The Impact of Garage – House Interface Leakage on Contaminant Transport

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ABSTRACT

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Many contaminants such as carbon monoxide, benzene, toluene and ethyl benzene in the living area of a house originate from attached garages. As houses are designed and constructed more airtight and energy efficient, these contaminants are retained in indoor air, jeopardizing the occupants' health. In this study a multi-zone model for indoor air quality and contaminant transport analysis, CONTAM, was employed to analyze the impact of garage-house interface on the contaminant transport from attached garages to living area. Parametric studies of two buildings have been carried out based on the experimental data of five normalized Effective Leakage Area (ELA) of the garage-house interface. The parametric study indicates that both natural ventilation (wind direction and speed) and mechanical ventilation system influence the pressure difference in the house and consequently affect the contaminant transport from the garage to the house. For the simulations of wind directions for one of the modeled house, the highest and lowest concentration in the living room occurs with the wind directions of 135˚ and 270˚ respectively, regardless of garage-house ELA. Furthermore, the simulation results of wind speeds demonstrate that as the wind speed increases, the peak contaminant concentration indoors increases. However, as the wind speed increases, the infiltration increases. As a result, the exposure to the contaminant actually decreases. Moreover, seven different exhaust ventilation flow rates in different locations were evaluated. The result shows that the worst case scenario is when implementing 52 L/s exhaust ventilation (master bath (10 L/s), hall bath (10 L/s), bedroom2 (22 L/s), living room (10 L/s)).

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ACRONYMS

ACGIH	American Conference of Governmental Industrial Hygienists
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
CS	Cold Start
CGSB	Canadian General Standards Board
CMHC	Canada Mortgage and Housing Corporation
GC/MS	Gas Chromatograph/Mass Spectrometer
ELA	Effective Leakage Area
EPA	Environmental Protection Agency
HS	Hot Start
HVAC	Heating, Ventilating and Air-Conditioning
HUD	Department of Housing and Urban Development
IAQ	Indoor Air Quality
INSA	Institut National des Sciences Appliquées
NMHC	Nonmethane Hydrocarbon
NPL	Neutral Pressure Level
PEL	Permissible Exposure Limit
ppm	Parts Per Million
REL	Recommended Exposure Limit
THC	Total Hydrocarbon
TWA	Time-Weighted Average

TLV	Threshold Limit Value
NIOSH	The National Institute for Occupational Safety and Health
OSHA	The current Occupational Safety and Health Administration
NIST	National Institution of Standard and Technology
NBCC	National Building Code of Canada
NPL	Neutral Pressure Level
VOC	Volatile Organic Compound

NOMENCLATURE

A	Area, m^2
K	Flow Coefficient, $m^3/sPa^n m$
C_D	Discharge Coefficient, dimensionless
C_p	Wind Surface Pressure Coefficient, dimensionless
$C_{\alpha,i}$	Concentration Mass Fraction of Contaminant α in zone i
$G\alpha,i$	Generation Rate of Contaminant α in zone i
h	Height above Reference Plane, m
$K_{\alpha,\beta}$	Kinetic Reaction Coefficient in zone *i* between species α and β
m_i	Mass of Air in zone i, kg
n	Pressure Exponent, dimensionless
P_{sv}	Wind surface pressure, Pa
P_s	Stack Pressure, Pa
P_r	Stack Pressure at Reference Height, Pa
P_v	Wind Surface Pressure Relative to outdoor static pressure in undisturbed flow, Pa
P_i	Zone Pressure, Pa
Q	Airflow Rate, m^3/s
R	Gas Constant, j/kg K
$R_{\alpha,i}$	Removal Coefficient of contaminant α in zone i
T	Time, s
T_i	Zone Temperature, °C
U_H	Approach Wind Speed, m/s
U_{met}	Wind Speed of Meteorological Data, m/s
V_i	Zone Volume, m^3
$W_{j,i}$	Mass Flow Rate from zone(j)to zone(i), kg/s
$\eta_{\alpha,j,i}$	Filter Efficiency for contaminant α in the path from zone *j* to zone *i*.
ρ	Air Density, kg/m^3

CHAPTER 1: INTRODUCTION

Typical single-family houses in Canada are designed with attached garages. These garages may have high concentration of pollutants since residents tend to store chemicals such as paints and solvents in the garage. In houses with attached garages, emissions from the exhaust of vehicles are the sources of many harmful contaminants such as Volatile Organic Compounds (VOCs), methanol, and carbon monoxide (CO). In the absence of a ventilation system in attached garages, the VOCs and other contaminants migrate from the garage to the rest of the house through the opening at the interface of the garage and the house. Following the energy crisis in 1970, buildings are designed more air tight to reduce air leakage and conserve energy. While houses are designed and constructed more airtight, the contaminants from attached garages are retained in indoor air, causing poor air quality and affecting occupants' health and comfort.

1.1 Indoor Air Quality

The United States Environmental Protection Agency (EPA, 2007) reports that approximately an average 90% of a person's life is spent indoors; hence, occupants' health and comfort are important factors in design of a building. Often, to design and construct a cost effective and energy efficient building, it is easy to forget that one of the major functions of the house is to provide a healthy and comfortable environment for the occupants. Figure 1.1 illustrates the design criteria for building a house. With recent strong emphasis in designing cost-effective and energy-efficient houses, health and comfort of occupants cannot be compromised.

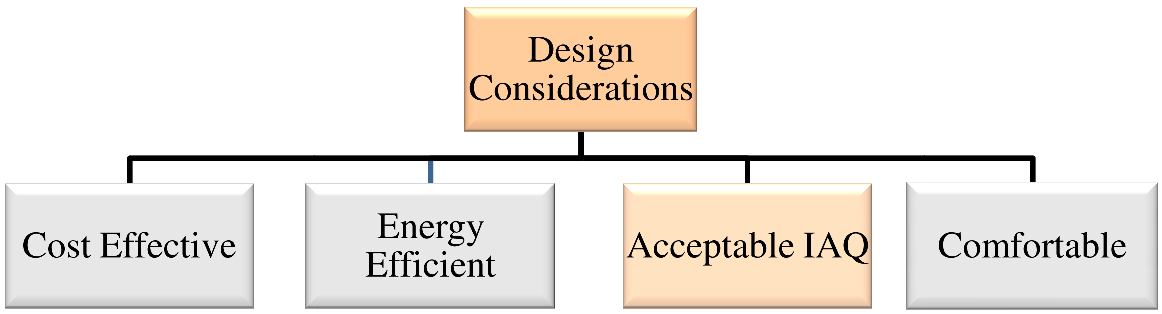

Figure 1.1 Design considerations to build a house

Since people spend most of their time inside, IAQ has a significant effect on their health. A twelve-month study on indoor contaminant shows that 80% of personal exposure to many contaminants such as nitrogen dioxide, carbon monoxide and volatile organic compounds (VOCs) occurs within an indoor environment (Crump *et al.*, 1999). These gases may have short or long term adverse health effects: they can cause headaches, dizziness, poor concentration, nausea, sinus infections, eye irritations, allergic reactions, and even cancer (Woodruff, 1998). Even with relatively low concentration of some indoor air contaminants, the annual occupant's exposure is relatively high because of the long duration that people spend inside (Leung & Harrison, 1998).

The contribution of pollutant emission from the vehicles in garages and infiltration to the houses has a significant effect on occupants' health. Approximately 40% of many VOC concentrations such as benzene, toluene, ethylbenzene, and xylenes in indoor air originate from the attached garages (Dodson *et al.*, 2008). The Avon

Longitudinal Study of Pregnancy and Childhood in the UK, stated that benzene concentrations level in homes with attached garages are likely to be higher than in those without attached garages (Mann *et al*., 2001). Many elderly individuals and children, who are more susceptible and fragile to pollutant levels, spend long periods of time in houses. Some houses with attached garages are used for daycares. Therefore, attached garages should be designed in a way that reduces the contribution of contaminants in indoor air.

1.2 General Statement of Problem

Air leakage through the interface of garages and houses depends on the air pressure difference across this interface and its air tightness. When a difference in pressure exists between two adjacent volumes of air and there is a leakage path between them, the air moves from a higher pressure to a lower pressure. Through the exfiltration in winter, the hot moist air from indoor passes through the envelope of the building, and in the case of high moisture load the condensation would occur in walls and ceilings which have a destructive effect on the building envelop. For this reason, in cold countries, depressurization of houses is recommended. However, in houses with lower pressure than their attached garages, polluted air from the garage is sucked to the living area and as a result, the level of contaminant inside the house increases.

To design a house with lower contaminant entry from the garage, it is important to consider the phenomena that lead to contaminant transport from the garage to the house. Wind direction, wind speed, envelope air tightness and ventilation system affect the pressure difference between the house and the garage (see Figure 1.2). Based on the leakage characteristic of the garage-house interface, a simulation study is carried out in this study to evaluate the effect of wind direction, wind strength and ventilation system on contaminant transport.

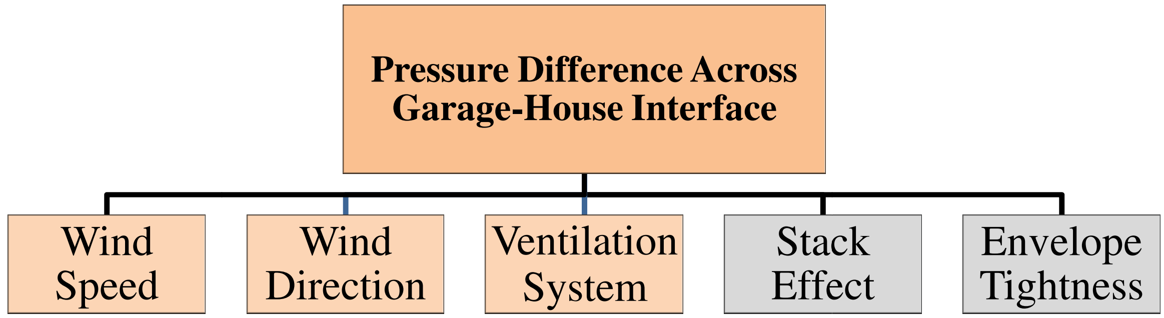

Figure 1.2 Parameters that create pressure difference between the house and the garage

CHAPTER 2: LITERATURE REVIEW

Attached garages are significant contaminant contributors to the indoor environment (Batterman 2006, Dodson et al. 2008, Graham et al. 1999, Emmerich et al. 2003, Moore & Kaluza 2002, Mann et al. 2001). In 1990s, many houses installed carbon monoxide (CO) sensors. The detectors were unexpectedly activated without any apparent sources of CO inside the houses. Initially, the fire department reported these incidents as false alarms; however, a research by Wilber & Klossner (1997) showed that the sensor's alarm was the indication of CO transport from the attached garages to the house with a time delay (CMHC, 2011). These incidents clearly showed that the contaminant in attached garages is transported to houses because of air leakage from attached garages to living areas (Wilber & Klossner, 1997).

Most garages have a higher concentration of Volatile Organic Compounds (VOCs), carbon monoxide and other contaminants since they are used as shelters for motor vehicles. Fugler *et al.* (2002) documented that in some cases up to 45% of the infiltrated air to houses is from the attached garages. Migration of VOC's and other pollutants from the garage to the house leads to elevation of contaminant level in indoor air. For instance, based on the evaporation emission test from a hot engine of a car after its shut down, the emission of methanol by the vehicles in the attached garages leads to the highest concentration of methanol level indoors (Pei & Weisel, 2000).

2.1 Previous Research

Several studies (Batterman 2006, Mann *et al*. 2001, Graham *et al.* 2004) have shown that the concentration of some VOCs such as benzene in houses with attached garages is higher compared to those without garages. For example, it is documented that the concentration of benzene in an attached garage containing approximately 18 month old car reaches 101 $\mu g/m^3$ (Mann *et al*., 2001). This amount is about thirteen times higher compared to typical outdoor concentration of benzene (ASHRAE Handbook, 2005). As a result of a high concentration of benzene in the garage, the house concentration reaches 40 $\mu g/m^3$ while the concentration in a house without a garage reaches 3.7 $\mu g/m^3$. The study of Mann *et al*. (2001) also showed that people who live in houses with attached garages are exposed to higher amounts of benzene.

Graham *et al*. (1999) have carried out an authoritative study to characterize pollutants transport from the garage to the house in Canada. They performed significant measurements to evaluate the air tightness of garage, house and garage-house interface of 25 Canadian houses during the winters of 1997-1998 and 1998-1999 in Ottawa. They also performed measurements of vehicle's contaminant emissions in attached garages. Two particular tests have been conducted for gasoline fuelled cars including hot soaked tests (HS) and cold start tests (CS). In hot soaked test, the driving vehicle with a warmed-up motor is parked in the garage in the afternoon, and in cold start test the engine of the vehicle is started after being rested for a while until it reached the ambient temperature.

Graham *et al*. (1999) concluded that the cold start up contributes much more to the contaminant concentration. In the cold the start test, depending on the temperature of the surrounding air, fuel is consumed for ignition. Moreover, since all chemical reactions are slower in cold temperature for starting up the car, the catalytic converter used to reduce the emissions from the vehicle is in low temperature and it is not activated until the car is warmed up (Graham *et al*., 2004). The result from their studies indicates that 6-13% of CO and a total 13-85% of the contaminant concentration in houses originated from the attached garages during the cold start up test.

Figure 2.1 presents the total mass of CO, CO_2, NO_x, and total hydrocarbon (THC) emitted from the vehicle during a test of 300 seconds. Thus the average emission rate can be acquired by dividing the total mass by the test duration. The average emission rate is calculated in Table 2.1, showing that the cold start emission in -10˚C ambient temperature has the highest emission rate for the mentioned compounds.

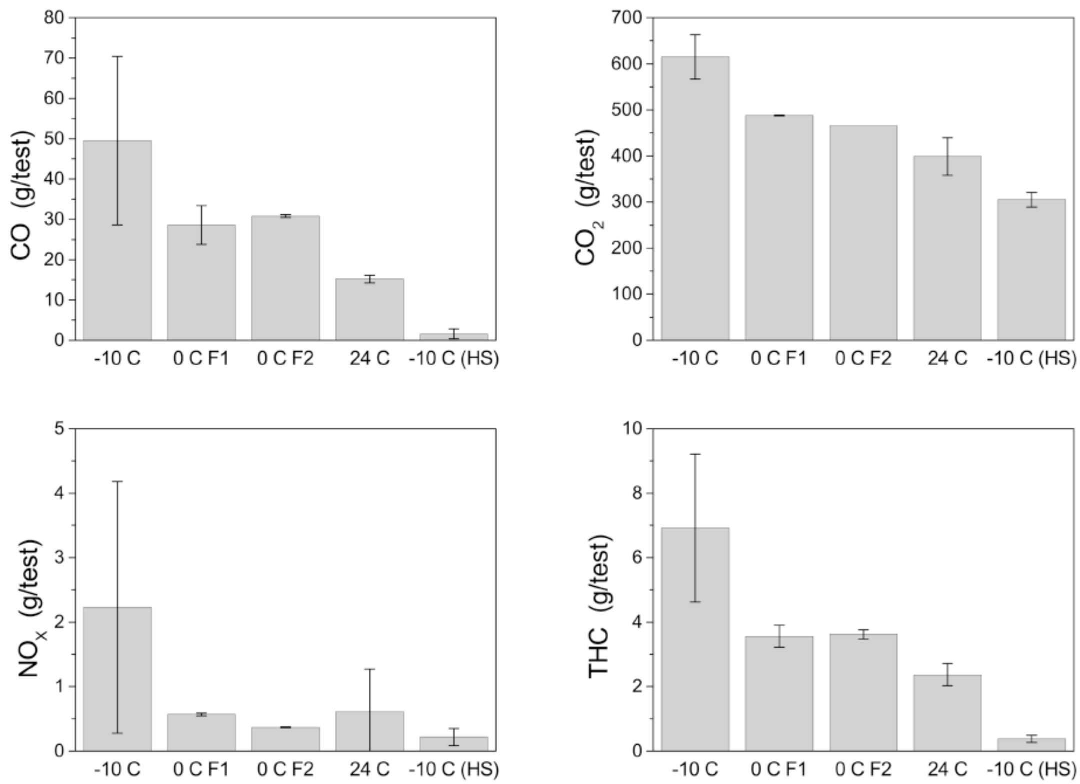

Figure 2.1 Average emission rate (g/test) for CO, CO2, NOx, and THC for all fuels and tests. (HS is the indication for the hot start emission) (Graham *et al*., 2004)

Table 2.1 Emission rate at -10C cold start (Graham *et al*., 2004)

Emission rate at -10 C cold start(each test is 300 sec)			
	(g/test)	g/sec	mg/s
CO	50	0.167	167
CO2	600	2.000	2000
NOx	2	0.007	7
THC	7	0.023	23

Figure 2.2 compares the emission rate of nonmethane hydrocarbons for cold start (CS) emission at different temperatures and Figure 2.3 compares the cold start (CS) and hot start (HS) emissions both at -10˚C.

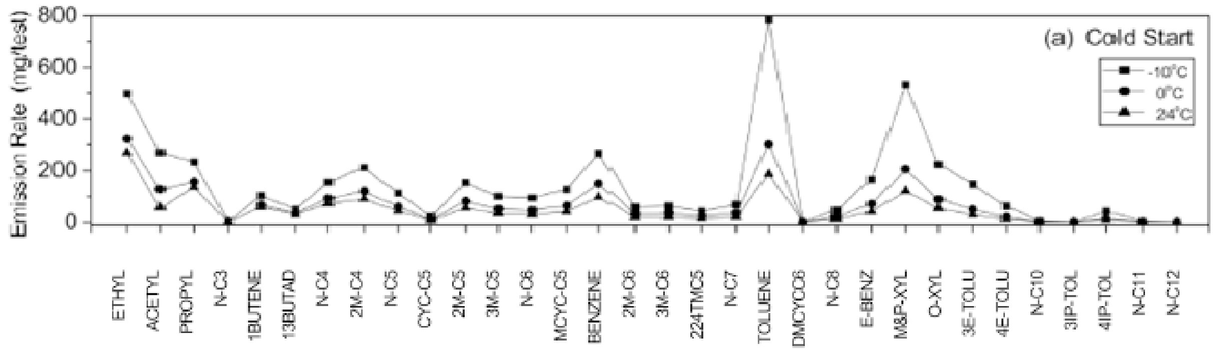

Figure 2.2 Comparison of NMHC emission rate for cold start of vehicles in different temperature (Graham et al., 2004)

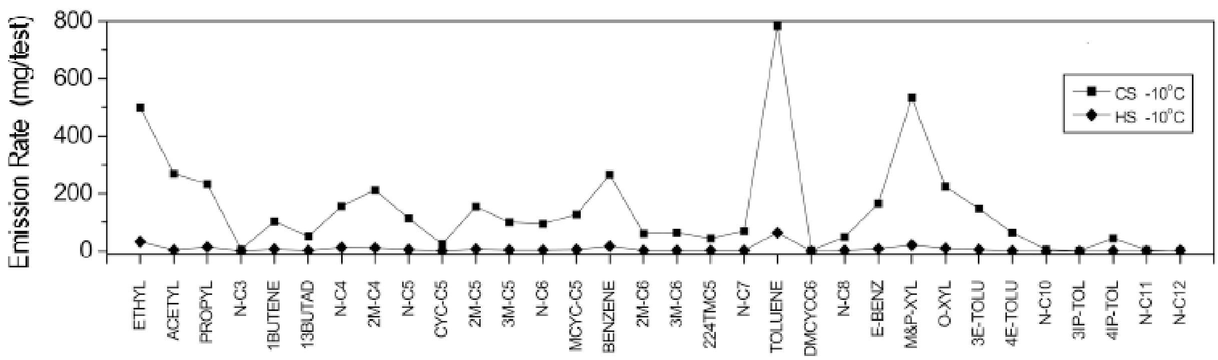

Figure 2.3 Comparison of NMHC emission rate for both cold start and hot start of vehicles (Graham *et al.*, 2004)

A study on evaporative emissions of vehicles in garages indicated that "among microenvironments impacted by mobile source emissions, residential garages have the highest concentration of methanol" (Lansari *et al.*, 1996). The experiment conducted by Dodson *et al.* (2008) in 11 houses with attached garages shows that "20–40% of the indoor concentration for compounds associated with gasoline sources, such as methyl *t*-butyl ether (MTBE), benzene, toluene, ethylbenzene, and xylenes, is from attached garages". For example, their experimental results showed that the mean concentration of benzene in the garage was 54 μg/m^3 compared to 2.6 μg/m^3 in indoor air.

Batterman *et al*. (2007) measured VOC concentrations and emissions at 15 residential garages in Michigan. VOCs concentration in garages and in outside air were measured “using 4-day passive sampling, thermal desorption, and GC-MS analysis.” They quantified 36 different VOCs in the garage air, and 20 in outdoor air. High concentration of evaporated gasoline, solvents, paints, oils, and cleaners in garages were also identified. Their result showed a high concentration of gasoline-related VOCs in most garages. For example, the measured benzene concentration reached 159 $\mu g/m^3$ in one of the garages.

Pei and Weisel (2000) measured the methanol, benzene and toluene in a house with attached garage. They evaluated the potential dose of these compounds and risk distribution for occupants based on concentration, duration of exposure, inhalation rate, life expectancy and body weight. Their result showed that the “risk associated with exposure to methanol, benzene and toluene were the highest for children between ages one to four. The total daily dose was 84.1 µg/kg, 2.71µg/kg and 39.4 µg/kg for methanol, benzene and toluene respectively” (Pei & Weisel, 2000).They used a multi-zone pollutant transport model to predict the air movement from the garage to the house and concentration level of methanol in the house. The result showed the infiltration of air to the adjacent room and the concentration level matched well with the measured data (Pei & Weisel, 2000).

Moore & Kaluza (2002) measured carbon monoxide and benzen in 65 houses in Alaska. The result of their study showed that the concentration of carbon monoxide and benzene in the house is highly correlated to the concentration of these contaminants in the garage. Their measurements showed that the house peak concentration of CO reached 10% of garage peak concentration with a five-hour time delay.

These studies demonstrate that sources of many contaminants in indoor air are from the attached garages. Even though some studies were conducted to determine the air leakage of garage-house interface, there is a lack of data on the correlation of interface of garage-house envelope air tightness, and parameters that cause a pressure difference between house and garage.

2.2 Envelope Leakage

Historically, houses have been so leaky, and a significant amount of outdoor air could infiltrate into the houses through leakages. Due to the recent energy shortage in the world, to minimize the energy consumption, buildings are designed more air tight. Therefore, new houses are constructed with better insulation material, tighter windows and doors, and better construction methods. Since recently built houses are more air tight, the infiltration of the house and consequently the air change rate is much lower (NBC, 1998). Furthermore, in an air tight building, there is a concern that the air change rate through infiltration may not provide adequate fresh air for the occupants. Even though these houses are more energy efficient, indoor air quality may be poor.

Air tightness is the building property that affects the infiltration of contaminant from the garages to houses. Emerich *et al*. (2003) used fan pressurization tests to evaluate the air tightness of the house, garage and the garage-house interface of five residential houses. The result of their experiments indicates that for the entire test, the garages were at least twice leakier than the houses. Based on their data, the following normalized ELA (effective leakage area) values of house and garage are found (Table 2.2). These results are normalized with respect to area and they can be used in other studies utilizing a multi-zone pollutant transport software (Emmerich *et al*., 2003).

Table 2.2 The interface and ELA values (Emmerich *et al*., 2003)

	House1	House2	House3	House4	House5
(ELA_4/SA)(cm^2/m^2) house-garage interface	20.4	2.97	2.35	2.67	1.2
±Δ(cm^2/m^2)	7.32	0.37	2.56	0.56	0.81
(ELA_4/SA) ($cm^2/m^{2)}$ house	3.00	1.71	3.09	2.64	2.24
±Δ(cm^2/m^2)	0.44	0.17	0.46	0.27	0.23

2.3 Factors that Effect Pressure Difference

Pressure difference between the house and the garage is caused by wind direction, wind speed, stack effect, combustion and ventilation effect. The amount of outside air leaking to the house depends on the size and location of the opening and the total leakage area of the envelope. Figure 2.4 shows the summary of flow directions caused by pressure difference.

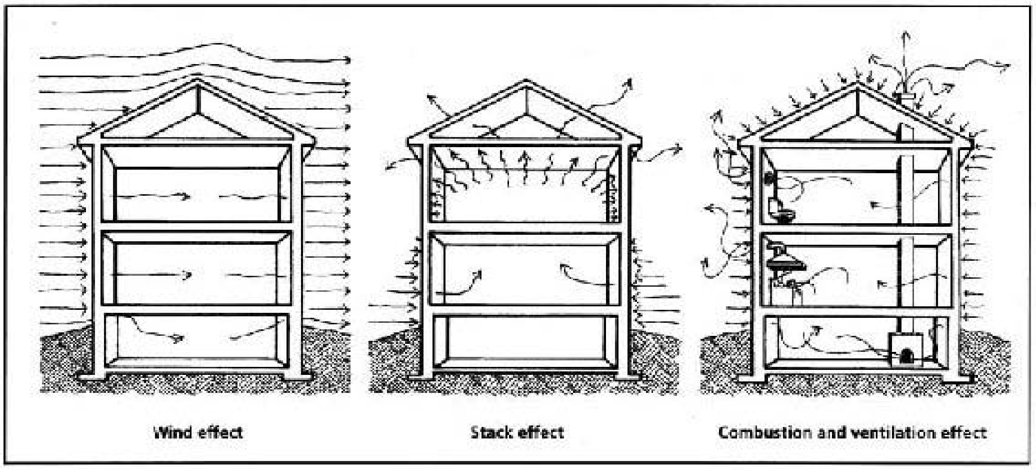

Figure 2.4 Forces that create pressure difference in houses. "Keeping the heat in" (www.nrcan.gc.ca)

2.3.1 Wind Pressure

Wind creates a pressure field around the building which produces a positive pressure filed on the windward side and a negative pressure on the leeward side. The pressure field around the house affects the house pressure and contaminant transport within it. The static surface pressure of the house is proportional to velocity pressure of wind (ASHRAE Handbook, 2005).

$$P_v = \rho U_H{}^2/2 \qquad \text{Equation 2-1}$$

P_v = wind surface pressure relative to outdoor static pressure in undisturbed flow, Pa
ρ = outside air density, kg/m^3
U_H = approaching wind speed at upwind wall height, m/s

Wind pressure depends on velocity, direction and shape of the house and the surrounded terrain. The U_H in equation 2.1 is estimated based on the hourly wind speed of nearby meteorological data U_{met}. U_{met} is adjusted for a height and location of the house. The pressure at a point of surface wall, i, is defined as:

$$P_i = C_{p,i,d} P_v = C_{p,i,d}\,\rho U^2/2$$ Equation 2-2

Where *Cp* is the wind pressure coefficient which is depend on building shape, wind direction, and influence of nearby buildings, vegetation and terrain features (ASHRAE Handbook, 2005).

2.3.2 Stack Effect

Stack effect or thermal buoyancy is caused by the difference in temperature between two adjacent zones. In this phenomenon, natural ventilation occurs when the air moves in or out of house. The density of air is calculated by the ideal gas law (ASHRAE Handbook, 2005):

$$\rho = P/RT$$ Equation 2-3

The following equation can be used to calculate the stack pressure assuming that the barometric pressure and temperature are constant in each vertical surface. As the equation shows that stack pressure decreases as the height increases (ASHRAE Handbook, 2005).

$$P_s = P_r - \rho g h$$ Equation 2-4

P_s = stack pressure, Pa
P_r = stack pressure at reference height, Pa
g = gravitational acceleration, 9.81 m/s^2
ρ = indoor or outdoor air density, kg/m^3
h = height above reference plane, m

2.3.3 Neutral Pressure Level

The difference between indoor and outdoor temperature causes stack pressure difference which results in an airflow across the building envelope. The neutral pressure level (NPL) is the location in the building height where the indoor and outdoor pressure is the same; hence, this location indicates in which region the building envelope infiltration or exfiltration occurs. Figure 2.5 shows stack pressure and wind pressure forces for a building that has uniform envelope leakage area. In this condition the NPL is at the mid height of the building. In Figure 2.5A, in winter condition, when the indoor air is warmer than the outdoor: air infiltrates at the lower openings. Figure 2.5B illustrates the pressure line which is caused by wind only. It shows both windward and leeward pressure lines. As it is demonstrated in this figure, the pressure in windward side is always higher than the leeward side. NPL does not exist in this figure since it is assumed uniform wind pressure on the wall. Figure 2.5C shows the combined effect of wind and stack effect.

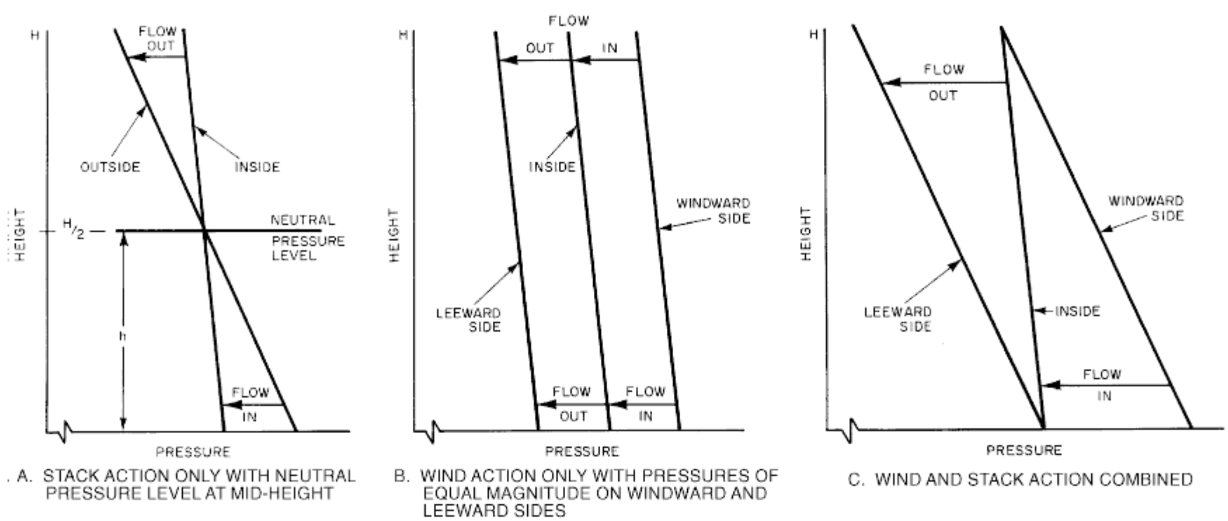

Figure 2.5 Distribution of inside and outside pressure over height of building (ASHRAE Handbook, 2005)

In low rise buildings, the position of NPL without any ventilation and wind effect is approximately in mid height; however, this location changes when unbalanced ventilation system is introduced.

In winter conditions, the infiltration occurs at the region below the NPL and the exfiltration occurs at the upper part of NPL. Therefore, to reduce the condensation in envelope, building's ventilation systems are designed to raise the NPL to minimize the exfiltration during colder weather. Depressurizing the house increases the level of NPL and consequently reduces exfiltration. Thus, the ventilation system in cold countries is designed to raise the neutral pressure level in houses. In addition to a ventilation system, other factors such as furnace operation, envelope characteristics, and dryer operation influence the pressure level in the house.

For example, according to the National Building Code of Finland, "buildings should be maintained under negative pressure conditions relative to outdoors to avoid moisture damage to the building envelope" (Kalamees *et al.*, 2010). As a result, "The Finnish guideline advises mechanical exhaust airflow to usually be adjusted to 15-25% more than supply airflow" (Kokotti *et al.*, 1994).

In addition, ASHRAE Standard 62.2P limits pressurization of a house in a cold climate. Standard 62.2P permits "mechanical ventilation systems to operate continuously or intermittently to provide whole-house ventilation". Based on the code, balanced ventilations are not specifically required which may allow higher exhaust airflow rate compared to supply air. However, the code specifically “prohibits unbalanced systems that pressurize the house to any extent in cold climates.” Nonetheless, “prohibitions are waived if the building envelope incorporates a moisture-resistant design” (Wray *et al*., 2000). Hence, buildings in Canada are designed to have a lower pressure compared to outside and their attached garages which may result in contaminant transport from garages.

In cold countries, the air leakage through the house and the garage interface is a result of an uncontrolled ventilation system (furnace operation), wind speed and direction and indoor and outdoor temperature differences. Experimental result also shows that in general, Canadian houses are designed to have a lower pressure compared to garages (Graham *et al*., 1999). Since in summer there is not a significant stack effect caused by indoor-outdoor temperature difference, the pressure difference between the garage and the house is lower. During the summer, the average interface pressure difference is about 1 Pa in Canadian houses, with a range of -2.3 Pa to 5 Pa. The negative sign indicates the air movement from the house to the garage. Moreover, the field measurement data shows that the garage pressure is consistently higher compared to the house in winter conditions. On average, the result shows that the pressure in the garage is 1 to 5 Pa higher. In some cases, this value reaches to 10 Pa (Graham *et al*., 1999). The Graham results are based on the condition that ventilation system is not in operation; therefore, these results may change when the ventilation system is operating.

2.3.4 Mechanical Ventilation

One of the main purposes of a ventilation system in a house is to provide a healthy environment for occupants by removing contaminants. With ventilation systems, the outdoor air which in most cases has a much lower contaminant concentration is brought indoors and the contaminated air inside is exhausted out. Hence, the operation of mechanical ventilation system introduces pressure difference across garage-house interface. The supply and exhaust fans pressurize or depressurize the house which influence contaminant transport between the garage and the house. Based on mass balance, the house pressure adjusts in a way that the infiltrated and the supplied air to the house would be equal to the exfiltrated and the exhausted air.

Most people think with higher ventilation rates, a higher amount of fresh air is introduced to the house which would result in a lower level of contaminant in the house. Since the recent buildings are more air tight, during heating seasons when the doors and windows are closed, the infiltration rate in a tight house is less than 0.3 ach. In these houses openings in the building envelope are not sufficient enough to provide an appropriate ventilation to remove contaminant from the house. Therefore, based on NBCC (2005), mechanical ventilation system is required in heating seasons. Nevertheless, the code only emphasises on ventilation rate and permits the depressurizations of the buildings when houses do not use solid-fuel-burning appliances or fireplaces, and contaminant transport from attached garages is not considered (NBCC, 2005).

In design of a house, it is important to recognize that the contaminant transport is based on air movement. Regulating the temperature and velocity of supplied air to accomplish a comfortable indoor environment, is not the only criterion for achieving an acceptable design of ventilation system. The ventilation system must be designed in a way to regulate the pressure difference between house and garage in order to prevent contaminant transport from the garage.

The most common approach for removing contaminants is “point exhaust ventilation” and it continues to be the most feasible system for application in buildings (Reardon *et al.*, 2001). This system is very simple and is inexpensive to install; however, it would greatly depressurize the house. This system uses exhaust fans in different parts of the house such as in the bathroom and in the hood fan of the kitchen, and it only relies on infiltrated air for the makeup air supply through the leakage path in the house. However, the supply air may be pulled through undesirable paths such as garages, crawl spaces, attics or they may entrain pollutants from combustion appliances (Barley, 2002).

As described, exhaust ventilation system influence pressure profile of the house, and it may cause a negative effect on indoor air quality when the house has attached garages. For example, that exhaust ventilation systems may increase the indoor levels of radon concentration. Therefore, balance ventilation system which does not create pressure difference is recommended to reduce the radon entry to the house (Bonnefous *et al.*, 1992). Figure 2.6 shows that how depressurization drives the air from the garage to the house. Even though one of the advantages of the system is that it raises the neutral pressure level, it also depressurises the house, and cause a potentially higher contaminant transport to the living area from an attached garage.

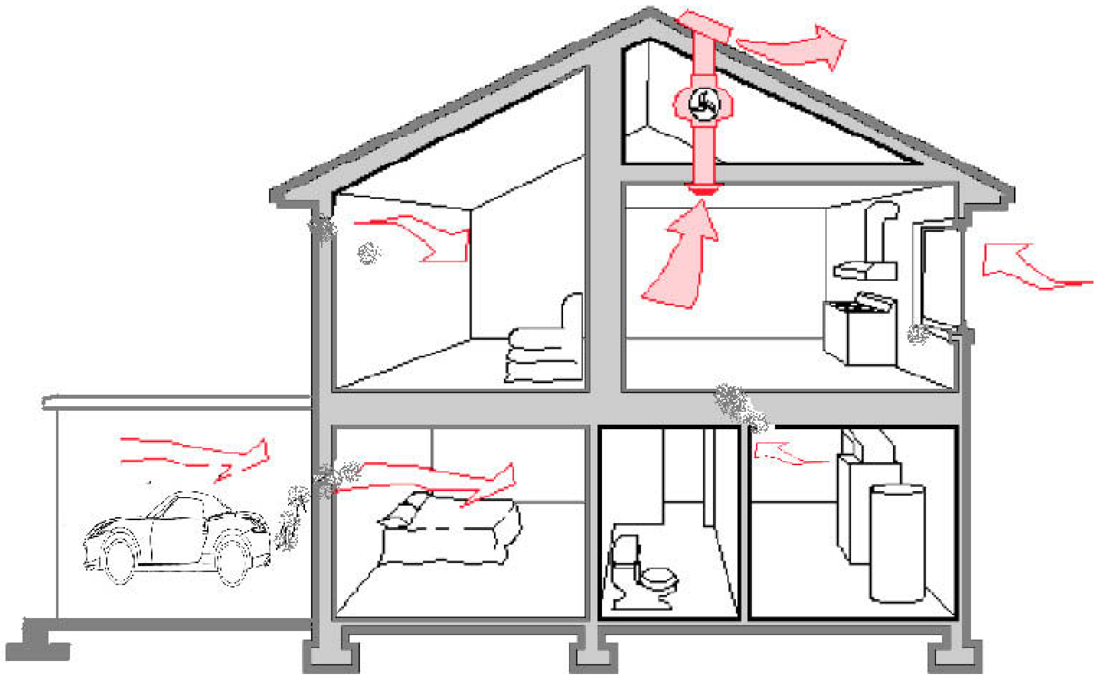

Figure 2.6 Central exhaust ventilation system (amended: Russell *et al*., 2005)

Table 2.3 shows the minimum and maximum exhaust capacity of the dwelling unit based on NBCC (2005).

Table 2.3 (NBCC, 2005, Table 9.32.3.3)

Normal operating exhaust capacity of principal ventilation		
number of bedrooms in Dwelling Unit	Normal Operating Exhaust Capacity of Principal ventilation fan L/s	
	Minimum	Maximum
1	16	24
2	18	28
3	22	32
4	26	38
5	30	45
more than 5	system must comply with 9.32.3.1 (1)(a)	

2.3.5 Cloth Dryer Operation

Another factor that influences the contaminant transport from the attached garages is the existence of a dryer in the house, since it requires the use of an exhaust fan while operating. This exhaust fan blows the indoor air to outside and creates a negative pressure at its location.

Based on a proposal for International Code Council (ICC), it is crucial that the hot air from dryers heated with electricity or natural gas to be exhausted outside because of the following reasons:

- ”Waste of energy: If the air conditioning is in use, energy will be wasted by removing the moisture and heat from the structure. Whereas the owner or occupant has an option to exhaust it outside, they may forget to make the change.
- Addition of humidity to the air. The humidity can condense on surfaces, especially on basements where dryers are often located. It also contributes to potential respiratory problems. In its 2004 report, the National Academy of Sciences concluded that there is sufficient evidence of an association between damp indoor environments and four respiratory problems: upper respiratory tract symptoms, coughing, wheezing, and asthma in sensitive individuals.
- Addition of unnecessary volatile organic compounds (VOCs) to the air. Many of the detergents used on clothes contain fragrances and other VOCs. These VOCs

may not be thoroughly removed in the washing rinse cycle. They will be removed in the dryer. These VOCs may have health effects" (Neltner, 2007).

Even though it is crucial to exhaust the clothes dryer air, the exhaust fan blows the inside air to outside, it depressurises the house and increases the infiltration of contaminated garage air. Despite the fact that the process time of dryers is short, in the cases that the garage has high level of contaminant, it can immensely increase the level of the contaminant.

2.4 General Objective

Depressurizing the house is one of the causes for the airflow from the garage to the house and consequently, contaminant transport to the living area. Depressurization of the house is not explicitly forbidden in Canada except in some cases that codes limit the depressurization based on heating appliances and existence of fireplaces. Based on the NBCC (2005), there is no limitation of house depressurization based on contaminant transport from attached garages to house. Also there is no regulation on the leakage of house and garage envelope interface to prevent contaminant transport from garages. Therefore, the objective of this study is to conduct a simulation study to demonstrate the impact of garage-house interface leakage on the contaminant transport. The result of this study would be used as a starting point for future standard development in order to minimize the occupant exposure to the contaminant originating from the garage.

2.4.1 Specific Objective

Numerical simulations require measured data from experiments to provide boundary conditions and validation information. Experiments are limited to a certain number of conditions, beyond which other scenarios that occur in different climates in Canada cannot be evaluated. To quantify the infiltration from garages to the living area, Graham *et al*. (2004) have measured and characterized the air tightness of garage-house interface of 25 houses across Canada. In this report the parametric study is carried out based on five selected effective leakage area (ELA) data of garage-house interface by Graham *et al*. (1999). The results of their experiments are implemented in two validated buildings models by Megri (1993) and Wang & Emmerich (2010). Therefore, the simulation study is carried out based on experimental results to analyze the different scenarios affecting the pressure differences across the envelope. The specific objective of this study is to develop a simulation study to identify the effect of garage-house interface leakage on contaminant transport. Simulations are conducted based on the significance of the following parameters to evaluate both natural and mechanical ventilation:

- Garage-house interface envelope
- Wind direction
- Wind speed
- Exhaust fans in the living area

CHAPTER 3: AIR AND CONTAMINANT FLOW MODELING

The knowledge about air flow pattern in a building is an important means to provide a healthy and comfortable indoor air environment. To determine flow patterns in buildings, two fundamental techniques are available: measurement and mathematical modeling. Blower door and tracer gas tests are experimental methods that can provide information about the airflow within a building (Feustel, 1999). However, these approaches are time consuming and the collected data are only based on specific weather and building location conditions. On the other hand, simulation models can be used to analyze the indoor air quality (IAQ) in a house for different weather conditions, building locations and different ventilation strategies.

Zonal and multi-zone models are two general techniques that are used to simulate and visualize airflow and contaminant distribution in buildings. Zonal models provide detailed information and microscopic view of airflow, temperature and contaminant concentration within a zone. Zonal models are very complex and use thousands of nodes per zone and take a long time to carry out the calculations. This model solves mass, energy, and momentum conservation equations to find out the temperature, air velocity and contaminant concentration in each zone (Emmerich *et al.*, 2004).

On the other hand, multi-zone models, such as CONTAM (Dols *et al.* 2000) and COMIS (Fuestel, 1999) calculate contaminant transport for the whole building. This technique takes a macroscopic view and assumes each zone as a node and solves mass balance equations (Dols, 2001).

3.1 Multi-Zone Model

Many airflow models have been developed in the last three decades. Fuestel and Kendon (1985) reviewed and summarized 15 different multi-zone models used by researchers and practitioners. In 1989, Feustel and Dieris (1992) conducted a survey which identified 50 multi-zone airflow models.

Airflow models are divided into single zone and multi-zone categories. Single-zone models assume the whole structure as a single zone with only one pressure and temperature. These models are used to analyze contaminant transport in a single family house with no internal partition. In multi-zone models, a building is divided into different zones with different thermal and pressure conditions. Figure 3.1 illustrates a simple multi-zone building.

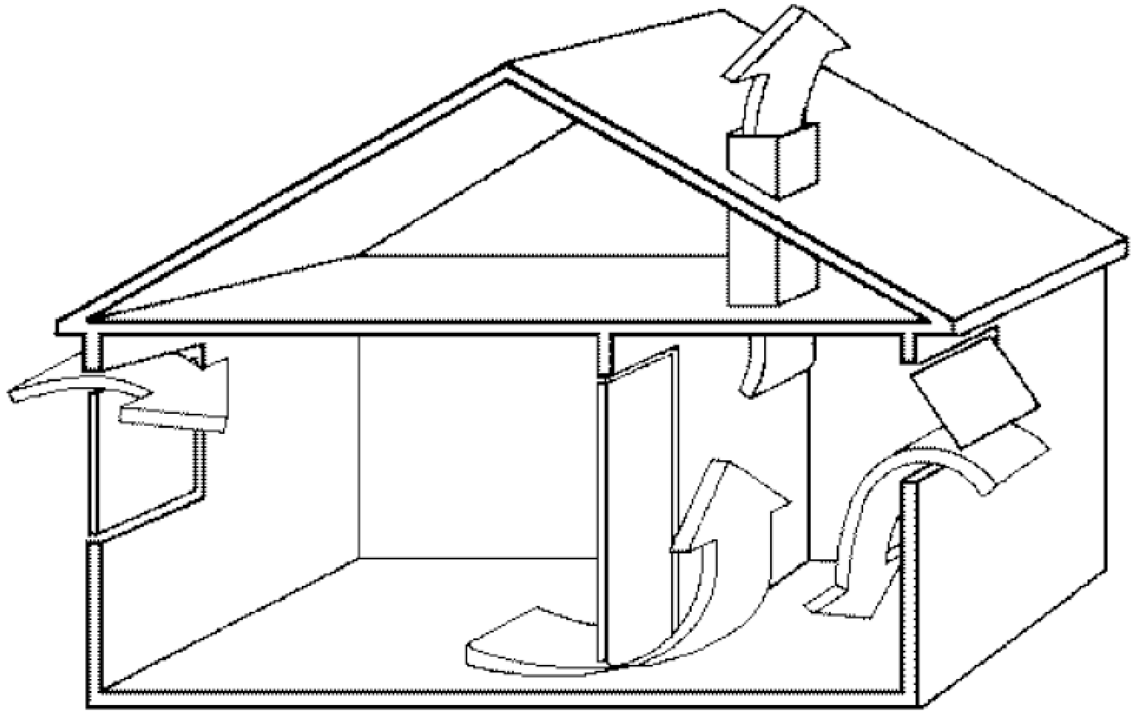

Figure 3.1 A simple multi-zone structure (Liddament, 1986)

As described in chapter two, airflow in a building is caused by pressure difference. Pressure difference is induced by wind, buoyancy effect, and mechanical ventilation. The airflow is also influenced by the leakage characteristic in the envelope and the interior partitions dividing various zones. To study airflow within a building, detailed information of parameters that influence pressure and the airflow distribution are required as shown in Figure 3.2. These parameters include wind velocity and direction, temperature differences and mechanical ventilation systems.

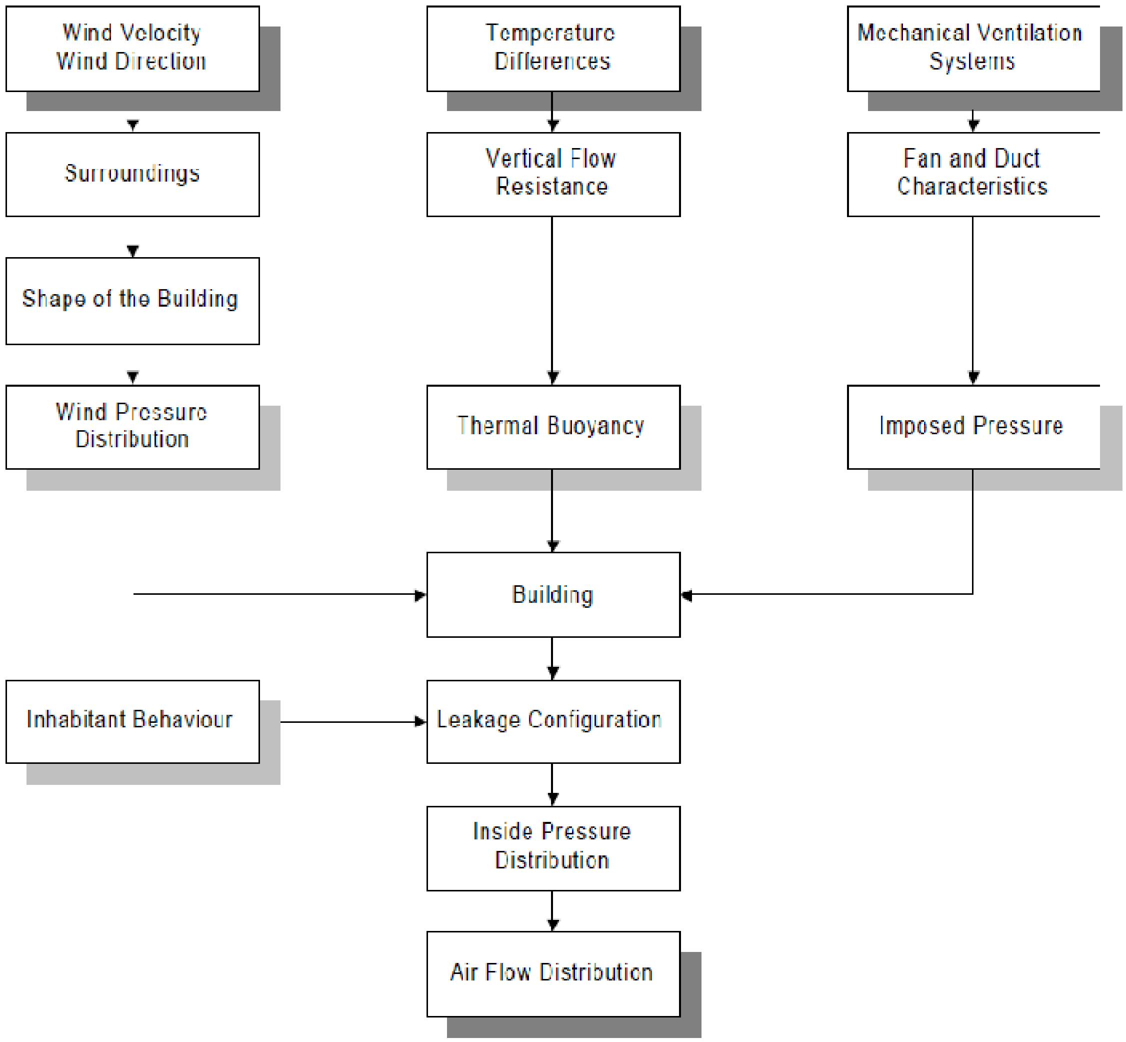

Figure 3.2 Influences on the airflow distribution in buildings (Feustel, 1984)

Multi-zone models use simple methods to calculate airflow, pressure difference and contaminant transport in buildings. In these models, a building is divided into a number of nodes where each node represents a zone. Each zone is considered to have a uniform temperature, pressure and contaminant concentration that exchange air with its adjacent zones. Multi-zone models are also called network-based tools. In these models, the concept of zone is not exactly the same as energy simulation models of heating, ventilation, and air conditioning (HVAC) systems; however, there are some similarities between the HVAC models and the multi-zone models. Most multi-zone models such as CONTAM, assume temperature as a fixed parameter during the calculation of air flow. This assumption avoids solving energy equations for zone temperature therefore simplifying the calculations of airflow system between the zones.

3.2 CONTAM

In this study, CONTAM (Dols *et al.* 2000) is used to predict the airflow and contaminants transport from the attached garage to the house. CONTAM was developed by the U.S. National Institute of Standards and Technology (NIST), and it is the most widely used and validated multi-zone program (Liu & Zhai, 2009).

CONTAM is a user-friendly software. It is designed to easily add building components and characteristics. CONTAM evaluates the building performance in terms of contaminant transportation by simulating the contaminant release within or outside the building and calculates the occupants' exposure. Persily *et al.* (2007) used CONTAM to model different criteria in terms of occupant exposure from contaminant transport. They also evaluated various retrofit options to reduce contaminant exposure.

3.2.1 CONTAM Description and Methodology

The two basic elements for multi-zone modeling are zone (node) and airflow path. In a multi-zone model, a building is considered as an interconnected volume or zones (rooms, hallway, and stairway). Using the input data, CONTAM solve air mass balance for each zone to find out zone pressure and the amount of airflow within each flow path (Walton 1995, Dols *et al.* 2001).

The following equation is used to determine the mass flow rate ($W_{j,i}$) from zone (j) to zone (i).

$$W_{j,i} = f(p_{j} - p_{i})$$ Equation 3-1

Bernoulli equation is used to determine ΔP_{ji} based on air density, height and wind pressure

The mass of air (m_i) in zone (i) is defined as:

$$m_i = \rho_i V_i = \frac{p_i V_i}{R T_i}$$ Equation 3-2

Where the following parameters are user defined for each zone:

V_i = zone volume
p_i = zone pressure
T_i= zone température
R= gas constant, 287.055 J/kgK

The transient solution is also defined as:

$$\frac{\partial m_i}{\partial t} = \rho_i \frac{\partial V_i}{\partial t} + V_i \frac{\partial \rho_i}{\partial t}$$ Equation 3-3

The following equation must be satisfied according to mass conservation principles (Walton 1995, Dols *et al.* 2001):

$$\sum_j W_{j,i} = 0$$ Equation 3-4

m_i = mass of air in zone i
$W_{j,i}$ = airflow rate (kg/s) between zone (j) and zone (i) (positive value is an indication that the flow is from zone (j) to zone (i) and vice versa)

Equation 3.4 leads to a set of non linear algebraic equations to be solved iteratively. CONTAM uses the Newton-Raphson method to solve these nonlinear equations to calculate pressure for each zone and mass flow rates for each flow paths. CONTAM has the option of keeping a constant pressure for a desired zone. It also defines the ambient air as a constant pressure zone (Walton 1995, Dols *et al.* 2001).

The result of the airflow rate for each zone is used to calculate the contaminant concentration in each zone. The mass of contaminant α in zone (i) is:

$$m_{\alpha,i} = m_i C_{\alpha,i}$$ Equation 3-5

m_i = mass of air in zone (i)
$C_{\alpha,i}$ = concentration mass fraction of α

The removal and added rate of contaminant is presented by Walton (1995) as follow:

<u>Contaminant is removed from zone (i) by:</u>

1. Outward airflows from the zone at a rate of $\sum_j W_{i,j} \times C_{\alpha,i}$ where $W_{i,j}$ is the rate of airflow from zone (i) to zone (j).

2. Removal at the rate $C_{\alpha,i} \times R_{\alpha,i}$ where $R_{\alpha,i}$ is a removal coefficient.

3. First-order chemical reactions with other contaminants $C_{\beta,i}$ at the rate $m_i \sum_\beta K_{\alpha,\beta} \times C_{\beta,i}$ where $K_{\alpha,\beta}$, is the kinetic reaction coefficient in zone (i) between species α and β (Positive k for generation and negative k for removal).

<u>Contaminant is added to the zone by:</u>

1. Inward airflows at the rate $\sum_j (1-\eta_{\alpha,j,i}) \times W_{j,i} \times C_{\alpha,j}$ where $\eta_{\alpha,j,i}$ is the filter efficiency for contaminant α in the path from zone (j) to zone (i).

2. Generation at the rate $G_{\alpha,i}$.

3. Reactions of other contaminants.

Conservation of mass for each contaminant species (assuming trace dispersal- $m_{\alpha,i} \ll m_i$) produces the following basic equation for the contaminant concentration for each zone:

$$\frac{dm_{\alpha,i}}{dt} = -R_{\alpha,i}\, C_{\alpha,i} - \sum_j W_{i,j} C_{\alpha,i} + \sum_j (1-\eta_{\alpha,j,i})\, W_{j,i}\, C_{\alpha,j} + m_i \sum_\beta K_{\alpha,\beta}\, C_{\beta,i} + G_{\alpha,i}$$

Equation 3-6

For each contaminant in each zone this equation is defined and solved simultaneously. “There are two major limitations in Equation 3.6. First is constant zone air mass. This is consistent with the zone temperature being constant and contaminant fraction being low. Second is the use of linear analysis which limits the kind of kinetic reaction which can be modeled” (Walton, 1995).

3.2.2 Assumptions in CONTAM

To find the contaminant level in each zone and airflow of each path, CONTAM implements assumptions to simplify the mathematical model (Samuel & Strachan 2006, Wang & Chen 2008).

- Mass flow is a function of pressure difference only.
- Each zone is defined as one node with the uniform pressure, density, temperature, contaminant concentration.
- Mixing of contaminant is instantaneous, and there are no contaminant transportation delays. For example, when a contaminant is released in a zone, CONTAM would assume that the contaminant level would be uniform in entire zone within the first time step.
- Heat transfer is not considered in simulations and the temperature in all zones remains constant as it is defined by the user.
- The contaminant density does not affect the density of the air and it has negligible partial pressure. For instance, thick smoke and moisture that change the air density cannot be handled by CONATM.

3.2.3 Validation of CONTAM

An essential part of developing a model from a real building is the validation of the model. As described previously, multi-zone modeling has many limitations and assumptions that may lead to inaccurate results in the output. Also, the difference in output may occur because of the actual weather condition such as humidity, wind speed and direction, and the input data in modeling software. Hence the real airflow path specification may be different from the assumed one used for modeling (Walton, 1981). Validating multi-zone models is very complex since there are many scenarios and pressure distributions in each flow path. Nevertheless, validation effort is crucial since it identifies and prevents large errors in simulations (Emmerich *et al*., 2004).

To verify a multi-zone model different techniques are used:

1) Multi-zone models are verified by comparing the prediction of one model with another model which is called inter-program comparison.
2) Validation by using experimental data in a controlled environment
3) Empirical validation with field measurement data.

As described, one of the verification of multi-zone modeling is comparison of the prediction made by different multi-zone models. Haghighat & Li (2004) showed an agreement between CONTAM, COMIS and ESP-r models. Haghighat and Megri (1996) also stated "good" agreement between prediction made by CONTAM and COMIS and of those made by AIRNET (Walton, 1989), CBSAIR (Haghighat and Rao, 1991), and BUS

(Tuomaala, 1993). The case study that they used for their validation study was experimental result based on a four-zone paper building with eight flow paths.

To validate multi-zone models with experimental data collected in a control environment, Haghighat & Li (2004) and Haghighat and Megri (1996) simulated a controlled environment building using CONTAM and COMIS. In controlled environment, the flow characteristic of each cracks and envelope permeability was measured by fan pressurisation, smoke and tracer gas tests. The measured results were compared with the predictions made by COMIS and CONTAM confirming a good agreement. Nonetheless, most of airflow rate prediction differences between these models and the measured data were within 20%.

To verify the result of CONTAM with field measurement data, Lansari *et al.* (1996) performed experimental evaluation on contaminant transport from the garage to the house. They designed an experiment to quantify the percentage of infiltrated contaminant from the garage to the house**.** They released sulphur hexafluoride (SF_6) that was diluted with nitrogen in garage. SF_6 is released for 20 minutes at a rate of 1 L/s while the garage door was closed till the total released SF_6 reached 7.23 mg. They used five samplers, three samplers in living area and 2 samplers in the garage. In the garage, one of the samplers was located on the roof of the car that was parked which labeled TOPGARAGE and the other one was placed on the garage floor labeled as Leftgarage (Lansari *et al.,* 1996).

The result of detected SF_6 in garage based on simulation of CONTAM and two samples are shown in Figure 3.3. As the figure shows there is a good agreement among the measurement result and simulated result with CONTAM in garage. Results from the samples in the living area showed that the peak concentration occurs after 30 minutes and "the model consistently under predicted the concentrations in all rooms of the house." Concentrations were under predicted by 30 percent in the kitchen and bedroom and by approximately 10 percent in the family room (Lansari *et al.*, 1996).

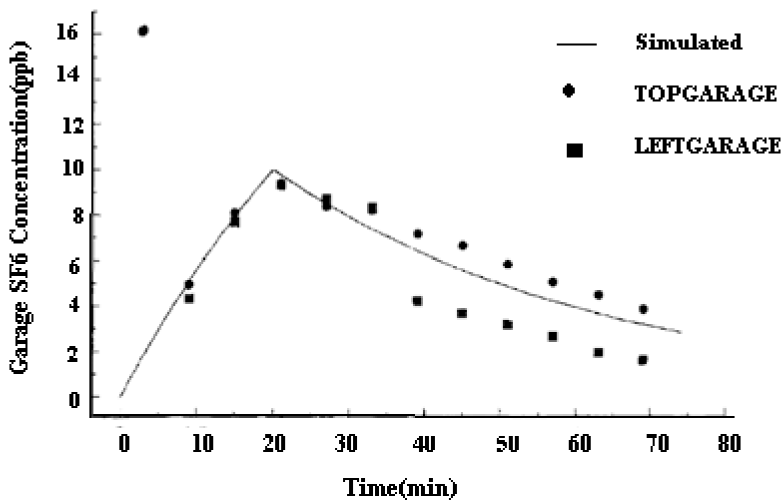

Figure 3.3 Comparison of measured and predicted concentrations of SF_6 in garage, 20min Release time, Q=6.03 μ/s (Lansari *et al.*, 1996)

To verify and validate the result of CONTAM, Emmerich *et al.* (2004) performed an experiment in an occupied three-storey townhouse in Reston Virginia, U.S.A. As conducted by Lansari *et al.* (1996), the experiment was executed by tracer gas. SF_6 was manually injected within one room of the house and its concentration was measured in other rooms. The house then modeled using CONTAM and the predicted result was compared with the experimental data. The result of this research demonstrates that the predicted average SF_6 concentration in all zones is within 10% of the average measured concentration (Emmerich *et al.*, 2004).

As validation studies (Haghighat & Megri 1996, Emmerich *et al.*, 2004, Lansari *et al*. 1996) showed, the multi-zone model CONTAM present correct estimations of air infiltration and contaminant transport within a building under well-mixed conditions. Therefore, to analyze contaminant distribution in the house from the attached garage, CONTAM is used to evaluate the contaminant concentration in the living area with the contaminant source in the garage. The data and parameters for the simulations are based on experimental data. Chapter 4 describes the data for garage-house interface leakage characteristic and the contaminant source in the garage. Chapter 5 illustrates the house models in CONTAM and depicts the simulations and results.

CHAPTER 4: DATA AND PARAMETERS FOR SIMULATIONS

The primary purpose of this study is to evaluate the effect of envelope characteristic of the garage-house interface on contaminant transport from garages to houses. To evaluate the characteristic of house and garage interface, the normalized effective leakage area (ELA) values of 25 garage-house interfaces are calculated based on the result of fan depressurization tests on 25 houses in Canada (Graham *et al.,* 1999). The ELA is a parameter to rate the air tightness effectiveness of the envelope. In this method all openings in one wall or the whole house is combined in one overall opening area. Carbon monoxide (CO) is selected as a contaminant source in the garage. Especially in cold temperatures, a significant amount of CO is emitted from the exhaust of a vehicle. In this study, the effectiveness of garage-house interface on house concentration level of CO is evaluated based on different parameters that affect pressure difference.

4.1 Fan Depressurization Test to Determine the ELA

To determine the leakage characteristic of a house, garage and their interface, Graham *et al* (1999) conducted fan depressurization test. Air leakage into buildings occurs through openings and cracks in buildings because of pressure difference acting across the cracks and openings. To characterize the building leakage through envelope, fan pressurization or depressurization tests are conducted, which is also called blower-door tests.

In this procedure, the airflow is adjusted to the point of required pressure difference, which is typically 50 Pa or 75 Pa. During the test, all the interior doors are left open in order to have a uniform pressure within the building (CAN/CGSB, 1986).
Some of the setups in CAN/CGSB-149.10-M86 standard requirements are as follows:

- All doors and windows are closed to make the building as air tight, as it is in heating season
- All exhaust fans, vented dryers, and air conditions are switched off
- All pilot lights of the vented gas-fired appliances are shut off
- Ventilation, and fireplace dampers are closed

4.1.1 Procedure

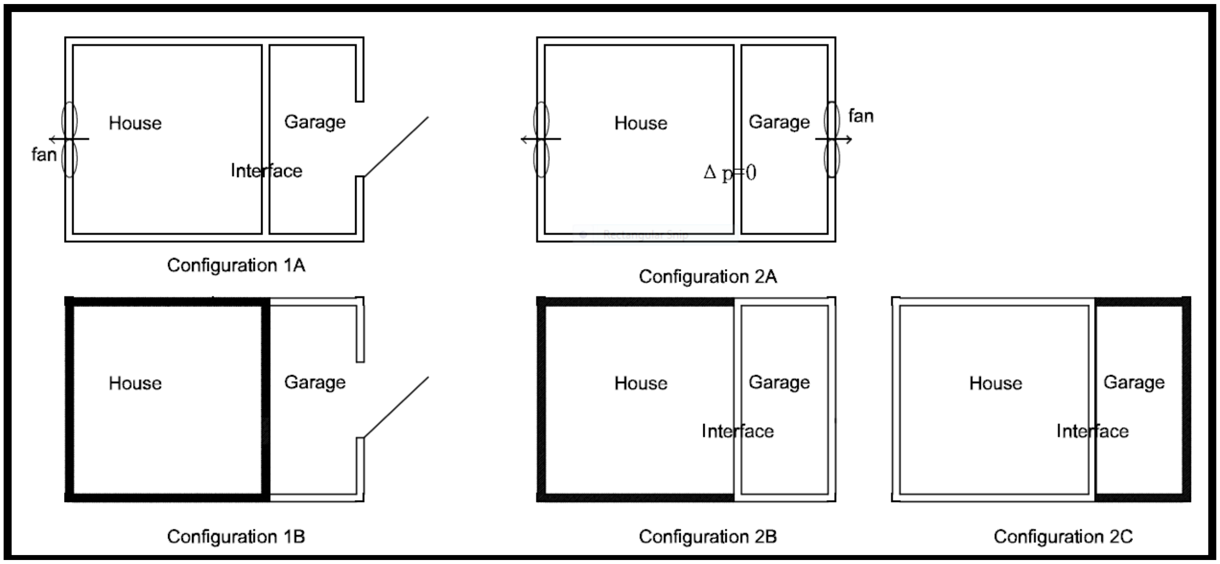

Figure 4.1 Building depressurization test configurations

Figure 4.1 depicts the two test configurations (1A & 2A). In this figure, a building is defined as two zones. One zone is the house and the other zone is the garage, separated by garage-house interface. The fan location is presented in configurations 1A and 2A. The description of each configuration is given in the following paragraphs. In both configurations, blower door fan is used to depressurize the house or garage. The set of result leads to a curve of airflow rate versus pressure difference (Graham *et al*, 1999).

Configuration 1A

In this configuration, the garage door is opened and a fan is located in the house which depressurizes the house continuously. In this configuration, the garage has an ambient condition with a zero pressure difference between the garage envelopes and outside. The flow of this test consists of the flow through the exterior envelope of the house and the garage-house interface (Bold lines in Figure 4.1, configuration 1B). The result of this test determines the leakage characteristic of the house separately from the garage (Graham *et al.*, 1999).

Configuration 2A

In this configuration, one fan depressurizes the house and the other fan in the garage simultaneously depressurizes the garage to avoid any flow transfer through the garage-house interface. As shown in Figure 4.1, there is a requirement of a zero pressure difference across the interface to eliminate the flow through the garage and the house. In this test, pressures and flows in both the garage and the house are recorded to determine the leakage characteristic of the house and the garage, excluding the interface (Graham *et al.*, 1999). The flow of this test consists of the flow through the exterior envelope of the house (bold lines in Figure 4.1, configuration 2B), and the exterior envelope of the garage (bold lines in Figure 4.1, configuration 2C).

Airflow and pressure differences from these two configurations are then fitted and regressed to the power-law equation of

$$Q = k\,\Delta P^{n} \qquad \text{Equation 4-1}$$

The air change rate in the garage-house interface is the difference of configuration 1B (test1: entire house + interface) and configuration 2B (test 2: entire house).

$$Q_{interface} = K_{interface}\;\Delta p^{n\text{-}interface} = k_{1B}\,\Delta P^{n1B} - k_{2B}\,\Delta P^{n2B} \qquad \text{Equation 4-2}$$

Where the air leakage characteristic in the first configuration represents the whole house ($Q1B = k_{1B}\ \Delta p^{n1B}$) and configuration 2B represents the house leakage characteristic without the interface ($Q_{2B} = k_{2B} \Delta p^{n2B}$). Based on the profile of Δp and $Q_{interface}$, a regression curve is used to determine the $K_{interface}$ and $n_{interface}$ at the reference pressure difference of 50 Pa (Graham *et al*., 1999).

The fan pressurization test does not provide any information for specific airflow rate from the openings such as cracks, doors, windows and exhaust ducts. Results of these tests only provide the overall leakage rate of the envelope providing an estimate of total leakage through all openings in the envelope. From these tests Graham *et al*. (1999) found that the air change rate through the interface of the house and the garage represents 13% of the total house leakage and that garages were 10 times leakier than the houses.

4.1.2 Effective Leakage Area (ELA)

In order to rate the air tightness of the building, the predicted airflow rate is converted to ELA by equation 4.3. The equivalent leakage area is a way to estimate the total area of the leaks in a wall or in the whole house (ASHRAE Handbook, 2005).

$$ELA = \frac{10000*K}{CD} \times \sqrt{\rho/2} * \ \Delta P_r^{(n-0.5)} \qquad \text{Equation 4-3}$$

ELA = equivalent or effective air leakage area, cm^2
ρ = air density, kg/m^3
ΔP_r = reference pressure difference, Pa
CD = discharge coefficient
n = pressure exponent, dimensionless

ELA of garage-house interface in Graham (1999) report was determined based on 10 Pa pressure difference. Their results showed the houses without any door connected to the garage and with only one common wall between the house and garage had the least ELA.

To model airflow in a multi-zone building, characterizing leakage path in garage-house interface is essential. The report of Graham (1999) provides very useful information about the average percentage of garage-house air leakage, ELA, and locations that most probable leakage paths may occur. The normalized ELA from garage-house interface of Graham's (1999) study are used in a multi-zone model to evaluate the effect of the interface on pollutant transport in a house.

To rate the effectiveness of the air tightness of the house and also to be able to compare the result, the ELA value is generally normalized by the building surface or volume. There are several ways to normalize the ELA value and also there are variety pressure references that are used to define the ELA value. Normalization factors generally are floor area, exterior envelope area, and building volume. The most used pressure differences are 4 and10 Pa since these pressures are very close to the actual air conditions. The discharge coefficient of effective air leakage area at 4 Pa is assumed 1.0 (Sherman and Grimsrud, 1980) and it is assumed 0.611 at 10 Pa pressure difference (CGSB *Standard* 149.10).

Air leakage areas at one reference pressure difference can be converted to air leakage areas at another reference pressure difference, according to the ASHRAE Handbook (2005) by the following equation:

$$ELA_2 = ELA_1(\frac{CD_1}{CD_2})(\frac{\Delta p_2}{\Delta p_1})^{n-0.5} \quad \text{Equation 4-4}$$

Where:

ELA_1 = air leakage area at reference pressure difference $\Delta P_{r,1}$, cm^2
ELA_2 = air leakage area at reference pressure difference $\Delta P_{r,2}$, cm^2
CD_1 = discharge coefficient used to calculate $A_{r,1}$
CD_2= discharge coefficient used to calculate $A_{r,2}$
n = pressure exponent

In this report, using equation 4.3, the ELA values of garage-house interface are calculated based on the result of the blowing door test of 25 houses in Canada (Graham *et al.,* 1999). The data of garage-house interface were normalized by dividing the ELA value by the area of the interface wall to compare the contaminant transport from the garage to the house in one specific house with different garage-house interface ELA.

Since the selected model in CONTAM is based on 4 Pa pressure difference, the result is converted to 4 Pa pressure difference by Equation 4.4. These are summarized in Table 4.1.

Table 4.1 Garage-house ELA value (Retrieved from Graham *et al.*, 1999)

	k(L/(s.Pa^n))	**n**	**ELA(@10Pa)**	**Area(m^2)**	**ELA(@4Pa)**	**ELA@4/area(cm^2/m^2)**
1	1.54	0.68	30	17.8	15.3	**0.86**
2	9.04	0.63	155	30.5	82.6	**2.71**
3	4.05	0.74	89	11.7	42.9	**3.66**
4	11.60	0.67	207	17.4	106.3	**6.11**
5	13.85	0.82	367	15.1	164.2	**10.88**
6	2.87	0.73	61	15.4	29.6	**1.93**
7	13.93	0.61	229	73.3	124.2	**1.69**
8	1.20	0.73	26	34.6	12.6	**0.37**
9	28.23	0.63	485	18.4	258.3	**14.04**
10	0.10	0.72	2	32.4	1.0	**0.03**
11	6.59	0.77	156	32.4	73.1	**2.26**
12	4.67	0.73	100	30.8	48.6	**1.58**
13	12.39	0.57	187	14.6	105.2	**7.21**
14	2.12	0.82	56	50.5	25.1	**0.50**
15	0.01	0.74	0	19.4	0.0	**0.00**
16	14.17	0.69	279	51.5	140.7	**2.73**
17	2.67	0.69	53	51.4	26.7	**0.52**
18	0.41	0.79	10	53.1	4.6	**0.09**
19	9.73	0.70	194	28.3	96.9	**3.42**
20	3.26	0.74	72	24.3	34.7	**1.43**
21	4.03	0.70	81	24.4	40.5	**1.66**
22	11.23	0.65	200	34.6	104.6	**3.02**
23	0.36	0.71	7	12.9	3.5	**0.27**
24	7.97	0.74	177	23.8	85.2	**3.58**
25	16.93	0.64	299	26.1	157.8	**6.05**

4.2 Carbon Monoxide

Many sources of contaminant in garages are due to exhaust of vehicles. For the purpose of this study carbon monoxide (CO) which is one of the contaminants from the vehicle exhaust is selected as a source of contaminant in the garage. Carbon monoxide (CO) is an odourless, colorless, and tasteless toxic gas and it may be emitted from many sources in a house such as tobacco smoke, woodstoves, unvented or improperly vented water heaters and gas stoves. The cold-start of a car in a garage results in significant CO emissions and may increase the CO concentration to several hundred parts per million inside the garage. The high level CO concentration can occur even if the garage door is open. When the vehicle is left from the garage and the garage door is closed, the level of CO and other contaminants from the vehicle exhaust would be relatively high for a few hours (CMHC, 2011). Some of the exposure regulations of indoor CO concentrations are as follows:

ACGIH: The American Conference of Governmental Industrial Hygienists has assigned the threshold limit value (TLV) of carbon monoxide exposure to 25 ppm (ACGIH 1994).

OSHA: "The current Occupational Safety and Health Administration permissible exposure limit (PEL) for carbon monoxide is 50 (ppm) as an 8-hour time-weighted average (TWA)"(EPA, 2011).

NIOSH "The National Institute for Occupational Safety and Health has established a recommended exposure limit (REL) for carbon monoxide of 35 ppm as an 8-hour TWA and 200 ppm as a ceiling" (NIOSH, 1992).

4.2.1 Contaminant Concentration in Garage

To simulate pollutant (e.g., CO) transport in CONTAM, it is assumed that the CO gas undergoes no chemical reaction inside the garage or in the house. Also, desorption and adsorption of CO from the surfaces is not considered in these simulations. However, based on the experimental result of Lansari *et al*. (1996), the model in CONTAM under-predicts the concentration of the contaminant in the zones that the source is not located. In order to get a reasonable source strength of CO gas in the garage, the result of CO emission from the car exhaust by Graham *et al*. (2004) is used from Table 2.1 in Chapter 2. Based on Table 2.1, the average strength of CO emission in a cold start up of a vehicle, in a 300 second sampling duration and in a temperature of -10° C, is 50 g/test. By dividing this result over the sampling duration, the emission rate is found to be 167 mg/sec (Graham *et al*., 2004).

CO transport from the garage to the house depends both on the pressure difference and the air tightness of the house, garage and their interface. In the next chapter, two buildings are simulated with different parameters that affect the pressure difference between the garage and the house for five normalized ELA values of garage-house interface based on Table 4.1.

CHAPTER5: SIMULATION AND RESULTS

CONTAM (Dols & Walton, 2002) is used in this chapter to carry out parametric simulations and to characterize the contaminant transport from the attached garage to the house. In this study two buildings are simulated. The first building is OPTIBAT which is a real scale experimental facility (Megri, 1993). The effectiveness of ELA of garage-house interface is evaluated on this experimental facility. The second building is a manufactured house with an attached garage, located at the National Institute of Standards and Technology (NIST) campus for ventilation, energy, and indoor air quality studies. The experimental data from the field measurement of this house is provided by Wang & Emmerich (2010). To gain insights on the effect of parameters on contaminant transport a number of simulations are performed for this house. In these simulations, the effect of wind direction, wind speed and ventilation system are investigated.

5.1 Description of OPTIBAT

"OPTIBAT is a real scale experimental building consisting of an 88 m^2 four-room dwelling built in the laboratory hall at the Institut National des Sciences Appliquées (INSA) in Lyon. This dwelling is an apartment in an actual building located near Lyon. Two façades of this dwelling are subjected to a controlled climate" (Furbringer *et al*., 1996) which means that the dwelling is impermeable from two sides and the air can only penetrate to or from the building from the two façades. The climate chamber at each façade can also control the boundary condition to implement a different pressure and temperature. Figure 5.1 and Figure 5.2 present the plan view of this facility with detailed information of zone dimensions.

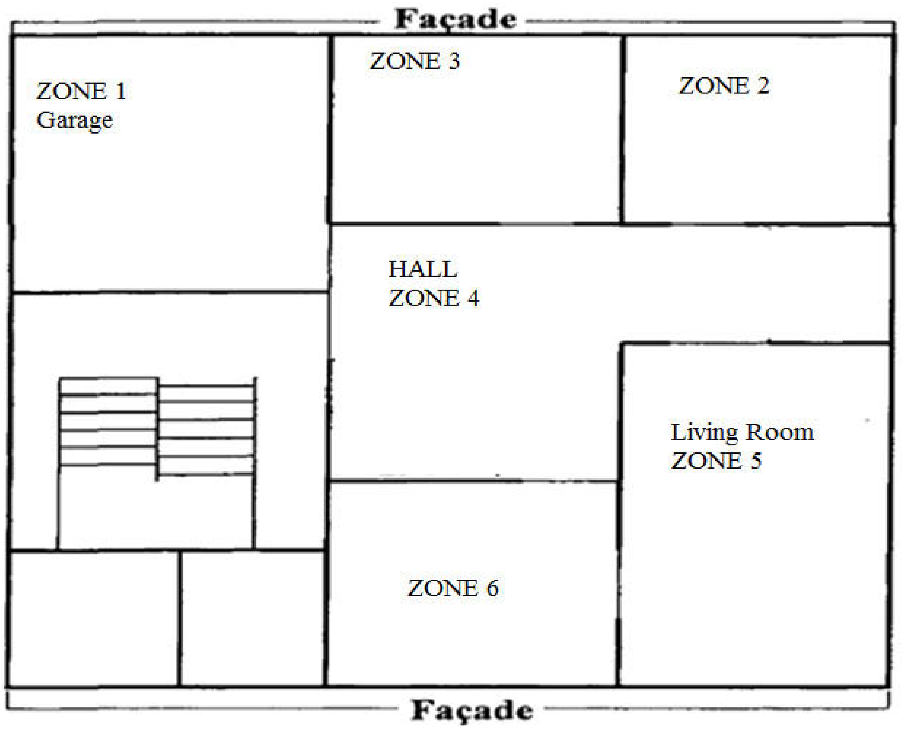

Figure 5.1 OPTIBAT facility for infiltration measurement (Furbringer *et al*., 1996)

In this facility, the measured airflow and envelope characteristics are more reliable compared to real houses because the measurements are taken in a controlled environment. For example, the exact pressures in façades are directly used for simulation which leads to a higher accuracy of results (Megri, 1993). OPTIBAT provides experimental data sets available to be used as a reference for evaluating multi-zone airflow models.

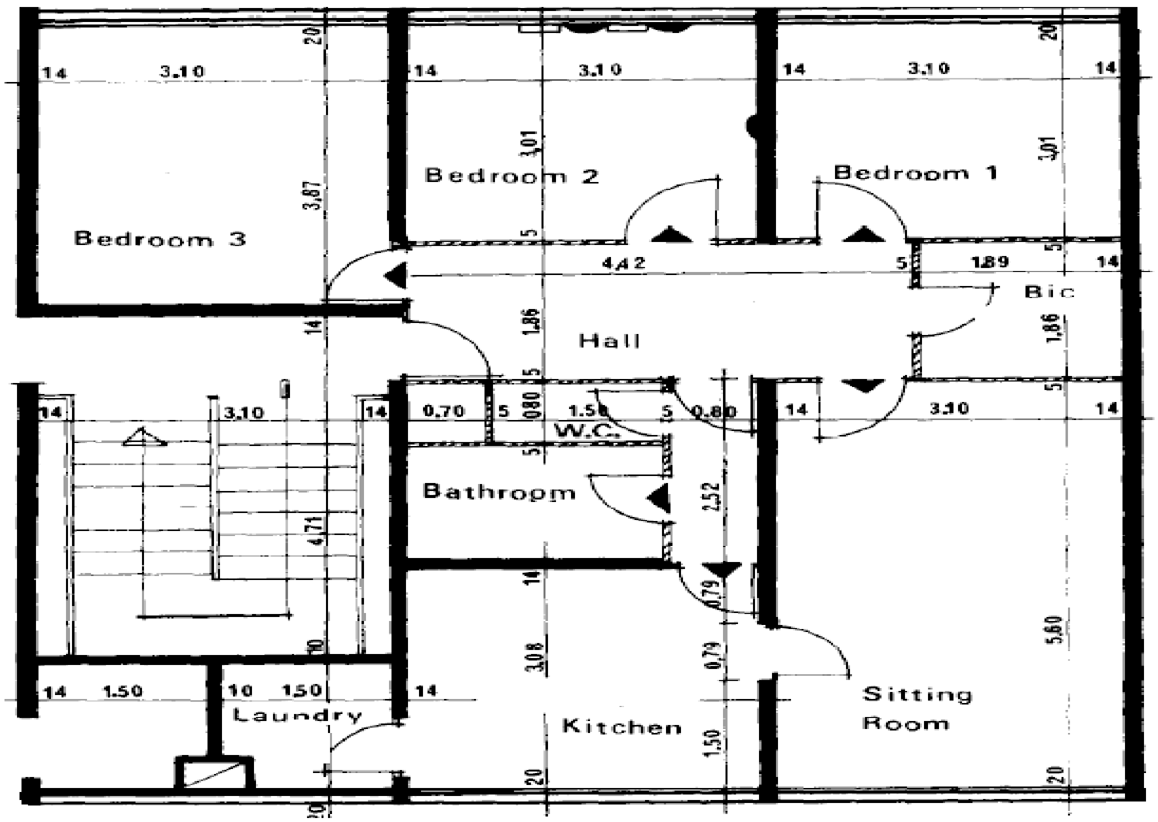

Figure 5.2 OPTIBAT plan view (units are in meter) (Allard *et al.*, 1986)

5.1.1 Experimental Measurement

To measure the leakage characteristic of envelope, fan pressurization was used in OPTIBAT facility. In this experiment, both active and passive methods were used. In active measurement, two fans (blower doors) were employed: one in the primary zone and the other in the secondary zone. The first fan in primary zone kept the pressure difference across the outer wall constant. The second fan was employed to create a number of different pressure differences in the secondary zone from -200 Pa to 200 Pa. At the end, the flow rate of the first fan to create constant pressure difference across the external walls were recorded, which is based on pressure difference in the secondary zone (Megri, 1993).

The passive method is less expensive compared to active method. However, this method is more time consuming compared to active method. It is also more complex since this method requires a set of non-linear equations coupled with statistical calculations to determine the flow coefficient. To measure the flow components in the specific room, one blower door (fan) was installed at the door. Megri (1993) provided a table with the result of flow coefficients and flow exponents of both active and passive methods. The result of their measurements shows that the active and passive methods have a good agreement and the confidence interval using in both methods mostly overlap each other.

5.1.2 OPTIBAT Facility Measurement

Table 5.1 provides temperature and pressure differences between the façade and outdoors. Figure 5.3 illustrates the flow path location as a network modeling. Zone 1 in this figure is selected as a garage. By this assumption, the airflow from this zone to the rest of the building can be predicted. Since garages are typically located at the corner of buildings and they are usually connected to stairways, this selection seems to be reasonable.

Simulation is performed using CONTAM applying information provided in Table 5.1. For airflow characteristics of each path, the required flow coefficients and the exponents are taken from Table 5.2. Subsequently, the simulation result of inter-airflow rate is compared to the result of Haghighat & Li (2004) for validation of the model. Since the garage is less air tight compared to the other zones (Graham *et al.,* 2004), for this simulation, another flow path (CRW14) is added to the garage to improve the infiltration. The pressure difference of this flow path is selected to be -2.8 Pa (pressure difference across façade 3).

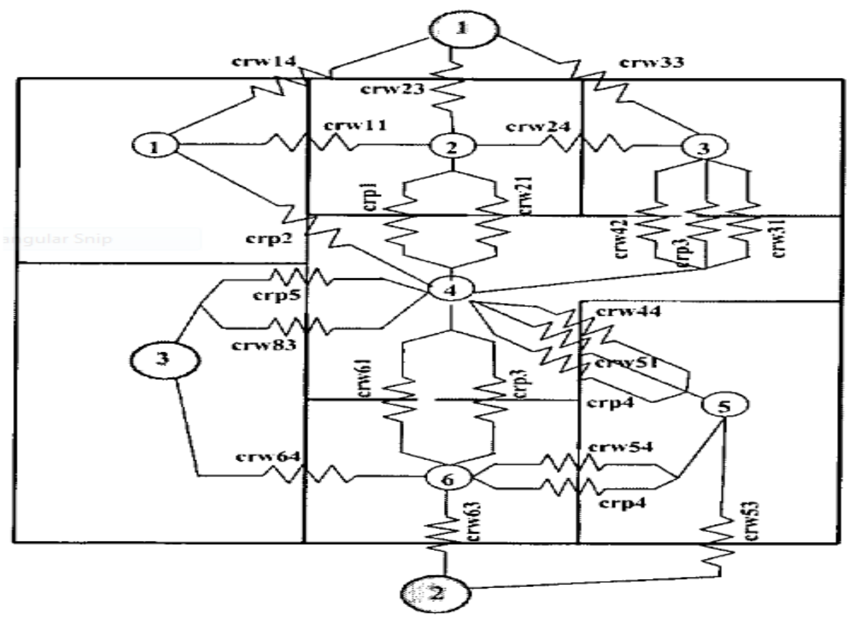

Figure 5.3 Network Modeling of the OPTIBAT (Furbringer *et al*., 1996)

Table 5.1 Climatic condition for OPTIBAT (Furbringer *et al*., 1996)

Scenario	T(out)°C	T(in) °C	ΔP(Pa) (façad 1)	ΔP(Pa) (façad 2)	ΔP(Pa) (façad 3)
summer	20 ±0.5	20 ±0.5	16	-81	-2.8
Winter	-1.1 ±0.5	20 ±0.5	52	-121	-12.6

Figure 5.4 illustrates the detail airflow description of the simulated model in the CONTAM sketchpad interface in a result display mode.

Table 5.2 Input air leakage parameters for simulation (Furbringer *et al*., 1996)

Crack	Flow coefficient K(m^3/hPa)	Flow exponent n
CRW 14	3.73 E-03	0.58
CRW 23	3.28 E-03	0.60
CRW 33	3.19 E-03	0.58
CRW 53	3.10 E-03	0.54
CRW 63	1.52 E-03	0.56
CRW 83	1.09 E-03	0.59
CRW 11	3.89 E-05	0.90
CRW 21	5.62 E-03	0.78
CRW 24	4.72 E-05	0.87
CRW 31	4.15 E-03	0.59
CRW 42	8.25 E-04	0.65
CRW 44	1.57 E-03	0.51
CRW 51	4.18 E-03	0.76
CRW 54	1.75 E-03	0.64
CRW 61	3.44 E-04	0.81
CRW 64	5.53 E-04	0.69
CRP 1	0.00825	0.50
CRP 2	0.01660	0.50
CRP 3	0.02490	0.50
CRP 4	0.02075	0.50
CRP 5	0.02490	0.50

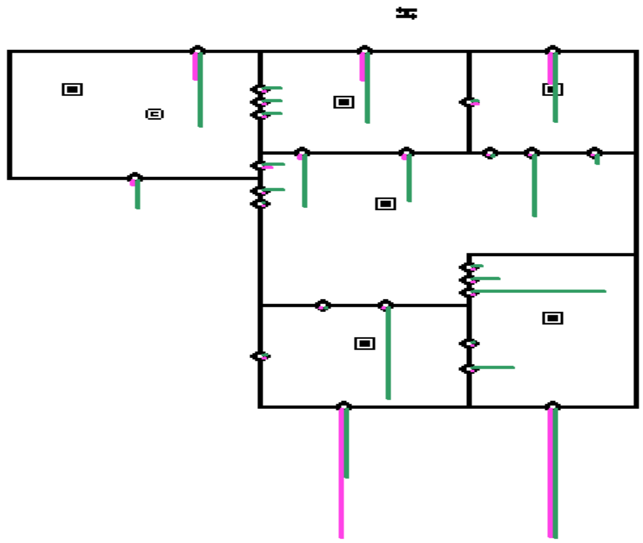

Figure 5.4 The detail airflow description of the simulated model in the CONTAM sketchpad interface in a result display mode

5.1.3 Results (OPTIBAT)

Five normalized ELA of the garage-house interface are selected (Table 5.3). The selected values are taken from Table 4.1 which is based on the measured data of garage-house interface of 25 houses in Canada.

Table 5.3 Garage-house interface ELA(cm^2/m^2)

Low	Median	Average	selected	Highest
0.27	1.93	3.06	7.00	14.00

The contaminant source is located in Zone 1 which is selected as the garage. The contaminant source is assumed to be a constant emission of the CO of a vehicle exhaust. While the exhaust emission period from a vehicle is estimated to last for 300 sec (Graham *et al*., 2004), to evaluate the effectiveness of garage-house interface, the emission rate in the garage is assumed to be constant. This constant emission rate can be referred to the emission rate from a generator (Wang & Emmerich, 2010). Figure 5.5 shows the simulation results of contaminant level for Zone 4 as a function of time for different values of ELA.

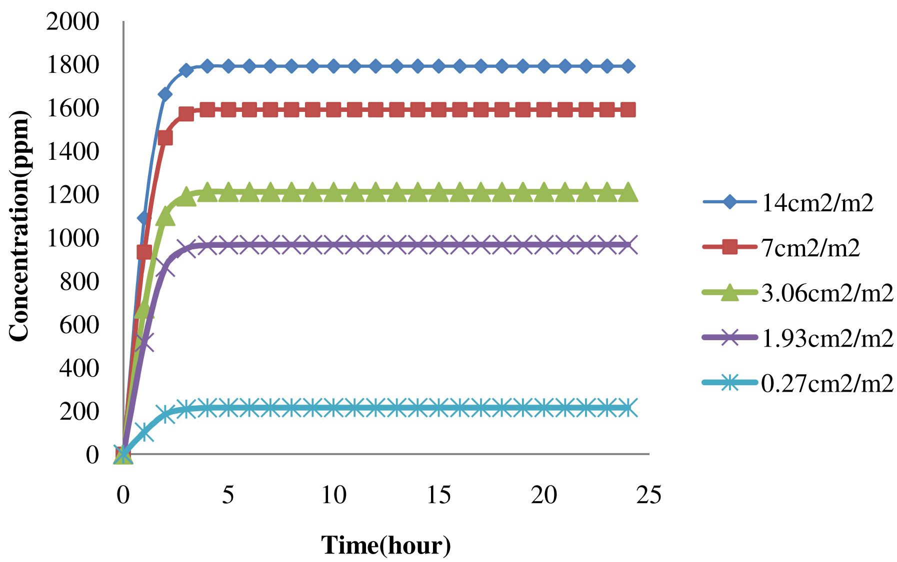

Figure 5.5 Comparison of zone 4 Concentration with different ELA values

The contaminant level as a percent of garage concentration is shown in Table 5.4. In this table, for each ELA value, two columns are designated. The maximum concentration in each zone is presented in the first column and the percentage of concentration from the garage is presented in the second column.

Table 5.4 Highest CO concentration (ppm) in each zone based on different ELA values

Zone	ELA =0.27 cm^2/m^2		ELA =1.93 cm^2/m^2		ELA =3.06 cm^2/m^2		ELA =7 cm^2/m^2		ELA =14 cm^2/m^2	
	max(ppm)	%	Max(ppm)	%	Max(ppm)	%	Max (ppm)	%	Max (ppm)	%
Garage	10100		8870		8510		8010		7770	
2	493	4.9	1850	20.9	2170	25.5	2510	31.3	2510	32.3
3	15.5	0.2	76.2	0.9	97.5	1.2	126	1.6	128	1.7
4	216	2.1	967	10.9	1210	14.2	1590	19.9	1790	23.0
5	215	2.1	963	10.9	1210	14.2	1580	19.7	1780	22.9
6	211	2.1	946	10.7	1190	14.0	1560	19.5	1750	22.5

Based on Table 5.4, as the garage-house ELA value increases, more contaminant from the garage to the house is transported. For example, when the ELA value is 0.27 cm^2/m^2, the maximum concentration in Zone 4 is 2.1% while the maximum concentration increases to 23.0% when the ELA value is 14 cm^2/m^2. This result illustrates the variation of the amount of contaminants transport in Canadian houses.

5.2 Manufactured Home

5.2.1 Description of the Manufactured House

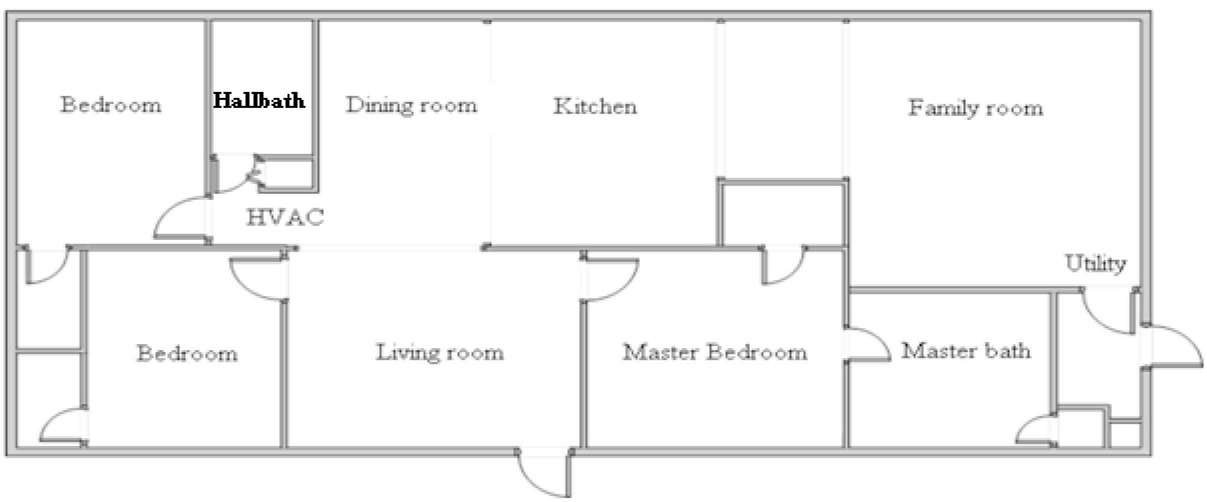

Figure 5.6 Plan view of the house (Presily *et al*., 2002)

To study energy performance and ventilation systems of U.S. manufactured houses, a manufactured house was built at the NIST campus. The Department of Housing and Urban Development (HUD, 1994) requires a minimum of 0.25 h^{-1} air change rate to the house due to infiltration. Persily *et al*. (2003) simulated this house in CONTAM to study mechanical ventilation requirements for U.S. manufactured homes and to investigate the systems used to meet these requirements. The simulation result of this manufactured house by Persily *et al*. (2003) represents that the predicted ventilation rates due to infiltration contributes less than 0.25 h^{-1} despite the assumption in the HUD standards.

Table 5.5 Floor areas and volumes of zones (Persily *et al.*, 2000)

	Floor Area(m^2)	**Volume(m^3)**
Crawl Space		
First Floor		
Kitchen / Living room	69.04	172.6
Master Bedroom	14.28	35.72
Bedroom2	11.28	28.02
Bedroom3	10.95	27.38
Master Bathroom	7.196	18.00
Hall Bath	2.99	7.49
Utility Room	2.97	7.43
Master Closet	2.50	6.25
Closet 1	2.40	6.02
Closet2	2.12	5.29
First Floor	125.70	

The house is a double-wide manufactured home consisting of three levels: crawl space, living area, and attic. The living area, with an approximate living space of 126 m^2, consists of three bedrooms, two bathrooms, and a combined kitchen and living area. This manufactured house is built with cathedral ceilings with an average height of 2.54 m. Figure 5.6 shows the plan view of the house which illustrates the location of each zone and Table 5.5 represents each zone floor area and volume used in COMTAM simulations (Persily *et al.*, 2003).

5.2.2 The Building Air Tightness

To model the house, CONTAM requires all the airflow paths characteristic of the simulated house. To monitor the house air temperature and pressure data, the house is equipped with an automated data acquisition system. The system is instrumented with tracer gas system which monitors the air change rate of the house. To determine the air change rate, SF_6 is injected into the house every 4 to 6 hours. By monitoring the concentration decay in major zones, air change rate of that zone is calculated (Persily *et al.*, 2002).

The pressurization test according to ASTM E779 (ASTM 1999) was performed to determine the whole exterior envelope leakage. The result of this measurement with unsealed ventilation system yielded to an air change rate of $11.1h^{-1}$ at 50 Pa and an ELA of 728 cm^2 at 4 Pa. The same measurement by sealing the exhaust and supply grills yielded a $10.1h^{-1}$ air change rate at 50 Pa and an ELA of 736 cm^2 at 4Pa. Pressurization by two blower doors is also employed to determine the air leakage through the living space to the belly and from the belly to the crawl space (Persily *et al.*, 2002).

To verify CONTAM, the measured air change rate was compared with the simulation. The measured and simulated air change rates are evaluated with the forced-air system off where the pressure distribution in the house is a function of indoor-outdoor air temperature difference at low wind speed conditions. “The result of this comparison showed that the measured value is in good agreement with predicted value specially in low value of ΔT, but tend to under predict by around 20% at higher values" (Persily *et al*., 2002).

5.2.3 Description of the Building in CONTAM

As it is shown in Figure 5.6, the simulated building by Persily *et al*. (2002) did not have a garage. Wang & Emmerich (2010) modified the same model to determine the effect of an outdoor gasoline power generator on indoor carbon monoxide exposures. In their analysis, the garage was added to the simulation model and some flow paths descriptions were changed. The garage was in the first floor and attached to the house. Figures 5.7 to 5.10 provide the detail description of the simulated model in the CONTAM sketchpad interface. The circles in Figure 5.7 indicate the location of fans which are used in simulations in section 5.2.5. The air leakage distribution of the house is represented in appendix A.

To investigate alternate configurations and the impact of garage-house interface on contaminant transport from the garage to the house, the CONTAM model of the manufactured house by Wang & Emmerich (2010) is simulated. The model in CONTAM has four levels which contain a crawl space, belly, living area, and attic. Crawl space and attic are both vented to the outdoors. The original model has one vent that brings the garage air to the attic. Since the simulation of this study is to evaluate the garage-house interface effectiveness, this vent is eliminated in the model. The modeled house also contains forced air heating and cooling systems that are eliminated for the purpose of this study.

The pressure distribution of each wall varies, since the temperature gradient differs based on the height of the wall. To account for this pressure difference, the area of the walls is divided into three equal parts at heights of 1.8 m, 1.2 m and 0.6 m. As it is shown in Figure 5.7, six flow paths connect the garage to the living area. The three of those connect the utility room to the garage, and the rest connect the living room to the garage. To determine the effectiveness of garage-house interface, the five normalized ELA values in Table 5.3 are simulated.

The CO entry to the house is based on 10 minute emission of 167 mg/s from the exhaust of a vehicle as described earlier (Graham *et al*., 2004). This amount may increase by cold starts of more cars in the garage.

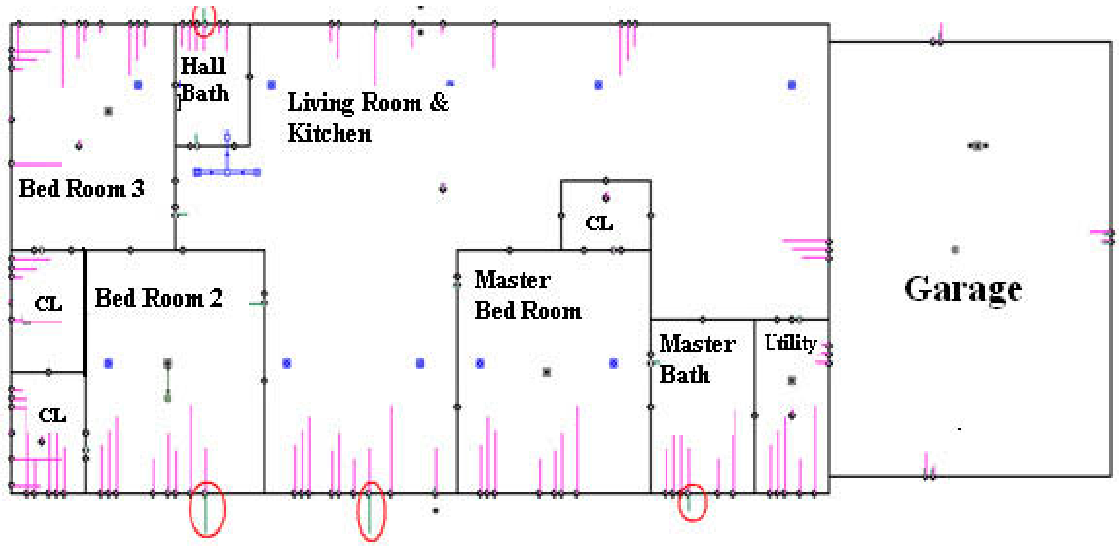

Figure 5.7 Simulated building in CONTAM (Living Area)

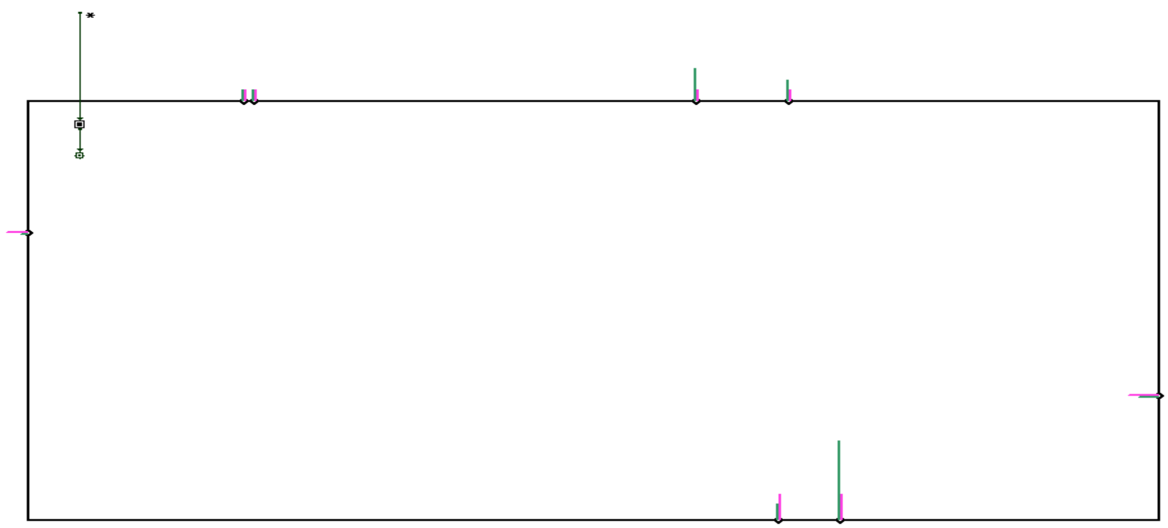

Figure 5.8 Simulated building in CONTAM (Crawl Space)

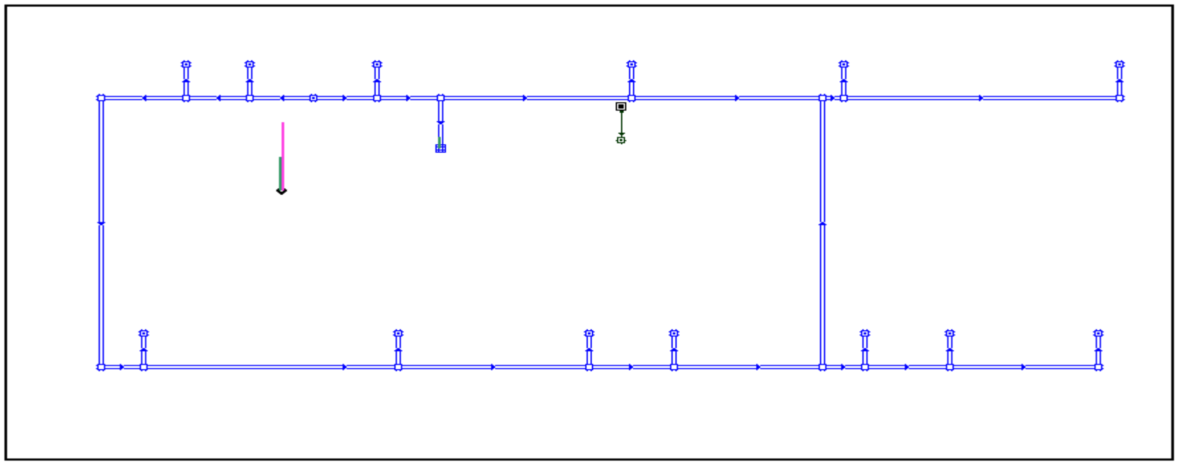

Figure 5.9 Simulated building in CONTAM(Belly)

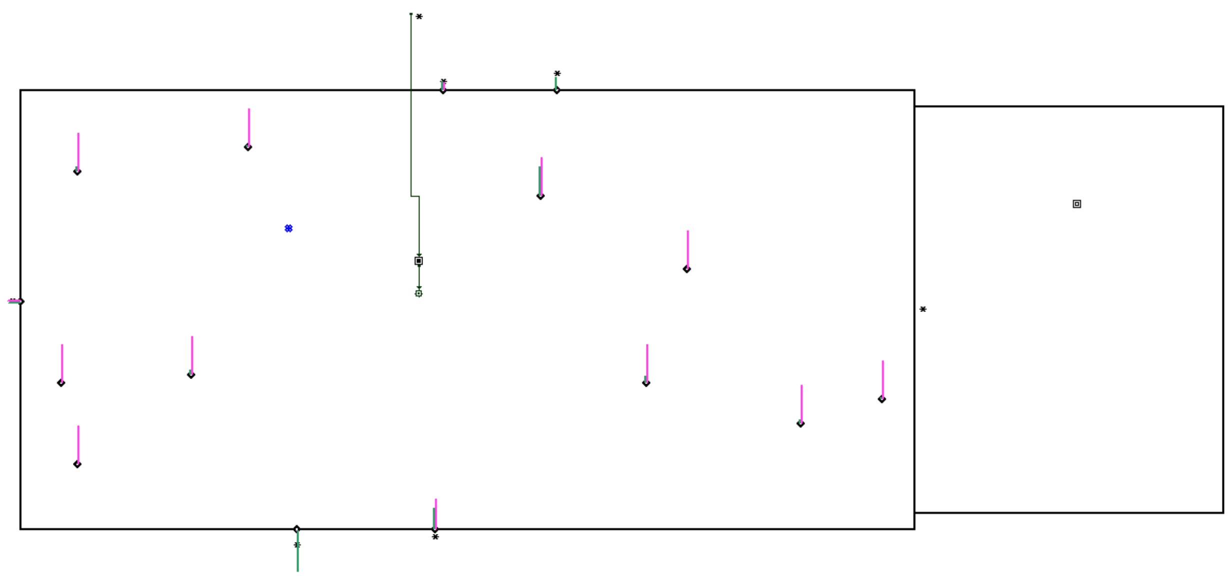

Figure 5.10 Simulated building in CONTAM(Attic)

5.2.4 Results (Manufactured Home)

5.2.4.1 The Effect of Wind Direction

In this section, eight different wind directions are simulated to evaluate the contaminant level in the house. The induced pressure in the building changes with wind direction. “Wind pressure coefficient depends on wind direction, location on the building façade, the orientation of the building, the surrounding terrain and the presence of obstructions in the immediate vicinity of the building” (Fang & Persily, 1995).

In this section, for each garage-house interface ELA value of Table 5.3, eight different wind direction are selected for simulations: N, NE, E, SE, S, SW, W and NW. For simulations, the wind speed is assumed to be 2 m/s. Tables 5.6 to 5.10 present the highest contaminant level of each zone for each garage-house interface based on different wind directions. Figure 5.11 is the combination of results of these tables for the living room. Each curve represents a different ELA value for garage-house interface. The variation in each curve corresponds to maximum concentration relative to centre point and each axis represents different wind directions. These simulations show that, indeed, wind direction affects the pressurization of the garage. Higher pressurization causes a higher magnitude of contaminant dispersion from the garage to the house.

The highest concentration level in the living room occurs by 135° of the wind direction from the North. The geometric view of the house shows that the living room is mostly connected to the north wall. On the other hand, the south direction of the wind

(180º) would create the highest negative pressure on the north wall. However, for a 180º wind direction, not much contaminant is transported to the living area. Based on the numerical study, the south–east (135º) direction creates both negative pressure on the north wall and also high pressure on both east and south wall of the garage wall, results in the highest contaminant transport.

Table 5.6 Maximum concentration for all rooms in ppm (ELA=0.27cm^2/m^2)

Wind direction	Maximum concentration for all rooms in (ppm) for (ELA=0.27cm^2/m^2)								
	Hallbath	Bedroom3	LivingRoom	Garage	bedroom2	Masterbed	Utilities	Masterbath	Attic
0°	0.14	0.12	1.79	383.00	0.53	0.48	16.70	0.09	0.97
45°	0.21	0.17	2.45	378.00	0.68	0.59	22.70	0.10	1.41
90°	0.25	0.20	2.28	368.00	0.29	0.23	20.90	0.02	1.55
135°	0.30	0.26	2.74	378.00	0.05	0.02	22.50	0.00	1.45
180°	0.22	0.28	2.01	383.00	0.03	0.02	16.40	0.00	1.00
225°	0.21	0.17	1.76	417.00	0.03	0.02	15.20	0.00	0.77
270°	0.17	0.12	1.45	434.00	0.11	0.22	13.20	0.03	0.74
315°	0.15	0.11	1.61	417.00	0.38	0.45	14.90	0.09	0.75

Table 5.7 Maximum concentration for all rooms in ppm (ELA=1.93cm^2/m^2)

wind direction	Maximum concentration for all rooms in ppm (ELA=1.93cm^2/m^2)								
	Hallbath	Bedroom3	LivingRoom	Garage	bedroom2	Masterbed	Utilities	Masterbath	Attic
0°	0.95	0.76	11.70	375.00	3.74	3.45	96.30	0.69	6.24
45°	1.35	1.08	15.10	371.00	4.78	4.31	111.00	0.83	8.31
90°	1.57	1.25	14.20	358.00	2.35	2.03	99.70	0.25	9.13
135°	1.95	2.42	17.20	371.00	0.32	0.16	105.00	0.00	8.60
180°	1.52	2.29	13.50	375.00	0.23	0.11	87.00	0.00	6.41
225°	1.44	1.13	11.80	407.00	0.21	0.12	85.00	0.00	4.88
270°	1.12	0.76	9.40	426.00	0.78	1.55	79.60	0.20	4.71
315°	0.99	0.74	10.50	407.00	2.61	3.10	90.50	0.62	4.76

Table 5.8 Maximum concentration for all rooms in ppm (ELA=3.06 cm^2/m^2)

wind direction	Maximum concentration for all rooms in ppm (ELA=3.06 cm^2/m^2)								
	Hallbath	Bedroom3	LivingRoom	Garage	bedroom2	Masterbed	Utilities	Masterbath	Attic
0°	1.45	1.17	17.80	370.00	5.90	5.50	128.00	1.15	9.25
45°	1.99	1.59	22.00	366.00	7.32	6.69	141.00	1.35	11.90
90°	2.39	1.91	21.40	352.00	3.90	3.51	130.00	0.47	13.50
135°	2.81	3.94	24.50	366.00	0.87	0.23	132.00	0.00	12.10
180°	2.35	3.76	20.40	370.00	0.35	0.17	116.00	0.00	9.50
225°	2.18	1.72	17.90	401.00	0.33	0.18	116.00	0.00	7.24
270°	1.69	1.16	14.30	420.00	1.26	2.43	112.00	0.33	6.95
315°	1.50	1.13	15.90	401.00	4.09	4.86	124.00	0.99	7.09

Table 5.9 Maximum concentration for all rooms in ppm (ELA=7 cm^2/m^2)

wind direction	Maximum concentration for all rooms in ppm (ELA=7 cm^2/m^2)								
	Hallbath	Bedroom3	LivingRoom	Garage	bedroom2	Masterbed	Utilities	Masterbath	Attic
0°	2.86	2.31	35.00	354.00	12.40	11.90	193.00	2.69	17.30
45°	3.92	3.14	43.10	350.00	15.90	15.10	212.00	3.41	22.30
90°	4.62	3.71	41.20	335.00	9.08	8.57	199.00	1.42	24.90
135°	6.46	9.84	47.30	350.00	4.24	0.44	206.00	0.02	22.50
180°	5.48	8.60	39.50	354.00	0.67	0.33	184.00	0.00	17.70
225°	4.40	3.40	35.30	383.00	0.64	0.35	176.00	0.00	13.70
270°	3.33	2.31	28.80	404.00	2.85	5.14	176.00	0.74	13.20
315°	2.98	2.24	31.70	383.00	8.72	10.20	183.00	2.22	13.40

Table 5.10 Maximum concentration for all rooms in ppm (ELA=14 cm^2/m^2)

wind direction	Maximum concentration for all rooms in ppm (ELA=14 cm^2/m^2)								
	Hallbath	Bedroom3	LivingRoom	Garage	bedroom2	Masterbed	Utilities	Masterbath	Attic
0°	4.46	3.65	55.20	332.00	20.40	20.00	253.00	4.86	26.50
45°	6.06	4.85	66.40	328.00	25.70	25.00	268.00	6.26	33.60
90°	7.01	5.65	62.80	312.00	15.80	15.20	253.00	2.94	37.10
135°	11.60	17.70	71.80	328.00	9.53	4.06	263.00	0.33	33.90
180°	9.59	15.20	61.60	332.00	1.63	0.52	243.00	0.00	26.90
225°	7.74	5.40	56.80	359.00	1.00	0.54	241.00	0.02	21.20
270°	5.43	3.76	48.00	380.00	5.06	8.92	235.00	1.33	21.00
315°	4.75	3.56	51.20	359.00	14.80	17.20	248.00	3.90	20.90

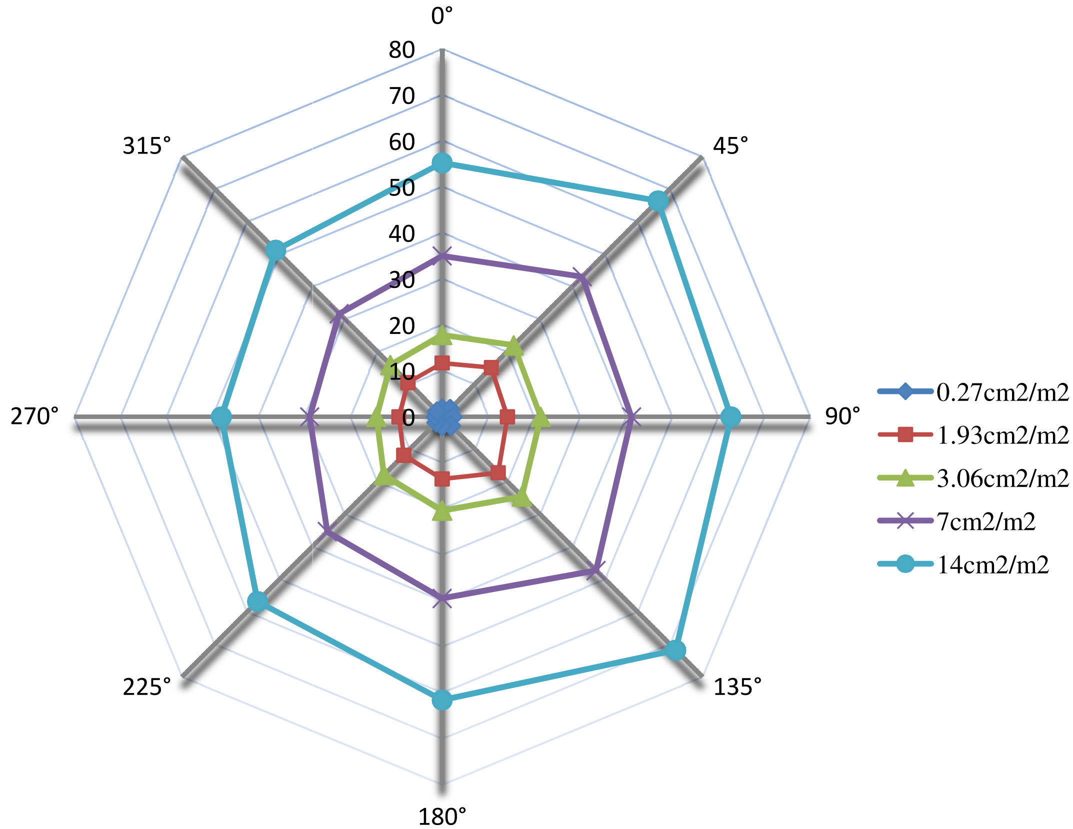

Figure 5.11 CO concentration in the living room (ppm) for different wind directions and ELA values (wind speed = 2 m/s)

Figure 5.12 demonstrates the hourly concentration of CO as a function of ELA. The house is simulated with the wind speed of 2 m/s and wind direction of 135˚. As the results show, the living room CO concentration level, with the garage-house ELA value of 3.06 cm^2/m^2 , reaches to 24.5 ppm. The TLV by ACGIH is 25 ppm; therefore, the ELA value higher than 3.06 cm^2/m^2 would be critical for this house.

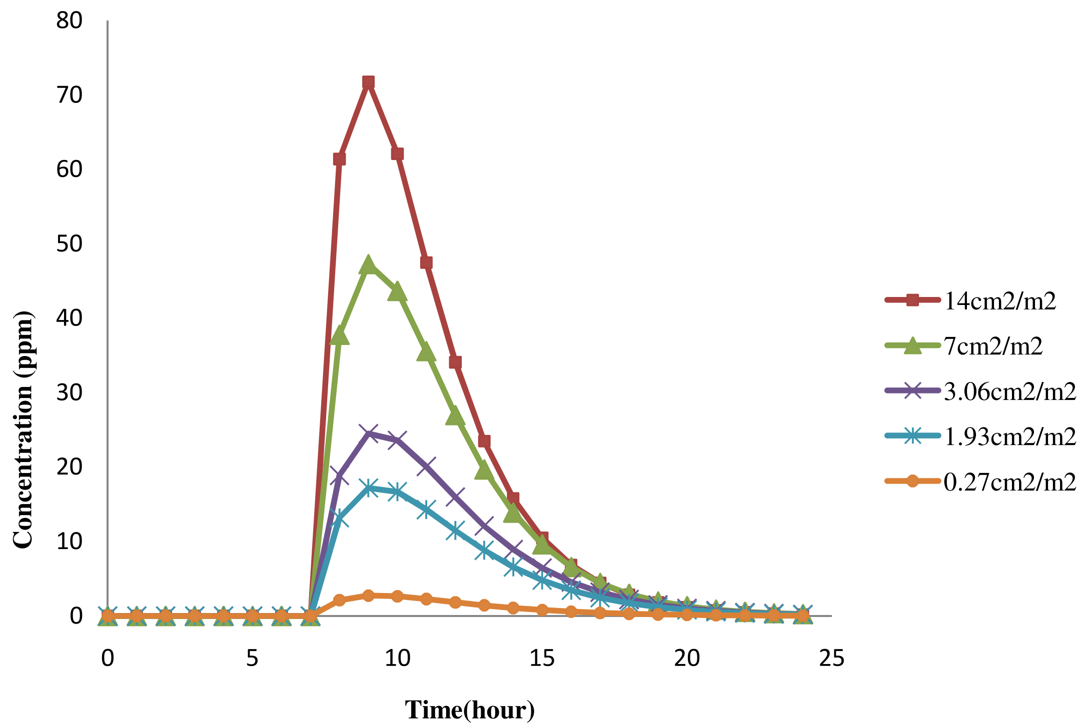

Figure 5.12 Comparison of living room concentration with different ELA values

5.2.4.2 The Effect of Wind Speed

To evaluate the pressure induced with wind speed and its effect on contaminant transport, five different wind speeds are selected based on a typical winter day in Montreal, 2, 4, 6, 8 and 13 m/s. Moreover, for each wind speed, the five different ELA values of garage-house interface (Table 5.3) are simulated. As illustrated in the Table 5.6 to

Table 5.10, regardless of the garage-house ELA, the highest peak concentration level in the living room occurred at a wind direction of 135˚. Therefore, 135˚ wind direction is selected for the rest of the simulations. Figures 5.13 to 5.17 show the effect of wind speed on CO transport to the house for all selected ELAs in living room.

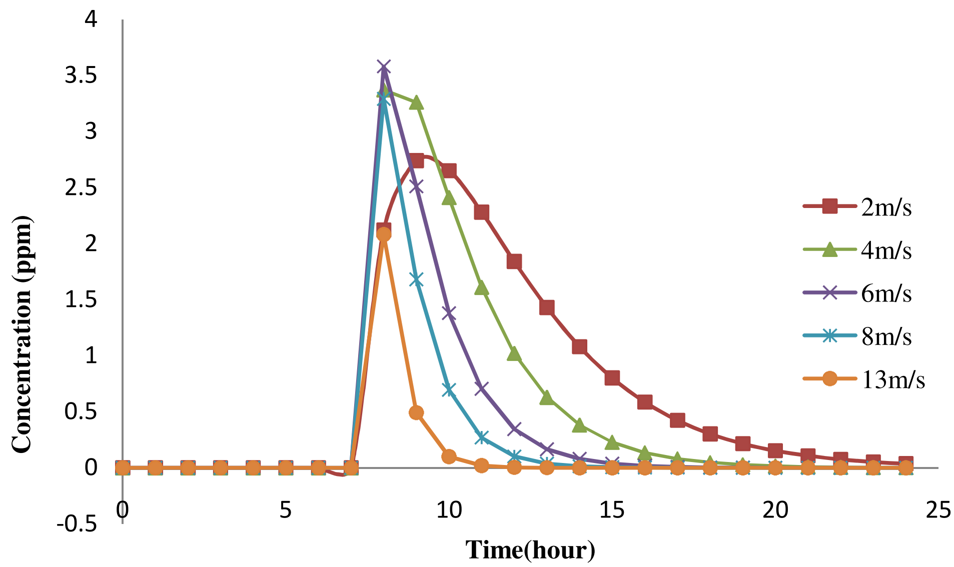

Figure 5.13The comparison of the living room concentration with different wind speeds (ELA=0.27 cm2/m2)

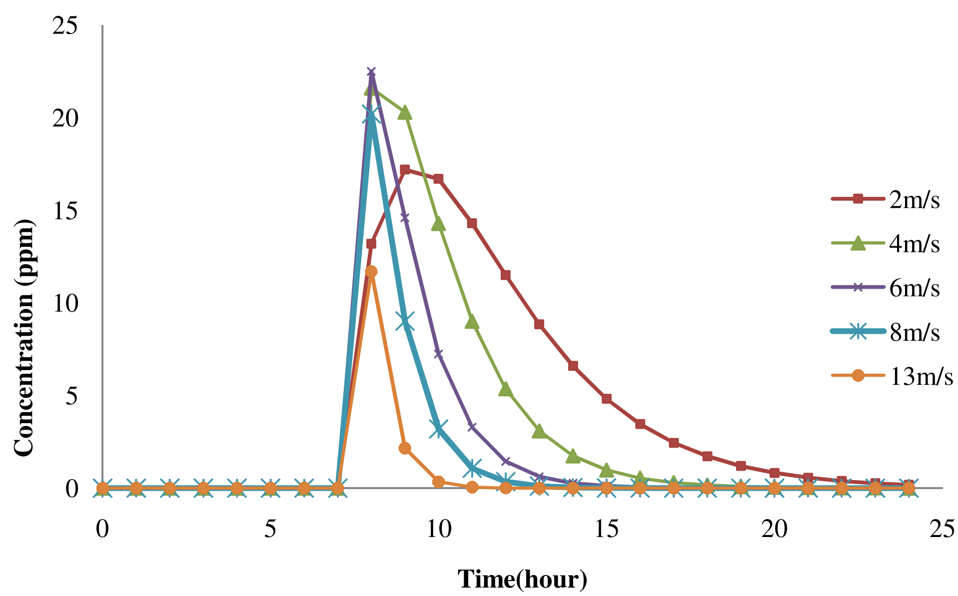

Figure 5.14 The effect of wind speed on concentration level in the living room (ELA=1.93 cm^2/m^2)

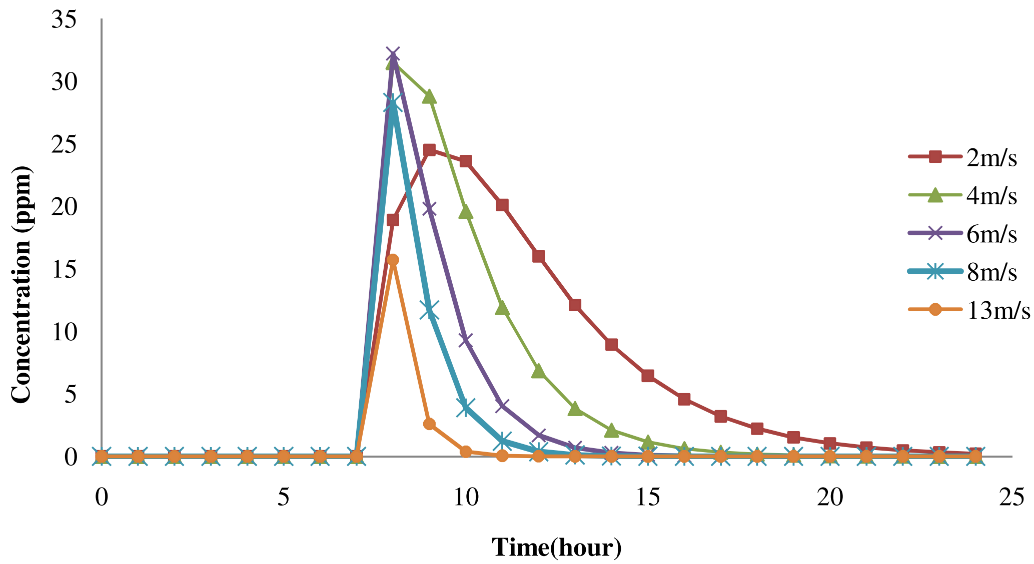

Figure 5.15 The effect of wind speed on concentration level in the living room (ELA=3.06 cm^2/m^2)

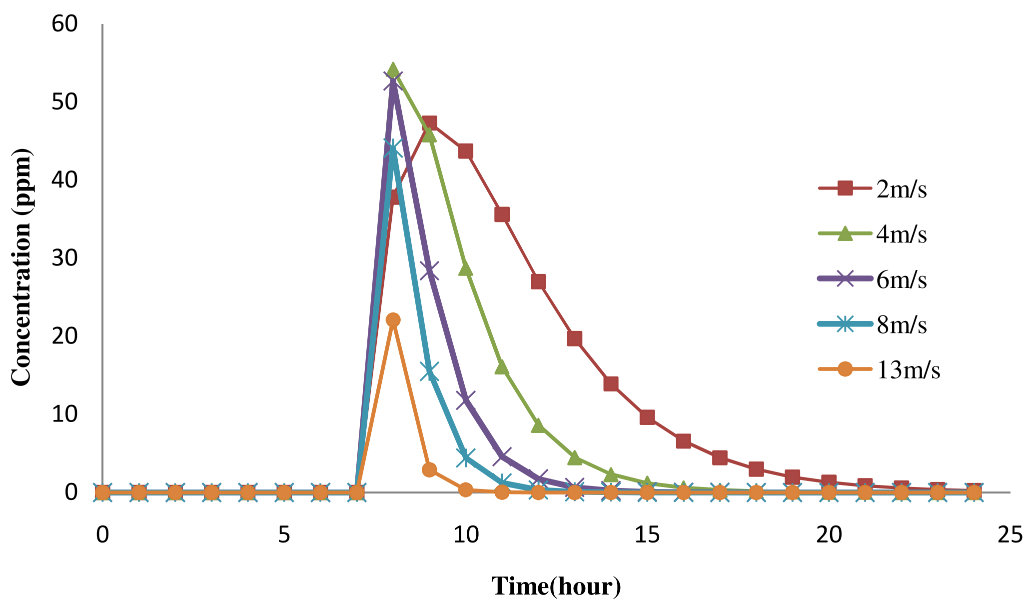

Figure 5.16 The effect of wind speed on concentration level in the living room (ELA=7 cm^2/m^2)

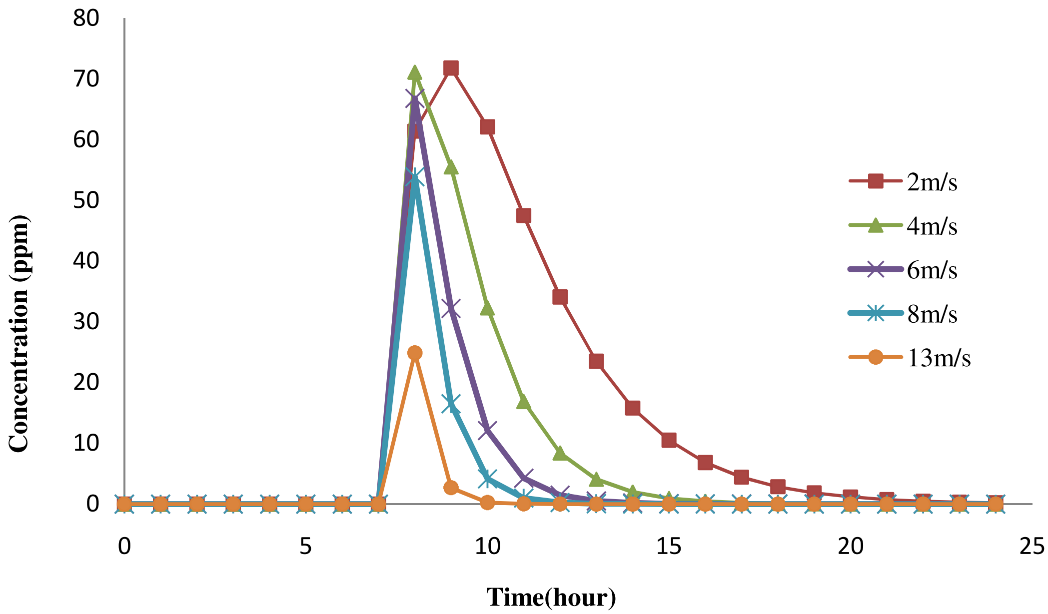

Figure 5.17 The effect of wind speed on concentration level in the living room (ELA=14 cm^2/m^2)

The result of these simulations show that wind speed is an important factor in depressurizing the building and drawing the contaminant from the garage into the house. The magnitude of contaminant entry rate in the house is increased by higher wind speed. However, higher wind speed causes higher airflow into the building envelope and consequently, higher air change rate. While exhaust or wind induced depressurization increases the contaminant entry rate from the garage to the house, it also increases the outdoor air dilution rate. Therefore, when the wind strength is high enough, the CO peak concentration is reduced.

As Figures 5.13 to 5.17 show, when the wind speed is 2 m/s, there is less infiltration; therefore, CO is trapped in the living room for longer hours. When the ELA is less than 7 cm^2/m^2, the peak concentration of CO for the wind speed of 4, 6 and 8 m/s is higher compared with the wind speed of 2m/s. Nevertheless, the concentration of CO for higher wind speed is decreased for the second hour and there is relatively lower exposure duration of CO. At the wind speed of 13 m/s, the outside air infiltration is so high that after one hour the concentration decreases dramatically.

Figure 5.18 illustrates the simulation result of the CO concentration in the garage. As it is shown in this figure, in terms of occupant exposure, the worst wind speed is 2 m/s. The magnitude of CO concentration in the garage decreases by increasing the wind speed since with higher wind speed, the garage is naturally ventilated. Table 5.11 represents the maximum concentration level for all zones with respect to wind speed and the garage-house interface ELA.

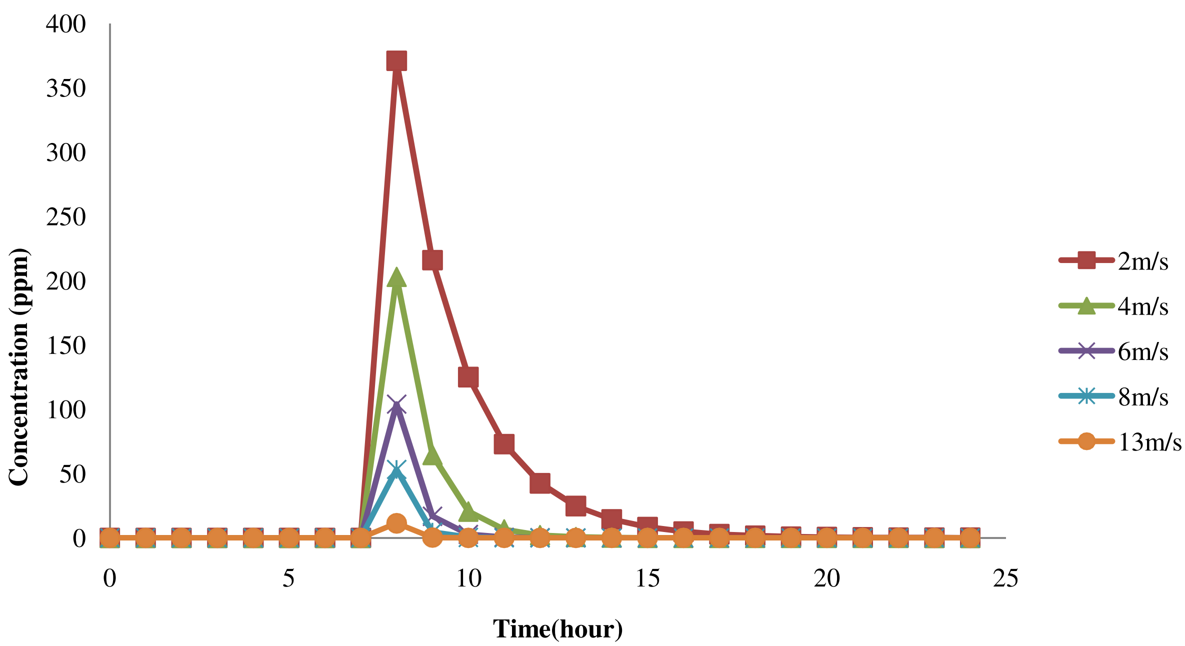

Figure 5.18 The effect of wind speed on concentration level in the garage (ELA=1.93 cm^2/m^2)

Table 5.11 The highest CO concentration(ppm) in each zone based on different wind speeds and ELA values

wind speed(m/s)	Hallbath	Bedroom3	LivingRoom	Garage	bedroom2	Masterbed	Utilities	Masterbath	Attic
	(ELA=0.27 cm^2/m^2)								
2	0.30	0.26	2.74	378.00	0.05	0.02	22.50	0.00	1.45
4	0.71	1.53	3.37	217.00	0.03	0.01	25.80	0.00	1.09
6	1.13	1.90	3.58	115.00	0.01	0.01	24.50	0.00	0.86
8	1.15	1.93	3.29	60.80	0.00	0.00	20.20	0.00	0.69
13	1.36	1.91	2.08	13.60	0.00	0.00	9.95	0.00	0.38
	(ELA=1.93 cm^2/m^2)								
2	1.95	2.42	17.20	371.00	0.32	0.16	105.00	0.00	8.60
4	5.75	10.40	21.60	203.00	0.22	0.10	116.00	0.00	6.81
6	8.22	12.40	22.50	104.00	0.11	0.05	91.80	0.00	5.42
8	8.09	13.00	20.20	53.30	0.03	0.01	63.30	0.00	4.27
13	9.09	11.70	11.70	11.30	0.00	0.00	20.80	0.00	2.24
	(ELA=3.06 cm^2/m^2)								
2	2.81	3.94	24.50	366.00	0.87	0.23	132.00	0.00	12.10
4	9.20	15.80	31.50	195.00	0.33	0.16	144.00	0.00	9.98
6	12.50	17.80	32.20	98.00	0.17	0.07	104.00	0.00	7.91
8	12.60	19.30	28.30	49.70	0.06	0.03	66.90	0.00	6.17
13	13.30	16.50	15.70	10.20	0.00	0.00	19.00	0.00	3.15
	(ELA=7 cm^2/m^2)								
2	6.46	9.84	47.30	350.00	4.24	0.44	206.00	0.02	22.50
4	18.90	29.50	54.20	178.00	0.60	0.29	175.00	0.00	17.70
6	22.80	30.30	52.70	85.70	0.34	0.16	109.00	0.00	13.80
8	24.40	34.10	44.10	41.90	0.19	0.08	61.00	0.00	10.60
13	22.50	25.80	22.10	7.98	0.00	0.00	13.70	0.00	5.06
	(ELA=14 cm^2/m^2)								
2	24.40	34.10	54.20	371.00	4.24	0.44	206.00	0.02	22.50
4	27.90	40.40	71.10	165.00	4.95	0.41	180.00	0.00	24.20
6	31.00	42.50	66.80	76.40	2.96	0.25	101.00	0.00	18.90
8	35.20	46.00	53.90	36.10	1.86	0.15	52.30	0.00	14.20
13	29.50	31.70	24.90	6.45	0.85	0.03	10.30	0.01	6.43

5.2.5 The Effect of Mechanical Ventilation System

One of the important factors that influence the contaminant dispersion in the house is the pressure difference by mechanical equipments. This pressure difference is caused by supplying or exhausting air from the house by mechanical ventilation system or by vented combustion devices. Mechanical equipment affects the pressure difference across the envelope of the house and consequently, the garage-house interface. Based on the conservation of mass, the interior static pressure adjusts in a way that the sum of all the airflows through the house from the openings in envelope and the mechanical induced airflow balances to be zero. Therefore, by introducing exhaust or supply ventilation systems, the amount of infiltration and exfiltration of air through the building envelope changes.

One of the simplest ventilation systems is the exhaust ventilation system. The exhausted air in this system must be balanced by increasing the infiltration into the building through envelope opening. As a result, more air from outdoor is introduced to the house. Nevertheless, the improper design of this system causes higher airflow rate from the garage to the house and increases the contaminant entry from the garage.

In this section, the effect of exhaust ventilation system on contaminant concentration in the living area is simulated with different normalized ELAs for garage-house interface. For each normalized ELA, seven scenarios are simulated based on number of exhaust fans in operation (Table 5.12) to show the effect of exhaust ventilation system in the house. Table 5.12 highlights the arrangement for each scenario. The exact locations of fans are indicated in Figure 5.7.

Figure 5.19 to 5.23 show the effect of exhaust fans on CO concentration in the house. In these simulations, the same conditions of the previous section are used with the wind direction of 135°.

Table 5.12 Exhaust ventilation description

1	**no fan**
2	Master bath (10 L/s)
3	Master bath(10 L/s),Hall bath(10 L/s)
4	master bath(10 L/s),hall bath(10 L/s), Bedroom2 (22 L/s),
5	Masterbath(10 L/s),Hallbath(10 L/s), Bedroom2 (22 L/s),LivingRoom(10 L/s)
6	Masterbath(10 L/s),Hallbath(10 L/s), Bedroom2 (22 L/s),LivingRoom(22 L/s)
7	Masterbath(10 L/s),Hallbath(70 L/s,8:00-9:00am), Bedroom2 (22 L/s)

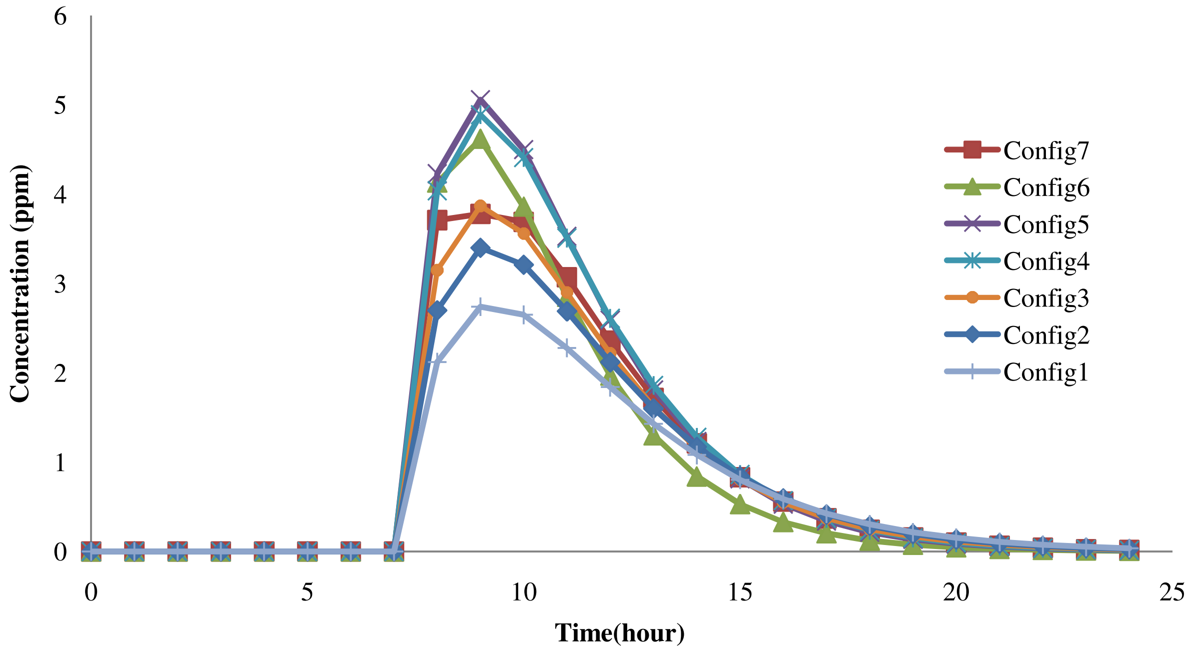

Figure 5.19 Comparison of the living room concentration with different fan locations (ELA=0.27 cm^2/m^2)

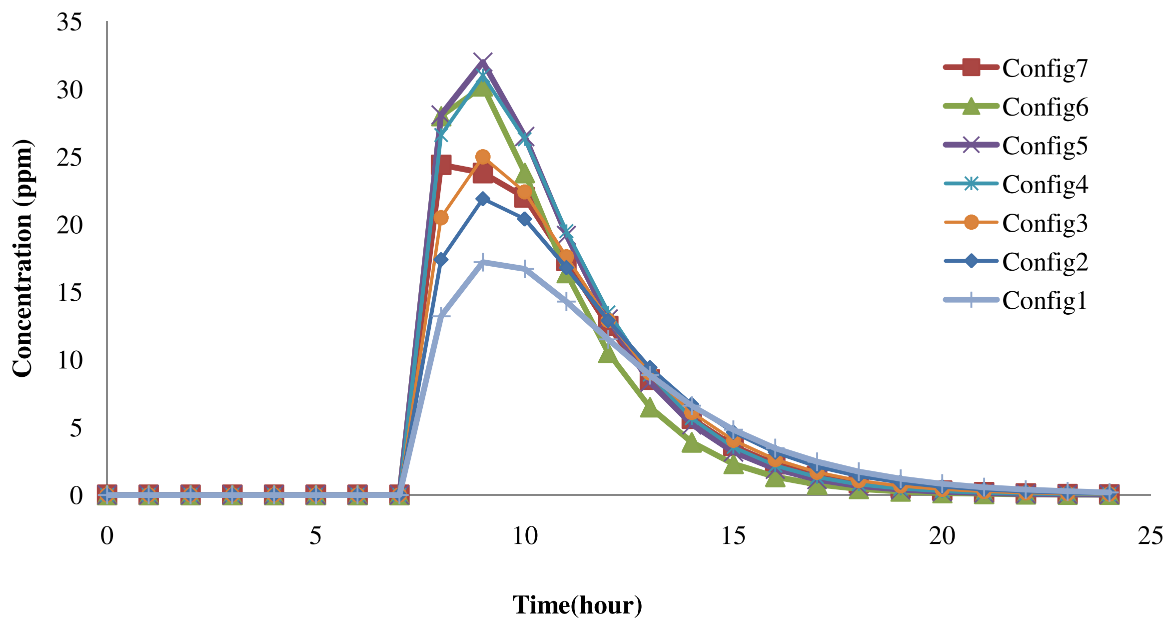

Figure 5.20 Comparison of the living room concentration with different fan locations (ELA=1.93 cm^2/m^2)

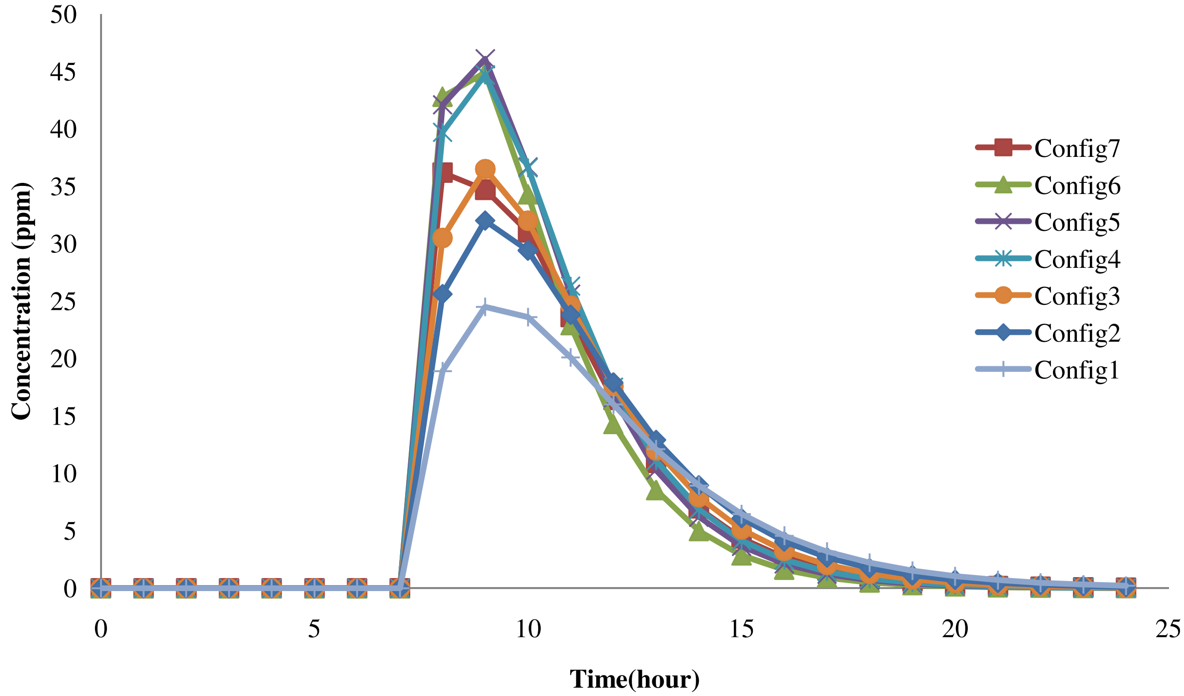

Figure 5.21 Comparison of the living room concentration with different fan locations (ELA=3.06 cm^2/m^2)

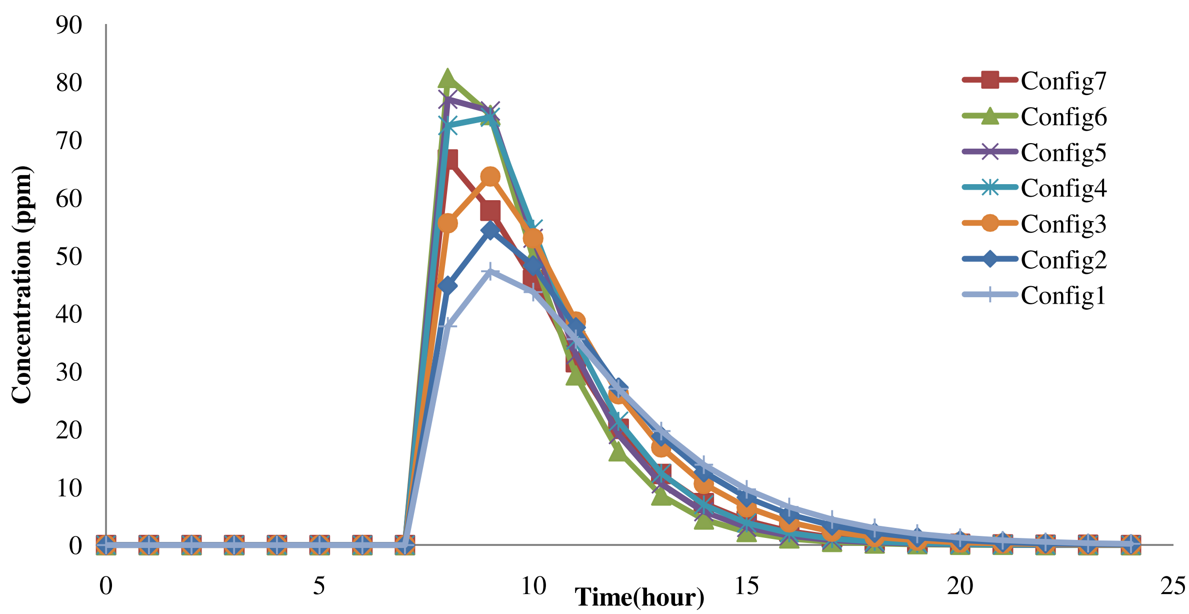

Figure 5.22 Comparison of the living room concentration with different fan locations (ELA=7 cm^2/m^2)

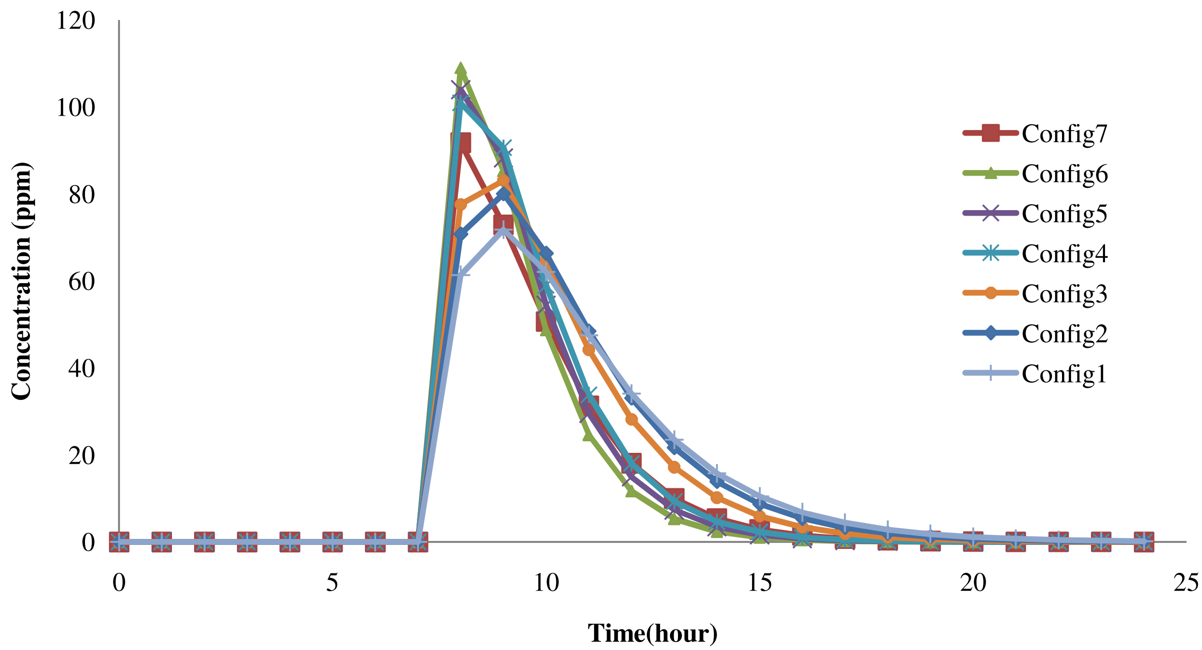

Figure 5.23 Comparison of the living room concentration with different fan locations (ELA=14 cm2/m2)

Table 5.13 Peak Concentration Level in Living Room (ppm) with different fan configurations

	Low	Median	Average	Selected	Highest
	$0.27cm^2/m^2$	$1.93cm^2/m^2$	$3.06cm^2/m^2$	$7cm^2/m^2$	$14cm^2/m^2$
config1	2.7	17.2	24.5	47.3	71.8
config2	3.4	21.9	32.0	54.4	80.1
config3	3.9	25.0	36.5	63.7	83.1
config4	4.9	31.0	44.7	73.9	101.0
config5	5.1	32.0	46.1	77.0	104.0
config6	4.6	30.2	44.9	80.7	109.0
config7	3.9	24.4	36.2	66.6	91.8

Configuration 1 represents the base case with no exhaust fan, and for each subsequent configuration the exhaust flow is increased. As it is illustrated in Figure 5.19 to 5.23, the lowest peak concentration occurs by the base case with no fan in operation. Table 5.13 provides the peak concentration value for each configuration with different

ELAs. Moreover, by increasing higher exhaust flow rate in each configuration, the peak concentration is increased except configuration 6 and 7. Moreover, for the ELA values of 7 cm^2/m^2 and 14 cm^2/m^2, the permissible CO level is not achieved for all the configurations. For the other cases, the worst case scenario is when implementing exhaust ventilation in configuration 5. For instance, for the ELA value of 1.93 cm^2/m^2, and for the base case with no exhaust fan in the house, the peak concentration is 17.2 ppm whereas it is 32 ppm in configuration 5. As this result shows, the concentration level increased by 86% and reached to an unacceptable CO level. However, by increasing the exhaust flow rate, the infiltration rate also increased which result in decrease of contaminant level in configuration 7 for all garage-house ELA values. For instance, with the average ELA of 3.06 cm^2/m^2 the highest concentration of 80.7 ppm occurs in configuration 6. Nevertheless, by adding an exhaust flow rate in Hall bath (70L/s, 8:00-9:00am), the peak concentration reduces to 66.6 ppm. To ensure that the CO concentration level in the living area is below permissible concentration in configuration 5 (worst case scenario), more simulations are carried out. The ultimate result showed that the garage-house ELA value should not exceed 1.4 cm^2/m^2.

CHAPTER 6: CONCLUSIONS

Parametric studies of two buildings have been carried out to analyze the impact of garage-house interface on the contaminant transport from attached garages to living area. The envelope characteristic of garage-house interface of a building is analyzed based on the experimental data of five normalized Effective Leakage Area (ELA) of the garage-house interface. The parametric study indicates that both natural ventilation (wind direction and speed) and mechanical ventilation system influence the pressure difference in the house and consequently affect the contaminant transport from the garage to the house.

In this study, two validated buildings models in CONTAM by Megri (1993) and Wang & Emmerich (2010) are used as a base model for parametric studies. The experimental data of the characteristic of the garage-house interface of 25 houses are provided from the report which was sponsored by Health Canada (Graham *et al.* 1999). The experimental results demonstrate that the interface between the garage and the house is not completely air tight and the pressure difference between the house and the garage causes the contaminant from the garage to be transported into the house.

Multi-zone model for indoor air quality and contaminant transport analysis, CONTAM, was employed to predict contaminant levels in living areas based on the garage-house interface. To model the building, the measured values from the experimental results are required. Nevertheless, experiments are limited to a certain number of conditions, beyond which other scenarios that occur in different climates in Canada cannot be evaluated. Therefore, by using a simulation model like CONTAM, different scenarios are easy to evaluate. CONTAM is validated in previous studies by comparing the prediction of one model with another model, experimental data in a controlled environment and empirical validation with field measurement data. Hence, this software is reliable to estimate the concentration level of contaminant in the house with the contaminant source in the garage.

Wind direction, wind speed and mechanical ventilation system are the factors that influence pressure difference across the exterior envelope and consequently the garage-house interface. Since each of these factors influence the air pressure independently, the building is simulated separately for each factor. The simulation result shows each of these factors influence the pressure difference garage-house interface in a specific way.

Wind direction impacts the inter-zonal airflow patterns within the house and from the garage to the house; hence, it affects the CO transport from the garage to the house and the CO level in each zone. The simulation study shows that the level of contaminant in the house is depend on both the zone location and the area of the zone. For example, the highest concentration in the living room occurs when the wind direction is 135˚ while the highest concentration for utility room occurs when the wind direction is 45˚. Since the area of the utility room is smaller than the living area, the concentration level exceeds the threshold value of 25 ppm (ACGIH, 1994) when the ELA value is higher than 1.93

cm^2/m^2. Therefore, this study strongly suggests that small bedrooms should not be attached to the garage with exceeding garage-house ELA value of 0.27 cm^2/m^2. However, for a large surface area of living room, the ELA between garage and house may be limited to 3$cm^2/m^2$for the tested house.

The simulation results on wind speed demonstrate that the higher wind speed, the more contaminant is transported to the house; however, the infiltration is also increases and the exposure duration of contaminant is decreased. By increasing the wind speed the peak concentrations are increased. For example, with the ELA of 1.93 cm^2/m^2, by increasing the wind speed from 2 m/s to 6 m/s, the concentration peak changes from 17.2 ppm to 22.5 ppm. Conversely, the peak concentration would decrease to 11 ppm with 13 m/s wind speed. This contrast is due to simulation result which is based on hourly steps. Therefore, the infiltration increase in this case is so high that overcoming the CO transport rate and improves the indoor air in less than one hour.

Moreover, the depressurization induced by exhaust ventilation system is simulated and contaminant level to the house is computed. As the result of this study shows, exhaust ventilation system is an important factor that creates pressure difference between the garage and the house. Seven configurations with different exhaust ventilation system locations are introduced in Table 5.12. Increasing exhaust flow rate in each configuration, the peak concentration is increased till configuration 6. For instance, the contaminant level in the living room with the garage-house ELA value of 1.93 cm^2/m^2 is increased by 86 % from configuration1 with no exhaust ventilation to configuration 5 with 52 L/s exhaust system in operation. In this case, without exhaust ventilation, the contaminant level in the living area is considerably lower than the threshold limit of 25 ppm; however, by introducing the exhaust fans as shown in configuration 5, the contaminant level exceeds the threshold limit value.

In this study a procedure is developed for evaluating the impact of garage-house interface on the dispersion of contaminant from a garage to indoor air. This study introduces the normalized ELA value for garage-house interface in Canadian houses and its effectiveness on contaminant transport. The parametric simulation of this study also demonstrates that the existence of exhaust ventilation, at 2 m/s wind speed and 135° wind direction, increases the contaminant entry rate from the garage to the house. The result shows that the worst case scenario is when a 52 L/s exhaust ventilation (master bath (10 L/s), hall bath (10 L/s), bedroom2 (22 L/s), living room (10 L/s)) is implemented. In this case, with an ELA value of 1.93 cm^2/m^2, the CO peak concentration level in the living room is escalated by 86% compared to the case with no exhaust ventilation. The change of CO concentration in the living room depends on the CO entry rate to the living room and also the rate of infiltrated outdoor air. The results of this study illustrate that the improper design of exhaust system causes higher airflow rate from the garage to the house and increases the contaminant entry rate from the garage.

6.1 Contributions

The main contribution of this thesis is the development of a procedure for evaluating the impact of garage-house interface on the dispersion of contaminant from a garage to indoor air. This technique can be used to study the building occupant's exposure to contaminant generated or stored in the garage and to develop procedure to reduce this exposure.

This study also illustrates that the garage-house interface of many houses in Canada is leaky and there is a high dispersion of contaminants from the garage to the living area. For example, the ELA value higher than 3.06 cm^2/m^2 results in an unacceptable contaminant level in the given house for most of the conditions. This study sheds light on the fact that the depressurization, caused by the exhaust ventilation system increases contaminant entry rate from the garage to the living area. Therefore, rather than using exhaust ventilation system, balance ventilation system in living area could be used.

6.2 Future work

There are very limited studies on contaminant transport from garages to residential houses. The procedure proposed in this thesis was utilized to study the impact of operation of exhaust ventilation in the living area on the contaminant transport through the garage-house interface. Further work should be carried out to develop a natural or hybrid exhaust ventilation technique to create a negative pressure between garage and living area. This could be based on demand ventilation technique. This requires further research to indentify the most common gas that can be found in a garage.

This study investigated numerically the garage-house interface characteristic with the assumption of well mixed zones. This assumption can be an acceptable assumption for this study. However, this assumption requires to be verified further by both experimental and numerical research, in which we need to identify under what conditions this assumption is invalid. In such a scenario, a single zone CFD model for the garage can be implemented within a CONTAM network. In this approach more precise value for the amount of contaminants level in living area can be predicted. Based on a more detailed result of contaminant entry rate to the house, a more accurate value for the ELA of garage-house interface could be determined.

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APPENDIX A: The air leakage distribution in the house

	Exterior Air Flow Path	ELA at 4 Pa
Living Space Envelope	Exterior Wall	0.11 cm^2/m^2
	Ceiling wall Interface	0.63 cm^2/m
	Floor Wall Interface	0.97 cm^2/m
	Window#1	5.00 cm^2
	Window#2	1.94 cm^2
	Corner interface	0.63 cm^2/m
	Exterior Doors	18.7 cm^2
	Living Space Floor to Belly	2.97 cm^2/m^2
Interior Air flow Path		
	Interior walls	2 cm^2/m^2
	Bedroom Doorframe	410 cm^2
	Open Interior Doors	2m×0.9m
	Bathroom Doorframe	330 cm^2
	Interior Doorframe	250 cm^2/m^2
	Closet Doorframe	4.6cm^2
Attic		
	Attic Floor	2 cm^2/m^2
	Roof Vents	0.135 cm^2
Crawl Space and belly	Exterior Wall of Crawl Space	25 cm^2/m^2
	Rear Crawl Space Vents	323 cm^2
	Front Crawl Space Vents	465 cm^2
	Crawl Space Access Door	206 cm^2
	Crawl Space to “Belly”	258 cm^2