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ORIGINAL ARTICLE

A novel methodology for enhancing refrigeration performance using regenerative expansion in VCR system

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Abstract

Refrigeration is indispensable for a wide array of applications, ranging from household cooling to industrial freezing. Traditionally, mechanical methods have been utilized to transfer heat between different temperature reservoirs. However, the quest for energy-efficient and low-maintenance systems has propelled innovations in refrigeration technology. One such innovation involves optimizing the utilization of flash gas within the system. This gas, if allowed to traverse the evaporator, can gradually deteriorate its components, resulting in heightened maintenance demands. To mitigate this issue, our modified system integrates a flash chamber downstream of the expansion device, such as a capillary tube. This chamber effectively segregates the flash gas from the liquid refrigerant. In our design, the separated flash gas is channeled into a shell and tube heat exchanger positioned adjacent to the condenser. Here, the flash gas circulates the tubes of the heat exchanger, efficiently extracting heat from the refrigerant flowing within the tubes. This strategic utilization of flash gas not only enhances the overall efficiency of the refrigeration system but also minimizes wear and tear on the evaporator components. Moreover, the outlet of the flash gas is connected to the inlet of the compressor, completing the cycle. By harnessing flash gas in this manner, our modified system not only enhances energy efficiency but also reduces maintenance requirements, offering a sustainable and economically viable solution for refrigeration needs. This innovative approach underscores the transformative potential of system modifications in advancing refrigeration technology, in line with the growing demand for environmentally friendly and efficient cooling solutions.

1. Introduction

The journey of refrigeration technology traces back to the pioneering work of Jacob Perkins and his revolutionary "Ice Machine" in 1834, marking the dawn of the modern era of refrigeration. Perkins' creation laid the groundwork for the simple vapour compression refrigeration (VCR) cycle, a fundamental concept that has since become indispensable in catering to the diverse refrigeration and air-conditioning needs of society [1-12]. Since its inception, the VCR cycle has remained a steadfast cornerstone of refrigeration technology, serving myriad applications across various industries. From preserving food and medicines to maintaining comfortable indoor environments, the versatility of the VCR cycle has significantly impacted human life, enhancing convenience, comfort, and health standards worldwide. However, as

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technology has advanced, so too have the demands and expectations placed upon refrigeration systems [9-22]. One prominent trend in recent years has been the relentless pursuit of miniaturization, driven by the need for compactness and efficiency in a wide range of applications. This shift towards smaller scales has necessitated adaptations and refinements to the traditional VCR cycle, spurring innovation in component design, system configuration, and operational strategies. Efforts to miniaturize the VCR cycle have been particularly pronounced in industries such as space exploration, aviation, military operations, automotive manufacturing, and biomedical research, where space constraints, portability, and energy efficiency are paramount [17-24]. The quest for compact refrigeration solutions capable of delivering high performance in demanding environments has spurred a wave of research and development aimed at optimizing every aspect of the VCR cycle.

In this context, the evolution of refrigeration technology has been characterized by a relentless march towards greater efficiency, reliability, and sustainability. Researchers and engineers have embraced the challenge of scaling down the VCR cycle while maintaining, and even enhancing, its performance characteristics [18]. By leveraging advances in materials science, thermodynamics, and control systems, they have pushed the boundaries of what is possible, ushering in a new era of compact and efficient refrigeration solutions. In the face of evolving societal needs and technological capabilities, the VCR cycle continues to evolve, adapting to new challenges and opportunities. From micro refrigerators capable of ultra-low temperatures to portable air-conditioning units for remote applications, the potential applications of miniaturized VCR technology are vast and varied [14]. As we look towards the future, the journey of refrigeration technology is far from over, with continued innovation driving progress towards a more sustainable and interconnected world.

The focal point of this research lies in the enhancement of performance and longevity within simple VCR systems, achieved through the innovative design and analysis of a regenerative expansion device. This endeavor aims to harness the potential of flash gas utilization within the VCR cycle by meticulously selecting appropriate components and optimizing heat transfer processes [10]. Such modifications not only hold the promise of elevating overall system efficiency but also augment the durability of individual components, thereby effectively addressing key challenges prevalent in refrigeration technology. Refrigeration systems encompass a vast spectrum of applications, each characterized by distinct demands and requirements. Sectors such as space exploration, aviation, military operations, automotive manufacturing, and biomedical research heavily rely on refrigeration technology. Particularly noteworthy is the advent of micro refrigeration systems, which have revolutionized hot spot applications by offering compactness, high coefficients of performance (COP), ultra-low cold plate temperatures, and reduced mass flow rates [20]. Amidst this diverse landscape, this research seeks to delve deeply into the intricacies of the VCR cycle, exploring its adaptability and optimization potential across various industries. By comprehensively understanding the underlying principles and challenges inherent in refrigeration technology, novel solutions can be cultivated to address contemporary needs and propel the field towards heightened efficiency and sustainability [4]. Through a blend of empirical analysis and theoretical modelling, this study endeavors to contribute meaningfully to the ongoing discourse surrounding the advancement of refrigeration systems, ultimately benefiting society as a whole by ushering in a new era of enhanced performance and longevity in refrigeration technology.

2. Literature Review

The investigation of the expansion device within a simple VCR system is imperative for unravelling the parameters that can bolster the system's overall performance. This study delved into the realm of capillary tubes, scrutinizing three distinct configurations: helical coiled, straight coiled, and serpentine coiled. The comprehensive analysis sought to discern the impact of configuration variations and capillary tube diameters on the system's overall efficacy. Notably, the experimental findings unveiled intriguing insights. It was observed that the straight configuration boasted the maximum mass flow rate, while the helical coiled configuration exhibited the highest refrigeration effect. Conversely, the helical coiled configuration showcased the lowest mass flow rate, with the straight coiled configuration lagging behind in refrigeration effect [1]. Intriguingly, as the system load increased, the compressor work exhibited a discernible reduction. Furthermore, the diminution of capillary tube diameter correlated with an augmentation in the system's mass flow rate, albeit at the expense of diminished refrigeration effect production. The elucidation of capillary tube geometry's influence on refrigeration system performance emerges as a critical necessity [7]. A meticulous review of pertinent literature underscores the pivotal role played by geometric parameters such as capillary tube length, bore diameter, coil pitch, number of twists, and twisted angle. The literature review illuminates avenues for further exploration, advocating the utilization of physical models and mathematical modelling concepts to delve deeper into these parameters' intricate dynamics. Moreover, it posits that the optimization of these parameters holds immense potential for augmenting the refrigeration system's performance, heralding a paradigm shift towards heightened efficiency and efficacy. In essence, this research underscores the paramount importance of scrutinizing the expansion device within VCR systems [6]. By comprehensively dissecting the influence of capillary tube geometry and configuration variations, this study not only unravels crucial insights but also paves the way for future advancements in refrigeration technology. With a relentless pursuit of optimization and innovation, the potential to revolutionize refrigeration systems and usher in an era of enhanced performance and sustainability beckons.

The research conducted by Hirendra Kumar Paliwal and

Keshav Kant delves into the intricate dynamics of capillary tube geometry within VCR systems. Their paper presents a comprehensive flow model tailored to design and evaluate the performance of helical capillary tubes, aiming to closely simulate real-world scenarios. Central to their model is the assumption of homogeneous flow of two-phase fluid through the adiabatic capillary tube, incorporating second law restrictions to ensure accuracy [5]. The model thoroughly examines several parameters, including the pressures in the condenser and evaporator, the rate of refrigerant flow, the degree of sub-cooling, the diameter of the tube, the internal roughness of the tube, as well as the pitch and helix diameter. By exploring the impact of these parameters on the length of the capillary tube, the researchers seek to offer valuable insights into optimizing refrigeration system design. Theoretical predictions of helical capillary tube lengths for R-134a refrigerant are compared against experimental data, revealing a remarkable alignment with a majority of predictions falling within 10% of the experimental values [4]. This close correspondence underscores the efficacy of the developed flow model and its potential to inform practical applications, paving the way for advancements in refrigeration system efficiency and performance optimization [3].

In their research, Nishant P. Tekade and Dr. U.S. Wankhede delve into the selection and optimization of spiral capillary tubes for refrigeration appliances, aiming to understand the nuanced effects of various parameters on the mass flow rate of refrigerant [2]. They explore how changes in capillary tube dimensions, such as diameter, coil pitch, and length, as well as inlet conditions of the refrigerant, including degree of sub-cooling and inlet pressure, influence the system's performance. Of particular interest is the investigation into the coiling effect of spiral capillary tubes on the mass flow rate of refrigerant under the same cooling load. The coil pitch emerges as a crucial characteristic coiling parameter, with its impact on the mass flow rate of refrigerant across several spiral capillary tube test sections playing a vital role in performance assessment. The study also delves into the influence of tube diameter, length, coil pitch, and inlet conditions on the mass flow rate of refrigerant through spiral capillary tubes, shedding light on their potential impact on system efficiency [2]. Furthermore, the researchers explore the implications of the coiling effect of capillary tubes on the COP of the system, recognizing the need for compact refrigeration systems in current trends. They highlight the efficiency of spiral capillary tubes in refrigeration appliances, suggesting their potential applicability in air conditioning systems as well. By meticulously examining the intricacies of spiral capillary tube design and operation, this research offers valuable insights into optimizing refrigeration system performance and compactness, contributing to advancements in the field of refrigeration technology.

In the investigation led by Mohammed Bilal, Ganpat Lal, and Rakesh, the focus lies on understanding the flow characteristics of refrigerants through capillary tubes and exploring the suitability of different working fluids for refrigeration systems. Specifically, the study delves into the usage of R600a refrigerant in household refrigerators, considering its distinct characteristics. It is widely acknowledged in existing literature that capillary tubes, when configured in a turn shape, can enhance efficiency. Building upon this understanding, the researchers aim to evaluate the efficacy of replacing conventional refrigerants like R12 and R22 with R600a, primarily due to its lower global warming potential and reduced ozone depletion potential [4]. Notably, R600a is found to require a smaller diameter hole compared to what is typically specified in literature, which holds significant implications for system design and efficiency. By advocating for the adoption of R600a in household refrigerators and highlighting its advantages over traditional refrigerants, this research contributes to efforts aimed at mitigating environmental impact and enhancing the sustainability of refrigeration systems. Moreover, the findings underscore the importance of considering alternative refrigerants and optimizing system configurations to achieve improved performance and environmental sustainability in the realm of refrigeration technology. In the study spearheaded by Rupesh Ingole and P. T. Nitnaware, the primary objective is to enhance the performance of domestic refrigerators. The research involves an examination of three refrigerants (R134a, R290, and R404a) in conjunction with three different inner diameters (0.3mm, 0.45mm, and 0.50mm) of capillary tubes. The study compares the performance parameters of the refrigeration system, considering various refrigerants and capillary tube diameters, while maintaining constant ambient temperature and compressor discharge across all test conditions. The results reveal that the coefficient of performance (COP) of the system is highest when using a capillary diameter of 0.30mm for all three refrigerants, with larger diameters leading to a decrease in COP. Interestingly, while the refrigeration effect values did not exhibit a consistent trend, the highest COP values for R134a, R290, and R404a were recorded for a capillary diameter of 0.30mm, indicating the significance of capillary tube diameter in system performance optimization [5]. On the other hand, Ishaan Dua, Prerna Choudhary, Shubham Soni, and Sheila Mahapatra focus on the design and development of a system that serves as both a temperature sensor and a warning system. The system's primary function is to continuously monitor the temperature of a machine, compare it to a predefined limit, and automatically shut down the machine if the temperature exceeds or falls below the set threshold. This system proves particularly useful for machines with a high dependence on specific temperature ranges. The research paper details the system's requirements, outlining the conceptual framework behind the project's development. Additionally, it covers the hardware and software components necessary for designing the system, including a detailed description of the project's basic design and block diagram. The design is divided into sub-circuits covering the bridge rectifier, relay driver, and A to D converter, with comprehensive software simulations conducted to validate the design's functionality. By presenting a robust system for temperature monitoring and control, this research contributes to enhancing operational safety and reliability in various industrial settings.

3. VCR System

The VCR cycle has four main components. They are the compressor, the condenser, the expansion valve and the evaporator. The major function of a refrigerator is to create a cold region by rejecting heat to the ambience as illustrated in Fig. 1. The basic components of a VCR cycle are shown in Fig. 2.

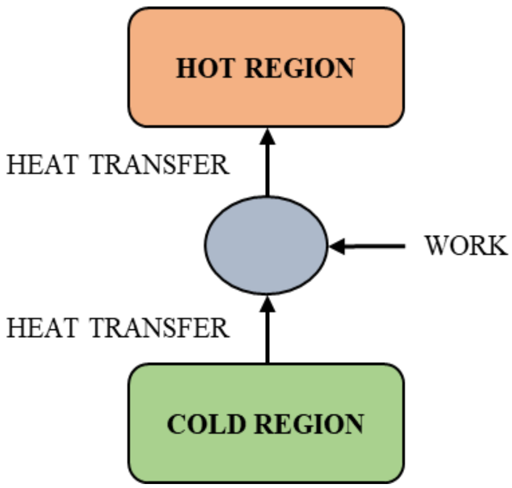

Figure 1: Refrigeration process

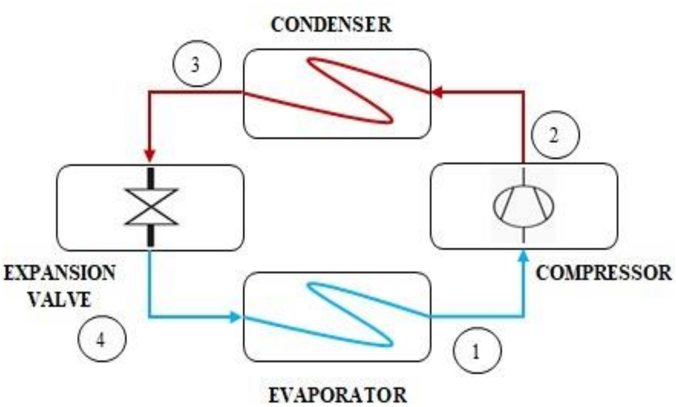

Figure 2: Basic components of a simple VCR cycle

The functions of the four main components of a VCR cycle can be summarized as follows:

Process 1-2 (compression process): The low-pressure saturated vapour is compressed to a high pressure superheated vapour under constant entropy value.

Process 2-3 (condensation process): The high pressure superheated vapour is desuperheater to saturated vapour state and then condenses into a saturated liquid state under constant pressure.

Process 3-4 (expansion process): The high-pressure saturated liquid is expanded to a low pressure and low temperature liquid-vapour mixture at constant enthalpy.

Process 4-1 (evaporation process): The low pressure two phase (liquid-vapour) mixture evaporates to saturated vapour under constant pressure.

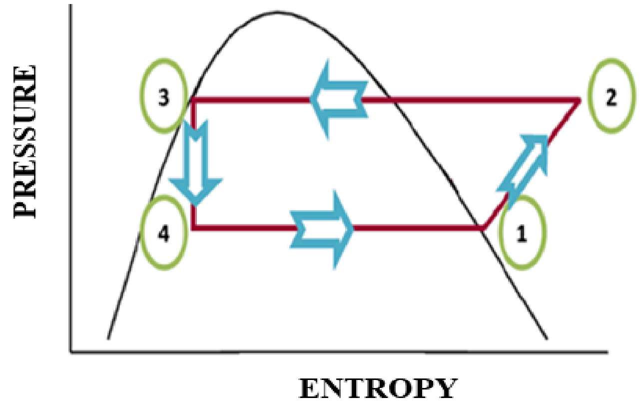

Figure 3: Pressure vs enthalpy (ideal VCR cycle)

4. Need of Modification in VCR Cycle

A simple VCR cycle consists of compressor, condenser, expansion valve and evaporator. The performance of a refrigerator is measured in term of COP. So, to increase performance of the system, COP of system should be increased. The COP is ratio of refrigeration effect in evaporator to work done in compressor. In order to increase COP, either evaporating effect should be increased, or compressor work should be reduced or both. Reducing the condenser pressure and temperature increases the refrigeration prompt and reduces the compressor's input work, thereby enhancing the coefficient of performance (COP). Similarly, raising the stress and temperature of the evaporator lessens the work input, fosters the refrigeration influence, and boosts the COP in a VCR system. This study focuses on enhancing the refrigeration effect in evaporators, which can be achieved through either superheating the vapor refrigerant or subcooling the liquid refrigerant. As the wet refrigerant exits the condenser, it is in a liquid state. It then enters the expansion valve, where the high-pressure and high-temperature liquid refrigerant is converted into a low-pressure and low-temperature liquid-vapor mixture. In the evaporator, only the liquid part of this mixture is effective in producing the refrigeration effect, while the vapor part does not contribute to this process. Therefore, in this project, the vapor part is separated from the mixture, allowing the maximum amount of liquid refrigerant to pass through the evaporator, thereby increasing the refrigeration effect.

During the passage of the liquid-vapor mixture into the expansion valve, flash gas is spontaneously generated. Flash gas refers to the vapor part of the liquid-vapor mixture. The presence of flash gas in the liquid line reduces the efficiency of the refrigeration cycle and can lead to improper functioning of several expansion systems, increasing superheating in the evaporator. This is typically seen as an undesired condition resulting from a mismatch between the system's volume, pressures, and temperatures necessary for the refrigerant to remain in a liquid state. However, the use of internal heat exchangers can improve condensation and prevent gas from entering the liquid lines. The primary consequence of flash gas in the liquid piping is a net loss of refrigeration capacity, which occurs in two main ways. Firstly, the expansion valve may not function properly when a liquid-vapor mixture, including refrigerant with flash gas, is injected. When the refrigerant changes from liquid to gas, it absorbs heat from the surroundings, including mechanical work from the compressor. One of the methods of increasing the refrigeration effect is to achieve the expansion process as possible as close to saturated liquid line. So this project mainly focuses on the expansion process in the capillary tube. A capillary tube serves as a narrow conduit for expanding the fluid in a system. It maintains a pressure differential between its entry and exit points equivalent to that between the condenser and the evaporator.

Compared to other expansion devices, the capillary tube offers advantages such as simplicity, cost-effectiveness, and the ability to initiate compressor operation with low torque due to pressure equalization when the system is inactive. Unlike thermostatic expansion valves, capillary tubes lack moving parts. The increasing availability of versatile compressors, improved refrigerants, and nearly leak-proof systems has made capillary tubes an appealing and widely adopted choice. A fundamental refrigeration and air-conditioning system comprise two heat exchanging devices and two pressure variations. As the diameter of the capillary tube decreases, the evaporator temperature decreases. The mass flow rate of refrigerant in the system tends to increase, while the refrigeration effect produced tends to decrease.

5. Case Study

The core of the vapor compression refrigeration (VCR) system lies in its meticulously crafted components, each boasting precise specifications tailored to enhance functionality. Anchoring the system is the Shriram model no. SR 412 compressor, renowned for its robust performance with a cooling capacity of 932 kCal/hr and a displacement of 11.26 cc/rev, operating at a swift 2800 rpm. Complementing this powerhouse is an air-cooled condenser, strategically designed to efficiently dissipate heat from the compressed refrigerant. Sporting a condensed tube diameter of 0.6 cm and extending over a length of 12.6 m, the condenser thrives within a compact 30×35×10 cm frame. Moreover, the system offers versatility in expansion devices, presenting options like the capillary tube or thermostatic expansion valve, enabling precise control over refrigerant flow dynamics. With R12 refrigerant fueling its operations, renowned for its superior cooling efficacy, this system epitomizes a harmonious blend of performance and reliability, catering adeptly to a spectrum of refrigeration requirements.

5.1 Simple VCR System

The simple vapor compression refrigeration cycle is comprised of four fundamental components: compressor, condenser, expansion device, and evaporator as shown in figure 4. These components form the backbone of the system and facilitate its operation through four basic processes, as explained in the preceding chapter. The test setup for the simple VCR system is designed to emulate this cycle, adhering closely to its fundamental components and processes.

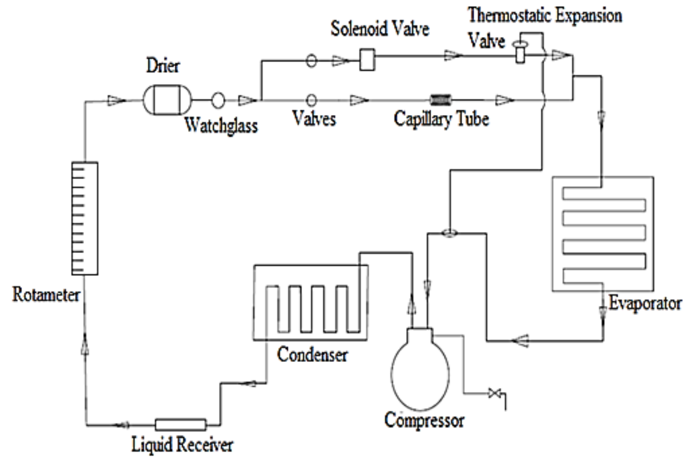

Figure 4: Test setup of simple VCR system

5.1.1 Procedure for finding coefficient of performance of refrigeration system

To find the COP of a simple VCR system, the procedure needs to be followed. Below are some observed values from Table1.
Te, Tc, n, C

Where, Te = Evaporator temperature (0C)
Tc = Compressor temperature (0C)
n = Isentropic efficiency of compressor
C = Capacity of VCR system (Ton)

Obtained Values:

The following values are obtained from the property chart for R-12.

(a) Temperatures: - T1, T2, T3, T4
(b) Enthalpies: - h1, h2, h3, h4

Where, Points 1- Exit of evaporator.
Point 2- Entrance of condenser
Point 3- Exit of condenser
Point 4- Entrance of evaporator

(c) Performance parameters- RE, W, COP, $\dot{m}$

Where, RE = Refrigeration effect
W = Work done by compressor
COP = Coefficient of performance of VCR system
$\dot{m}$ = Mass flow rate of refrigerant

5.1.2 Calculations for Capillary Tube

Note: T: Temperature in °C, t: Temperature in K,
c: Capacity in kW, C: Capacity in ton

Finding enthalpies of different points:

T1 = Te
T3 = Tc
te = Te+273
tc = Tc+273
t1 = T1+273
t3 = T3+273

$c = C * 3.5(kW)$

P1 = Saturation pressure corresponding to Te
P2 = Saturation pressure corresponding to Tc
P3 = P2 and P4 = P1
h1 = hg at pressure P1
h3 = hl at pressure P2

$$s1 = s1g + Cp1g * log\left(\frac{t1}{te}\right) \quad (1)$$

s2 = s1

$$t2 = tc * e\^{}(((s1 - s2g)/Cp2g)) \quad (2)$$

$$T2 = t2 - 273$$

$$h2 = h2g + Cp2g * (T2 - Tc) \quad (3)$$

$$h3 = h3l - Cp2l * (Tc - T3) \quad (4)$$

$$h4 = h3$$

COP calculations:

$$W = h2 - h1$$

$$COP = RE/W \quad (5)$$

$$RE = h1 - h4$$

$$m^{\cdot} = (c)/RE$$

$$x\_4 = ((h3 - h4l))/((h1g - h4l)) \quad (6)$$

The following are the calculations for COP when capillary tube is used as expansion device in simple VCR system.
Values obtained from Table 1.

Pc = 1.068 MPa
Pe = 0.2274 MPa
Tc = 420C
Te = -80C

Table 1: Reading Taken for Capillary

S. No	Description	Symbol	Units	Readings		
				1	2	3
1	Condenser pressure	P_c	MPa	1.06	1.06	1.06
2	Evaporator pressure	P_e	MPa	0.22	0.22	0.22
3	Mass flow rate of refrigerant	$\dot{m}$	g/s	5.02	5.02	5.02
4	Condenser inlet temperature	T_1	^{0}C	53	56	56
5	Condenser outlet temperature	T_2	^{0}C	28	28	28
6	Evaporator inlet temperature	T_3	^{0}C	-5	-6	-7
7	Evaporator outlet temperature	T_4	^{0}C	5	4	1
8	Compressor energy – Time for 10 rev	t_c	sec	76	76	76
9	Compressor current	A	amp	3	3	3
10	Compressor voltage	V	volt	230	230	230
11	Calorimeter temperature	T_5	^{0}C	4	5	7
12	Heater energy – Time for 10 rev	t_h	sec	288	62	37

A. Carnot COP

T_l: Saturation temperature at low pressure in K = 265K
T_h: Saturation pressure at high pressure in K = 315K

$$COP_{carnot} = \frac{T_l}{T_h - T_l} \quad (7)$$

$$= \frac{-8 + 273}{42 + 8} = 5.3$$

B. Theoretical COP

Sketch theoretical cycle on p-h diagram and obtained the enthalpies at corresponding state points (h_1, h_2, h_3, h_4).

h_1 =357.5 kJ/Kg
h_2 =385 kJ/Kg
h_3 =225 kJ/Kg
h_4 =225 kJ/Kg

$$COP_{theo} = \frac{h_1 - h_4}{h_2 - h_1} \quad (8)$$

$$= \frac{357.5 - 225}{385 - 357.5} = 4.81$$

C. Actual COP

Actual refrigerating effect is equals to

$$COP_{act} = \frac{RE}{W_{act}} \quad (9)$$

$$= \frac{\left[\frac{10*3600}{288*1200}\right]}{\left[\frac{10*3600}{76*1200}\right]}$$

$$= 3.7895$$

5.2 Modified VCR System

A modified vapor compression refrigeration (VCR) system with a regenerative expansion device. Figure 5 illustrates the block diagram of the modified VCR system, which includes the design of the regenerative expansion device. The goal is to enhance system efficiency by optimizing the utilization of flash gas within the VCR cycle. Through careful component selection and heat transfer process optimization, the regenerative expansion device aims to improve overall system performance and sustainability.

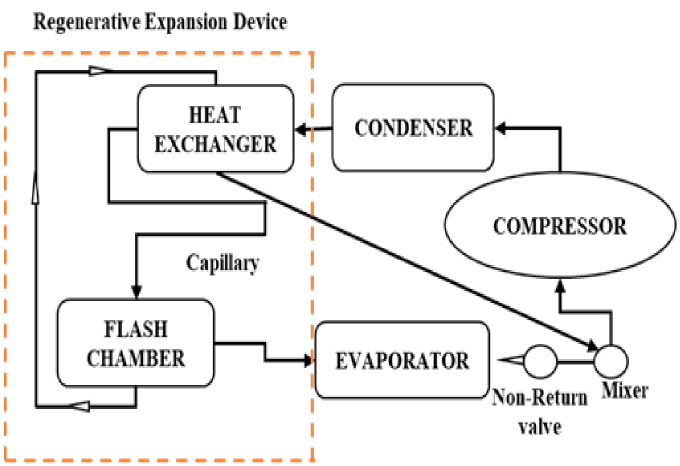

Figure 5: Block diagram of modified VCR system

The input parameters for the system are as follows: a capacity of 1 ton, an evaporator temperature of 4°C, and a condenser temperature of 40°C. The assumptions made include a compressor efficiency of 100% and a heat exchanger effectiveness of 60%. These parameters and assumptions provide the basis for the analysis and design of the refrigeration system. The vapor compression refrigeration system comprises essential components: compressor, condenser, expansion device, and evaporator. However, in a modified system, the inclusion of a flash chamber and heat exchanger enhances its functionality. The compressor plays a pivotal role in maintaining low pressure and temperature in the evaporator, allowing the refrigerant to extract heat from the refrigerated space. It accomplishes this by compressing the refrigerant, thereby increasing its pressure and temperature.

The condenser, another vital component, receives the refrigerant in a superheated state and desuperheats it before condensing it by rejecting heat to an external medium. The expansion device, in conjunction with the flash chamber and heat exchanger, constitutes the regenerative expansion device, optimizing the refrigeration process. Subsequent to condensation, the heat exchanger facilitates subcooling, crucial for enhancing system efficiency. The capillary tube induces a pressure drop in the refrigerant, leading to a temperature decrease, essential for effective cooling. The flash chamber separates liquid from vapor refrigerant, ensuring only liquid refrigerant enters the evaporator. The flash gas produced undergoes heat exchange in the heat exchanger, resulting in subcooling. The efficiency of the heat exchanger dictates the extent of heat exchange, with higher effectiveness yielding optimal results. After expansion, refrigerant cools in evaporator, creating desired refrigerating effect, improving system efficiency.

5.2.1 Design of Regenerative Expansion Device

A modified system with regenerative expansion device designed using evaporator temperature and condenser temperature as 40C and 400C respectively. Following are the values acquired from MATLAB program.

Condenser pressure	=	1.0166 MPa
Evaporator pressure	=	0.3377 MPa
Refrigeration effect	=	154.6276 kJ/kg
Work done in compressor	=	23.5567 kJ/kg
Theoretical COP	=	6.5641
Carnot COP	=	7.6944
h1	=	405.9788 kJ/kg
h2	=	429.5355 kJ/kg
h3	=	251.3512 kJ/kg
h4	=	251.3512 kJ/kg

5.2.2 Design of Capillary Tube

The expansion process within the capillary tube induces changes in the properties of the refrigerant. To facilitate calculations, this process is segmented into nine sections, with each section representing a node. These nodes correspond to specific points along the capillary tube, where the properties of the refrigerant are assumed to remain constant. This approach allows for accurate analysis and calculation of the expansion process, leveraging known inlet and outlet temperatures of the capillary tube, as depicted in Figure 6. By dividing the process into discrete sections, the variations in refrigerant properties can be effectively accounted for, ensuring precise calculations and reliable results.

5.2.3 Calculations

Following steps are done to find out dimensions of capillary tube such as length and diameter.

(a) Calculation of Dryness Fraction

Following values are taken from property chart of R-12:

(1) Enthalpies- hl, hg, h3

hl- Enthalpy of saturated liquid refrigerant in kJ/kg
hg -Enthalpy of saturated vapour refrigerant in kJ/kg
h3- Enthalpy of refrigerant = 256.41 kJ/kg

(2) Saturation Pressures (MPa)

To find: dryness fraction -x

To determine the dryness fraction at various nodes along the capillary tube, the enthalpy of the liquid (hl) and the enthalpy of the vapor (hg) at ten nodes across nine sections are required. In the second column of Table 2, temperatures are segmented to match the number of nodes. Corresponding saturation pressures are listed in the succeeding column.

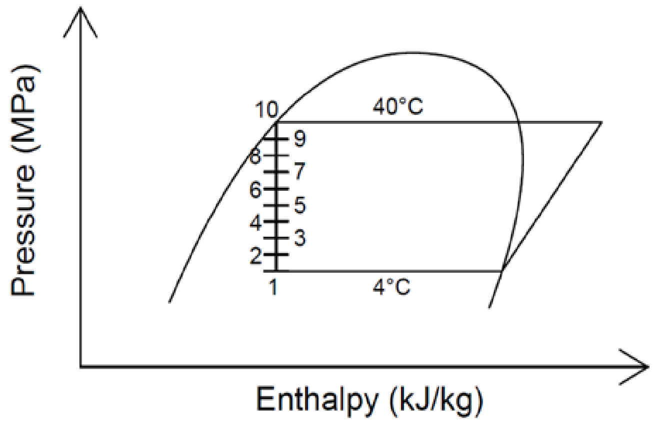

Figure 6: Sections of expansion process

Pressure differentials across the sections are provided in the fourth column. Enthalpy values (hl and hg) are obtained based on the saturation pressures at each node using the refrigerant chart for R-12 (refer to Table 2 for specific values). With ten pressures at ten nodes, there are nine pressure differences corresponding to the nine sections of the expansion process. As depicted in Figure 7, the dryness fraction at the tenth node is zero, as this node falls on the saturated liquid line of the refrigerant. The dryness fraction increases progressively from the condenser temperature of 40°C to the evaporator temperature of 4°C.

Calculation of dryness fraction is as below:

$$x = \frac{(h_3 - h_l)}{(h_g - h_l)}$$

(b) Calculation of Density and Viscosity of Mixture

Following values are taken from property chart of R-12

- µl-dynamic viscosity of liquid refrigerant (10^{-6} N.m/s^2)
- µg-dynamic viscosity of gaseous refrigerant (10-6 N.m/s2)
- ρl -Density of liquid refrigerant (kg/m^3)
- vg- Specific volume of gaseous refrigerant (m^3/kg)

To Find:

- µ- Dynamic viscosity of mixture (10^{-6} N.m/s^2)
- ρ -Density of mixture (kg/m3)

Calculations

To find out properties of mixture of gaseous and liquid refrigerant, properties of pure gaseous and pure liquid refrigerant are used (refer Table 3 for values).

(1) Dynamic viscosity of mixture of gaseous and liquid refrigerant is calculated as follows

Table 2: Dryness Fraction at Different Nodes in Capillary Tube

Node No	T (0C)	P (MPa)	Δp (MPa)	hl (kJ/kg)	hg (kJ/kg)	x
1	4	0.3376	0.05	205.4	400.92	0.2609
2	8	0.3876	0.0554	210.84	403.2	0.2369
3	12	0.443	0.0612	216.33	405.43	0.212
4	16	0.5042	0.0675	221.87	407.61	0.186
5	20	0.5717	0.074	227.47	409.75	0.1588
6	24	0.6457	0.0811	233.12	411.82	0.1303
7	28	0.7268	0.0886	238.84	413.84	0.1004
8	32	0.8154	0.0964	244.62	415.78	0.0689
9	36	0.9118	0.1048	250.48	417.65	0.0355
10	40	1.0166	-	256.41	419.43	0

Table -3: Density and Viscosity of Mixture

Node No.	µl (10-6 N.m/s2)	µg (10-6 N.m/s2)	µ (10-6 N.m/s2)	ρl (kg/m3)	vg (m3/kg)	Mixture Sp. V. (m3/kg)	ρ (kg/m3)
1	257.6	10.9	193.24	1281.4	0.06039	0.001051	951.41
2	244.9	11.06	189.5	1267.9	0.0528	0.001029	972.02
3	233.9	11.23	186.7	1254	0.04633	0.001007	992.79
4	221.5	11.4	182.43	1239.8	0.04078	0.000986	1013.81
5	210.7	11.58	179.09	1225.3	0.036	0.000966	1035.17
6	200.4	11.76	175.81	1210.5	0.0318	0.000946	1056.83
7	190.5	11.95	172.57	1195.2	0.02826	0.000927	1078.75
8	181.1	12.14	169.46	1179.6	0.02513	0.000908	1101.09
9	172.1	12.34	166.43	1163.4	0.02238	0.00089	1123.72
10	163.4	12.55	163.4	1146.7	0.01997	0.000872	1146.7

$$\mu = (1 - x) \times \mu_l + x \times \mu_g \quad (10)$$

Density of mixture of gaseous and liquid refrigerant is calculated as follows:

$$\rho = (1 - x) \times \rho_l + x \times \rho_g \quad (11)$$

(c) Calculation of Capillary Length Required

Mass flow rate of refrigerant is calculated by using capacity of refrigeration system and length of capillary is to be found out for given diameter of the capillary tube.
Mass flow rate, m=0.02264kg/s and Diameter, d=0.006m
To find:

- V : Velocity at different nodes
- Vm : Mean velocity across different sections
- Re : Reynolds Number at different nodes
- f : Friction factor at different nodes
- L : Total Length of capillary tube

Table 4: Capillary Length Required

Node No.	V (m/s)	Re	f	Vm (m/s)	ΔL (m)
1	8.42	248750.7	0.014329	8.331	0.621
2	8.24	253652.1	0.014259	8.156	0.706
3	8.07	257454.2	0.014206	7.986	0.8
4	7.9	263487	0.014124	7.821	0.906
5	7.74	268406.5	0.014059	7.66	1.019
6	7.58	273401.4	0.013994	7.503	1.145
7	7.43	278535.9	0.013929	7.351	1.283
8	7.28	283651	0.013866	7.203	1.431
9	7.13	288812.8	0.013804	7.058	1.595
10	6.99	294173.4	0.01374	-	-

Velocity (V) at a given node is determined by dividing the mass flow rate by the density of the refrigerant mixture at that node, and then dividing the result by the cross-sectional area of the capillary tube. The mean velocity (Vm) across a section is calculated as the average of velocities at the end nodes of that section. Reynolds number (Re) and friction factor (f) are subsequently calculated using the prescribed formulas (refer to Table 4 for specific values).

Velocity: $V = \frac{\dot{m}}{\rho \times A}$ (12)

Reynolds number: $Re = \frac{\rho v d}{\mu}$ (13)

Friction factor: $f = \frac{64}{Re}$ (14)

Head loss due to friction: $h_f = \frac{f \times \Delta L \times v^2}{2 \times g \times d}$ (15)

Pressure drops: $\Delta P = \rho \times g \times h_f$ (16)

$\Delta P = \rho \times g \times \frac{f \times \Delta L \times v^2}{2 \times g \times d}$ (17)

Length of capillary section

$\Delta L = 2 \times d \times \frac{\Delta P}{f \times \rho \times v^2}$ (18)

Total length of capillary tube is calculated by taking sum of lengths of all sections.
Dimensions of capillary tube: -
Length = 9.5055 m
Diameter = 0.006 m

(d) Design of Flash Chamber

The next part in designing of modified system with regenerative expansion device is design of flash chamber. The following values are obtained from the calculations done in design of capillary tube.

$\dot{m}$ = 0.02264 kg/s

Density at evaporator outlet

$\rho = 951.41\ kg/m^3$

$Q = \frac{\dot{m}}{\rho}$

$Q = 0.00002379\ m^3/s$

Assume refrigerant stays in flash chamber for ten seconds.
Volumetric capacity of flash chamber = $0.0002379\ m^3$
Item number - 470063
Dimensions of flash chamber: -
Diameter = 152 m and Length = 387 mm

(e) Design of Heat Exchanger

To find out the dimensions of heat exchanger to obtain desired heat exchange following values are required,

- Mass flow rate of hot liquid refrigerant ($\dot{m}_l$) = 0.02422kg/s
- Mass flow rate of cold gaseous refrigerant ($\dot{m}_g$) = 0.00569kg/s
- Inlet temperature of hot liquid refrigerant = 40^0C
- Inlet temperature of cold gaseous refrigerant = 40C
- Specific heat capacity of hot liquid refrigerant (C_{pl})= 1.1322kJ/kg.K
- Specific heat capacity of cold gaseous refrigerant (C_{pg}) = 0.640kJ/kg.K

The primary goal of the heat exchanger is to lower the temperature of the saturated liquid refrigerant exiting the condenser. This is accomplished by utilizing the cold gaseous refrigerant obtained at the outlet of the flash chamber. In order to significantly enhance the refrigerating effect within the modified system, a temperature drop of 10°C across the hot liquid refrigerant is considered. Therefore, the temperature of the liquid refrigerant at the outlet of the heat exchanger is set at 303 Kelvin (K). Subsequent calculations proceed accordingly.

$Q_l = \dot{m}_l \times C_{pl} \times \Delta T_l$ (19)

$= 0.02422 \times 1.1322 \times 10$

$= 0.2742\ Kj$

$Q_g = \dot{m}_g \times C_{pg} \times \Delta T_g$ (20)

$Q_l = Q_g$
$0.2742 = 0.00569 \times 0.640 \times \Delta T_g$
$\Delta T_g = 15.3°C$
$\Delta T_1 = 40 - 19.3$
$\Delta T_1 = 20.7°C$
$\Delta T_2 = 30 - 4$
$\Delta T_2 = 26°C$

$$LMTD = \frac{\Delta T_1 - \Delta T_2}{\ln \frac{\Delta T_1}{\Delta T_2}} \quad (21)$$

$LMTD = 27.22\ °C$

$$Q_l = U \times A \times LMTD \quad (22)$$

$0.2742 \times 1000 = 113 \times A \times 27.22$
$A = 0.089145 m^2$

$$A = \pi \times d \times l \quad (23)$$

Assume, d = 11 mm
$0.089145 = \pi \times 0.011 \times l$
l = 2.57 m
Dimensions of heat exchanger: -
Total length of tube = 2.57 m and Diameter of tube= 11 mm

6. Analysis of Modified System

After establishing the initial design parameters for the refrigeration system based on predefined values, a comprehensive analysis of the modified VCR system is conducted across a range of conditions. This analysis facilitates the calculation of the COP for the modified system under varying scenarios. Concurrently, the COP for the conventional simple VCR system is also computed for these same conditions. Following this analysis, a thorough comparison is undertaken between the performance metrics of the simple and modified refrigeration systems. This comparative evaluation aims to ascertain the efficacy and efficiency enhancements achieved through the modifications introduced in the VCR cycle.

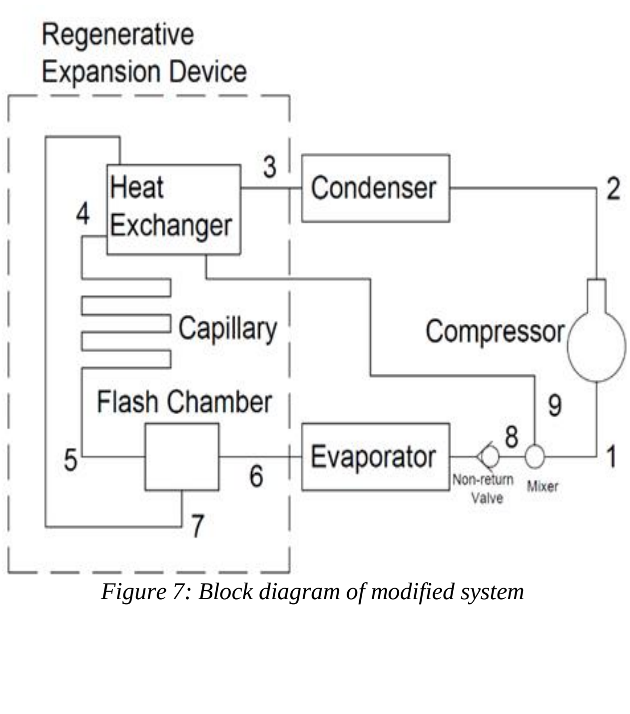

Figure 7: Block diagram of modified system

The comparative assessment is visually represented in Figure 8, which provides an illustrative overview of the performance disparities between the two systems. Additionally, the block diagram of the modified VCR system, delineating key points at various locations within the system, is depicted in the same figure.

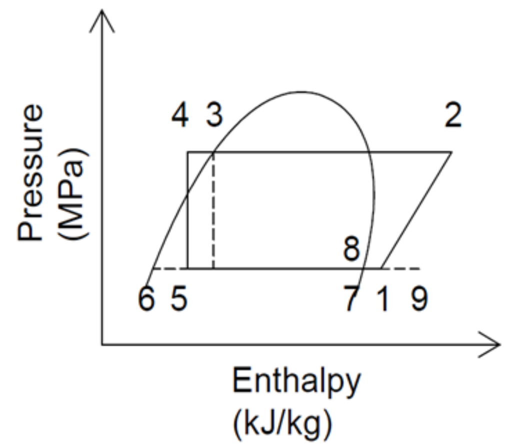

Figure 8: Pressure vs enthalpy graph of modified system

This visual aid aids in understanding the spatial distribution of crucial operational points within the modified system. Furthermore, Figure 8, offers insights into the enthalpy and pressure conditions prevalent at these designated points, providing a comprehensive understanding of the thermodynamic states throughout the system. Notably, specific points such as the compressor suction (Point 1), compressor discharge (Point 2), condenser outlet (Point 3), capillary tube sections (Points 4 and 5), flash chamber outlets (Points 6 and 7), and mixer inlets (Points 8 and 9) are identified and characterized for detailed analysis. Of particular interest is the observation that despite the different positional representations of Points 7 and 8 in the modified VCR system's block diagram, both points exhibit identical enthalpy and pressure conditions. This uniformity underscores the critical role of these points in maintaining consistency and efficiency within the modified refrigeration system. Through this comprehensive analysis and comparative evaluation, insights into the performance enhancements and operational nuances of the modified VCR system are gleaned, contributing to the broader understanding of advanced refrigeration technologies and their practical implications.

6.1 Design of Capillary Tube

In the analysis of the heat exchange process within the modified VCR system, the effectiveness of the heat exchanger plays a pivotal role. The effectiveness metric serves as a key determinant of the efficiency and performance of the heat exchange mechanism. In an ideal scenario where the heat exchanger operates at 100% effectiveness, the heat transfer between the two fluid streams reaches its maximum potential. Consequently, the exit temperatures of both the hot and cold fluid streams become equal, indicating optimal thermal equilibrium. This idealized condition represents the pinnacle of heat exchange efficiency, where the heat exchanger operates at its peak performance, facilitating maximum heat transfer between the fluid streams.

$T7 = Te,\ \ T8 = Te,\ \ T3 = Tc,$
$P3 = P2,\ \ P4 = P1$
$h7 = h1g,\quad h8 = h7,\quad h6 = h4l,\quad h3 = h3l$
$Q_{\text{lost (hot refringent)}} = Q_{\text{gained (cold refrigerant)}}$

Once the exit temperatures for a 100% effective heat exchanger are determined, the next step involves applying the specified effectiveness value of the heat exchanger in question. By incorporating this effectiveness value into the analysis, the exit temperatures of both heat exchanging fluids can be calculated accordingly. Subsequently, the amount of heat transferred from the given heat exchanger can be accurately determined, providing valuable insights into its performance under real-world conditions. This iterative approach allows for a comprehensive assessment of the heat exchange process, accounting for the efficiency of the heat exchanger in transferring thermal energy between the fluid streams.

$$T4 = (1 - e/100) * Tc + T * e/100 \tag{24}$$
$$h4 = h3 - Cp2l * (Tc - T4) \tag{25}$$
$$h5 = h4$$
$$x = (h5 - h6)/(h7 - h6) \tag{26}$$
$$T9 = Te + Cp2l * (Tc - T4)/Cp1g/x \tag{27}$$
$$h9 = h7 + Cp1g * (T9 - Te) \tag{28}$$
$$h1 = x * h9 + (1 - x) * h7$$
$$T1 = Te + (h1 - h7)/Cp1g \tag{29}$$
$$exp = (\mathrm{s1g} - \mathrm{s2g} + \mathrm{Cp1g} * (\log(\mathrm{T1} + 273) - \log(\mathrm{Te} + 273)))/\mathrm{Cp2} \tag{30}$$
$$T2 = [(Tc + 273) * 2.71\text{^}exp] - 273 \tag{31}$$
$$h2 = h2g + Cp2g * (T2 - Tc) \tag{32}$$
$$h2n = h1 + (h2 - h1) * 100/n \tag{33}$$

6.2 COP calculation

$$RE = h1 - h4$$
$$W = h2 - h1$$
$$COP = RE/W \tag{34}$$
$$m = c/RE \tag{35}$$
$$x = (h5 - h6)/(h8 - h6)$$

Table 5 displays various temperature conditions for both the condenser and the evaporator. The corresponding saturation pressures are obtained from the refrigerant chart specific to R-12. Using the data provided in Tables 6 and 7, the enthalpies of four points within the VCR system are determined. Utilizing these values, the coefficients of performance (COP) for both the simple VCR system and the modified VCR system are computed. The analysis reveals that the COP of the modified VCR system surpasses that of the simple VCR system.

Table 5: Temperature and Pressure Readings

No.	T_c (^{0}C)	T_e (^{0}C)	C (tons)	e (%)	P_c (MPa)	P_e (MPa)	Carnot COP
1	42	-8	1	60	1.0722	0.2169	5.54
2	40	-6	1	60	1.0166	0.2343	6.0217
3	38	-4	1	60	0.9631	0.2527	6.5952
4	36	-2	1	60	0.9119	0.2722	7.2895
5	34	0	1	60	0.8626	0.2928	8.1471

6.3 Future Aspects

The future of refrigeration technology holds promising avenues for further enhancement and innovation. Building on the foundation laid by our modified system, several key areas can be explored to advance the efficiency, functionality, and user-friendliness of refrigeration systems.

6.4 Condition Monitoring and Health Analysis

Implementing robust condition monitoring and health analysis techniques can enable real-time assessment of system performance and early detection of potential issues. By integrating sensors and data analytics, the system can automatically diagnose faults, optimize operations like refrigerant and flash gas, and alert users to necessary maintenance or repairs [25-34].

6.5 Machine Learning and Artificial Intelligence

Leveraging machine learning and artificial intelligence algorithms can further optimize system operation. These technologies can analyze complex data patterns, predict system behavior, and dynamically adjust parameters such as refrigerant flow rate and flash gas utilization to meet changing demands and environmental conditions [25-34].

6.6 Self-Tuning Mechanism

Introducing a self-tuning mechanism that senses evaporation load and adjusts refrigerant flow rate and flash gas accordingly can significantly enhance system efficiency and reliability. This mechanism can continuously monitor system parameters and make real-time adjustments to optimize performance while reducing energy consumption and maintenance requirements.

6.7 User-Friendly Interface

Incorporating an electronic display for users to adjust refrigerant settings as per demand can enhance user experience and system usability. This interface can provide intuitive controls, real-time performance feedback, and maintenance alerts, empowering users to optimize system operation according to their specific requirements and preferences.
By exploring these future aspects, the refrigeration industry can further advance towards sustainable, energy-efficient, and user-friendly solutions, meeting the growing demand for environmentally friendly cooling technologies.

Table 6: Calculation of Enthalpy and COP For Simple System

S. No.	h1 (kJ/kg)	h2 (kJ/kg)	h3 (kJ/kg)	h4 (kJ/kg)	RE (kJ/kg)	W (kJ/kg)	COP	ṁ (kg/s)
1	393.87	427.16	259.41	259.41	134.46	33.29	4.03	0.02603
2	395.06	425.6	256.41	256.41	138.65	30.54	4.53	0.02524
3	396.25	424.05	253.43	253.43	142.82	27.82	5.13	0.02451
4	397.43	422.55	250.48	250.48	146.95	25.12	5.84	0.0232
5	398.6	421.03	247.54	247.54	151.06	22.43	6.73	0.02317

Table 7: Calculation of Enthalpy and COP For Modified System

S. No.	h1 (kJ/kg)	h2 (kJ/kg)	h4 (kJ/kg)	h5 (kJ/kg)	RE (kJ/kg)	W (kJ/kg)	COP	ṁ (kg/s)
1	402	437.1	251.1	251.1	151.05	34.93	4.32	0.2317
2	402.31	434.17	249.15	249.15	153.667	31.85	4.8	0.2285
3	402.51	431.33	253.43	253.43	155.34	28.82	5.38	0.2253
4	402.75	428.65	245.15	245.15	157.6	25.9	6.08	0.2221
5	403.03	426.04	243.1	243.1	159.92	23	6.95	0.2189

7. Conclusions

In this research, we concentrated on the design and examination of a modified vapor compression refrigeration (VCR) system incorporating a regenerative expansion device. By subjecting it to thorough evaluation and comparing it with a traditional VCR setup, we were able to showcase a substantial enhancement in the Coefficient of Performance (COP) of the modified system, achieving a noteworthy 5% increase compared to the standard configuration. Moreover, our scrutiny uncovered a considerable decrease in the volume of flash gas that traverses the evaporator in the modified system, signaling an augmentation in efficiency and overall performance. Looking towards the future, there exists considerable potential for further progressions in this domain. The utilization of sophisticated tools like MATLAB, alongside temperature sensors and Arduino devices, offers promising avenues for obtaining deeper insights into real-world functionality and refining system design. These discoveries highlight the significance of innovative methodologies in perfecting vapor compression refrigeration systems, thus laying the groundwork for future research endeavors geared towards attaining heightened efficiency and sustainability in refrigeration technology.

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Biography

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