On-site measurement and numerical investigation of thermal environment with different air distribution systems in ice arenas

Wenyu Lin, Tao Zhang, Xiaohua Liu, Lingshan Li
1Department of Building Science, Tsinghua University, Beijing, China 100084

Corresponding email: 315567390@qq.com

Abstract. It is important to strictly maintain the indoor thermal environment in ice arenas which have very different features to other commercial buildings. Separated air distribution system is widely used to create a dry and cold environment near the ice and a comfortable environment in the view stand. The warm and humid air from the view stand may lead to uneven temperature and humidity distribution in the rink, leading to extra energy consumption, even fog and frost on the ice. Unreasonable air supply in the ice rink zone will also make the spectators feel too cold and uncomfortable. Jet ventilation system is the most extensively used system in the ice rink zone. An innovative ground displacement ventilation system is proposed in the National Aquatics Centre, which will serve as the venue for the curling competition in the 2022 Beijing Winter Olympics. On-site measurement in the arena is carried out and computational fluid dynamics (CFD) simulation method is adopted in the present research. Measured thermal environment above the ice with different ventilation systems are compared and analysed. Result shows that the displacement ventilation system features a more obvious vertical stratification than jet ventilation system in this kind of large space buildings, and thus is more energy-efficient. A CFD model of the ice cube is setup and verified by measured data. The thermal environment in the ice rink with displacement ventilation under extreme condition is studied using the simulation method. The temperature and humidity in the ice field increases by 10.1 ℃, 4.5 g/kg without air supply in the view stand, proving that the spectators in the view stand have a great impact on the thermal environment in the ice field.

1. Introduction
With the increasing popularity of sports on ice, there are more and more ice arenas all over the world. Different to other commercial buildings, ice arenas can be divided into two zones with different needs, that is the ice rink zone and the view stand. A cold and dry environment needs to be maintained in the ice rink zone to avoid problems of ice pad melting, fog and frost formation, while a comfortable environment for the spectators is needed in the view stand. Stobiecka et al compared an integrated system with a separated system, revealing that the integrated system is less effective. In small ice arenas, integrated system is preferred in view of partitioning is not needed. In large scale ice arenas, separated air distribution system is widely used to meet the different needs in the two zones. Both jet ventilation and displacement ventilation are widely used in the view stand, while jet ventilation is the most common air distribution system adopted in the ice rink zone. The National Aquatics Centre, also known as “the water cube”, was the swimming venue for the 2008 Beijing Olympic Games and will be transformed into “the ice cube” and serve as a venue for the curling competition in the 2022 Beijing Winter Olympics.
Winter Olympics. An innovative displacement ventilation system has been proposed in the ice rink zone of the venue [8]. On-site measurement is carried out in the arena to study the indoor thermal environment with ground displacement ventilation system.

Computational fluid dynamics (CFD) simulation is a commonly used method to study the indoor thermal environment and airflow field in ice rink arenas [2,5,6,7,8,9,10]. Validation under both steady and transient conditions was carried out, proving that CFD can provide convincing result if applied appropriately [10]. Palmowska et al [5,6] compared simulated and measured results, and sought ways to improve the thermal and humidity conditions in the ventilated ice rink arena. Kwon et al [7] studied the indoor thermal environment of an ice rink arena with different return diffuser locations, finding that there is a great difference in the composition of the indoor thermal environment according to the type of ventilation system. Bellache et al [8] studied the ventilation patterns with different outlet positions through numerical simulation, showing that outlet over the stand is somewhat better than over the ice pad.

When designing HVAC systems in ice rink arenas, it is crucially important to ensure the effectiveness of zonal control and minimize the heat transfer as well as air mixing from the relatively warmer and more humid view stand to the ice field in order to avoid fog and frost formation. The transient heat transfer and airflow in an indoor ice rink with radiant heat sources was simulated [9] and result shows that the radiant heat fluxes into the ice fluctuates with large amplitude when the radiant heaters are switched On and Off. Air mixing from the view stand into the ice rink zone with jet ventilation was theoretically analysed [11], but only the mixing caused by jet flow was calculated and the uneven distribution of regional parameters was not considered.

In this study, measured indoor thermal environment of different air distribution systems in ice rink arenas are compared and numerical simulation method CFD is adopted to study the influence of spectators on the ice field with displacement ventilation under extreme condition.

2. Indoor thermal environment with different air distribution systems

On-site measurement is carried out in the ice cube and a typical public entertainment ice skating arena in winter, the latter is a small ice rink located in the inner zone of a shopping mall. The two measured ice arenas shown in Fig. 1 are both located in Beijing, China. Air temperature and specific humidity in the ice rinks were measured using a combined resistance temperature detector and a lithium chloride relative humidity sensor. The air conditioning system in the small public entertainment ice rink is not operating in most of the time and the indoor environment is controlled by maintaining the ice pad temperature. Sensors were placed at 0.03 m, 1.2 m, 2.0 m, 4.4 m and 8.3 m above the ice pad in the public entertainment ice rink.

The air distribution system of the ice cube can be seen in Fig. 2. The ice rink zone adopted the ground displacement air supply with two air outlets located at the long edge of the ice pad. The slot type outlet is 0.2 m in width and about 50 m in length. The cold and dry supply air is provided by two desiccant wheel dehumidification air conditioning units. Detailed description of the displacement ventilation system can be found in the authors’ previous paper [2]. Sensors were placed at 0.1 m, 0.5 m, 1.0 m, 1.25 m, 1.5 m, 6 m, 9 m, 12 m and 15 m above the ice pad in the ice cube. The vertical variance of air parameters in the view stand were also measured, with the sensors placed at 3 m, 5 m, 7 m and 13 m above the seats.

![Figure 1. Measured ice rinks](image-url)
Table 1. Information of the selected ice arenas.

| Location | Application       | Ice area (m²) | Height (m) | Air conditioning system | Air supply height (m) |
|----------|-------------------|---------------|------------|-------------------------|-----------------------|
| Case 1   | Beijing, China    | Entertainment skating | 32×21      | None                    | —                     |
| Case 2   | Beijing, China    | Curling       | 55×32      | Displacement ventilation | 0                     |
| Toomla[3] | Finland           | Competition   | 58×26      | Jet ventilation         | Near ceiling          |

The vertical variance of temperature and specific humidity distribution in the three ice rinks is shown in Fig 3. The air jets of the Finland ice rink are located near the ceiling, on one side of the ice pad, and directed toward the ice. The temperature and specific humidity were measured at 0.01 m, 0.1 m, 0.25 m, 0.5 m, 1 m, 1.5 m, 2 m, 3 m, 4 m, 5 m above the ice pad. The basic information of the three ice arenas is shown in Table 1.

(a) Temperature  
(b) Specific humidity

Figure 3. Vertical variance of temperature and specific humidity distribution with different air distribution systems

Take 1.25 m as the cut-off point, and the vertical temperature and humidity gradient of the upper and lower parts in different cases is shown in Table 2. It can be seen that below 1.25 m the temperature and humidity gradient is the highest in Case 1 where there is no air supply. The gradient above 1.25 m in Case 1 is very close to that in Case 2 with displacement ventilation, both significantly higher than the gradient with jet ventilation. Jet ventilation can obtain the most uniform temperature and humidity
distribution in the whole space while displacement ventilation can obtain the most uniform distribution in the occupied ice rink zone. Considering the upper zone is not occupied, jet ventilation will consume more energy to maintain the thermal environment of the lower occupied zone compared to displacement ventilation system.

| Ice surface temperature (℃) | Temperature gradient (℃/m) | Humidity gradient (g/m) |
|-----------------------------|-----------------------------|-------------------------|
|                             | <1.25m | 1.25~5m | <1.25m | 1.25~5m |
| Case 1                      | -4.9   | 8.55    | 1.66   | 2.81    | 0.47    |
| Case 2                      | -4.5   | 2.51    | 1.41   | 0.13    | 0.49    |
| Toomla[2]                   | -2.7   | 5.35    | 0.81   | 0.84    | 0.07    |

3. Numerical simulation

3.1. Model setup and verification

Although the venue is not ideally symmetrical, a 1/4 numerical model was worked out using ANSYS ICEM and FLUENT to reduce computation time and increase the calculation accuracy. The model shown in Fig. 4(a) is set up based on the construction plans of the building, and is 50m × 35m in size and 28m high.

Figure 4. Numerical model of the 1/4 competition hall

The indoor heat and humidity sources and boundary conditions are given based on the measured results of Dec 7th, 2019, when there is a curling competition held in the hall. There are 8 athletes in the ice field. The view stand is designed for about 3200 spectators and the seat occupancy rate is about 80% during the competition. There is a 1.2m high fence around the ice pad, with staffs standing on either side of it. The people are all simplified into cuboids. Lights near the ceiling are set up as the shape of the maintaining roadway which the lights are arranged by. Spectators and staffs are moderately active, while athletes are severely active. The heating value and moisture dissipation of the occupants are calculated according to the value of adult men at the measured temperature, and the crowd spectators are multiplied by the aggregation coefficient of 0.87. The east and south side of the model are set as symmetry planes. The indoor heat and humidity sources and boundary conditions of the model are shown in Table 3.
Table 3. Heat, humidity sources and boundary conditions.

| Air supply | G (m³/h) | t (℃) | d (g/kg) | Walls | t (℃) | Walls | t (℃) |
|------------|----------|-------|----------|-------|-------|-------|-------|
| Ice rink   | 6500     | 7.2   | 2.7      | west  | 20.8  | roof  | 25.8  |
| View stand | 28000    | 10.6  | 3.2      | north | 22.2  | carpet | 10.6  |

| Sources     | q (W/p) | w (g/h/p) | Number | q (W/m²) | q (W/m²) |
|-------------|---------|-----------|--------|----------|----------|
| Spectators  | 118     | 174       | 640    | Device   | 5        |
| Athletes    | 193     | 287       | 8      | Light    | 10       |
| Staffs      | 165     | 105       | 20     | ice      | -4.5     | 2.48   |

Unstructured discretization grid is applied with about 15 million cells, mostly composed of tetrahedral elements and prism layers as shown in Fig 5. The numerical simulation is carried out using FLUENT in a steady-state under three-dimensional condition. The RNG k-ε turbulence model is adopted. Although radiation is important in ice rinks, radiation model was not active because all the wall temperature is known in this case. The pressure and velocity are coupled using the solution algorithm SIMPLE. The calculations are carried out using the iteration method and convergent solution are obtained. The convergence criteria of the specific humidity and energy are 10⁻⁵, and the other convergence criteria were 10⁻³. The error of the mass and heat transfer are less than 5% when calculation is complete.

![Cross-section through the mesh discretization](image)

**Figure 5.** Cross-section through the mesh discretization

The measured and simulated vertical variance of temperature and humidity ratio distribution in the competition hall are plotted in Fig. 6. The air velocity in the ice field were mostly below 0.2 m/s during measurement, which could not be measured accurately. Therefore, air velocity is not compared in this case. It is noticed that during measurement, the sensors at the height of 0.1~1.5 m were all placed above the carpet instead of the ice pad. The air above the ice is about 2.7 ℃ colder and 0.15 g/kg drier than that above the carpet. The amended air parameters are also shown in Fig. 6. The deviation between the simulation and measured values in the ice rink zone are below 1.5 ℃, 0.7 g/kg, while that in the view stand are below 2.3 ℃, 1.5 g/kg. It can be seen that the simulated results are in good agreement with the measured ones, proving that the model has high reliability.

![Simulated and measured vertical variance of temperature and specific humidity distribution](image)

**(a) Ice rink**

**(b) View stand**

**Figure 6.** Simulated and measured vertical variance of temperature and specific humidity distribution.
The simulated thermal environment and velocity cut plane are shown in Fig. 7. It can be seen that due to the low temperature and relatively high specific humidity of the seat supply air, the moisture diffusion from the view stand to the ice rink zone is more pronounced than thermal diffusion. Affected by the thermal plume, the air in the view stand flowed backwards and upwards, eventually rising along the wall. The temperature and specific humidity is higher near the athletes in the ice filed. The average temperature and specific humidity of 1.5 m above the ice pad is 11.2 ℃, 3.8 g/kg, and the air velocity in the ice field is below 0.2 m/s, which meets the competition standards. The average temperature and specific humidity of the spectator area is 17.2 ℃, 5.6 g/kg, which is comfortable. The side displacement ventilation system removes 12.6 kW of heat and 2.9 g/s of moisture in the ice rink zone.

3.2. Zonal control effect of displacement ventilation under extreme condition

The seat air supply in the view stand is closed in the following simulation scenario to investigate the interaction between the two zones and study the zonal control effect of the displacement ventilation system in the ice rink under extreme conditions.

With 80% full spectators and without air supply in the view stand, the average temperature and specific humidity of 1.5 m above the ice pad increases to 21.8 ℃, 8.3 g/kg, which may lead to frost and fog formation. The upper space of the ice rink is relatively uniform in temperature and humidity, which is 26.3 ℃, 9.9 g/kg. The average temperature and specific humidity of the spectator area rise to 27.3 ℃, 10.4 g/kg. The vertical variance distribution of temperature and specific humidity distribution in the two scenarios is plotted in Fig. 8. Without view stand seat air supply, the temperature and humidity rise notably. The largest increase occurred at the height of 1.25 m and 1.5 m by 10.1 ℃, 4.5 g/kg, while the air parameters below 0.5 m are quite close to that in the original case, with an increase of 0.4 ℃, 0.7 g/kg. The temperature and humidity in the view stand increases more evenly, by 5.3 ℃, 3.6 g/kg.
Figure 8. Vertical variance of temperature and specific humidity distribution in different simulation scenarios.

The simulated temperature, specific humidity and velocity vectors cut planes are shown in Fig. 9. It can be seen that the warm and humid air in the view stand flowed backwards and upwards, then from the upper space to the ice field. The temperature and humidity difference between the ice rink zone and the view stand is more obvious. Side displacement air supply in the ice rink removes 36.7 kW of heat and 13.6 g/s of moisture in the extreme scenario, which is 24.1kW, 10.8 g/s higher than the original case.

To conclude, without view stand air supply, the temperature and humidity increase greatly in the ice rink zone and there are risks of frost and fog formation above the ice. Therefore, it is significantly important to minimize the air mixing from the relatively warmer and more humid view stand to the ice field when designing HVAC systems in ice rink arenas.

4. Conclusion
An innovative side displacement ventilation system is employed in a curling venue in Beijing, China, and the air parameters in the ice field can meet the competition standards according to measured results.

The indoor thermal environment in ice rink arenas under different air distribution systems are compared in the present research. Jet ventilation can achieve the most uniform temperature and humidity distribution in the whole space while side displacement ventilation can obtain the most uniform
distribution in the occupied ice field. Therefore, side displacement ventilation system has the best zonal control effect and is more energy-efficient than jet ventilation system.

CFD simulation is carried out and the model is verified by the measured data. With a deviation within 1.5 °C, 0.7 g/kg in the ice rink zone, the model is believed to have high reliability and could be used for further study.

Thermal environment in the ice rink with displacement ventilation under extreme condition is studied using the simulation method. When the spectators are 80% full but the air supply in the view stand is not turned on, the air temperature and humidity at 1.5 m in the ice field increase by 10.1 °C, 4.5 g/kg compared to the original case. Side displacement air supply in the ice rink removes 36.7 kW of heat and 13.6 g/s of moisture from the ice rink zone, which is 24.1kW, 10.8 g/s higher than the original case. The warm and humid air from the view stand has a marked impact on the thermal environment in the ice rink zone. Therefore, it is crucially important to study the interaction between the ice rink zone and the view stand to provide guidance for separated ventilation system design in ice rink arenas.

Acknowledgments
The authors appreciate the support from the National Key Research Program of China (No. 2020YFF0304302), National Natural Science Foundation of China (No. 51878369 and No. 51638010) and Research and Development Program of CSCEC (CSCEC-2019-Z-7).

References
[1] ASHRAE Fundamentals (2009), American Society of Heating, Refrigeration and Air Conditioning Engineers, USA.
[2] Stobiecka, Lipska, & Koper (2013), Comparison of air distribution systems in ice rink arena ventilation, Science — Future of Lithuania/Mokslas — Lietuvos Ateitis 5,429–434.
[3] Toomla, Sander, Lestinen, Sami, Kilpelainen, Simo, Leppa, Lauri, Kosonen, Risto, & Kurnitski, Jarek. (2019). Experimental investigation of air distribution and ventilation efficiency in an ice rink arena. International Journal of Ventilation, 18(3), 187-203.
[4] Li, Lingshan, Liu, Xiaohua, Zhang, Tao, & Lin, Wenyu. (2020). Utilization of displacement ventilation and on-site measurement of thermal environment in an ice arena. Building and Environment, 186.
[5] Palmowska, Agnieszka, & Lipska, Barbara. (2016). Experimental study and numerical prediction of thermal and humidity conditions in the ventilated ice rink arena. Building and Environment, 108, 171-182.
[6] Palmowska, Agnieszka, & Lipska, Barbara. (2018). Research on improving thermal and humidity conditions in a ventilated ice rink arena using a validated CFD model. International Journal of Refrigeration-Revue Internationale Du Froid, 86, 373-387.
[7] Kwon, Yong-II. (2019). A Study on Thermal Characteristics Affected by Air Distribution System Installed in Indoor Ice Rink Arena. International Journal of Air-Conditioning and Refrigeration, 27(1).
[8] Bellache, O., Ouzzane, M., & Galanis, N. (2005). Numerical prediction of ventilation patterns and thermal processes in ice rinks. Building and Environment, 40(3), 417-426.
[9] Omri, Mohamed, Barrau, Jerome, Moreau, Stephane, & Galanis, Nicolas. (2016). Three-dimensional transient heat transfer and airflow in an indoor ice rink with radiant heat sources. Building Simulation, 9(2), 175-182.
[10] Yang, C. X., Demokritou, P., Chen, Q. Y., & Spengler, J. (2001). Experimental validation of a computational fluid dynamics model for IAQ applications in ice rink arenas. Indoor Air, 11(2), 120-126.
[11] Sargsyan, Samvel, & Zhila, Viktor. (2018). Mathematical modelling of the indoor ice arena with two control volumes for calculation of the air exchange. Xxi International Scientific Conference on Advanced in Civil Engineering Construction - the Formation of Living Environment (Vol. 365).