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An experimental method for contaminant dispersal characterization in large industrial buildings for IAQ applications.

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ABSTRACT

Spatial contaminant distribution in large semiopen building areas such as sports arenas, warehouses, atriums, malls and other industrial halls is critical to estimating exposure, health risks and building energy performance. It is considered a challenge to measure experimentally how effectively the ventilation system removes or dilutes the pollutant in a large open space, taking into consideration the usual non uniformity of the air flow created by local heat and contamination sources, geometrical obstructions and the air distribution system. An experimental method is presented in this paper which can be used for both the experimental evaluation of ventilation effectiveness as well for CFD modeling validation in large open space applications. The developed method which is based on a passive perfluorocarbon tracer gas (PFT) system previously used for infiltration measurements in homes has been successfully used for the experimental evaluation of ventilation effectiveness in an ice skating arena in the Boston area and for the validation of a developed CFD model for the analysis of the IAQ in ice rink facilities. The method is very easy to use, fast and fairly inexpensive and it does not interfere with human and other activities within the building environment.

Key word Index : IAQ, contaminant dispersal, CFD modeling, Ice Skating Arenas

1. INTRODUCTION.

Exposure to air contaminants in the building environment constitutes a potential health hazard especially in large industrial halls and commercial buildings with air pollution sources such as combustion byproducts and other chemical emissions from equipment. Dilution ventilation along with other pollution source control measures, is the most

widely applied strategy to lower the contaminant level below the threshold limit. But even if an acceptable average room concentration can be achieved at a given ventilation rate it does not mean that localized areas with unacceptably high concentrations do not exist in such a large space.

Characterizing the contaminant distribution in a large scale industrial building is considered a difficult technical task, taking into consideration the non uniformity of the indoor air flow created by local heat sources, geometrical obstructions and the air distribution method. The significant spatial variation of contaminant concentration was found in many IAQ field studies in manufacturing plants and other laboratory experiments (Niemala et al, 1994, Bach et al, 1992). The sensitivity of concentration to various flow nonuniformities is also identified in many studies (Hagstrom et al, 1999). Therefore, a significant number of points is required in order to get a reliable contamination distribution over the whole space.

An important parameter which links the contaminant distribution and the ventilation system performance is ventilation effectiveness. Many definitions have been used to describe how effectively the ventilation system removes the contaminant from the space. According to Sandberg (1983), ventilation effectiveness, n_v , can be defined as follows:

$$n_v = \frac{\int_0^{\infty} C_{ref} dt}{\int_0^{\infty} C_{ave} dt} \quad (1)$$

where C_{ave} is the average concentration in the space and C_{ref} is the concentration at a reference point (i.e. exhaust grille). A more simplistic definition was proposed by Nielsen (1992) as:

$$n_v = \frac{C_R}{C_{ave}} \quad (2)$$

where C_R is the concentration in the return opening.

Tracer gas methods and various gases have been used successfully to measure air infiltration rates and ventilation characteristics in large buildings. (P. Lagus et al, 1985). Various tracer gases have been used such as He, H₂, SF₆ and CO₂. Usually, electron capture, thermal conductivity, flame ionization or infrared absorption detectors (R. J. David, 1974) are being used to measure the tracer gas level. At present, all this instrumentation requires a fair amount of expertise, is bulky and is considered very expensive. Taking into consideration that many sampling points are needed to realistically characterize the contaminant distribution, many detectors or multipoint samplers may be required. Another significant limitation particularly in Sports arenas, is also the fact that the instrumentation method and samplers must not interfere with activities. For example, it would not be an easy task to distribute SF₆ gas around the ice

surface of the arena or to walk around with bulky SF₆ detectors to take measurements while there is a hockey game going on.

The research reported here was focused on an experimental method which can be used to evaluate the ventilation effectiveness in a large scale space. The method can also be used for CFD contaminant dispersal modeling validation, since many sampling points can easily and inexpensively be obtained and also the contaminant source strength is constant. The method is also very easy to use and nonobtrusive. As a typical application of the method, the indoor air environment of an ice skating arena was studied and a developed CFD model was successfully validated with the experimental data.

2. EXPERIMENTAL METHOD.

The tracer gas system:

The tracer gas system which was used was developed at Brookhaven National Laboratory, NY (R. Dietz et al, 1986) and has been widely used since then for infiltration and air exchange measurements, mainly in residential applications. It consists of miniature passive perfluorocarbon tracer gas (PFT) sources and capillary adsorption sampling tubes (CAT). Figure 1 shows a typical source and CAT.

The PFT source is only 32mm long and the 6.6 mm inside diameter cylindrical aluminum shell is filled with 0.4 ml of PFT gas. There are four commonly used perfluorocarbon tracer gases, perflourodimethylcyclobutane (PDCB), perflourodimethylcyclopentane (PMCP), perflouromethylcyclohexane (PMCH) and perflouromethylcyclohexane (PDCH).. PMCH was used on this study. The PFTs are non-toxic and found in the background natural air environment in concentrations approximately 10³ times lower than the analytical working limit of detection (LOD); thus there is insignificant background interference in these measurements. It is worth to point out that the most widely used tracer gas ,SF₆ , has an atmospheric background of 900 fL/L while PMCH :has only 3.6 fL/L. The shell is fitted with a silicone rubber plug and crimped to achieve a tight seal. At constant temperature the PFT vapor permeates through the silicone rubber at a constant rate. The permeation rate is measured in the lab during the calibration process. PMCH sources have a useful lifetime of about 4 years during which the only changes seen in permeation rates have been attributed to recorded temperature differences.

The PFT sources were prepared and calibrated in our laboratory. Each source has a unique identification number engraved on its side for quality control. The permeation rate at a given temperature (24 C) was determined by measuring the source weight loss during a specified time interval using a high precision microbalance. The effect of temperature on the permeation rate was previously experimentally determined in our lab. A 3% increase /decrease of the emission rate for every degree C temperature increase/decrease from the reference point of 24 C was measured respectively. Therefore, a correction factor has to be applied on the reference source emission rates, based on the source temperature.

The passive samplers (CATs) are deployed in the field to collect the PFT vapor. The CAT consists of a glass tube, 6.4 cm long, 4 mm inside diameter, 6 mm outside diameter, and is protected with two PFT impermeable polyurethane end caps. A centrally-positioned charcoal-like adsorbent bed is secured in the tube by stainless steel screens. PFT vapor is collected passively by diffusion. Using Fick's Law of Diffusion, the sampling rate of 8.38 ml/hour was calculated from the tube's geometry and the PFT diffusion coefficient. Gas chromatography with electron-capture detection (GC-ECD) is used to determine the amount of PMCH on the CAT after the exposure of the CAT in the field for a given time interval. The analytical method is described in more detail in a following section.

Field Deployment of sources and samplers:

The sources are distributed in the space. After remaining in the space for some time to reach steady state conditions and with the HVAC system running continuously, the passive samplers were deployed in the selected locations and remained in place for a designated sampling period. At the end, both sources and samplers are removed. The air temperature close to the sources is also measured in order to correct the source permeation rates.

There are some critical issues related to the deployment of the sources and samplers. The first issue is how long will it take to obtain equilibrium therefore steady state conditions. The second issue is how long the samplers have to remain in place in order to collect enough tracer gas for the analysis. The third issue is the location and the number of sources and samplers. Obviously, the number and the location of the sources as well as the air exchange rate and ventilation effectiveness affect the amount of sampled gas.

Applying a single zone IAQ model (Sparks, L.E., 1988) to the space the space concentration levels can be expressed as follows:

$$V \frac{dC_{PMCH}}{dt} = \sum_n ER(t) - (ACH)VC_{PMCH}(t) \quad (3)$$

Where C_{PMCH} is the concentration level in pL/m^3 , ACH is the air exchange rate (hr^{-1}), $\sum ER$ is the sum of the permeation rates of all sources placed in the space (pL/hr) and V is the volume (m^3).

The PFT sources were designed to provide a constant emission rate in the building, therefore $\sum ER$ can be considered time independent (Dietz, 1986).

Under steady state conditions and under the assumption that the pollutant is uniformly mixed instantly within the space and its outdoor concentration level is equal to zero, the average concentration level can be estimated according to the following formula:

$$C_{PMCH}^{Steady} = \frac{\sum_n ER}{(ACH)V} \quad (4)$$

For example, on a number of 150 PFT sources, Figure 2 shows the amount of PMCH gas to be sampled in correlation to the air exchange rate and the sampling duration time for an ice rink arena. The theoretical ACH rate for well mixed conditions for this space is 0.65 hr^{-1} which represents approximately 4 pL and 8 pL sampled PMCH for 24 hrs and 48 hrs sampling periods, much higher than the method's limit of detection of 1 pL. Of course, the perfectly mixed air assumption might not be the case which means certain areas might be overventilated or underventilated. In the underventilated areas the ACH rate will be lower than the theoretical, thus the sampled PMCH will be higher. Conversely, in overventilated areas the ACH will approach higher values (i.e. areas very close to the main supply air diffusers) which means the sampled PMCH can be very low. Therefore, overventilated areas are a concern because PMCH values close to the LOD are possible.

The samplers are located in such a way to measure the concentrations at certain characteristic points. Obviously, the more samplers there are in the space, the more concentration points will be obtained for a better contamination characterization. The sources usually are located in such a way to simulate the contamination source in the space.

For a mechanically ventilated building in which ACH rate is considerably constant or with only small time variations due primarily to weather changes, the space concentration as a function of time as derived from the solution of the above differential equation is as follows:

$$C_{\text{PMCH}}(t) = \frac{\sum ER}{V(ACH)} (1 - e^{-(ACH)t}) = (C_{\text{PMCH}}^{\text{Steady}}) (1 - e^{-(ACH)t}) \quad (5)$$

From a practical point of view, equilibrium is obtained when the ratio $C_{\text{PMCH}}(t) / C_{\text{PMCH}}^{\text{Steady}}$ is 0.99. Therefore from equation 5 the time needed for equilibrium, t_e , can be estimated as follows:

$$t_e(\text{hours}) = 4.6 / (ACH) \quad (6)$$

A 24 hrs time interval between the deployment of sources and samplers is usually for forced convection air flows and air exchange rates 0.5 to 1, more than enough for a steady state condition to be reached. For non forced convection flows with very small ACH rates, a higher equilibrium interval can be used to ensure steady state conditions (48 or 72 hours). In this particular case study the developed CFD model was also used to predict the transient period.

Analytical Procedure :

Gas chromatography with electron-capture detection (GC-ECD) is used to determine the amount of PMCH on every CAT. Because the analysis is unique and complex, a detailed description is beyond the scope of this paper. In short, the CAT is thermally desorbed and the released gases and vapors are processed in a multi-dimensional gas Chromatograph to isolate and concentrate the PFTs, which are quantified with the ECD. The unit has an autosampler accessory which can accommodate up to 23 CATs simultaneously. Each run consists of 9 CAT standards, 1 lab blank, 1 field blank, and 12

unknown samples. One run takes about 3.5 hours instrument time which means the results can be obtained in a very short period of time.

The analytical limit of detection is approximately 1 picoliter for PMCH and sensitivity for repeat injections is of the order of 3%. Duplicate field samples are usually in agreement with less than 3% relative percent deviation (RPD). Field blanks are consistently in the lower end of the 0.0 - 1.0 pl range.

CATs are cleaned carefully after analysis by thermally desorbing them for 50 minutes at high temperature, and running them on the instrument prior to redelivery to the field for more sampling. Our QA stipulates that any residual PMCH on a CAT cannot exceed 1.0 pl for it to be usable in the field. Following the cleaning procedure, CATs are stored in resealable plastic bags, and protected with a source of activated charcoal, currently charcoal-impregnated paper.

3. A CASE STUDY- AN ICE RINK ARENA.

Building description:

The building environment investigated in this study was an ice skating arena in the Boston area. In such a facility, the major source of contamination is the combustion byproducts from the ice resurfacing equipment which has had health implications for both athletes and spectators. (Brauer et al. 1997, Coueffin 1981, Hampson 1985, Pennanen et al. 1997, Pennanen et al. 1998)

There are about 2000 ice rink arenas in Canada and 1500 in U.S.A. with most of them using fuel powered ice re-surfacing machines. The fuel-powered re-surfacer's emissions include NO₂, NO and CO. Usually, the propane-fueled re-surfacer have higher NO₂ emissions than gasoline-fueled engines, while the gasoline-fueled engines have higher CO, hydrocarbons (HC), and particle emissions (Brauer and Spengler 1994; Yoon et al. 1996; Brauer et al. 1997; Clark, 1988). Since the ice surface has a low temperature, the negative buoyancy induced by the temperature difference between ice surface and indoor air create a contaminant accumulation above the ice surface. In most cases, the ventilation systems are not sufficiently effective to remove the contaminants and, therefore, the indoor air quality (IAQ) in an ice rink can be poor. The CO and NO₂ concentrations in ice rinks have been measured up to 100 times as high as the usual urban air concentrations (Spengler et al. 1978; Lee et al. 1994; Brauer and Spengler 1994; Berglund et al. 1994).

There are several technical operational factors that can potentially contribute to poor IAQ in ice rinks. These factors include the power and fuel of the ice re-surfacer, resurfacing frequency, volume of the arena, the use of ventilation system and its ventilation effectiveness. A detailed analysis of the contributing factors to the IAQ especially the contamination dispersal and ventilation performance is very critical for estimating the human exposure to air pollution.

In the present study, in order to study the contamination dispersal within an ice rink arena, two methods were applied, a Perfluorocarbon tracer gas (PFT) method and a CFD model. The PFT tracer gas system has been used extensively in our lab to estimate air exchange rates in residential applications. The CFD model with an eddy-viscosity

turbulence model was developed and used to address several modification scenarios and various control strategies related to the ventilation system including the method of air distribution, amount of supply air, etc. The developed CFD model including its complex thermal and flow boundary conditions was successfully validated in terms of predicting air velocities, air temperatures and concentrations by using the experimental data obtained from this experimental method. The CFD model development will be reported separately. (Yang, Demokritou, 2000).

The basic geometrical features of the 20,000 m³ facility and the air distribution system are shown on Figure 3 and table 1. A propane powered ice resurfacer is being used with a 10 to 12 times a day frequency of use emitting gaseous pollutants such as NO_x and CO. The mechanical ventilation system supplies the space with air from outside to dilute the contaminants. The 100% outside air pass through a plate and frame heat exchanger along with the air exhausted from the space and preheated (Heat recovery). Then, the air is heated to 50 C and then supplied into the space. There is little information available on how the ventilation system in such a large space interacts with the contaminants and how effectively are being removed. The non uniformity of the air flow created by the negative buoyancy and the protective glass screen around the ice surface has a significant impact on the indoor air environment and particularly on contamination dispersal.

Field Deployment of sources and samplers:

The 150 sources were distributed around the ice skating surface (attached to the glass protective screen) as shown on Figure 4 , at a height of 1.4m. Source characteristics are shown on Table 2. After 24 hrs, and with the HVAC system running continuously in order to reach an equilibrium- steady state condition, the passive samplers were deployed in the selected locations (Figure 5) and remained in place for approximately 48 hours. After the 48 hours both sources and samplers were removed. Both air temperatures and relative humidity as well as air velocity were measured throughout the arena. The air temperature close to the sources was also measured (10 C) in order to correct the source permeation rates . The samplers were located in such a way to measure the concentrations in two different height horizontal xy planes. (at 5.7 m and 4.5 m height from ice surface) One vertical riser with 5 samplers in various heights from the ice surface was also located close to the spectator's area in order to obtained the vertical concentration profile in that area.

4. EXPERIMENTAL RESULTS - CONCLUSIONS.

All the analytical results including sampled PMCH gas and concentrations are shown on Table 3 for the total of 43 points. The number of points was good enough to validate our contamination dispersal CFD model. Figure 6 shows the comparison of the experimental and the CFD data for various locations in the arena with a good agreement. Figure 7 also shows a vertical concentration profile close to the spectators area. From the vertical profile, it is obvious that concentration levels are higher in the occupancy zone (height<1.8m) than the upper area. This is because the air distribution system supplies the air at a high level which means at a high level the air mixing is considerably better than the arena level. The protective glass around the ice skating area in combination with

the negative buoyancy because of the cold ice surface (-2.5 C) also decreases significantly the ventilation effectiveness in the skating area. It was found that within this area the average concentration level was 200 mg/m³, approximately 20% higher than the average PMCH concentration in the upper zone.

The proposed experimental method successfully was used to evaluate the ventilation effectiveness in such a large scale open space. The method also was used with success for CFD contaminant dispersal modeling validation, since both a significant number of points can be obtained and also the contaminant source strength is known and constant. The method also proved to be a very easy to use, nonobtrusive and fairly inexpensive tool for indoor air quality applications. The success of the method in the case of the ice skating arena with such a unique thermal boundary conditions suggests that the method works well in large semi-open enclosures even with obstacles and under arbitrary thermal boundaries. However, more tests under more complicated thermal and flow boundary conditions such as natural convection, have to be performed in both laboratory chamber experiments and field studies to test the method under extreme conditions.

The method can also be used for transient conditions with CATs to be removed from the space in a specific time manner, which means every sampling point would have more than one CAT, depending on the required time interval. For transient contaminant dispersion applications, a real time monitoring system based on other tracer gas systems such as SF₆ might be more convenient to be used. Another drawback of the method is that a gas chromatographer is needed for the analysis of the samplers and not many labs are equipped with such an instrument.

Despite this fact, the simplicity of the field deployment, the minimum interference with building activities and the friendliness to obtain multiple points make this method a unique tool for CFD validation and IAQ applications.

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FIGURE CAPTIONS:

Figure 1: PFT equipment.

Figure 2 : Estimated Sampled PMCH vs ACH for an Ice Rink Arena.

Figure 3 Building Characteristics

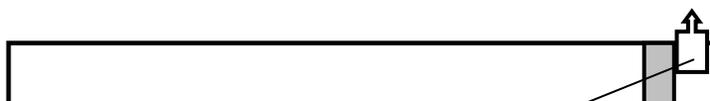
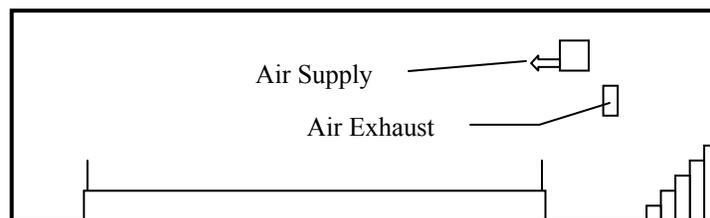
Figure 4 Illustration of source location in the ice rink arena(Top view)

Figure 5: Illustration of CATs location in the ice rink arena (Top view)

Figure 6: Experimental and numerical (CFD) gas concentrations under steady state conditions.

Figure 7: Vertical Concentration profile in the arena.

Fig. 3 Building Characteristics



(Elevation-Section)

(Top view)

Figure 2 : Estimated Sampled PMCH vs ACH for an Ice Rink Arena.

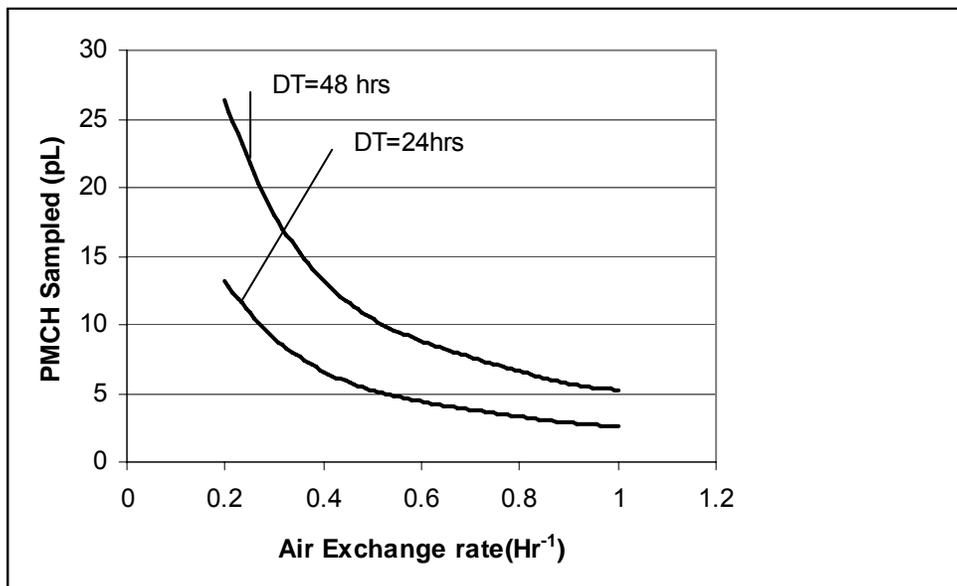


Fig. 4 Illustration of source location in the ice rink arena(Top view)

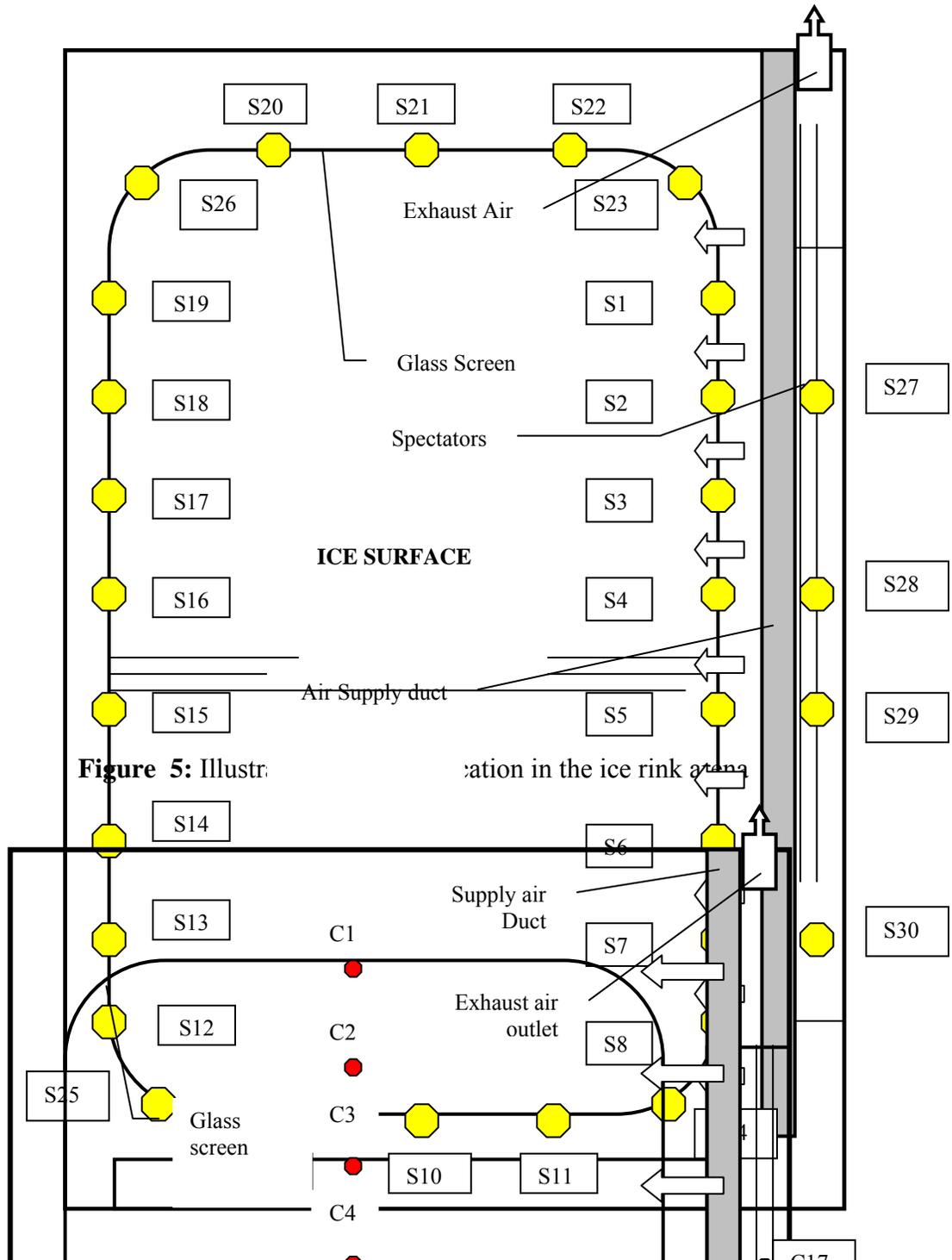
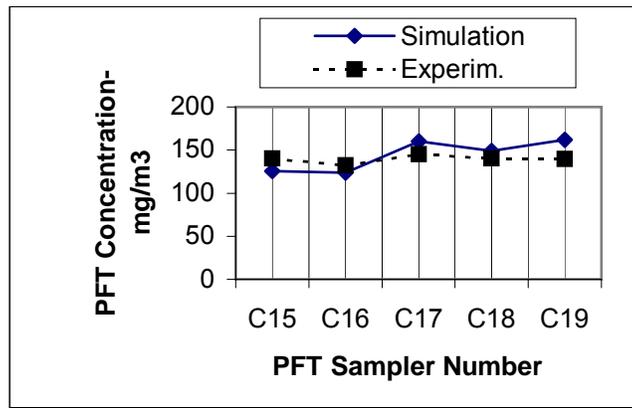


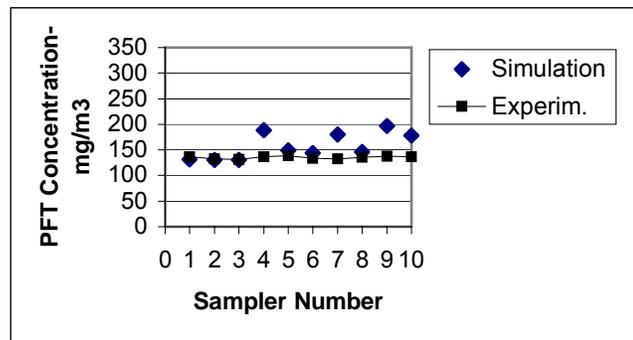
Figure 5: Illustration of source location in the ice rink arena

Figure 6: Experimental and numerical (CFD) gas concentrations under steady state



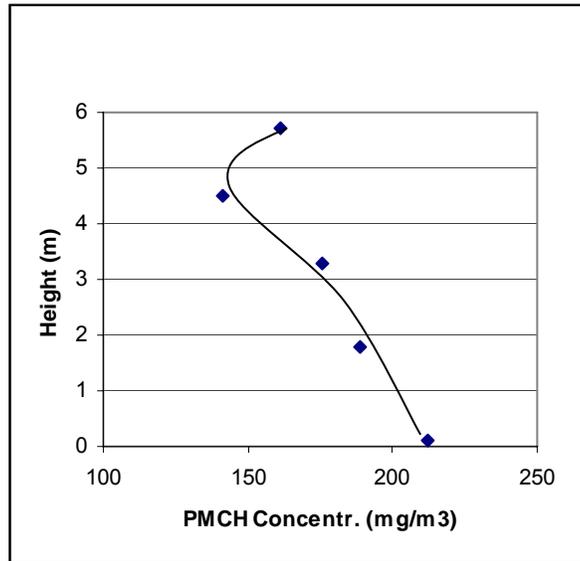
conditions.

(a) Tracer gas concentrations at spectators zone (height $z=5.7$ m)



(b) Tracer gas concentrations at height $z=5.7$ m

Figure 7: Vertical Concentration profile in the arena.



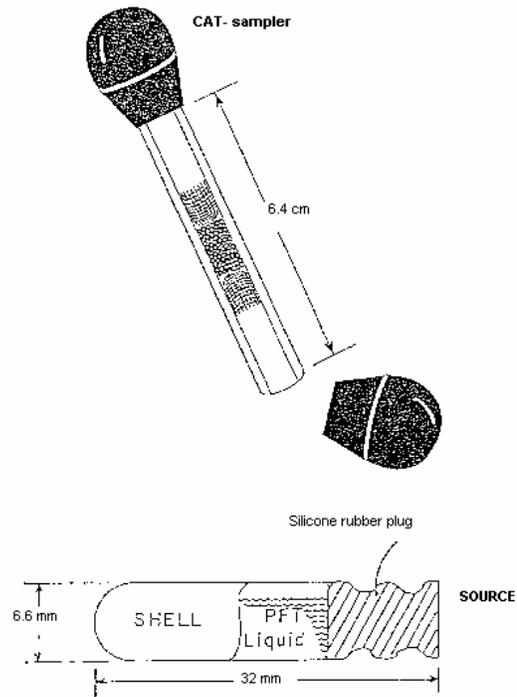


Figure 1: PFT equipment.

Table :1 Building description.

Facility	Capacity (Persons)	Length (m)	Width (m)	Height (m)	Volume (m ³)	Supplied air (CFM)	Air exchange rate (1/h)
Ice Skating Arena	2,500	66	36	8.5	20,200	8,000	0.65

Table 3 : Passive sampler concentrations at xy planes.

Location	XY plane / height =5.7m			XY plane / height =4.5m	
	PMCH sampled (pL)	Concen. (mg/m ³)	Sampling time (hours)	PMCH sampled (pL)	Concen. (µg/m ³)
C1	4.09	131.8	53	4.17	134.5
C2	4.06	130.9	53	4.13	133.1
C3	2.36	76.1	53	3.20	103.1
C4	5.85	188.5	53	3.79	122.2
C5	4.64	149.6	53	6.36	204.9
C6	--	--	52	6.02	197.8
C7	5.48	180.0	52	5.15	169.2
C8	4.45	146.2	52	4.39	144.2
C9	5.99	196.7	52	4.79	157.4
C10	5.42	178.0	52	3.40	111.7
C11	--	--	51	9.42	309.5
C12	7.27	243.5	51	6.75	221.7
C13	11.34	379.8	51	--	--
C14	--	--	51	3.40	113.8
C15	3.68	125.7	50	2.83	96.7
C16	3.62	124.0	50	4.51	151
C17	4.71	160.0	50	4.42	154
C18	4.38	149.0	50	4.80	164
C19	4.74	162.0	50	5.02	171

Table 2 : Source Characteristics

Source No.	Permeation Rate (@24 C) (ng/min).	Permeation Rate (@9 C) (ng/min).	Source No.	Permeation Rate (@24 C) (ng/min).	Permeation Rate (@9 C) (ng/min).
S1	1932.5	1062.9	S16	1876.4	1032.0
S2	1839.1	1011.5	S17	1812.2	996.7
S3	1803.7	992.0	S18	1980.6	1089.3
S4	1927.5	1060.1	S19	1892.4	1040.8
S5	1715.3	943.4	S20	1874.4	1030.9
S6	1741.8	958.0	S21	1892.4	1040.8
S7	1865.6	1026.1	S22	1788.1	983.5
S8	1913.4	1052.4	S23	1750.7	962.9
S9	1860.3	1023.3	S24	1916.4	1054.0
S10	1780.1	979.1	S25	1780.1	979.1
S11	1844.3	1014.4	S26	1716.0	943.8
S12	1996.6	1098.1	S27	1796.2	987.9
S13	2004.7	1102.6	S28	1772.1	974.7
S14	2060.1	1133.1	S29	1956.5	1076.1
S15	2051.3	1128.2	S30	1828.2	1005.5

Notes :

- a. Permeation rates were measured at 24 C.
- b. Temperature correction was based on 9 C source temperature.