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Experimental Research to Compare the Effect of Varying Inlet and Outlet Temperatures of a Heat Exchanger on the Performance of A Cascade Cooling System

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Abstract:
Heat exchangers are not merely cooling devices that transfer heat between fluids; they are an effective way to conserve resources, save money, and contribute to global efforts to reduce energy waste, with positive implications for economic security and resource sustainability. Good design and the selection of the best materials for heat exchanger manufacturing ensure optimal exchange. The heat exchanger capacity required for a refrigeration system must achieve the smallest possible difference between the inlet temperature of the heat exchanger evaporator and the outlet temperature of the heat exchanger condenser. The overall system capacity depends on the temperature difference within the heat exchanger to minimize energy consumption. This study demonstrates the importance of the difference between the inlet temperature of the heat exchanger evaporator and the outlet temperature of the heat exchanger condenser, as this difference has a specific value for each main evaporator temperature. For every main evaporator temperature (T_e), there is a corresponding outlet temperature (T_3) in a low-pressure refrigeration cycle (LPC). The operation of heat exchangers is crucial in all refrigeration and air conditioning systems; therefore, careful selection of the heat exchanger type and the materials used in its manufacture is essential. Taking into account several factors to ensure accurate and reliable results, and using the specialized REFPRO refrigeration software, a 24-layer plate heat exchanger was selected to achieve optimal heat exchange between the two refrigeration circuits in this research. To reduce energy consumption in the cascade refrigeration system, the efficiency of the heat exchangers must be improved, pressure loss minimized, and refrigerants selected for the required temperature range must be chosen. Advanced control strategies must be employed to optimize system performance under varying operating conditions, and ambient conditions must be considered during the design and operation of the cascade refrigeration system due to its heavy reliance on the heat exchanger. When using R407C with R32, the refrigerant temperature upon exiting the heat exchanger two hours after system startup is 1.25°C. However, when using R407C with a mixture (90%/10% R32/R600A by mass), the temperature is 0.8°C, a difference of 0.45°C compared to the mixture. The highest temperature recorded for the heat exchanger evaporator in this study was -2.6°C, followed by a low temperature of -5.2°C, which was the lowest temperature recorded for the evaporator in both experiments. The mixture and R32 gas had the same values at the condenser outlet in the low-pressure cycle at the end of the system's operation. The compressor outlet temperature curve in the low-pressure cycle shows that, two hours after startup, the mixture exits the discharge line at a lower temperature than R32 gas. The temperatures of both the mixture and R32 gas allow for determining the optimal compressor outlet temperature, which in turn determines the appropriate compressor size, condenser pipe capacity, and pipe thickness. The compressor inlet temperature in the low-pressure cycle reaches a maximum of 13°C, which is the highest temperature the mixture can reach.

Keywords: Heat exchanger inlet and outlet temperatures, sequential cooling, flow rate, heat transfer coefficient, performance rate.

بحث تجريبي لمقارنة تأثير تغير درجات حرارة الدخول والخروج لمبادل حراري على أداء نظام تبريد متسلسل

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الملخص
لا تُعد المبادلات الحرارية مجرد أجهزة تبريد تنقل الحرارة بين الموائع، بل تمثل وسيلة فعالة للحفاظ على الموارد، وتوفير المال، والمساهمة في الجهود العالمية للحد من هدر الطاقة، مما ينعكس إيجابًا على الأمن الاقتصادي واستدامة الموارد. إن التصميم الجيد واختيار أفضل المواد لتصنيع المبادلات الحرارية يضمنان تحقيق تبادل حراري مثالي.
يجب أن تحقق سعة المبادل الحراري المطلوبة لنظام التبريد أصغر فرق ممكن بين درجة حرارة دخول مبخر المبادل الحراري ودرجة حرارة خروج مكثف المبادل الحراري. وتعتمد السعة الكلية للنظام على فرق درجات الحرارة داخل المبادل الحراري بهدف تقليل استهلاك الطاقة.
تُظهر هذه الدراسة أهمية الفرق بين درجة حرارة دخول مبخر المبادل الحراري ودرجة حرارة خروج مكثف المبادل الحراري، حيث تكون لهذا الفرق قيمة محددة لكل درجة حرارة رئيسية للمبخر. فلكل درجة حرارة للمبخر الرئيسي(T_e) ، توجد درجة حرارة خروج مقابلة (T_3) في دورة التبريد ذات الضغط المنخفض.(LPC)
يُعد تشغيل المبادلات الحرارية عنصرًا أساسيًا في جميع أنظمة التبريد وتكييف الهواء، لذلك فإن اختيار نوع المبادل الحراري والمواد المستخدمة في تصنيعه بعناية أمر بالغ الأهمية. وبمراعاة عدة عوامل لضمان نتائج دقيقة وموثوقة، واستخدام برنامج التبريد المتخصص(REFPRO) ، تم اختيار مبادل حراري صفائحي مكوّن من 24 طبقة لتحقيق تبادل حراري مثالي بين دائرتي التبريد في هذا البحث.
ولتقليل استهلاك الطاقة في نظام التبريد المتسلسل، يجب تحسين كفاءة المبادلات الحرارية، وتقليل فاقد الضغط، واختيار وسائط التبريد المناسبة لنطاق درجات الحرارة المطلوبة. كما ينبغي استخدام استراتيجيات تحكم متقدمة لتحسين أداء النظام تحت ظروف التشغيل المختلفة، مع الأخذ في الاعتبار الظروف البيئية المحيطة أثناء تصميم وتشغيل نظام التبريد المتسلسل، نظرًا لاعتماده الكبير على المبادل الحراري.
عند استخدام وسيط التبريد R407C معR32 ، تبلغ درجة حرارة وسيط التبريد عند خروجه من المبادل الحراري بعد ساعتين من بدء تشغيل النظام 1.25 درجة مئوية. أما عند استخدام R407C مع خليط 10% / 90%) من R32/R600A بالكتلة(، فتبلغ درجة الحرارة 0.8 درجة مئوية، أي بفارق 0.45 درجة مئوية مقارنة بالخليط.
سُجلت أعلى درجة حرارة لمبخر المبادل الحراري في هذه الدراسة عند -2.6 درجة مئوية، تليها درجة حرارة منخفضة بلغت -5.2 درجة مئوية، وهي أدنى درجة حرارة تم تسجيلها للمبخر في كلتا التجربتين. كما سجل كل من الخليط وغاز R32نفس القيم عند مخرج المكثف في دورة الضغط المنخفض عند نهاية تشغيل النظام.
يوضح منحنى درجة حرارة مخرج الضاغط في دورة الضغط المنخفض أنه بعد ساعتين من بدء التشغيل، يخرج الخليط من خط الطرد بدرجة حرارة أقل مقارنة بغاز .R32 وتُستخدم درجات حرارة كل من الخليط وغاز R32 لتحديد درجة حرارة الخروج المثلى للضاغط، والتي بدورها تحدد الحجم المناسب للضاغط، وسعة أنابيب المكثف، وسُمك الأنابيب.
تصل درجة حرارة مدخل الضاغط في دورة الضغط المنخفض إلى حد أقصى يبلغ 13 درجة مئوية، وهي أعلى درجة حرارة يمكن أن يصل إليها الخليط.

الكلمات المفتاحية: درجات حرارة دخول وخروج المبادل الحراري، التبريد المتسلسل، معدل التدفق، معامل انتقال الحرارة، معامل الأداء.

INTRODUCTION
A heat exchanger contributes to improving the overall efficiency of a cascade refrigeration system by reducing heat loss and increasing the coefficient of performance. It allows for efficient heat exchange between the two different refrigerants used in the two cycles. The difference between the outlet temperatures of the refrigerant in each of the two refrigeration cycles of the heat exchanger affects the overall efficiency of the system; the larger the heat exchange area, the closer the two temperatures will be. The heat exchanger should be designed to achieve the smallest possible difference between the outlet temperatures of the two cycles.

In air conditioning and refrigeration systems, heat exchangers are used to exchange heat between two fluids at different temperatures, thus enabling heat exchange between the fluids. In terms of area and weight, these are important factors in some applications; therefore, careful consideration should be given to selecting the appropriate heat exchanger for each refrigeration system.
The plate heat exchanger, as shown in Figure 1, consists of a series of corrugated metal plates stacked together. Hot and cold fluids flow through the channels formed between the plates. Heat exchange occurs between the fluids through the plates. The plate heat exchanger is characterized by high heat transfer efficiency, a large heat exchange surface area, and is often used in refrigeration and air conditioning applications. It is also relatively small in size.

Figure 1 Plate Heat Exchanger

Extremely high or low temperatures can affect the durability and reliability of a heat exchanger. Studying the impact of temperature on the exchanger is crucial for identifying conditions that can lead to its failure or longevity, thus improving its design and selecting appropriate materials for its construction. Increasing the temperature difference between the inlet and outlet of the heat exchanger increases the heat transfer rate, and vice versa. Fluid viscosity changes with temperature, affecting the flow rate and pressure drop in the heat exchanger. This change in viscosity also affects the heat transfer coefficient. Furthermore, fluid thermal conductivity changes with temperature, impacting the fluid's ability to transfer heat. These changes in thermal conductivity affect the efficiency of the heat exchanger and, consequently, the overall system efficiency.
A comprehensive performance analysis was conducted, combining thermodynamic analyses using REFPRO simulation software to determine theoretical results and identify the operating conditions that achieve the optimal balance between performance efficiency and operating costs through laboratory experiments. Environmentally friendly fluids with a low impact on the ozone layer and global warming should be selected. Non-flammable and non-toxic fluids are also preferable for safety. Humidity affects heat exchanger performance. High humidity can reduce the heat transfer rate and efficiency, especially on the heat exchanger surface, thus decreasing heat transfer efficiency and increasing energy consumption. Therefore, the heat exchanger should be insulated from the surrounding air.
This study investigates the impact of various structural parameters in a plate-finned heat exchanger on the performance of a cascade cooling system, focusing on five key factors: fin thickness, type, height, porosity, and axial length. We analyze their contributions to the coefficient of performance (COP), available energy loss, and system entropy. The results reveal that fin type does not significantly affect system performance, while axial length is the most influential factor, followed by fin height, porosity, and finally thickness [1]. This study addresses the field of energy and exergy analysis, aiming to improve the performance of the cooling cycle using cycle performance coefficients (COPs). The conventional heat pump cycle was replaced with a cascade cycle, and this new architecture was studied from the perspective

of the first and second laws of thermodynamics. The analysis was performed using EES software and included the cycle components subject to these laws. R407C refrigerant was used. Through comprehensive energy and exergy analyses, significant results emerged. Assuming a constant cooling capacity, the study revealed the potential for a significant 21% increase in the coefficient of performance (COP) and a substantial 32% improvement in the second law of thermodynamic efficiency within the cycle. Subsequently, an in-depth investigation was conducted, including the selection of cascade refrigerants – R290, R134a, and R500. This study meticulously compares the impact of key parameters, such as inlet pressure, intermediate heat exchanger outlet temperature differential, evaporator inlet temperature, and condenser outlet temperature, on the performance and efficiency of the refrigeration cycle for each refrigerant [2]. Cascade refrigeration systems comprise two or more distinct refrigeration circuits: a low-temperature (LTC) circuit and a high-temperature (HTC) circuit. These circuits are connected via a heat exchanger, facilitating heat transfer from the condenser (LTC) to the evaporator (HTC). The primary focus is on achieving an optimal temperature differential within the cascade heat exchanger to enhance overall system efficiency. This was further validated through practical application [3]. This study aimed to understand the performance characteristics of a cascade refrigeration system integrated with an internal heat exchanger, using R744 for the low-temperature refrigeration cycle and R404A, R448A, and R449A for the high-temperature refrigeration cycle [4]. The ejector refrigeration (ERC) cycle, with its simple structure and low cost, has significant application potential in cascade refrigeration cycles to improve overall system performance by removing or recovering heat from the main cycle [5]. This study simulated the heat transfer process in micro plate heat exchangers within a cascade refrigeration system using R134a and R744 refrigerants, using COMSOL Multiphysics 6.2 software. Phase change characteristics, such as temperature field, vapor ratio, and density, were addressed [6]. Cascade refrigeration systems have become the preferred choice for low-temperature applications, resulting in significant energy waste due to the lack of practical control strategies. Currently, refrigeration simulations rely primarily on simplified thermodynamic models or artificial intelligence models [7]. This work focuses on a four-dimensional analysis of a 50 kW cascade refrigeration cycle, covering energy, exergiance, economics, and environmental aspects. A numerical study and multi-objective optimization of the system were performed using the R170-R600a and R41-R600a refrigerant pairs. The refrigerant pair was selected based on its environmental impacts in terms of global warming potential (GWP) and ozone depletion potential (ODP) [8]. Cascade refrigeration systems with multiple cooling temperature ranges are used in various fields, such as seafood processing and cold storage. The use of multiple compressors, each dedicated to a different temperature range, is the most common method for controlling the evaporator temperature and cooling capacity [9]. Condensation heat recovery is a way to save energy and reduce carbon emissions. In a self-starting cascade refrigeration system, raising the heat recovery temperature conflicts with ensuring optimal cooling performance. Therefore, a staggered cascade refrigeration system with a heat recovery system was designed [10]. A numerical study of the energy, thermal efficiency, economic and environmental performance of a 50 kW cascade cooling system was conducted, using four different pairs of refrigerants, namely: R41–R404A, R170–R404A, R41–R161 and R170–R161 [11].

The energy crisis that followed the coronavirus pandemic, and the ever-increasing environmental degradation, call for researchers to study cooling systems as key contributing factors to these problems, with the aim of minimizing the environmental impact and maximizing performance. The optimization results show that for a 10 kW plant, the TCRS, COP, and available energy efficiency are achieved under optimal conditions (evaporator temperature = -101.023 °C, condenser temperature = 36.545 °C, total plant temperature = -69.047 °C, and overall plant temperature = -34.651 °C) [12]. This work focuses on a four-dimensional analysis of a 50 kW cascade refrigeration cycle, covering energy, exergy, economics, and environmental aspects. A numerical study and multi-objective optimization of the system were performed using the R170-R600a and R41-R600a refrigerant pairs. The refrigerant pair was selected based on environmental impacts in terms of global warming potential (GWP) and ozone depletion potential (ODP) [13]. A two-stage cascade pressure refrigeration (CRST) system using the R1150/R717 refrigerant combination was investigated as an alternative to a three-stage cascade refrigeration system (TCRS). Using a range of R1150/R41/R717 refrigerants, with the aim of improving the operating efficiency of the industrial refrigeration system in the temperature range from -120°C to -80°C [14].

In the food refrigeration industry, single-stage compression refrigeration systems cannot meet the operating requirements at high pressure ratios with low evaporating temperatures. Cascade refrigeration (CRS) systems offer a technical alternative to this problem. This paper investigates the single-refrigerant pairs used in CRS systems. The following single-refrigerant pairs were selected: R32/R32, R125/R125, R1270/R1270, R143a/R143a, R404A/R404A, R407A/R407A, R410A/R410A, and R507A/R507A, to evaluate their operating characteristics compared to the conventional R23/R404A cascade refrigeration system. Compressor adaptability, optimal operating parameters, coefficient of performance (COP), and seasonal energy efficiency ratio (SEER) were analyzed using different single-refrigerant pairs. The results demonstrate the potential for improving the performance coefficient of a conventional refrigeration system using single refrigerant pairs [15]. The proposed system was found to be more sensitive to refrigerant changes at low condensing temperature (LTC) compared to those at high condensing temperature (HTC) [16]. This paper contributes to the design and construction of an optimal thermodynamic system, as well as the evaluation of its performance to achieve high efficiency and meet the global needs of daily applications in extremely low temperatures, temperature-controlled and heat-sensitive storage for vaccines, pharmaceuticals, blood products, and biological materials [17].

Current operating fluid selection methods for absorption refrigeration cycles rely solely on steady-state cycle performance. Under actual operating conditions, the cycle is subject to external disturbances, negatively impacting its performance and leading to increased resource consumption or even the inability to meet load requirements [18]. Autonomous cascade refrigeration systems are among the most commonly used cycles for preserving products at extremely low temperatures (-80 to -60°C). Interest in these systems has increased due to the need to preserve and distribute COVID-19 vaccines. However, there is a lack of experimental validation of the theoretical models used to analyze and optimize them [19]. System performance was evaluated considering three key operating temperatures: evaporator temperature, low-temperature (LTC) condensing temperature, and high-temperature (HTC) condensing temperature [20].

Research Methodology:

In this experimental study to determine the effect of the inlet and outlet temperature difference of the heat exchanger on the performance of a cascade refrigeration cycle (CRC) system, several aspects must be considered to ensure accurate and reliable results. The REFPRO software, specialized in refrigeration circuits, was used.

The basic steps in the study design were defined as follows:

Independent variables: Inlet temperature to heat exchanger evaporator T_8, Inlet temperature to heat exchanger condenser T_3, High-pressure cycle refrigerant flow rate $\dot{m_{HPC}}$, Low-pressure cycle refrigerant flow rate $\dot{m_{LPC}}$.

Dependent variables: Evaporator outlet temperature to heat exchanger T_2, Condenser outlet temperature to heat exchanger T_5, Total heat transfer coefficient U, System coefficient of performance (COP), System power consumption (i.e., the amount of energy consumed by the system in a given period, usually measured in kilowatt-hours, kWh).

The heat exchanger used: After testing various types, the appropriate heat exchanger was selected for this research; it is a 24-layer plate-type heat exchanger. Choosing the right heat exchanger helps ensure efficient heat exchange between the two cycles.

Precision measuring devices were used to measure temperatures, flow rates, and pressures, while energy meters were used to measure energy consumption in the compressors and all other equipment in the system. A computer-controlled system was also employed, utilizing a VID data projector to allow for the modification or stabilization of independent variables through the software installed on the computer. A control system was used that enabled data recording and analysis via Excel files.

Figure 2 shows the components of the system and their application to the temperature and entropy curve of the cascade cooling system.

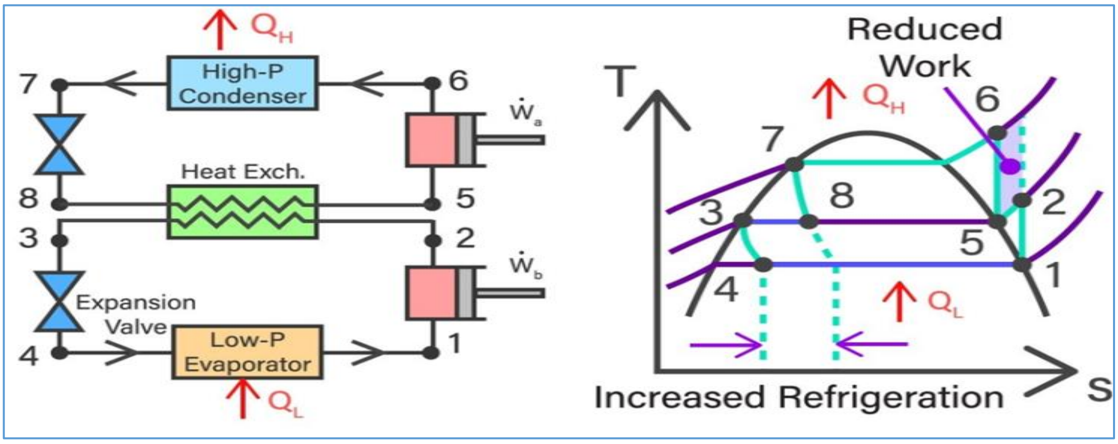

Figure 2 shows the relationship between temperature and entropy corresponding to the phases of the two cycles.

Figure 3 shows the stages that the refrigerant goes through in the high-pressure cycle shown in red and the stages that the refrigerant goes through in the low-pressure cycle by comparing the entropy curve and temperature on the right with the enthalpy curve and pressure shown in blue on the left of Figure 3.

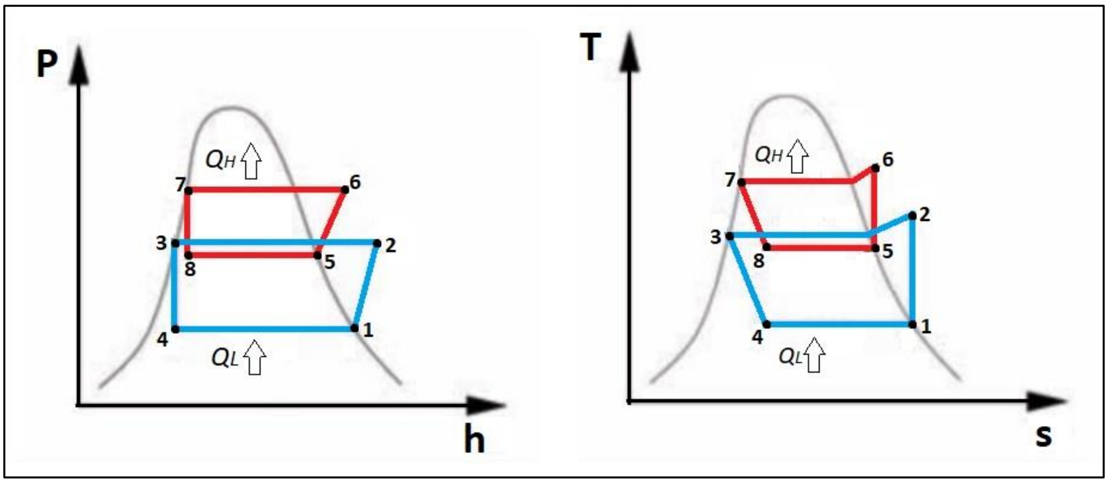

Figure 3 relationship between temperature - entropy, and pressure - enthalpy in LPC,HPC.

In the low-pressure cycle (LPC), both the enthalpy at the compressor inlet h_1 and the enthalpy at the electronic expansion valve h_4 are calculated, along with the compressor's operation in the low-pressure cycle, from the following equation:

$$W_c^{LPC} = (h_2 - h_1) \quad (1)$$

Enthalpy at compressor exit in LPC h_2

$$COP_{LPC} = \frac{(h_1 - h_4)}{(h_2 - h_1)} \quad (2)$$

Mass flow rate in LPC LPC

$$\dot{m}_{LPC} = \frac{Q_{LPC}}{(h_1 - h_4)} \quad (3)$$

$$W_{LPC} = \frac{\dot{m}(h_2 - h_1)}{\eta_{C,LTC}} = \dot{m}_{LPC} \, (h_2 - h_1) = \frac{Q_L \, (h_2 - h_3)}{(h_1 - h_4)} \quad (4)$$

From the following equation, we obtain the work done by the compressor in the high-pressure cycle (HPC), along with the calculation of the total flow rate:

$$\dot{m}_{HPC} = \frac{Q \, W_{LPC}}{h_s - h_g} \quad (5)$$

The condenser heat load, the sum of compressor work, and the system efficiency (COP) are calculated using the following equations:

$$COP = \frac{T_{COLD}}{T_{HOT} - T_{COLD}} \quad (6)$$

The Kelvin unit of measurement is used with the temperatures used in the equation above, by adding 273 to the Celsius temperature to obtain the corresponding temperature in Kelvin:

$$COP_{LPC} = \frac{Q_e}{W_{Comp \; LPC}} = \frac{T_4}{T_2 - T_4} \quad (7)$$

The overall system performance factor (COP) calculates the cooling-to-energy-consumption ratio using the following equations:

$$COP_{HPC} = \frac{Q_{heat\ exchanger\ in}}{W_{Comp \; HPC}} = \frac{T_8}{T_6 - T_8} \quad (8)$$

$$\dot{m}_{HTC} \cdot (h_5 - h_8) = \dot{m}_{LTC} \cdot (h_2 - h_3) \quad (9)$$

Pressure loss: Pressure loss in the system was measured for both cycles, as each temperature corresponds to a specific pressure. It is worth noting that the pressure drop through the piping and the piping design significantly affect the power and size of the compressor used. Analysis of variance (ANOVA) was used to analyze the effect of independent variables on dependent variables. Two-way ANOVA is a statistical method designed to evaluate the effect of two independent factors, or variables, on one dependent variable. This multifaceted analysis not only assesses the main effects of each factor but also explores potential interactions between them. Tests and measurements of the temperature values (T) were used to compare the means

measured during repeated experiments. The values of all pressures (P) were calculated to determine the statistical significance of the results as mean values.
At 4 degrees Celsius, both the subcooling temperature, which is the process of cooling the liquid to below its condensation or boiling point without changing its phase, and the superheat, which is the temperature of the refrigerant vapor above its boiling point at a certain pressure, are fixed, as shown in Figure 5 below.

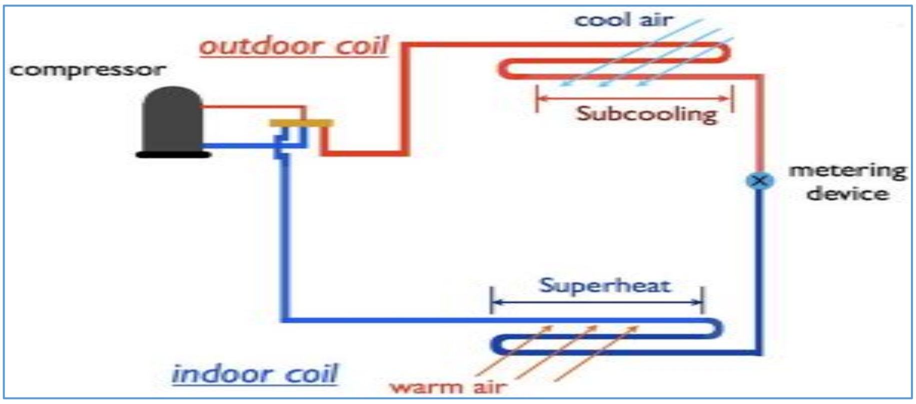

Figure 5 illustrates the importance of downward cooling and added heat in the refrigeration cycle.

Data Analysis: The effect of independent variables on dependent variables was analyzed. In HPC, the evaporator capacity of the heat exchanger, Q_E, is calculated in kilowatts using the following equations:

$$Q_E = \dot{m}\,(h_5 - h_8) \quad (10)$$
$$Q_E = Q_C - W_C \quad (11)$$

3. Experimental Method:

Recording the Variable Range: The cooling load value covered the operating range of the system. 7.5 liters of water in 0.5-liter plastic bottles were used to generate the system's heat load. The water was replenished each time the experiments were conducted or repeated to ensure reliable results. Measurements were taken and recorded under stable operating conditions, and the data were analyzed periodically. The heat exchanger efficiency was 80% according to the manufacturer. The experiments were repeated several times to ensure reliable results, and the averages and standard deviations of the data were calculated. The calibration of the measuring instruments was verified before conducting the experiments, and the integrity of the experimental setup was confirmed. We installed the temperature measuring devices using thermal cables connected to a reading device linked to a computer. The readings were recorded in Excel spreadsheets at each of the required measurement points: the water bottles representing the cooling load, and both the inlet and outlet of the heat exchanger in both the high- and low-pressure cycles of the cooling system. The readings were taken hourly until the desired temperature was reached by the thermostat.

The main variables are:
Independent variables: These are the inlet temperature of the heat exchanger evaporator T_8 and the inlet temperature of the heat exchanger condenser T_2.
Dependent variables: These are the outlet temperature of the heat exchanger evaporator T_5 and the outlet temperature of the heat exchanger condenser T_3.
Refrigerant type: The physical properties of the fluids used, such as viscosity and thermal conductivity, were considered, as these properties change with temperature. In this research,

R407C was used in the high-pressure cycle (HPC) in both experiments, and in the low-pressure cycle (LPC) in the first experiment with R32 and the second with a 90/10% mixture of R32/R600A by mass.

Ambient conditions: Ambient temperature of 25°C and relative humidity of 65% were recorded as they affect the results.

Table (1) Abbreviations with symbols used in equations:

P_1&T_1	Compressor inlet pressure & temperature in LPC	$\dot{m}$	Coolant mass flow rate
P_2&T_2	Heat exchanger inlet pressure & temperature in LPC	W_C	Compressor Work (kJ/kg)
P_3&T_3	Pressure & temperature of the heat exchanger outlet in LPC	LPC	Low pressure cycle
P_4&T_4	Evaporator inlet pressure & temperature to LPC	HPC	High pressure cycle
P_5&T_5	HPC heat exchanger outlet pressure & temperature	h	Enthalmic content (kJ/kg)
P_6&T_6	Inlet pressure & temperature of the condenser in HPC	T_e	Evaporation temperature of LPC
P_7&T_7	Condenser outlet pressure & temperature in HPC	T_C	HPC condensation temperature
P_8&T_8	HPC heat exchanger inlet pressure & temperature	T_a	outside air temperature
ΔT	$(T_8 - T_3)$	T_1 &T_5	compressor discharge temperature LPC and HPC
COP_H	HPC Performance Factor	COP_L	LPC Performance Factor
COP_{MCRS}	MCRS Performance Factors	MCRS	Miniature cascade cooling system
η_{LPC}	Energy efficiency available for LPC compressor operation	η_{HPC}	Energy efficiency available for HPC compressor operation

Table (2) Range of variables entered into the REFPRO program as the minimum and maximum limits**:**

limit	Value	unit of measurement
Convection in the cold room (Q_e)	1000	Watt (W)
Outside air temperature (T_a)	From 25 to 35	Celsius (°C)
Condensation temperature (T_C)	From 35 to 45	Celsius (°C)
Evaporator temperature (T_e)	من -25 الى -35	Celsius (°C)
LPC Superheating	4	Celsius (°C)
HPC Superheating	4	Celsius (°C)
$\Delta T = T_8 - T_3$	15	Celsius (°C)
Efficiency of two-cycle compressors and heat exchangers η_{LPC} & η_{HPC}	80%	

4. Documented Results of this Research:

Figure 5 shows the change in compressor inlet temperature during operation for both R32 and the mixture.

Firstly, for R32 gas, after two operating hours, the compressor inlet temperature in the low-pressure cycle reaches 13°C. It then rises to 13.5°C during the third hour, remains at this temperature from the third to the fourth hour, then increases to 14°C during the fifth hour, before stabilizing at 12.6°C during the final two hours.

Secondly, regarding the mixture, it reaches 11°C in the second hour after startup, then rises to 12°C and 12.5°C during the third and fourth hours respectively, and stabilizes at 12.5°C between the fourth and fifth hours. During the sixth hour, the compressor inlet temperature in the low-pressure cycle rises to 13°C, which is the maximum temperature the mixture reaches. From there, the mixture begins to decrease to 12.25°C at the seventh hour, and then rises again to 12.7°C during the eighth hour.

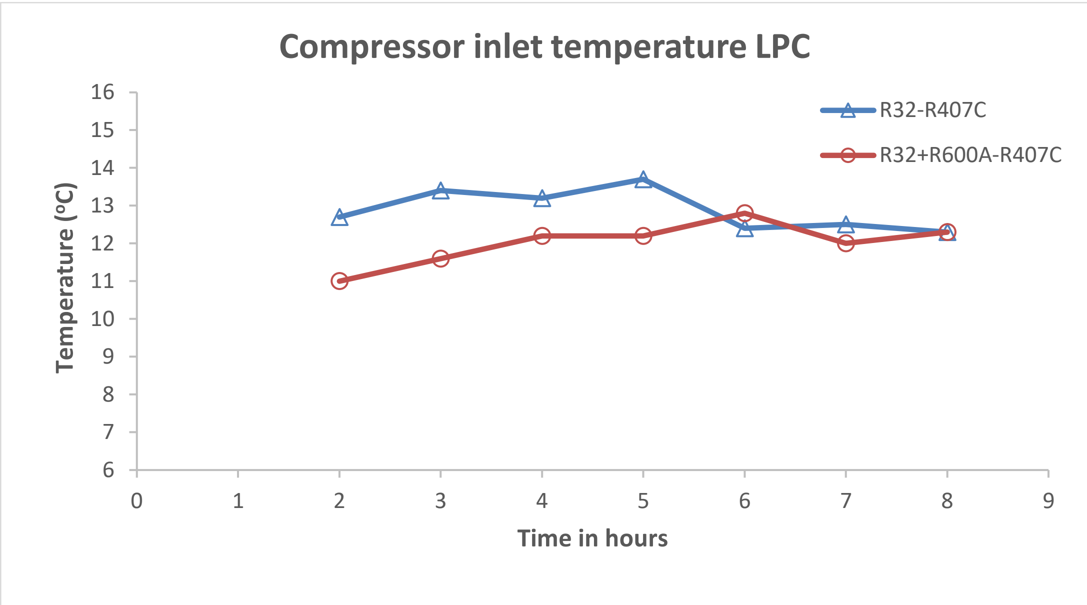

Figure 5 shows the relationship between the compressor inlet temperature to LPC in both experiments.

Figure 6 shows the compressor outlet temperature curve in LPC, where the mixture and R32 are 119°C and 121°C, respectively. This means that two hours after startup, the mixture exits the discharge line at a lower temperature than R32 gas. At four hours after startup, the initial temperature is 119°C for both the mixture and R32 gas. Within two hours, the mixture rises to 121°C, the same temperature as R32 gas at the start of the diagram. From there, the mixture drops to 114°C, while R32 gas drops to 119°C after eight hours. Figure 6 illustrates the temperatures of both the mixture and R32 gas, which allows for determining the optimal compressor outlet temperature. This determines the appropriate compressor size, condenser piping capacity, and piping thickness.

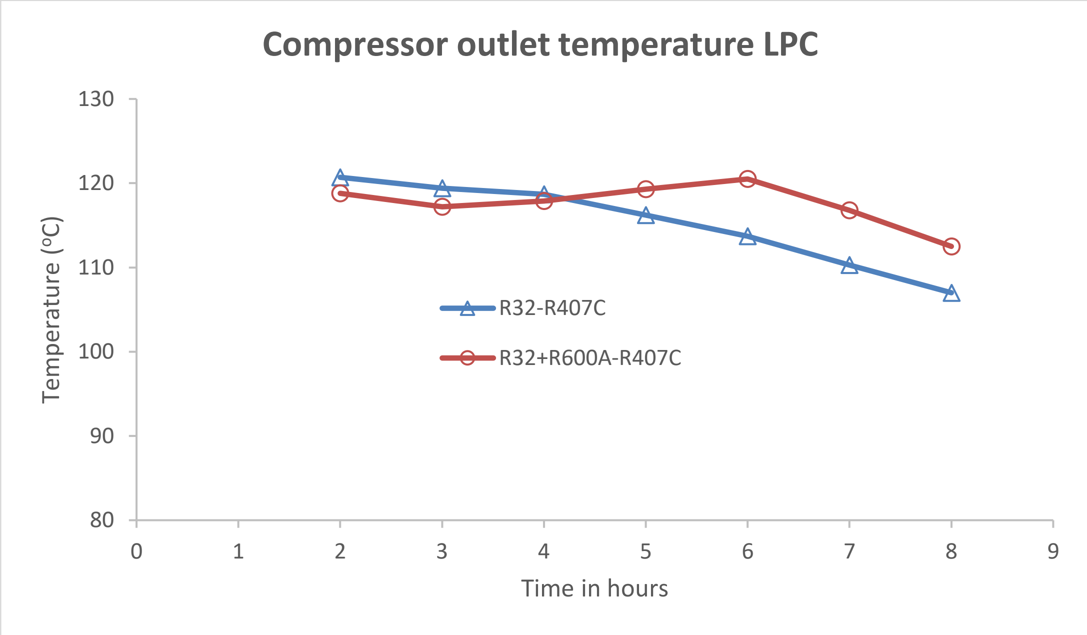

Figure 6 shows the relationship between the outlet temperature of the compressors in LPC in both experiments.

Figure 7 shows the inlet temperature curve of the heat exchanger representing the condenser in LPC. We observe that both the mixture and the R32 gas are at the same temperature of 79°C after two hours of operation. The R32 gas temperature remains constant at this level until the fourth hour, after which it gradually decreases by three degrees per hour, reaching 68°C by the end of the eighth hour.

We also observe that the inlet temperature of the mixture in the heat exchanger fluctuates more significantly, rising and falling from 79°C to 67°C during the third hour of operation. It then rises to the same temperature at the fourth hour and remains constant from the fourth to the fifth hour. From the fifth to the sixth hour, it reaches its highest experimental temperature of 81°C. During the final two hours, the inlet temperature of the heat exchanger gradually decreases to 74°C and 71°C at the seventh and eighth hours, respectively. We note that the difference between the mixture and the R32 gas is only two degrees Celsius.

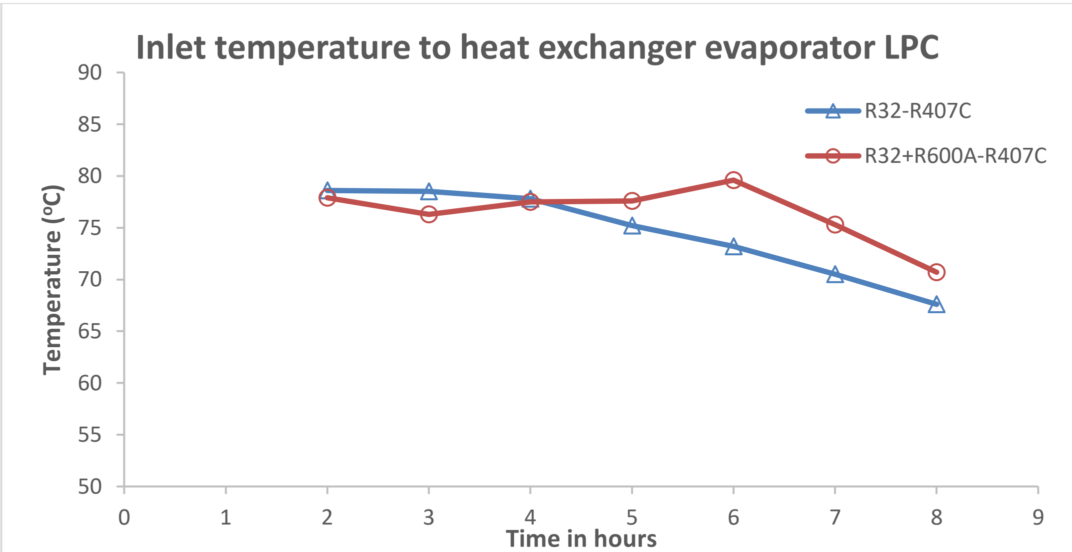

Figure 7 compares the relationship between the inlet temperature of LPC heat exchanger in both experiments.

In Figure 8, tracing the two curves at the outlet of the heat exchanger condenser in LPC reveals a successive decrease in temperature in both experiments. The highest temperature recorded in both experiments for R32 gas is 23°C, decreasing to 17°C at the third hour. The temperature remains stable at this level from the third to the fifth hour, rising slightly to 20°C at the sixth hour before dropping to 16°C at the seventh hour and finally reaching 10°C at the eighth hour. It is clear from Figure 8 that the mixture and R32 gas have the same values at the condenser outlet in LPC at the end of the curve.

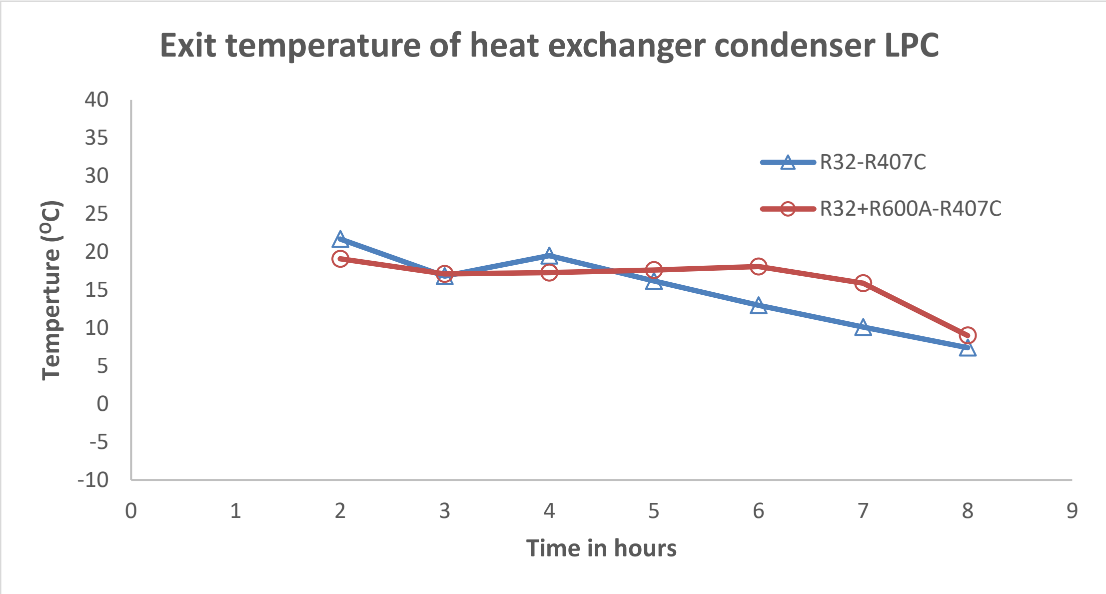

Figure 8 compares the relationship between the outlet temperature of LPC heat exchanger in both experiments.

In Figure 9, an analysis of the diagram showing the relationship between the inlet temperature of the heat exchanger in HPC reveals the following: When using R407C (shown in blue) with R32, the temperature at the beginning of the curve is -3.5°C. After one hour, it rises to -3.2°C, which is the highest temperature of the refrigerant at the evaporator inlet of the heat exchanger in HPC during the first experiment using R32. The temperatures then gradually decrease during the fourth hour to -3.3°C, then to -3.7°C, and by the sixth hour to -4.3°C. By the seventh hour, the temperature reaches -4.6°C, and finally, in the last hour, it reaches -5.2°C, which is the lowest temperature of the heat exchanger evaporator during both experiments.

Looking at the curve in red, which represents the second experiment, i.e., with the same refrigerant in HPC with the mixture in LPC, the first degree in the curve is equal to -3.8 degrees Celsius. From there, it begins to rise during the third hour of the refrigerant entering the heat exchanger evaporator to reach -3.6 degrees Celsius. From there, it continues to rise at a higher rate during the fourth hour of operation to reach -3.1 degrees Celsius. From there, it decreases at a slow rate during the fifth hour to reach -3.3 degrees Celsius. After that, it rises at a rapid rate during the sixth hour to achieve the highest degree of entry into the heat exchanger evaporator during this research, which is equal to -2.6 degrees Celsius. From there, it decreases at a constant rate during the last two hours to reach -3.5 and -4.2 degrees Celsius for both the seventh and eighth hours, respectively.

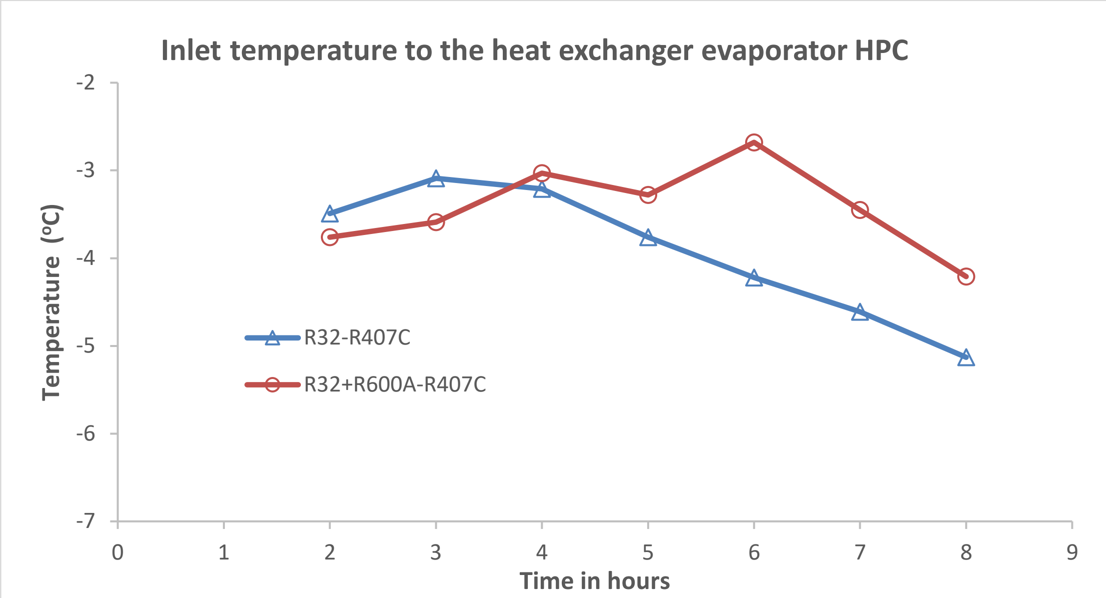

Figure 9 shows the relationship between the inlet temperature of the heat exchanger evaporator in HPC in both experiments.

From curve 10, the relationship between the temperature decrease of the refrigerant as it exits the heat exchanger in a high-pressure cycle is evident, as follows:

First: When using R407C with R32 (shown in blue), after two hours of operation, the exit temperature of R407C reaches 1.25°C. During the third hour, it rises to 1.6°C, and in the fourth hour, the refrigerant exiting the heat exchanger condenser begins to decrease to 1.5°C. From there, it continues to decrease sequentially over the hourly operating time as follows: 1°C, then 0.5°C, then 0°C, and finally -0.5°C at the end of the eighth hour.

Second: When using R407C with a 90/10% mixture of R32/R600A (by mass), in the second experiment, we find that the exit temperature of R407C from the evaporator of the heat exchanger after two hours of operation is 0.8°C, which is lower than the temperature in the first experiment at the same time. This difference is due to the different molecular compositions of the two refrigerants used in each experiment.

We also observe a rise in the exit temperatures during the third, fourth, and fifth hours, reaching up to the sixth hour of operation. Specifically, at the third hour, the temperature rises by 0.2°C, then increases to 1.5°C during the fourth hour, remaining constant at the same temperature until the fifth hour. During the sixth hour, it reaches its highest value at 1.9°C, after which it begins a gradual decrease during the last two hours of operation, reaching 1.3°C at the seventh hour and continuing to decrease until it reaches 0.4°C during the eighth hour.

When using R407C with R32, the refrigerant temperature at the exit of the heat exchanger two hours after system startup is 1.25°C. The temperature difference between R407C and the mixture (90/10% R32/R600A by mass) is 0.8°C, which is 0.45°C less than of the mixture. After eight hours of operation, the temperature difference is -0.5°C when using R407C with R32, and 0.4°C when using the mixture (90/10% R32/R600A by mass), which is 0.9°C less than R32. This difference is due to the different molecular compositions of the two refrigerants used in the two experiments.

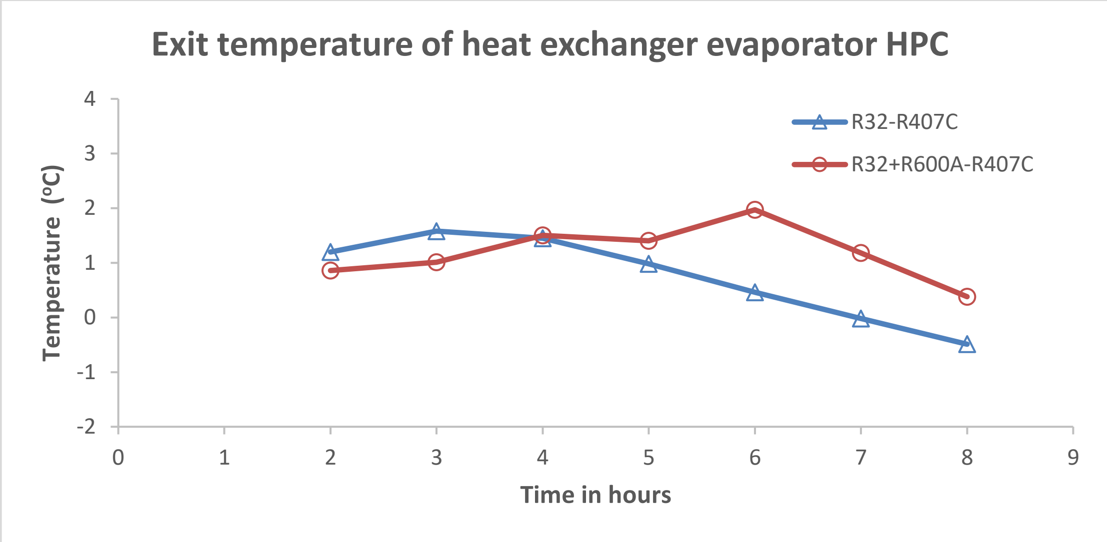

Figure 10 shows the relationship between the outlet temperature of the heat exchanger evaporator in HPC in both experiments.

5. Discussion:

- The differences in results between the two experiments are due to the different compositions of the refrigerants used.
- The results of this research demonstrate the importance of selecting materials that can withstand the expected temperatures while maintaining their thermal and mechanical properties. We also recommend continued research into new materials with higher thermal conductivity. The results help in determining the optimal dimensions of the heat exchanger to achieve the best performance under the expected operating conditions. They also encourage the development of innovative designs that increase the heat exchange surface area and reduce pressure loss.
- The results help in selecting suitable refrigerants for the required temperature range to achieve optimal efficiency. Therefore, we recommend continued research into new refrigerants with better thermal properties and a lower environmental impact. The results of this research encourage the analysis of the properties of the refrigerants used, such as thermal conductivity and viscosity, to interpret the results and improve performance. They also demonstrate the development of advanced control strategies to improve system performance under varying operating conditions. This research encourages the use of AI-based control systems to improve system efficiency and reduce energy consumption. The research findings improve the system's response to rapid temperature changes and analyze the impact of using rapid control systems to achieve better thermal stability, where both the added temperature and the added cooling were computer-controlled. The results identify operating conditions that reduce energy consumption by minimizing the temperature difference between the evaporator inlet and the condenser outlet in the heat exchanger. They also encourage the development of new technologies to reduce energy consumption in cascade refrigeration systems and improve the system's coefficient of performance (COP) by controlling the inlet and outlet temperatures of the heat exchanger.
- Recommendations for future studies include investigating other types of heat exchangers and cascade refrigeration systems, as well as the impact of other variables such as humidity and the use of new materials and advanced manufacturing techniques.

6. Conclusion:

The most important findings regarding the effect of inlet and outlet temperatures of the heat exchanger on a cascade refrigeration system are summarized as follows:

1) Effect of the temperature difference between the inlet temperatures of the evaporator and condenser of the heat exchanger: Increasing the inlet temperature of the condenser leads to an increase in the heat transfer coefficient, indicating an improvement in the heat transfer efficiency of the heat exchanger. This also leads to an increase in the overall efficiency of the heat exchanger, indicating an improvement in its heat transfer performance.
2) Effect of the temperature difference between the outlet temperatures of the evaporator and condenser of the heat exchanger: Effect on the coefficient of performance (COP): A decrease in the temperature difference between the outlet temperatures of the evaporator and condenser of the heat exchanger leads to an increase in the COP, indicating an improvement in the overall system efficiency in terms of the cooling-to-energy-consumption ratio.
3) Effect on cooling capacity: A high temperature difference between the outlet temperatures of the evaporator and condenser of the heat exchanger affects the cooling capacity of the system, negatively impacting the temperature of the main evaporator in the cycle.
4) Effect of Flow Rate and Heat Transfer Coefficient: Increasing the flow rate leads to an increase in the heat transfer coefficient, indicating improved heat transfer efficiency.
5) Reduced Pressure Loss: Increasing the flow rate affects pressure loss within the heat exchanger. Analysis of this effect shows that increasing the flow rate reduces pressure loss in the heat exchanger.
6) Effect of Refrigerant Type: Performance Comparison: Different refrigerant types result in performance variations, highlighting the importance of selecting the appropriate refrigerant for the required temperature range.
7) Optimal Operating Conditions: Keeping the heat exchanger clean, well-ventilated, and with minimal humidity ensures optimal operating conditions and achieves the best performance for the heat exchanger and the cascade refrigeration system.

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Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.