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A Novel Direct-Expansion Radiant Floor System Utilizing Water (R-718) for Cooling and Heating

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Abstract: While forced-air convective systems remain the predominant method for heating and cooling worldwide, radiant cooling and heating systems are emerging as a more efficient alternative. Current radiant cooling systems primarily rely on hydronic chilled water systems. This study introduces direct-expansion radiant cooling as a novel technique that could enhance the efficiency of radiant cooling and reduce its environmental impact. Water (R-718) has been tested as a refrigerant due to its favorable thermodynamic properties and environmental advantages; however, to the author's knowledge, it has yet to be tested in direct-expansion radiant cooling. This research investigated several refrigerants, including water (R-718), ammonia (R-717), R-410a, R-32, R-134a, and R-1234yf, for this application. The findings indicate that water demonstrates efficiency comparable to other non-natural refrigerants, making it a promising candidate, given its favorable thermodynamic properties and substantial environmental benefits. Despite challenges such as a high compression ratio necessitating multi-stage compression, a high compressor discharge temperature exceeding 300 °C and requiring specialized blade materials, and a high suction volume flow rate, direct-expansion radiant cooling operates within a different temperature range. Consequently, the compressor discharge temperature can be reduced to 176 °C, and the compression ratio can be lowered to approximately 3.5, making water a more viable refrigerant option for this application.

Keywords: heating; ventilation and air conditioning (HVAC); vapor compression cycle (VCC); coefficient of performance (COP)

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1. Introduction

Heating, ventilation, and air-conditioning (HVAC) systems play a crucial role in ensuring thermal comfort in buildings by regulating temperature, humidity, indoor air quality, pressure, and air drafts [1]. The HVAC industry offers various systems, including hydronic, direct expansion, and evaporative cooling systems, each employing distinct methods for thermal regulation. Hydronic systems use water, steam, or water-based solutions as heat transfer fluids and can be categorized into water–air forced convective systems and radiant systems, depending on how energy is delivered to the conditioned spaces. Conversely, direct-expansion (DX) systems utilize a refrigerant loop directly within the space, eliminating the need for water as a heat transfer medium. DX systems are theoretically more efficient than hydronic systems because of fewer heat transfer stages and less mechanical complexity [2].

Radiant systems, particularly those that incorporate radiant floor cooling and heating, have gained popularity due to their ability to provide more uniform thermal distribution, enhance occupant satisfaction, and reduce energy consumption [3]. Numerous studies have emphasized the superior occupant comfort offered by radiant floor cooling systems. For instance, Fang et al. (2013) conducted a field study in office buildings, reporting that over 80% of occupants experienced enhanced thermal comfort compared to conventional air-conditioning systems [4]. Similarly, Kim et al. (2015) found that radiant floor cooling in residential buildings led to higher occupant satisfaction due to its uniform temperature distribution and minimized draft sensations [5]. Radiant systems operate at temperatures closer to ambient room temperature, which contributes to considerable energy savings. However, despite these advantages, the widespread adoption of radiant floor cooling is limited, primarily due to challenges like condensation risks and the system's lower cooling capacity compared to traditional methods [6]. The performance benefits of radiant systems are well documented in the literature. Research has shown that radiant systems can reduce building energy consumption by 27–59% without sacrificing thermal comfort, especially when hydronic systems are used [7]. Bojić et al. (2013) noted that radiant systems allow for higher supply temperatures in cooling and lower temperatures in heating, reducing the temperature lift in the vapor compression cycle (VCC) and boosting the system's coefficient of performance (COP) [8]. Moreover, the thermal inertia of buildings with radiant systems enables load-shifting capabilities, lowering operational costs and enhancing overall system efficiency [9].

Existing research predominantly emphasizes hydronic radiant systems. For example, Leigh and Song (2005) examined integrating dehumidification ventilation with radiant floor cooling, reporting energy savings of up to 67% compared to all-air cooling systems [10]. Similarly, Zhang et al. (2020) demonstrated that hydronic radiant systems operating at moderate temperatures could improve the COP of chillers or heat pumps, further enhancing energy conservation [11]. Conversely, research on direct-expansion radiant cooling systems is limited. Li and Yang (2021) conducted a numerical study on direct-expansion radiant cooling using R-410A, revealing notable energy savings while maintaining acceptable thermal comfort [12]. Zhao et al. (2022) explored the dynamic thermal behavior of direct-expansion radiant cooling with R-22 in residential applications, showcasing its potential for reduced energy use and enhanced system responsiveness compared to hydronic systems [13]. While these studies provide valuable insights, research on direct-expansion radiant cooling using natural refrigerants remains nascent, with substantial gaps in understanding their long-term performance, occupant comfort, and environmental impact. Though natural refrigerants like water and CO_2 offer promising environmental advantages, their application in direct-expansion radiant cooling is underexplored. Further research is needed to assess these systems' feasibility, energy efficiency, and sustainability, particularly in comparison to conventional refrigerants. Addressing these gaps is crucial to advancing environmentally friendly cooling technologies in buildings.

Despite hydronic systems' demonstrated benefits, the potential for using water as a refrigerant in direct-expansion radiant cooling systems has seen little attention. The current literature mainly focuses on conventional refrigerants like HFCs, which, though effective, present environmental challenges such as high global warming potential (GWP) [12]. Natural refrigerants, including water, offer significant environmental advantages, yet their application in direct-expansion systems is largely unexplored. This study sought to fill that gap by investigating the feasibility, performance, environmental benefits, and energy-saving potential of using water as a refrigerant in direct-expansion radiant cooling systems.

This manuscript is organized as follows: the introduction reviews the significance of direct-expansion radiant cooling systems, highlighting existing research on hydronic and direct-expansion systems and identifying key research gaps, especially regarding natural refrigerants like water, in particular. Section 2 outlines the methodology for simulating refrigeration cycles, detailing compressor efficiency assumptions and exploring the potential of integrating an internal heat exchanger (IHX). Section 3 presents the results and discussion, evaluating various refrigerants' performance under different configurations and focusing on key performance indicators like COP, suction volume flow rate, compression ratio, compressor discharge temperature, and the environmental aspects, as in Section 3.6. Section 4 addresses the validation of the results, comparing simulated outcomes with experimental data and benchmarks to ensure accuracy and reliability. Lastly, Section 5 concludes by summarizing key findings, discussing the study's limitations, and suggesting future research directions.

2. Methodology

This research used CYCLE_D-HX software (Version:2.0) to investigate the potential of using direct expansion in radiant floor cooling. CYCLE_D can simulate the performance of the subcritical refrigeration cycle of a single-component refrigerant or blend. Unlike other vapor compression cycle models, this software does not require the refrigerant saturation temperatures in the evaporator or condenser as inputs. Instead, it utilizes the temperature profiles of the heat source and heat sink and the temperature difference of the evaporator and condenser as the system inputs. This approach makes the program suitable for comparing the performance of different refrigerants for a particular application [14]. The floor surface temperature must be within a specific range to achieve an acceptable space temperature. According to ASHRAE, when the radiant floor is in direct contact with the human body, the floor surface temperature should be between 17–21 °C [15]. However, some researchers suggest 19 °C as the minimum accepted floor surface temperature [16,17]. This research aimed to provide a comparative evaluation of different refrigerants, including water (R-718), ammonia (R-717), R-410a, R-32, R-134a, and R-1234yf, for direct-expansion radiant cooling applications.

The evaporation and condensing temperatures selected for this study were 18 °C and 37 °C, representing the low- and high-side temperatures of the cycle. This research compared several factors affecting the cycle performance and its feasibility for natural and synthetic refrigerants. These factors include the system coefficient of performance, compressor discharge temperature, compressor suction volume flow rate, volumetric capacity, compressor power, and compression ratio.

In the simulation, typical values for compressor efficiencies were considered:

- Compressor isentropic efficiency: 0.70%;
- Compressor volumetric efficiency: 0.95%;
- Compressor electric motor efficiency: 0.97%.

In the simulation, the chosen values for compressor efficiencies aligned with industry standards and practical expectations for centrifugal refrigerant compressors. The isentropic efficiency of 70% reflects a typical range for these compressors, which often falls between 70% and 85% in practice [18,19]. This value is representative of standard centrifugal compressors, accounting for energy losses due to non-ideal processes. The volumetric efficiency of 95% is consistent with high-performance centrifugal compressors, where such values are common due to advanced design features that minimize leakage and maximize the effective compression volume [15]. Additionally, the electric motor efficiency of 97% aligns with modern, high-efficiency motors used in conjunction with these compressors, reflecting advancements in motor technology that improve energy conversion and reduce electrical losses [20]. These assumed efficiencies provided a realistic basis for the simulation, ensuring that the results accurately represent the performance of current centrifugal refrigerant compressor systems.

These values apply to most applications and compressor types [21,22]. A superheat of 2 °C was considered on the suction side of the compressor to avoid mixed-phase conditions during compression and ensure system reliability. Additionally, 2 °C subcooling was considered on the condenser side. This study simulated a basic refrigeration cycle with only four key components and without the inclusion of an internal heat exchanger (IHX) as illustrated in Figure 1. However, incorporating an IHX into the actual cycle could significantly enhance system efficiency by improving the thermodynamic performance of various refrigerants. For instance, adding an IHX can increase the efficiency of refrigerants like water (R-718) and ammonia (R-717) by enhancing the subcooling of the liquid refrigerant, leading to better heat transfer in the evaporator. Similarly, for synthetic refrigerants such as R-410A, R-32, R-134a, and R-1234yf, an IHX can reduce throttling losses in the expansion device, thereby boosting the overall coefficient of performance (COP) of the system.

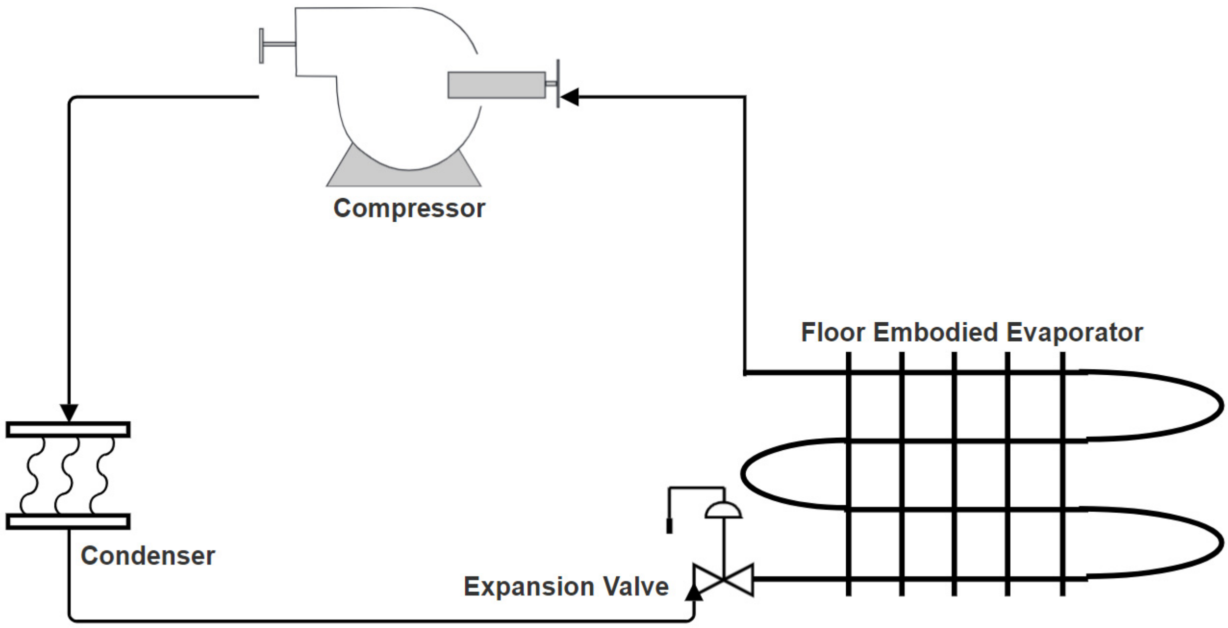

Figure 1. Schematic diagram showing the system components.

However, for applications like radiant floor cooling, where the temperature range is relatively close to ambient conditions and the temperature lift is reduced, the impact of adding an IHX on the cycle's efficiency may be less pronounced. This is because the benefits of enhanced subcooling and reduced throttling losses are diminished when the system operates under conditions of lower temperature differences. Consequently, while the IHX could still offer improvements, its effect on energy efficiency might be more limited in these specific low-lift scenarios.

To evaluate the feasibility of the DX radiant cooling system in comparison to conventional systems, three distinct refrigeration cycles were developed for various applications, including Variable Refrigerant Flow (VRF) systems and chillers, to serve as benchmarks against the proposed direct-expansion (DX) radiant floor cooling system, which utilizes water (R-718) as a refrigerant. An internal heat exchanger (IHX) was incorporated into the chiller cycle, given its suitability for handling high-temperature lifts. Each system was assessed based on key performance indicators, including Seasonal Energy Efficiency Ratio (SEER), Total Equivalent Warming Impact (TEWI), Lifetime Energy Cost (LTEC), and Global Warming Potential (GWP).

Different refrigerants have various thermophysical properties, and the heat a refrigerant can absorb through superheating is directly related to the refrigerant's heat capacity (Cp), the degrees of superheating, and the mass flow rate through the cycle. Accordingly, refrigerants with higher specific heat can absorb more heat for the same level of superheating, thereby enhancing cycle efficiency. The superheating stage has benefits beyond improving system efficiency; it significantly impacts system reliability by preventing liquids from entering the compressor and causing damage to its parts. While system efficiency, environmental impact, and operating conditions are significant in refrigerant selection criteria, other factors, such as refrigerant flammability and toxicity, must also be considered. Table 1 shows some of the properties that impact refrigerant selection for an application.

Table 1. The tested refrigerants and their main properties [17].

Refrigerant	R-410a	R-32	R-134a	R-1234yf	R-717	R-718
Molar Mass (g/mol)	72.58	52.01	102.03	114.04	17.03	18
NBT (°C)	−48.5	−51.7	−26.1	−29.5	−33.34	100
Critical Temperature (°C)	72.8	78.2	101.06	94.7	132.4	374
Critical Pressure (MPa)	4.90	5.78	4.06	3.38	11.36	22.1
GWP (100 Years)	2088	677	1550	<1	Zero	Zero
Atmospheric Life	17 y	4.9 y	13.8 y	11 d	NA	NA
Flammability range (volume%)	Zero	13.3–29.2	Zero	6.2–12.3	15–28	Zero
Burning velocity (cm/s)	NA	6.7	NA	1.5	7.2	NA
ASHRAE safety classification	A1	A2L	A1	A2L	B2L	A1

The Mathematical Model for VCC

This study proposes using direct-expansion VCC for radiant floor cooling and investigated the effect of the VCC operating temperature on the system performance for different refrigerant options. The mathematical model considers the four main components of the VCC: the evaporator, condenser, compressor, and expansion valve. In the evaporator, the refrigerant changes states from a saturated liquid to superheated vapor. Similarly, the refrigerant changes from vapor to a sub-cooled liquid in the condenser. The evaporation and condensing are ideally iso-baric, while the compression and expansion processes are ideally adiabatic, as no heat is added or removed in these processes. The rate of heat absorbed by the evaporator can be calculated by Equation (1) as

$$q_{eva} = \dot{m}.h_{fg} + \dot{m}C_p\Delta T_{superheating} \tag{1}$$

where $\dot{m}$ is the refrigerant mass flow rate, h_{fg} is the latent heat of vaporization for the refrigerant at the lower cycle pressure, C_p is the specific heat capacity, and $\Delta T_{superheating}$ is the refrigerant superheating measured in kelvins. This heat is equivalent to the heat transferred to the fluid when using a heat transfer medium fluid. However, when a direct-contact heat exchanger is used, it should be equivalent to the heat transfer rate to the conditioned space:

$$q_{fluid} = \dot{m}_{fluid}C_p\Delta T_{fluid}, \tag{2}$$

where $\dot{m}_{fluid}$ is the heat transfer fluid mass flow rate, C_p is the heat transfer fluid specific heat, and ΔT_{fluid} is the temperature difference of the heat transfer fluid across the evaporator.

The rate of heat dissipated to the surroundings or the heat transfer fluid through the condenser can be represented by Equation (3):

$$q_{con} = -\left(\dot{m}.h_{fg} + \dot{m}C_p\Delta T_{subcooling}\right), \tag{3}$$

where $\dot{m}$ is the refrigerant mass flow rate, h_{fg} is the latent heat of vaporization for the refrigerant at the higher cycle pressure, C_p is the specific heat capacity, and $\Delta T_{subcooling}$ is the refrigerant subcooling measured in kelvins. This heat is equivalent to the rate of heat transfer to the heat transfer fluid:

$$q_{fluid} = -\dot{m}_{fluid}C_p\Delta T_{fluid} \tag{4}$$

where $\dot{m}_{fluid}$ is the heat transfer fluid mass flow rate, C_p is the heat transfer fluid specific heat, and ΔT_{fluid} is the temperature difference of the heat transfer fluid across the condenser.

The compressor power can be expressed by the enthalpy difference across the compressor with consideration of the mechanical efficiency as in Equation (5):

$$W_{comp} = \dot{m_{ref}}.(h_{con} - h_{eva}).\frac{1}{\eta_{mec}}. \tag{5}$$

where W_{comp} is the compressor power in W, $\dot{m}_{fluid}$ is the heat transfer fluid mass flow rate, h_{con} and h_{eva} are the condenser and evaporator enthalpies, and η_{mec} is the mechanical efficiency.

The expansion process is essential for the VCC to operate, as it is required to reduce the refrigerant pressure to allow for the refrigerant to evaporate at a lower cycle pressure. The net rate of energy wasted through the expansion device can be estimated by Equation (6):

$$E_{exp=}\left(W_{comp} + q_{eva}\right) - q_{con}. \tag{6}$$

where q_{eva} is the rate of absorbing heat by the evaporator, and q_{con} is the heat dissipation rate in the condenser section; this should be equivalent to the enthalpy difference across the expansion device.

The vapor compression cycle energy performance is measured by the coefficient of performance, which is a unitless number. The coefficient of performance can be calculated by Equations (7) and (8) in the cooling and heating:

$$COP_C = \frac{q_{eva}}{W_{comp}/\eta_{elec}} \text{ and} \tag{7}$$

$$COP_h = \frac{q_{con}}{W_{comp}/\eta_{elec}}, \tag{8}$$

where η_{elec} is the electrical efficiency of the compressor motor. One of the common ways to evaluate the cycle performance is to compare it to the ideal cycle, which is the Carnot cycle. The Carnot cycle COP can be calculated by Equations (9) and (10) for cooling and heating:

$$COP_{C(cooling)} = \frac{T_{Evap}}{T_{Cond} - T_{Evap}} \text{ and} \tag{9}$$

$$COP_{C(Heating)} = \frac{T_{Cond}}{T_{Cond} - T_{Evap}}, \tag{10}$$

where T_{Evap} and T_{Cond} are the evaporator and condenser temperatures in K.

In radiant cooling and heating systems, the heat transfer process involves several stages, starting with the heat exchange between the heat transfer fluid and the inner wall of the pipe, followed by conduction through the pipe wall. Subsequently, heat is transferred between the outer wall of the pipe and the screed layer, then through the screed layer to the tiles, and, finally, from the top surface of the radiant floor to the conditioned space. A small portion of heat also transfers through the insulation layer below the pipes. Calculating the heat transfer between the screed layer surface and the pipe's outer surface is challenging due to the complex nature of two-dimensional heat transfer. However, in these systems, the temperature of the heat transfer fluid is close to the conditioned space temperature, resulting in a nearly uniform surface temperature distribution for both the screed layer and the pipe [23]. The heat exchange between the outer surface of the pipe and the screed layer surface can be calculated using the conduction shape factor, as described in Cole et al. (2014) and X. Wu et al. (2015) [24,25], using Equation (11):

$$S = \frac{2\pi l}{\ln\left[\frac{2M}{\pi D_{\circ}} sh \frac{\pi(d_1 + D_{\circ}/2)}{M}\right]} \tag{11}$$

$$d_1 = \delta_{scr} - D_{\circ} \tag{12}$$

The upper and lower surface temperatures of the floor are different. In order to solve this problem, we assumed a fully insulated surface below the pipe. The conduction shape factor between the pipe and the upper surface of the floor can be regarded as the conduction shape factor obtained from Equation (11).

$$R_{eq} = \frac{M.l}{S.\delta_{scr}} \tag{13}$$

$$R = \frac{1}{\alpha_u} + \frac{\delta_t}{\lambda_t} + \frac{M.ln(D_o/D_i)}{2\pi\lambda_p} + \frac{M}{\pi\alpha_r D_i} + R_{eq}, \tag{14}$$

where M is the pipe spacing in meters, Di/Do is the inner/outer diameter of the pipe, λ_t and δ_t are the thermal conductivity and the thickness of the tiles, λ_p and δ_p are the thermal conductivity and the thickness of the pipe, α_u is the total heat transfer coefficient between the upper surface of the radiant floor and the indoor environment, R_{eq} is the resistance between the pipe's outer surface and the screed layer, and α_r is the heat transfer coefficient between the refrigerant and the pipe's inner surface.

Based on the experimental results of the evaporation heat transfer with two refrigerants in small channels, Tran et al. (1996) found that nucleation is the dominant mechanism of evaporation heat transfer in coil tubes. The authors of this study correlated heat transfer coefficients by evaporation as a function of boiling number B_o, liquid Weber number We_l, and liquid to vapor densities [26].

$$\alpha_r = 6,400,000\left(B_o^2 We_l\right)^{0.27}\left(\rho_l/\rho_g\right)^{-0.2} \tag{15}$$

where the boiling and Weber numbers are given, respectively, as

$$B_o = \frac{\acute{q}}{h_{fg}\dot{m}} \quad \text{and} \tag{16}$$

$$\mathrm{We_l = D\dot{m}^2/\sigma\rho_l} \tag{17}$$

To validate the simulation results, a sample calculation was performed and compared to the simulation results using the below equations:

$$Q = \dot{\mathrm{m}}h_{fg} + \dot{\mathrm{m}}\Delta T_{sh} \tag{18}$$

$$\text{Flow Rate} = \dot{\mathrm{m}}v_s \tag{19}$$

$$\text{COP} = Q_E/W_c = (h_1 - h_4)/(h_2 - h_1) \tag{20}$$

where ΔT_{sh} is superheating, v_s is the refrigerant specific volume at vapor state, and h is the enthalpy.

3. Results and Discussion

The key indicators of a refrigerant's applicability and performance include the system coefficient of performance, which reflects energy efficiency and impacts the operational cost of the equipment. The compression ratio is another crucial measure, influencing the compressor type and the number of compression stages required. Additionally, the refrigerant's volumetric capacity, which directly affects the suction volume flow rate, determines the appropriate compressor type. Lastly, the compressor discharge temperature is critical in deciding the compressor material. The following sections discuss these aspects in detail.

3.1. System Coefficient of Performance (COP)

The coefficient of performance is a fundamental measure for evaluating the performance of a vapor compression refrigeration cycle. It indicates the system's ability to transfer thermal energy relative to its energy consumption. Several factors impact the COP, including the evaporating and condensing temperatures, the thermodynamic properties of the refrigerant, the effectiveness of the evaporator and condenser, and the design of mechanical and electrical components such as the compressor, expansion valve, and system controls.

Additionally, the heat exchanger area plays a significant role in cycle performance. Increasing the heat exchanger area enhances its effectiveness, allowing for it to absorb or dissipate more heat to the conditioned space, thus improving the COP. The simulated COPs of the studied refrigerants are shown in Figure 2. The study demonstrated that ammonia achieved the highest COP among the selected refrigerants, followed closely by water and R-134a, which had nearly the same values. R-32 and R-1234yf followed, with R-410a having the lowest COP value. The basic cycle for the vapor compression cycle was modeled by the Carnot cycle. As shown in Equations (9) and (10), the Carnot cycle efficiency is a function of the cycle's operating temperature and is independent of refrigerant properties. However, the refrigerant properties significantly impact the deviations from the ideal Carnot cycle.

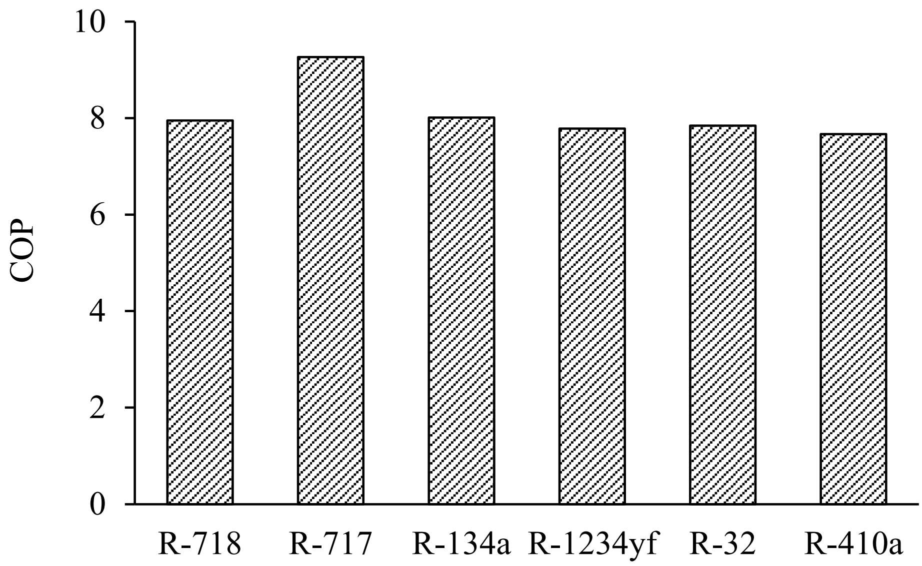

Figure 2. COP of different refrigerants at 14 °C evaporation and 37 °C condensing temperatures.

The losses of the refrigerant through the cycle are intricately tied to the thermodynamic and thermophysical properties of the refrigerant itself. Key properties such as thermal capacity, viscosity, and conductivity play crucial roles in determining the energy losses across the refrigeration circuit. These properties directly influence the efficiency of heat transfer processes within the system, affecting the overall performance and effectiveness of the refrigeration cycle. Therefore, understanding and optimizing these properties are essential for minimizing energy losses and improving the efficiency of the refrigeration system. For benchmarking purposes, R-134a refrigerant serves as our baseline. In this comparison, ammonia demonstrates the most substantial improvement in the COP, approximately 16%, as illustrated in Figure 3. However, when examining all other studied refrigerants, their COPs range from 97% to 99% in comparison to R-134a, with water achieving the closest COP to R-134a. The rationale behind selecting R-134a as the baseline is its status as the most efficient among contemporary non-natural refrigerants.

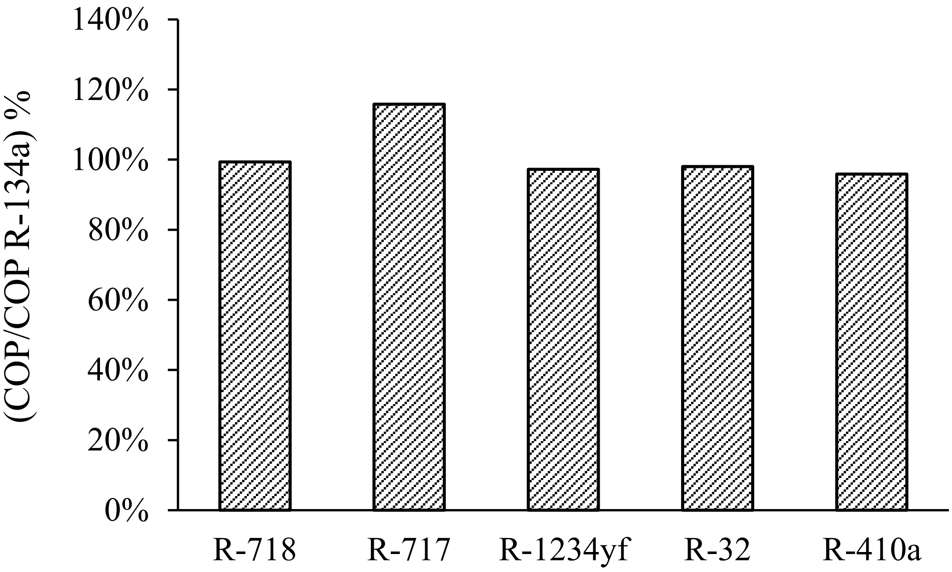

Figure 3. The COP of different refrigerants compared to R-134a at 14 °C evaporation and 37 °C condensing temperatures.

The choice of R-134a as the baseline for comparison is common in refrigeration studies due to its widespread usage and established performance characteristics. In this comparison, ammonia stands out with a notable improvement in the COP compared to R-134a. This enhancement can be attributed to various factors, including favorable thermodynamic properties such as high latent heat of vaporization and a lower condensing temperature, which contribute to more efficient heat transfer and energy utilization in the refrigeration cycle. Additionally, ammonia's lower viscosity and higher thermal conductivity facilitate smoother flow through the system and more effective heat exchange, leading to an improved COP. Other refrigerants studied show marginal differences in the COP compared to R-134a, suggesting comparable performance characteristics within the context of the refrigeration cycle under consideration. Water emerges as a competitive option, with its COP closely matching that of R-134a. This result is significant because water is a natural refrigerant with environmental advantages, including low global warming potential and ozone depletion potential. In summary, the observed variations in COP among different refrigerants reflect their distinct thermodynamic properties and performance characteristics, with ammonia demonstrating the most significant improvement and water emerging as a promising environmentally friendly alternative to synthetic refrigerants like R-134a.

3.2. Compression Ratio

The compression ratio is a critical consideration in refrigerant selection, as it directly impacts the system's coefficient of performance, as well as its size and cost. It is defined as the ratio of the compressor's absolute discharge pressure to its absolute suction pressure. This ratio is influenced by various factors, including the thermodynamic and thermophysical properties of the refrigerant and the temperature lift across the system. Typically, a lower compression ratio is preferable as it signifies a more efficient cycle. Figure 3 illustrates how different refrigerants necessitate varying compression ratios for operation at the same temperature lift, owing to their unique thermodynamic properties. Water, despite its advantageous thermodynamic properties, presents a significant challenge due to its high compression ratio. Compared to other refrigerants in the study, water requires nearly double the compression ratio, as depicted in the figure. Previous studies on water as a refrigerant for low-temperature building cooling have highlighted the need for multi-stage compression systems [27]. However, some researchers have demonstrated that single-stage compression can achieve compression ratios below a value of 4 [28–30]. Although water vapor compression systems typically require ratios of around 5.5 to 6.0 for standard air-forced building cooling, radiant floor cooling demands lower temperature lifts, necessitating a lower compression ratio. In the proposed direct-expansion radiant floor cooling system, the compression ratio was approximately 3.5. While this remains higher than that of other refrigerants, it is within the range feasible for single-stage compression, as indicated in Table 2. Despite its challenges, this compression ratio aligns with the requirements of radiant floor cooling applications, showcasing the potential for the effective utilization of water as a refrigerant in such systems.

Table 2. Thermal performance of different refrigerants at 14 °C evaporation temperature.

	R-718	**R-717**	**R-134a**	**R-1234yf**	**R-32**	**R-410a**
Compressor Discharge Temperature (°C)	175.9	80.1	47.3	42.3	61.7	53.3
Compression Ratio	3.58	1.94	1.91	1.85	1.77	1.77
Compressor Power (kW)	5.033	4.839	4.993	5.141	5.1	5.216
Compressor Suction Volume Flow Rate (m^3/h)	4732.0	22.7	37.9	40.1	16.2	17.3
COP, Cooling	7.9	9.3	8.0	7.8	7.8	7.7
Compressor Discharge Pressure (kPa)	6.2	1426.2	943.7	951.7	2288.1	2247
COP/COP, R-134a (%)	99%	116%	100%	97%	98%	96%
Flow Rate, Vs, R-134a (%)	12476%	60%	100%	106%	43%	46%

Although water exhibits a high compression ratio, as illustrated in Figure 4, it does not inherently result in high compressor power. In our investigation, we determined the compressor power for R-718 to be approximately 5.0 kW, which was comparable to other refrigerants and notably lower than that of R-410a, R-32, and R-1234yf. While the compression ratio of water (R-718) may be higher compared to other refrigerants, such as R-410a, R-32, and R-1234yf, this does not inherently translate to increased compressor power. In fact, the compressor power for R-718 was found to be comparable to other refrigerants, indicating that factors beyond compression ratio play a significant role. This observation suggests that the specific properties of water, such as its density and specific heat capacity, may influence the compressor power differently than other refrigerants. Additionally, the saturation temperature drops across the evaporator coil, indicative of the pressure drop, highlight the importance of efficient heat exchange within the system. While higher pressure drops typically require a larger temperature drop for effective cooling, optimizing this balance is crucial for achieving desired performance without unnecessarily increasing the compressor's workload. Therefore, understanding the thermodynamic behavior and heat transfer characteristics of the refrigerant is essential for accurately assessing its performance in the system.

The evaporator coil's size in the proposed system plays a crucial role in determining the saturation temperature drop, with larger coils typically necessitating higher saturation temperature drops for effective operation. Figure 5 illustrates how different refrigerants' compression ratios correlate with the saturation temperature drop. Notably, R-718 demonstrates a significant sensitivity to the saturation temperature drop, indicating its capability to manage high static pressures while maintaining relatively stable temperatures across the coil. This characteristic renders it particularly well-suited for applications requiring large-coil direct-expansion cooling. Moreover, the cycle's operating pressure and compression ratio are directly linked to the refrigerant's boiling temperature and critical pressure, with refrigerants possessing higher boiling temperatures typically exhibiting lower cycle operating pressures. In the case of water, its high boiling temperature results in a notably low cycle operating pressure, potentially presenting operational challenges as it may fall below atmospheric pressure. However, these challenges can be effectively mitigated with proper installation and maintenance protocols.

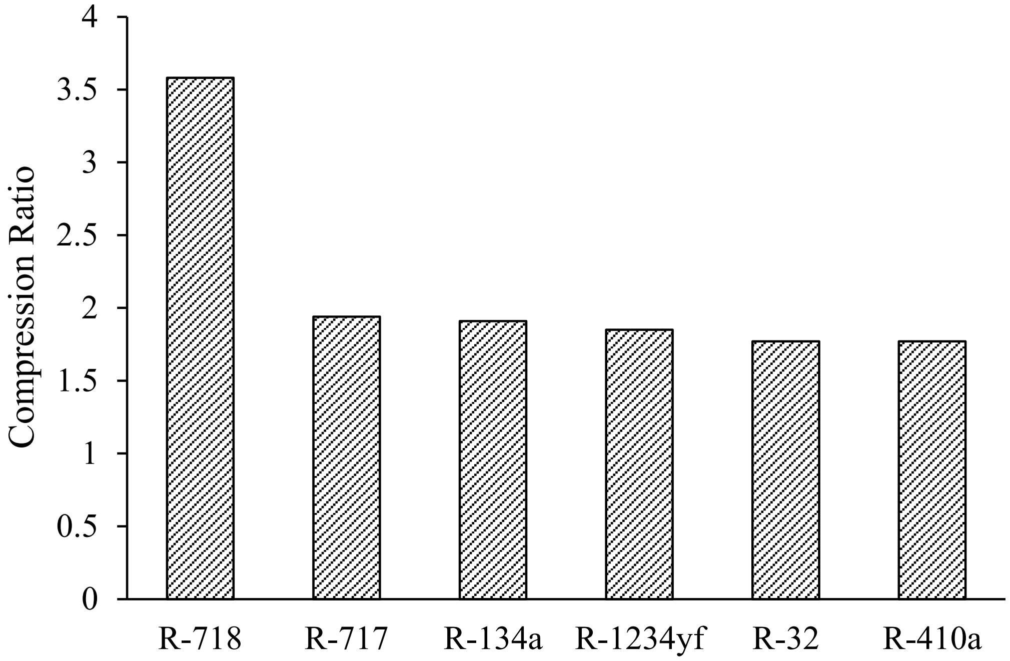

Figure 4. The compression ratio of different refrigerants at 14 °C evaporation and 37 °C condensing temperatures.

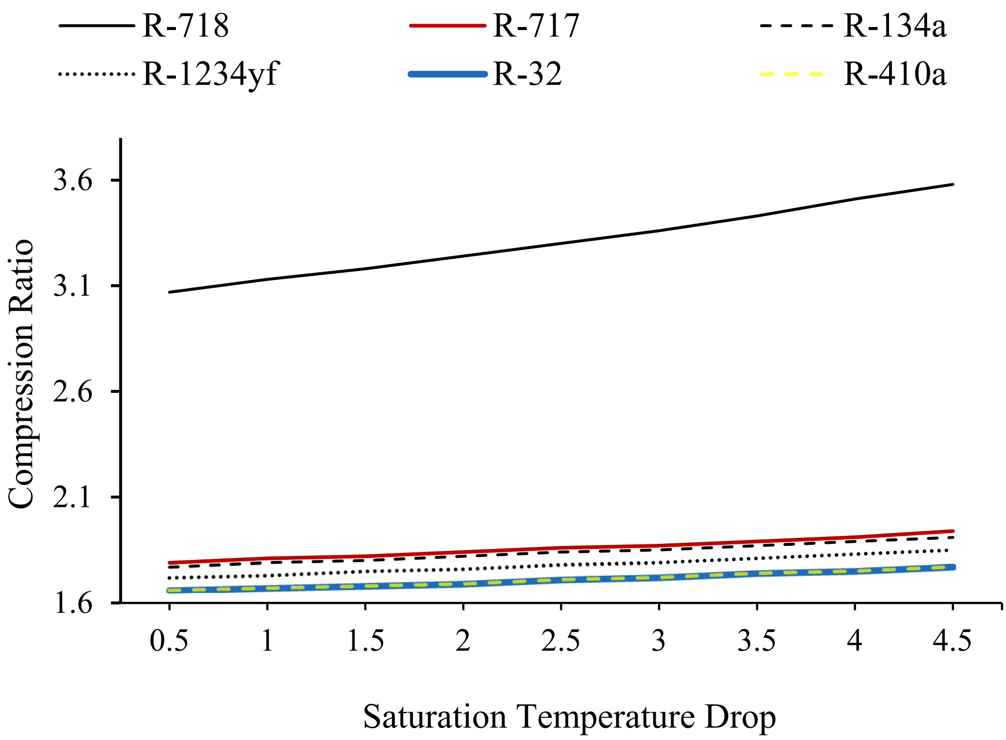

Figure 5. Refrigerants' compression ratio (CR) for different saturation temperature drops.

3.3. Compressor Discharge Temperature

The compressor discharge temperature stands as a pivotal consideration in refrigerant selection for specific applications, primarily due to its profound impact on compressor blade durability. The elevated discharge temperature characteristic of water vapor chillers presents a significant challenge, necessitating materials capable of withstanding exceptionally high temperatures to ensure chiller operation within standard temperature ranges. Previous investigations have revealed water vapor compressor discharge temperatures exceeding 300 °C, prompting researchers to explore various approaches to mitigate this issue, including internal heat exchangers, wave rotors, and ejectors [31,32]. However, in the context of direct-expansion radiant floor cooling, which operates within a distinct temperature range, the discharge temperature observed in this study was approximately 176 °C (as depicted in Figure 6), notably lower than reported in previous studies. While this discharge temperature may appear high compared to other natural or synthetic refrigerants, it poses no significant challenge in material science and can be effectively managed without necessitating specialized materials. Notably, compressor discharge temperatures across all refrigerants studied closely align, except for water, which exhibited the highest temperature at approximately 176 °C, and R-1234yf, which registered the lowest at 42 °C. It is crucial to consider the system's lifetime, reliability, and stability during refrigerant testing, as these factors are heavily influenced by the compressor's discharge temperature, impacting not only compressor blades but also the refrigerant and lubricant. Opting for water as a refrigerant eliminates the risk of decomposition due to high temperatures, making simultaneous use as a lubricant and refrigerant the most effective approach when employing water as a refrigerant.

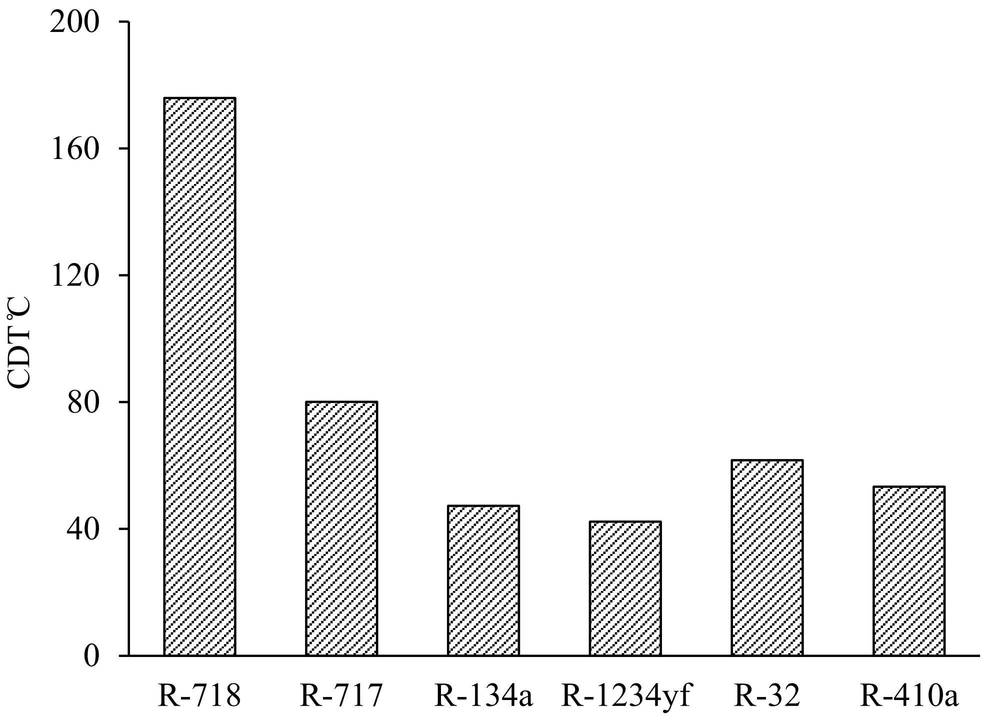

Figure 6. Compressor discharge temperature for different refrigerants at 14 °C evaporation and 37 °C condensing temperatures.

3.4. Compressor Suction Volume Flow Rate

One of the most significant challenges encountered when utilizing water as a refrigerant stems from its exceptionally high specific volume in vapor form at the low pressures necessary for refrigeration cycles. This heightened specific volume necessitates specialized compressors, such as axial or centrifugal compressors, capable of accommodating substantial volume flow rates. Even with the utilization of these compressor types, their size must be significantly larger compared to those employed for other refrigerants, potentially reaching magnitudes up to 100 times larger. Such substantial compressor dimensions have a profound impact on the capital cost of water vapor compressors, substantially increasing overall expenses. In the proposed system, the compressor's suction volume flow rate remains notably elevated, contributing to the requirement for a considerably large compressor size. As illustrated in Figure 7, the water vapor compressor's suction volume registers approximately 124 times higher than that of R-134a for an equivalent system capacity. This suction volume flow rate is contingent upon the refrigerant's specific volume in its gaseous state, which inversely corresponds to its density. Notably, water vapor exhibits a lower density than all other refrigerants, with a value of 0.014 kg/m^3, contrasting starkly with the highest density associated with R-410a.

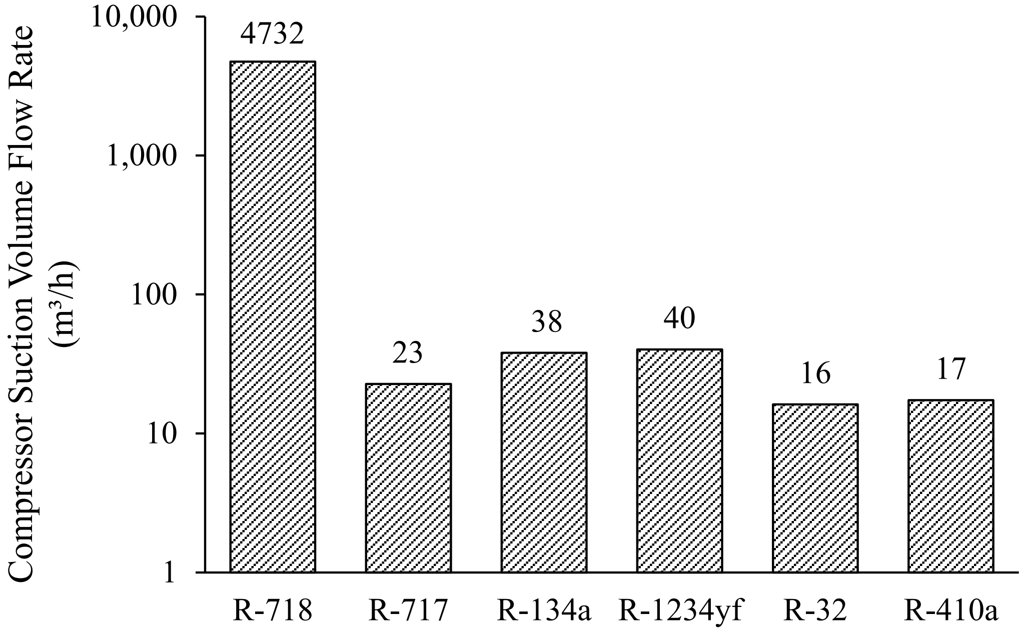

Figure 7. Compressor suction volume flow rate for different refrigerants at 14 °C evaporation and 37 °C condensing temperatures.

The density of a refrigerant in its vapor state significantly influences the size of the compressor impeller required for effective operation. Analyzing various refrigerants, it can be inferred that employing R-410a yields the smallest compressor size, followed by R-32, R-1234yf, R134a, and ammonia, respectively. The compressor discharge temperature, in conjunction with the compression ratio, determines the type of compressor and the necessary number of compression stages for different refrigerants. Previous studies focusing on water as a refrigerant recommended employing a centrifugal compressor for water vapor refrigeration cycles due to its capacity to manage high volume flow rates and handle high compression ratios efficiently, whether single- or multi-stage. Despite water's elevated compressor suction volume flow rate, attributable to its high specific vapor volume, it also exhibits the lowest mass flow rate, as depicted in Figure 8. The refrigerant mass flow rate, conversely, correlates with the refrigerant's latent heat of vaporization, with lower mass flow rates associated with refrigerants boasting higher latent heat of vaporization. Figure 9 underscores that the mass of water required to meet design capacity falls below that of all other refrigerants, with ammonia, R-32, R-410a, R-134a, and R-1234yf following in sequence. Understanding the suction volume flow rate's significance stems from its direct impact on the system's volumetric capacity, defined as the cooling capacity per unit volume of refrigerant exiting the evaporator. A higher suction volume flow rate corresponds to a lower volumetric capacity, resulting in a reduced cooling capacity for a given volume [33].

While this study effectively outlines the implications of different refrigerants on compressor sizing and system performance, it is crucial to consider the broader implications of these findings. The observed trends highlight the intricate balance between refrigerant thermodynamic properties, system design, and operational efficiency. For instance, while water as a refrigerant exhibits notable challenges such as high compressor suction volume flow rates and discharge temperatures, its potential benefits in terms of environmental impact and energy efficiency cannot be overlooked. Furthermore, the comparison with conventional refrigerants like R-134a underscores the trade-offs involved in selecting the most suitable refrigerant for a given application, balancing factors like COP, compressor size, and material compatibility. This critical analysis emphasizes the need for a holistic approach to refrigerant selection, considering not only thermodynamic performance but also practical considerations such as equipment size, cost, and long-term sustainability.

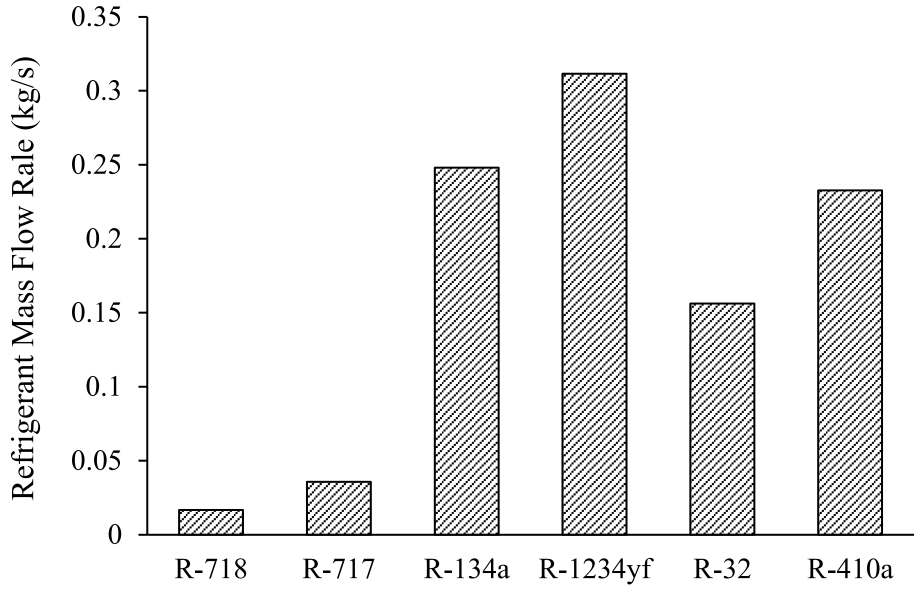

Figure 8. Mass flow rate for different refrigerants.

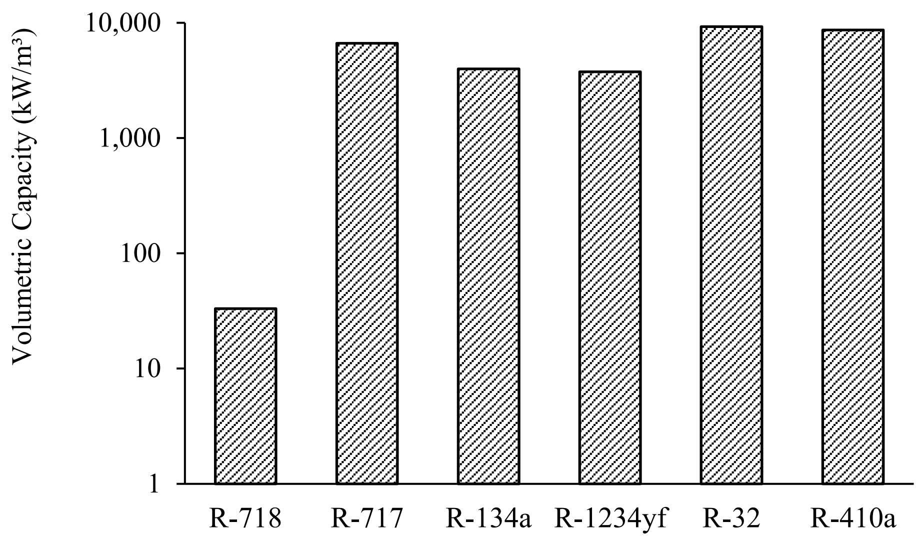

Figure 9. The volumetric capacity of different refrigerants.

The inverse relationship between critical temperature and volumetric capacity, as illustrated in Figure 9, underscores the importance of considering thermodynamic properties when evaluating refrigerant performance. Refrigerants with higher critical temperatures tend to exhibit lower volumetric capacities, indicating their reduced ability to absorb heat per unit volume. Conversely, refrigerants like R-32 demonstrate higher volumetric capacities despite their lower critical temperatures, suggesting greater efficiency in heat transfer processes. This observation highlights the intricate interplay between critical temperature, thermodynamic efficiency, and system performance, emphasizing the need for a nuanced understanding of refrigerant properties in optimizing HVAC systems for diverse applications.

The relationship between critical temperature and volumetric capacity stems from the thermodynamic properties of refrigerants. The critical temperature represents the threshold above which a substance cannot exist in a distinct liquid and gas phase, transitioning into a supercritical fluid state. Refrigerants with higher critical temperatures typically have stronger intermolecular forces and greater molecular sizes, leading to reduced volumetric capacities. This phenomenon occurs because higher critical temperatures imply lower densities for the refrigerant vapor, meaning that a larger volume of refrigerant is required to achieve a given cooling capacity. Consequently, refrigerants with lower critical temperatures tend to exhibit higher volumetric capacities, as they can absorb more heat per unit volume due to their denser vapor states. This relationship underscores the importance of selecting refrigerants with optimal critical temperatures to ensure efficient heat transfer and system performance in HVAC applications.

3.5. The Effect of Elevated Evaporator Temperature on the Performance of the VCC

As shown in Figure 10, water demonstrates performance on par with commonly used HVAC refrigerants such as R-134a, R-410a, and R-32, with potential for significant advantages. However, the challenges it faces stem from its unique thermodynamic properties. The elevated compressor discharge temperature of water vapor refrigeration cycles, exceeding 300 °C in previous studies [31,32], poses durability concerns for compressor components, necessitating specialized materials. Additionally, the high specific volume of water vapor at low pressures required for evaporation presents challenges in compressor design and size. Unlike traditional refrigerants, water's high compression ratio requirements for the necessary temperature lift in evaporation and condensing demand multiple compression stages and intercooling, adding complexity and cost to the system [34]. These technical challenges underscore the need for innovative solutions to harness water's potential as a refrigerant effectively.

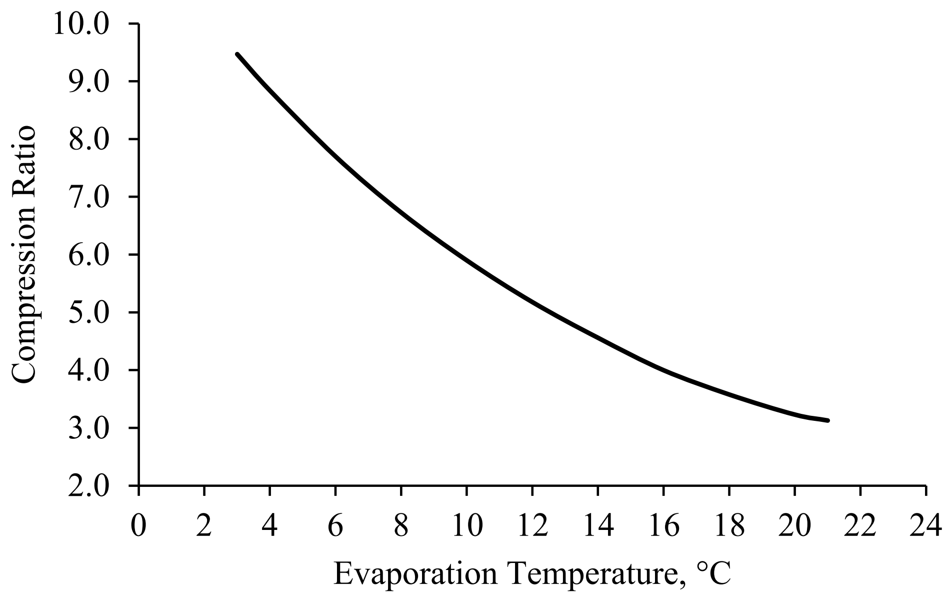

Figure 10. The effect of evaporation temperature on the compression ratio of the water vapor compression cycle at a fixed condensing temperature of 37 °C.

Direct-expansion radiant cooling systems offer a promising application for water as a refrigerant due to their higher evaporation temperatures, typically around 20 °C, compared to traditional cooling systems [28]. At these temperatures, water vapor compression cycles exhibit a compression ratio of around 3.23, enabling single-stage compression, as demonstrated in previous research [28]. However, the low operating pressures associated with water as a refrigerant, ranging from 1.888 to 6.230 kPa, compared to other refrigerants like R-32 with values up to 1340 to 2290 kPa, present unique operational and maintenance challenges [28]. Despite these challenges, the negative pressure within the evaporator coil for water vapor refrigeration systems presents fewer leakage risks compared to refrigerants with a positive pressure, highlighting an area where water may offer advantages in system reliability and safety. These technical nuances emphasize the importance of comprehensive assessment and innovative engineering solutions when considering water as a refrigerant for HVAC applications. The technical analysis reveals both challenges and opportunities in utilizing water as a refrigerant for HVAC applications. While the challenges surrounding compressor discharge temperatures and compressor design complexity are significant, they can be addressed through innovative engineering solutions and specialized materials. The potential benefits, such as comparable performance to traditional refrigerants and lower leakage risks due to negative pressure within the system, suggest that water refrigerant systems could offer improved reliability and safety. Additionally, the feasibility of single-stage compression in direct-expansion radiant cooling systems indicates potential cost savings and simplified system design. Overall, the practical implications of these findings underscore the importance of further research and development to optimize water refrigerant systems for widespread adoption in HVAC applications, potentially leading to more efficient and environmentally friendly cooling solutions.

The compressor exit temperature is a crucial consideration when assessing the viability of R-718 for HVAC applications, particularly due to its impact on compressor blade durability in centrifugal compressors. In applications where water vapor cycles operate at elevated evaporation temperatures, there is a notable reduction in compressor exit temperature from approximately 300 °C within the chiller's operational range to below 160 °C. This decrease in temperature can be effectively managed using existing materials and does not necessitate the use of specialized materials [35]. Figure 11 illustrates the correlation between evaporation and compressor discharge temperatures. For instance, at an evaporation temperature of 20 °C, the compressor discharge temperature was recorded at 159.8 °C. Conversely, if water were utilized as a refrigerant in standard chiller applications, where the evaporation temperature is around 4 °C, the compressor discharge temperature would exceed 275 °C, posing durability challenges for the system. This highlights the significance of tailoring refrigerant selection to specific operating conditions to ensure optimal system performance and longevity.

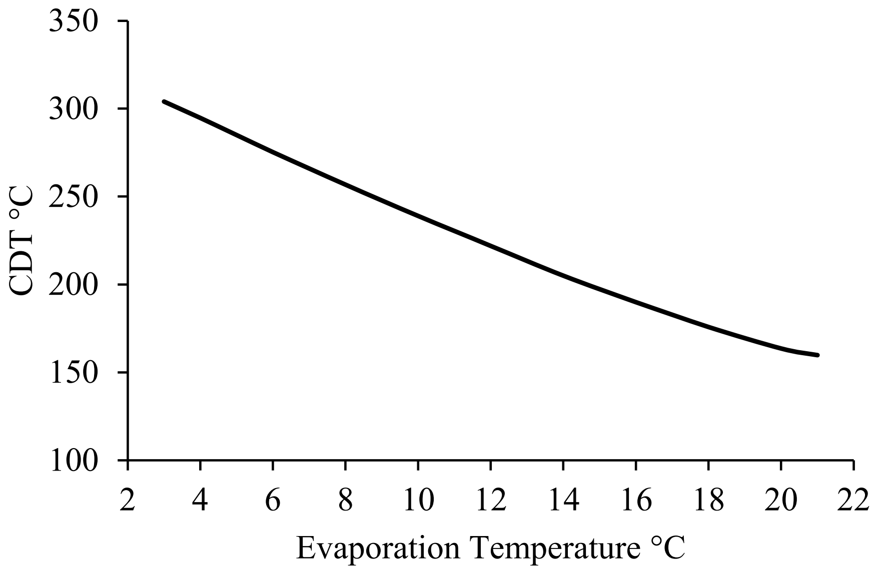

Figure 11. The effect of evaporation temperature on the compressor discharge temperature (CDT) of the water vapor compression cycle at a fixed condensing temperature of 37 °C.

The COP stands as a pivotal metric for comparing VCC performance, given its reliance on the Carnot cycle, where efficiency hinges on the temperature differential between evaporation and condensing. Figure 12 underscores the impact of heightened evaporation temperatures on enhancing the COP of the water vapor compression cycle. Notably, the system's COP surged from approximately 5.0 within the traditional cooling temperature range to around 9.0 in the radiant floor cooling temperature range, marking an impressive 84% boost in energy efficiency or, equivalently, an 84% reduction in energy consumption. This substantial enhancement underscores the potential advantage of employing water vapor for direct contact radiant cooling, not only for its environmentally friendly attributes in terms of direct contributions to global warming and ozone depletion but also for its indirect effect manifested through reduced energy consumption. It is worth noting that the compressor discharge temperature directly correlates with the adiabatic index of the refrigerant, with a higher adiabatic index associated with elevated compressor discharge temperatures [36]. This interplay further underscores the significance of selecting appropriate refrigerants tailored to specific operational requirements to optimize system performance.

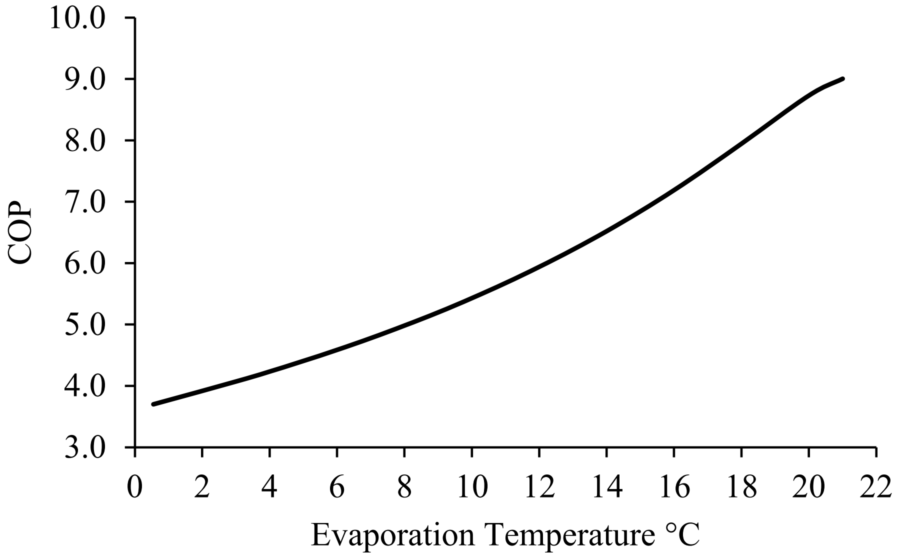

Figure 12. The effect of evaporation temperature on the coefficient of performance (COP) of the water vapor compression cycle at a fixed condensing temperature of 37 °C.

The coefficient of performance within the refrigeration cycle does not solely pivot on either the evaporation or condenser temperature but also hinges on the temperature lift between evaporation and condensing. Decreasing this temperature lift leads to an increase in the system's COP. Figure 13 illustrates this phenomenon succinctly, showcasing how the COP escalates from 4.0 at a 34 °C temperature lift to approximately 9.0 at 16 °C. This highlights the critical role that minimizing temperature lift plays in enhancing the efficiency of the system, offering valuable insights for optimizing system design and operation to achieve maximum energy efficiency. The observed increase in the COP with a reduced temperature lift can be attributed to the thermodynamic characteristics of the refrigeration cycle. As the temperature lift decreases, the difference in enthalpy between the evaporator and condenser decreases, resulting in a more efficient heat transfer process. This phenomenon is consistent with the principles of thermodynamics, where minimizing temperature differentials leads to improved energy conversion efficiency. Additionally, the reduction in temperature lift reduces the work required by the compressor to achieve the desired refrigerant pressure, resulting in lower energy consumption. From a technical perspective, this underscores the importance of optimizing system parameters such as evaporator and condenser temperatures to achieve maximum efficiency in refrigeration cycles. It also highlights the potential benefits of utilizing advanced compressor technologies and refrigerant blends tailored to specific temperature ranges to further enhance system performance.

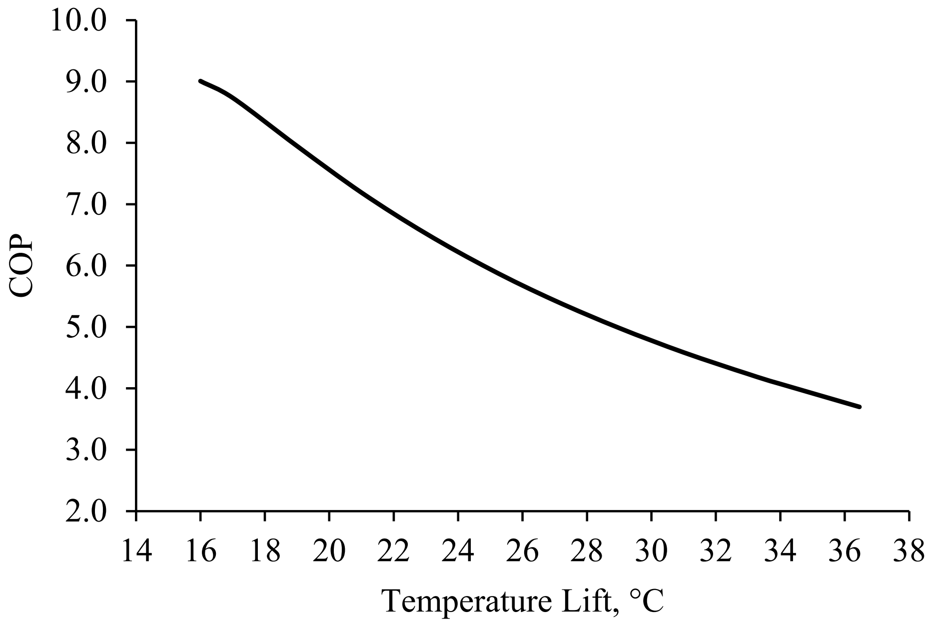

Figure 13. The effect of temperature lifts on the coefficient of performance (COP) of the R-718 refrigeration cycle.

The specified temperature range for maintaining the floor temperature ensures optimal comfort and prevents issues such as condensation. By keeping the cooling fluid temperature within the range of 18 °C to 22 °C, efficient heat transfer from the conditioned space can be achieved while avoiding overcooling. This contrasts with traditional systems, like chilled water or direct expansion, which typically require lower evaporation temperatures, resulting in higher energy consumption and environmental impact. Despite the challenges associated with water as a refrigerant, its unique thermophysical properties, particularly its high specific volume in the vapor state, make it well-suited for radiant floor cooling applications. This advantage becomes evident in large-coil setups required for radiant floor cooling, where water's ability to efficiently exchange heat proves beneficial.

Additionally, the technical analysis reveals insights into the surface heat flux across the evaporator coil, depicted in Figure 14. The observed decrease in heat flux as the fluid passes through the coil indicates efficient heat transfer mechanisms at play. This underscores the importance of proper fluid management to ensure optimal cooling performance in radiant floor applications. Moreover, the comparison of different refrigerants in the context of radiant floor cooling highlights water's suitability despite its challenges. While other refrigerants may offer lower compression ratios or discharge temperatures, water's unique properties, such as its high specific volume in the vapor state, contribute to its effectiveness in large-coil setups. However, further research and development are warranted to address operational challenges and optimize system performance for widespread adoption in radiant floor cooling applications. The heat transfer on the radiant floor surface is dependent on the convective heat transfer coefficient, and it varies between different industry standards, as presented in Table 3 [37–39].

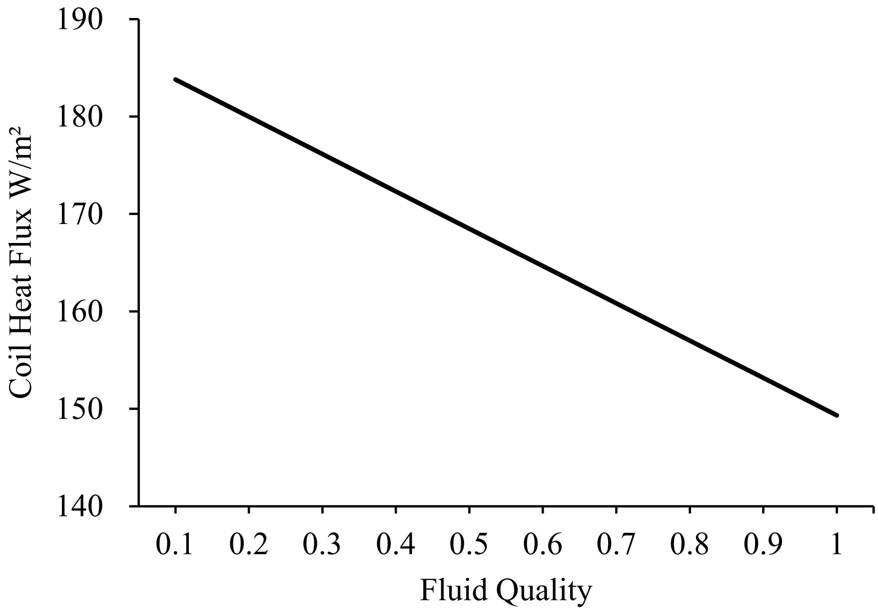

Figure 14. The floor surface heat flux variation with the fluid quality.

Table 3. Heat transfer coefficient for different standards.

Reference	Process	h_{tot} (W/(m^2·K))
REHVA	Cooling	7
	Heating	11
EN1264-5	Cooling	6.5
	Heating	10.8
ISO 11855-2	Cooling	7
	Heating	$8.92\left(T_s - T_{op}\right)^{0.1}$

According to established standards, the maximum attainable surface heat flux under specified conditions, such as a floor surface temperature of 20 °C and an operative space temperature of 25 °C, is capped at 55 W/m^2. This limit is set based on natural heat transfer mechanisms, predominantly reliant on radiant heat transfer, as evidenced by prior studies. For instance, Karakoyun et al. (2020) conducted experiments to assess heat transfer coefficients and flux in radiant cooling systems, revealing that radiant heat transfer accounted for approximately 90% of total heat transfer. In their study, the maximum observed heat flux for radiant floor cooling reached approximately 106 W/m^2, a value deemed sufficient for achieving desirable thermal comfort across various scenarios [40]. Moreover, there exists potential to augment convective heat transfer by introducing forced air onto the floor surface. This addition enhances the overall heat transfer coefficient, consequently boosting heat flux. Figure 15 illustrates the computed total heat flux for different scenarios, encompassing both natural heat transfer and forced air at air velocities of 3 m/s and 6 m/s. Furthermore, the potential enhancement of convective heat transfer through forced air introduces an intriguing avenue for improving system performance. This underscores the interconnectedness of various factors, such as airflow velocity and surface characteristics, in shaping heat transfer dynamics. Overall, the nuanced interplay between thermal comfort requirements, energy efficiency goals, and system design highlights the complexity inherent in optimizing radiant cooling systems for real-world applications.

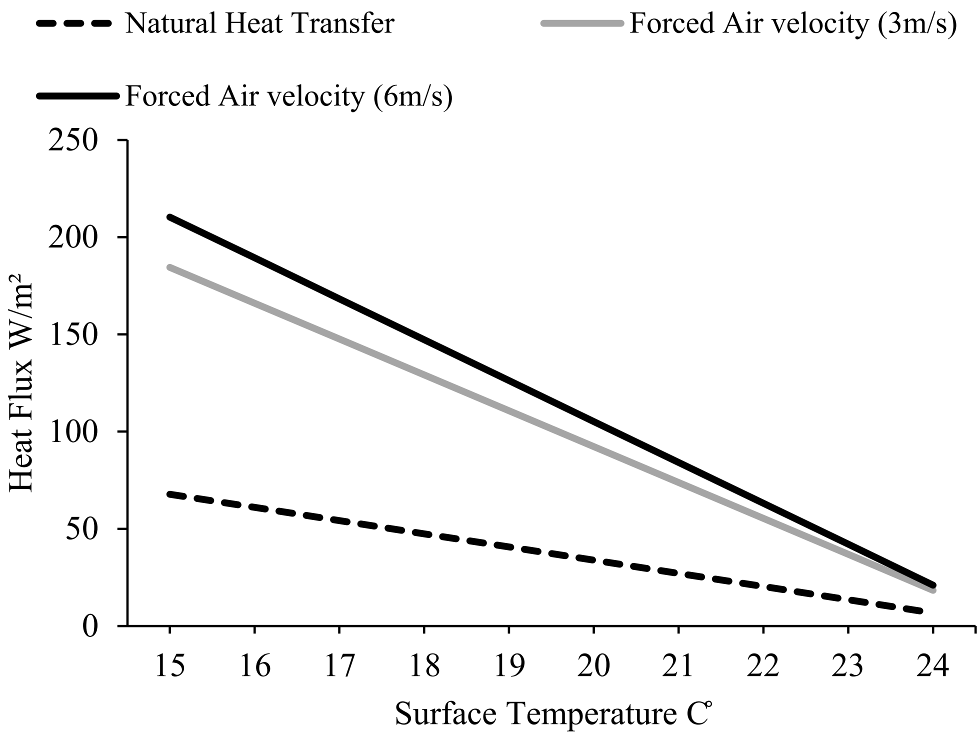

Figure 15. The surface heat flux of radiant floor cooling variation with surface temperature.

The figure illustrates that by introducing forced air movement at the floor surface, radiant floor cooling systems can achieve higher heat flux levels. This observation underscores the adaptability and versatility of radiant floor cooling across diverse applications and site conditions. By leveraging straightforward techniques such as forced air circulation, designers and engineers can tailor radiant floor cooling systems to meet specific performance requirements and environmental contexts. This versatility enhances the applicability of radiant floor cooling in various settings, from residential and commercial buildings to industrial facilities. Ultimately, the ability to optimize heat transfer rates through simple yet effective strategies underscores the practicality and effectiveness of radiant floor cooling as a viable HVAC solution.

3.6. Economic Feasibility and Practicality Analysis

Table 2 compares the performance of various refrigerants, including water (R-718), across key parameters such as compressor discharge temperature, compression ratio, compressor power, suction volume flow rate, COP, compressor discharge pressure, and refrigerant mass flow rate. Water, as a natural refrigerant, offers both notable advantages and certain limitations, particularly when considered for direct-expansion radiant floor cooling systems.

Water (R-718) stands out for its environmental benefits. It has zero global warming potential (GWP) and no ozone depletion potential (ODP), making it an environmentally friendly alternative to synthetic refrigerants like R-410a and R-134a. This makes water an appealing choice in systems where sustainability and regulatory compliance are critical. Additionally, water achieves a high coefficient of performance (COP) of 7.9, which reflects strong energy efficiency. This efficiency is particularly advantageous for radiant floor cooling systems, where minimizing operational costs and energy use is a priority. The low compressor discharge pressure of water, recorded at 6.2 kPa, suggests reduced mechanical stress on the compressor, potentially leading to longer equipment life and lower maintenance costs.

However, using water as a refrigerant also presents significant challenges. One major limitation is its high compressor discharge temperature, which reaches 175.9 °C—substantially higher than that of other refrigerants. This elevated temperature could necessitate more robust thermal management strategies to prevent overheating and ensure system reliability. Moreover, the use of water requires a much higher suction volume flow rate of 4732.0 m^3/h, which demands larger compressor sizes and complicates system design, particularly in space-constrained applications like radiant floor cooling. Furthermore, the compression ratio for water, at 3.58, is higher than that of other refrigerants, indicating a greater pressure differential and potentially higher energy consumption in compression, which could somewhat offset the benefits of its high COP.

In the context of direct-expansion radiant floor cooling, where the temperature lift is relatively low, the impact of water's limitations might be less significant, making it a more viable option. Nonetheless, optimizing system components such as compressors and heat exchangers will be crucial to fully harness the advantages of water while mitigating its drawbacks. Further research and development are necessary to refine the application of water as a refrigerant in these systems, ensuring that its environmental and efficiency benefits can be fully realized.

As the demand for energy-efficient and environmentally sustainable HVAC systems grows, the exploration of alternative refrigerants for direct-expansion (DX) radiant floor cooling has gained momentum. Water (R-718), a natural refrigerant with zero global warming potential (GWP) and no ozone depletion potential (ODP), has emerged as a promising candidate. This assessment explores the feasibility and practical applications of using water as a refrigerant in DX radiant floor cooling systems, with a focus on expected costs and system size considerations.

Water's properties as a natural refrigerant offer significant environmental benefits, including high specific heat capacity, which enables it to absorb and transfer large amounts of thermal energy. This is particularly advantageous in radiant floor cooling systems, where maintaining consistent and comfortable thermal conditions is critical. Moreover, using water aligns with global trends toward reducing the environmental impact of cooling systems, eliminating concerns related to GWP and ODP that are prevalent with synthetic refrigerants like R-410A and R-134a.

However, applying water as a refrigerant in DX systems poses challenges, particularly in compressor design and system size. Due to water's low vapor pressure at typical operating temperatures, systems require significantly higher volumetric flow rates compared to traditional refrigerants. This necessitates the use of larger compressors and associated components, which can lead to increased system size, higher initial capital costs, and potential spatial constraints, especially in residential or commercial buildings where space is limited. Additionally, the high discharge temperatures associated with water require robust thermal management strategies to ensure system reliability and efficiency over time.

The system size is a critical factor in assessing the feasibility of water-based DX radiant floor cooling systems. The need for larger compressors, heat exchangers, and piping networks due to water's unique thermodynamic properties results in systems that are substantially larger than those using synthetic refrigerants. This increased size impacts the design and installation process, as larger components require more space and may necessitate structural modifications to existing buildings. Consequently, this contributes to higher initial capital costs. Larger components are more expensive to manufacture, transport, and install. Moreover, the increased complexity of the system due to enhanced thermal management requirements further drives up costs. Although water's operational efficiency can lead to long-term energy savings, the high initial expenditure may pose a barrier to widespread adoption, particularly in cost-sensitive markets.

In terms of costs, implementing a water-based DX system is generally expected to be more expensive initially than systems using conventional refrigerants. Larger compressors and heat exchangers, along with the need for specialized control and thermal management systems, contribute to these increased costs. Installation costs may also rise due to the need for custom fittings and potential modifications to accommodate the larger system size. However, despite the high upfront investment, operational costs are likely to be lower over the system's lifetime due to the high coefficient of performance (COP) associated with water as a refrigerant. Water's energy efficiency, combined with its environmental benefits, can lead to significant energy consumption savings, especially in climates where radiant floor cooling is effective. Nevertheless, maintenance costs might be higher due to the system's larger size and more complex thermal management requirements. However, using water, a benign and non-toxic refrigerant, may reduce some maintenance hazards and costs associated with synthetic refrigerants.

Practical applications of water-based DX radiant floor cooling systems are most likely to be found in settings where environmental benefits outweigh higher initial costs. Such applications include green building projects, government and institutional buildings, and residential developments that prioritize sustainability and long-term energy savings. For example, water-based systems align well with the goals of green building certifications like LEED or BREEAM, where minimizing the environmental impact of building operations is paramount. Similarly, government and institutional buildings, which often have larger budgets for capital expenditures and a longer-term view of operational costs, could implement these systems to demonstrate leadership in sustainability while showcasing environmentally friendly technology. In high-end residential developments, where energy efficiency and environmental sustainability are key selling points, water-based DX radiant floor cooling systems could be a market differentiator, with the higher initial costs potentially justified by long-term energy savings and appeal to environmentally conscious consumers.

As a result, while the feasibility of using water as a refrigerant in DX radiant floor cooling systems is supported by its environmental benefits and energy efficiency, the practical implementation is challenged by the need for larger system components and higher initial costs. The increased system size required by water's thermodynamic properties can complicate design and installation, leading to elevated capital expenditures. However, water-based DX systems offer a promising alternative to conventional refrigerants in applications where sustainability is a priority and long-term operational efficiency can offset the initial investment. As the industry continues to innovate, further research and development will be crucial in overcoming current limitations and realizing the full potential of water as a refrigerant in DX radiant floor cooling systems.

To assess the feasibility of the DX radiant cooling system in comparison to conventional systems, we established three distinct refrigeration cycles suitable for various applications, including Variable Refrigerant Flow (VRF) systems and chillers, to compare against the proposed direct-expansion (DX) radiant floor cooling system utilizing water (R718) as a refrigerant. Each system was evaluated based on key performance indicators, such as Seasonal Energy Efficiency Ratio (SEER), Total Equivalent Warming Impact (TEWI), Lifetime Energy Cost (LTEC), and Global Warming Potential (GWP), and the results are shown in Table 4 below.

Table 4. Energy and environmental analysis of different cooling options.

System	GWP	SEER	TEWI	Lifetime Energy Cost	Total LTEC (kWh)
(R718) DX Radiant Cooling	0	38.40	102,858.3	$38,043	140,902
Chiller (R-1234yf)	4	16.86	237,251.2	$87,715	324,870
VRF (R-410A)	2088	20.23	246,902.5	$72,786	269,576
Chiller (R134a)	1340	16.63	273,137.6	$89,129	330,106

The results show that the (R718) DX radiant cooling system demonstrates significant advantages in both energy efficiency and environmental sustainability. With a SEER of 38.40, it outperforms the VRF system (R-410A) with a SEER of 20.23 and the chiller systems using R-1234yf and R134a, which have SEERs of 16.86 and 16.63, respectively. This high efficiency translates into substantially lower Lifetime Energy Costs for the R718 system, totaling $38,043 over 15 years, compared to $72,786 for the VRF system, $87,715 for the R-1234yf chiller, and $89,129 for the R134a chiller.

In terms of Total Lifetime Energy Consumption (LTEC), the R718 system is also superior, consuming 140,902 kWh over its lifespan, significantly lower than the VRF system's 269,576 kWh and the chillers' consumption, which ranges from 324,870 kWh for R-1234yf to 330,106 kWh for R134a.

Environmental impact assessments further solidify the R718 system's sustainability credentials. Its zero Global Warming Potential (GWP) stands in sharp contrast to the 2088 GWP of the VRF (R-410A) system and the 1340 and 4 GWPs of the R134a and R-1234yf chillers, respectively. This is reflected in the Total Equivalent Warming Impact (TEWI) values, where the R718 system produces 102,858.3 kg of CO_2 equivalent emissions, significantly lower than the VRF (R-410A) at 246,902.5 kg and the chillers with R-1234yf and R134a, which emit 237,251.2 kg and 273,137.6 kg, respectively.

Thus, the comparison demonstrates that the R718 DX radiant cooling system not only offers higher energy efficiency but also ensures lower environmental impact, making it a highly attractive option for applications where sustainability and long-term operational efficiency are paramount. The low Lifetime Energy Costs and reduced energy consumption further highlight its economic feasibility, especially in settings that require large-scale cooling with minimal environmental footprints.

4. Validation of Results

To validate the results of the study, we conducted a sample calculation to calibrate the simulation, yielding the results shown in Table 5. Additionally, we compared our findings with those from similar studies, as detailed in this section.

Table 5. Calculation vs. simulation results for the refrigerant mass flow rate, volumetric flow rate, and COP.

	Calculation Result	Simulation Result	Deviation %
Mass Flow Rate (kg/s)	0.01666	0.0167	−0.27%
Volume Flow Rate (m^3/s)	4539	4732	−4.25%
COP	7.73	7.948	−2.82%

The calculations exhibited a high level of agreement with the simulation model, with a maximum deviation of 2.82% observed for the COP results. Conversely, deviations for other parameters, such as mass flow rate and volumetric flow rate, were negligible at 0.27% and 4.25%, respectively.

In a study by Šarevski and Šarevski (2014), the authors explored the use of a two-phase ejector alongside a single-stage compressor, reporting COP values of 5.17, 6.35, and 8.23 for temperature lifts of 35 °C, 30 °C, and 25 °C, respectively [34]. In comparison, our study yielded slightly lower COP values of 4.2, 4.9, and 6.2 for the same temperature lifts, as depicted in Figure 13. These values ranged from 18% to 25% lower than those reported in the aforementioned study, possibly influenced by the use of a two-phase ejector to enhance refrigeration cycle efficiency.

Devecioğlu and Oruç (2017b) conducted research to identify the optimal refrigerant for mobile air conditioning systems operating within a temperature range of −5 °C to 5 °C for evaporation and 30 °C to 60 °C for condensing [41]. To validate our results, the COP outcomes obtained using Cycle-D were compared, showing agreement levels of around 90% to 95% with the original study findings. R-1234yf emerged as the selected refrigerant, with consistent results across four distinct cases, as illustrated in Figure 16.

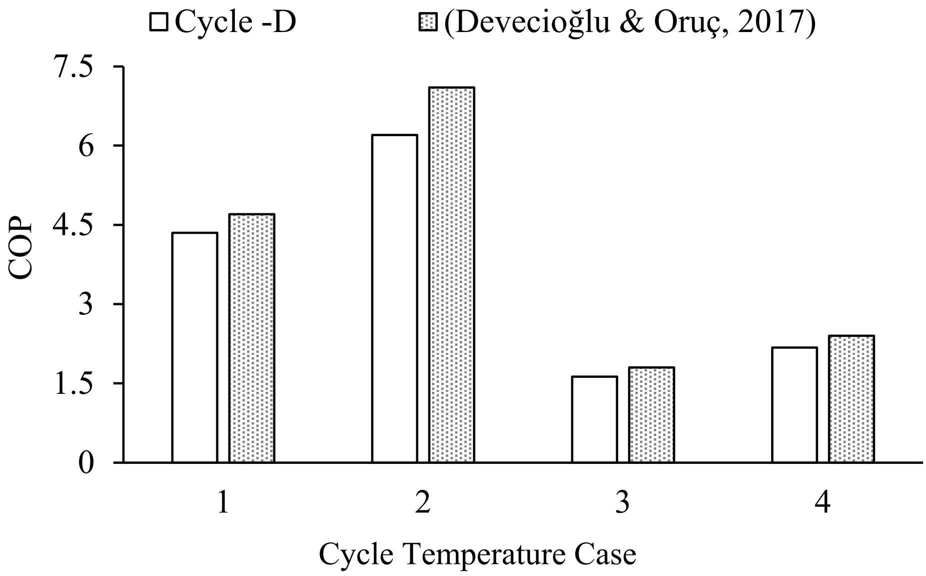

Figure 16. Comparison for result validation $1: T_e = -5\ ^\circ\mathrm{C}, T_c = 30\ ^\circ\mathrm{C}, 2: T_e = 5\ ^\circ\mathrm{C}, T_c = 30\ ^\circ\mathrm{C}, 3: T_e = -5\ ^\circ\mathrm{C}, T_c = 60\ ^\circ\mathrm{C}, 4: T_e = 5\ ^\circ\mathrm{C}, T_c = 60\ ^\circ\mathrm{C}$ [41].

Table 6 provides a compilation of studies investigating water as a refrigerant across various evaporation and condensing temperatures, all with similar temperature lifts. Since the performance of the vapor compression cycle is primarily influenced by temperature lift, these studies serve as valuable references for validation purposes. Remarkably, the COPs reported in these studies align closely with our findings, underscoring the consistency and reliability of our results. Additionally, De'Rossi et al. (1991) conducted a study utilizing computer programming to analyze R-718 alongside other refrigerants. Their research highlighted water's superior performance compared to numerous common refrigerants, attributed to its favorable thermodynamic properties, a conclusion that corroborates our study's findings [42].

Table 6. Comparison with previous studies.

Study	Methodology	Temperature Lift, °C	Reported COP
2014, Chamoun et al. [43]	Simulation	27	5.5
2014, Larminat et al. [44]	Experimental	25–40	5.5–8.1
2019, Wu et al. [45]	Simulation	25–80	2.19–6.33
2019, Wu et al. [46]	Experimental	34.4–42.5	3.6–4.4

5. Conclusions

This study advocates for the adoption of direct-expansion (DX) radiant cooling as a viable alternative to conventional all-air cooling systems, particularly by exploring the potential use of water (R-718) as a refrigerant. By addressing past technical challenges associated with water vapor refrigeration cycles, this research provides valuable insights for both researchers and industry practitioners. Radiant floor cooling emerges as a promising method for cooling and heating buildings across diverse climate zones, albeit with certain technical considerations.

The study demonstrates that water, despite historical challenges, exhibits promising performance characteristics for radiant cooling applications. Comparative analyses showed that water (R-718) performs favorably when compared to common refrigerants like R-134a, R-1234yf, R-32, R-717, and R-410A while offering distinct advantages in environmental sustainability, efficiency, and system durability:

- **Environmental Impact:** In terms of environmental sustainability, water stands out with a Global Warming Potential (GWP) of zero, in stark contrast to R-410A's GWP of 2088, R-134a's GWP of 1340, and R-1234yf's GWP of 4. As a refrigerant with no direct contribution to global warming, water represents an optimal choice for reducing the environmental impact of cooling systems. The Total Equivalent Warming Impact (TEWI) for water (R-718)-based direct-expansion radiant system was recorded to be 102,858.3 kg CO_2, which is significantly lower than the values for R-410A VRF (246,902.5 kg CO_2) and R-134a chiller (273,137.6 kg CO_2)
- **Performance Metrics:** The comparative analysis reveals competitive performance metrics for water in DX radiant cooling systems. Water achieves a competitive Coefficient of Performance (COP) of 7.9, closely rivaling R-134a (8.0) and R-717 (9.3). This demonstrates that water can achieve high cooling efficiency without significant performance trade-offs compared to traditional refrigerants. Additionally, the water-based system demonstrates a Seasonal Energy Efficiency Ratio (SEER) of 38.40, which significantly exceeds the SEER of other refrigerants, such as R-134a (16.63) and R-1234yf (16.86), when used in the chiller-suitable temperature range. In terms of the compression ratio, water exhibits a higher value of 3.58, which is greater than that of R-717 (1.94), R-134a (1.91), R-1234yf (1.85), R-32 (1.77), and R-410A (1.77). This suggests that water requires a higher degree of compression to achieve the desired cooling effect, but the benefits of simplicity in system design and lower compressor power requirements make it feasible. The compressor suction volume flow rate for water (4732.0 m^3/h) is significantly higher than for any other refrigerant, which is advantageous for large-coil evaporators, potentially increasing system efficiency.
- **Compressor Discharge Temperature:** Although water exhibits a higher compressor discharge temperature of 175.9 °C compared to synthetic refrigerants like R-410A (53.3 °C) and R-32 (61.7 °C), this is still lower than other industrial applications where water is used as a refrigerant. Importantly, this temperature does not require the use of specialized materials or components, allowing for conventional materials to be employed without compromising system durability or efficiency.
- **Compressor Power and Cooling Capacity:** While water demands a compressor power of 5.033 kW, slightly higher than R-717 (4.839 kW) and similar to R-134a (4.993 kW), the difference is marginal, and the increased power requirement is offset by water's higher specific volume of vapor and cooling efficiency. Additionally, water's mass flow rate of 1.67×10^{-2} kg/s is substantially lower than the mass flow rates of R-134a (2.48×10^{-1} kg/s), R-1234yf (3.12×10^{-1} kg/s), R-32 (1.56×10^{-1} kg/s), and R-410A (2.33×10^{-1} kg/s), demonstrating that water requires less refrigerant mass to achieve effective cooling. This further highlights the efficiency and practicality of water in radiant cooling applications.
- **Cooling Capacity Augmentation:** Mechanical devices can be employed to augment the cooling capacity of the water-based system by increasing air velocity over the floor surface, thereby enhancing the overall system performance in radiant cooling applications.
- **Specific Volume Advantage:** Water's high specific vapor volume, resulting in a compressor suction volume flow rate of 4732.0 m^3/h, proves advantageous for large-coil evaporators, potentially increasing system efficiency and reducing compressor power requirements, which stand at 5.033 kW.

Despite these promising findings, there remains a need for further research into the behavior of water vapor in large-coil applications, particularly concerning pressure drop, temperature distribution, and evaporator capacity. Future research should focus on detailed investigations into the evaporator section's performance and compressor blade tip temperatures to refine the understanding of water vapor's behavior in DX radiant cooling and heating applications.

Collaborative efforts between researchers and industry stakeholders are crucial to overcoming these challenges and unlocking the full potential of water as a refrigerant in radiant cooling systems. The continued exploration of water as a refrigerant offers a pathway to more energy-efficient and environmentally sustainable building cooling solutions, which can significantly reduce lifetime energy costs and total energy consumption.

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