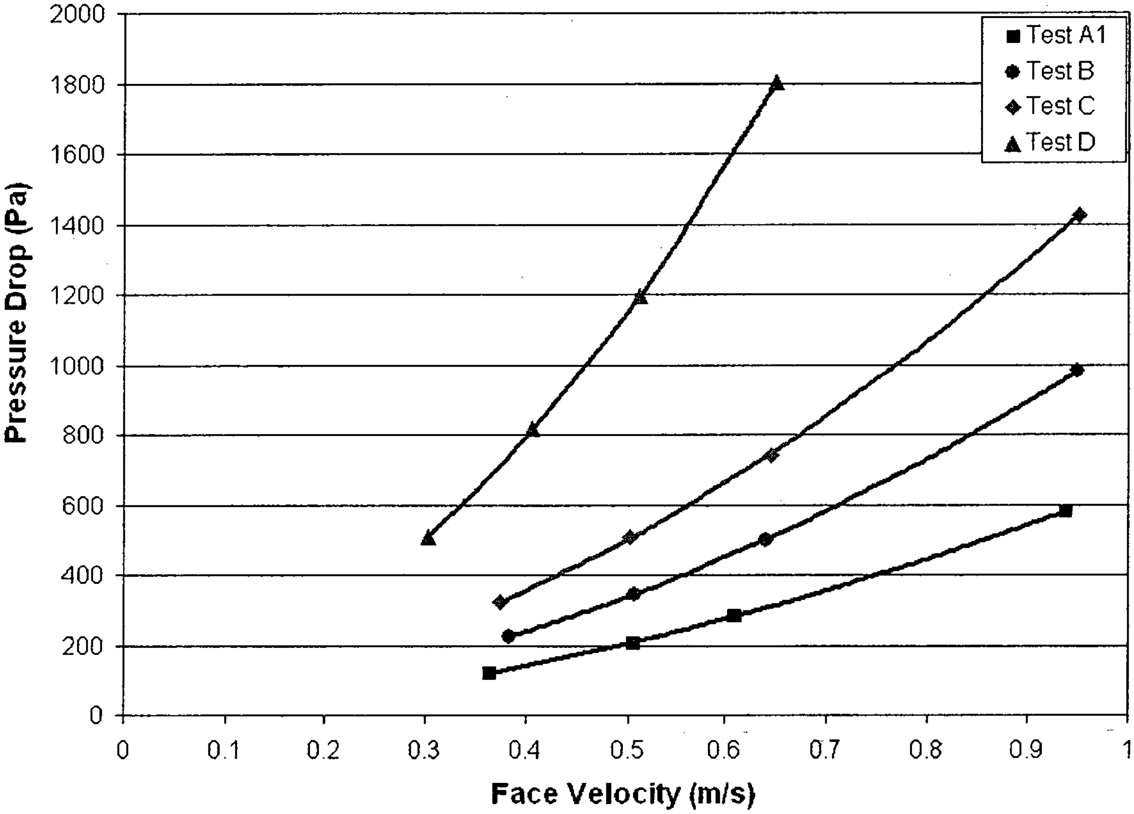
APPENDIX A

PRESSURE DROP ACROSS DIFFERENT GAC TESTED FILTERS



Pressure drop across different filters as function of the face velocity (m/s)

APPENDIX B

VOC STANDARD MIXTURE SOLUTION PREPARATION (PROCEDURE FOR CALCULATION)

To make 25 ml of solution with a concentration of 2000 ppm (μg/ml) for each compound:

1 ml	2 mg
25 ml	X=50 mg

VOC	Density (mg/μl)	Required volume (μl) of each VOC (X/Density)
P-Xylene	0.861	58
Toluene	0.867	57.7
2-butanone	0.805	62.1
n-Hexane	0.655	76.3

Required volume for preparing the mixture standard samples of 1000, 500, 250, 100 and 50 ppm:

Solution (μg/ml)	Required volume (μl) of solution of 2000 μg/ml	Required volume of methanol (μl)
1000	500	500
500	250	750
250	125	875
100	50	950
50	25	975

APPENDIX C

ESTIMATION OF THE SET-POINT TEMPERATURE FOR THE HEATING SYSTEM

The temperature of the heater was set on approximately 35° C. Two conditions were used in establishing this temperature setting:

1. For safety, the temperature of hot water should be less than the ignition temperature of each VOC. Among the selected VOCs, 2-butanone has the lowest ignition temperature, which is equal to approximately 200° C.

2. The temperature of the heater should have a certain temperature to prevent any possible condensation on the surface of the perforated tube located inside the test duct. To determine this temperature, the inequity (detailed below) was used. The inequity shows the amount of enthalpy change of vaporized chemicals should be less than the sum of latent heat and heat transfer between the gasous contaminant and the perforated tube:

$$\Delta h_g < C_p \, \Delta\theta + L_v,$$

where Δh_g is the enthalpy change of the gasous contaminant from the mixing chamber environment into the duct environment (kj/kg), C_p is the heat capacity of the gasous contaminant, $\Delta\theta$ is the temperature difference between the mixing chamber and the test duct, and L_v is the latent heat of the gasous contaminant (kj/kg).

In this study, toluene was considered as the VOCs representative and the chemical properties of toluene are derived from the Perry's handbook and are shown in the following table:

$h_{g(1)}$ (kj/kg) in T=35°C	$h_{g(2)}$ (kj/kg) in T=23°C	C_p (kj/kg)	L_v (kj/kg)
787	772	1.1	351

Inserting the above values in the inequity supports the fact that the set-point temperature of 35° C is suitable for the heater in the generation system.