#13000

Ventilation and Air Quality in Indoor Ice Skating Arenas

Chunxin Yang, Ph.D.

Philip Demokritou, Ph.D.
Member ASHRAE

Qingyan Chen, Ph.D.
Member ASHRAE

John Spengler, Ph.D.

Austin Parsons

ABSTRACT

There are thousands of indoor ice rink arenas in the United States, Canada, and Europe. The combustion byproducts from the fuel-powered ice resurfacing equipment are a potential health risk to both athletes and spectators. A field survey of ten ice rink arenas in Greater Boston and Halifax, Nova Scotia, indicates that the fuel type used by the resurfacer as well as the air exchange rate, the air distribution method, and the operation strategy of the ventilation system are significant contributing factors to the indoor air quality (IAQ). Computational fluid dynamics (CFD) has been used to systematically investigate the impact of the air exchange rate, air distribution method, and ventilation control strategies on the IAQ in an arena. With CFD, it is possible to develop design and operating guidelines for ventilation systems in order to reduce contamination levels in the arenas.

INTRODUCTION

There are several thousands ice rink arenas in the United States and Canada. Some of the arenas have compromised air quality because of high levels of various pollutants. The concentration level within an ice rink facility depends highly on the fuel type of the ice resurfacer, the frequency of resurfacing, and the degree of ventilation (Pennamen et al. 1998). Most of the studies on ice rinks report only the presence or absence of a ventilation system. Common pollutants in ice skating arenas include NO_x, CO, and hydrocarbons (HC). Usually, the propane-fueled resurfacers emit more NO_2 than gasoline-fueled engines, while the gasoline-fueled engines emit more CO, hydrocarbons (HC), and particles (Brauer and Spengler 1994; Yoon et al. 1996). Dilution ventilation is the most widely applied strategy to lower the indoor contaminant level below the threshold limit. However, in many cases, the ventilation systems are not sufficiently effective to reduce the contamination level (Lee et al. 1993; Yoon et al. 1996) and both acute and chronic health effects have been reported (Anderson 1971). Previous studies reported CO and NO_2 concentration levels up to 100 times as high as the usual urban air concentrations (Spengler et al. 1978; Lee et al. 1994; Brauer and Spengler 1994).

Little information is available on how the ventilation system in an ice rink interacts with the contaminants, or what air distribution method leads to a high ventilation effectiveness, or which kind of ventilation method is most effective. This paper will address these issues.

FIELD SURVEY

The present study conducted a field survey on ten ice rink arenas in the Greater Boston area and Halifax, Nova Scotia, focusing on the effect of ventilation and its parameters on the indoor air quality (IAQ). In the field survey, detailed information about the arena, type of resurfacing equipment, and the ventilation system were collected. The temperatures of the air, ice surface, and walls, relative humidity, and major gaseous pollutant concentrations were also measured.

Table 1 shows the building characteristics of the ten ice rinks investigated. The set of ice rinks can be categorized into two groups according to their building volume. The small ice rink arenas have a volume less than 60,000 m^3, and the large ice rinks have a volume larger than 60,000 m^3. The small ice rinks are usually used by communities and high schools, and the large ones are for colleges and professionals.

Small ice rinks may have a mechanical ventilation system with a mechanical air supply inlet and an exhaust outlet. Four

Chunxin Yang is a visiting scholar, **Qingyan Chen** is an associate professor, and **Austin Parsons** is a visiting assistant professor in the Building Technology Program, Massachusetts Institute of Technology, Cambridge. **Philip Demokritou** is a research associate/instructor and **John Spengler** is a professor in the Environmental Science and Engineering Program, School of Public Health, Harvard University, Cambridge, Mass.

TABLE 1
The Building Characteristics of the Ice Rink Arenas in Greater Boston and Halifax, Nova Scotia

Ice Rink No.	Capacity (person)	Length (m)	Width (m)	Height (m)	Volume (m^3)	Flow rate (m^3/h)	Air exchange rate (1/h)
1	300-400	64	67	52[b], 26[c]	51,021	34,000	0.6664
2	1,200	64	34	7.6[b], 3.5[c]	11,326	—	—
3	4,000	71	30	7	15,175	——	
4	2,500	67	37	8.5	20,926	13,592	0.6495
5	9,000	90	39	18.0	65,242	44,000	0.6744
6[a]	1,200	62	40	9.75[b], 4.9[c]	18111	47,412	2.6179
7[a]	2,000	76	46	13.7[b], 6.0[c]	34,511	5,100	0.1477
8	4,500	100	46	26[b], 13.7[c]	117,338	——	
9	500	74	30	9.75[b], 5.5[c]	16,990	59,465	3.5000
10	300	64	33.5	7.4[b],4.5[c]	15,530	14,268	0.9187

[a]There are two ice rinks.
[b]Ridge height.
[c]Eaves height.

of the eight small ice rink arenas have a small mechanical ventilation system consisting of one or more air supply inlets located up high on one wall and one or more exhaust air outlets on the opposite wall. Figure 1 shows a typical rink with one air supply inlet and one exhaust outlet. The other four arenas have only an exhaust fan, and it is up to the facility manager to decide when and how long the fan will run.

The ventilation systems result in a highly nonuniform indoor air environment in the small ice rink arenas. On the contrary, in large ice rink arenas, air is uniformly distributed and exhausted from multiple locations. The indoor air distribution is therefore uniform. This observation leads to the question of how critical is the air distribution method for IAQ.

Another important ventilation parameter documented in our survey is the air exchange rate, which is defined as the supply airflow rate divided by the volume of the ice rink. The air exchange rates for the ten arenas are listed in Table 1. It can be seen that the values of the air exchange rate can be very scattered.

The survey also examined the control strategy for the ventilation system. None of the ice rinks has exact guidelines for the operation of the ventilation system. The managers operate the system according to their experience. In most cases, the ventilation system runs only during the resurfacing period. The ventilation system is often shut off when the resurfacing equipment leaves the ice sheet. For example, three ventilation units supply air in three different zones in ice rink No. 3. However, only one unit serving the spectators' zone was utilized. The other two units, which were designed to supply air to the skating zone, were not used because the manager thought the supplied air tended to make the ice soft and unsuitable for skating. In another case, because of noise issues, the ventilation system is shut down when there are skaters in the arena.

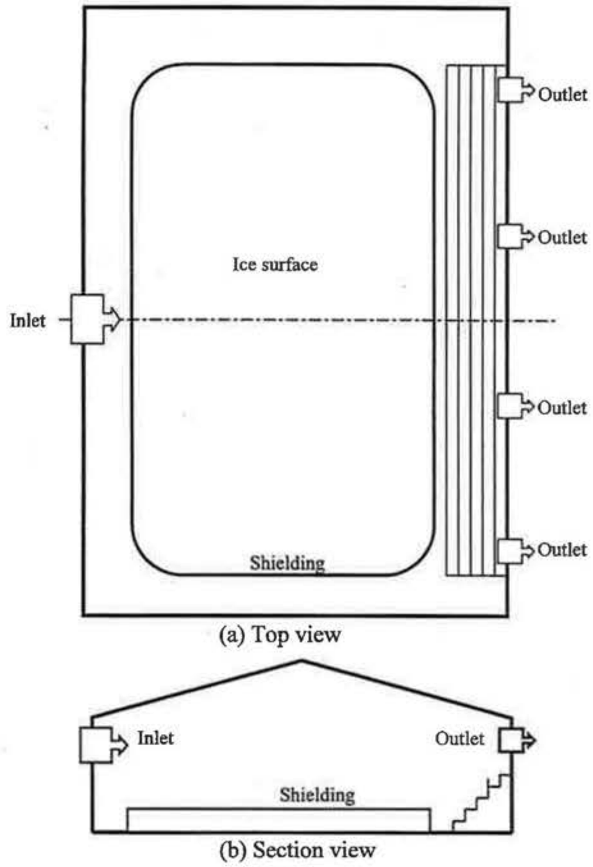


Figure 1 *Illustration of the ventilation system in an ice rink.*

The survey investigated all the possible CO and NO_2 sources in those ice rinks (e.g., resurfacers, edgers, forklifts, heaters, furnaces, stored chemicals, parking facilities, battery recharging facilities, refrigerants, cleaners, etc.). CO and NO_2 concentrations are regularly monitored in all the ice rinks surveyed because of Massachusetts regulations, usually three or four times a week. Table 2 shows the CO and NO_2 data records for ice rink No. 3. It is obvious that the World Health Organization (WHO) threshold limit of 0.11 ppm NO_2 for one hour was exceeded on some occasions. CO levels were also elevated up to 18 ppm.

This study confirms that the fuel type of the resurfacing equipment is the most important parameter affecting indoor air quality in an ice rink. Five of the surveyed arenas use electric resurfacers, four use resurfacers fueled by propane or gasoline without a catalytic converter, and three arenas use propane- or gasoline-powered resurfacers with some type of catalytic converter. Note that some of the rinks used more than one type of resurfacer. Those arenas with electric resurfacing equipment did not have elevated CO and NO_2 concentration levels.

The frequency and duration of resurfacing are also important parameters affecting the IAQ in an arena. Usually the resurfacer is used every half-hour to one hour (approximately 8 times on weekdays or 16 times on weekends). The resurfacer usually moves on the ice surface in a circular pattern. A resurfacing cycle lasts about 15 to 20 minutes. Five to seven circles on the ice sheet are usually needed for the resurfacer to prepare the ice surface.

In summary, our field survey indicates that the air distribution method of the ventilation system, the air exchange rate, the fuel of the resurfacer, and the operation strategy are important to the IAQ in an ice rink environment. The ventilation system in some cases may not have been operated properly to generate an acceptable level of indoor air quality. There is also a lack of guidelines for proper ventilation system design and operation for such a building environment. A ventilation system designer does not know how to design the best air distribution method for an ice rink. Ice rink managers may not know how long it would take for the ventilation system to reduce a pollutant's level below the threshold level after a resurfacing cycle.

TABLE 2
CO and NO_2 Concentration Records for Ice Rink No. 3

Date	CO (ppm)	NO_2 (ppm)	Date	CO (ppm)	NO_2 (ppm)
1/28/98	22	0.2	11/9/98	10	0
1/30/98	7	0	11/15/98	7	0.2
2/1/98	0.6	0	1/5/99	2	0
2/2/98	13	0	1/10/99	7	0
2/9/98	15	0.2	1/27/99	7	0
2/15/98	0	0.2	2/4/99	4	0
2/20/98	16	0	2/8/99	5	0
2/22/98	12	0.4	2/15/99	2	0
2/27/98	14	0.2	2/19/99	18	0
3/6/98	5	0	2/21/99	10	0
3/10/98	3	0.2			

AIRFLOW AND INDOOR AIR QUALITY IN ICE RINK ARENAS

Since ice rink arenas are large, it is time consuming and expensive to measure field data of the effectiveness of ventilation systems and air distribution methods. Experimentally, tracer gas methods has been used to study the contamination dispersal and the ventilation effectiveness (Demokritou et al. 1999). Due to development in turbulence modeling and computer capacity and speed, the computational fluid dynamics (CFD) technique has also been used extensively to study airflow and IAQ in buildings (Chen 1997).

The present study used a CFD program to calculate airflow, temperature, and contaminant concentration profiles for the ice rink arenas. With the distributions of airflow, temperature, and contaminant concentration, the effect of fundamental ventilation parameters such as air exchange rate, air distribution method, and ventilation effectiveness on IAQ can be investigated. The study can further obtain significant conclusions, design guidelines, and operational strategies for ventilation systems in ice rinks.

The CFD technique solves a set of partial differential equations for the conservation of mass, momentum, energy, and species concentrations governing the transport phenomena in ice rinks. The CFD approach needs corresponding boundary conditions for airflow, temperature, and species concentrations. Since most airflow in buildings is turbulent, a turbulence model is needed to reduce the computing costs. With an eddy-viscosity turbulence model, the airflow, temperature, and species transport can be described by the following time-averaged Navier-Stokes equations:

$$\frac{\partial(\rho\Phi)}{\partial t} + div(\rho V\Phi - \Gamma_{\Phi,eff} \cdot grad\Phi) = S_\Phi \qquad (1)$$

where

ρ = air density, kg/m^3
Φ = 1 for mass continuity
= V_j (j = 1, 2, 3) for three components of momentum;
= k for turbulent energy
= ε for the dissipation rate of k
= T for energy transport equation
= C_i for contaminant concentration i
= τ for age of air
V = velocity vector
$\Gamma_{\Phi,eff}$ = effective diffusion coefficient
S_Φ = source term.

The effective diffusion coefficient and source term for the equations are listed in Table 3. The effective viscosity, μ_{eff}, is the sum of molecular viscosity, μ, and turbulent viscosity, μ_t:

$$\mu_{eff} = \mu + \mu_t, \tag{2}$$

where μ is a fluid property while μ_t depends on flow conditions. The effective diffusivity for mass transfer of contamination is

$$D_{eff} = \mu / (\rho \, Sc) + \mu_t / (\rho \, Sc_t), \tag{3}$$

where Sc and Sc_t are the molecular and turbulent Schmidt numbers for the species.

The governing equations can be closed with appropriate boundary conditions at all the boundaries, such as air inlets and outlets and wall surfaces. The values of velocity, temperature, kinetic energy and its dissipation rate, and species concentration should be set at the boundaries. Those boundary conditions were either measured on site or determined from the design blueprints.

A CFD program (CHAM 1998) has been used to solve the time-dependent conservation equations together with the corresponding boundary conditions. The program discretized the space of the ice rink into nonuniform computational cells, and the discrete equations were solved with the SIMPLE algorithm (Patankar 1980). The convergence criteria at each time step were to ensure the total normalized residual to be less than 1% for flow and 3% for NO_2 and CO concentrations.

Figure 2 shows the computed distributions of airflow, temperature, CO concentration, and the mean age of air at the symmetric section of ice rink No. 6. The computation is for steady-state conditions. The ventilation system is on all the time and the resurfacer operates on the ice all the time. Under steady-state conditions, the contaminant source, CO, is uniformly distributed over the ice surface. The emphasis of steady-state simulation is placed on the prediction of air velocity, temperature, and contaminant profile in the arena. The results shown in Figure 2a illustrate that the supplied air is exhausted from the top and forms a short circuit. As a result, the air temperature above the ice remains very low and has a large stratification because of the thermal buoyancy. Due to the short circuit and thermal buoyancy, very little fresh air can reach the ice surface. Therefore, a high CO concentration is present close to the ice surface, caused by the exhaust of the resurfacer. The CO should be considered as a normalized contaminant source. It can also represent other contaminants, such as NO_x and HC. Figure 2d further indicates that the oldest mean age of air is close to the ice. Therefore, the ventilation system is not effective.

TABLE 3
Values of Φ, $\Gamma_{\Phi,\,eff}$, and S_Φ

Equation	Φ	$\Gamma_{\Phi,eff}$	$S\Phi$
Continuity	1	0	0
x-momentum	V_1	$\mu + \mu_t$	$-\partial P/\partial x$
y-momentum	V_2	$\mu + \mu_t$	$-\partial P/\partial y$
z-momentum	V_3	$\mu + \mu_t$	$-\partial P/\partial z - \rho g \beta (T - T_0)$
T-equation	T	$\mu/\sigma_1 + \mu_t/\sigma_t$	S_T
k-equation	k	$(\mu + \mu_t)/\sigma_k$	$G - \rho\varepsilon + G_B$
ε-equation	ε	$(\mu + \mu_t)/\sigma_\varepsilon$	$[\varepsilon (C_{\varepsilon 1} G - C_{\varepsilon 2} \rho \varepsilon)/k] + C_{\varepsilon 3} G_B (\varepsilon/k)$
Species	C	$(\mu + \mu_t)/\sigma_c$	S_C
Age of air	τ	$\mu + \mu_t$	ρ
$\mu_t = \rho C_\mu k^2/\varepsilon$ $G = \mu_t (\partial U_i/\partial x_j + \partial U_j/\partial x_i)\, \partial U_i/\partial x_j$ $G_B = -g(\beta/C_P)(\mu_t/\sigma_{T,t})\, \partial T/\partial x_i$			
$C_{\varepsilon 1} = 1.44$, $C_{\varepsilon 2} = 1.92$, $C_{\varepsilon 3} = 1.44$, $C_\mu = 0.09$ $\sigma_t = 0.9$, $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.3$, $\sigma_C = 1.0$			

In addition to the distributions of contaminant concentrations and the mean age of air, the present investigation used ventilation effectiveness to evaluate the performance of the ventilation system. Many definitions have been used to describe how effectively the ventilation system removes the contaminant from the space. According to Sandberg and Sjoberg (1983), ventilation effectiveness, η_v, can be defined as follows:

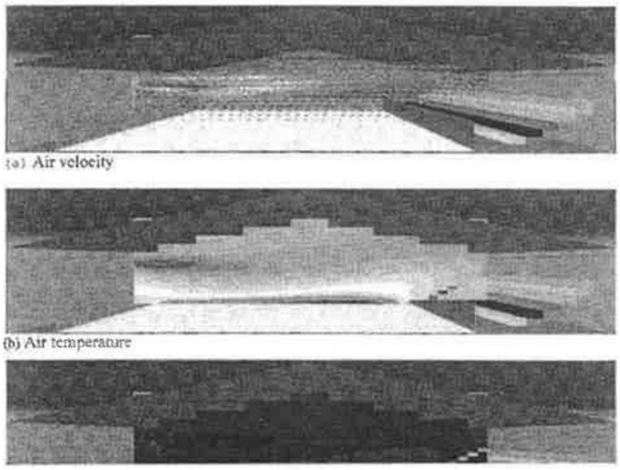


Figure 2 *The computed distributions of airflow, temperature, CO concentration, and the mean age of air at the symmetric section of the ice rink.*

$$\eta_v = \frac{\int_0^\infty C_{ref} dt}{\int_0^\infty C_{ave} dt} \tag{4}$$

where

C_{ave} = the average concentration in the space and

C_{ref} = the concentration at a reference point (i.e., the exhaust grille).

A more simplistic definition was proposed by Nielsen (1994) as

$$\eta_v = \frac{C_{ex}}{C_{ave}}, \tag{5}$$

where

C_{ex} = the concentration in the return opening, kg/m^3, and

C_{ave} = the average concentration, kg/m^3.

For steady-state conditions, the mass equilibrium of the emissions from the resurfacer can be described as

$$S = MC_{ex}, \tag{6}$$

where

S = emission rate of a pollutant, kg/s, and

M = mass flow rate of the ventilation system, kg/m^3.

Therefore, the average concentration, C_{ave}, can be expressed as

$$C_{ave} = \frac{S}{M\eta_v}. \tag{7}$$

With the CFD results as shown in Figure 2, it is possible to further evaluate how the basic ventilation parameters, such as air exchange rate, air distribution method, and ventilation operation, affect indoor air quality in the arena. The simulations have also been performed for transient conditions. Transient conditions were applied to investigate the dynamic contamination dispersal during and after an ice resurfacing cycle. In this case, the resurfacer resurfaces the ice surface for only a period of time and the ventilation system is on all the time.

For the ten ice rinks listed in Table 1, Figure 3 summarizes the computed results by the average CO concentration, the mean age of air, and the ventilation effectiveness. As discussed in the previous section, many factors can significantly affect airflow and IAQ in an ice rink. Those factors include the ventilation system (the location, number, and area of inlets and outlets), air exchange rate, and rink size and geometry. Therefore, the CO concentration level, the mean age of air, and the ventilation effectiveness in the ten ice rinks are very different, as shown in Figure 3.

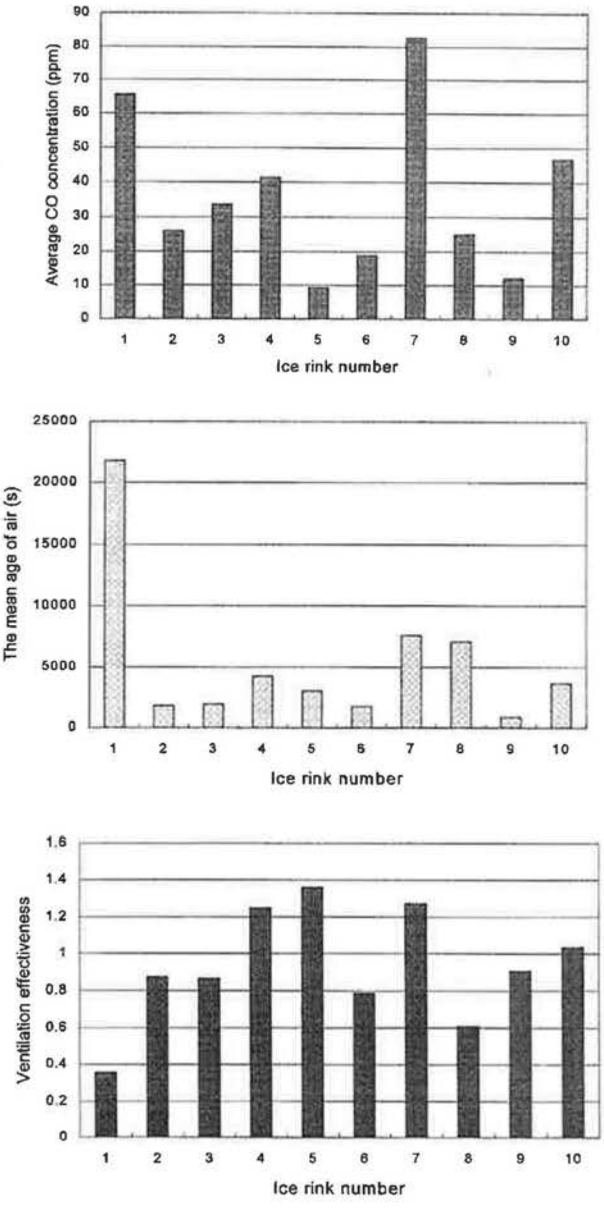


Figure 3 *Ventilation system performance for the ten ice rink arenas.*

Ice rink Nos. 1, 2, 9, and 10 have similar ventilation systems, but the air exchange rates are very different. The results show that the higher the air exchange rate, the better the IAQ. The average CO concentration in ice rinks No. 5 and No. 8 is low. This is because their supply flow rates are much larger than the others, although the ice rink areas and the CO sources are almost the same for all the cases. Obviously, larger airflow rate will give smaller CO concentration.

Note that the ventilation effectiveness of rink Nos. 2, 9, and 10 is almost the same, although their air exchange rates are very different. There is no apparent relation between CO concentration and ventilation effectiveness. The level of average concentration is determined by the flow rate. Using ventilation effectiveness alone is not proper for evaluating IAQ in ice rinks.

It is interesting to compare the results of the No.4 and No. 10 ice rinks because they use different ventilation systems. The air exchange rate for rink No.4 is smaller than that of rink No.10, but the CO concentration in rink No.4 is also lower. The air distribution method really matters in the IAQ of the ice rinks.

The CFD technique enables us to perform a systematic evaluation of IAQ in ice rink arenas. In addition, the transient behavior of the ice rink should be studied. The resurfacer is not running all the time and, in many cases, neither is the ventilation system. In order to save energy, a variable air supply system may be used in ice rinks. Therefore, following the results obtained from the ten ice rinks, the present investigation studied further the impact of the air exchange rate, the air distribution method, the transient operating procedure of resurfacers, and ventilation control strategies on the performance of the ventilation system.

Air Exchange Rate

The study of the ten ice rinks shows that the air exchange rate is the most fundamental ventilation parameter. Table 4 shows the average CO concentration, ventilation effectiveness, and mean age of air for various air exchange rates for ice rink No. 6. For all the scenarios, the emission rate of the resurfacer was assumed uniformly applied on the ice surface as a concentration source of 200 mg/m^2. The emission rate was also assumed constant all the time, a steady-state condition.

It is apparent that average CO concentration and mean age of air in the ice rink decreases with the increase of air exchange rate. Ventilation effectiveness remains almost the same, approximately 0.6, which is anticipated since the air distribution method is the same for all three scenarios.

Figure 4a shows the correlation between average CO concentration and air exchange rate for this particular air distribution method and resurfacer emission rate. From this figure, the air exchange rate required to reduce average CO concentration below a certain limit can be estimated, providing valuable design guidelines for the ventilation system.

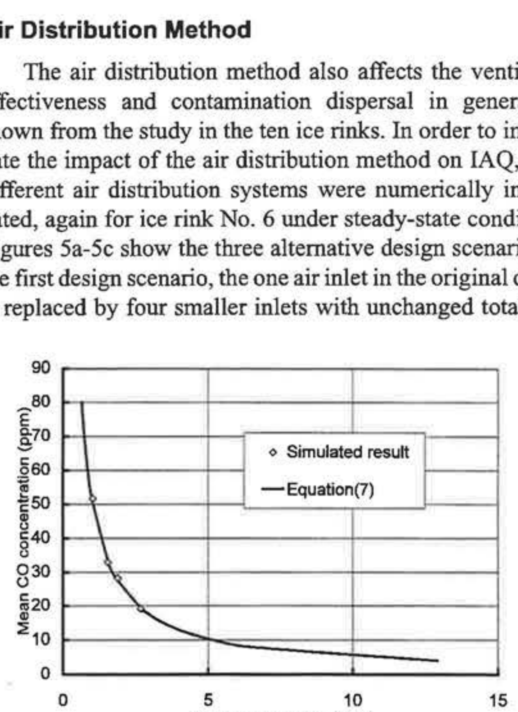
TABLE 4
Simulated Results of Parameter Analysis for Ice Rink No. 6

Air exchange rate (1/h)	Average CO concentration (ppm)	Mean age of air (s)	Ventilation effectiveness
2.6	19.48	1818	0.6418
1.9	28.34	2516	0.6617
1.5	33.04	2971	0.6546
1.0	51.65	4057	0.6281

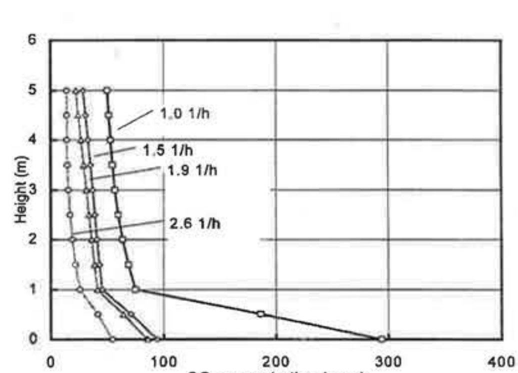
Figure 4b also shows the vertical CO concentration profile at the center of the rink under the four different air exchange rates. There is a concentration gradient at the ice surface. This is a result of the negative buoyancy created by the cold ice surface that drives air contaminants close to the ice surface. This is one of the unique characteristics of indoor airflows in ice rink arenas.

Air Distribution Method

The air distribution method also affects the ventilation effectiveness and contamination dispersal in general, as shown from the study in the ten ice rinks. In order to investigate the impact of the air distribution method on IAQ, three different air distribution systems were numerically investigated, again for ice rink No. 6 under steady-state conditions. Figures 5a-5c show the three alternative design scenarios. In the first design scenario, the one air inlet in the original design is replaced by four smaller inlets with unchanged total inlet



(a) Mean CO concentration as a function of air exchange rate



(b) CO cencentration at the center of the rink as a function of air exchange rate

Figure 4 *Indoor air quality of ice rink No. 6 with different air exchange rates.*

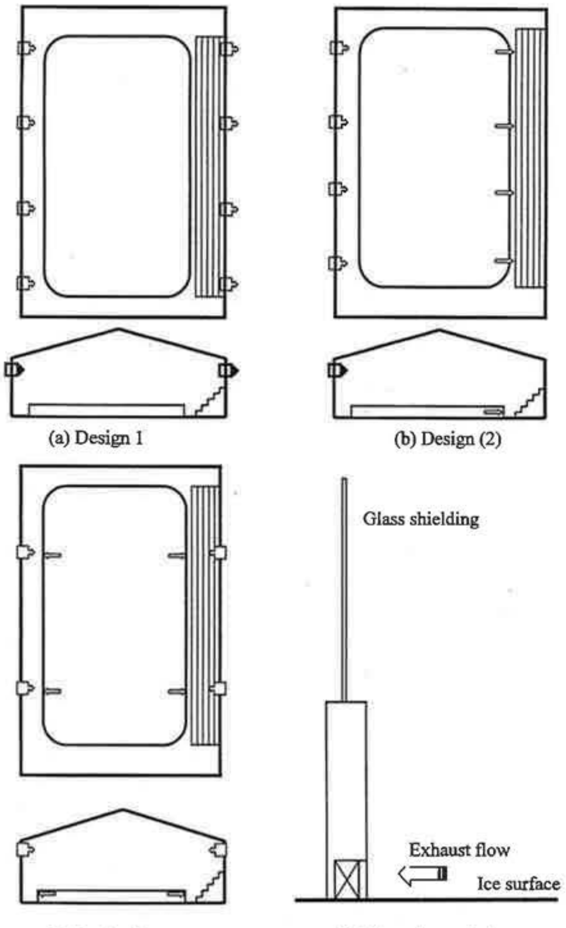


Figure 5 *The alternative design of the ventilation systems.*

area and total air flow. The second hypothetical design scenario has four exhaust air outlets located at the bottom of the rink's side shielding, close to the ice surface, as detailed in Figure 5d. The third design scenario distributes air supply inlets at both side walls and exhaust air outlets at both sides of the ice rink shielding. The average CO concentration, mean air age, and ventilation effectiveness of the original design and the hypothetical design scenarios are listed in Table 5.

It is apparent that design scenario 1 does not significantly affect the IAQ in the ice rink since the average CO concentration, mean age of air, and ventilation effectiveness remain the same as with the existing system. This is expected since the buoyancy effect that dominates the air flow pattern in the arena is still the primary driving force for the airflow. On the contrary, for design scenarios 2 and 3 in which the exhaust is located close to the ice surface, the CO concentration, mean

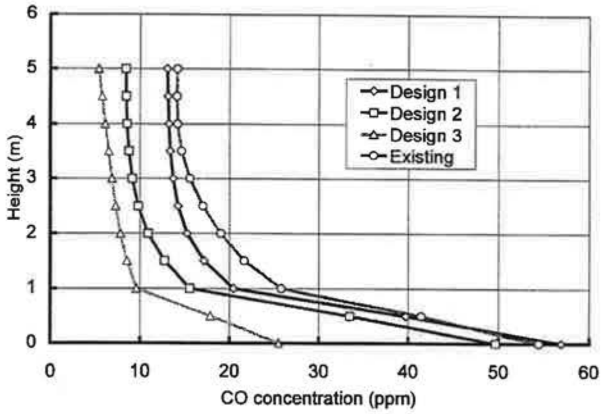


Figure 6 *The CO concentration at the center of ice rink No. 6 with different air distribution methods.*

TABLE 5
Simulated Results of Various Air Distribution Methods for Ice Rink No. 6

Case	Average CO concentration (ppm)	Mean age of air (s)	Ventilation effectiveness
Existing design	19.48	1818	0.6418
Design 1	18.89	1823	0.6617
Design 2	13.00	1152	0.9614
Design 3	13.44	1155	0.9301

age of air, and ventilation effectiveness are considerably improved.

Figure 6 shows the vertical CO concentration profile at the center of the rink for the different air distribution methods. It is clearly shown that the CO concentrations in the skaters' zone can be reduced by a factor of three with a proper air distribution system.

Transient Operating Procedure

In order to investigate the dynamic contamination dispersal during and after an ice resurfacing cycle, a numerical simulation was performed on ice rink No. 3 (Figure 7). Under transient conditions, the basic assumption is that the resurfacer moves in circles around the ice area for a certain period of time while the ventilation system is on all the time. In order to simulate the circular motion of the ice resurfacer, a number of contamination sources were distributed over the ice surface. The contamination sources were activated sequentially for only a period of time to simulate the movement of the resurfacer. Figure 7 shows the location of the sources (Sn, n = number of source). Table 6 shows the emission rate of each source and the duration of activation.

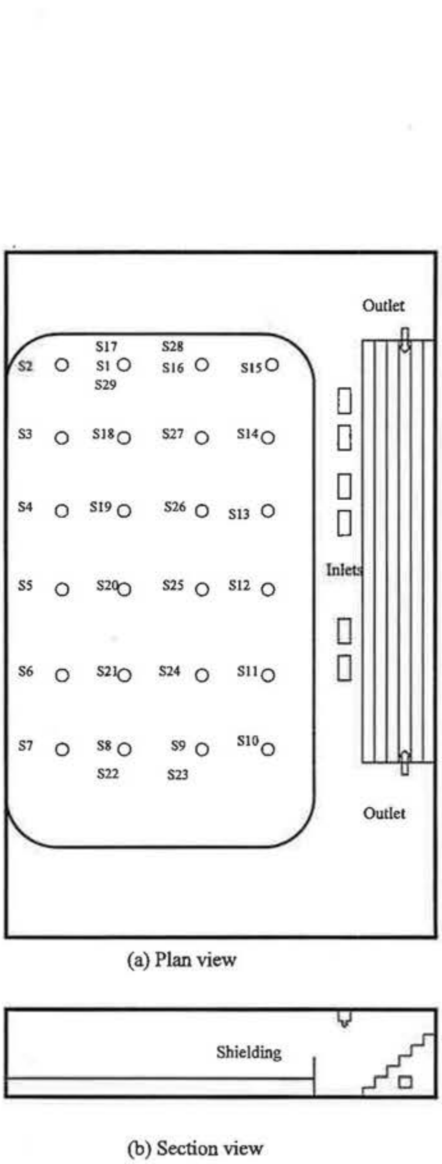


Figure 7 *Illustration of the ventilation system and CO source distribution for ice rink No. 3.*

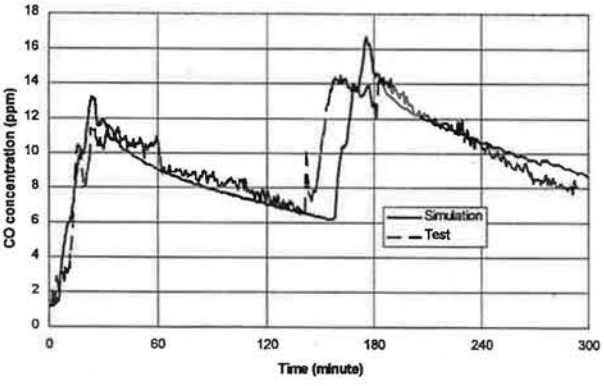


Figure 8 *Comparison of the predicated and measured CO concentration in ice rink No.3.*

TABLE 6
Emission Source Characteristics for Transient Conditions

Time step No.	Time (s)	Source No.	Time step No.	Time (s)	Source No.
1	0~10	S1	16	150~160	S16
2	10~20	S2	17	160~170	S17
3	20~30	S3	18	170~180	S18
4	30~40	S4	19	180~190	S19
5	40~50	S5	20	190~200	S20
6	50~60	S6	21	200~210	S21
7	60~70	S7	22	210~220	S22
8	70~80	S8	23	220~230	S23
9	80~90	S9	24	230~240	S24
10	90~100	S10	25	240~250	S25
11	100~110	S11	26	250~260	S26
12	110~120	S12	27	260~270	S27
13	120~130	S13	28	270~280	S28
14	130~140	S14	29	280~290	S29
15	140~150	S15			

Figure 8 shows the computed CO concentration and the comparison with the experimental data for ice rink No. 3. The computed results are in good agreement with the experimental data. How to simulate the transient CO source has proved to be very important in order to obtain the correct results. For this rink, the ventilation system has to be on all the time in order to keep the contamination level within the threshold limit.

The study suggests two parameters for the evaluation of IAQ under transient conditions: purge time and maximum contaminant concentration. The purge time is the time from the beginning of the resurfacing cycle until the average concentration level returns to its levels before the resurfacing. The maximum value of the contaminant concentration during the resurfacing process is the maximum contaminant concentration. Both the purge time and maximum contaminant concentration during the resurfacing process are related to the ventilation system and its fundamental parameters, such as air exchange rate, air distribution method, etc., as well as the other building characteristics such as volume and rink shielding. The purge time and maximum contaminant concentration can be predicted by the CFD technique, as shown in Figure 8.

A possible ventilation control strategy to lower contamination exposure both in terms of time and peak level is to increase the air exchange rate for a certain period of time during and after the ice resurfacing cycle or to activate a supplementary exhaust system located close to the ice surface. Another strategy might be to evacuate both athletes and spectators from the rink for the purge time period. More thorough investigation is needed in order to quantify the effect of the various ventilation control strategies.

The studies reported in this paper indicated that with the CFD technique, it is possible to develop design and operating guidelines for the ventilation systems in order to reduce contamination levels in the arenas.

CONCLUSIONS

This investigation has conducted a field survey and numerical simulations of the ventilation system performance and indoor air quality (IAQ) in the ten ice rinks. The average CO concentration level, the mean age of air, and ventilation effectiveness are used to evaluate the ventilation system performance and IAQ under steady-state conditions. The ventilation parameters that can significantly affect the airflow and IAQ in an ice rink environment include the air distribution method (location, number, and area of inlets and outlets), flow rate of supplied air or air exchange rate, and the rink size and geometry.

The type of resurfacer power determines the emission concentration level. For the ice rinks that use a propane- or gasoline-fueled resurfacer, adequate ventilation flow rate is necessary to reach an acceptable IAQ level.

This paper presents a systematic evaluation of IAQ in ice rinks influenced by the air exchange rate, air supply method, and transient operating procedure of resurfacers. The contaminant concentration and the mean age of air in the ice rink decrease with the increase of air exchange rate, while the ventilation effectiveness remains almost the same. Locating the exhaust air outlets low at the rink shielding area can reduce considerably the contamination level in the athletes' zone. It is possible to predict the purge time and maximum contaminant concentration when the rink is operated under transient conditions.

ACKNOWLEDGMENT

The authors thank Mr. Shiping Hu, Mr. Jui-Chen R. Chang, and Ms. Beth A. Manoogian for their assistance in the field survey and experimental measurements. The project is sponsored jointly by Frank J. Zamboni & Co., Inc., New England Ice Skating Managers Association, the Ice Skating Institute, Ice Skating Institute of America Education Foundation, and the Nova Scotia Sport and Recreation Commission.

REFERENCES

Anderson D. 1971. Problems created for ice arenas by engine exhaust. *Am. Ind. Hyg. Assoc. J.* 32: 790-801.

Brauer, M., and J.D. Spengler. 1994. Nitrogen dioxide exposures inside ice skating rinks. *Am. J. Publ. Health* 84: 429-433.

CHAM. 1998. Phoenics 3.1. London: CHAM Ltd.

Chen, Q. 1997. Computational fluid dynamics for HVAC: successes and failures. *ASHRAE Transactions* 103 (1): 178-187.

Demokritou, P., C. Yang, Q. Chen, and J. Spengler. 1999. An experimental method for contaminant dispersal characterization in large industrial buildings for IAQ applications. Submitted to *Building Environment.*

Lee, K., Y. Yangisawa, and J.D. Spengler. 1993. Carbon monoxide and nitrogen dioxide levels in an indoor ice skating rink with mitigation methods. *Air Waste* 43: 769-771.

Lee, K., Y. Yangisawa, J.D. Spengler, and S. Nakai. 1994. Carbon monoxide and nitrogen dioxide levels in indoor ice skating rinks. *J. Sports Sci.* 12: 279-283.

Nielsen, P.V. 1994. Prospects for computational fluid dynamics in room air contaminant control. *Proc. 4th Int. Symp. on Ventilation for Contaminant Control, Stockholm.*

Patankar, S.V. 1980. *Numerical heat transfer and fluid flow.* New York: Hemisphere Publishing Corp.

Pennamen, A.S., M. Vahteristo, and R.O. Salonen. 1998. Contribution of technical and operational factors to nitrogen dioxide concentration in indoor ice arenas. *Environment International* 24 (4): 381-388.

Sandberg, M., and M. Sjoberg. 1983. The use of moments for assessing air quality in ventilated rooms. *Building and Environment* 18: 181-197.

Spengler, J.D., K.R. Stone, and F.W. Lilley. 1978. High carbon monoxide levels measured in enclosed skating rinks. *J. Air Pollut. Control Assoc.* 28: 776-779.

Yoon, D.W., K. Lee, Y. Yanagisawa, Y. Spengler, and J.D. Spengler. 1996. Surveillance of indoor air quality in ice rinks. *Environ. Int.* 22: 309-314.