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Evaluation of the thermodynamic performance of R449A and R404A in a prototype of an ice rink

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Introduction

The constant population growth significantly impacts energy demand, particularly in industrial refrigeration applications. As Dong et al. (2021) note, population increases lead to urbanization, with more people living and working in densely populated urban areas. This raises the demand for air conditioning systems in homes, commercial buildings, and industrial settings, thus increasing the load on energy systems. Additionally, there is a higher demand for industrial products, as many industries require refrigeration processes to maintain the quality and integrity of their products, further boosting energy demand. This heightened demand for energy in various industrial refrigeration applications puts pressure on energy resources and underscores the need for energy-efficient and sustainable solutions (Touaibi and Koten, 2021).

A refrigeration system with a chiller cools the working fluid, which is then used to cool a specific space or process. A chiller extracts heat from the working fluid using a vapor compression or absorption cycle and dissipates it into an external environment (Song et al., 2024). In ice rinks, a refrigeration system with a chiller is essential to maintain the rink in suitable conditions for use. Ice rinks require specific temperatures to keep the water frozen appropriately for skating. According to Snyder et al. (2021), a well-designed refrigeration system can improve energy efficiency, lowering long-term operational costs. Additionally, it can be reliable and durable, reducing the likelihood of unplanned downtime. This reliability is crucial to avoid interruptions in the operation of the ice rink, which can negatively impact users and associated revenue (Taebnia et al., 2020).

Traditional refrigeration technologies often use refrigerants that are harmful to the ozone layer and contribute to global warming. According to a study by Anderson et al. (2021), new technologies, considering sustainable development, can opt for less harmful refrigerants or systems that use natural refrigerants, such as hydrocarbons, which have a lower environmental impact. This approach not only reduces operational costs for users but also decreases energy demand and the carbon footprint. These solutions can include designs that are more robust against extreme weather conditions or that utilize renewable energy sources, reducing dependence on fossil fuels and conventional energy supplies. With the growing number of regulations and standards related to refrigerant use and energy efficiency, industries adopting sustainable refrigeration technologies are better positioned to comply with these regulations (Hara-Chakravarty et al., 2022).

Heredia-Aricapa et al. (2020) reviewed the restrictions and environmental impact of fluorinated refrigerants, highlighting the need to replace hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) with more sustainable alternatives, such as natural refrigerants or those with low global warming potential (GWP). The choice of refrigerant is crucial, and selecting refrigerants with a low GWP that does not contribute to ozone depletion is essential. It is anticipated that by 2024, HFC production will be reduced by approximately 40 %. Refrigeration system designs must adapt to the selected refrigerant, potentially requiring adjustments in compression capacity, performance, and refrigerant distribution within the system. Additionally, the thermodynamic and transport properties of the refrigerant must be considered to ensure proper performance. A design that facilitates proper maintenance allows easy access to key components for cleaning and inspection.

Chen et al. (2023) conducted a historical review of substances with high Global Warming Potential (GWP), noting that the development of refrigerants has been driven by the search for compounds that are safer for the environment and have less impact on climate change. R404A, a synthetic refrigerant, began to be widely used in the 1990s as an alternative to refrigerants banned due to their impact on the ozone layer, such as R502. R404A was noted for its high cooling capacity and chemical stability, making it a popular choice in commercial and transport refrigeration systems. However, with increasing awareness of global warming and the need to reduce greenhouse gas emissions, more sustainable alternatives have been considered, as R404A has a GWP of 3922 CO_2e. One such alternative is R449A, a blend of hydrofluorocarbon (HFC) refrigerants proposed as a more environmentally friendly replacement for R404A.

Ghanbarpour et al. (2021) used neural network modeling to analyze the replacement of R404A with R449A. R449A has gained attention as a transitional option due to its lower GWP compared to R404A. While it offers similar performance in terms of cooling capacity, its GWP is significantly lower, with a value of 1397, making it more compatible with efforts to reduce greenhouse gas emissions. Therefore, R449A is considered a more sustainable replacement for R404A, aligning with global efforts to adopt refrigerants with a lower environmental impact. Reducing the environmental impact caused by the use of R404A in chiller refrigeration systems for ice rinks involves adopting several sustainable strategies. Alternatives like R449A, which has a lower GWP than R404A, can be an intermediate step towards refrigerants with an even lower environmental impact, close to zero. Improving system efficiency can reduce the total amount of refrigerant required and thus its environmental impact.

Lucchini et al. (2024) analyzed the thermodynamic properties of R449A as a replacement for HFC refrigerants like R404A and R507A. R449A is considered a viable replacement for R404A for several reasons, despite R404A potentially having slightly better performance in some applications. R449A has been designed to be compatible with existing equipment that uses refrigerants like R404A, facilitating the transition to a more sustainable alternative without significant changes to refrigeration infrastructure. As the demand for low GWP refrigerants increases, the availability and cost of R449A are likely to become more favorable compared to R404A in the future. Additionally, the cost of not complying with environmental regulations can be significant, making the use of more sustainable alternatives economically viable in the long term.

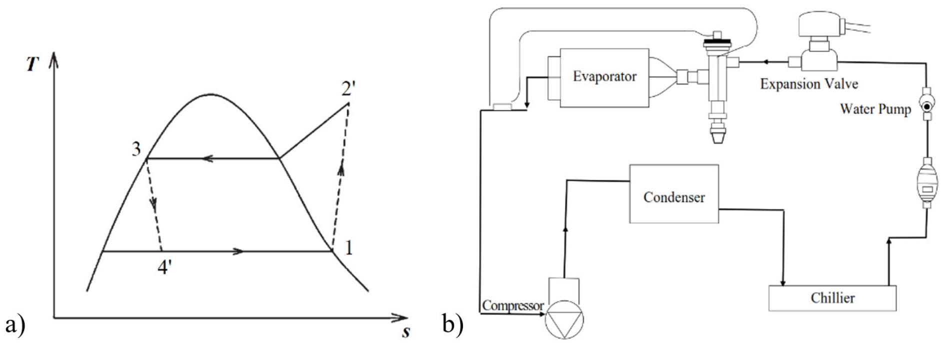
This research proposes a comparative analysis of the performance of a refrigeration system with a chiller using R404A and R449A as working fluids. A prototype ice rink was constructed to study the system thermodynamically until the rink surface crystallizes. This document is organized as follows: Materials and Methods describes the system's operation and presents the equations required for the thermodynamic analysis. Results showcase the equipment and temperature measurements, including comparative graphs of operational parameters with respective descriptions. In the Discussion, a relationship between the calculated results and existing literature is established to validate this work. Finally, the Conclusions summarize the most relevant information, emphasizing the comparative analysis of the system's thermodynamic performance using different working fluids.

Materials and Methods

System Description

A refrigeration system with a chiller is used to cool liquids and transfer heat from a space or process through a refrigeration cycle. Figure 1a presents the T-s diagram of the vapor compression refrigeration cycle. The process begins by compressing the refrigerant to increase its pressure and temperature. Next, the superheated vapor refrigerant passes through the condenser, where it travels through a series of tubes, cools, and condenses by releasing its heat to the surrounding medium. It is important to note that condensers can be air-cooled or water-cooled. The refrigerant exiting the condenser is in a subcooled liquid state but still at high pressure, so an expansion valve is used to regulate the refrigerant flow to the evaporator, reducing its pressure and temperature before entering this component. The analysis concludes with the evaporator, where heat transfer from the medium to be cooled (in this case, water) to the refrigerant occurs. The refrigerant evaporates, absorbing heat from the water and lowering the temperature of this medium [12]. Additionally, in a system with a chiller, a water pump is used to circulate water between the chiller and the point of use [13]. Figure 1b shows a schematic layout of the components for the prototype under analysis.

Figure 1
Refrigeration cycle a) T-s diagram, b) components



Thermodynamic analysis

The following is an analysis of a refrigeration system equipped with a chiller for water cooling, commonly used across various industrial, commercial, or comfort applications. An energy balance was conducted for each component of the system based on enthalpies. The energy balance equation for the system, as proposed by Gado et al. (2022), can be formulated as equation (1):

$$\dot{Q}_{evap} + \dot{W}_{comp} = \dot{Q}_{cond} \quad (1)$$

Where $\dot{W}_{comp}$ represents the required power by the compressor, while $\dot{Q}_{cond}$ is the heat flow released in the condenser to the surroundings. In the evaporator, the refrigerant, operating at low pressure and temperature, absorbs heat from the water, thereby cooling it and transitioning back into a superheated vapor state. The heat absorbed by the evaporator $(\dot{Q}_{evap})$ is determined using equation (2), as provided by Nikhil-Babu et al. (2021):

$$\dot{Q}_{evap} = \dot{m} \cdot (h_{evap,o} \text{-} h_{evap,i}) \quad (2)$$

Where $h_{evap,o}$ and $h_{evap,i}$ represent the enthalpies of the refrigerant at the outlet and inlet of the evaporator, respectively. The mass flow rate of the refrigerant $(\dot{m})$ is calculated by Simbaña et al. (2022) using equation (3):

$$\dot{m} = \frac{\eta \cdot N \cdot V_D}{v_{comp,i}} \quad (3)$$

Where $v_{comp,i}$ denotes the specific volume of the refrigerant at the compressor inlet, η represents the volumetric efficiency, N signifies the rotational speed, and V_D is the displacement volume of the compressor. As the refrigerant transitions into the gaseous state, it is compressed, thereby increasing its pressure and temperature. The energy consumption of the compressor is determined through an energy balance, as outlined by Sabry and Ker (2020) with equation (4):

$$\dot{W}_{comp} = \dot{m} \cdot (h_{comp,o} \text{-} h_{comp,i}) \quad (4)$$

The coefficient of performance (*COP*) serves as a metric for assessing the efficiency of a refrigeration system, defined as the ratio of the useful energy provided, for the ice rink, the heat extracted from the cooled water to the amount of electrical energy consumed. According to Pan et al. (2021), the *COP* of the refrigeration system is calculated using equation (5):

$$COP = \frac{\dot{Q}_{cond}}{\dot{W}_{comp}} = \frac{h_{comp,o} \text{-} h_{cond,o}}{h_{comp,o} \text{-} h_{comp,o}} \quad (5)$$

The heat transfer from the water, where the evaporator is submerged, to the rear surface of the ice rink occurs via convection. The heat released by the water $(\dot{Q}_w)$ is determined by Qu et al. (2023) using equation (6):

$$\dot{Q}_w = \varphi \cdot A_{ir} \cdot \Delta°T \quad (6)$$

Here, φ represents the convective heat transfer coefficient, A_{ir} denotes the surface area of the bottom of the ice rink, and $\Delta°T$ is the temperature differential. Additionally, the cooling transmitted to the ice rink must cool the water on its surface, thus it is transmitted via conduction. The heat conducted through the ice rink plate $(\dot{Q}_{ir})$, as proposed by Lee et al. (2020), is determined using equation (7):

$$\dot{Q}_{ir} = k \cdot \Delta°T \cdot \frac{A_t}{L} \quad (7)$$

Where k is the conductive heat transfer coefficient, A_t is the cross-sectional area of the ice rink plate, and L represents the length.

Results

Figure 2 illustrates the prototype of the constructed ice rink, featuring a 1.5 HP compressor, model NJ9238GK, with a displacement of 26.11 cm^3 and a rotation speed of 3500 rpm. Pressure measurements were taken using low and high analog gauges at the compressor's inlet and outlet, respectively, while temperature readings were obtained via thermocouples connected to a digital display. The water tank for cooling had dimensions of 450 x 450 x 600 mm, and copper pipes were employed for the heat exchangers.

Figure 2
Experimental prototype of ice rink with chiller

a) 

b) 

Given the presence of uninsulated components and areas susceptible to ambient temperature influence on thermocouple readings, a thermal imaging camera was utilized to capture these measurements. In Figure 3a, the compressor's operational temperatures are shown after 10 minutes of activity, with an average outlet temperature of 41.6 °C, closely aligning with the thermocouple measurement. Figure 3b displays the surface temperatures of the ice rink, where the crystallization of surface water was visually observed, with an average temperature of -1.4 °C. Notably, the expansion valve froze nearly instantly, reaching temperatures below -25 °C.

Figure 3
Thermography a) compressor, b) ice rink surface

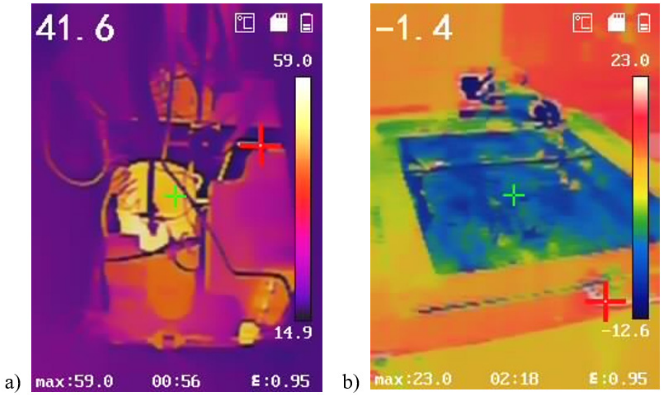


Figure 4 displays the evaporation and condensation temperatures for the R404A and R449A refrigerants over the water-cooling duration. For R404A, the peak evaporation and condensation temperatures were -32.5 and 59.7 °C, respectively, whereas for R449A, these values stood at -27.3 and 58.6 °C. The heat extracted from the water for cooling varied as well; the ice rink surface began to crystallize after 212 and 226 minutes of operation with R404A and R449A, respectively. Figure 4b depicts the decline in the ice rink's surface temperature during operation. After 4 hours with R404A, the temperature reached -2.4 °C, whereas with R449A, it cooled to -1.6 °C.

Figure 4
Temperature concerning operating time a) evaporation and condensation of refrigerants, b) surface of the ice rink

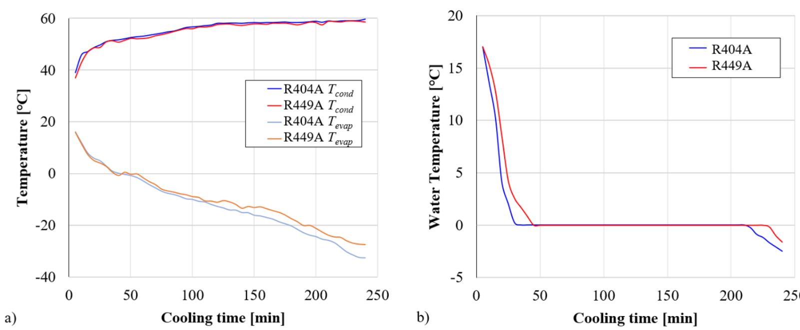


Figure 5 compares the cooling capacity in the evaporator relative to the evaporation temperature of the refrigerants under examination. R449A exhibited a higher maximum value than R404A, with 3.98 versus 3.68 kW, respectively, representing an average difference of 330 W during operation.

Figure 5
Cooling capacity vs. evaporation temperature

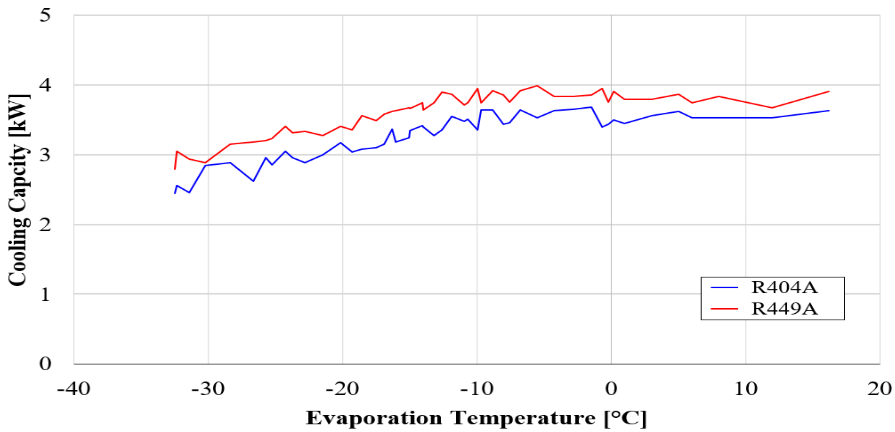


Figure 6 illustrates the COP variation in the system with the refrigerants used, indicating a downward trend for this parameter over the operating period. The highest COP values were 4.65 and 4.32 for R449A and R404A, respectively, with an average difference of 3.08% during system operation with the refrigerants in use.

Figure 6
Coefficient of performance of the system

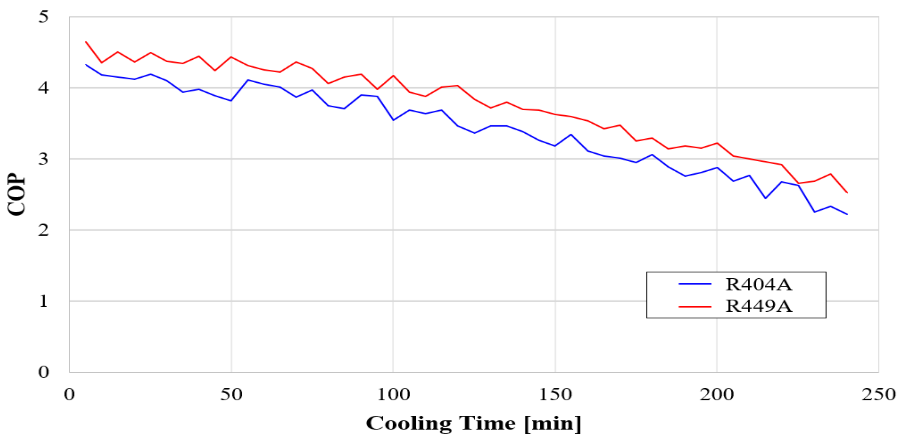
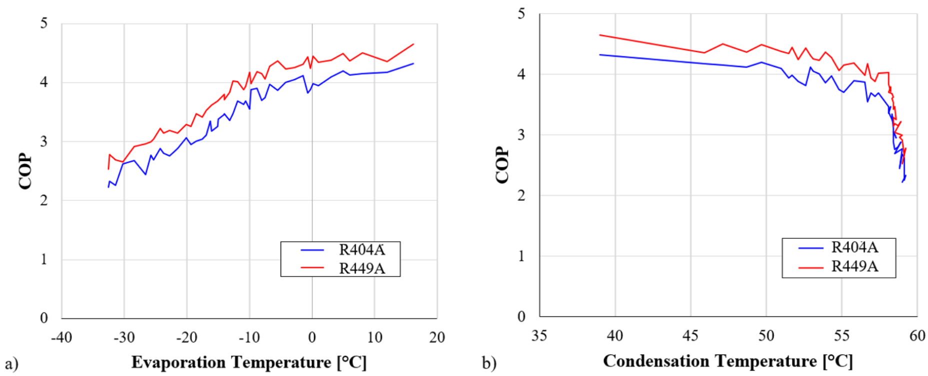


Figure 7a shows the COP variation concerning the evaporation temperature using R404A and R449A in the refrigeration system. For R404A, achieving the lowest temperature of -32.5 °C resulted in a COP of 2.22, whereas with R449A, the lowest temperature of -27.3 °C corresponded to a COP of 2.53. Figure 7b presents the COP values of the system relative to the condensation temperature of the refrigerants used. The maximum COP of the system with R404A was 4.32 at a temperature of 38.9 °C, decreasing by 51.39% during operation until reaching 59.7 °C. Conversely, using R449A, the system's COP reached a maximum value of 4.65 at 37 °C, declining by 54.38% until the refrigerant reached 59.6 °C.

Figure 7
COP vs. temperatures a) evaporation, b) condensation



In this study, conducting experimental tests with the prototype revealed a maximum difference of 3.08 % in the Coefficient of Performance when comparing the use of R404A and R449A refrigerants during the cooling process. The *COP* is a measure of the energy efficiency of refrigeration systems, where a higher value indicates better performance, and the observed difference suggests that the prototype operates slightly better with R449A. In the research presented by Yildirim et al. (2023), a numerical analysis was performed to assess the feasibility of R449A as a sustainable alternative to R404A. In that study, it was determined that R449A offered approximately 5 % higher performance than R404A. This implies that, according to that analysis, refrigeration systems using R449A can operate with better performance and lower environmental impact than those using R404A. Comparing the experimental results obtained in this study with the numerical findings of that research shows consistency in the findings. Although the maximum calculated difference was 3.08 %, it is important to note that both studies suggest that R449A outperforms R404A. By experimentally obtaining a higher *COP* with R449A compared to R404A, and considering that this difference is similar to that found in the scientific literature, it can be affirmed that the prototype is functional. Furthermore, these results support the idea that R449A is a viable and more efficient alternative to replace R404A in refrigeration systems, aligning with efforts towards more sustainable solutions in the industry.

In the experimental tests conducted for this study, a *COP* of 4.32 was achieved for the R404A refrigerant. This value is consistent with the trends observed in the study conducted by Altinkaynak (2021), who also reported similar *COP* values when using R404A. This suggests that this prototype ice rink and the system analyzed in that research have comparable performance, thus validating the accuracy and effectiveness of the experimental tests conducted. On the other hand, when using the R449A refrigerant, a *COP* of 4.65 was obtained, which subsequently decreased to 2.52 during the cooling time. To better understand these results, the research by Alam and Jeong (2020), was analyzed, who calculated the thermodynamic properties of R449A using molecular dynamic simulation. Their studies also presented similar *COP* values, indicating that the experimental tests are aligned with theoretical models and simulations. As indicated by Jeyakumar et al. (2022), a high *COP* indicates a more efficient refrigeration system. This means that the system requires less energy to perform the same amount of cooling work, which in turn reduces operating costs.

A higher *COP* implies lower electricity expenses and more economical operation of the refrigeration system, which is beneficial both economically and environmentally. Therefore, the *COP* has not only allowed the evaluation and comparison of the refrigeration system's performance in the prototype but has also been fundamental for selecting the most suitable refrigerant for our specific application. In this case, R449A, with a higher *COP* than R404A under the same conditions, emerges as a more viable alternative, reinforcing the idea that it may be a better option in terms of energy efficiency and operational cost reduction.

Conclusions

A comparative experimental analysis of a refrigeration system equipped with a chiller for cooling the surface of an ice rink prototype has been conducted. The prototype was built considering the vapor compression refrigeration cycle, utilizing a 1.5 HP electric compressor, and incorporating pressure gauges for measuring pressure at the inlet and outlet of this component. While thermocouples connected to a digital display were used for measuring the fluid's temperature, a thermal imaging camera was also employed to take measurements in areas exposed to ambient temperatures, such as the ice rink's surface. It was observed that R404 reached maximum evaporation and condensation temperatures of -32.5 and 59.7 °C, respectively, while for R449A, these temperatures were -27.3 and 58.6 °C. The crystallization of the ice rink's surface was observed after the system had been operating for 212 and 226 minutes with R404A and R449A, respectively.

In the thermodynamic analysis, it was determined that the maximum cooling capacity was 3.68 kW using R449A as the working fluid, whereas with R404A, it was 3.63 kW. Consequently, it was established that the Coefficient of Performance (*COP*) for the system using R404A reached a maximum value of 4.32 when the refrigerant temperature was 38.9 °C and decreased by 51.39 %. Conversely, when using R449A as the working fluid, the system's maximum COP was 4.65 and decreased by 54.38 % during operation. Thus, an average difference of 3.08 % for the *COP* of the system between the refrigerants during the cooling time until the ice rink's surface completely crystallized after four hours was established.

R449A requires a slightly lower evaporation pressure than R404A to achieve the same evaporation temperature conditions, which influences the required amount of refrigerant. The system's performance using R449A is superior to that using R404A, as it necessitated lower refrigerant loads and, consequently, lower electricity consumption. From the literature review, it is evident that R404A has been widely utilized in the past due to its performance, but it is gradually being replaced by more sustainable alternatives owing to its high Global Warming Potential (GWP).

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