Full-scale Experimental Set-up for Evaluating the Performance of Commercial Air

Cleaners for Building Applications

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ABSTRACT

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Improving the indoor air quality (IAQ) is considered an important issue in building science. Applying gaseous air cleaning devices to purify the air is an effective way to reduce the levels of gaseous contaminants and have a positive influence on IAQ. However, there is a lack of an acceptable approach to study the performance of these devices for non-industrial buildings.

In this study, a methodology was developed to evaluate the removal performance of gaseous filters. A full-scale experimental apparatus was set up and a series of experiments were carried out to calibrate the system. These tests quantitatively validated the reliability of experimental set-up. Furthermore, it was applied to study the performance of four sorptive filters; a coconut shell-based and a coal-based virgin granular activated carbon (GAC), an impregnated GAC and a blend of virgin GAC and impregnated activated alumina. These filters were ranked based on their effectiveness for removing toluene. The test showed that the virgin GACs had better performance in removing toluene. The 50% breakthrough time of bituminous coal based virgin GAC was 40% and 50% higher than the impregnated GAC and the mixed GAC with activated alumina, respectively. Also, the results indicated that the coconut shell-based GAC has a better removal performance than the coal-based one.

On the other hand, the resistance of these filters against desorption was characterized by measuring their retentivity. For cross-comparison of the retentivity among the tested filters, a novel analysis method was developed. The coconut shell based GAC showed the strongest resistance against desorption.

ACKNOWLEDGMENTS

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LIST OF ABBREVIATIONS

Abbreviation	Description
ACGIH	American Conference of Governmental Industrial Hygienists
AFC	Activated Carbon Fibers
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
ASME	American Society of Mechanical Engineers
BET	Brunauer, Emmett, and Teller
BOCA	Building Officials and Code Administrators
BRI	Building Related Illness
CADR	Clean Air Delivery Rate
cfm	Cubic Feet per Minute
DAS	Data Acquisition System
EPA	Environmental Protection Agency
GAC	Granular Activated Carbon
HVAC	Heating, Ventilating and Air-Conditioning
IAQ	Indoor Air Quality
OPEC	Organization of the Petroleum Exporting Countries
ppb	Parts per Billion
ppbv	Part per Billion by Volume
ppm	Parts per Million
ppmv	Parts per Million by Volume
RH	Relative Humidity
SPC	Standard Project Committee
SBS	Sick Building Syndrome
SEM	Scanning Electron Microscope
VOC	Volatile Organic Compound
WHO	World Health Organization

LIST OF SYMBOLS

English Symbols	Description
C	concentration
$C_{adsorption}$	total computed capacity
C_{dc}	discharge coefficient of flow nozzle
$C_{down,\,t}$	downstream concentration at time t
C_T	capacity after elapsed time T_{ads}
$C_{up,\,t}$	upstream concentration at time t
C_0	initial concentration
D	flow nozzle throat diameter
E_t	efficiency at time t
$F_{R,\,t'}$	percentile retentivity fraction of the total computed capacity at elapsed time t'
I	injection rate
K_{BET}	BET equilibrium constant
K_L	temperature dependant Langmuir constant
M	molecular weight
M_{media}	mass of removal media
N_U	unit coefficient
P	pressure
p	adsorbate partial pressure in fluid
P_t	contaminant penetration at time t
p_s	adsorbate saturated vapor pressure
Q	airflow rate
q	equilibrium adsorbed-phase concentration
Q_N	nitrogen flow rate
q_s	temperature independent surface saturation concentration
Re	Reynolds number
$R_{t'}$	retentivity at elapsed time t'

T	temperature
t	time
T_{ads}	elapsed time of adsorption test
t_b	breakthrough time
t'	elapsed time of desorption test
V	volume
W	duct width

Greek Symbols	**Description**
ρ	density
ΔP	pressure difference

CHAPTER 1 INTRODUCTION

1.1 BACKGROUND

The advent of energy crisis in the 1970's instigated by the Arab oil embargo has made the energy conservation as a global concern. Presently, the oil price is escalating intensively due to the increased geopolitical tensions in Middle East. According to the Organization of the Petroleum Exporting Countries (OPEC) monthly oil market report (2008), the OPEC reference basket reached more than $125/b in June 2008. These issues have created a need to reduce the overall energy consumption in buildings. According to National Resources of Canada (2005), 30% of the total secondary energy is used by residential and commercial/institutional buildings in 2005. Also, their data show that space conditioning accounts up to 58% of the total secondary energy used in these non-industrial buildings. Consequently, the efforts have focused on improving the insulation and the air tightness of the buildings and decreasing the ventilation requirement. These actions, as well as the use of synthetic construction and furnishing materials which result in off gassing, deteriorate the indoor air quality (IAQ).

The United States Environmental Protection Agency (EPA) (2007-b) has reported that people spend approximately 90% of their time inside the indoor environments. Also, their studies indicate that the pollutants levels may be higher in indoors than outdoors even in the largest and most industrialized cities (EPA 2007-b). Taking these issues into consideration, controlling indoor air pollutants has received the attention of many

researchers. Poor indoor air quality causes sick building syndrome (SBS)[1] and building related illness (BRI)[2] (EPA 2008). Headache, poor concentration, dizziness, nausea, sinus inflection, allergic reaction, asthma, cancer, irritation of eyes, throat, and skin are some related illnesses caused by indoor pollutants (Maroni et al. 1995). In addition to negatively impacting their employees, physical health, the businesses are economically suffering from poor IAQ. According to Hennessey (1992), the IAQ related health problems cost over $1 billion per year in direct medical costs and about $60 billion per year due to lost productivity.

Indoor pollutants consist of both airborne particles and gaseous contaminants. Volatile organic compounds (VOC) constitute a major portion of gaseous pollutants in indoors. More than 250 VOC have been detected indoors at concentration higher than 1 ppbv (Ramanathan et al. 1998). According to the World Health Organization (WHO) (1989), VOCs are chemical agents with boiling points ranging between 50°C and 260°C, excluding pesticides. The indoor concentration of VOC, though low (ppb level), is higher than outdoors (Salthammer 1999). Therefore, the main source of VOC is located indoors. Building materials, adhesives, furnishing, human activities and their bioeffluent are the common generators of VOC (Liu and Huza 1995, Guo et al. 2004). These sources may have different generation patterns (VanOsdell and Sparks 1995);

1. high emission rate and short exposure duration,

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[1] SBS is the condition that the most occupants display symptoms of discomforts for the duration of exposure to the indoor environment and the sources of illness are not known (EPA 2008).

[2] BRI is the condition where the source of illness can be identified as a specific building source. The symptoms are associated the exposed person even after leaving the building (EPA 2008).

2. moderate emission rate and moderate exposure duration, and

3. low emission rate and high exposure duration

It has to be emphasized that the exposure to VOC has a risk of acute and chronic health problem (Maroni et al. 1995).

As the awareness of the IAQ-related problem increased, demands and efforts for better indoor environment were raised to ensure adequate indoor air quality. According to the ASHRAE Standard 62.1-2007, an indoor environment is assumed to have an acceptable IAQ when it has "air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction". There are three methods to control the contaminant concentrations within a desirable level; source control, dilution with increased ventilation, and recirculation and cleaning the conditioned air.

Ideally, the most effective way to deal with poor indoor air is controlling and eliminating the sources of emission. Prohibiting smoking inside the building, isolating some typical office equipment such as printers and copy machines in a separate room, and substituting some organic solvent based materials for water based materials are some approaches to reduce/eliminate pollutant sources. Nevertheless, identifying all of the sources requires extensive knowledge of air contaminating factors; a knowledge that is not currently known to many. Moreover, removing or replacing some of the identified sources is not feasible.

Other selected strategies may be either dilution through increasing the ventilation rate or recirculation of cleaned air. The heating, ventilation and air conditioning (HVAC) system is responsible for air handling and provides the thermal comfort and adequate air quality of the conditioned space. To guarantee the thermal comfort and provide acceptable IAQ, there are some certain requirements and regulations which are dictated by the ASHRAE Standard 55-2004 and the ASHRAE Standard 62-2007, respectively. ASHRAE Standard 62.1 (2007-d) recommends two procedures; the Ventilation Rate Procedure and the IAQ Procedure. The Ventilation Rate Procedure prescribes the minimum intake rate of outdoor air to satisfy the adequate IAQ. This required ventilation rate is determined based on the occupancy level, activity and the area of conditioned space as well as the outdoor conditions. In addition, the outdoor air has to be conditioned to meet occupants thermal comfort regulations. Also, depending on the indoor/outdoor contaminant sources, the necessity of excessive ventilation rate is explicated. This process helps to dilute the indoor air contaminants and keep its concentration level within an acceptable range. The overall energy consumption, however, increases due to the introduction and conditioning of the outdoor air.

On the other hand, in the alternative procedure, IAQ Procedure, controlling and reducing the air contaminant through air cleaners can be considered. Filtration and air purification are two promising strategies to improve the IAQ while reducing the energy consumption. The ASHRAE standard-62.1 (2007-d) allows the recirculation of cleaned air if it can be demonstrated that the contaminant concentration is below the required criteria. Applying the air cleaning technology reduces the outside air intake rate equivalent to the recirculation rate. This rate is a function of the type of the air cleaning devices and their

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removal efficiency. The Building Officials and Code Administrators (BOCA) National Mechanical Code (1989) allows up to 67% of the required ventilation air to be re-circulated when the particulate filters are effectively applied and the concentration of these airborne is kept below the specified criteria. Moreover, it permits up to 85% recirculation when the gaseous air cleaners have been employed. Thus, the air cleaner provides the proper approach for both requirements; energy conservation and healthy indoor environment. They can significantly improve the quality of indoor air while reduce the overall building energy consumption. These filters can be integrated into the HVAC system for both particulate and gaseous removal application. For this purpose, numerous scrubbers with diverse characteristics and capability are available in the market. The effluence of these devices has to be ideally clean to re-supply to the room. Thus, the effectiveness and removal performance of these filters have a significant role in the proper and efficient design of the HVAC system. The removal efficiency of particulate filters is comprehensively studied and they can be evaluated by using the ASHRAE standard 52-1999. However, the standard method to evaluate the gaseous air cleaners has yet to be developed and there is no such a general guideline to quantify the performance of these devices.

As mentioned before, the noticeable gaseous pollutant inside the building environment is VOC. Different processes have been applied to trap the contaminants and control the concentration level of these chemicals in indoors. Due to its low concentration level in indoor air, adsorption is the most efficient technique to control the level of VOC in air cleaning devices (Gupta and Verma 2002). While different sorptive media such as activated carbon, activated alumina and zeolite can be used in mechanical ventilation

system, the common scrubber for building application is activated carbon due to its high capacity and affinity for VOC. In addition, its effectiveness and capability have been proven in industrial applications (Liu and Huza 1995). Activated carbon is available, in the market, in several forms; activated carbon fibers, activated carbon cloth, and granular activated carbon (GAC). The removal performance of these sorbents is a function of various factors such as filters structure and properties, VOC physical and chemical properties and environmental conditions (Mahajan 1987, Popa and Haghighat 2003). The removal efficiency for a defined operation condition, target contaminant and its concentration level determines useful life-time of a filter and provides essential information for HVAC designers to apply suitable air cleaners in building, and set a reasonable maintenance-schedule for it. Hence, the long-term performance beside the initial removal ability of the filter should be evaluated. Also, the possible desorption of the adsorbed VOC and undesirable effect of the filter as a new source of pollutant should be investigated (Chen et al. 2005). All of these issues insist on the necessity of a general method to quantitatively determine the removal performance of gaseous filters which is a subject of scholarly discussion.

1.2 OBJECTIVES

The objectives of this study are:

- To construct a full-scale experimental set-up and develop an experimental method for evaluating the removal performance of complete commercial gaseous contaminants air cleaners.

- Applying the full-scale experimental set-up and the developed experimental method to rank different gaseous filters based on their removal effectiveness and verify the method.

1.3 THESIS OUTLINE

Chapter 2 contains the fundamental of mass transfer in sorptive gaseous filters and the critical reviews over previous studies made on the removal performance of filters. Chapter 3 presents the full-scale experimental setup and the details of its construction. Also, the procedure of the system pre-qualification tests and their results are discussed in this chapter. Chapter 4 explains the developed experimental method for studying the performance of gaseous filters and contains the analysis method applied to quantitatively determine the efficiencies, capacities and retentivities of the filters. In addition, a novel analysis method was developed to characterize the resistance of the filters against desorption which is described in this chapter. Chapter 5 discusses the results stemmed from this research. And Chapter 6 provides the conclusions and the recommendations for future work.

CHAPTER 2 LITERATURE REVIEW

2.1 INTRODUCTION

In today's world, improving the quality of indoor air is considered as an important issue in building science. The problems accompany poor indoor air motivate researchers to find a solution to enhance IAQ. Reducing the level of contaminant has a positive effect on the IAQ. Applying air cleaning devices to purify the recirculated air as well as outdoor air is one of the promising ways to have a healthy indoor environment. Also, from an energy perspective, this method is more efficient than diluting the indoor air with excessive outdoor air under certain conditions, i.e., contaminated outdoor air, hot and humid or extremely cold weathers, etc.

VOCs are a major group of gaseous pollutants in the indoor environment. Sorptive filters can remove VOCs from air by adsorption on the adsorbents. These adsorbent could be applied in the building HVAC system as well as particulate filters (Mahajan 1987). Depending on the application requirement, different sorptive media such as GAC and activated alumina could be used in mechanical ventilation system. The removal efficiency and the useful life of these media could provide essential information for HVAC designers to use in selecting suitable air cleaners in building and set a reasonable maintenance-schedule for them. Therefore, a general evaluation method to determine the efficiency of these filters as a function of time is required. Although the standard for particulate filters is developed and widely accepted (ASHRAE standard 52.2-1999), standards for gaseous filters are currently under development (ASHRAE 2007-c). Despite the attempts that have been made in these decades, there is no general method to

determine the removal efficiency of gaseous air cleaners for application in mechanical ventilation system which is the purpose of this thesis.

In this chapter, the previous studies done on the removal performance of gaseous filters with an emphasis on activated carbon and VOC have been presented and the advantages and disadvantages of these methods have been critically reviewed. First, however, the fundamental of the adsorption process and mass transfer in removal bed have been explained.

2.2 POROUS MATERIAL

Porous materials are known for their extensive surface area and high volume of their internal pore network. These pores could be cylindrical shape or slit-shaped (Chiang et al. 2001). Different methods such as the micropore method (MP-method), Horvath and Kawazoe (HK) method and Dubinin-Stoeckli (DS) method can be used to predict the pore size distribution in the porous material (Chiang et al. 2001, Cal 1995). The International Union of Pure and Applied Chemistry adapted the proposed classification of pore sizes by Dubinin (Cal 1995). This classification presents in Table 2- 1.

Table 2- 1   Pore classification

Pore Category	Pore Size Range
Micropore	Less than ~ 20 Å
Mesopore	Between ~ 20 Å and ~ 500 Å
Macropore	More than ~ 500 Å

This classification is based on the effect of each pore size on the adsorption forces on the adsorbate molecule (Lee 2003). According to Dubinin et al. (1991) the adsorbent which the micropore is dominant has slit-shaped pores. Due to the proximity of pore walls in micropores, interaction potential is much higher in these pores; hence, the adsorption forces are much higher in micropores. Also, highly microporous materials are suggested as the best removal media for low concentrations of VOCs (Carrott et al. 1991, Foster et al. 1992).

The mass transfer process between gas phases and porous material has three main steps (Noll et al. 1992, ASHRAE 2007-a);

- External diffusion

- Internal diffusion

- Surface adsorption

Figure 2- 1 depicts all mass transfer steps inside a porous media. During external diffusion, the gaseous molecules diffuse through the surrounding boundary layer of porous particle and transfer from bulk fluid to the external surface of solid particle (Noll et al. 1992). The external film mass transfer coefficient and the transferred compound concentration gradient between the bulk of the gas and solid surface govern the external diffusion rate (Noll et al. 1992). For this reason, the diffusion rate decreases as the adsorbed phase concentration increases. Also, a low concentration in gas phase causes a lower diffusion rate (ASHRAE 2007-a). The gaseous molecules which enter the pore network inside the porous media move within the fluid filling the pores or on the interior surface of the pores as the adsorbed molecules (Noll et al. 1992, and Treybal 1968). The

interior diffusion flux is a function of the concentration gradient, described by Fick's first law (Treybal 1968).

The gas-phase molecules adsorbing on the surface of solid compound is called surface adsorption. This stage is relatively faster than the two previous steps and governs the equilibrium between two phases (Noll 1992). In addition, the adsorbed molecules could be desorbed to the pure air passed through the media or replaced by another compound which has the stronger bond with the solid.
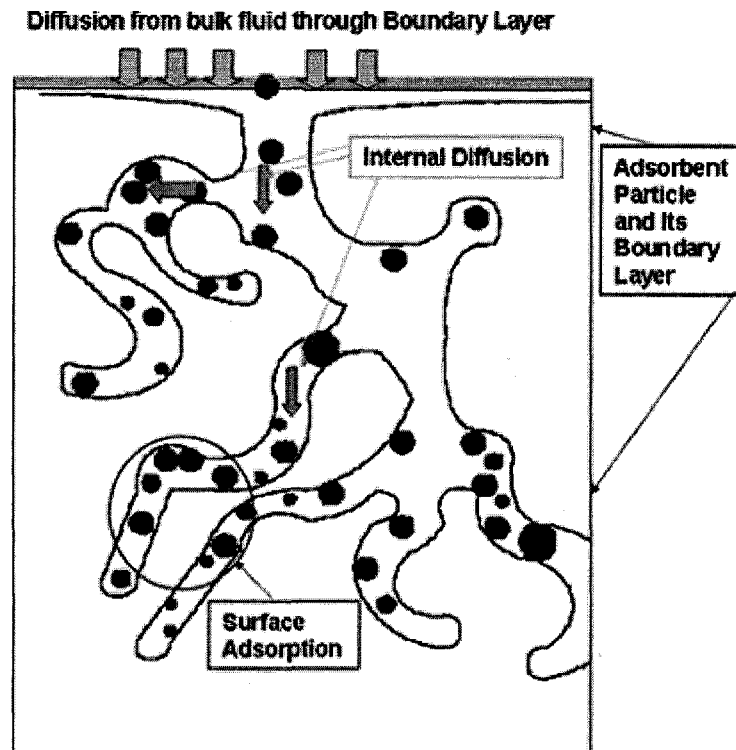
Figure 2- 1   Mass transfer stages in porous material[3].

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[3] The picture was adopted from (Hunter and Oyama 2000) and modified for better comprehension.

2.3 SURFACE ADSORPTION PROCESS

2.3.1 Adsorption

Adsorption is a mass transfer process which occurs between two phases of materials. The compound (adsorbate) transfers from gas phase to a solid or liquid material which is called the adsorbent. This relocation causes the accumulation of that compound at the surface of the adsorbent or at the interface of two phases. At an inner level of solids or liquids, molecules are surrounded by other molecules in all directions. At the surface, however, the molecules just have a link on one side with the inner layer molecules. Because of this unbalanced force, they have an attraction to the surrounding gas molecules (Noll et. al. 1992).

According to the intermolecular forces between an adsorbent and an adsorbate, adsorption is classified into two categories; physical adsorption and chemical adsorption (chemisorption). While relatively weak intermolecular forces are involved in physical adsorption, in chemisorption a chemical bond is formed between the sorbate and the adsorbent. The transfer of the electron between two phases results in a chemical reaction.

Involved forces in physical adsorption are Van der Waals forces (dispersion-repulsion) and electrostatic interactions (Ruthven 1984). The presence of electrostatic interactions is significant for the adsorbent of ionic structure such as zeolite while the contribution of Van der Waals forces is always present. This intermolecular force is the consequence of attraction of opposite charges and repulsion of like charges between instantaneous induced dipoles, induced dipole-induced quadrupole, and induced quadrupole-induced

quadrupole (Atkins 1998). Dispersion forces represent the major contribution in physical adsorption and they are significantly stronger in micropores than the outer layer surfaces of adsorbent (Gregg and Sing 1967).

According to the type of forces, the adsorption heat of physical adsorption is low as compared with chemisorption. As a matter of fact, there are a number of criteria which physical adsorption can be distinguished from chemisorption. Physical adsorption is reversible; hence all adsorbed compounds can be desorbed at the same temperature. It can occur either as monolayer adsorption or multilayer adsorption and the adsorbed layer is always in equilibrium with the compound molecules in the gas phase (Attard and Barnes 1998). The adsorbate molecules are able to cover all sites on the surface of adsorbent and they are not limited to specific sites. Chemisorption is, however, irreversible and regeneration of adsorbent needs an elevated temperature and even that may not be sufficient. The interaction always occurs at specific adsorption sites and only one layer of adsorbed phase takes place on the surface of adsorbent.

2.3.2 Adsorption Isotherm

Adsorption isotherm explains the relation between adsorbed mass in the solid-phase and either the adsorbate concentration or partial pressure in gas-phase, at equilibrium, at a constant temperature. Brunauer et al. (1940) classified adsorption isotherms, below the critical temperature of the gas, into five categories which are shown in Figure 2- 2.
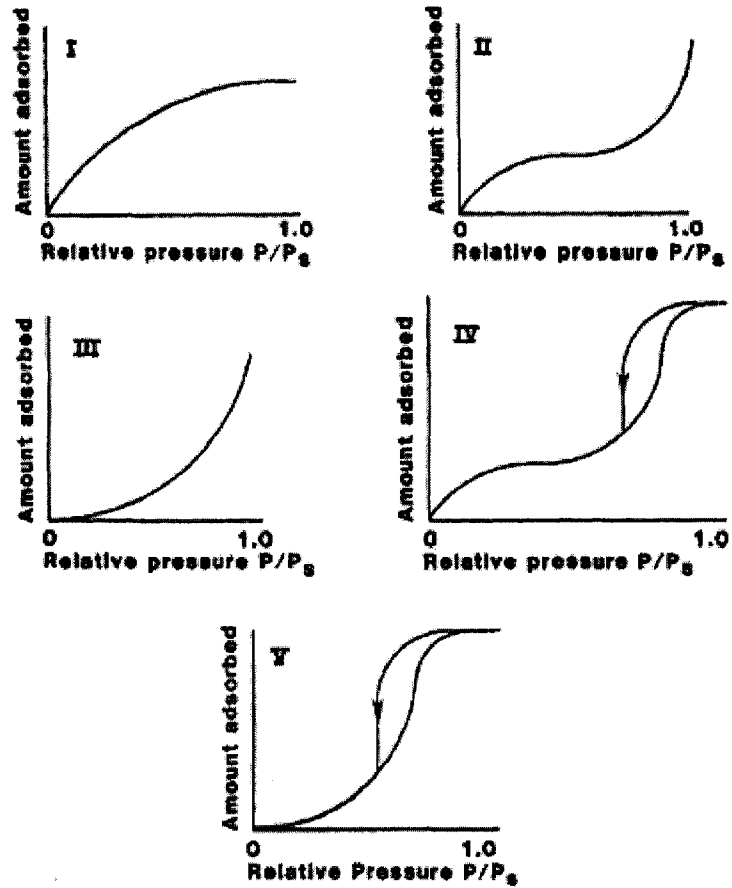
Figure 2- 2   Brunauer's classification of adsorption isotherms (from Hines et al. 1993)

Type I isotherm (Langmuir isotherm) is for a system with monolayer molecular adsorption. It occurs in micropores solids such as activated carbon which has pore size not much greater than the adsorbate molecule size. Thus, the adsorption limit is governed by the accessible micropore volume (Noll et al. 1992). This isotherm equation represents the type I isotherm (Brunauer et al. 1940);

$$q = q_s \times \frac{K_L p}{1 + K_L p}$$

(2- 1)

where q and q_s are equilibrium adsorbed-phase concentration and temperature-independent surface saturation concentration, respectively. K_L is the temperature-dependent Langmuir constant and p is the adsorbate partial pressure in the fluid.

The other types are for multilayer adsorption on the surface of adsorbent (Young and Crowell 1962). Generally, the adsorbents with a wide range of pore sizes present an adsorption isotherm similar to type II and III of Brunauer's classification (Figure 2- 2). The monolayer adsorption is progressed to multilayer adsorption and then to capillary condensation in pores with wider diameter by increasing the load of adsorbate (Ruthven 1984). These types are generally expressed by Brunauer, Emmett, and Teller (BET) isotherm equation which was developed to explain the multilayer adsorption in addition to the monolayer adsorption. The equation is as follows (Ruthven 1984);

$$q = q_s \times \frac{K_{BET}\left(\dfrac{p}{p_s}\right)}{\left(1-\left(\dfrac{p}{p_s}\right)\right)\left(1-\left(\dfrac{p}{p_s}\right)+K_{BET}\left(\dfrac{p}{p_s}\right)\right)}$$ (2- 2)

where K_{BET} is the BET equilibrium constant and p_s is the saturated vapor pressure.

Both type IV and V exhibit flattening of the isotherm shape before the saturation of the adsorbate in gas-phase ($p/p_s=1$). Also, a hysteresis loop has been shown during desorption which is the result of capillary condensation in mesopores (Adamson 1990, and Hines et al. 1993). However, if the capillary condensation occurs in pores with wider diameters, types II and III would be observed (Attard and Barnes 1998).

2.4 SORPTION MEDIUM

To remove VOCs, the adsorbent should have the following characteristics (Guo et al. 2006):

- Large pore volume

- No attraction for water adsorption (hydrophobic)

- Thermal stability

- No catalytic activity

- Easily regenerable

Commonly, activated carbon in various types and forms, especially GAC, has been used in air cleaning devices (VanOsdell and Sparks 1995, and Henschel 1998). It is an effective media for the removal of VOC at a low concentration level. Noll et al. (1992) compared the structure of graphite and turbostratic carbon which is similar to activated carbon structure as presented in Figure 2- 3. The activated carbon consists of thin microcrystallites with a width of less than 100 Å. These microcrystallites are connected together in different orientations and provide the micropores (Ruthven 1984).
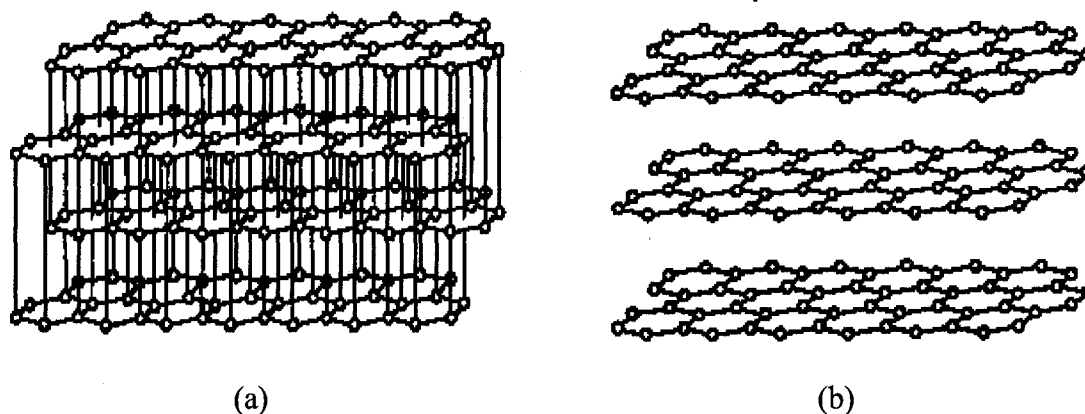
Figure 2- 3 Structure of (a) graphite (b) turbostratic carbon (Noll et al. 1992)

They can be made from various raw materials such as coal and nut shells. There are generally two preparation methods; Physical activation and chemical activation (Hayashi et al. 2002). In physical activation, the carbonaceous material (raw material) is pyrolyzed and then activated with steam or carbon dioxide at a temperature between 700-1100°C (Ruthven 1984). However, in chemical activation, the raw material is impregnated with a chemical agent, heated under an inert environment and then activated by steam or CO_2 (Guo and Lua 2000). The type of raw material and the activation process affect the pore size distribution and total pore volume (Ruthven 1984). Figure 2- 4 shows the scanning electron microscope (SEM) of activated carbon. Different pore sizes can be observed in this picture. The most active sites of activated carbon are provided by inner pore surface area and its pore network volume. For instance, more than 99% of the adsorption sites in a GAC are in the interior part of the media (Noll et al. 1992).
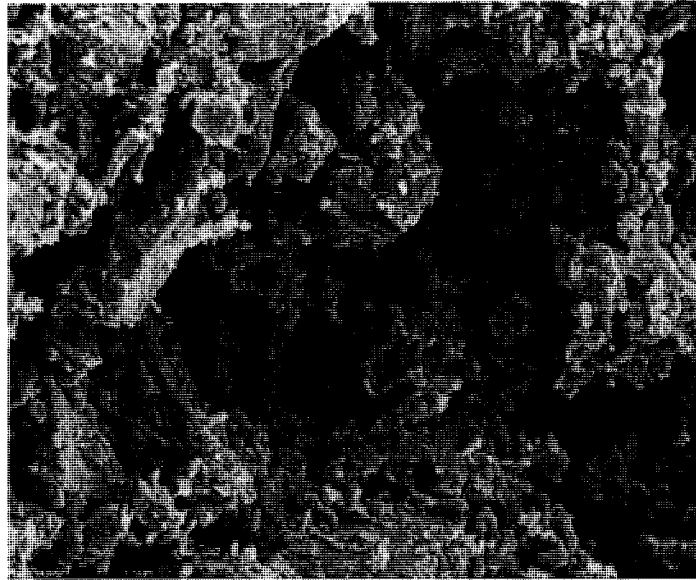
Figure 2- 4   SEM photograph of activated carbon

The activated carbon is hydrophobic and organophilic. It has a higher affinity for non-polar compounds than polar ones. To improve the selectivity in removal performance (targeted compounds), the activated carbon could be impregnated with some chemical agents such as KOH, H_3PO_4, and HCl (Kim et al. 2006). In this study, coal-based and coconut shell-based virgin GAC and coal-based GAC impregnated with KOH were used as the removal media.

Another common removal media which was used in this study is activated alumina that is aluminum oxide based and prepared by dehydration and recrystalization at elevated temperature (Ruthven 1984). In contrast with activated carbon, activated alumina is strongly polar and commonly used as a desiccant. Also, it is an efficient media for removing acidic gases such as H_2S and NO_x.

As there are various gaseous contaminants in the indoor environment, the single media approach is not adequate for air purification process. Therefore, applying different scrubbers either as two separate filters or a filter containing blended media is recommended to provide a broad spectrum gaseous air cleaner.

The granular or pellet media are commonly used as cleaning devices for the HVAC system (ASHRAE 2007-a). They are mounted in a HVAC system as held in retaining constructions such as modules, media trays and panel adsorber. These containers are perforated structures which have holes smaller than the smallest size of the granule medium. Thus, their configuration allows air to pass through the removal media for treatment by the filter. To ensure the effective removal process, the gas should have a defined contact time with the mediums. Generally, this contact time ranges between 0.02-0.2 s which is known as residence time (Holmberg et al. 1993). Taking the typical range of air velocity in mechanical ventilation system duct (2-3 m/s, 394-591 ft/min.) into account, the bed depth has to be in a range of 4-60 cm [10-15 inch.] to satisfy the recommended residence time which would create a large pressure drop inside the air handling unit. Thus, these holders are designed in various arrangements such as V-shape, zig-zag and Z-shape to extend the contact surface area of the holders. The V-shape arrangement which was used in this study is depicted in Figure 2- 5.
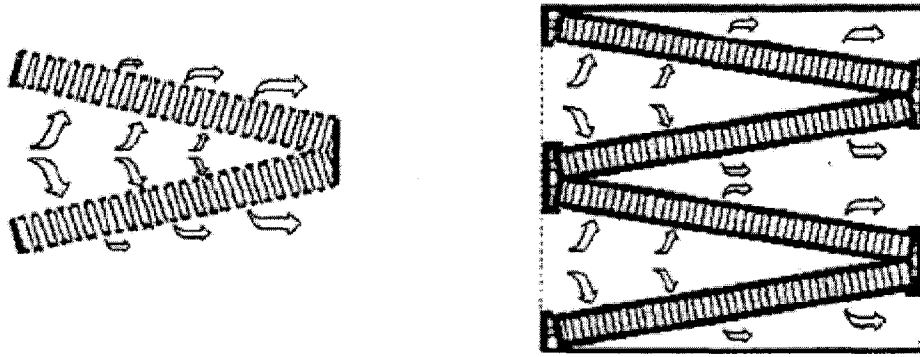
Figure 2- 5   V-shape fashion of refillable or disposable modules (ASHRAE 2007-a).

2.5   ASSESSMENT METHODS FOR GASEOUS-FILTER REMOVAL PERFORMANCE

Although GAC is conventionally and efficiently used in industrial applications, the knowledge of its application in HVAC system in non-industrial buildings is limited (Liu and Huza 1995, Muller and England 1995, and VanOsdell and Sparks 1995) due to the lack of an acceptable method for rating and performance evaluation. Nelson and Harder (1974), Nelson and Harder (1976), and Nelson et al. (1976) comprehensively studied the application of activated carbon in a respirator cartridge. They studied the impact of different compounds, relative humidity, temperature and VOC concentration on the removal performance of activated carbon. However, the minimum challenge gas concentration level which was studied by them was 100 ppm, whereas the typical VOC concentration in indoor environment is less than 2 ppm. The VOC concentration as well as other aspects affects the removal performance of filter. The GAC lifetime and its removal capacity are not clear for application as in-duct air cleaners. For instance, Liu (1990) predicted that the removal efficiency of GAC reaches 0% after 3.5 years for

indoor applications. In contrast, Graham and Bayati's (1990) prediction was less than 20 days. Although these two research groups studied the performance of GAC, different testing methods could result in large discrepancies. According to Ostojic (1985), there are some requirements which the test method has to satisfy them:

- The test conditions should be similar to the operation conditions

- Sufficiently simple to conduct by the technician

- Could be carried out in a reasonable time length

- Could assess any type of air cleaners with different configuration and arrangement

VanOsdell (1994) cited two classifications of the test method for gaseous contaminant removal media; static test and dynamic test. In a static test, the interaction between the adsorbate and adsorbent is studied at equilibrium condition. The adsorbed amount of adsorbate in equilibrium with its various concentrations in gas-phase is measured at a constant temperature which results in the determination of the adsorption isotherm. Furthermore, this information could be incorporated in mass transfer models such as the Wheeler equation to translate into filter penetration and lifetime (VanOsdell 1994). However, the outcome of this method is limited for the HVAC designer. The second method is the dynamic test which studies the interaction of gas and solid as well as the air stream conditions and removal bed features. Indeed, the removal media size, its pore size distribution and the removal bed packing affect the removal process of the filter along with the challenge gas conditions and its concentration. In this method the gas with a known concentration passes through a fixed bed which is filled with adsorbent media

such as GAC. As the air flows through the bed, its concentration decreases due to the mass transfer from bulk fluid to the bed media. Thus, the concentration profile in the gas and solid phase changes with time and position in bed length. The portion of the bed, in which the mass transfer process occurs between two phases, and the adsorbents are loaded with contaminant is called the mass transfer zone; Figure 2- 6 illustrates this portion.
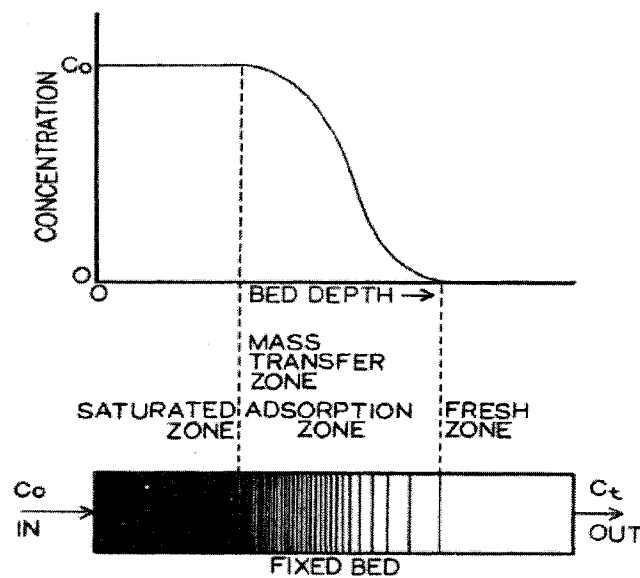
Figure 2- 6   Gas concentration profile inside the bed and mass transfer zone (from Noll et al. 1992)

As time elapsed, the filter inlet zone is saturated and the mass transfer zone moves down the bed. While all adsorbate are removed by the filter, the effluent of the bed is clean and the contaminant concentration after the bed is zero. This process can be interpreted as 100% removal efficiency of the filter. Once the mass transfer zone passes the bed outlet, the adsorbate starts to penetrate the removal bed and the filter removal efficiency would decrease. The elapsed time which the adsorbate is traced in the bed effluent is called the

breakthrough time. The profile of penetration ratio versus elapsed time is known as the breakthrough curve. As penetration ratio increases the removal efficiency of the filter decreases. Once the entire mass transfer zone has passed the filter, the downstream concentration of the bed equals the upstream concentration and the adsorbent is in equilibrium with the adsorbate. Studying the breakthrough time of a filter at different endpoints is favored by the HVAC designer and the ASHRAE has proposed the development of a dynamic test method (VanOsdell 1994). Therefore, various test methods were carried out to investigate the dynamic performance of gaseous filters which are discussed in the rest of this chapter.

Gravimetric method was selected by some researchers to study the removal capacity of gaseous filters (Graham and Bayati 1990, and Foster et al. 1992). In this method, the test specimen is located in a balance and the total adsorbed mass of VOC is continuously recorded till the interaction of gas and solid reaches the equilibrium. In equilibrium condition, the balance does not show anymore change in the mass of the filter. The tested media could be conditioned in different temperatures and relative humidity. The total capacity of the activated carbon for various challenge VOC concentrations and the required time to reach the equilibrium can be determined. Graham and Bayati (1990) applied this method to characterize the removal capacity of GAC in low concentration level of benzene (0.3, 0.9, 3.3 ppmv). They conducted the test at different gas flow rates and the impact of the flow rate reflected in the required time duration to reach the equilibrium. Despite the presentation of flow rate impact and capacity of tested activated carbon, this method could not clearly project the breakthrough time and the effluent

characteristic of the filter. Also, the effect of packing and the size of media on the performance of the filter cannot be investigated by conducting the gravimetric method.

Another technique to assess the performance of filters is called concentration decay method. It could be conducted in a sophisticated environmental chamber. Chen et al. (2005) characterized the VOC removal efficiency of in-duct gaseous air cleaners in a 55 m^3 (1942 ft^3) stainless steel environmental chamber. They carried out the test at a constant temperature and relative humidity (25±1 °C and 50±5%, respectively) and measure the single-pass efficiency and clean air delivery rate (CADR) for sorptive filters and other types of scrubber. A HVAC system was dedicated to the chamber to control the air flow rate and environmental conditions. Also, it provided a fully mixed air inside the chamber. The tested mediums were installed and sealed in the HVAC duct. The test procedure had two phases. At first, the contaminant was generated inside the chamber for a defined period while the air cleaner unit was not operating. The achieved concentration was maintained at a steady level before the air cleaner unit operation was started. In the second phase which is called dynamic phase the generation of contaminant was terminated and decayed concentration was monitored to measure the removal efficiency and CADR of in-duct activated carbon. The proposed test procedure can study the removal performance of activated carbon in wide range of relative humidity and temperature. Also, the impact of bed depth, packing, airflow rate, residence time can be projected by changing the tested air cleaner aspects and flow rate. In real practice, however, there is a continuous VOC generation from various indoor and outdoor sources which was neglected in their study during the dynamic phase. Moreover, operating a chamber with these features would be difficult and expensive. Howard-Reed et al. (2005)

modified the procedure and applied it in a real building to conduct a field measurement. They continued the generation of VOC at a constant rate after the air cleaner was activated. Thus, a "quasi-steady-state" of VOC concentration was achieved and used to measure the effectiveness of air cleaner. Generally, the field measurement has some difficulties. The challenge concentration could change by time as a result of emission from the existing material in the tested building. In addition, water vapor concentration and temperature could have a large fluctuation and studying the impact of these parameters has some limitations.

Many researchers used a small-scale bed filled with granular sorptive medium such as activated carbon to investigate the removal performance of these types of gaseous air cleaners (Mahajan 1987, Liu 1990, VanOsdell et al. 1996, Angelsio et al. 1998 and Guo et al. 2006). This bed simulates a bed filled with granular medium in a mechanical ventilation system. The air stream is conditioned and contaminated to a pre-determined concentration level of VOC and passed through the bed. Then after, the removal performance of the granular media is investigated by monitoring the penetrated concentration during the test. In the small-scale method, the airflow rate and bed depth are adjusted to provide a residence time similar to the real application in HVAC system. Liu (1990) utilized a 2.5 cm (1") diameter bed of GAC with a residence time of 0.1s and measured the breakthrough time of heptane and acetone with upstream concentration between 0.2-118 ppm. For high concentrations of heptane (15 and 118 ppm), the 10% breakthrough time was less than 10 hours. For the lowest concentration of heptane, however, the penetration ratio was 3% after 20 hours. VanOsdell et al. (1996) carried out the same method at 25°C and 50% relative humidity to characterize GAC for a vast range

of VOC challenge concentration. They used a 5 cm (2") bed diameter with nominal residence time of 0.11s. They utilized 1,1-dichloroethane (1,1-DCE), hexane, methylethylketone (MEK), toluene and decane in the range of 0.1-1000 ppm as VOC contaminants and measured 10% breakthrough time and capacity of the GAC. The difficulty of test with low concentration level of VOC is noticed in their results. For toluene concentration of almost 1 ppm, the 10% breakthrough time was more than 14 days (344 h). This penetration was achieved after 26 days (625 h.) for toluene concentration of 0.44 ppm. Therefore, conducting the test in low concentration to measure the expected lifetime of activated carbon for indoor air contaminant concentration requires long period of test duration and it is costly and not technically reasonable. Thus, the experiments are usually conducted at elevated concentrations and the results are extrapolated for real indoor condition. Nelson and Harder (1976) proposed an equation to predict the result in low concentration;

$$t_{b,\ Low\ Concentration} = t_{b,\ High\ Concentration} \left(\frac{C_{Low\ Concentration}}{C_{High\ Concentration}} \right)^{n} \tag{2-3}$$

where t_b is the breakthrough time at low or high concentration and C is the concentration. The n depends on the type of VOC. Nelson and Harder (1976) proposed an average value of $n = -0.67$ for all VOCs.

The BSR/ASHRAE standard 145.1 (2007-b) proposed a method for small-scale measurement of the removal performance of loose granular media. According to this test standard, the air stream is conditioned to 50% relative humidity and contaminated up to

100 ppm concentration of the challenge VOC. Next, the contaminated air is passed

through the bed of granular sorptive medium. This bed has around 0.1 s residence time

and its effluent is monitored up to 50% penetration. 5 cm (2") inside diameter is proposed

for the bed to decrease the wall effect. The general schematic diagram of the test rig for

this method is presented in Figure 2- 7.
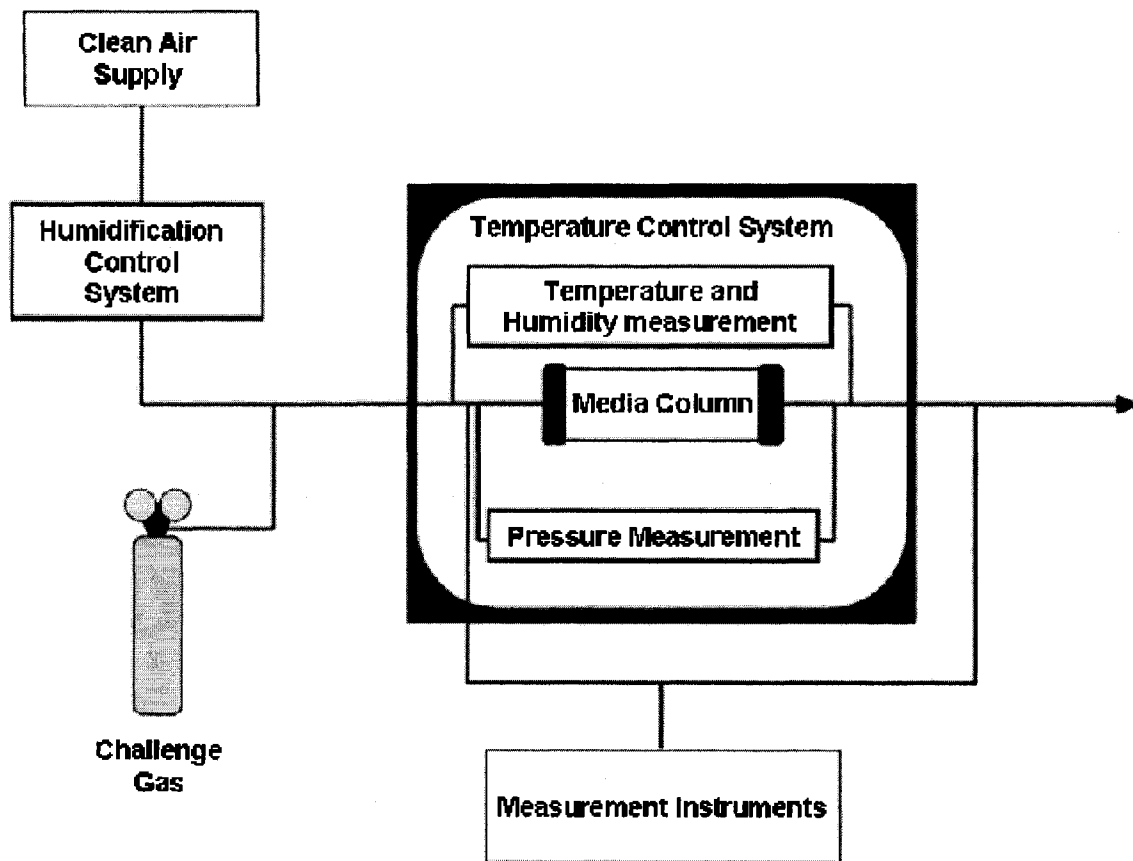
Figure 2- 7   General schematic diagram of small-scale setup (ASHRAE 145.1 2007-b)

Generally, the small-scale test method provides some information to rank granular filters

for different applications. Although some researchers studied the performance of

activated carbon in low concentration, conducting the test in relatively high concentration

based on ASHRAE proposal reduces the test duration. However, the capacity of the activated carbon would be overestimated in this condition. This method, also, is able to project the impact of water vapor, temperature and airflow rate on the performance of GAC. Nevertheless, this method can not be applied for other filter than granule medium such as carbon cloth and bonded carbon panel. In addition, there is a limitation to the method in assessing the effect of packing and different arrangement of the GAC bed in HVAC system such as zig-zag and Z in small-scale method.

Lee et al. (2006) setup a closed-loop test system and investigated the dynamic performance of four activated carbon fibers (ACF). The scale of their system was relatively larger than small-scale test rig (10 cm [4"] diameter) and could simulate the overall HVAC duct in laboratory-scale with full air recirculation. The researchers contaminated the air inside the test rig by injecting a certain volume of VOC liquid at a constant injection rate. This phenomenon caused an increasing profile of upstream concentration due to deterioration of filter sample. The test was started with almost 20 ppm concentration of toluene and increased up to 120 ppm during the test. Haghighat et al. (2007) modified the apparatus and investigated its application for eight GACs. Bastani et al. (2008) investigated the applicability of the method for a pleated rigid filter imbedded with GAC. These researchers employed the concept of high recirculation rate in the mechanical ventilation system and constant generation of contaminant from common indoor sources. Figure 2- 8 presents the schematic diagram of the laboratory-scale closed-loop setup.
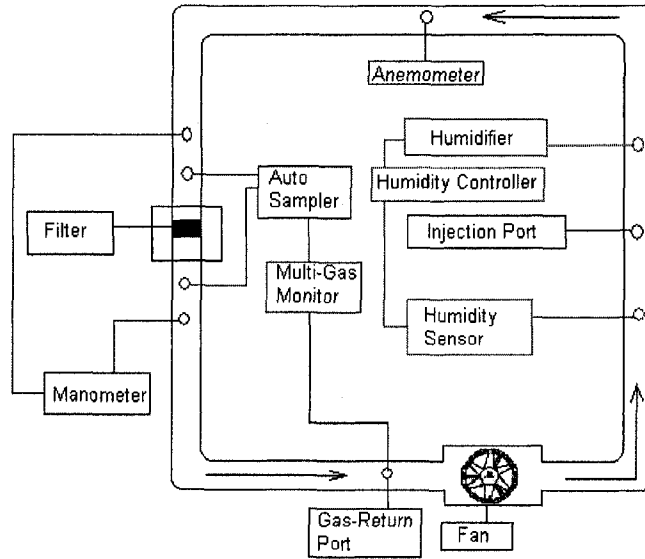
Figure 2- 8 Schematic diagram of the laboratory-scale closed-loop setup.

Although the test method could be applied for different types of gaseous air cleaner over the small-scale method and would be less costly, the impact of increasing challenge concentration of contaminant on the filter performance is questionable.

ASHRAE standard project committee (SPC) initiated developing standard method for evaluating the performance of gaseous air cleaning devices (VanOsdell et al 2006). There are three planned standards (SPC 145) for the assessment of loose granular media (SPC 145.1), air cleaning devices in full-scale system (SPC 145.2) and field measurement (SPC 145.3). The full-scale method was initially investigated by Ostojic (1985). He applied the modified apparatus of ASHRAE standard 52 (1999) for particulate filters. To overcome the difficulty of conducting the test in low concentration level, he investigated the "accelerated loading" technique. In this technique, the medium was exposed to a low concentration for a determined period and followed by a high concentration level loading.

Then, the introduced concentration was reduced to the low level again. He concluded that the proposed technique was applicable for irreversible adsorbent (chemisorption process). For reversible adsorbent (physical adsorption process), however, the technique could not be employed as the adsorbed compound during accelerated loading desorbed to the air with low concentration level. VanOsdell (1994) proposed a new approach for the full-scale method. He suggested two separate test methods to investigate outdoor air purification and indoor air purification. As VOC is the dominant gaseous contaminant in indoor environment, the process to control its concentration level was studied with the indoor purification test method. Also, VanOsdell (1994) characterized his test method with mixture of VOCs in challenge concentration up to 10 ppm per compound. The recommended test rig is the same as the test apparatus used for the ASHRAE standard 52 (1999) for particulate filter; it is modified for gaseous filters. The schematic diagram is shown in Figure 2- 9.
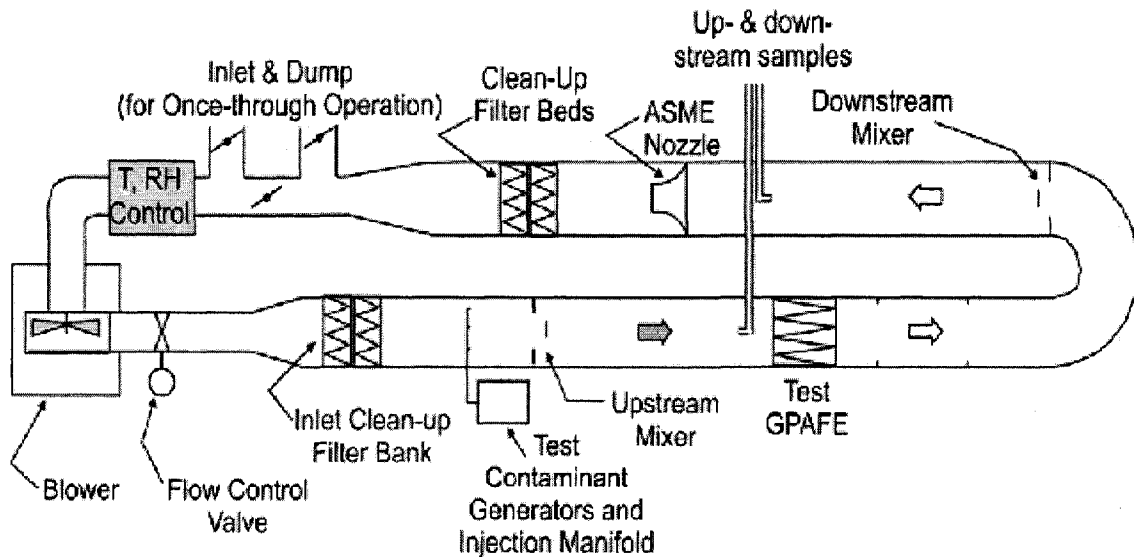
Figure 2- 9   General full-scale schematic diagram (from VanOsdell 2006)

ASHRAE draft 145.2 (2007-c) proposes the same apparatus and conducting the test in 100 ppm concentration of the challenge gas. The endpoint is set to 100% penetration which is followed by a two-hour desorption procedure to measure the retentivity of gaseous air cleaner. The retentivity visualizes the resistance of filter against stripping the adsorbed compound. The proposed conditions are 25° C and 50% relative humidity with 0.5 m^3/s [1000 cfm] airflow rate inside the duct. Indeed, the high challenge concentration is proposed to finish the test in one day. However, this proposal needs more investigation and discussion. According to adsorption isotherm of sorptive filters (Figure 2- 2), the high concentration level of contaminant overestimates the removal capacity of filters. In addition, and more critical, conducting the test at this level of concentration needs some excessive protection and precaution for the operators and technicians. The chance of exposure to this high concentration of these chemical compounds would be higher during the generation of contaminant and leakage from the test rig. Also, the exhaust of the system needs specific treatment before venting out into the urban air.

VanOsdell et al. (2006) carried out a full-scale experiment to investigate the removal performance of three gaseous air cleaners. They compared the removal bed arranged in a zig-zag fashion filled with GAC with a 50% bypass filter and a carbon/fiber matrix composite. The air stream contaminated with an equimolar mixture of hexane, MEK, isobutanol, toluene, and perc with a concentration of 0.2 ppm each. The bed of GAC showed the best removal performance for all five VOC between the tested air cleaners due to its high amount of carbon. Also, heavier VOCs had the lowest penetration during the test period. After almost five days (120 h) the penetration ratio of toluene and perc was around 10%. This result shows the long test period requirement to characterize the

lifetime and removal performance of GAC at a low concentration level. This research was the only study on full-scale assessment method using one-pass test. Overall, the full-scale method projects the most realistic results. Also, only by testing complete gaseous air cleaners can the effect of packing, leakage around filter holder and typical arrangement of the bed in the real HVAC system be studied. In addition, this testing allows for the proper investigation into the impact of airflow rate, residence time and environmental conditions. However, limited research has been carried out on a full-scale system and there is still a need for more investigation and discussion. Also, a standard method for full-scale measurement of gaseous air cleaners has yet to be developed. The method has to be feasible and safe and economical by applying a suitable challenge concentration. Moreover, developing a systematic method for full-scale assessment of gaseous air cleaners is required to quantitatively study and classify the gaseous filters for building applications which is the aim of this study.

CHAPTER 3 EXPERIMENTAL SETUP AND SYSTEM QUALIFICATION

3.1 INTRODUCTION

As extensively discussed in the previous chapter, the removal performance of commercially available gaseous air cleaners can be completely studied by applying the full-scale experimental method. On the other hand, the lack of a systematic method creates an obstacle in assessing the removal performance of these filters with a generally acceptable procedure. The aim of this research is to develop a experimental method for quantitatively measuring the performance of gaseous air cleaners. For this purpose, a full-scale setup was designed to simulate a building HVAC system. Also, a generation system was developed to generate the chemical contaminant agent. The details of this test setup and the generation system are explained in this chapter.

Furthermore, prior to study the performance of air cleaners, system qualification tests were carried out on the test rig. These series of tests quantitatively verified that the results come from the experimental procedure are reliable. The procedure of these tests and their results are discussed later in this chapter.

3.2 TEST RIG

3.2.1 Test Apparatus Description

To develop a method for assessing gaseous air cleaners' performance, a full-scale setup was designed based on the proposed ASHRAE standard 52.2 (1999). Figure 3- 1 presents the schematic diagram of the test apparatus. The designed test rig is made of stainless steel duct with 61cm*61cm [24"*24"] cross section area, 11.5 m [37.6 ft.] length and 10 m^3 [363.4 ft^3] volumes. It has a smooth interior finish to minimize the adsorption of contaminant on interior surface area of the system. The system can provide up to 0.9 m^3/s [2000 cfm] flow rate with a radial fan mounted in the test rig (Point D in Figure 3- 1). This flow rate is close to the actual flow in a mechanical HVAC system. The room air was introduced to the system through the inlet damper (Point B in Figure 3- 1). The conditions of the inlet air were determined by the temperature and relative humidity sensors located near the inlet opening. A humidifier (Nortec, MES-U Electrode Stem Humidifiers) and a cooling coil were located before the blower (Point C in Figure 3- 1). Hence, they could condition the inlet air and control the temperature and relative humidity of challenge air during the experiment. Also, the temperature and relative humidity at upstream and downstream of the tested filter were monitored by temperature and relative humidity transmitters (Vaisala HUMICAP® series HMT100). Their probes were mounted in upstream and downstream of the filter at the same sections for challenge gas concentration sampling zones. They were connected to a data acquisition system (DAS) (Agilent 34970A Data Acquisition/Switch Unit) which is plugged in a personal computer (PC). Data are acquired in DC voltage difference and converted to relative

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humidity and temperature in percentage and Celsius by a developed program provided by the installed software (Agilent IO Libraries Suite) in the computer, respectively.

Two dampers were mounted on the apparatus; one (damper A-1 in Figure 3- 1) before the exhaust and the other one (damper A-2 in Figure 3- 1) before the inlet air opening. Consequently, the apparatus can perform either in once-through (open-loop) or recirculation (closed-loop) modes by opening or closing the dampers. While the damper "A-1" controls the air flow through the exhaust of the system, the damper "A-2" used to switch the test rig between once-through or recirculation mode. The outlet of the system is connected to the exhaust duct of laboratory and directly sent out of the building. To reduce the contaminant level of system exhaust, a clean-up bed (Point H in Figure 3- 1) (GAC packed in the same modules for testing devices) was installed before the damper "A-1". Furthermore, the same scrubbers (Point E in Figure 3- 1) and a HEPA filter (Point F in Figure 3- 1) were mounted after the blower to provide a pre-filter for the inlet air. So, the aerosol and gaseous contaminant concentration are reduced in the challenge inlet air. In the case of the closed-loop study, both clean-up banks have to be removed.

The challenge gas is injected into the air stream after the clean-up bed and HEPA filter. To have a uniform dispersion of the tested contaminant in the air stream, a 30 cm [12"] diameter orifice plate (Point G-1 in Figure 3- 1) and a 15 cm [6"] diameter 40% perforated plate (Point H-1 in Figure 3- 1) are located after the injection point as a mixing baffle. The same orifice and mixing baffle (Point G-2 and H-2 in Figure 3- 1) are installed downstream of the duct to provide a uniform downstream concentration. This

combination allows single point downstream sampling. The applicability of these orifices and baffles is examined and the results are given in section (3.3.3, 3.3.4 and 3.3.5).

This system has the ability to test removal devices with nominal cross section area of 61cm*61cm [24"*24"]. Three different sections have been designed to study gaseous filters in the type of panel or filled modules with granular removal devices (Point I-1, I-2 and I-3 in Figure 3- 1). In addition, cleaners with diverse bed depth (5, 10, 15, 30 and 45 cm [2", 4", 6", 12" and 18"]) could be tested in each section. In this study, filled modules with bed depth of 18 inch were used to conduct experiments and they were mounted in section "I-3" in Figure 3- 1.
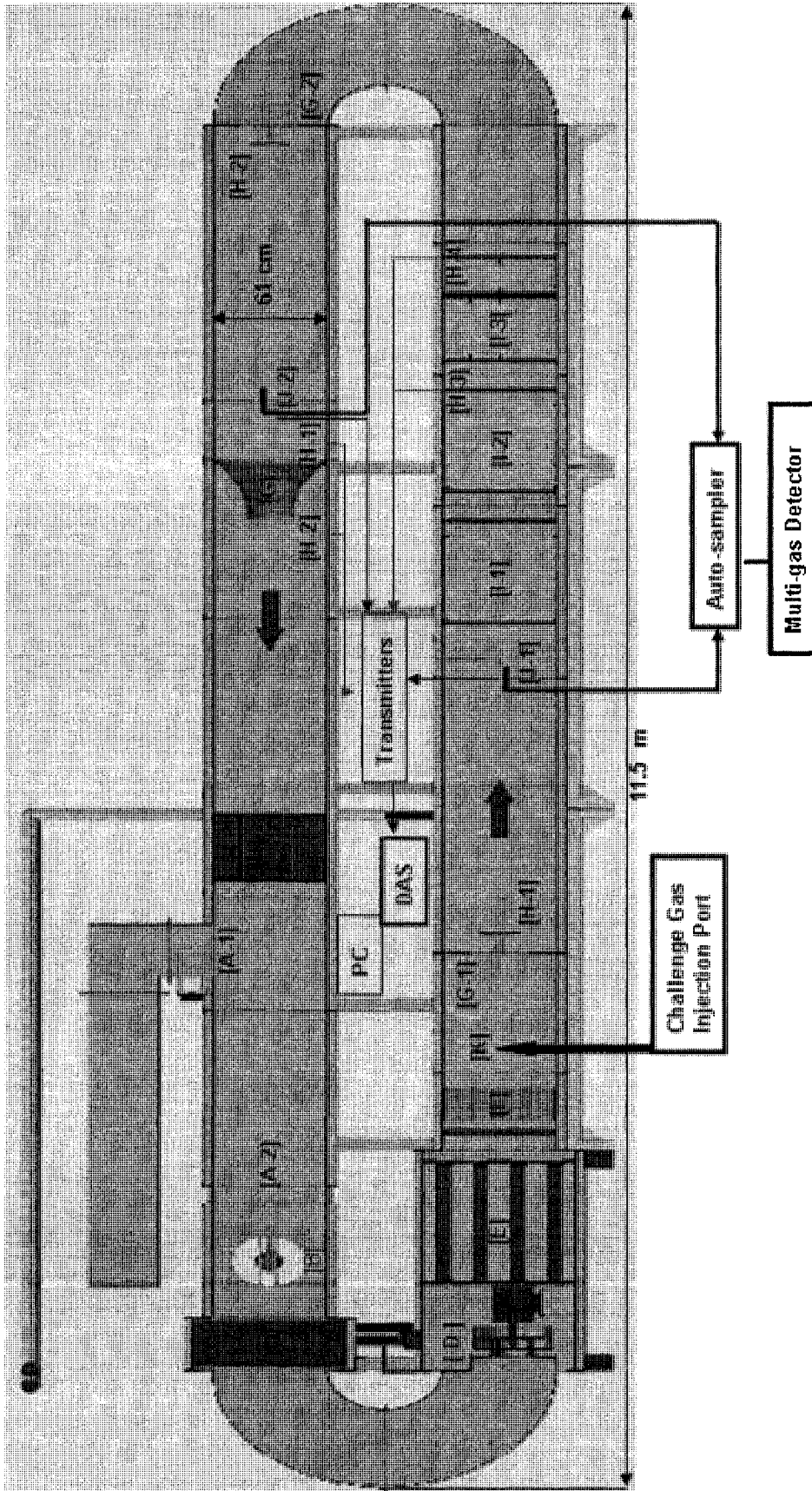
Figure 3- 1 Test apparatus schematic diagram

3.2.2 Measuring Flow Rate

A 25 cm [10"] diameter American Society of Mechanical Engineers (ASME) long-radius flow nozzles were used to determine the flow rate following the ASHRAE standard 52 (1999). Its schematic diagram and required dimensions have been depicted in Figure 3- 2. This flow nozzle was located downstream of the system near the sampling probe and temperature, relative humidity transmitter sensor (Point G in Figure 3- 1). A pressure difference transmitter (Cuba Control pressure difference transmitter type-694) and two static taps were mounted before and after the flow nozzle (Point H-1 and H-2 in Figure 3-1) to measure the pressure drop created by the nozzle. These static taps were built according to ASHRAE standard 52.2-1999. The pressure difference was measured in DC voltage difference by DAS and converted to inch of water. This pressure transmitter was calibrated for six different pressure differences. By knowing the created pressure drop with the given diameter nozzle and downstream air conditions (temperature and relative humidity) the flow rate of the air stream was calculated (ASME standard 1990);

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

where N_U is the unit coefficient and equal to 1.1107×10^{-6} (SI) and 5.9863 (I-P), Q is the airflow rate (m^3/s, cfm), D is the nozzle throat diameter (mm., in.), ΔP is the pressure drop (Pa, in. of water), and ρ is the air density in the nozzle inlet (kg/m^3, lb/ft^3).

β and C_{dc} have to be derived by following equations;

$$\beta = \frac{D}{W} \tag{3-2}$$

$$C_{dc} = 0.9975 - 6.53 * \text{Re}^{-0.5} \tag{3- 3}$$

where W is the duct width (mm, in.) and C_{dc} is the discharge coefficient of nozzle and it

is a function of air stream Reynolds number. Reynolds number is calculated by:

$$\text{Re} = \frac{K_R * \rho * Q}{D} \tag{3- 4}$$

where K_R is equal to 5.504×10^{-7} (SI) and 16393 (I-P)

D = Nozzle throat diameter, mm (in.)
T = Nozzle wall thickness, mm (in.)
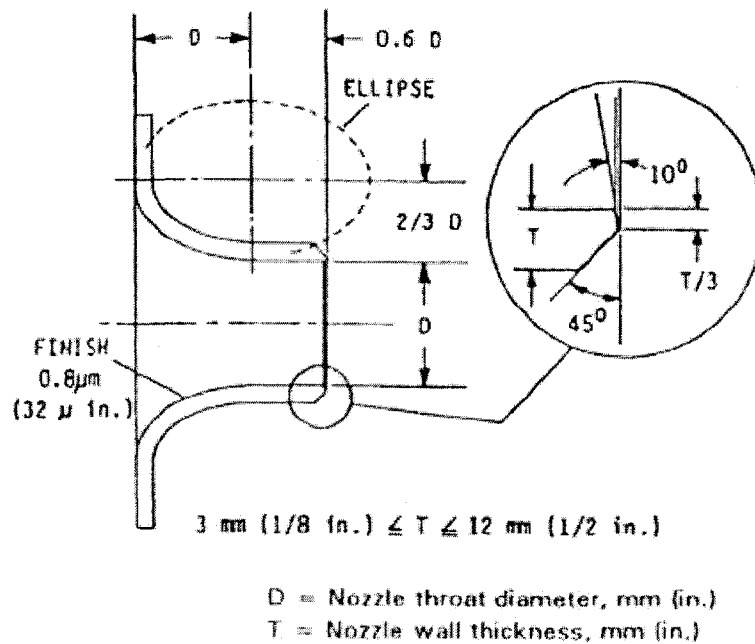
Figure 3- 2   ASME long-radius flow nozzle schematic diagram (ASHRAE 1999)

3.2.3 Contaminant Generation System

As the selected contaminant in this study, toluene, is liquid in room temperature, a bubbling system was used to introduce challenge gas to the test rig. The laboratory compressed air was used as the carrier gas and its flow rate was controlled by a mass flow controller [Omega FMA 5400/FMA 5500]. By passing through the bottles of toluene, the air became almost saturated and the potential droplets were removed in the following empty bottle. Figure 3- 3 shows the schematic diagram of generation system. The contaminated flow was introduced to the system after the clean-up bed (Point K in Figure 3- 1). To avoid the condensation of the compound on the interior duct surface and have a uniform injection in the whole duct cross section area, a perforated stainless steel tube was mounted inside the apparatus which was connected to the contaminant vapor carrier line. The contaminant dispersal uniformity was tested, and the results are presented in Section (3.3.4).
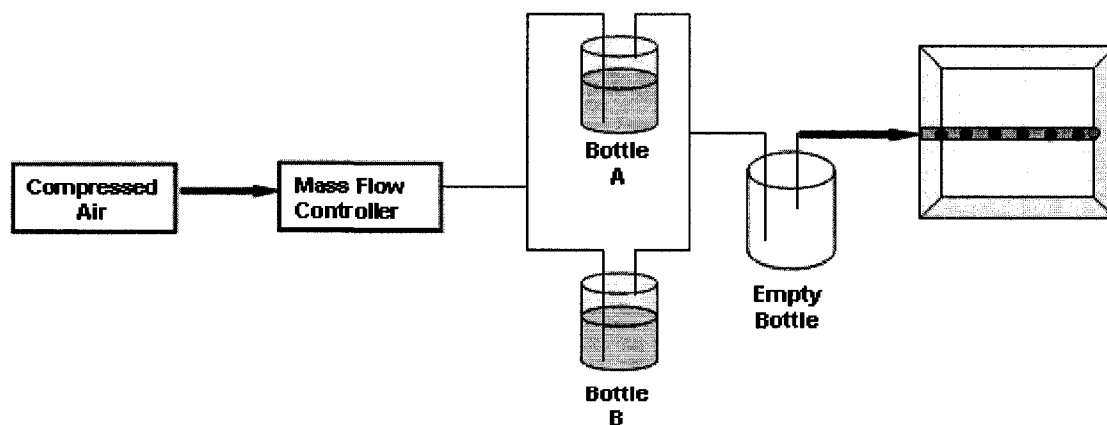
Figure 3- 3   Contaminant generation system

3.2.4 Gas Sampling and Analyzing

To evaluate the removal efficiency of a filter, the filter upstream and downstream concentrations of the air stream were measured. Two probes were mounted 2.25 m [90"] away from the mixing baffles located before the filter and after the bend in the downstream (Point J-1 and J-2 in Figure 3- 1). The probes are 0.6 cm [1/4"] stainless steel tubes with a 90° long-radius bend at their inlet and perpendicular to the air flow direction. Also, they were located exactly in the center of the duct cross section. Both probes were connected to an automatic multi-channel sampler (CAI Intelligent Sampling System MK2) by poly tetra fluoro ethylene (PTFE) tubes to decrease possible loss of measured compound in the line. The auto sampler was connected to a multi-gas analyzer detector (INNOVA AirTech Instrument 1312). Data were acquired from upstream and downstream continuously.

3.2.5 Instruments

<u>Auto Sampler:</u> The auto sampler (CAI Intelligent Sampling System MK2) was programmed to take sample from upstream and downstream probes alternatively. It was connected to a photo-acoustic multi-gas detector and sent the sample to the gas detector. The sampling interval was adjusted by gas detector and auto sampler switched between upstream and downstream sampling points.

<u>Multi-Gas Detector:</u> A photo-acoustic gas detector (INNOVA AirTech Instrument 1312) was used to measure the concentration of challenge gas before and after the filter. To measure the concentration, the gas-detector irradiates the component molecules by infrared radiation (IR). As this IR is absorbed by the molecule, sound waves are

generated (Kawamura and Mackay 1987). Two microphones mounted in the system detect the sound waves which their amplitude is proportional to the concentration of detected compound.

Humidity and Temperature Transmitter: Two Vaisala HUMICAP® humidity and temperature transmitter series HMT100 were used to measure temperature and relative humidity at upstream and downstream zones. Their probes were mounted in the same place of concentration sampling ports. Based on the air condition at these two regions, they had analog outputs in the range of 0-10 V which were sent to Agilent DAS. They have the ability to measure relative humidity in the range of 0-100% and temperature in the range of -40-60° C.

Pressure Difference Transmitter: Two Cuba Control pressure difference transmitters type-694 were used to measure the pressure drop created by the testing filter and the flow nozzle. They had an output voltage between 0-10 V and measure pressure drop in the range of 0-6.2 and 0-1.2 inch H_2O. Both of them were connected to the Agilent DAS.

DAS: All relative humidity/temperature and pressure difference transmitters were connected to Agilent 34970A Data Acquisition/Switch Unit. The output voltages from transmitters were converted to the appropriate unit. The 82357A-USB/GPIB Interface provides connection between data acquisition system and computer.

3.3 PRE-QUALIFICATION TEST

To investigate the removal performance of air cleaners in full-scale test rig, the test system has to provide a uniform airflow of the air stream before and after the filter. In addition, the contaminant has to be uniformly dispersed in upstream and downstream regions in order to have a valid single point sampling. The existence of these conditions has to be validated by conducting the system qualification tests.

According to proposed draft of ASHRAE 145.2P (ASHRAE 2007-c), some tests are suggested for apparatus qualification testing. The same procedure was suggested for particulate filters in ASHRAE standard 52.2. However, these tests have to be modified for gaseous air cleaners. Therefore, qualification tests proposed are:

1. Test duct leakage
2. Gas analyzer calibration
3. Test duct velocity uniformity
4. Upstream contaminant dispersal uniformity
5. Downstream mixing of contaminant
6. No filter Test

In this study the qualification tests (3) to (5), were carried out at airflow rate of 0.2 and 0.9 m³/s [500 and 2000 cfm]. Test duct leakage and no filter tests were done at 0.9 m³/s [2000 cfm].

3.3.1 Test Duct Leakage

To measure the system leakage, tracer gas decay method was used. In this method, tracer gas injected into the system till it reaches a certain concentration. Then its concentration

is measured continuously. Since this is a closed loop system and there is no known opening, the decrease of tracer gas concentration is the result of system leakage.

The experiment was performed at 0.9 m^3/s [2000 cfm] airflow rate. SF$_6$, as tracer gas, was injected inside the duct (Figure 3- 4 (a)). The photo-acoustic gas-analyzer, calibrated for SF$_6$ gas, was used to monitor the concentration of SF$_6$ inside the rig (Figure 3- 4 (b)). The air sample was then returned to the system after the analysis. Figure 3- 5 presents the SF$_6$ concentration decay inside the chamber

(a) (b)
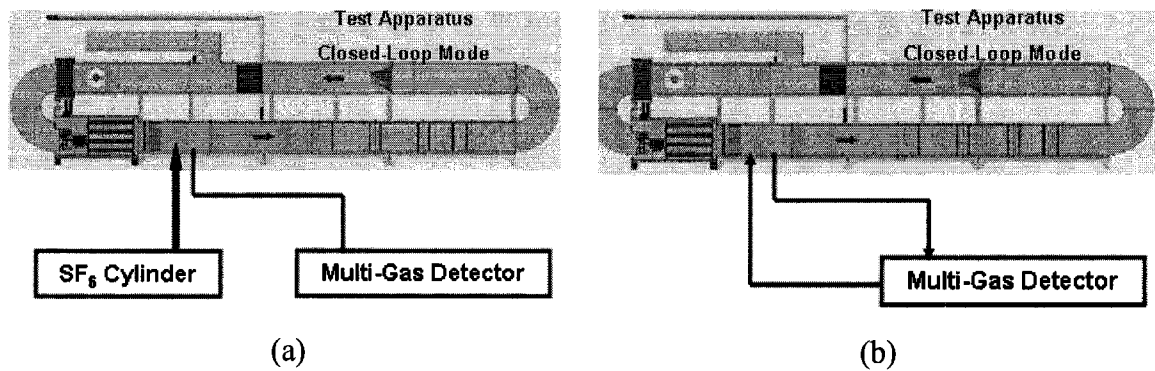
Figure 3- 4 Test duct leakage determination (a) system contamination (b) decay concentration monitoring
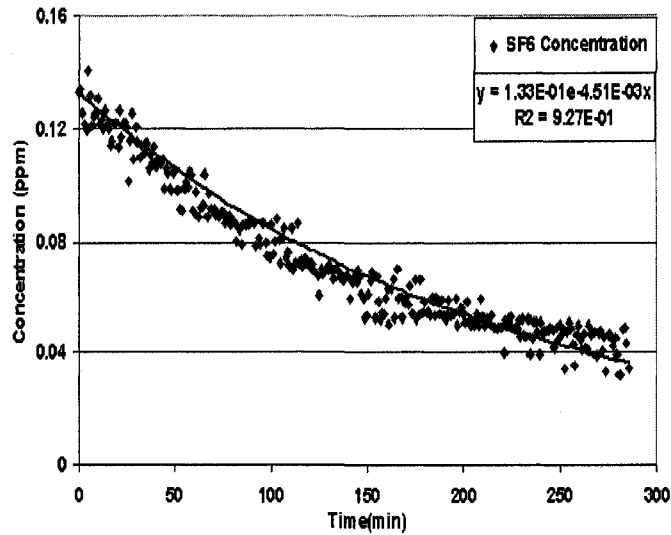
Figure 3- 5   SF$_6$ concentration decay inside the duct

By writing the mass balance equation for SF$_6$, the decay concentration equation will be:

$$C = C_0 \cdot e^{-\frac{Q}{V}t}$$

(3- 5)

where, C (ppm) is the SF$_6$ concentration inside the duct as function of time (t, min.), C_o is

the initial tracer gas concentration, V is the volume of system and the Q is the airflow

rate. For the above experiment, the expression is:

$$C = 1.33E^{-1}e^{-4.51E-3\ t}$$

(3- 6)

where Q/V was obtained from the curve in Figure 3- 5.

$$-\frac{Q}{V} = -4.51E^{-3}$$

(3- 7)

The duct volume is 10 m^3 [363.4 ft^3]. Therefore, by using Equation (3-7), the air leakage flow rate is 1.4x10^{-5} m^3/s [1.64 cfm], which satisfies the ASHRAE standard 52.2-1999 leakage rate requirements which must be less than 1% of in-duct flow rate: it is 0.082% leakage.

3.3.2 Gas Analyzer Calibration

The Photo-acoustic gas detector (INNOVA) was calibrated for toluene in concentrations between 0-100 ppm. The schematic of the setup for calibration is presented in Figure 3-6. A known amount of toluene was continuously introduced to the carrier gas (i.e. ultra-high purity nitrogen) and passed through the gas-analyzer. This procedure was done in six different concentrations; approximately, 0, 2, 10, 20, 50, 100 ppm. Also, the calibration was conducted in ascending order of concentration due to possible adsorption/desorption in the system. 2.2*10^{-3} m^3/min [0.08 cfm] ultra-high purity Nitrogen was used as a carrier gas and toluene was automatically injected by a syringe pump into the nitrogen stream.
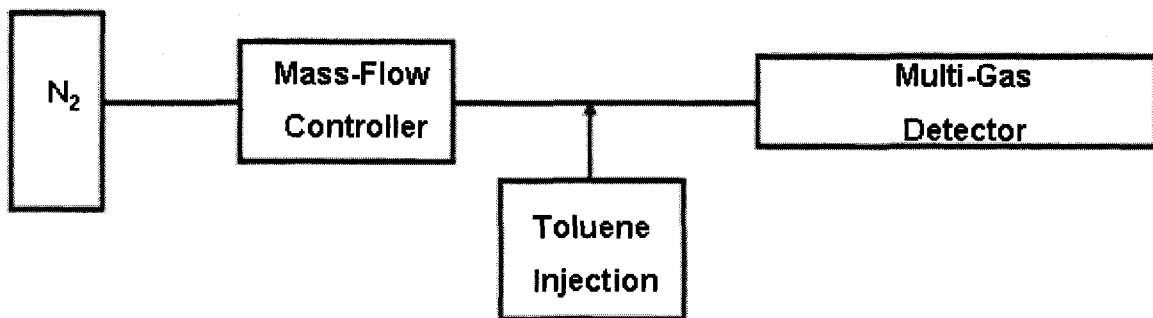
Figure 3- 6 Multi-gas detector calibration setup

For converting the volume of injected liquid of toluene to its gas phase concentration in ppm inside the gas stream, the mass balance between the liquid phase and the gas phase was written.

$$\frac{I \times \rho}{Q_N} = C = ppm \times M \times \frac{P}{8.314 \times (273.15 + T)} \qquad (3\text{-}8)$$

where, C is the toluene concentration (mg/m^3) I is the toluene injection rate (μl/min.), ρ is the toluene density (mg/μl), Q_N is the nitrogen flow rate (m^3/min), ppm is the volumetric concentration (ppm), M is the molecular weight of compound, P is the pressure (kPa), and T is the temperature (K). For toluene, the molecular weight is 92.10 g/mol, and the density is 0.87 mg/μl. Also, Equation (3-8) can be simplified to:

$$\frac{I \times \rho}{Q_N} = C = ppm \times F \qquad (3\text{-}9)$$

which F is a function of temperature and pressure. Table 3- 1 shows the calculated concentration of toluene for each injection rate.

Table 3- 1   Calculated concentration for each injection rate

I=Injection Rate (μl/min)	Mass Injection Rate(mg/min)	C (mg/m^3)	ppm
0	0	0	0
0.02	0.01734	7.868	2.076
0.1	0.0867	39.338	10.379
0.2	0.1734	78.675	20.758
0.5	0.4335	196.688	51.895
1	0.867	393.376	103.789

The multi-gas detector readings for each challenge concentration were used to derive its calibration curve for toluene. The curve and its equation are given in Figure 3- 7.
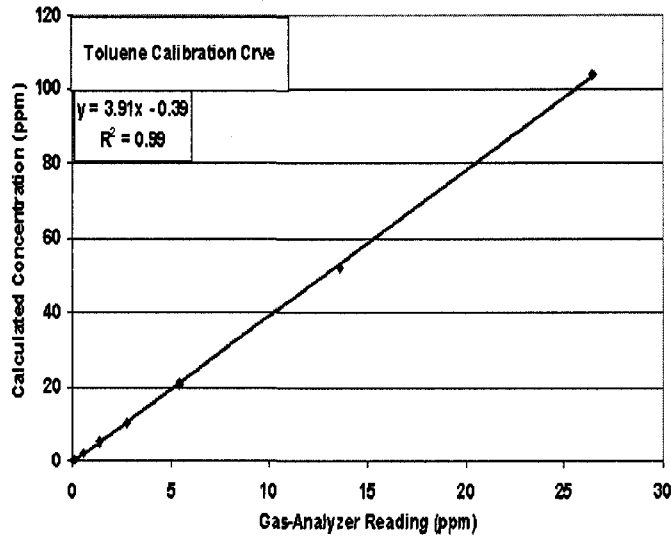
Figure 3- 7   Toluene calibration curve of gas-analyzer

3.3.3 Velocity Uniformity Test

The velocity uniformity test was conducted following the ANSI/ASHRAE Standard 52.2-1999; section 5.2; "Velocity Uniformity in the Test Duct". According to this standard, the velocity has to be measured at nine points of the duct cross section area and the coefficient of variation (CV) (CV is calculated by dividing the standard deviation of all measured nine point with the mean average velocity of these measuring points) has to be less than 10%.

This standard can provide a good evaluation of the uniformity of velocity inside the duct. This is a prerequisite to guarantee the good dispersion of contaminants introduced into the test duct.

ASHRAE 52.2 recommends testing the velocity uniformity at three different flow rates: 0.2, 0.5, 1.4 m^3/s [472, 1070 and 2990 cfm]. Since the fan installed in the test duct could

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not provide a flow more than 0.9 m^3/s [2000 cfm], the velocity uniformity was conducted at about 0.2 m^3/s [500 cfm] and 0.9 m^3/s [2000 cfm] of flow rates.

The velocity measured at the center of nine evenly divided cross-sectional area of the test duct. The distance from one measurement point to another one is 20 cm [8"]. Figure 3- 8 shows the velocity measurement locations.
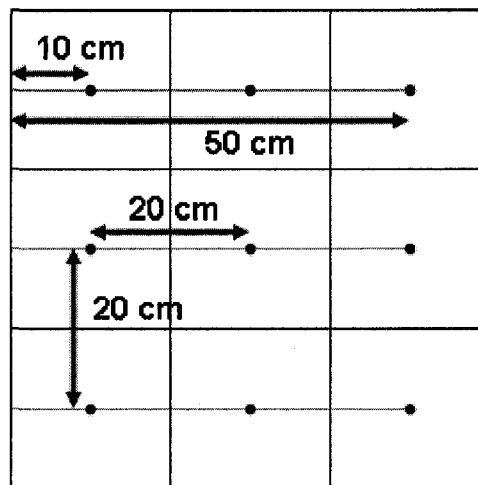
Figure 3- 8   Grid to measure the velocity

For each measuring point at a given velocity level, 12 samples with 5 seconds of sampling time interval were taken for one-minute period and repeated three times at every measuring point. In addition, the whole procedure was carried out twice to verify the repeatability. The results for 0.9 m^3/s [2000 cfm] flow rate are presented in Table 3- 2 and Table 3- 3.

For each flow rate at each grid point, the average of three measurements was computed. The mean average of those values and their standard deviation were used to compute the

CV for 0.9 m^3/s [2000 cfm] flow rate which was 8.61% and 9.00% in both tests, respectively. The results for 0.2 m^3/s [500 cfm] have been tabulated in Table 3- 4 and Table 3- 5.

The CV for these two repeated tests was 6.49% and 8.58%, respectively, which are less than 10%. Therefore, the airflow through the duct satisfied the velocity uniformity required by the ANSI/ASHRAE Standard 52.2-1999.

Table 3- 2   Velocity uniformity test at 0.9 m^3/s [2000 cfm]

Flow Rate:	0.9 m^3/s [2000 cfm]			Calculated Pressure Drop:			0.799		in.H$_2$O
Location		ΔP [in.H$_2$O]	Velocity #1 [m/s]			Velocity #2 [m/s]			Velocity #3 [m/s]		
			Ave	Max	Min	Ave	Max	Min	Ave	Max	Min
Top	50 cm	0.799	3.18	3.32	3.01	3.23	3.41	3.00	3.24	3.44	3.04
	30 cm	0.799	2.65	3.05	2.36	2.74	2.95	2.60	2.74	2.91	2.59
	10 cm	0.799	3.02	3.20	2.81	2.98	3.17	2.82	3.00	3.12	2.87
Mid	50 cm	0.798	3.29	3.47	3.15	3.26	3.45	3.09	3.31	3.49	3.16
	30 cm	0.799	2.62	2.82	2.50	2.66	2.84	2.49	2.63	2.80	2.41
	10 cm	0.798	3.24	3.35	3.08	3.22	3.31	3.09	3.27	3.43	3.13
Bottom	50 cm	0.799	3.19	3.30	2.96	3.24	3.40	3.13	3.19	3.28	3.07
	30 cm	0.799	2.91	3.11	2.61	2.91	3.02	2.66	2.89	3.04	2.68
	10 cm	0.799	3.35	3.50	3.20	3.37	3.48	3.18	3.39	3.59	3.25

Table 3- 3 Velocity uniformity test at 0.9 m³/s [2000 cfm] (Repeatability)

Flow Rate: 0.9 m³/s [2000 cfm]		Calculated Pressure Drop:		0.799	in.H₂O				
Location		ΔP [in.H₂O]	Velocity #1 [m/s]			Velocity #2 [m/s]			Velocity #3 [m/s]		
			Ave	Max	Min	Ave	Max	Min	Ave	Max	Min
Top	50 cm	0.798	3.20	3.32	2.92	3.18	3.44	2.98	3.17	3.38	2.91
	30 cm	0.798	2.69	2.97	2.45	2.65	2.87	2.43	2.73	2.98	2.38
	10 cm	0.799	2.92	3.22	2.50	2.95	3.13	2.59	3.01	3.16	2.78
Mid	50 cm	0.799	3.30	3.49	3.19	3.29	3.48	3.12	3.25	3.34	3.17
	30 cm	0.799	2.57	2.66	2.42	2.62	2.78	2.40	2.58	2.72	2.31
	10 cm	0.799	3.21	3.31	2.98	3.14	3.29	2.93	3.22	3.36	3.03
Bottom	50 cm	0.799	3.15	3.30	2.86	3.18	3.36	2.98	3.16	3.28	2.85
	30 cm	0.799	2.87	3.01	2.51	2.80	2.99	2.59	2.79	3.00	2.56
	10 cm	0.799	3.40	3.57	3.25	3.34	3.56	3.15	3.33	3.56	3.20

Table 3- 4 Velocity uniformity test at 0.2 m³/s [500 cfm]

Flow Rate: 0.2 m³/s [500 cfm]		Calculated Pressure Drop: 0.211		in.H₂O					
Location		ΔP [in.H₂O]	Velocity #1 [m/s]			Velocity #2 [m/s]			Velocity #3 [m/s]		
			Ave	Max	Min	Ave	Max	Min	Ave	Max	Min
Top	50 cm	0.212	0.89	1.12	0.66	0.84	0.96	0.51	0.78	0.97	0.52
	30 cm	0.212	0.77	1.00	0.58	0.83	1.02	0.60	0.72	1.02	0.55
	10 cm	0.211	0.75	0.93	0.58	0.76	0.95	0.58	0.74	0.98	0.52
Mid	50 cm	0.211	0.86	1.03	0.57	0.84	0.09	0.69	0.84	1.05	0.58
	30 cm	0.211	0.73	0.84	0.59	0.69	0.82	0.57	0.72	0.85	0.59
	10 cm	0.211	0.80	0.94	0.64	0.81	0.93	0.66	0.84	1.06	0.57
Bottom	50 cm	0.211	0.78	1.00	0.52	0.86	1.04	0.63	0.85	1.07	0.58
	30 cm	0.211	0.73	0.86	0.56	0.73	1.00	0.49	0.77	0.96	0.65
	10 cm	0.211	0.79	0.98	0.58	0.90	1.17	0.55	0.87	0.99	0.70

Table 3- 5   Velocity uniformity test at 0.2 m³/s [500 cfm] (Repeatability)

Flow Rate: 0.2 m³/s [500 cfm]		Calculated Pressure Drop: 0.211 in.H₂O									
Location		ΔP [in.H₂O]	Velocity #1 [m/s]			Velocity #2 [m/s]			Velocity #3 [m/s]		
			Ave	Max	Min	Ave	Max	Min	Ave	Max	Min
Top	50 cm	0.211	0.88	1.19	0.70	0.93	1.17	0.64	0.91	1.25	0.59
	30 cm	0.211	0.68	0.75	0.55	0.82	0.94	0.63	0.74	0.99	0.63
	10 cm	0.211	0.79	0.98	0.66	0.71	1.07	0.53	0.79	1.01	0.63
Mid	50 cm	0.211	0.90	1.23	0.76	0.76	0.89	0.58	0.82	1.17	0.59
	30 cm	0.211	0.68	0.82	0.50	0.68	0.77	0.57	0.72	0.90	0.55
	10 cm	0.211	0.84	0.97	0.55	0.85	0.98	0.69	0.83	1.00	0.64
Bottom	50 cm	0.211	0.84	1.20	0.53	0.92	1.20	0.56	0.79	0.93	0.55
	30 cm	0.211	0.69	0.89	0.54	0.74	0.89	0.57	0.76	0.90	0.54
	10 cm	0.211	0.89	1.08	0.68	0.78	1.08	0.55	0.82	1.08	0.62

3.3.4 Upstream Contaminant Dispersal Uniformity

The contaminant dispersal uniformity test was conducted following the ANSI/ASHRAE Standard 52.2-1999, section 5.3; "Aerosol Uniformity in the Test Duct". Although this standard is for particulate filters, because the diffusion rates of particles are lower than gaseous, it is acceptable to follow the structure of this standard and modify it for gaseous contaminants.

In this test the uniformity of contaminant gas concentration was checked. The concentration of challenge gas has to be uniformly dispersed in nine points of duct cross section area, exactly at the place of probe for upstream sampling, before the filter. Hence the same grid points used for the velocity uniformity test were adopted for this test

(Figure 3- 8). Toluene was introduced to the system at the injection point (Point K in Figure 3- 1). Before introducing the challenge gas, the background concentration of toluene was measured. Also, monitoring of toluene concentration was continued after injection until it became stable. Then, the toluene concentration at each point was measured. For this purpose, a probe was connected to the gas analyzer and monitored the concentration continuously for 10 minutes at each point. Only one probe was used for measuring the concentration at all points. The nozzle cross section of the probe was perpendicular to the air flow direction. Due to repositioning of sample probe, the sampling has been done after stabilization of concentration in each point. This test was conducted for open-loop case (damper A-1 was open and damper A-2 was close). The CV less than 15% is required for aerosol dispersal uniformity in ANSI/ASHRAE Standard (52.2-1999, 5.3) and this criterion was adopted in this study.

The concentration of each measuring point at 0.2 m^3/s [500 cfm] air stream flow rate is presented in Figure 3- 9. Also, the mean average concentration for all nine measuring points and their position at the duct cross-section area is shown in Figure 3- 10.
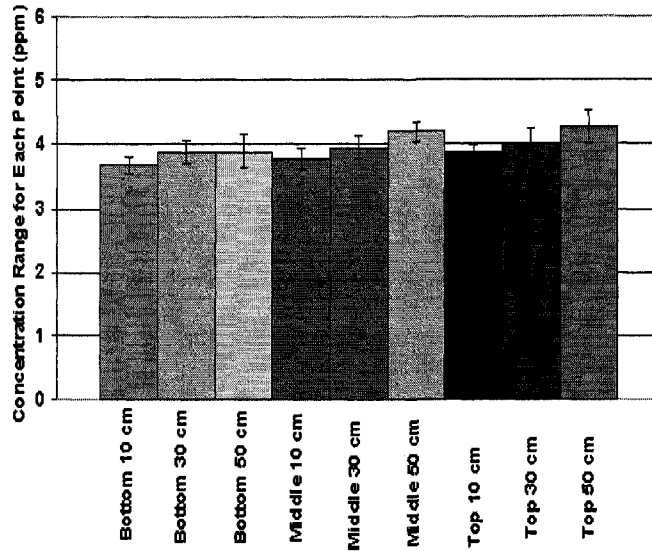
Figure 3- 9 Toluene concentration range at each measuring point at 0.2 m³/s [500 cfm] flow rate (first test)

	10 cm	30 cm	50 cm
Top	3.87E+00	4.02E+00	4.27E+00
Middle	3.78E+00	3.95E+00	4.20E+00
Bottom	3.68E+00	3.89E+00	3.89E+00

Figure 3- 10 Mean average concentration (ppm) at each measuring point at 0.2 m³/s [500 cfm] flow rate (first test)

The CV is the ratio of the standard deviation to the mean average concentration of all the points and presented in percentage; it was 4.78%. Furthermore, the whole procedure was repeated and the CV was 4.98% for the second test. The concentration range and its mean

average for each of nine points for the second test are shown in Figure 3- 11 and Figure

3- 12, respectively.
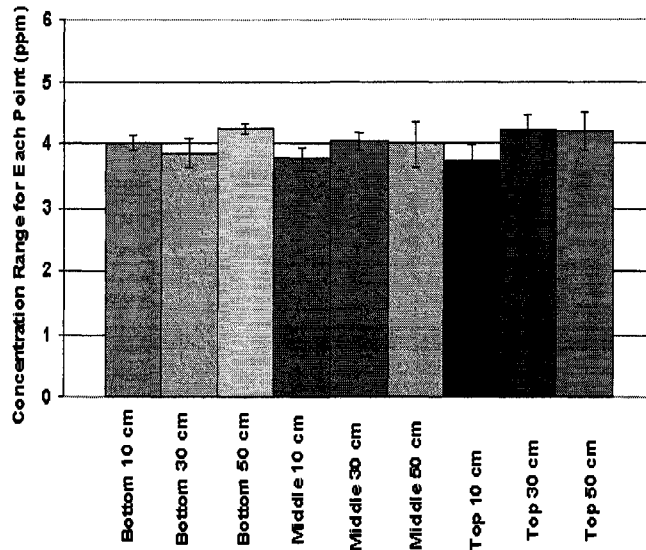
Figure 3- 11 Toluene concentration range at each measuring point at 0.2 m³/s [500 cfm]
flow rate (second test)

	10 cm	30 cm	50 cm
Top	3.72E+00	4.22E+00	4.20E+00
Middle	3.76E+00	4.04E+00	4.00E+00
Bottom	4.01E+00	4.24E+00	4.24E+00

Figure 3- 12 Mean average concentration (ppm) at each measuring point at 0.2 m³/s
[500 cfm] flow rate (second test)

Similarly, dispersal uniformity test for 0.9 m³/s [2000 cfm] was conducted twice. Both tests had CV less than 15% (5.23% and 6.23%). Toluene concentration range and mean average concentration of toluene in each measuring point for both tests are shown in the following figures (Figure 3- 13 to Figure 3- 16). Hence, the system satisfied the ASHRAE standard 52 (1999) requirement.
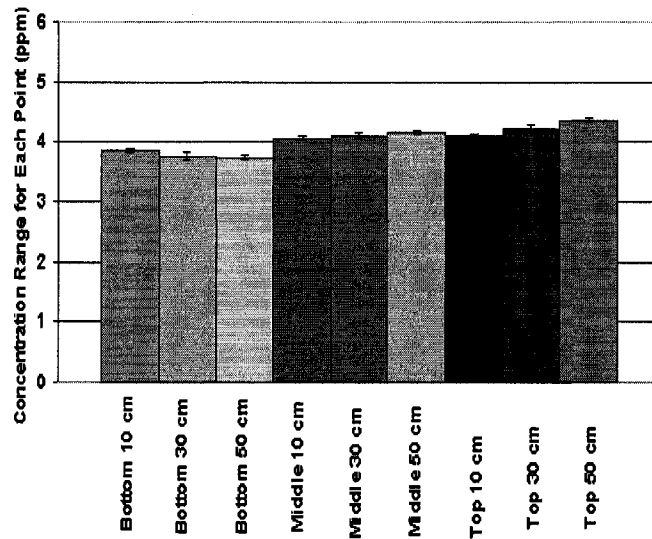
Figure 3- 13   Toluene concentration range at each measuring point at 0.9 m³/s [2000 cfm] flow rate (first test)

	10 cm	30 cm	50 cm
Top	4.12E+00	4.23E+00	4.35E+00
Middle	4.07E+00	4.11E+00	4.16E+00
Bottom	3.85E+00	3.77E+00	3.74E+00

Figure 3- 14   Mean average concentration (ppm) in each measuring point at 0.9 m³/s [2000 cfm] flow rate (first test)
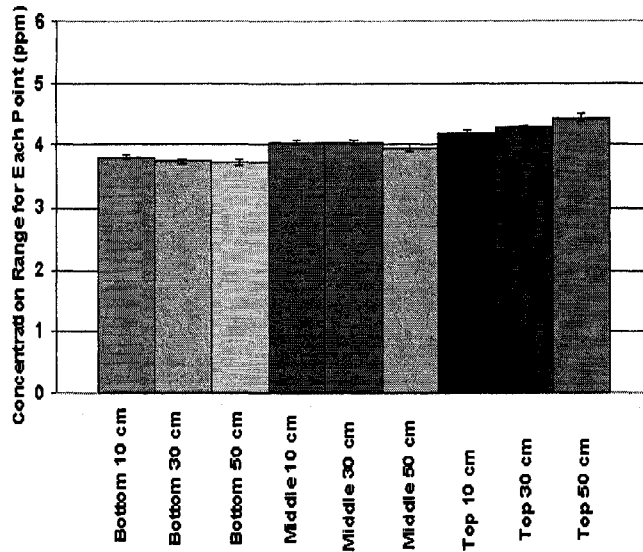
Figure 3- 15   Toluene concentration range at each measuring point at 0.9 m³/s [2000 cfm] flow rate (second test)

	10 cm	30 cm	50 cm
Top	4.20E+00	4.29E+00	4.45E+00
Middle	4.04E+00	4.04E+00	3.96E+00
Bottom	3.81E+00	3.74E+00	3.72E+00

Figure 3- 16   Mean average concentration (ppm) in each measuring point at 0.9 m³/s [2000 cfm] flow rate (second test)

3.3.5 Downstream Mixing of Contaminant

The Downstream Mixing of Contaminant Test was conducted following the ANSI/ASHRAE Standard 52.2-1999, section 5.4; "Downstream Mixing of Aerosol". Due to lower diffusion rate of particles than gaseous compound, as well as upstream dispersal

uniformity test, it is acceptable to follow the structure of this standard and modify it for gaseous contaminants.

This test is vital for calibrating the test rig downstream mixing baffle. The result of this test ensures that the contaminants penetrate through the filter media, can be detected by the downstream probe and the sample from the center of duct cross section area can represent the downstream concentration of contaminant. The downstream probe was located 2.25 m [90"] further from the downstream mixing nozzle. All contaminants penetrate through the filter, pass the mixing nozzle and will be sampled as downstream concentration.

In this test, the contaminant (i.e. toluene) was injected at nine points representing the leak and penetration from the air cleaner. These nine points were located immediately after the filter in the duct cross section area. Eight points were located around the perimeter of the test duct cross section and had 2.5 cm [1"] difference from the duct wall. One point was located in the center of the duct cross section area. The location of these injection points is shown in Figure 3- 17.

The contaminant generation system was connected to a 0.6 cm [¼"] stainless steal tube which could reach each point. The outlet of the tube was perpendicular to the cross section area of duct and the injected stream was in the direction of in-duct airflow. The injected stream from each point was sampled in exactly the same place of downstream measuring point (Point J-2 in Figure 3- 1). For each injection point, the downstream concentration was monitored continuously for 15 minutes. Before injection, the background concentration was measured. The sampling was launched after the

contaminant concentration of inlet stream and in-duct airflow was stable. The test was conducted for open-loop case (damper A-1 was open and damper A-2 was close). In addition, the test was conducted twice for both 0.2 m³/s [500 cfm] and 0.9 m³/s [2000 cfm] in-duct airflow rates to check the repeatability of the results. According to the ANSI/ASHRAE Standard 52.2-1999, section 5.3 the CV less than 10% is acceptable for the downstream mixing of aerosol which was adopted in this study for the gaseous compound.
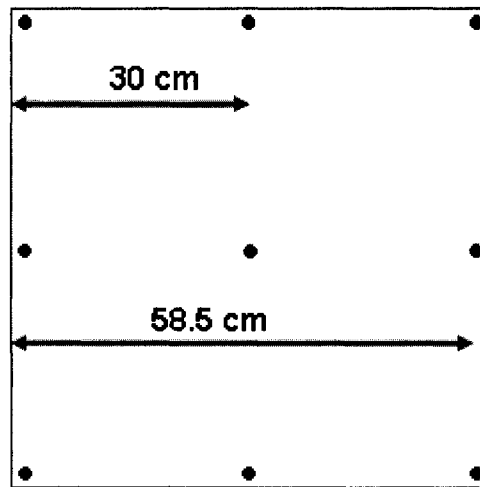
Figure 3- 17   Injection grid points for downstream mixing contaminant test

Figure 3- 18 to Figure 3- 21 present the downstream concentration range and the mean average detected concentration for each injection point for both tests at 0.2 m³/s [500 cfm] in-duct airflow rate.
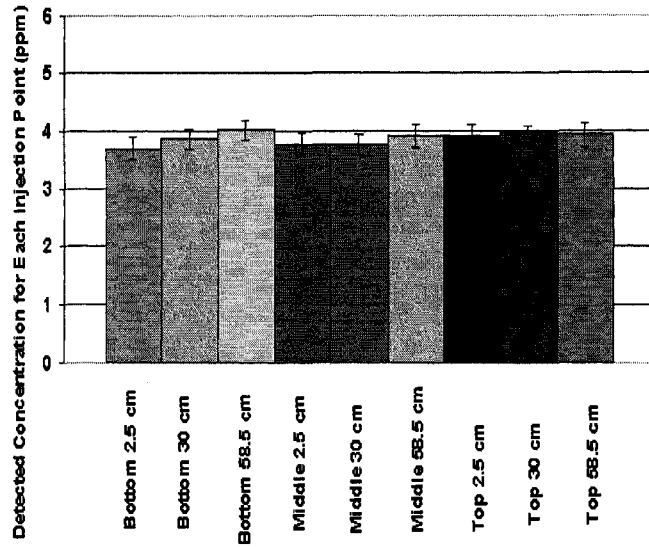
Figure 3- 18   Toluene concentration range for each injection point at 0.2 m³/s [500 cfm]

flow rate (first test)

	2.5 cm	30 cm	58.5 cm
Top	3.92E+00	3.96E+00	3.93E+00
Middle	3.77E+00	3.77E+00	3.90E+00
Bottom	3.68E+00	3.85E+00	4.01E+00

Figure 3- 19   Mean average detected concentration for each injection point at 0.2 m³/s

[500 cfm] flow rate (first test)
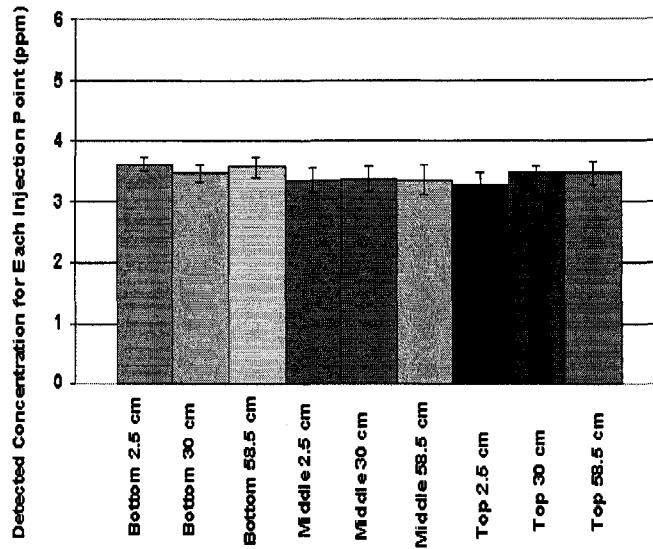
Figure 3- 20   Toluene concentration range for each injection point at 0.2 m³/s [500 cfm]

flow rate (second test)

	2.5 cm	30 cm	58.5 cm
Top	3.27E+00	3.45E+00	3.46E+00
Middle	3.35E+00	3.37E+00	3.36E+00
Bottom	3.60E+00	3.46E+00	3.58E+00

Figure 3- 21   Mean average detected concentration for each injection point at 0.2 m³/s

[500 cfm] flow rate (second test)

The CV was 2.77% and 3.12% for 0.2 m³/s [500 cfm]; and 2.12% and 2.04 % for 0.9 m³/s [2000 cfm] (see Figure 3- 22 to Figure 3- 25). Hence, the system satisfied the required criterion; the CV was less than 10%.
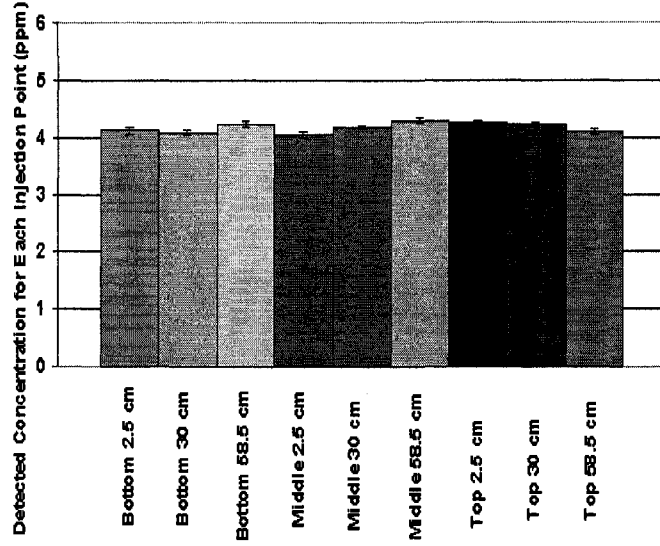
Figure 3- 22   Toluene concentration range for each injection point at 0.9 m³/s [2000 cfm]

flow rate (first test)

	2.5 cm	30 cm	58.5 cm
Top	4.26E+00	4.23E+00	4.09E+00
Middle	4.05E+00	4.19E+00	4.31E+00
Bottom	4.12E+00	4.08E+00	4.25E+00

Figure 3- 23   Mean average detected concentration for each injection point at 0.9 m³/s

[2000 cfm] flow rate (first test)
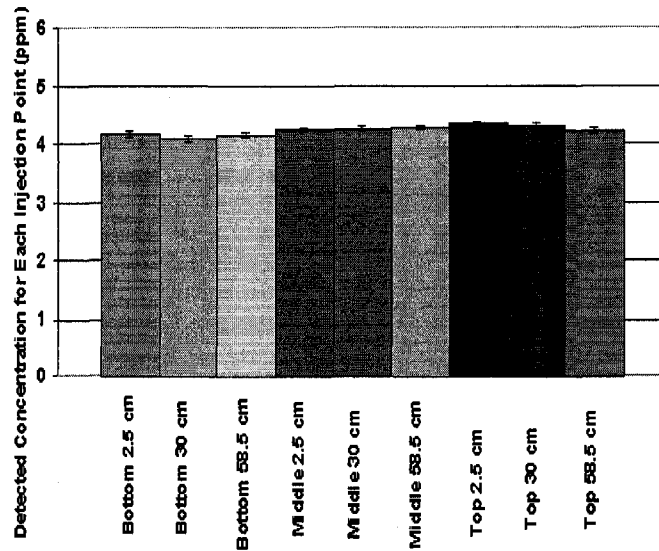
Figure 3- 24   Toluene concentration range for each injection point at 0.9 m^3/s [2000 cfm] flow rate (second test)

	2.5 cm	30 cm	58.5 cm
Top	4.35E+00	4.30E+00	4.22E+00
Middle	4.24E+00	4.25E+00	4.27E+00
Bottom	4.16E+00	4.08E+00	4.14E+00

Figure 3- 25   Mean average detected concentration for each injection point at 0.9 m^3/s [2000 cfm] flow rate (second test)

3.3.6 No Filter Test

To test the accuracy of sampling procedure and removal efficiency calculation, the upstream and downstream sampling of the contaminated air stream inside the duct was conducted for the specific test flow rate without removal devices. As no filter was installed in the test apparatus, the calculated efficiency shows the loss of challenge compound as a result of test rig leakage, duct interior surface adsorption and insufficient purging time of analyzing device.

The test was conducted twice with 0.9 m^3/s [2000 cfm] flow rate and the average efficiency with 95% confidence was 1.65±0.25% and 2.91±0.25% for the first test and the second one, respectively. According to proposed ASHRAE standard 145.2 P (2007-c), the efficiency has to be less than 5% which was satisfied in this study.

CHAPTER 4 DEVELOPED EXPERIMENTAL METHODOLOGY

4.1 INTRODUCTION

As mentioned earlier, there is a need for a standard method to assess the removal performance of full-scale gaseous air cleaners, which has yet to be developed. VanOsdell (1994) proposed an experimental method to measure the removal performance of filters for VOCs and acidic gases. He suggested a higher concentration level for VOC than the actual level found in the indoor environment to decrease the test duration. The test duration directly affects the cost of proposed method. To have an acceptable test procedure, this aspect (test duration) is critical (VanOsdell et al. 2006). He proposed the range of 1-10 ppm concentration for VOC representatives in the experiment. Later on, the ASHRAE (2007-c) recommends 100 ppm concentration of the challenge compound in order to finish the test in one day. However, this concentration is much higher than the real scenario in an indoor environment. The previous studies identified 113 compounds in residential and commercial buildings which have concentrations around 2 ppb while the TVOC concentration is in the range of 0.05-2 ppm (200-7000 $\mu g/m^3$) (Daisey et al. 1994, Oston et. al 1994, Ekberg 1994, Brown et al. 1994, Griman et al. 1999, Ullrich et al. 1996, and Hadwen et al. 1997). Therefore, conducting the test in a lower level of concentration is desirable until its cost is reasonable and technically applicable. In addition, the risk of exposure to the chemical compound will decrease when the test is conducting at low concentration.

The full-scale test setup was constructed and calibrated by conducting the system's qualification tests presented in Chapter 3. Based on the features and capacity of this test

rig, an experimental method was developed to quantitatively measure the removal performance of gaseous air cleaners.

4.2 CHEMICAL AGENT AND REMOVAL MATERIALS

The developed method was evaluated by conducting a set of experiments to rank the performance of filters. One chemical compound was selected as a representative of indoor VOC and removal performance of four filters were studied.

4.2.1 Chemical Agent Selection

According to VanOsdell (1994), the VOC representative should have the following characteristics;

- Must be found frequently in indoor space.

- Can be analyzed easily

- Should not have any serious health risks and can be worked with safely without any extraordinary safety precautions.

- The cost of performing the test should be reasonable.

Therefore, toluene was selected as a representative VOC in this research. It has been recommended by several researchers as a VOC representative (VanOsdell and Sparks 1995, VanOsdell 1994, Liu 1996, and Lee et. al. 2006). Also, toluene is one of the recommended compounds in the ASHRAE standard 145.1 P which is for assessing loose granular media as gas-phase air cleaner (ASHRAE 2007-b). Furthermore, Yu and Raber (1992) recommended toluene as an appropriate representative of VOCs based on its

boiling point. The boiling point of toluene is near the concentration-averaged boiling point of bio-effluent from human and the concentration-averaged boiling point of 35 VOCs in indoor environment (excluding formaldehyde). It is an aromatic compound with low molecular weight and water miscibility which is found in paint, wallpaper, adhesive, joint compound and chipboard. Its molecular weight and boiling point are 92.14 g/mol and 110.6°C, respectively. In the study conducted by the EPA Building Assessment Survey and Evaluation (BASE), toluene was detected in all 56 office-buildings (Girman et al. 1999). Based on the EPA classification, toluene is in group D; it is not carcinogenic (EPA 2007-a). According to the American Conference of Governmental and Industrial Hygienists (ACGIH) (1999), its threshold limit value-time weighted average (TLV-TWA) is 100 ppm for the occupational inhalation. However, it has both short-term and long-term exposure health effects. According to the EPA, exposure to toluene causes dizziness, sore throat, mucous membrane irritation, headache, and nausea (EPA 2007-a).

4.2.2 Removal Media

Four types of commercially available gaseous filters have been used in this study include activated carbon and activated alumina. Three activated carbons have been tested. Two of them were virgin activated carbons: one is activated from a coconut shell base (referred as VA) and the other one is activated from a bituminous coal substrate (referred as VB). The third one was palletized activated carbon which was 1-2% impregnated with potassium hydroxide (referred as IC). The fourth one was palletized activated alumina which was impregnated with potassium permanganate (referred as IAA). The supporter for this study provided a 50/50 blend of IAA and VB, which was used as a removal bed in this research (referred as IAA-VB). The characteristics and properties of these media

have been shown in Table 4- 1. To apply these pellets, each was packed in four V-shape 45 cm [18"] length, 61 cm [24"] width, 15 cm [6"] height and 2.5 cm [1"] depth modules which were made of steel and all air-face surfaces were 33% perforated. Each module had 5729.0 cm^2 [888 in^2] air-face surface area and the total bed face area enlargement[4] was 6.2. Figure 4- 1 shows the module. Each unit was wrapped to prevent its exposure to the external humidity and chemical compound till the test time.
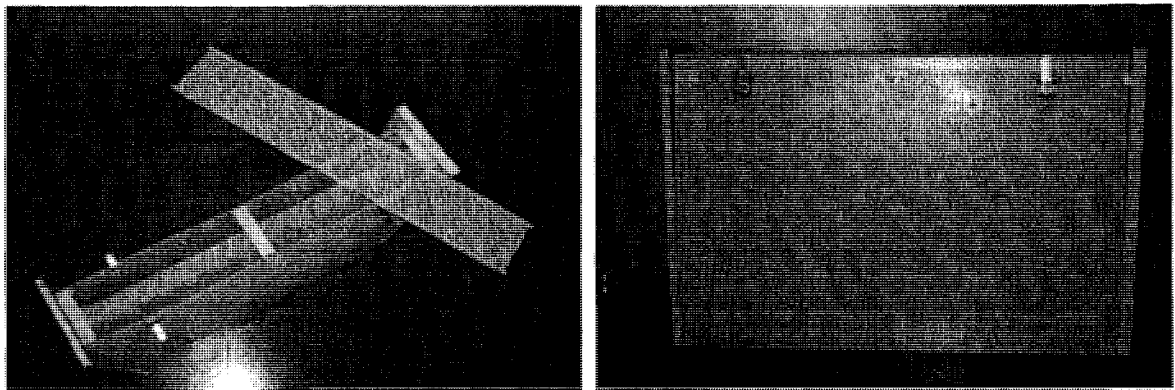
Figure 4- 1   Perforated module used as filter holder

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[4] Face area enlargement is a dimensionless parameter and defined as:
(Filter air-face Surface [A]/Duct cross section Area [A])

Table 4- 1   Media characteristics and properties[5]

Characters / Media	Activated Carbon (%)	Impregnated by	Apparent Density (gr/cm^3)	Shape	Particle Diameter (mm)	Hardness (minimum) (wt %)	Moisture (maximum) (wt %)
VA	100 coconut shell base	N/A	0.48	Chips	4x8 mesh	95	2
VB	100 bituminous Coal base	N/A	0.48	Pellet	3	95	2
IC	90-95 bituminous coal base	1-2% Potassium Hydroxide	0.56	Pellet	3	95	15
IAA	0 Activated Carbon 75-85 Aluminum Oxide	4% Potassium Permanganate	0.88	Spherical Pellet	3.2	N/A	22

[5] Media characteristics and properties were provided by the supporter of this study.

4.3 EXPERIMENTAL TEST METHOD

The objective of this research is to develop an experimental method to determine the VOC removal efficiency and capacity of full-scale (61x61 cm^2) gaseous air cleaners. For this purpose, the full-scale test set-up was used to implement the removal tests. This measuring technique consists of three main phases;

1. Pressure drop measurement

2. Adsorption efficiency and capacity measurement

3. Desorption and retentivity determination

Before introducing the challenge gas inside the system, the created pressure drop by the removal media was measured at different airflow rates. In the next step, the contaminated stream was introduced to the system and the concentration before and after the filter were measured. When the removal efficiency of the scrubber dropped to 30%, the injection was stopped and the desorption phase was launched. More details about each phase are explained in the following sections.

4.3.1 Phase 1: Pressure Drop Analysis

The pressure drop created by the air cleaner inside the mechanical ventilation system is principle information for HVAC designers. It directly affects the fan capacity requirement and energy consumption of the ventilation system. At typical air velocity in ventilation system, the air cleaning devices should produce a pressure drop not exceeding around 100 Pa (0.4 in. H_2O) (Holmberg et al. 1993). To obtain these data, for each

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removal media, the pressure drop measurement was conducted at six different flow rates 0.2, 0.4, 0.5, 0.6, 0.7 and 0.9 m^3/s [500, 750, 1000, 1250, 1500 and 2000 cfm]. All filled modules were installed inside the duct and then fully sealed. The sealing was done by aluminum sealing tape and all connections between the edges of modules and duct interior surfaces and between two modules were sealed. Hence, the bed was gap free and there was no by-pass for the air around the removal bed after the sealing. Therefore, the determined pressure drop was created only by the removal media and media holders. To conduct the measurement, two pressure taps were mounted before and after the removal bed zone inside the duct (Point H-3 and H-4 in Figure 3- 1) and connected to the pressure transmitter (Cuba control pressure difference transmitter type-694). The results for filter VA is shown in Figure 4- 2.
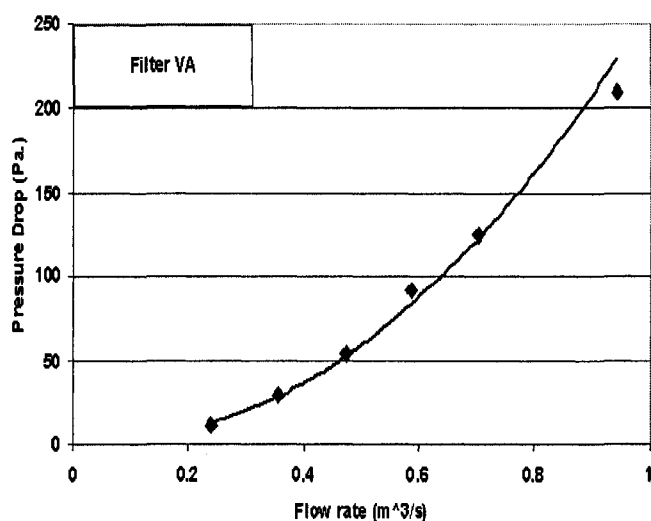
Figure 4- 2 Pressure drop analysis of filter VA

4.3.2 Phase 2: Adsorption Efficiency and Capacity Measurement

Conducting the pressure drop analysis test preconditioned the removal bed with the same test conditions (room air relative humidity and temperature) for more than 6 hours. Prior to the introduction of challenge gas (toluene) to the system, the background concentration of the system was measured for 1 hour. Also, this pre-measuring period was used to stabilize the air flow rate. All the experiments were carried out at 0.89 m^3/s [1900 cfm] airflow rate which provide an air velocity of 2.4 m/s (typical airflow rate in mechanical ventilation system is between 2-3 m/s). To measure the adsorption efficiency of removal media, toluene was introduced to the system. The bubbler air flow for generating the challenge gas was adjusted to introduce 4 ± 0.1 ppm concentration of toluene to the tested filter. The toluene concentration before and after the removal media were measured continuously every two minutes. Also, the temperature and relative humidity of the air stream inside the duct were measured every five minutes at both upstream and downstream measuring points, as well as the pressure drop across the filter. The injection was halted when the performance of filter dropped to less than 30%. Figure 4- 3 shows the upstream and the downstream concentration profiles for filter VA during adsorption phase.

The arithmetic average of upstream concentration and its 95% confidence was 4.08 ± 0.01 for whole adsorption phase duration of the test. This shows the consistency of the generation system. To provide a constant upstream concentration by bubbling generation system, the liquid level inside the containers (Figure 3- 3) was controlled and kept in a given range. Therefore, both bottles were refilled every 24 hours of injection. The weight

of toluene was measured by a balance (OHAUS Corporation CHAMP II) before and after

refilling the bottles. Hence, the injected toluene was measured for each test.
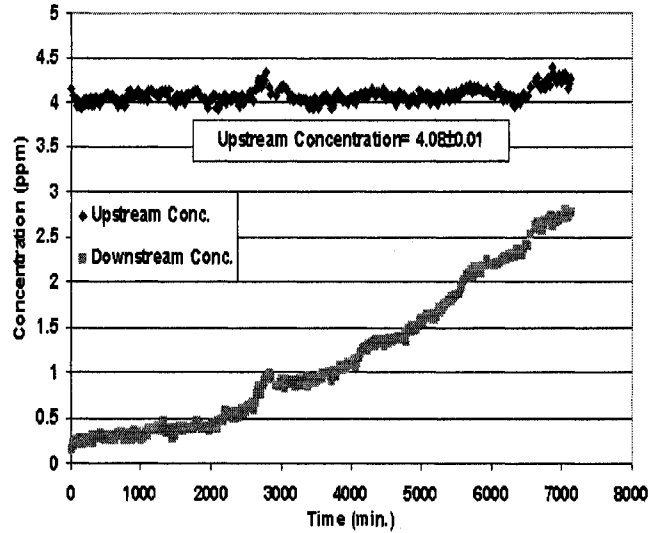
Figure 4- 3   Adsorption upstream and downstream concentration profile of filter VA

From the upstream and downstream concentrations of the filter during adsorption phase,

penetration (or breakthrough), removal efficiency and capacity of gaseous air cleaners

were calculated. Contaminant penetration at each time step was calculated by the ratio of

downstream concentration to the upstream.

$$P_t = \frac{C_{down,t}}{C_{up,t}}$$ (4- 1)

where,

P_t= contaminant penetration at time t

t= time (min)

$C_{up,\,t}$ = upstream concentration at time t (ppm)

$C_{down,\,t}$ = downstream concentration at time t (ppm)

The breakthrough curve is a plot of contaminant penetration versus elapsed time. The breakthrough curve obtained from the concentration profiles of filter VA is presented in Figure 4- 4. Since only one gas-detector was used in this study, both upstream and downstream concentration could not be measured simultaneously. The time-wise identical upstream concentration was calculated by applying linear interpolation.
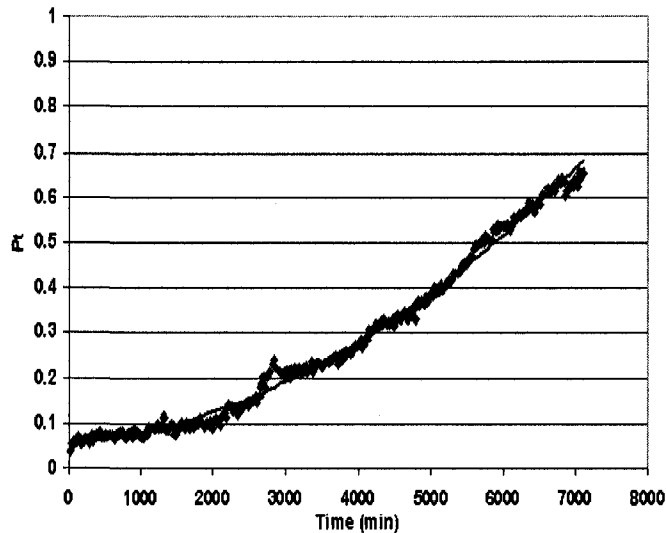
Figure 4- 4   Breakthrough curve of filter VA

The breakthrough time is the time duration from the beginning of the test in which the contaminant penetration reaches the specified amount. The percentile difference of upstream and downstream concentration over the upstream concentration is known as the

filter efficiency. It expresses the relative amount of challenge gas that removed by the filter in comparison with the amount that introduced to the filter at that time. The efficiency curve shows the filter efficiency profile versus the test elapsed time. As time passes and more adsorption sites are occupied by the contaminant, the filter efficiency decreases. Equation (4-2) was used to calculate the filter efficiency at each time.

$$E_t = \left(\frac{C_{up,t} - C_{down,t}}{C_{up,t}} \right) \times 100\% = (1 - P_t) \times 100\% \qquad (4\text{-}2)$$

where, E_t is efficiency at time t (%).

The removal efficiency profile of filter VA is shown in Figure 4- 5. To analyze the removal performance of filter in this research $t_{50\%}$ (min), the elapsed time for each media to reduce its performance to 50%, is used.
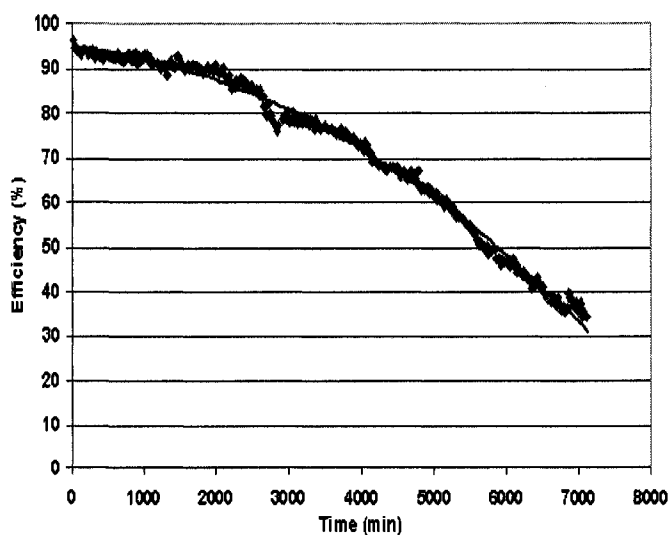
Figure 4- 5   Removal efficiency of filter VA

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The other concept for evaluating gaseous filters is the removal capacity which is expressed as the percentile fraction of total adsorbed mass of challenge gas over the removal media weight. For specified elapsed time of the test, the filter capacity can be calculated as follow;

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

where C_T is the filter capacity after specified elapsed time of the test, T_{ads} is the elapsed time, Q is the air flow rate, $C_{up}(t)$ and $C_{down}(t)$ are the upstream concentration and downstream concentration as a function of elapsed time, and M_{media} is the mass of removal media. The ASHRAE proposal 145.2 (2007-c) recommends the 50% breakthrough time as the specified elapsed time for determining the capacity. This definition results to calculation of 50% capacity (filter capacity at 50% efficiency) of the filter. For this purpose, T_{ads} in Equation (4-3) is equal to the required elapsed time for the penetration (Equation (4-1)) to reach 0.5.

4.3.3 Phase 3: Desorption and Retentivity Determination

Once the removal efficiency reached about 30%, the challenge gas injection was terminated and the third phase of the test was launched. The pure air was passed through the loaded filter. Hence, the removal bed unloads the adsorbed VOC to the air stream. This procedure is called desorption. When the air stream has a lower concentration than the filter, desorption process will be inevitable, thus the filter acts as a source of contaminant.

Desorption test was conducted in the same air flow rate of adsorption for each experiment. Also, the upstream and downstream concentrations were measured at the same time interval as adsorption phase. Figure 4- 6 shows the upstream and downstream concentration profile for the adsorption and desorption phases of filter VA together.
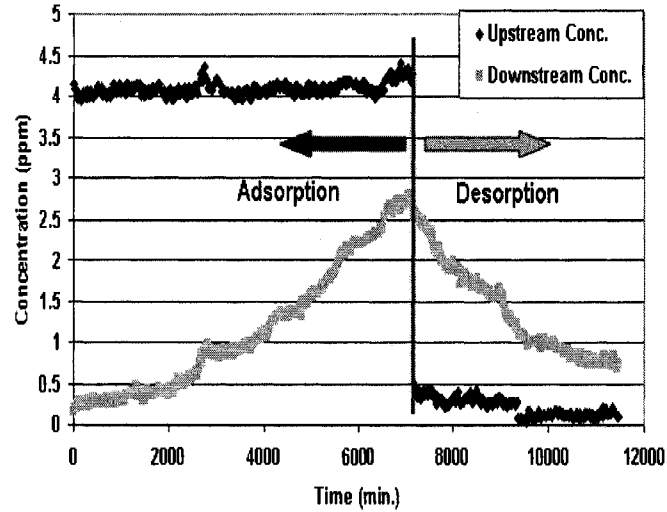
Figure 4- 6 Upstream and downstream concentration profile for the adsorption and desorption test: filter VA

Retentivity presents the resistance of adsorbent against sweeping off the adsorbed molecules. It is the percentile fraction of retained adsorbed mass over the removal media mass during the purging of the filter with pure air. To measure the retentivity, the following equation has been used.

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

where $R_{t'}$ is the retentivity (% weight), $C_{adsorption}$ is the total computed capacity of the media after adsorption phase, t' is the elapsed time of desorption test, Q is the airflow rate, M_{media} is the media mass, and $C_{up}(t)$ and $C_{down}(t)$ are the upstream and downstream concentration profiles for the whole desorption phase duration, respectively. Figure 4- 7 presents the capacity and the retentivity profile of filter VA.
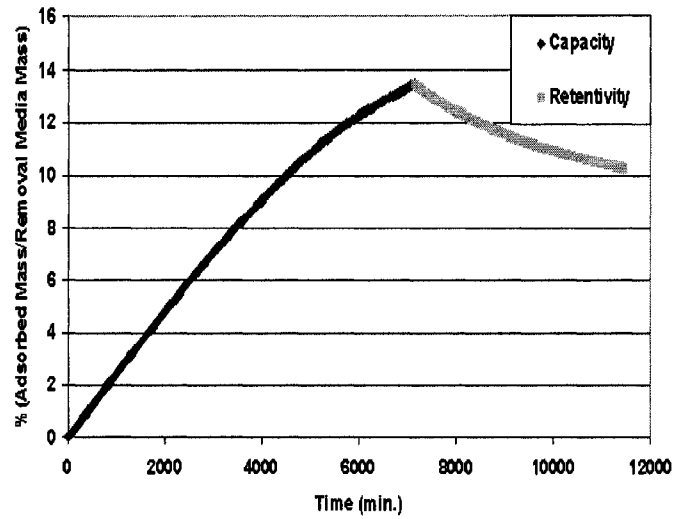
Figure 4- 7   Capacity and retentivity of filter VA

To properly explain the resistance of filter against off-gassing, a new analysis method was developed in this study. The retentivity was described as a fraction of total computed capacity as follow:

$$F_{R,t'} = \frac{R_{t'}}{C_{adsorption}} \times 100\%$$

(4- 5)

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$F_{R, t'}$ is the percentile retentivity fraction of the total computed capacity at elapsed time t' of desorption phase. This parameter shows the desorbed fraction of total adsorbed contaminant during desorption. Figure 4- 8 shows $F_{R, t'}$ of GAC VA.
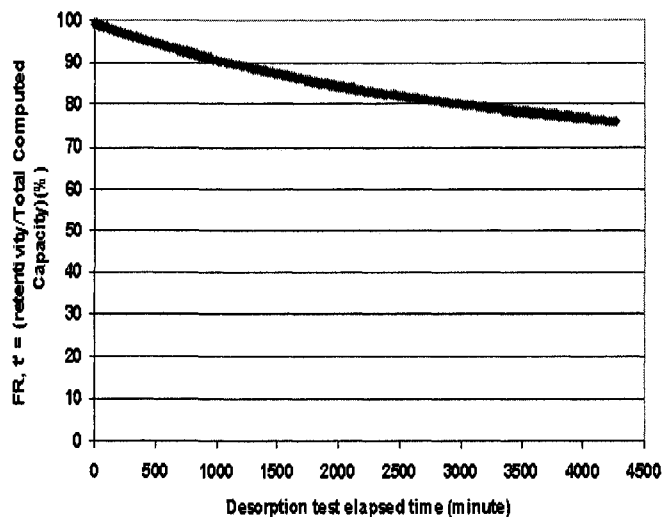
Figure 4- 8   Percentile retentivity fraction of total computed capacity: filter VA

$F_{R, t'}$ at two periods was used for cross-comparison of resistance against desorption among the tested filters. The primary period was after 120 minutes (2 h) of starting desorption test (t'=120 min) and secondary period was after 720 minutes (12 h) (t'=720 min). These calculated $F_{R, t'}$ show the percentile adsorbed toluene lost by the filter after these two periods of desorption.

CHAPTER 5 FILTER RANKING TEST RESULTS AND DISCUSSION

5.1 INTRODUCTION

The developed method for determining the efficiency and capacity of gaseous air cleaning devices was evaluated by conducting experiments for four commercially available gaseous filters. These filters are two GAC, one impregnated GAC and a half-half (by the volume) blend of GAC and impregnated activated alumina. They were provided by a manufacturer filled in four identical modules (Figure 4- 1). The total mass of these filters was not identical due to their different structure and material; Table 5- 1. Each filter was challenged by a 0.89 m^3/s [1900 cfm] airflow rate containing toluene up to 4.0±0.1 ppm concentration and the adsorption process was assessed by monitoring toluene concentration before and after the filter. This adsorption phase was continued until the removal efficiency of the tested filter reduced to 30%. Thereafter, the toluene injection was terminated and desorption test was conducted.

In this chapter, the outcomes of developed technique are explained for each test. Also, the results were applied to rank the tested filters in the order of their effectiveness.

Table 5- 1   Tested filter total mass

Test Name	Tested Filter	Filter Mass (kg)
A-1	VA	30.450
A-2	VA	30.686
B-1	VB	31.510
C-1	IC	33.095
D-1	50/50 IAA-VB	45.130

5.2 PRESSURE DROP ANALYSIS

The pressure drop measurements for all filters were carried out at six different flow rates

(i.e., 0.2, 0.4, 0.5, 0.6, 0.7 and 0.9 m³/s) as mentioned in Chapter 4. To check the

repeatability, the test with VA was conducted twice and the results are presented in

Figure 5- 1. It shows that test A-2 replicated the results of test A-1. Also, the created

pressure drop for all tested filters is depicted in Figure 5- 2. As mentioned in chapter 4,

the filter should create a pressure drop less than 100 Pa [0.4 in. H_2O] at typical air

velocity to accommodate gaseous filters without significant modification of mechanical

ventilation system. This velocity was provided by 0.90 m³/s [2000 cfm] airflow rate

inside the duct. None of these filters satisfied the criteria and all of them created more

than 200 Pa [0.8 in. H_2O] pressure drop at 0.90 m³/s. Holmberg et al. (1993) studied the

pressure drop created by four filters including two GAC. They conducted the test in a

duct with the same dimension as this present research. Also, the GAC was packed in V-

shape modules as well. According to their results while the foam bed filter and cylinder

bed filter presented acceptable pressure drop, the GAC bed had a pressure drop more than

200 Pa.
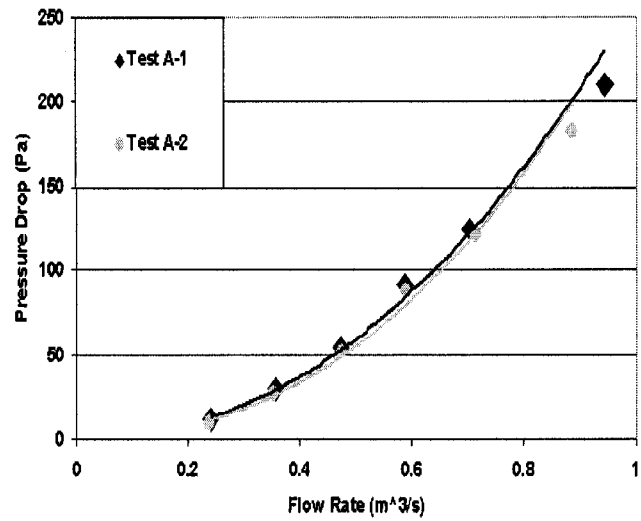
Figure 5- 1   Filter pressure drop repeatability test with VA (Test A-1 and A-2)
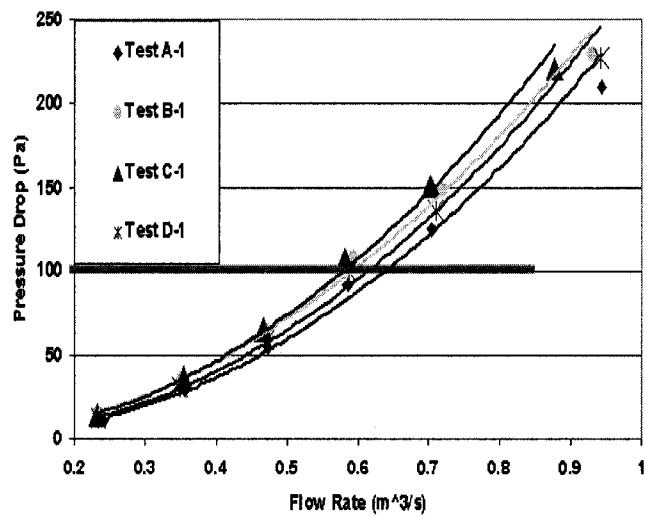
Figure 5- 2   Pressure drop of all tested filters

5.3 METHOD QUALITY CONTROL

5.3.1 Adsorption Test Repeatability

To evaluate the repeatability of the developed method, VA was tested twice in the identical conditions (test A-1 and A-2). The upstream and downstream concentration profiles of these tests are shown in Figure 5- 3. Figure 5- 4 shows the efficiency profile of these tests. The obtained efficiency profile from both tests describes similar results. The 50% breakthrough time, which is the time required to reach 50% efficiency, was 5642 minutes for test A-1 and 5712 minutes for test A-2. The discrepancy is less than 2%.
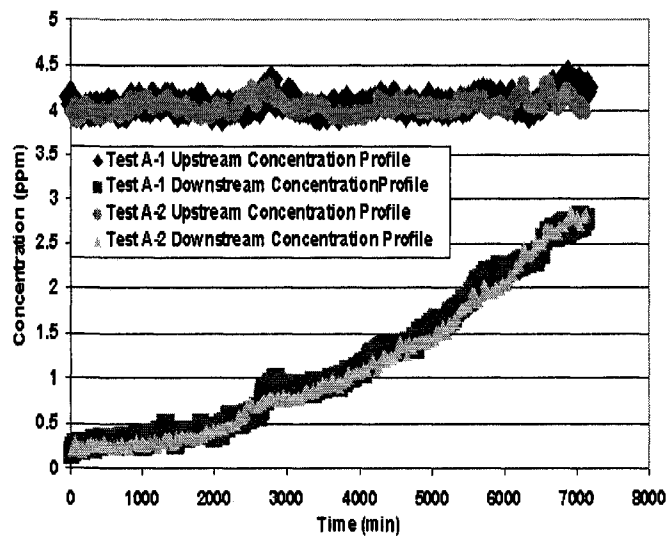
Figure 5- 3   Upstream and downstream concentration profile of tests A-1 and A-2
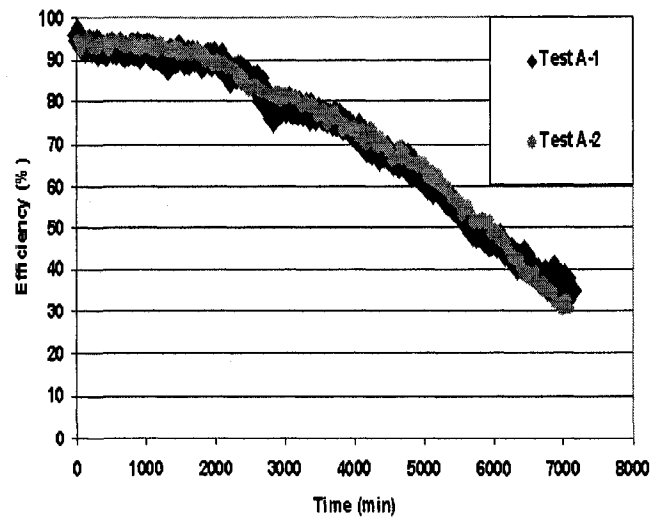
Figure 5- 4 Repeatability evaluation for GAC type A (test A-1 and A-2)

Moreover, the capacity profile of VA is replicated and it is presented in Figure 5- 5 (a).

The 50% capacity of test A-1 and A-2 are 11.80 and 11.75, respectively; Figure 5- 5 (b).

The error in 50% capacity is less than 0.5%, which is much less than the limit proposed

by the ASHRAE draft 145.2 (i.e., ±10% agreement) (ASHRAE 2007-c).
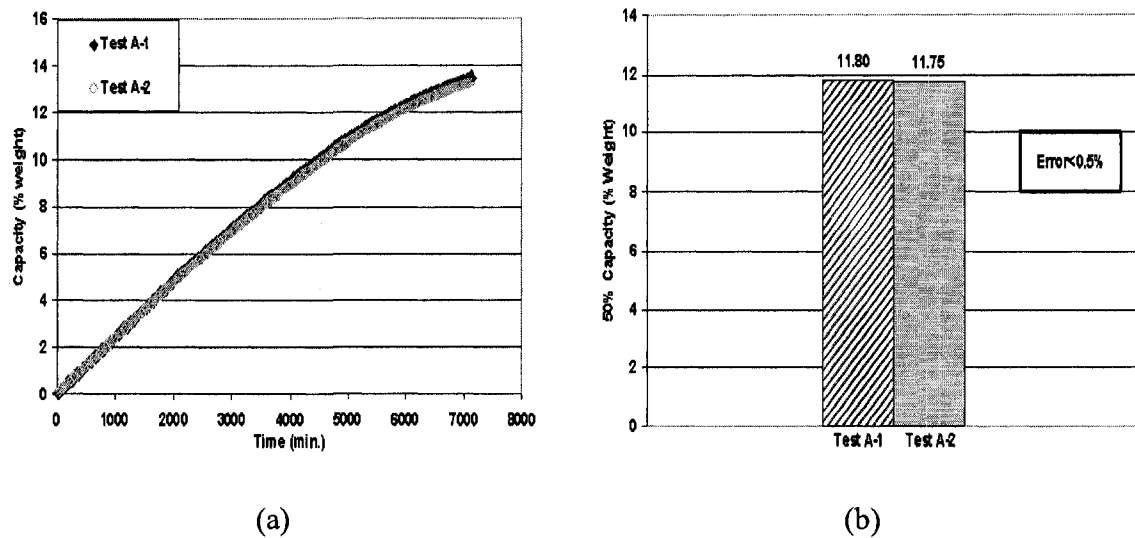
Figure 5- 5   Test A-1 and A-2 (a) capacity profile (b) 50% capacity

5.3.2 Test Conditions Stability

The test should be conducted in a consistent challenge air stream conditions. Hence, temperature and relative humidity in both upstream and downstream zones were recorded to demonstrate the consistency of these conditions during the tests. Furthermore, the stability of blown air in duct and its challenged gas concentration in upstream of the filter were investigated for the whole test duration. These test conditions with their mean average, standard deviation and 95 % confidence of the recorded samples are presented in Table 5- 2.

Table 5- 2 Test conditions

Test Name / Conditions	A-1	A-2	B-1	C-1	D-1
Flow rate (m³/s)	0.89	0.88	0.89	0.88	0.87
STDEV *	0.02	0.01	0.01	0.03	0.02
95% Confidence	$6.13 \, e^{-4}$	$6.61 \, e^{-4}$	$6.13 \, e^{-4}$	$1.89 \, e^{-3}$	$1.27 \, e^{-3}$
CV ** (%)	2.2	1.1	1.1	3.4	2.3
Upstream Concentration (ppm)	4.08	4.05	4.00	4.08	3.92
STDEV *	0.1	0.1	0.19	0.19	0.18
95% Confidence	0.01	0.01	0.01	0.01	0.02
CV ** (%)	2.54	2.45	4.86	4.66	4.59
Upstream RH (%)	22.38	27.98	33.51	28.22	28.36
STDEV *	3.54	2.17	3.82	2.30	2.80
95% Confidence	0.14	0.08	0.12	0.12	0.16
Downstream RH (%)	22.30	27.77	33.67	28.01	28.20
STDEV *	3.45	2.20	3.97	2.36	2.99
95% Confidence	0.14	0.08	0.12	0.12	0.17
Upstream Temperature (°C)	26.57	26.67	25.80	27.00	27.00
STDEV *	0.34	0.24	0.87	0.34	0.48
95% Confidence	0.01	0.01	0.03	0.02	0.03
Downstream Temperature (°C)	26.85	26.95	26.05	27.28	27.28
STDEV *	0.34	0.24	0.97	0.33	0.47
95% Confidence	0.01	0.01	0.03	0.02	0.03

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

The tabulated results in Table 5- 2 imply consistent flow through the duct in all tests. The ASHRAE draft (2007-c) proposes the requirement of ±5% variation for the airflow rate. This criterion was satisfied in all five tests with gaseous air removal devices in this study. According to the calculated CV, the maximum deviation from the arithmetic mean flow rate was less than 4% for each test.

Constant generation of toluene inside the test rig, furthermore, was verified by Table 5- 2. The deviation from mean upstream concentration was less than 5 % for all tests which has coincidence with the ASHRAE draft 145.2 (2007-c) recommendation.

For temperature and relative humidity, the ASHRAE proposal is 25±2 °C and 50%±5%, respectively (ASHRAE 2007-c). In this study, the humidifier was working during the test to keep the relative humidity of air stream at the given amount. Thus, the air stream was heated up and as a limitation of the test rig; it was not possible to cool down the blown air to that specified temperature. Therefore, the temperature was in the range of 25-27 ° C and it was stable in both upstream and downstream of the filter as reflected in Table 5- 2.

Despite the fact that the humidifier of the system was working for the whole test duration at a set point of 50%, except for the test B-1, the relative humidity level was rarely more than 30%. To avoid condensation on the wall and window surfaces, the humidity level of the indoor space is kept lower throughout the cold seasons and specifically in the region with cold climate such as Canada. Thus, the air supplied to the laboratory was not humidified and the relative humidity was always below 20% during the ranking test periods. At 26°C, to increase the relative humidity from 20% to 50% in air with 1900 cfm airflow rate, it is required to introduce 24.6 kg/h of water (calculated from ASHRAE Psychometric chart No. 1 (ASHRAE 2005)). Since the capacity of the humidifier installed in the test system was not sufficient, tests were done at about 30% relative humidity. Also, based on previous studies, the impact of relative humidity less than 50% on removal performance of GAC is negligible (Nelson et al. 1976, Owen et al. 1995), hence; this discrepancy between ASHRAE proposal (2007-c) and proposed method in this study is reasonable. Consistency of relative humidity during the test period has to be emphasized based on the results tabulated in Table 5- 2.

5.3.3 Ranking Test Results

The developed method was applied to determine the removal efficiency and capacity of four commercial gaseous cleaning devices and to verify the applicability of the technique. The outcome results of these tests were used to rank them based on their capability to remove toluene.

<u>Efficiency and 50% Capacity:</u>

By applying Equation 4-2 and measuring the upstream and downstream concentration, the removal efficiency of each filter was calculated. Figure 5- 6 reflects the efficiency profile of all tested filters versus the elapsed time. It implies that the filter with higher percentage of activated carbon had better removal performance for toluene. GAC VA and VB with 100% activated carbon (Table 4- 1) had higher initial efficiency and higher 50% breakthrough time than the other two filters. The impregnation of activated carbon with a base compound (IC is the activated carbon impregnated with KOH) blocks some pores by placing alkali on the surface of the activated carbon (Kim et al. 2006). Therefore, the surface area and active sites for VOC adsorption decrease. While it took 5642 minutes and 3410 minutes for VA and VB to reach their 50% performance, respectively; the removal efficiency of IC and the 50/50 IAA-VB reduced to 50% after 2004 minutes and 1788 minutes, respectively. In addition, 50% removal capacity of IC was 27% and 50/50 IAA-VB was 17% of VA capacity for toluene. The 50% breakthrough time and 50% removal capacity of all filters are shown in Figure 5- 7 and Figure 5- 8, respectively. Overall, the tested filters are ranked as; VA>VB>IC>50/50 IAA-VB based on their toluene removal efficiency and capacity.
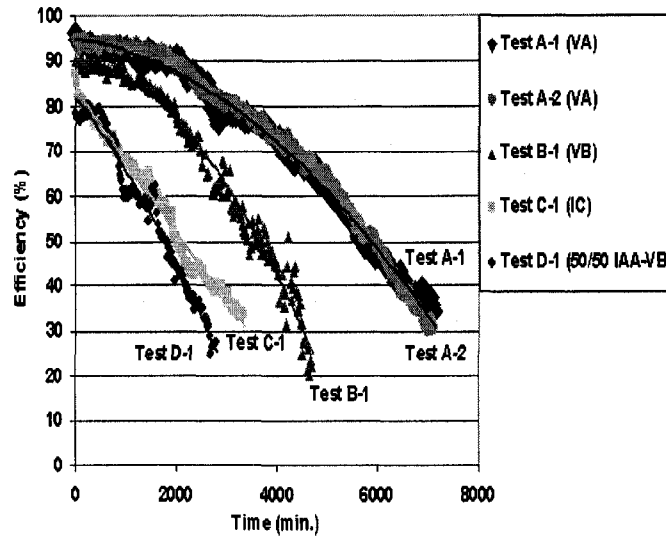
Figure 5- 6   Filter removal efficiency for each test

Filter 50/50 IAA-VB exhibited the worst performance and lowest capacity in removing

toluene. IAA is activated alumina impregnated with potassium permanganate which is

used for removing acidic gases such as hydrogen sulfide and sulfur dioxide and not

suitable for VOCs. Chen et al (1989) compared the removal performance of activated

alumina with GAC and the results show that the capacity of GAC is much higher than

activated alumina for removing VOC. Also, Muller and England (1995) studied the

breakthrough time and capacity of GAC, activated alumina impregnated with potassium

permanganate and 50/50 blended of these two media. They concluded that the

breakthrough time of the blended filter was half of the single GAC in removing organic

compound. Also, the single impregnated activated alumina has low removal capacity for

toluene. However, the blended filter had better performance in cleaning the acidic

gaseous than the single GAC and better performance in removing organic compounds

than the single impregnated activated alumina. Thus, the blended filter could be applied

for controlling a larger number of contaminants than the single filter (Muller and England 1995).

Although both VA and VB are virgin activated carbon, VA had a better efficiency in removing toluene and its capacity is almost twice the VB. This discrepancy may stem from the difference in their raw material. GAC VA has coconut shell based which has mainly micropores and has a small mean pore size while the bituminous coal based activated carbon (VB) has a larger mean pore size (Chiang et al. 2001). Indeed, the major adsorption of low molecular weight VOCs such as toluene occurs in micropores of activated carbon. Therefore, a higher removal capacity for toluene in coconut shell-based GAC (GAC VA) was expected.
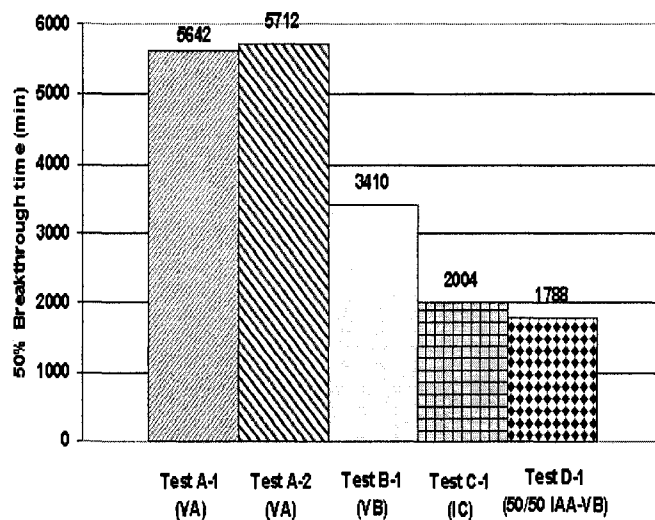
Figure 5- 7   50% breakthrough time of tested filters
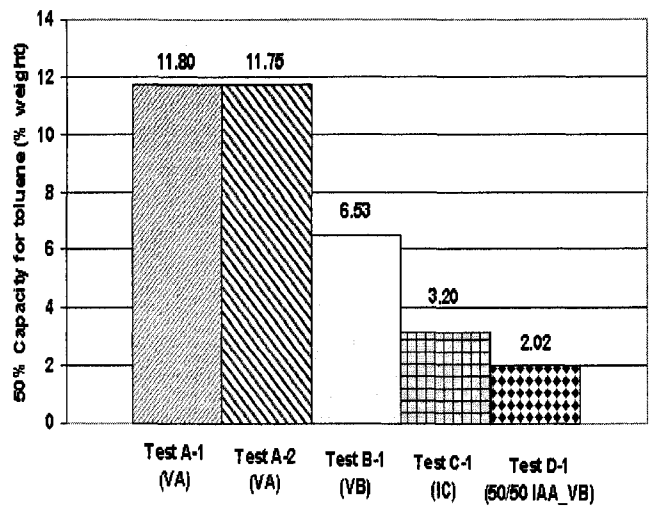
Figure 5- 8   50% removal capacity of tested filters

Desorption and Retentivity:

The resistance of the filter against desorption was studied by measuring the effluent of

filters after termination of challenge gas injection. The downstream concentration of each

filter was monitored for a period of more than 50% of total adsorption test duration, while

the pure air passed through the filter in desorption phase of the test. By applying Equation

4-4, the percentile retained contaminant fraction of removal bed mass was calculated for

whole duration of desorption phase in each test. Figure 5- 9 shows the capacity and

retentivity profile of all tested filters. The retentivity of each filter after a desorption

period equal to half of the total adsorption test duration, was compared with the capacity

of the filter after the same period and tabulated in Table 5- 3. All of the tested filters had

a retentivity higher than capacity at that specified period due to the resistance of the

filters against the off-gassing.

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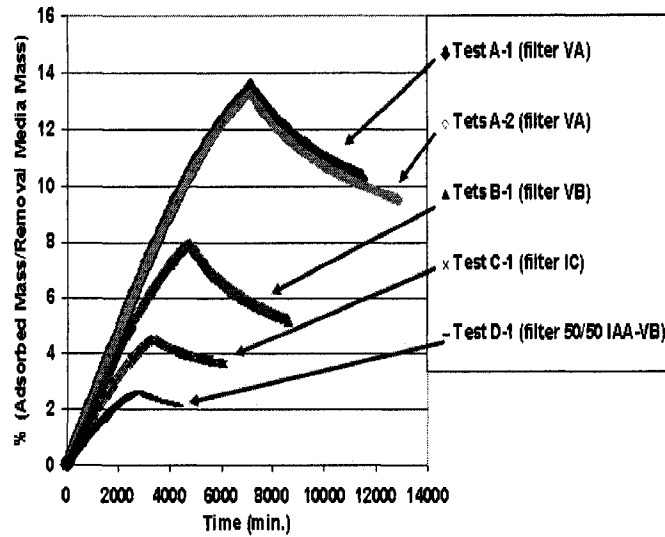
Figure 5- 9   Capacity and retentivity profiles for all filters

For cross-comparison of the retentivity between the tested filters, the percentile retentivity fraction of total computed capacity ($F_{R,\,t}$) was determined at two periods by applying Equation 4-5. The primary period was after 120 minutes (2 h) which is recommended by the ASHRAE proposal (2007-c) as desorption test duration. The secondary period was after 720 minutes (12 h). This period is almost equal to the time duration in which the ventilation system of the office buildings is shut down[6]. Thus, the resistance of the filters could be analyzed for a longer period. The calculated data are presented in Table 5- 3. It shows that all filters lost less than 2% of their adsorbed toluene during the two-hour purging with clean air except 50/50 IAA-VB (it lost 5% of the adsorbed toluene). Therefore, 50/50 IAA-VB had the least resistance against desorption during the first two hours. The other filters performed almost the same as each other.

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[6] Generally, the ventilation rate is reduced or shut down after the working hours in office buildings. Thus, the accommodated filter in the HVAC system starts to desorb the adsorbed contaminant to the room air and acts as a source of contaminant.

Table 5- 3   Retentivity comparison

Test	A-1	A-2	B-1	C-1	D-1
Total Adsorption Time Duration (min.)	7152	7128	4744	3376	2812
50% of Total Adsorption Time Duration (min.)	3576	3564	2372	1688	1406
Total Computed Capacity (%)	13.49	13.26	7.91	4.57	2.66
Capacity After 50% of Total Adsorption Time Duration (%)	8.20	8.14	4.87	2.78	1.67
Retentivity After 50% of Total Adsorption Time Duration (%)	10.52	10.27	5.85	3.86	2.14
Retentivity After 120 Minutes (Two Hours)	13.27	13.02	7.79	4.49	2.54
$F_{R,t'}$ **After 120 minutes (2 h) of the desorption test (%)**	98	98	98	98	95
$F_{R,t'}$ **After 720 minutes (12 h) of the desorption test (%)**	93	93	88	90	88

However, by continuing desorption test; the filters did not present the same resistance against desorption; $F_{R,t'}$ was not equal in different filters. Figure 5- 10 present $F_{R,t'}$ of the tested filter during their desorption process. It shows that the resistance of filter VA against desorption was stronger than the others. Chiang et al. (2001) studied the adsorbate-adsorbent interaction energy in coconut shell based GAC and bituminous coal based GAC. They concluded that this energy is higher in coconut shell based GAC due to its microporosity, hence; the adsorbate molecule is attached to the adsorbent by a stronger bond. Therefore, the higher resistance against desorption is expected for this filter. It lost 7% of its adsorbed toluene after 12 hours. However, the others desorbed 10% and more of the adsorbed toluene. Also, both filters VB and 50/50 IAA-VB showed the same resistance against desorption. Toluene was dominantly adsorbed and desorbed by VB in filter 50/50 IAA-VB and the amount adsorbed by IAA was negligible. Thus, the percentile desorbed toluene in both filters should be the same. They both desorbed 12%

of their total adsorbed toluene after 12 hours. Filter IC exhibited higher resistance than

VB which was a virgin GAC. This can be attributed to the possibility of chemical

reactions occurred in this impregnated filter with KOH. Desorption of chemically reacted

toluene needs an elevated temperature to overwhelm the chemical bond between toluene

and filter.
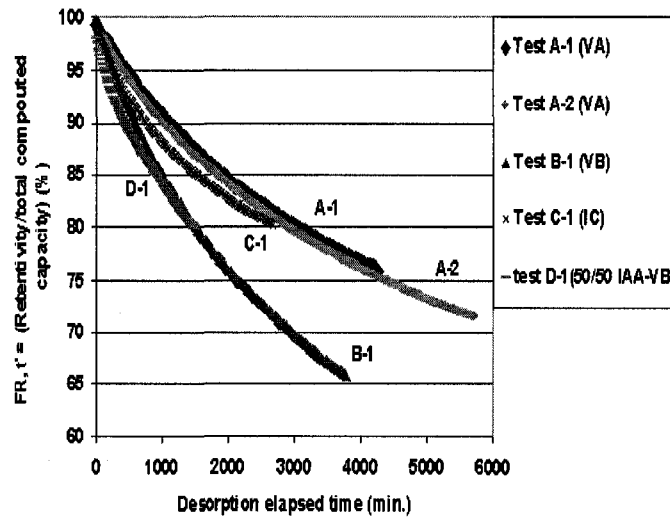
Figure 5- 10   Percentile retentivity fraction of total computed capacity versus desorption
time

CHAPTER 6 CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORK

6.1 CONCLUSIONS

The objective of the present research was to develop an experimental full-scale set-up to quantitatively evaluate the removal performance of gaseous air cleaners for application in building mechanical ventilation system. The strong attention was paid to the sorptive filters and controlling the level of VOC in indoors. The method provides HVAC designers with a better understanding of the removal efficiency and the useful life time of these filters.

To achieve the objective of this study, a full-scale setup was designed to simulate a building HVAC system. This test apparatus provided the removal performance-assessment of 61cm*61cm [24"*24"] commercially available gaseous filters. Thus, the chemical agent was introduced to the system by the contaminant generation system and the removal efficiency of the tested filters was determined. Furthermore, the test apparatus performance was qualified by carrying out the system qualification tests. These tests were designed to calibrate the system and quantitatively verify the reliability of the outcomes of the experiments. According to the results of these pre-qualification tests:

- The air stream passed through the filter had a uniform velocity over the entire duct cross section area.

- The introduced contaminant dispersed uniformly in the upstream of the tested filter. Thus, the upstream sample took from the center of the duct cross section

was an acceptable representative for upstream measurement. In addition, the entire surface area of the filter challenged with an identical concentration of gaseous contaminant and the performance of all sections of the filter deteriorated identically.

- Contaminant penetrated through the filter was fully mixed and its concentration was uniformly dispersed in the downstream of the filter. Therefore, the one point sampling from the center of the duct cross section area accurately represented the downstream concentration of the filter.

As the test setup had been calibrated, an experimental method was developed to completely study the performance of a gaseous filter in three main phases; its pressure drop, removal efficiency and retentivity. This method was applied to study the performance of four granular filters (include two virgin GAC, one impregnated GAC and one 50/50 (by volume) blend of GAC and Impregnated activated alumina) to verify the applicability of the developed method.

The resistance of these filters against airflow was characterized by measuring their pressure drop for a range of airflow rates. All filters created a higher pressure drop than the recommended pressure drop at typical airflow rates in mechanical ventilation system which supports the result of the previous study for granular filters (Holmberg et al. 1993).

Thereafter, to rank the performance of the filters, their efficiency and capacity for removing toluene at 4.0±0.1 ppm concentration was determined. Throughout all the

experiments the quality of the method was controlled. Thus, the conducted experiments showed:

- The repeatability of the developed experimental method was verified. The results stemmed from the two tests with the same conditions had coincidence. The determined 50% breakthrough time of the filter VA in both tests had less than 2% difference. Also, its 50% capacity measured in the second test changed less than 0.5%. It satisfied the criterion recommended in the ASHRAE proposal (2007-c).

- The air stream inside the duct had consistent conditions for the whole test period which for some filters it was around one week. The deviations from mean average of air stream flow rate and challenge gas concentration were in agreement with the ASHRAE proposal (2007-c).

- All tests were conducted in the environmental conditions similar to the application conditions of gaseous filters in cold climate regions such as Canada. The measured temperature and relative humidity proved the consistency of these conditions for the whole test duration.

- Virgin GAC showed better performance in removing toluene than two other tested filters.

- The impregnation of GAC with KOH blocked some pores by placing alkali on the surface of GAC (Kim et al. 2006). Thus, some active sites were not accessible and the removal capacity of GAC was reduced. As expected, the 50% capacity of impregnated GAC was half of the virgin one with bituminous coal base.

- As half of the volume of the bituminous coal base GAC filter was replaced with impregnated activated alumina (filter IAA), the 50% breakthrough time was reduced 48%. This indicates that the removal capacity of activated alumina for VOC is much lower than GAC. This drastic reduction in the performance of the filter was also observed by Muller and England (1995).

- The raw material which the GAC is made of, affects the removal performance of the filter. The coconut shell base GAC has a smaller mean pore size than the bituminous coal base GAC (Chiang et al. 2001). Thus, the higher removal capacity of the coconut shell base GAC for low molecular weight VOC such as toluene was expected. The measured 50% capacity of bituminous coal base GAC (VB) was 45% less than the coconut shell base one (VA).

- By applying the developed method, the tested filters were ranked based on their removal performance as follow: VA>VB>IC>50/50 IAA-VB. Thus, the developed experimental method could accurately study the efficiency and capacity of gaseous filters and provide the HVAC engineer with the data needed to design the filters for building application.

The resistance of the tested filters against desorption was characterized by measuring the retentivity of the filters after desorption period equal to half of the total adsorption test duration and compared with the capacity of the filter after the same period. Also, a novel method was developed for cross-comparison of the retentivity among the filters. The percentile retentivity fraction of total computed capacity ($F_{R, t}$) of each filter was calculated to present the desorbed fraction of total adsorbed toluene during desorption

and used for cross-comparison. This parameter was analyzed at two periods; primary and secondary. The primary period was two hours after stating desorption test and the secondary period was after 12 hours. The retentivity analysis concluded;

- All tested filters showed resistance against the off-gassing during desorption process due to the Van der Waals forces holding toluene to the filters.

- Filter VA (coconut shell based GAC) had the strongest resistance against desorption. The adsorbate-adsorbent interaction energy in a coconut shell based GAC is higher than a bituminous coal based GAC (Chiang et al. 2001). This energy directly relates to the strength of bonding between adsorbate and adsorbent. Thus, higher resistance against desorption is expected for coconut shell based GAC.

- Impregnated GAC with KOH had a stronger resistance against desorption than the virgin one due to the possibility of chemical reactions occurring in this filter.

6.2 RECOMMENDATIONS FOR FUTURE WORK

The recommended future research work on gaseous filter performance assessment follows from the advancements and limitations of the present study:

- The method should be applied to investigate the effect of environmental parameters such as temperature and relative humidity on the removal performance of gaseous filters. The removal performance of sorptive filters is a function of environmental conditions (Mahajan 1987). Owen et al (1995) pointed out while relative humidity has negligible effect under 50%, the performance of GAC

significantly decreases by increasing the relative humidity form 50% to 70%. Nevertheless, the mentioned study was carried out in small-scale system with its own limitations.

- The full-scale method has the ability to assess the performance of other types of gaseous filters such as carbon cloth and bonded carbon panel. Thus, the method should be applied to investigate the removal performance of these types of gaseous filters.

- The generation system should be improved to be applicable for a mixture compound generation. This improvement makes it possible to investigate the effect of mixture of gaseous compounds on the performance of gaseous filters.

- As a progressive step, a mathematical model should be developed based on transfer phenomena inside the filter to investigate the performance of gaseous filter for building application less costly and more flexibly.

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