# Ventilation and Air Quality in Indoor Ice Skating Arenas

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## 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 impose 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 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.

Keywords: Air distribution, health, skating rink, indoor air quality, space environment, ventilation

## INTRODUCTION

There are several thousands ice rink arenas in the United States and Canada. Some of the arenas are with compromised air quality because of high concentration level 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 for ice rinks report only the presence or absence of the 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 and 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 and 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, and 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 and, which kind of ventilation method is most effective. This paper will address these issues.

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## FIELD SURVEY

The present study conducted a field survey on ten ice rink arenas in Greater Boston area and Halifax, Nova Scotia focusing on the effect of ventilation and its parameters to the indoor air quality (IAQ). In the field survey, detailed information about the arena, type of resurfacing equipment and the ventilation system are collected. The temperature of 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 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 non-uniform indoor air environment in the small ice rink arenas. On the contrary, in large ice rink arenas, air is uniformly distributed and exhausted from multi-locations. The indoor air distribution is therefore uniform. The observation leads to a critical 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 supply airflow rate divided by the volume of the ice rink. The air exchange rates for the 10 arenas are listed in Table 1. It can be seen that the values of air exchange rate can be very scatter.

The survey also exam the control strategy of the ventilation system. None of the ice rinks has exact guidelines for the operation of ventilation system. The managers operated 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 the ice rink No. 3. However, only one unit serving the spectators zone was utilized. The other two units designed to supply air to the skating zone were not used because the manager thought that the supplied air tends to make 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.

The survey investigated all the possible CO and $NO_2$ sources in those ice rinks (e.g. resufacers, 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 the Massachusetts regulations, usually 3 or 4 times a week. Table 2 shows the CO and $NO_2$ data records for the 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 in some occasions. CO levels were also elevated up to 18 ppm.

The study confirms that the fuel type of the resurfacing equipment is 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 converters. 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 resurfacing frequency and duration time are also important parameters affecting the IAQ in an arena. Usually the resurfacer is used every half to one hour (approximately 8 times/weekday or 16 times/weekend). 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 the pollutant's level below the threshold level after a resurfacing cycle.

## 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 system and air distribution method. 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 has used a CFD program to calculate airflow, temperature and contaminant concentration profiles for the then 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 operation strategies for the ventilation system 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 (Launder and Spalding 1974), the airflow, temperature, and species transport can be described by the following time-averaged Navier-Stokes equations:

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

Where

$\rho$ =Air density, kg/m3

$\Phi$ =1 for mass continuity;

=$V_j$ (j=1, 2, 3) for three components of momentum;

=k for turbulent energy;

=$\varepsilon$ for the dissipation rate of k;
=T for energy transport equation;
=$C_i$ for contaminant concentration i;
= $\tau$ for age of air ;
V = velocity vector
$\Gamma_{\Phi,\mathrm{eff}}$ =effective diffusion coefficient
$S_\Phi$ =source term.

The effective diffusion coefficient and source term for the equations are listed in Table 3. The effective viscosity, $\mu_{\mathrm{eff}}$ is the sum of molecular viscosity, $\mu$, and turbulent viscosity, $\mu_t$:

$$\mu_{\mathrm{eff}} = \mu + \mu_t \qquad (2)$$

where $\mu$ is a fluid property while $\mu_t$ depends on flow conditions. The effective diffusivity for mass transfer of contamination is as follows:

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

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, 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 blue prints.

A CFD program, PHOENICS 3.1 (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 non-uniform 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 2(a) 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 2(d) further indicates that the oldest mean age of air is close to the ice. Therefore, the ventilation system is not effective.

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

$$\eta_{v}=\frac{\int_{0}^{\infty} C_{ref}\,dt}{\int_{0}^{\infty} C_{ave}\,dt} \qquad (4)$$

where

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

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

A more simplistic definition was proposed by Nielsen (1992) as:

$$\eta_{v}=\frac{C_{ex}}{C_{ave}} \qquad (5)$$

where:

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

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

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

$$S = MC_{ex} \qquad (6)$$

Where:

S = the emission rate of a pollutant, kg/s;

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

Therefore, the average Concentration, $C_{ave}$ , can be expressed as:

$$C_{ave}=\frac{S}{M\eta_{v}} \qquad (7)$$

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 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, respectively. As discussed in the previous section, many factors can effect significantly on airflow and IAQ in an ice rink. Those factors include the ventilation system (the location, number, and area of inlet and outlet), 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.

Ice rink No.1, 2, 9 and 10 have similar ventilation systems, but the air exchange rates are very different. The results show that the higher of the air exchange rate, the better the IAQ. The average CO concentration in ice rinks No. 5 and 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.

Noted that the ventilation effectiveness of rink No.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 10 ice rink 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, nor the ventilation system. In order to save energy, variable air supply system may be used in ice rinks. Therefore, according to the results obtained from the ten ice rinks, the present investigation has studied further the impact of air exchange rate, air distribution method, and transient operating procedure of resurfacers and ventilation control strategies on the performance of the ventilation system.

## Air exchange rate

The study on the ten ice rinks shows that air exchange rate is the most fundamental ventilation parameter. Table 4 shows the average CO concentration, ventilation effectiveness and the mean age of air for various air exchange rates for the ice rink arena No. 6. For all the scenarios, the emission rate of the resurfacer was assumed uniformly applied on 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 the three scenarios.

Figure 4(a) 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.

Figure 4(b) 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 consists one of the unique characteristics of indoor air flows in ice rink arenas.

## Air distribution method

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 have been numerically investigated, again for the ice rink No. 6 under steady state conditions. Figures 5(a) to 5(c) show the three alternative design scenarios. In the first design scenario, the only one air inlet in the original design is substituted by four smaller inlets with unchanged total inlet 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 5(d). 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 affect significantly the IAQ in the ice rink since the average CO concentration, mean age of air and ventilation effectiveness remain the same with the existing system. This is expected since the buoyancy effect which dominates the air flow pattern in the arena is still the primary driving force for the airflow. On the contrary, for the design scenarios 2 and 3, on which the exhaust is located close to the ice surface, the CO concentration, mean 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 has been 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 have been distributed over the ice surface. The contamination sources are 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 time of activation.

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 is proved to be very important 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 and 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 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 for certain period of time during and after the ice resurfacing cycle the air exchange rate 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

The investigation has conducted a field survey and numerical simulations on 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 effect the airflow and IAQ in an ice rink environment, include the air distribution method (location, number, and area of inlet and outlet), flow rate of supplied air or air exchange rate, and the rink size and geometry.

The type of the 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.

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**Table 1.** The building characteristics of the ice rink arena in greater Boston and Halifax, Nova Scotia area.

| 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.

**Table 2.** CO and NO2 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 | | | |

**Table 3.** Values of $\Phi$, $\Gamma_{\Phi,eff}$ and $S_\Phi$

| Equation | $\Phi$ | $\Gamma_{\Phi,eff}$ | $S_\Phi$ |
|---|---|---|---|
| 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 | $\mu/\sigma_l + \mu_t/\sigma_t$ | $S_T$ |
| k-equation | k | $(\mu+ \mu_t)/\sigma_k$ | $G-\rho\varepsilon +G_B$ |
| ε-equation | $\varepsilon$ | $(\mu+ \mu_t)/\sigma_\varepsilon$ | $[\varepsilon (C_{\varepsilon1}G-C_{\varepsilon2}\rho\varepsilon)/k] +C_{\varepsilon3}G_B(\varepsilon/k)$ |
| Species | C | $(\mu+ \mu_t)/\sigma_c$ | $S_C$ |
| Age of air | $\tau$ | $\mu+ \mu_t$ | $\rho$ |
| $\mu_t =\rho C_\mu k^2/\varepsilon$<br>$G=\mu_t (\partial U_i/\partial x_j +\partial U_j/\partial x_i) \partial U_i/\partial x_j$<br>$G_B=-g(\beta/C_P)( \mu_t/\sigma_{T,t}) \partial T/ \partial x_i$ | | | |
| $C_{\varepsilon1}=1.44$, $C_{\varepsilon2}=1.92$, $C_{\varepsilon3}=1.44$, $C_\mu=0.09$<br>$\sigma_t=0.9$, $\sigma_k =1.0$, $\sigma_\varepsilon =1.3$, $\sigma_C=1.0$ | | | |

**Table 4.** Simulated results of the parameter analysis for ice rink No. 6.

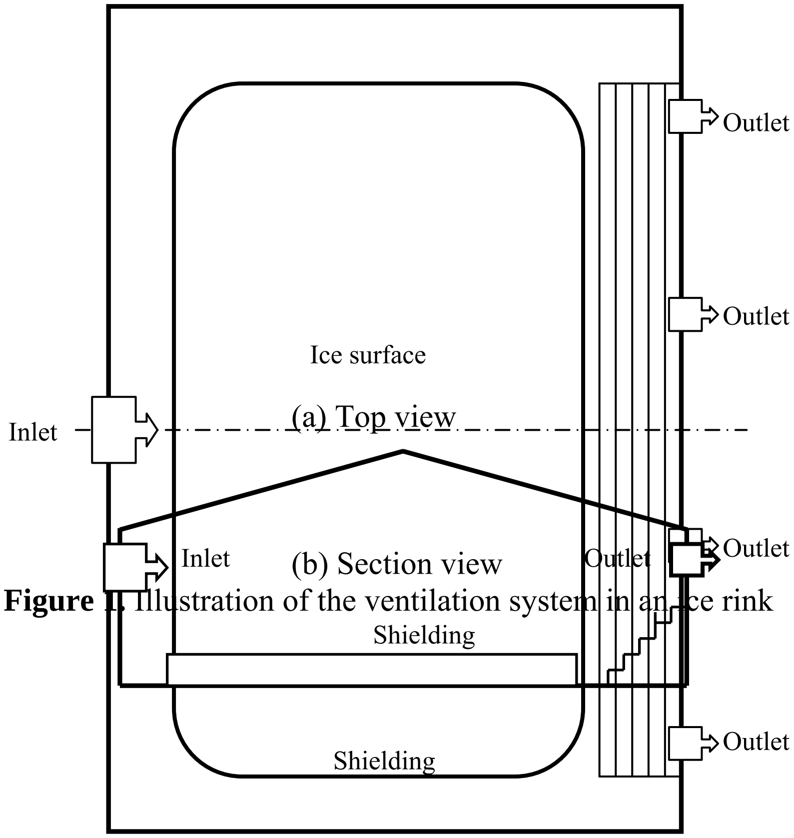
| Air Exchange rate (1/hr) | Average CO concentration (ppm) | Mean age of air (s) | Ventilation effectiveness |
|---|---|---|---|
| 2.6 | 19.48 | 1818 | 0.6418 |
| 1.9 | 28.34 | 2516 | 0.6617 |
| 1.5 | 33.04 | 2971 | 0.6546 |
| 1.0 | 51.65 | 4057 | 0.6281 |

**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 |

**Table 6.** Emission source characteristics for transient conditions.

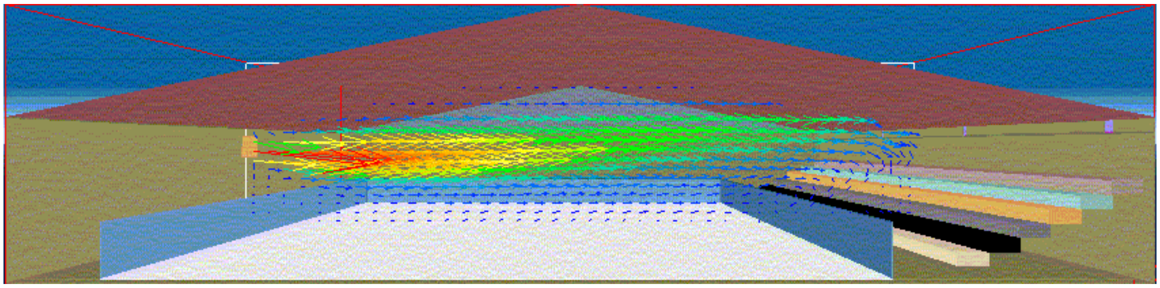
| Time step No. | Time (s) | Source No. | Time step No. | Time (s) | Source No. |
|---|---|---|---|---|---|
| 1 | 0~10 | S1 | 16 | 150~160 | S16 |
| 2 | 10~20 | S2 | 17 | 160~170 | S17 |
| 3 | 20~30 | S3 | 18 | 170~180 | S18 |
| 4 | 30~40 | S4 | 19 | 180~190 | S19 |
| 5 | 40~50 | S5 | 20 | 190~200 | 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 |  |  |  |



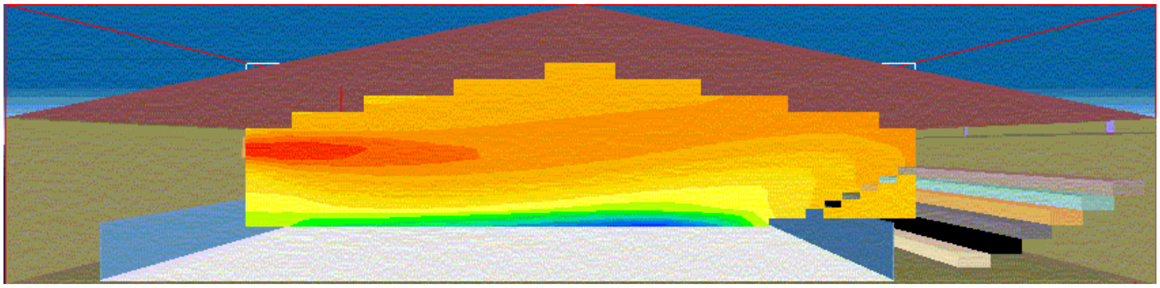
(a) Top view

(b) Section view

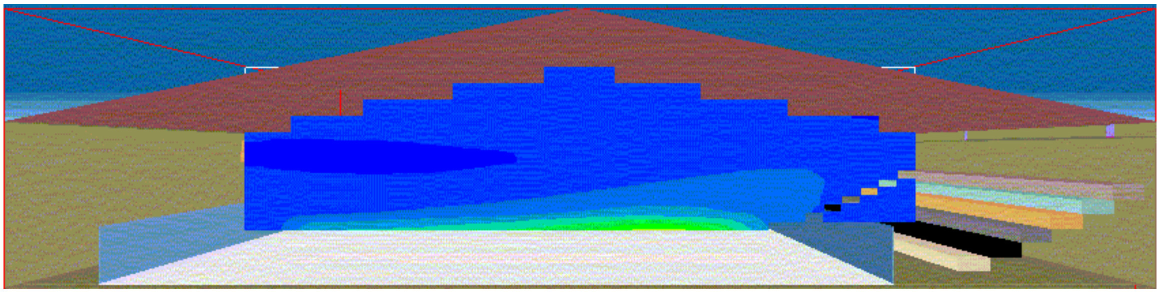
**Figure 1.** Illustration of the ventilation system in an ice rink



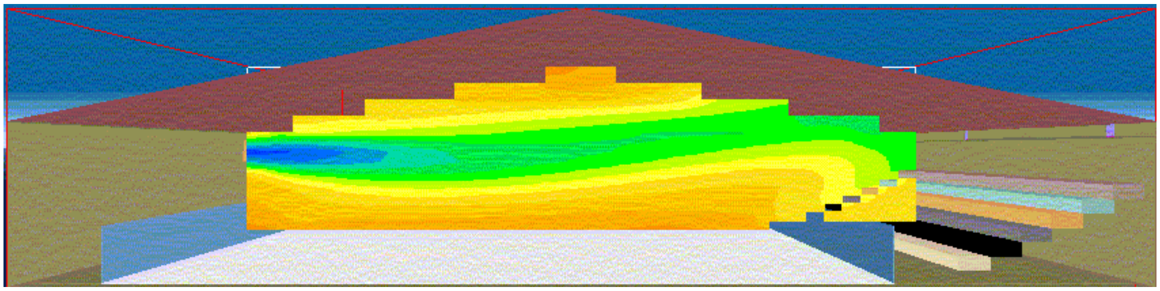
(a) Air velocity



(b) Air temperature



(c) CO concentration



(d) The mean age of air

**Figure 2.** The computed distributions of airflow, temperature, CO concentration and the mean age of air at the symmetric section of the ice rink (blue – low, green – low moderate, yellow – high moderate, red – high).

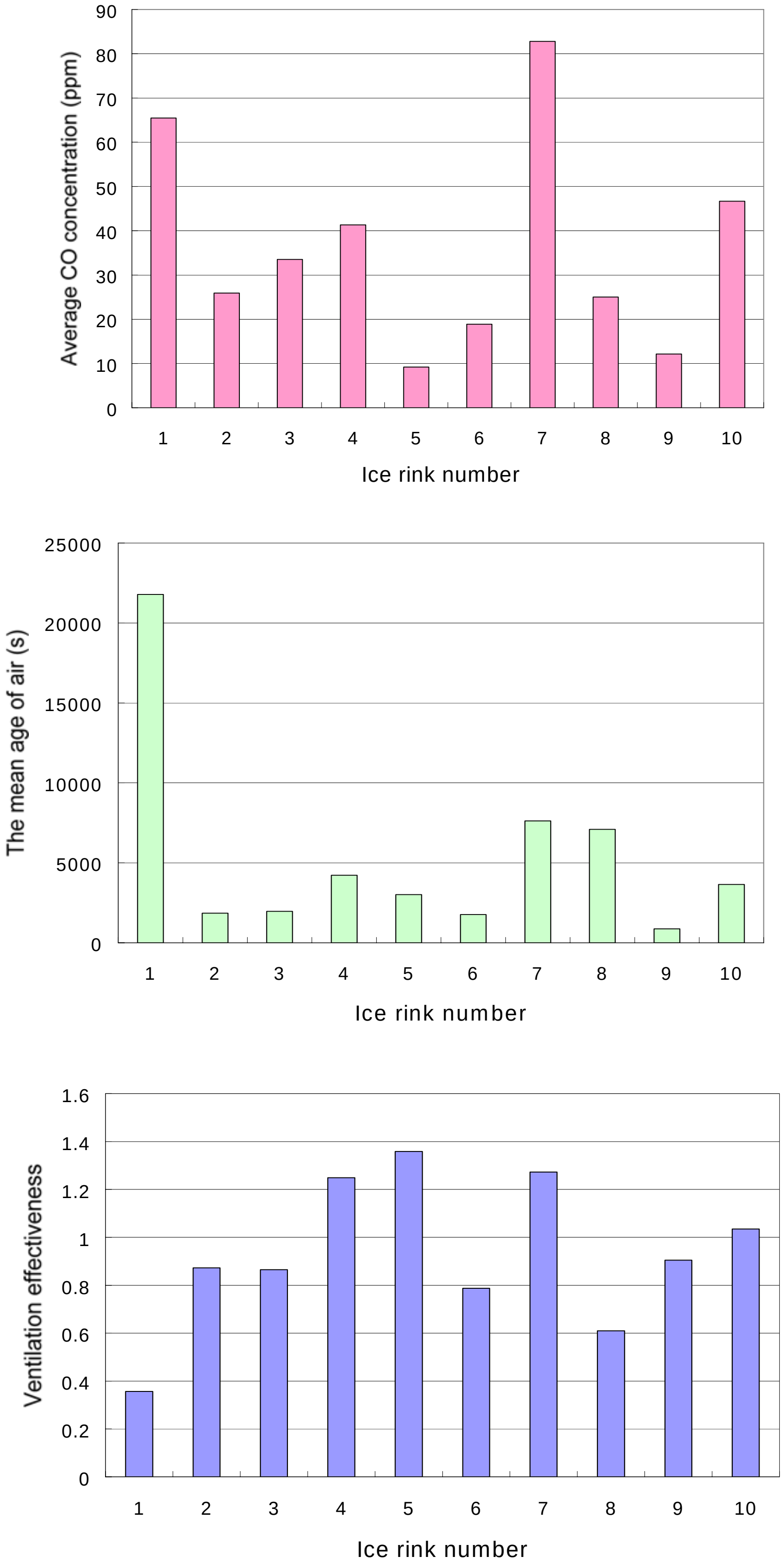
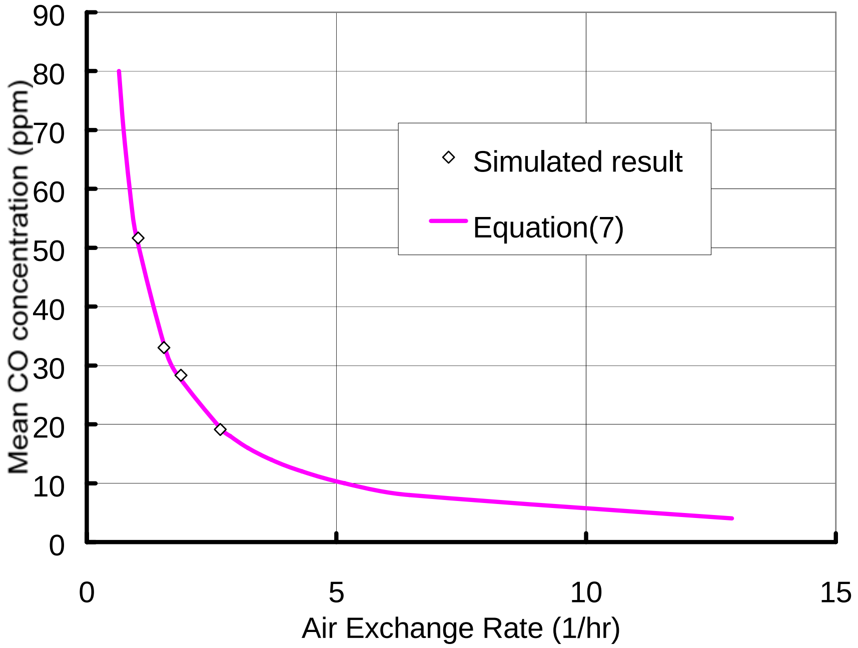
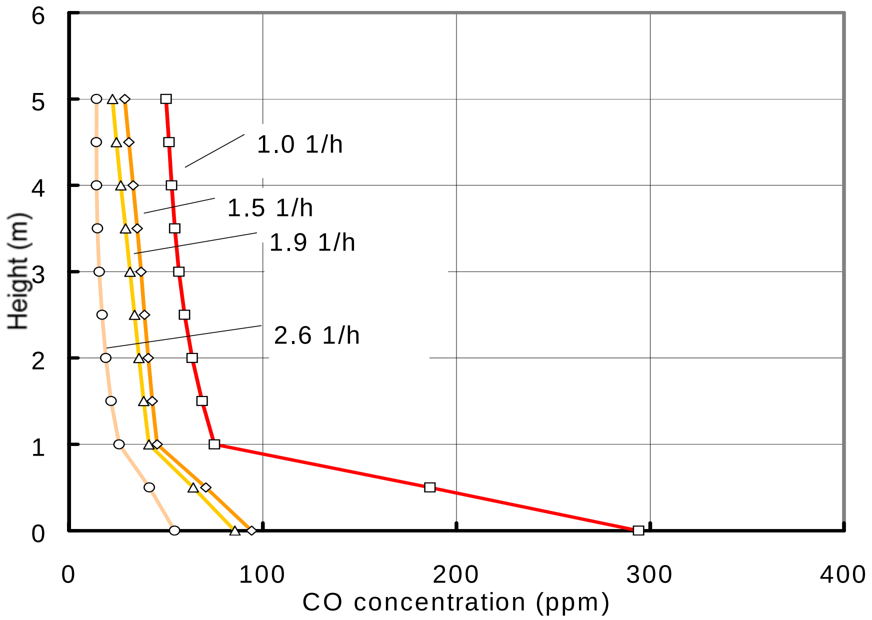


**Figure 3.** Ventilation system performance for the ten ice rink arenas.

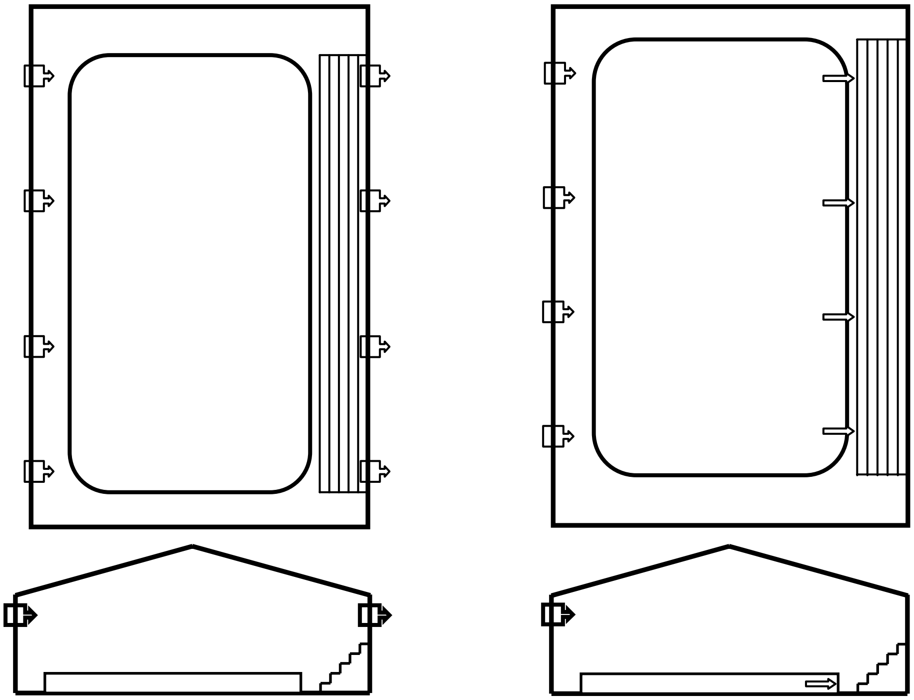


(a) Mean CO concentration as a function of air exchange rate



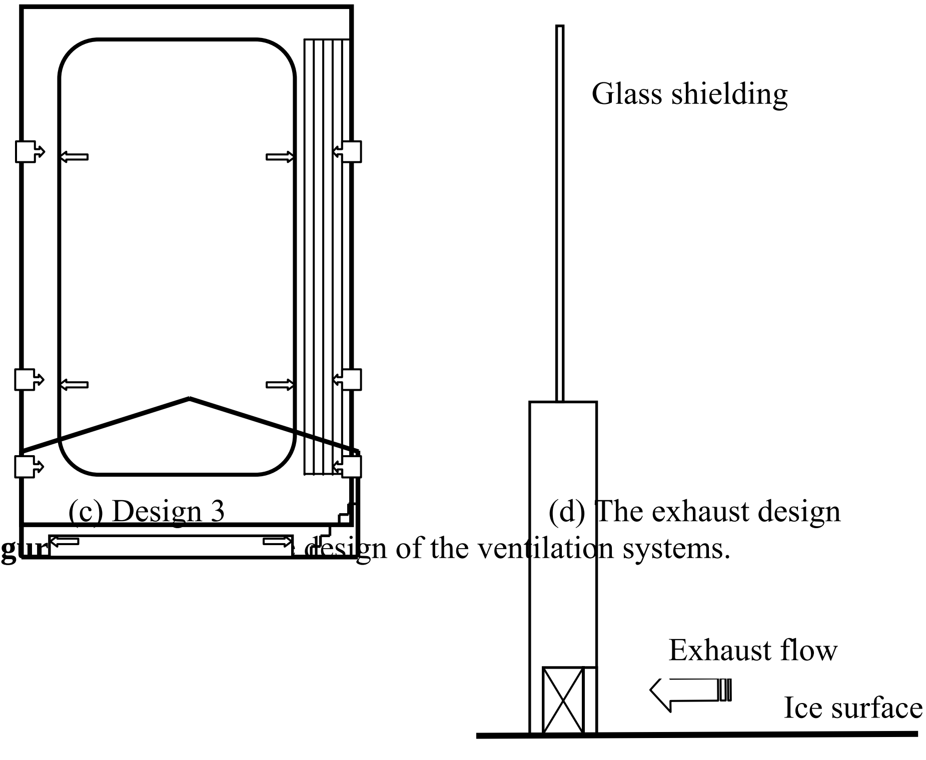
(b) CO cencentration at the center of the rink as a function of air exchange rate

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



(a) Design 1

(b) Design (2)



(c) Design 3

(d) The exhaust design

**Figur** design of the ventilation systems.

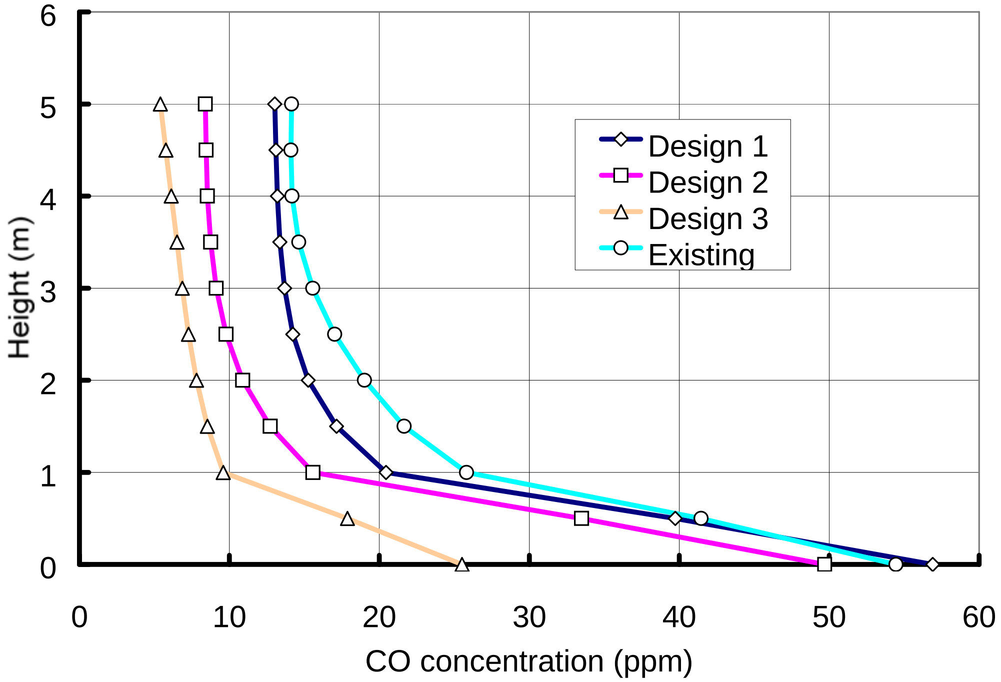


**Figure 6.** The CO concentration at the center of ice rink No. 6 with different air distribution methods.

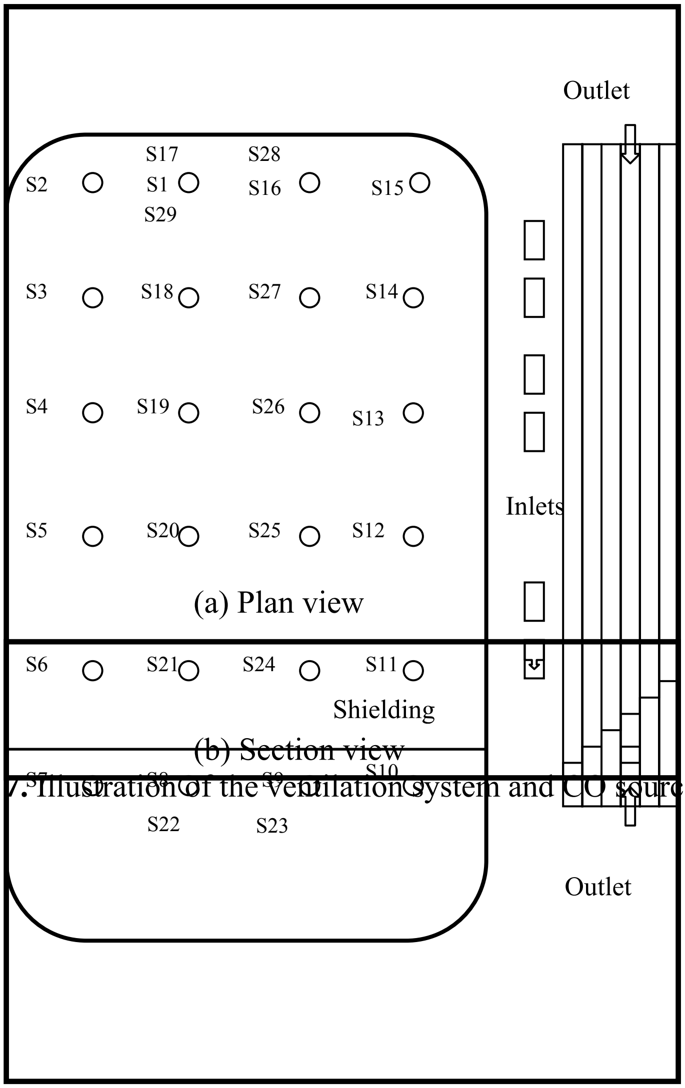


**Figure 7.** Illustration of the ventilation system and CO source distribution for ice rink No. 3.

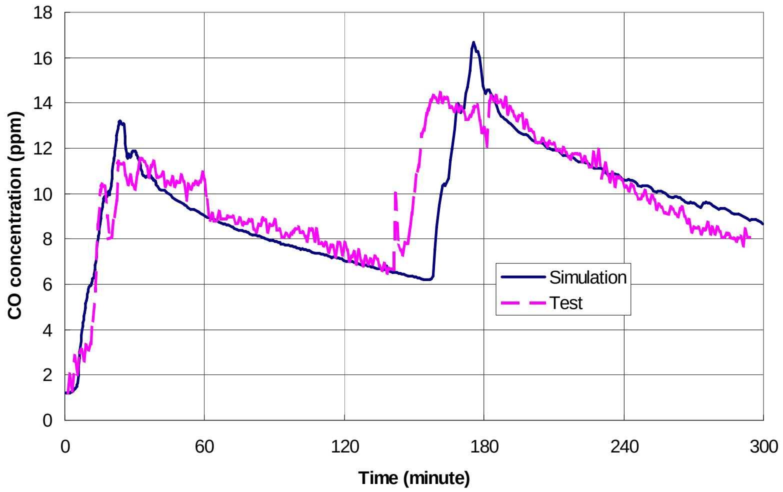


**Figure 8.** Comparison of the predicated and measured CO concentration in ice rink No.3.