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Performance analysis of DX and flooded evaporators with eco-friendly refrigerants in medium-scale food storage systems

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Abstract

The environmental impact of refrigerants with high Global Warming Potential (GWP) used in refrigeration systems within the food industry drives the need for sustainable alternatives. This study comprehensively compares the performance of Direct Expansion (DX) and Flooded evaporator systems utilizing low-GWP refrigerants R290 (Propane), R1270 (Propene), and R717 (Ammonia) in a medium-scale food storage facility, using the CoolPack simulation program. Simulations were conducted under realistic operating conditions, with an evaporator temperature of -18°C, a condenser temperature of 28°C, and a fixed cooling capacity of 20 kW. The analysis focuses on key performance parameters, including Condenser Capacity ($\dot{Q}_o$), Compressor Power Consumption ($\dot{W}_c$), Coefficient of Performance (COP), Refrigerant Mass Flow Rate ($\dot{m}$), and Annual Energy Consumption. The simulation results demonstrate that R717 (Ammonia) exhibits the best performance, achieving the highest COP values for both DX (COP = 3.318) and Flooded (COP = 3.342) systems, alongside the lowest annual energy consumption (DX = 52926 kWh, Flooded = 52552 kWh). While R1270 (Propene) and R290 (Propane) showed lower COP values than R717, with 3.282 and 3.283 for DX systems and 3.254 and 3.243 for Flooded systems, respectively, they still presented good energy efficiency. This study provides a comprehensive comparison for selecting sustainable refrigerants in medium-scale refrigeration systems.

1. Introduction

The preservation of food safety and quality is a critical element within the global food supply chain. Cold storage, a fundamental component of this chain, plays a crucial role by retarding the deterioration of food products, extending shelf life, minimizing waste, and helping to prevent foodborne illnesses [1,2]. Medium-scale food storage facilities are widely used in various businesses, including supermarkets, restaurants, hotels, and distribution centers, playing a vital role in the final stages before food products reach the consumer [3].

However, the hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) commonly used as refrigerants in traditional cold storage systems pose significant environmental concerns due to their high Global Warming Potential (GWP), contributing to ozone depletion and global warming [4,5]. International agreements, such as the Montreal Protocol and the Kigali Amendment, mandate the phase-out of these harmful refrigerants and necessitate a transition to more environmentally friendly alternatives [6,7].

In this context, natural refrigerants and low-GWP synthetic refrigerants are emerging as promising alternatives to traditional refrigerants. R290 (Propane), R1270 (Propene), and R717 (Ammonia) are considered potential candidates for medium-scale food storage systems due to their low GWP values, favorable thermodynamic properties, and potential for energy efficiency [8-10]. R290 and R1270 are hydrocarbon (HC) refrigerants with zero Ozone Depletion Potential (ODP) and very low GWP values. R717, a natural refrigerant used in industrial refrigeration systems for many years, also has zero ODP and zero GWP; however, due to its flammability and toxicity concerns, its use requires specific safety precautions, as outlined in ASHRAE Standard 34 [11].

The type of evaporator used in refrigeration systems significantly impacts overall system performance and energy efficiency. DX and Flooded evaporators are two primary evaporator types commonly used in medium-scale food storage applications [12,13].

Numerous studies in the literature compare the performance of different refrigerants and evaporator types in various refrigeration systems [4,8,9,14]. However, there is limited research providing detailed performance analysis and comparison of the combined use of environmentally friendly refrigerants like R290, R1270, and R717 with DX and Flooded evaporators, specifically in medium-scale food storage facilities.

This study aims to address the aforementioned gap in the literature. To this end, the performance of DX and Flooded evaporators, using R290, R1270, and R717 as refrigerants, was comparatively analyzed in a medium-scale food storage facility using the CoolPack simulation program [15]. The simulations were conducted under realistic operating conditions (including an evaporator temperature of -18°C, a condenser temperature of 28°C, and a cooling capacity of 20 kW), and primarily evaluated critical performance parameters such as energy efficiency Coefficient of Performance (COP), compressor power consumption ($\dot{W}_c$), refrigerant mass flow rate ($\dot{m}$), and annual energy consumption. Since the cooling capacity ($\dot{Q}_e$) reached the target value in all systems, it was not considered a primary variable in the comparative analysis. The results of this study aim to contribute to the selection of the optimal refrigerant and evaporator type combination for medium-scale food storage facilities, improving energy efficiency, reducing environmental impact, and enhancing understanding of refrigerant safety requirements.

2. Material and Method

This study analyzed the performance of DX and Flooded evaporator refrigeration systems in a medium-scale food storage facility using the CoolPack simulation program [15]. The refrigerants R290 (Propane), R1270 (Propene), and R717 (Ammonia) are considered.

2.1. System description and modeling approach

The simulations were conducted on a highly effective single-stage vapor-compression refrigeration cycle, as depicted in Figure 1. This advanced system comprises four critical components: a compressor, a condenser, an expansion valve—either a throttling valve or a thermostatic expansion valve—and an evaporator. In a DX evaporator system, the refrigerant fully transforms into a vapor as it flows through the evaporator tubes, emerging in a superheated vapor state. The precision of this expansion process is expertly managed by a thermostatic expansion valve (TEV) or an electronic expansion valve (EEV), ensuring optimal performance and energy efficiency. In contrast, the flooded evaporator system features evaporator tubes that are either partially or fully filled with liquid refrigerant. This innovative design allows for a seamless separation of the vapor and liquid refrigerant as they exit the evaporator. The liquid refrigerant is efficiently recycled back into the evaporator, while the vapor is directed to the compressor. Notably, the expansion process in flooded evaporators is intelligently controlled by a float valve or a level control valve, further enhancing reliability and performance.

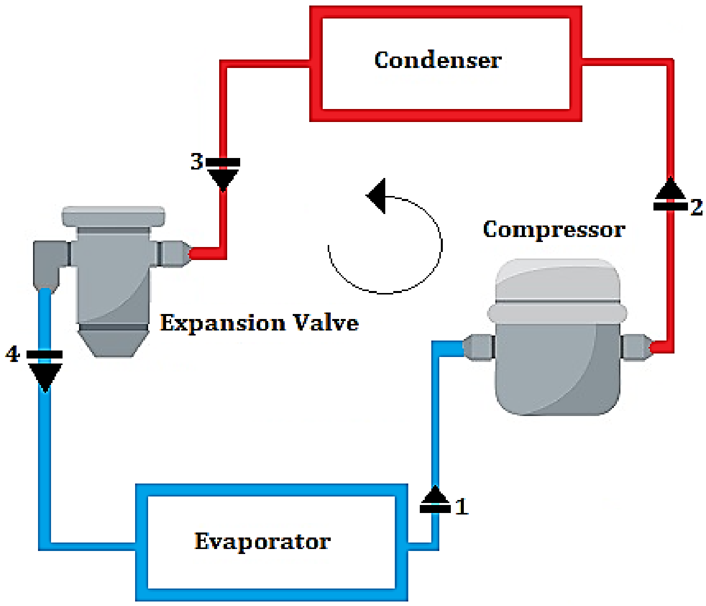

Figure 1. Schematic representation of single stage vapor compression refrigeration cycle.

2.2 Operating Conditions and Simulation Parameters

Simulations were conducted for both DX and Flooded evaporators using parameters typical for medium-scale food storage facilities, along with the default values from the CoolPack program [15]. The operating conditions are detailed in Table 1. It is important to emphasize that the outlet from a flooded evaporator contains either saturated vapor or a vapor-liquid mixture, which makes superheat an irrelevant parameter for this configuration. This distinction highlights the effectiveness and precision of employing flooded evaporators in these applications.

Table 1. Simulation parameters and operating conditions.

Parameter	Value	Unit
Evaporator Temperature (T_e)	-18	°C
Condenser Temperature (T_o)	28	°C
Superheat (ΔT_{sh})	5	K
Subcooling (ΔT_{sc})	2	K
Cooling Capacity ($\dot{Q}_e$)	20	kW
Compressor Isentropic Efficiency (η_{is})	0.75	-
Heat Loss Factor (f_x)	0.1	-
Evaporator Pressure Drop (ΔP_e)	0.5	bar
Condenser Pressure Drop (ΔP_o)	0.5	bar

2.3 Refrigerant Properties

The essential thermophysical and environmental properties of the refrigerants used in the simulations, referenced as R290, R1270, and R717, are shown in Table 2.

Table 2. Properties of refrigerants.

Refrigerant Property	R290 (Propane)	R1270 (Propene)	R717 (Ammonia)
Chemical Formula	C_3H_8	C_3H_6	NH_3
Molecular Weight (kg/kmol)	44.10	42.08	17.03
Normal Boiling Point (°C)	-42.10	-47.60	-33.30
Ozone Depletion Potential (ODP)	0	0	0
Global Warming Potential (GWP)	3	<2	0
Safety Class (ASHRAE 34)	A3	A3	B2L
Flammability	High	High	Low
Toxicity	Low	Low	High

2.4 Performance Evaluation Criteria and Basic Equations

Several parameters were used to evaluate the performance of the refrigeration system. The refrigerant mass flow rate, denoted as $\dot{m}$ (kg/s), represents the amount of refrigerant circulating through the system per unit of time and is a crucial factor in system design and component sizing. The cooling capacity, represented as $\dot{Q}_e$ (kW), refers to the rate of heat removal from the evaporator and is a key measure of the system's ability to meet the desired cooling load. The cooling capacity can be calculated using Equation (1) [16]:

$$\dot{Q}_e = \dot{m}(h_1 - h_4) \tag{1}$$

Here, $\dot{m}$ (kg/s) signifies the mass flow rate of the refrigerant, while h_1(kJ/kg) represents the enthalpy of the refrigerant at the evaporator outlet. In contrast, h_4 (kJ/kg) denotes the enthalpy at the evaporator inlet. The condenser capacity is a critical metric that quantifies the heat rejected by the refrigerant during the condensation process. Understanding this capacity is essential for optimizing the energy rejection characteristics of the refrigeration system. To accurately determine the condenser capacity, we can utilize Equation (2), which is outlined as follows [15]:

$$\dot{Q}_o = \dot{m}(h_2 - h_3) \tag{2}$$

Where, h_2 (kJ/kg) is the refrigerant enthalpy at the compressor outlet and h_3 (kJ/kg) is the refrigerant enthalpy at the condenser outlet. The compressor power consumption, $\dot{W}_c$ (kW), is a critical parameter for evaluating the energy efficiency of the refrigeration system, as it represents the rate at which the compressor consumes energy. It is calculated using Equation (3) below [16]:

$$\dot{W}_c = \dot{m}(h_2 - h_1)/\eta_{is}=\dot{m}(h_{2s} - h_1) \tag{3}$$

Where, h_2 (kJ/kg) is the actual enthalpy of the refrigerant at the compressor outlet, h_{2s} (kJ/kg) is the theoretical enthalpy at the compressor outlet assuming an isentropic (ideal, reversible adiabatic) compression process, and η_{is} is the isentropic efficiency of the compressor. The Coefficient of Performance (COP), a dimensionless parameter that quantifies the energy efficiency of the refrigeration system, is defined as the ratio of the desired cooling effect to the required work input. It is calculated using Equation (4) below [16]:

$$COP = \frac{\dot{Q}_e}{\dot{W}_c} \tag{4}$$

The annual energy consumption, which represents the total energy used by the system over a one-year period, is used to estimate the annual energy costs. It can be calculated using Equation (5) below [17]:

$$E_a = \dot{W}_{avg} \times T \times 365 \tag{4}$$

Where, $\dot{W}_{avg}$ is the average compressor power consumption (kW), T s the daily operating time (hours/day), and the calculations assume continuous operation (24 hours/day) for 365 days per year.

2.5 Assumptions made in the study

The simulations were conducted under the assumption of steady-state operation. Both the evaporator and condenser pressure drops were set to 0.5 bar, while the pressure drops in the connecting pipes were ignored. Heat losses from the compressor and piping were estimated to be 10% of the total cooling capacity (f_x = 0.10). The isentropic efficiency of the compressor was set at 0.75, and the expansion valve process was treated as isenthalpic ($h_3 = h_4$). The refrigerant properties were based on ideal fluid definitions provided by CoolPack [14]. An ambient temperature of 20°C and 2 K of subcooling at the condenser outlet were also assumed. The "Refrigeration Utilities" package in CoolPack was utilized for the simulations. For each refrigerant (R290, R1270, and R717), the performance of both DX and Flooded evaporator systems was evaluated, based on the operating conditions and assumptions detailed in Table 1. Key performance parameters for the systems were calculated using the "DX Evaporator" and "Flooded Evaporator" options within CoolPack for the respective models.

3. Results

This section comparatively presents the performance of DX and Flooded evaporator refrigeration systems, designed for a medium-scale food storage facility, using the environmentally friendly refrigerants R290 (Propane), R1270 (Propene), and R717 (Ammonia). Results were obtained via the CoolPack simulation program. Simulations were conducted under equivalent conditions, with all systems delivering a constant cooling capacity of 20 kW; thus, cooling capacity $\dot{Q}_e$ (kW) is not a variable in this comparative analysis. The analysis focuses on five key performance parameters: Condenser Capacity $\dot{Q}_o$ (kW), Compressor Power Consumption $\dot{W}_c$ (kW), Coefficient of Performance (COP), Refrigerant Mass Flow Rate $\dot{m}$ (kg/s) and Annual Energy Consumption.

Condenser capacity $\dot{Q}_o$ (kW), an important indicator of the system's energy balance, represents the heat rejected by the environment. Lower condenser capacity values indicate higher efficiency, as the system achieves the same cooling effect with less energy expenditure. Table 3 presents the condenser capacity values for the different refrigerant and evaporator type combinations.

Table 3. Kondenser kapasitesi değerleri.

Refrigerant	Evaporator Type	Condenser Capacity (kW)
R290 (Propane)	DX	25.67
R290 (Propane)	Flooded	25.70
R1270 (Propene)	DX	25.66
R1270 (Propene)	Flooded	25.70
R717 (Ammonia)	DX	25.49
R717 (Ammonia)	Flooded	25.50

As illustrated in Table 3, R717 (Ammonia) exhibited the lowest condenser capacity, which indicates the least waste heat generation. This superior performance is attributed to R717's favorable thermodynamic properties, allowing it to achieve the same cooling duty with reduced energy input. R290 (Propane) and R1270 (Propene) demonstrated very similar condenser capacity values, slightly higher than that of R717. The use of flooded evaporators resulted in a minor increase in condenser capacity for all refrigerants. Since the compressor is the primary energy-consuming component in a refrigeration cycle, the compressor power consumption ($\dot{W}_c$) is a critical parameter that directly affects the overall energy efficiency of the system. Table 4 offers a comparative overview of the compressor power consumption values for the various combinations of refrigerants and evaporator types.

Table 4. Compressor power consumption ($\dot{W}_c$) values.

Refrigerant	Evaporator Type	Compressor Power Consumption (kW)
R290 (Propane)	DX	6.129
R290 (Propane)	Flooded	6.200
R1270 (Propene)	DX	6.128
R1270 (Propene)	Flooded	6.200
R717 (Ammonia)	DX	6.042
R717 (Ammonia)	Flooded	6.000

Table 4 compellingly illustrates that ammonia (R717) not only leads but significantly outperforms its competitors in compressor power consumption across both DX and Flooded systems. This remarkable efficiency can be attributed to ammonia's exceptional thermodynamic properties, particularly its high latent heat of vaporization and reduced specific volume. In contrast, propane (R290) and propene (R1270) demonstrate closely aligned compressor power consumption, yet both fall short of ammonia's efficiency, with only a negligible difference between these hydrocarbons. Moreover, the implementation of Flooded evaporators results in only a slight increase in compressor power consumption for all three refrigerants. This minor uptick can be linked to the additional energy required for liquid level control and vapor-liquid separation that are inherent to the operation of Flooded evaporators. The Coefficient of Performance (COP) stands as a vital benchmark for assessing the efficiency of refrigeration systems. Defined as the ratio of the produced cooling effect (cooling capacity) to the energy input (compressor power consumption), a higher COP reflects superior energy efficiency. Figure 2 powerfully showcases a comparative visualization of the COP values for various refrigerant and evaporator-type configurations, reinforcing the advantage of ammonia in the quest for energy-efficient refrigeration solutions.

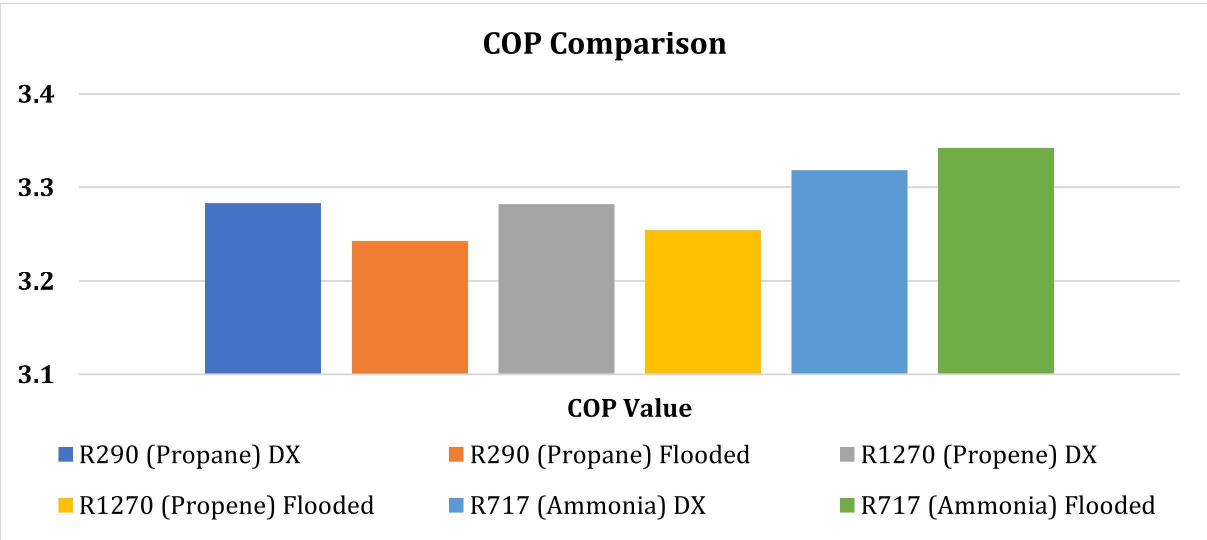

Figure 2. COP values for different refrigerants and evaporator types.

Figure 2 demonstrates the superior energy efficiency of R717 (Ammonia), which achieved significantly higher coefficient of performance (COP) values in both DX and Flooded evaporator systems, with COP values of 3.318 and

3.342, respectively. This establishes it as the most efficient refrigerant. R1270 (Propene) and R290 (Propane) also showed commendable COP performance. In DX systems, they recorded COP values of 3.282 and 3.283, respectively, while in Flooded systems, their values were 3.254 and 3.243. Although these values are lower than those of R717, they still represent acceptable levels of energy efficiency for refrigeration systems. The use of Flooded evaporators resulted in a slight decrease in COP values. This reduction, while practically negligible, should be considered given the increased complexity involved in designing and controlling Flooded systems.

The refrigerant mass flow rate $\dot{m}$ is a crucial parameter in system design, as it directly affects pipe sizing, compressor selection, and overall system configuration. Lower mass flow rates can lead to smaller pipe diameters and lower initial investment costs. However, excessively low mass flow rates may cause higher pressure drops within the system, which could compromise energy efficiency. Table 5 provides a comparative analysis of the mass flow rates for the various refrigerant and evaporator type combinations.

Table 5. Refrigerant mass flow rate ($\dot{m}$) values.

Refrigerant	Evaporator Type	Mass Flow Rate (kg/s)
R290 (Propane)	DX	0.06787
R290 (Propane)	Flooded	0.07000
R1270 (Propene)	DX	0.06632
R1270 (Propene)	Flooded	0.06900
R717 (Ammonia)	DX	0.01770
R717 (Ammonia)	Flooded	0.01800

Table 5 highlights a remarkable disparity in the mass flow rate for R717 (Ammonia) compared to other refrigerants. This significant difference is a direct result of ammonia's superior latent heat of vaporization, which means that it requires a considerably smaller mass to deliver the same cooling effect. This advantage not only allows for more compact systems with smaller pipe diameters but also raises an important consideration: very low mass flow rates can lead to increased pressure drops, potentially diminishing compressor efficiency. On the other hand, R290 (Propane) and R1270 (Propene) exhibited comparable mass flow rates, suggesting that similar considerations for pipe sizing and system design apply to both refrigerants, maximizing their operational efficiency. Moreover, the implementation of flooded evaporators resulted in a modest increase in mass flow rates across all refrigerants, further enhancing their effectiveness.

Annual energy consumption serves as a pivotal determinant of a refrigeration system's operating costs. A reduction in energy usage not only translates to lower electricity bills but also fosters a more sustainable and environmentally responsible operation. Table 6 provides a compelling comparison of annual energy consumption values for various refrigerant and evaporator type combinations, calculated under the assumption of continuous, year-round operation (8,760 hours). This data underscores the importance of selecting an efficient refrigeration system for economic and environmental benefits.

Table 6. Annual energy consumption values.

Refrigerant	Evaporator Type	Annual Energy Consumption (kWh)
R290 (Propane)	DX	53691
R290 (Propane)	Flooded	54378
R1270 (Propene)	DX	53683
R1270 (Propene)	Flooded	54163
R717 (Ammonia)	DX	52926
R717 (Ammonia)	Flooded	52552

Table 6 shows that the lowest annual energy consumption was achieved with Ammonia (R717), with values of 52926 kWh for the DX system and 52552 kWh for the Flooded system. This is directly related to Ammonia's highest COP values. R290 (Propane) and R1270 (Propene) had very similar energy consumption values to each other, higher than R717, but with a relatively small difference between the two hydrocarbons. Flooded evaporators increased energy consumption compared to the corresponding DX systems.

4. Discussion

This study compared the performance of DX and Flooded evaporator refrigeration systems for a medium-scale food storage facility, using three environmentally friendly refrigerants (R290, R1270, and R717) and the CoolPack simulation program. The findings reveal significant implications for energy efficiency, system design, environmental impact, and safety.

The simulation results clearly show that R717 (Ammonia) achieved the highest COP, indicating superior energy efficiency, in both DX and Flooded systems (Figure 2). This is attributable to ammonia's favorable thermodynamic properties, namely its high latent heat of vaporization and low specific volume. These properties enable the same cooling capacity with a lower mass flow rate, reducing compressor work. R290 (Propane) and R1270 (Propene) provided acceptable, though lower, COP values, particularly in DX systems. The difference in COP between these two hydrocarbons was negligible. Flooded evaporators generally resulted in slightly lower COP values than DX systems, due to the additional energy needed for liquid-level control and vapor-liquid separation. However, this minor difference may be offset in some applications by the benefits of Flooded evaporators, such as more stable operation and higher heat transfer coefficients.

R717's (Ammonia) significantly lower mass flow rate offers a potential design advantage: smaller pipe diameters, potentially reducing initial investment costs. However, this low mass flow rate can also increase system pressure drops, increasing compressor work and potentially reducing efficiency. Therefore, careful optimization of pipe diameters and compressor selection is crucial for ammonia systems. The similar, higher mass flow rates of R290 and R1270 suggest that larger pipe diameters may be necessary for systems using these refrigerants.

All refrigerants studied are environmentally friendly alternatives, having zero Ozone Depletion Potential (ODP) and low Global Warming Potential (GWP). However, their safety characteristics differ significantly (Table 2). R717 (Ammonia), while a natural refrigerant, is toxic and has low flammability, necessitating strict adherence to international standards (e.g., ASHRAE Standard 34, EN 378) in system design, installation, operation, and maintenance. Leak detectors, ventilation, and emergency procedures are essential. R290 (Propane) and R1270 (Propene) are highly flammable hydrocarbons, requiring spark-proof equipment, leak detection, and adequate ventilation. System design and installation must comply with relevant safety standards.

The findings of this study align generally with existing literature. For instance, Mota-Babiloni et al. (2015) highlighted the energy efficiency potential of low-GWP refrigerants, particularly ammonia [4]. Bolaji and Huan (2013) underscored the environmental benefits of natural refrigerants, including their zero ozone depletion potential and low global warming contribution [8]. For instance, Mota-Babiloni et al. (2015) highlighted the energy efficiency potential of low-GWP refrigerants, particularly ammonia [4]. Similarly, Dalkılıç and Wongwises (2010) found that hydrocarbons (such as R290) could be viable alternatives in refrigeration systems. However, it is important to note that the specific COP and mass flow rate values obtained in this study are dependent on the specific system parameters, operating conditions, and simulation model employed [9].

The results of this study can provide some suggestions for future research, such as experimental verification, investigation of system performance under different operating conditions such as different evaporation and condensation temperatures, different superheating and subcooling values, investigation of the dynamic behavior of the system, development of system control strategies, conducting a comprehensive economic analysis considering factors such as initial investment costs, operating costs and payback periods of different refrigerant and evaporator types, and investigation of different cooling loads.

5. Conclusion

This study presents a comprehensive, comparative performance analysis of DX and Flooded evaporator refrigeration systems using environmentally friendly refrigerants (R290, R1270, and R717) in a medium-scale food storage facility. The findings provide valuable insights for selecting refrigerants and evaporators to enhance energy efficiency, minimize environmental impact, and ensure system safety. R717 (Ammonia) demonstrated superior energy efficiency, while R290 (Propane) and R1270 (Propene) offer viable, environmentally conscious alternatives. Crucially, the safety requirements of each refrigerant must be meticulously addressed, with appropriate measures implemented according to relevant standards.

Simulation results unequivocally showed that R717 (Ammonia) achieved the highest COP values in both DX and Flooded systems, a direct consequence of its favorable thermodynamic properties. R290 and R1270, while exhibiting lower COP values, particularly in DX systems, still provided acceptable energy efficiency. Their zero ODP and low GWP make them attractive, environmentally friendly options. R717's significantly lower mass flow rate impacts system design considerations, including pipe sizing and compressor selection. Flooded systems generally showed slightly lower performance than DX systems, a minor difference that may be offset by other operational advantages. Refrigerant selection must prioritize not only energy efficiency and environmental impact but also critical safety factors. The toxicity and low flammability of R717, and the high flammability of R290 and R1270, demand rigorous adherence to safety protocols.

This study, based on simulation results, assessed the performance of environmentally friendly refrigerants and different evaporator types in medium-scale food storage systems. Real-world performance may vary; therefore, these findings should be validated through practical implementation and experimental studies. Future research, incorporating different operating conditions, dynamic modeling, and comprehensive economic analyses, will further contribute to this field.

Conflicts of interest
The author declares no conflicts of interest.

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