A Low-carbon CO_2 Ice Rink Technology for the Winter Olympics

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The issue of climate change is among the most difficult environmental problems faced by human beings [1] and affects all social aspects of human life. In 2015, the Paris Agreement set the goal of reducing global greenhouse gas (GHG) emissions to limit the global temperature increase to 2°C and even further to 1.5°C [2]. In response to climate change, the International Olympic Committee has announced a positive climate target through carbon-neutral measures, such as sustainable zero-carbon solutions for the Olympic Games and beyond. In the Winter Olympic Games, ice sports accounted for 1/3 of all events, and more than 75% of the energy consumption was associated with ice rink technology. Low-carbon and efficient ice rink technology is significant in terms of realizing carbon-neutral games in the Beijing 2022 Winter Olympics [3].

For ice rink technology, vapour-compression refrigeration comprising compression, condensation, expansion, and evaporation processes [4] is commonly used to provide cooling capabilities for ice making. In most previous Winter Olympic Games, synthetic refrigerants, including chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and hydrofluorocarbons (HFCs), were widely used as working medium. For instance, R507A (HFCs) was employed in the Sochi 2014 and Pyeongchang 2018 Winter Olympics. In the past few decades, these synthetic refrigerants have had a great impact on human society and have received much more attention due to their environmental impact in terms of ozone layer destruction and climate change. From 1987, the Montreal Protocol and later revisions phased out the use of CFCs and HCFCs with ozone destruction potential (ODP) before 2010 and 2040 [5]. In 2006, the Kigali Amendment phased down the use of HFCs with high global warming potential (GWP) before 2036 in developed countries and 2047 in developing countries [6]. Therefore, approaches including finding environmentally friendly refrigerants with zero ODP and low GWP and implementing new thermodynamic cycle configurations are recommended in ice rinks [7].

Carbon dioxide (CO_2), a nontoxic, nonflammable natural gas with zero ODP and low GWP (only 1), has attracted increasing interest as a refrigerant. CO_2 fluid has been first used as a secondary refrigerant in Dornbirn ice rink in Austria, in 1999, and CO_2 refrigerant has been first used in the direct ice rink system installed in St Gedeon, Quebec, Canada, constructed in 2010 [8]. This system is a single-stage transcritical cycle with a heat reclaim system to heat the swimming pool complex and itself. The comparative study showed that the CO_2 system has the lowest total energy consumption (CanmetENERGY, Comparative Study of refrigeration systems for ice rinks). One of the reasons is derived from its heat reclaim system [9]. In addition, the CO_2 system performs good adaptation to wide weather conditions (John D. Collins PE, Analysis of package chiller systems: comparison of natural (NH_3 and CO_2) and HFC/HFO refrigerants), and it has the smallest GHG emissions.

(1) CO_2 ice rink technology

The development and maturity of CO_2 ice rink technology worldwide makes it possible for the CO_2 direct evaporation ice rink technology (CO_2-DEIT) being implemented in the history of Winter Olympic Games. Capital Indoor Stadium, where figure skating and short-track speed skating competitions were performed, and 14 gold medals were awarded, was renovated by replacing previous refrigeration system with CO_2-DEIT (Fig. 1 (a)). Compared with ice rinks that use CO_2 refrigeration system, the CO_2-DEIT at Capital Indoor Stadium in Beijing Winter Olympics is based

on an efficient heat reclaimed dual-compression split cycle (Fig. 1 (b)) and includes the following innovations: 1) The two-stage compression with an intercooler is designed to effectively reduce compression work. There are 12 individual compressors, half of which are high-pressure stage compressors (HPCs), and the rest are low-pressure stage compressors (LPCs), and their frequency can be modulated according to the dynamic cooling demand. A dual-compression process with internal heat reclaim is applied in Winter Olympics based on the development of ice rink technology worldwide, shown in Supplementary Materials. 2) As CO_2 has very low viscosity and a small liquid-to-vapour density ratio, a high heat transfer rate can be obtained from a turbulent and homogeneous distribution in the pipe [10]. A direct evaporation scheme is presented, which means that liquified CO_2 evaporates in the coil pipe heat exchanger (HX) directly laid under the ice. 3) The operation of an ice stadium requires heating capacity such as hot water for ice resurfacing, dehumidifiers, domestic operations, and terrace freeze-proofing, normally provided by electricity in previous Winter Olympic stadiums. Therefore, a multitemperature heat reclaim system with high-temperature (HTHR), medium-temperature (MTHR), and low-temperature (LTHR) heat exchangers is proposed to recover exhaust heat after compression, which can produce hot water with temperature ranges of 50°C-70°C, 45°C-50°C, and 15-35°C, respectively. In addition, the split cycle is achieved with the design of internal HXs, subcoolers, and flash gas bypasses to improve the performance of the CO_2-DEIT (Fig. 1 (c)).

For comparison to the ice rink technology used for the previous Winter Olympic Games, we designed another R507A refrigeration with a secondary loop ice rink technology (R507A-SLIT) for the National Ice Sports Arena for People with Disabilities, which also serves as a training venue for the Beijing 2022 Winter Olympic Games. A single stage vapour compression cycle with four main processes is adopted in this R507A-SLIT arena. A secondary refrigerant cycle of ethylene glycol (EG) solution is used to transfer the cooling capacity to the ice surface. Employing a heat reclaim system in R507A-SLIT is not able to provide sufficient medium and high temperature hot water because exhaust temperatures of R507A after the compressor reached only 55°C (low adiabatic index for R507A), and a pinch point exists below the phase-change region which limits the high temperature heating process.

(2) Energy efficiency and ice quality

The comprehensive COP (CCOP) test results for CO_2-DEIT and R507A-SLIT during the Beijing Winter Olympic Games showed that compared to the R507A-SLIT with a CCOP of approximately 2.0-3.2, the average CCOP of CO_2-DEIT is 3.10 when only the LTHR is on, and the average value can reach 6.51 when the HTHR and MTHR are also used with an improvement of 103.4% compared with R507A-SLIT (Fig. 1 (d)). The dynamic test processes and data are shown in Supplementary Movie 1. In addition to high energy efficiency, CO_2-DEIT also has great advantage in generating high-quality ice surface. Temperature uniformity of the ice surface is the main indicator of ice quality, which greatly helps athletes achieve better performance because the smaller the temperature difference between the ice surface, the better the smoothness and stability of the ice surface. The abundant statistical ice temperature results indicated that CO_2-DEIT makes the ice surface temperature more uniform, with average temperature differences of less than 0.3°C. In contrast, when using R507A-SLIT, the average temperature difference is approximately 1.3°C (Fig. 1 (e)). Taking short-track speed skating as an example, Olympic records were broken ten times, and six

Olympic records as well as one world record were witnessed in Capital Indoor Stadium.

(3) Potential for CO_2 emission reduction

The use of CO_2 will continue to produce large impact on reducing CO_2 emission and the International Energy Agency has considered CO_2 refrigeration to be a significant pathway highly consistent with the CO_2 direct utilization method (IEA, Putting CO_2 to Use). In addition to the indirect emissions caused by very high energy consumption (nearly 20% of the total world's energy demands) [11], direct emissions from synthetic refrigerants with high GWP values result in a large amount of GHG emissions. In total, refrigeration accounts for 7.8% of GHG emissions and will be as high as 9 Gt CO_2 equivalents per year by 2050 [5]. Therefore, considering the proposed CO_2-DEIT with high energy efficiency and low GWP working fluid, large-scale application of CO_2 refrigerant would contribute significantly to carbon neutrality and sustainable development. In comparison, we conducted Total Equivalent Warming Impact (TEWI) assessment of ice rinks under scenarios of current, carbon peak and carbon neutral, with five ice rink technologies: R507A-SLIT(EG), R507A-SLIT(CO_2), NH_3-SLIT(EG), NH_3-SLIT(CO_2), and CO_2-DEIT. The lifetime TEWI of CO_2-DEIT proposed in this work is the lowest. The decrement ratio of 83.1% compared with the R507A-SLIT(EG) in the 2021 scenario indicates the greatest potential for CO_2 emission reduction (Fig. 1 (f)). In fact, the direct warming impact caused by both refrigerant leakage and disposal contributes to a relatively small proportion of TEWI.

Based on technical impacts, CO_2 refrigeration with new systems can be regarded as gorgeous representative of the next generation of ice rink technology from the view of maximizing energy efficiency and minimizing CO_2 emission with full lifecycle as much as possible. In addition to its superior characteristics in the ice rink, the use of CO_2 systems is considered an advantageous technique path in combined cooling and heating systems and distributed energy resources where both cooling and heating energy with large temperature difference is required.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

Hua Tian and Kai Liu developed the refrigeration system. Hua Tian, Yitai Ma, and Gequn Shu conceptualized the project. Ligeng Li, Jinwen Cai, and Xuan Wang organized the data and designed the figures. Ligeng Li, Jingyu Wang, and Lingfeng Shi conducted the supplementary analysis. Xingyu Liang and Christos N. Markides provided significant suggestions and contributed to paper writing. Ligeng Li, Kai Liu, Hua Tian, and Jinwen Cai contributed equally to this work. All authors contributed to the interpretation of the results and the writing of the paper.

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Figure captions

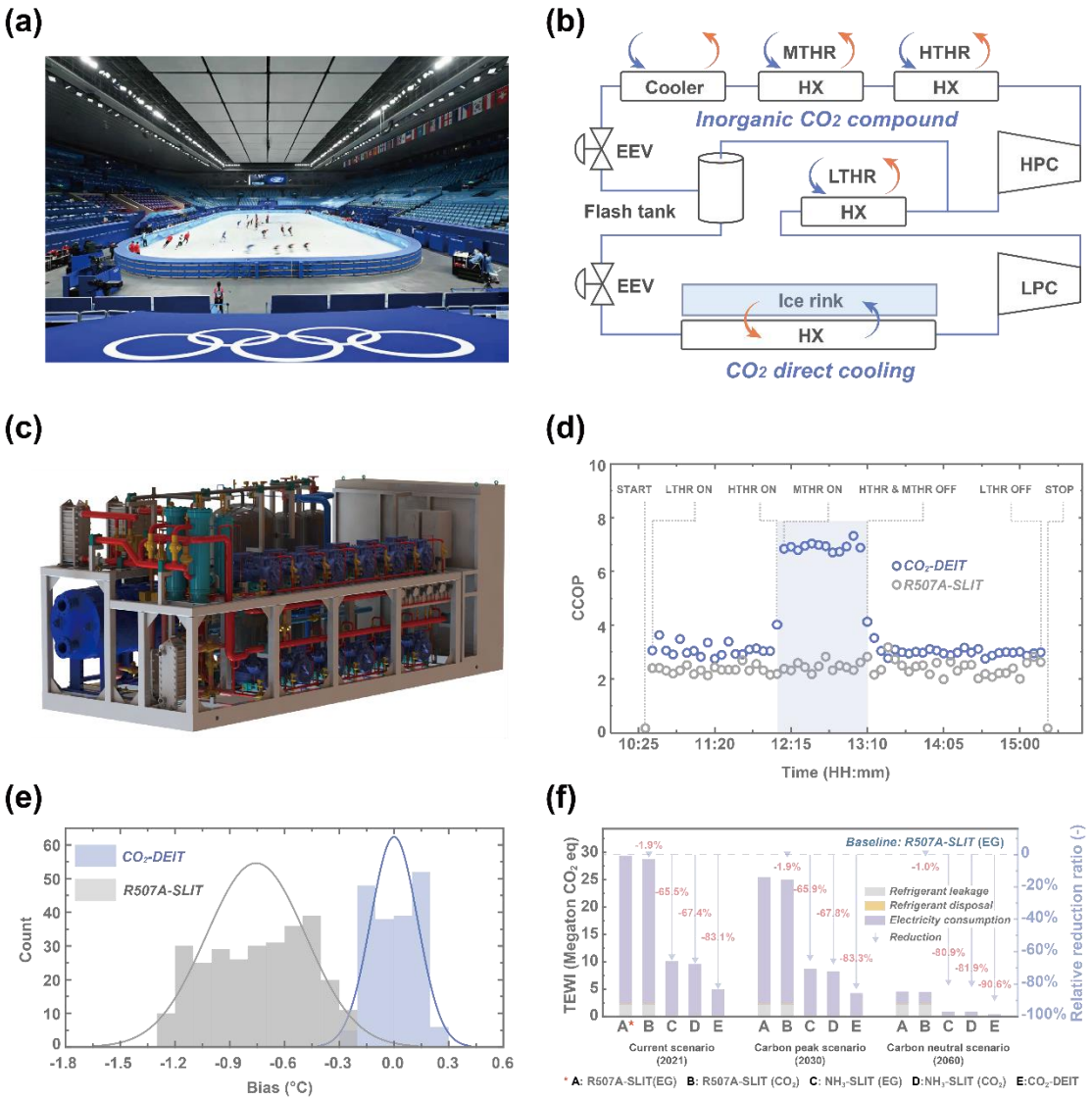


Fig. 1. CO_2 Ice Rink Technology. (a) Photograph of the ice rink of the Capital Indoor Stadium; the competition venue for figure skating (FS) and short-track speed skating (SS) in Beijing 2022 Winter Olympics. (b) Schematic diagram of CO_2-DEIT; two-stage compression with intercooling, heat reclamation, and direct evaporation. (c) 3D diagram of the integrated system of CO_2-DEIT. (d) CCOP comparison between CO_2-DEIT and R507A-SLIT. (e) Comparison of the ice temperature distribution between CO_2-DEIT and R507A-SLIT. (f) Evaluation and prediction of the potential in CO_2 emission reduction.



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