COVENANT JOURNAL OF ENGINEERING TECHNOLOGY (CJET), VOL. 8, NO.2, DECEMBER 2024; DOI: XXX XXXX XXX

A Review of the Energy and Exergy Analysis of a Cascade Refrigeration System for Process Optimization

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Received: 18.02.2024 **Revised**: 29.06.2024 **Accepted**: 30.06.2024 **Published**: 02.07.2024

Abstract:
An overview of thermodynamic energy and exergy analysis is provided in this work with the goal of developing, constructing, and improving a cascade cooling apparatus for extremely low-temperature managing goods and gas-efficient building operations. A review of the classes of cascade systems was carried out, stating the benefits and setbacks. Every part of the refrigeration mechanism cascades was identified, explained, and designed theoretically. Energy and exergy techniques were used to analyze every component of the system separately, model it, and evaluate it to minimize energy destruction. Necessary equations for calculating energy and exergy destructions were outlined to ensure effective modeling and optimization of the system processes. Process losses were identified, determined, and reduced using the application of exergy analysis. There was an improvement in comprehension of the process's deceptive efficiency and energetic effectiveness. The result aids in detecting the locations of energy degradation and mapping out the system's optimal performance. By lowering operational and process design costs and resolving energy-associated environmental issues, the analysis eventually contributed to sustainable growth. This offers a rationale for enhancing an exceptionally low-temperature freezer's functionality for the handling of susceptible-to-heat vaccines. The effective modeling and building of cascade refrigeration systems for zero energy destruction and high efficiency are made possible.

***Keywords*:** Energy, Exergetic Effectiveness, Exceptionally low-temperature, Performance Optimization, Process Losses

I. INTRODUCTION

Industrial refrigeration machines are among the most common and universal sources of cold, which can ensure production of cold in the range of a few hundred watts to several megawatts. The modern industry demands that they reach temperatures below -100 ^{o}C with the goal of liquefying gases, liquefying air, and using cryogenic temperatures in medical applications [1]. Obtaining such low temperatures is associated with a number of challenges associated with increased energy consumption, such as the construction of the refrigeration machine and the minimum possible pressure of the suction compressor, which can practically ensure the desired temperature. Some medical applications that require moderately low temperatures make Simple (VCRS) ineffective and impractical. This results in serious outflow problems and low volumetric productivity because of a substantial compression ratio [2].

Nevertheless, the cascade method is noticeably more effective. When used in combination with a cascade condenser unit, the low-temperature circuit (LTC) and the high-temperature circuit (HTC) are two VCRS cycles that are typically combined to create cascade refrigeration techniques. This cascade condenser primarily acts as an HTC condenser, afterwards as an evaporator for LTC. While the high-temperature circuit employs refrigerants with high boiling rates, the low-temperature circuit utilizes low-boiling refrigerants [3]. Performing the cooling process in multiple phases that run-in sequence is one way to handle such situations. Two autonomously operating single-stage cooling systems make up a cascade refrigeration system: a lower-temperature circuit that generates a chilling effect by maintaining a lesser evaporating temperature, and an increased system that runs at a greater evaporating temperature. The process of chilling a particular item or space to a predetermined temperature, usually beyond -50 ^{o}C, is known as ultra-temperature freezing [4]. As a result, plant accounts emerged, claiming that maintaining vaccinations at such temperatures is a significant technical challenge. Machines designed around vapor compression are typically used for cooling at these temperatures**.** Investigations and procedures pertaining to extremely small temperatures are insufficient, which would encourage the development of contemporary, eco-friendly remedies. Exploring the widest range of designs extensively is necessary to determine how energy consumption affects comparable greenhouse gas releases. Industrial ultra-low-temperature refrigerators often have cascade and auto-cascade units installed. These systems operate between 20 and 30 ^{0}C for outside temperatures and between 50 and 80 ^{0}C for frigid temperatures [5]

A. Characterization of Cascade Refrigeration System

Two separate single-stage cooling systems, one higher and one lower, that both maintain a different evaporation temperature and provide a different chilling effect make up a cascade-type plant [6]. A cascade condenser connects the two distinct systems, allowing the evaporator in HTC to absorb heat from the LTC condenser and select the best refrigerant for each temperature range. One refrigerant condenses another main refrigerant to the desired evaporator temperature. Additionally, refrigerants with increasingly decreasing boiling temperatures are used for evaporator and condenser conditions in a number of different temperature ranges [7]. This raises the overall effectiveness of the system's coefficient of performance (COP). The refrigerator, however, requires a properly lagged storage chamber (evaporator compartment) for handling heat-sensitive temperature-related products, such as vaccines and blood products. A cascade system is employed where a very wide range of temperatures between low and high is desired. The reliability of this system relies on computations for design and refrigerant choices, operating at temperatures between -18°C and -86°C [8]-[9]. The best arrangement for high temperature (60 ºC and higher) is a two-phase cascade. Consequently, optimal power efficiency in two-stage cascades depends on the regulation of operating factors. Pressure is released to the lesser evaporator temperature cycle by the higher low-temperature (LT) compressor.

A two-stage vapor compression refrigeration mechanism is the base of a multiple-phase refrigeration circuit used for extremely minimal chilling purposes. The most widely recognized and extraordinarily model-efficient method, utilized for many different applications, is the vapor-compression cascade refrigeration system (VCRS) [10]. For example, blood banks, vaccines, bone banks, and other biological substance preservation facilities in healthcare require cascade refrigeration equipment. Since very low-temperature freezing facilities are not always available, it might be challenging to store contraceptives susceptible to heat at the correct temperature, even if they are essential. Due to its numerous advantages in everyday human necessities and technological domains including medicine, biology, business, agriculture, and industry, this device's uses have raised interest lately in industries as well as academia [10].

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B. Principles of a Two-Stage Cascade Refrigeration System

One method of achieving the process of distilling refrigerants is to reach extremely low temperatures, as the ultimate objective is to condense and sub-cool the fluid prior to it passing through a metering apparatus. In two-phase cascade refrigerators, a variety of compressor machinery is employed. The compressors link up to ensure the evaporator of the initial cycle chills the condenser of the next cycle, and both cycles are run individually with different refrigerants [11]. The components of the refrigeration cycle include the compressor, condenser, evaporator, expansion valve, condenser fan, filters, condenser fan, electric motors, controls (thermostat), refrigerant pipes, drain pipes, and shell.

C. Classes of Cascade Refrigeration Systems

Multiple refrigeration devices are being developed as an outcome of the number of ideas being explored to accomplish the refrigeration effect. Each refrigeration system has a distinct use, each with a distinctive combination of advantages and disadvantages. The two most common types of refrigeration systems that may be used for a variety of applications are vapor compression and absorbent systems [12].

i. Two-Stage Compression Cascade Refrigeration System (CCRS)

The high-temperature circuit (HTC) of the two-stage compression refrigeration system uses Zeotropes and Azeotropes blends as refrigerants, while the low-temperature circuit (LTC) makes use of CO2 and Azeotropes combinations. These two separate subsystems make up the structure of the two-stage compression refrigeration network. A heat exchanger that simultaneously functions as the condenser and the evaporator in the HTC and the LTC connects the compressor, condenser, expansion valve, and evaporator in each cycle. The use of refrigerants with suitable temperature characteristics for both low- and high-temperature cycles allows for exceptionally low-temperature operation that is resilient, inexpensive to operate, and easily fixed. This technique results in energy savings if you juxtapose a two-stage compression cascade refrigeration system (CCRS) with a single-stage compression system (SCRS).

ii. Two - Stage Cascade Absorption Refrigeration System (CARS)

Utilizing the HTC evaporator to cool the condenser in LTC and reduce the evaporating temperature, the cascade absorption refrigeration technique is founded on STARS. The economical way to reclaim thermal waste and save energy is by using an absorption cooling device. An effective tactic to improve the efficiency of the absorption refrigeration system is the cascade technique. Examples of cascades that have been proposed include the Rankine cycle and the absorption refrigeration circuit. LTC is used for refrigeration, while HTC uses its surplus heat loss to create power. The residual heat from the power subsystem is also recovered by the refrigeration mechanism.

iii. Compression–Absorption Cascade Refrigeration System (CACRS)

In a compression-absorption double-stage (CADS) system, adding an additional economizer and a condenser generator linked to an absorption cycle raised the system's coefficient of performance (COP). The schematic diagram of the system is shown in Figure 1 [12].

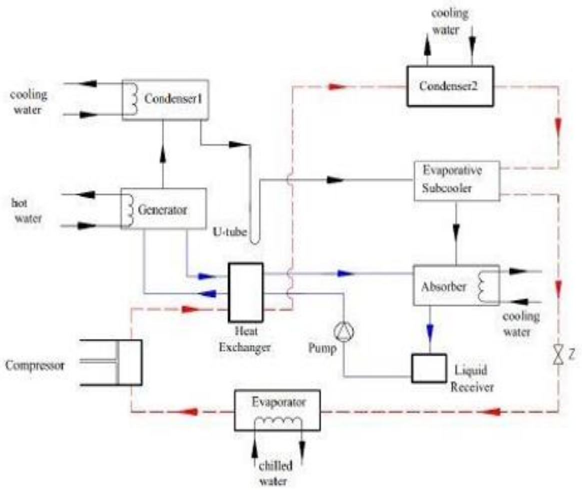

Figure 1: Compression – Absorption Refrigeration System

iv. *Auto-Cascade Refrigeration System (ACRS)*

The auto-cascading method has broad potential usage at a low temperature of about -60°C for its architecture and operational reliability, with an outstanding durability level [13]. ACRS acknowledges cascading between high- and low-boiling-point components by an evaporative condenser. It has a broad usage area and is capable of achieving a low evaporation temperature beneath it. The principle involves using multiple blended working fluid compositions under different pressure processes alongside varying evaporated and condensed temperatures.

D. *Components of Cascade Refrigeration System and Applications*

The basic components of cascade refrigeration system are:

i. *Compressors*

Refrigerant vapor is pumped from the evaporator by the compressor during a refrigeration cycle to keep the evaporator at the proper pressure and temperature. By compressing the refrigerant vapor, it raises its temperature and pressurization.

The reciprocating compressor and centrifugal compressor are characterized as shown in Table 1.

Table 1. The comparison between centrifugal and reciprocating compressors [14].

S/N	Particular	Centrifugal compressor	Reciprocating compressor
1	Suitability	Suitable for handling large volumes of air at low pressure	Suitable for low discharges of air at high pressure
2	Operational speeds	Usually, high	Low
3	Air supply	Continuous	Pulsating
4	Balancing	Less vibrating	Cyclic vibrations occur
5	Lubrication system	Simple lubrication systems are required	Complicated
6	Quality of air delivered	Air delivery is relatively cleaner	Generally contaminated with oil
7	Air compressor size	Small for given discharge	Large for same discharge
8	Free air handled	2000 – 3000m^3/min	250 – 300m^3/min
9	Delivery pressure	Normally below 10bar	500 to 800bar
10	Usual standard of compressor	Isentropic compression	Isothermal compression
11	Action of compressor	Dynamic action	Positive displacement

The compressor applications are:

i. It eliminates the evaporator of its vapor.
ii. At low pressures and temperatures, it draws in the refrigerant, or gas.
iii. It is employed to compress the evaporator's vapor refrigerant.
iv. It increases the temperature and pressure of the gas to the point when the cooling medium's matching saturation temperature is exceeded.
v. It delivers the gas to the coil of the condenser.
vi. It keeps the refrigerant flowing through the refrigerating system continuously.

High credibility, extended lifespan, ease of servicing, silent operation, compact design, and cheap cost are projected for the refrigerant compressors.

ii. *Condensers*

These are a crucial part of an indirect-contact exchanger of heat, which removes all of the heat discarded from the refrigerant using a cooling agent, usually air or water.

Condenser applications are stated below:

i. It creates a surface for heat transmission, allowing heat to move from the heated refrigerant vapor to the condensing phase.
ii. It cools food products by dispersing the hot vapor refrigerant release across the compressor.
iii. In moving the gas to the walls of the condenser tubes and then from the tubes to the cooling medium, it condenses and transforms the gas at high pressure and temperature to the liquid phase.
iv. It functions as a reception tank, storing condensed liquid to ensure the evaporator always has access to liquid when needed.

The refrigerant condenser must fulfill certain requirements, including weight, size, and repairs, and be capable of being economically fabricated and operated in a variety of circumstances, including design position.

iii. *Evaporators*

They are an essential component of a refrigeration system's low-pressure side. After passing through the expansion valve and into the evaporator, the liquid refrigerant bubbles and turns into vapor. An evaporator's primary job is to draw in heat from the air outside and use refrigerant to chill the air.

The system has the capacity to:

i. offers a surface for heat transmission so that heat may go from the chilled area onto the refrigerant that is vaporizing.
ii. uses refrigerant to chill the things by absorbing heat from the medium's (the refrigeration system's) surroundings.

iv. Expansion Valves

These are employed to control the liquid-refrigerant circulation to the evaporator and load qualities, as well as to lower the refrigerant condensing high pressure to the evaporating low pressure through a throttling action. Thermostatic expansion valves, constant pressure expansion valves, float valves, and capillary tubes are the most commonly used throttling devices. The following is a list of device applications:

i. Before being fed into the evaporator, it lowers high-pressure liquid refrigerant to low-pressure liquid refrigerant.
ii. It keeps the system's high- and low-pressure sides at the appropriate pressure differential, allowing liquid refrigerant to evaporate in the evaporator at the intended pressure.
iii. It regulates the flow of refrigerant into the evaporator based on the load on the evaporator in order to cause liquid to evaporate at the appropriate low temperature and remove an adequate quantity of heat.

v. Capillary Tube

It is a device that controls the flow of refrigerant and can be utilized in lieu of an expansion valve. The refrigerant enters the evaporator through small-diameter tubes called capillary tubes. These units maintain a uniform evaporating pressure regardless of changes in the refrigeration load by lowering the condensing pressure to the evaporating pressure in a copper tube with a tiny internal diameter. One of the most important components of the refrigeration system is the pipe design, which must be carefully and properly thought out in order to minimize noise from the refrigerant flow and potentially explode the pipe owing to variations in pressure.

i. The low-pressure vapor from the evaporator is transferred to the compressor's suction intake through the suction line.
ii. The receiver tank's liquid refrigerant is sent to the refrigerant flow control through the liquid line.

vi. Heat exchanger

An efficient means of transferring heat from one fluid to another is through a heat exchanger. A wide range of industries, including natural gas processing, air conditioning, power plants, petrochemical, chemical, and petroleum refineries, use this application. When converting a gas into a liquid, it is employed. Equation1 is used to do this.

$$\dot{m}_A(h_5 - h_8) = \dot{m}_B(h_2 - h_3) \qquad (1)$$

vii. Dryer

Water vapor from compressed air is eliminated using a compressed air drier. Many different types of commercial and industrial establishments frequently include compressed-air dryers. Compressing air results in a concentration of airborne pollutants, such as water vapor.

II. MECHANICAL DESIGN FOR PIPES

A. Pipe design for LTC

The suction pipe design for LTC is achieved as follows:

The fluid-flow speed at the pipe inlet inner diameter is calculated by the equation 2.

$$V = \dot{m}v \qquad (2)$$

Applying the continuity equation, the fluid volume is defined by equation 3.

$$V = V_r A_{iL} \qquad (3)$$

Therefore, the inner area of the pipe is calculated as stated in (4).

$$A_{iL} = \frac{V}{V_r} \qquad (4)$$

Then, the diameter of the inner pipe, D_{iL} is determined by equation 5.

$$D_{iL} = \sqrt{\frac{4A_{iL}}{\pi}} \qquad (5)$$

The outer diameter is found using equations 6, 7and 8.

$$\sigma_{\tau L} = \frac{Pi(r_o^2 + r_i^2)}{r_o^2 - r_i^2} \qquad (6)$$

$$\sigma_{\tau L}{}^2 + P_i \, x \, \sigma_{\tau L} + P_i^2 = \frac{S_y{}^2}{n^2} \qquad (7)$$

$$D_{oL} = 2r_o \qquad (8)$$

$$\text{Length, } L = D_{oL} - D_{iL} \qquad (9)$$

The discharge pipe design for LTC is achieved as follows:

At discharge pressure, the area and inner diameter were found by equations 10 and 11.

$$A_{iL} = \frac{V}{V_r} \qquad (10)$$

$$D_{iL} = \sqrt{\frac{4A_{iL}}{\pi}} \qquad (11)$$

The results of the outer pipe diameter are obtained by using equations 12, 13 and 14

$$\sigma_{\tau L} = \frac{Pi(r_o^2 + r_i^2)}{r_o^2 - r_i^2} \qquad (12)$$

$$\sigma_\tau{}^2 + P_i \, x \, \sigma_{\tau L} + P_i^2 = \frac{S_y{}^2}{n^2} \qquad (13)$$

$$D_{oL} = 2r_o \qquad (14)$$

B. Pipe design for HTC

The suction pipe design for HTC is achieved as follows:

At inlet velocity, the inner diameter of the pipe is obtained by equation 15.

$$V = mv_r \qquad (15)$$

The inlet area and diameter are calculated by equations 16 and 17.

$$A_{IH} = \frac{V}{V_r} \qquad (16)$$

$$D_{iH} = \sqrt{\frac{4A_{iH}}{\pi}} \qquad (17)$$

The outer diameter is defined by equations 18, 19 and 20.

$$\sigma_\tau{}^2 + P_i \, x \, \sigma_{\tau H} + P_i^2 = \frac{S_y{}^2}{n^2} \qquad (18)$$

$$\sigma_{\tau H} = \frac{Pi(\,r_o^2 + r_i^2)}{r_o^2 - r_i^2} \qquad (19)$$

$$D_{oH} = \sqrt{\frac{4A_{oH}}{\pi}} \qquad (20)$$

The discharge pipe design for HTC is achieved as follows:

The inner diameter and area are calculated by equations 21 and 22.

$$A_{IH} = \frac{V}{V_r} \qquad (21)$$

$$D_{iH} = \sqrt{\frac{4A_{iH}}{\pi}} \qquad (22)$$

The pipe outer diameter is determined by employing equations 23, 24 and 25.

$$\sigma_\tau{}^2 + P_i \; x \; \sigma_{\tau H} + P_i^2 = \frac{S_y{}^2}{n^2} \qquad (23)$$

$$\sigma_{\tau H} = \frac{P_{i(r_o^2 + r_i^2)}}{r_o^2 - r_i^2} \qquad (24)$$

$$D_{oH} = \sqrt{\frac{4A_{oH}}{\pi}} \qquad (25)$$

III. REFRIGERANTS AND REFRIGERATION SYSTEMS

An essential part of refrigeration systems are refrigerants. The efficiency of the refrigeration system is greatly influenced by the characteristics of the chosen refrigerants. Refrigerants are necessary for cooling machinery, but some of them also contribute to ozone layer depletion and climate change, which is a serious environmental hazard. Two of the most important global issues that need more research are ozone layer depletion (ODP) and global warming potential (GWP) [15]. Thus, factors such the boiling point, freezing point, critical temperature, molecular mass, safety (non-flammability and non-toxicity) at evaporation temperature, impact on the environment, and availability of refrigerant define the refrigerant parameters for selection.

Refrigerants are classified based on halogen molecules, as stated below [16].

i. CFC refrigerants ii. HCFC refrigerants
ii. HC refrigerants; iv. PFC refrigerants (hydrofluorocarbons)
iii. HFO refrigerants (F-gases) vi. Inorganic refrigerants
iv. HFC refrigerants (hydrofluorocarbons, F-gases)

A. *Physical properties*

Refrigerants are expected to have the following physical properties [15]:

i. Lower freezing point than under typical working circumstances ii. low pressure during condensation; iii. high pressure during evaporation; iv. high pressure at critical point; v. high density of vapor; vi. strong dielectric; vii. high latent heat of vaporization; viii. high heat transfer coefficient; ix. low specific volume; x. low heat specific to liquid xi. High heat specific to vapor (xii) high vapor and liquid phase thermal conductivity (xiii). Low viscosity (xiv) Low price

B. *Chemical properties*

The chemical characteristics of high-quality refrigerants should be present in refrigerants.

i. It must not ignite or burst into flames. It ought not to be harmful.
ii. Lubricating oil should not react with it.
viii. Moisture shouldn't cause it to respond.
iv. The food stored within the refrigeration system shouldn't become contaminated by it.
v. There ought to be no irritation.

C. *Physicochemical properties.*

Other physicochemical characteristics of refrigerant are its high density, ease of leak detection, requirement that the pressure in the evaporator and condenser be higher than the ambient pressure, small compression ratio, chemical stability and inertness, and inability to react with rubber and plastics.

Thermodynamic properties: Heat is taken from a low-temperature item and rejected at a higher temperature in a thermodynamic refrigeration cycle. The quantity or size of matter in the system determines the value of a costly attribute. The large number of variables aids in defining the particular system under study. The following trustworthy thermodynamic characteristics of refrigerants are necessary for the design and selection of refrigeration equipment via mass, volume, specific heat capacity, pressure, temperature, Gibbs free energy, enthalpy, entropy and internal energy.

The following characteristics of a good and desired refrigerant should be present in its impact on the environment and health-conscious properties:

i. Leak identification: It ought to be simple to locate leaks.
ii. Flammability: Refrigerants shouldn't cause airborne explosive combinations.
iii. ODP: The proportionate quantity of ozone layer depletion that a refrigerant might generate is known as its ozone depletion potential. Thus, ODP represents a refrigerant's capacity to deplete ozone.
iv. Global warming potential (GWP): The amount of heat a refrigerant trap in the atmosphere is measured relative to its value.
v. STEC: The highest concentration to which a person may be exposed for a maximum of 15 minutes is known as the short-term exposure limit.
vi. Time-weighted average (TWA): This is the concentration at which five days a week of consecutive eight-hour exposures is deemed safe.

IV. SPECIFIC APPLICATIONS OF CASCADE REFRIGERATION SYSTEMS

A. *Food processing, preservation, and distribution*

Cold storage freezers are necessary to ensure the safety of products like ice cream, frozen goods, meats, and shellfish. Portable ultra-low-temperature freezers are a useful tool for food service companies, ranging from manufacturers to merchants, to maintain the quality of products such as fish, meats, fruits, and vegetables. Manufacturers can freeze almost any goods, save for meals in cans and eggs in shells, to preserve it. In general, the application is found in: i. food preparation (milk, curd milk, etc.); ii. frozen meat and poultry packaging (fish, turkey, chickens, and cows); iii. drinks and raw fruit storage as listed below, the primary uses of refrigeration are divided into four equally significant categories. as well as veggies (candy).

Frozen meat and vegetables, frozen baked goods, cooler storage, home refrigerators, and freezers are all involved in the disbursement and preservation of food. Dairy goods require air conditioning and refrigeration to preserve the nutritional value of their milk, buttermilk, and ice cream. Refrigeration systems are used to preserve beverages including wine, beer, fruit juice concentrate, and candy (chocolate) for extended periods of time. It is used to maintain the flavor of frozen food during handling and shipping, particularly frozen bakery goods.

B. *Chemical and process industries:*

Huge chilling capacities are needed for manufacturing sectors like petroleum, petrochemical plants, and paper pulp. The chemical and process industries use refrigeration primarily for the following applications: i. material hardening; ii. process a cooling sensation; iii. fermentation management; iv. fluid recuperation; v. heat from reactions removal; vi. cooling for preservation; vii. storage space as liquid at low pressure; viii. dehumidification of air; ix. low-pressure storage in liquid form; x. Condensation of artificial gases xi. Gas separation by fractional distillation

C. *Special applications of refrigeration*

This article examines the use of refrigeration systems in medical and construction settings. i. desalting sea water; ii. constructing ice rinks; iii. cold treating metals; iv. building (using building materials in a thermal activity). v. Production of ice vi. The production of antibiotics and blood plasma in the medical profession [16].

D. *Industrial and comfort air-conditioning:*

Air conditioning system is necessary for enhancing processes and materials, personal comfort, the efficiency of electronic devices, the efficient functioning of computer and microprocessor-based equipment, etc. The application is categorized into two, namely:

1. Industrial air conditioning: applications include printing, precision part manufacturing, textile and pharmaceutical industries, steel production, farm animals, computer rooms, power plants, and automobile air conditioning, among other things.
2. Comfort air conditioning: This refers to the temperature at which people and equipment feel comfortable in homes, workplaces, shopping malls, stores, big structures, theaters, hospitals, restaurants, grocery stores, recreation centers, auditoriums, amusement parks, and vehicles [17].

Vapor compression refrigeration systems, which have forced convection-style evaporators and condensers with a sealed compressor, are used in air conditioning and refrigeration systems.

E. *Importance of Cascade Refrigeration Systems in Transfusion Medicine*

ULT refrigerators are used for keeping and preserving life-sustaining products, blood banks and blood components, pharmaceuticals, medications, enzymes, and other medical supplies in clinics, laboratory settings, drug manufacturing resources, cold storage facilities, and food preparation and packaging companies. Of all these factors, the COVID-19 pandemic has been extremely advantageous. The pandemic has led to a sharp increase in the global demand for blood product components, which has helped the extremely low-temperature freezer market. A critical analysis of studies revealed that the maximum amount and quality of proteins and coagulation factors are determined by the rapid freezing procedure of fresh plasma following collection. Consequently, a cascade refrigeration system is the best device for quickly applying freezing and preserving blood products, including fresh blood plasma. In the event of plasma preservation, it can also store any product below -18 ºC below room temperature. Common uses for ultra-low temperature storage systems include the following:

i. Pharmaceuticals

Antibacterial medications and vaccines are among the medicinal products that must be stored in freezers with extremely low temperatures. For example, all immunizations containing varicella should be stored frozen and between -50 and -15 degrees Celsius until they are needed. Certain immunizations may be stored in freezers, including the MMR (measles, mumps, and rubella) vaccination. To keep pharmaceuticals safe and dependable, they need to be stored carefully. Insufficient storage can lead to the waste of priceless resources and the exorbitant cost of remodeling.

ii. *Biological Samples*

Ultra-low-temperature coolers are essential for the proper storage of biological products, including blood and plasma. In particular, plasma has to be maintained at -18 ºC or colder before it thaws. Freezing preserves the blood and plasma together with their vital constituents, guaranteeing a steady flow of life-sustaining transfusions.

V. ENERGY AND EXERGY ANALYSIS FOR A TWO-STAGE VCR SYSTEM

The quantity of work that a system is capable of generating when it reaches thermal equilibrium with its surroundings is known as its energy. The amount of effort that is accessible for use is called exertion. It measures the energy quality and the amount of work that can be created to the highest or lowest, subject to how much the system has to do tasks in order to go through a process that can be reversed with the surroundings. It elevates energy economics to a high priority. It facilitates the creation of effective procedures and the best possible use of resources. Finding a system's optimum efficiency and the locations of energy loss are often the goals of an exergy analysis. Multi-system energy characterization may be carried out by dissecting the system's constituent parts. Process losses may be found, measured, and minimized through the use of energy examination. This also provides an inaccurate view of process effectiveness and improves our understanding of the energetic functionality of systems [18]. The anticipated benefits of exercise analysis included lowering operational and process building costs, addressing energy-associated environmental concerns, and eventually promoting long-term growth. Reactors, pumps, turbine compressors, and distillation columns are among the devices that use it. Complex chemical reactions, thermal energy, electrical devices, etc. are examples of additional energy uses. The integration of thermodynamics and economics facilitates the allocation of manufacturing expenses among various operational paths, ultimately leading to optimal construction [19].

The effectiveness and efficiency of VCR are assessed using the system coefficient of performance and energetic consumption. The quantity of work that a system could do after reaching a temperature balance with its environment is known as its energy. Exergy is defined as work or energy that is available and ready to be used. It is an evaluation of the kind of energy utilized, the quantity of work that is capable of being performed with that energy, and the quantity of energy required to build anything or initiate a process in a system that is reversible with respect to its environment. The second law of thermodynamics' method of identifying a system's maximum performance and the places where energy is lost is called "exergy analysis." When analyzing the energy of complex systems, each component is examined independently. The instrument is employed to assess the efficiency of processes and maximize the use of materials. The system's component and flow process efficacy may be tracked at all levels using the following basic equations [20].

A. Application of Energy Analysis to a Two-Stage VCR System

As seen in Figure 2, the temperature-entropy relations (equations) are employed to compute the energy losses in system components [21]-[22].

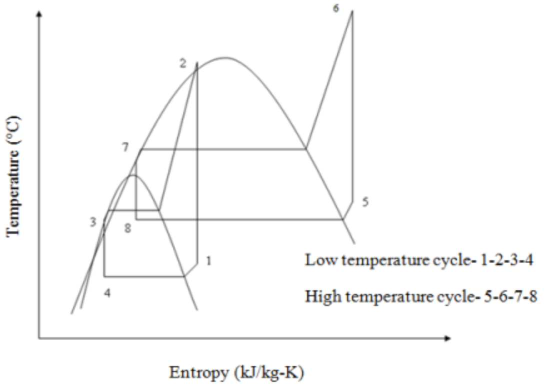

Figure 2: Temperature – Entropy diagram of a two stage CRS

i. The evaporator capacity is calculated by equation 26.

$$R_E = \dot{m}_L[h_1 - h_4] \quad (26)$$

ii. The Power consumed by HTC compressor is found by equation 27.

$$W_H = \dot{m}_H[h_6 - h_5] \quad (27)$$

iii. The Power consumed by LTC compressor is determined by equation 28.

$$W_L = \dot{m}_L[h_2 - h_1] \quad (28)$$

iv. The exchange of heat by refrigerants in cascade condenser are obtained by 29 and 30.

a. $Q_{CAS} = \dot{m}_L[h_2 - h_3\,]$ (29)

and

b. $Q_{CAS} = \dot{m}_H[h_5 - h_8\,]$ (30)

v. Equating the two equations of the cascade refrigerating system gives equation 31.

$$Q_{CAS} = \dot{m}_L[h_2 - h_3\,] = \dot{m}_H[h_5 - h_8\,] \quad (31)$$

vi. The mass flow ratio to the enthalpy is expressed by using equation 32.

$$\frac{\dot{m}_L}{\dot{m}_H} = \frac{h_5 - h_8}{h_2 - h_3} \quad (32)$$

i. Quantity of heat exchange in cascade condenser is calculated by equation 33.

$$Q_{cas} = \frac{h_5 - h_8}{h_2 - h_3} \quad (33)$$

viii. Heat rejected by condenser is calculated by equation 34

$$Q_C = \dot{m}_H[h_6 - h_7\,] \quad (34)$$

ix. Coefficient of performance of the system is determined by equation 35.

$$\text{COP} = \frac{Q_C}{W_{LTC} + W_{HTC}} \quad (35)$$

xi. Reversible work input of system is found by equation 36.

$$W_{rev} = \dot{m}_L[h_1 - h_4\,][\frac{T_O}{T_I} - 1] \quad (36)$$

B. Exergy Loss in System Components

As a variable parameter that establishes the exergy, the inter-stage saturation temperature reaches its maximum when it approaches or equals one. When the inter-stage saturation temperature is extremely near to 0.5, there are very little energy losses. The expander, condenser, compressor, and evaporator can all experience energy losses [23]. The impact of evaporator temperature on coefficient of performance, energy loss, and energetic efficiency are frequent consequences of system components. Whereas economic research focuses on the cost of equipment and necessary overall expenditures, energy addresses the topic of the location and size of thermodynamics in process efficiency [24]-[25].

i. Exergy loss in Evaporator is determined by the equation 37

$$\eta_{exe} = \frac{w_{rev}}{w_{act}} w_{rev} = \dot{m}_L(h_1 - h_4)\left[\frac{T_o}{T_1} - 1\right] Q_c = \dot{m}_H(h_6 - h_7) \quad (37)$$

ii. Exergy loss in Compressor is found by the equation 38

$$T_o(S_2 - S_1) \quad (38)$$

iii. Exergy loss in Condenser is estimated by the equation 39.

$$Q_{ref} - T_o = (S_2 - S_3) \quad (39)$$

iv. Exergy loss in throttling process is calculated by the equation 40.

$$T_o = (S_4 - S_3) \quad (40)$$

v. The mass flow rate in the LTC is found by 41.

$$m_L = \frac{Q_1}{h_1 - h_4} \quad (41)$$

vi. Compressor power in the LTC is estimated by equation 42.

$$P_{CL} = \dot{m}_L(h_2 - h_1) \quad (42)$$

vii. Heat load in cascade heat exchanger is found by equation 43.

$$Q_{cc} = m_L(h_2 - h_3) = Q_1\left[\frac{h_2 - h_3}{h_1 - h_4}\right] \qquad (43)$$

C. Exergy of the Cascade Refrigeration System

The exergy of the evaporator is found by equation 44.

$$I_{evap} = \dot{m}\,[h_4 - T_o\,S_4] + Q_{evap}\,[1 - \frac{T_o}{T_{evap}}] - \dot{m}[\,h_1 - T_o\,S_1] \; (44)$$

The total exergy of the compressor is calculated by equation 45.

$$I_{comp} = \dot{m}\,[h_1 - T_o\,S_1] + W_{comp} - \dot{m}[\,h_2 - T_o\,S_2] \; (45)$$

The total exergy of the condenser is calculated as stated in equation 46.

$$I_{cond} = \dot{m}\,[h_2 - T_o\,S_2] - \dot{m}[h_3 - T_o\,S_3] - Q_{cond}\,[1 - \frac{T_o}{T_{evap}}] \quad (46)$$

The Exergy of the expansion valve is determined by equation 47.

$$I_{exp} = \dot{m}T_0[S_4 - S_3] \qquad (47)$$

Total irreversibility of the refrigerator is obtained by the summation of the system components using equation 48 [26]. Thus;

$$I_{Total} = I_{evap} + I_{comp} + I_{con} + I_{exp} \qquad (48)$$

D. Exergetic Efficiency

By using the total exergy and the second law of thermodynamics, the exergy efficiency of the vapor compression system can be ascertained. Consequently, the total exergy efficiency may be defined as the ratio of exergy intake to exergy release [27].

Mathematically, the exergetic efficiency of the system is calculated by equations 49, 50, 51 and 52.

$$\eta_{Exe} = \frac{W_{rev}}{W_{act}} \qquad (49)$$

$$\eta_x = \frac{X_{out}}{X_{in}} \times 100\% \qquad (50)$$

$$X_{out} = X_{in} - X_{Total} \qquad (51)$$

$$\eta_x = (1 - \frac{X_{out}}{X_{in}}) \times 100\% \qquad (52)$$

E. Cascade Refrigeration Cycle Optimization

Improved VCRS coefficient of performance was achieved by the newly adopted mechanical subcooling cycle, which reduced the pressure gradient at each stage, reduced compressor effort, increased evaporator temperature, and limited energy loss [26]. Using Taguchi, ANOVA, and statistical analysis techniques, the vapor compression cascade refrigeration cycle was optimized [27]. Within the constraints of the operating parameters, the analysis revealed that the energy efficiency and performance coefficients were, respectively, 3.274% and 37.63%. The performance of the auto-refrigeration cascade (ARC) systems was improved to -83 oC by the combination of R600a, R23, and R14. Results [28]-[29] suggest that the R600a/R23/R14 ternary combination might be a viable, environmentally friendly substitute for auto-refrigeration cascade systems.

A computer investigation was conducted on the energy, exegetical, economic, and environmental performances of a 50kW freezing capacity cascade refrigeration system employing four distinct refrigerant pairs: R41/R404A, R170/R404A, R41/R161, and R170/R161. The outcome demonstrated that, for the system running at the same circumstances, the refrigerant pairings with the highest coefficients of performance and energetic efficiency were R41/R161 and R170/R161. To computationally examine the energy, exegetical, economic, and environmental performances of a 50kW chilling capacity cascade refrigeration system, four alternative pairings of refrigerants—R41/R404A, R170/R404A, R41/R161, and R170/R161—were used. The result showed that the refrigerant pairings with the maximum energy efficiency and coefficients of performance for the system, under the same operating conditions, were R41/R161 and R170/R161 [30].

Utilizing the pull-down capabilities of an ultra-low-temperature freezer running at -80 ºC, looked into possible cascade system optimization. The investigation discovered that high-temperature cycle compressors showed greater potential for performance improvement and that their volumetric efficiency declined more dramatically across the pull-down operation [31].

The components of the LTC are a low-temperature compressor, a pre-cooled condenser, a low-temperature capillary, and an evaporator connected to a heat exchanger; in contrast, the HTC is composed of a high-temperature compressor, an air-cooled condenser, and a high-temperature capillary. Liquid reservoirs, drying filters, process seals, and oil separators are among the other connected parts of the refrigeration system. Enhancing the efficiency of the CRS and lowering the freezer's cooling temperature is accomplished by installing an anti-condensation loop in the door seal and placing a pre-cooled condenser in the LTC [32]-[33]. Water vapor condensation at the freezer door is prevented by passing high-temperature discharge gas through the anti-condensation loop. The high-temperature fluid in the HTC and the low-temperature fluid in the LTC are made from two natural refrigerants: R290 and R170. To track the temperature variation of two refrigerants, measurements were taken at many sites [34].

Figure 3 presents the P-h diagram for the cascade refrigeration system. A CRS is created by combining the environmentally benign refrigerants R290 for high-temperature applications and R170 for a ULT freezer. With the correct adjustments to reduce cold loss and add spray foam insulation, it is possible to reach a temperature of -60 ºC, according to experimental evaluations of the ULT freezer's performance [35].

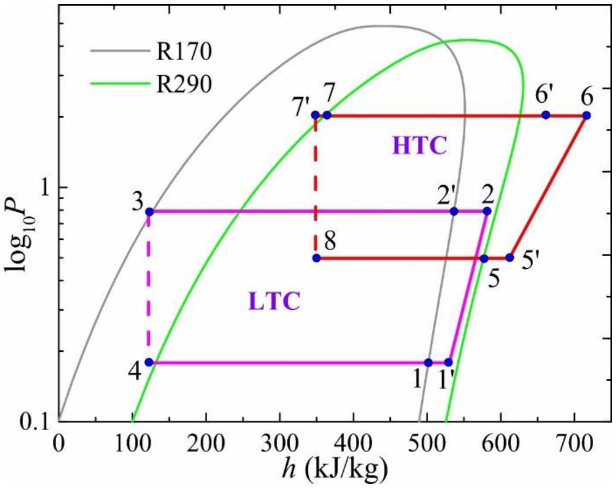

Figure 3: Pressure-Enthalpy of Cascade Refrigeration System [35]

In a two-stage VCRS, the following elements raise the coefficient of performance:

i. A decrease in the pressure ratio at each step.
ii. Less effort is put into the compressor.
iii. Raising the temperature of the evaporator
iv. A reduction in energy loss

VI. APPLICATION OF EXERGY ANALYSIS TO ENERGY SYSTEMS

The application of energy and exergy modeling techniques for energy utilization assessment to attain desired temperatures and financial savings includes [36]:

i. Utility: This is found useful in the design, evaluation, optimization, and improvement of thermal power plants. The energy-utilization efficiency of a microsystem includes processes for electricity generation, fossil and nuclear power plants, solar energy, hydropower, biomass, geothermal, wind, etc.
ii. Industrial: Exergetic analysis is used in many industries because the powerful tool provides for analyzing, assessing, designing, improving, and optimizing systems and processes such as petrochemical, chemical, and metallurgical processes, heating and cooling systems, etc.
iii. Residential-Commercial: The application includes residential, commercial, public, and agricultural activities such as lighting, water heating, space heating, cooking, refrigerating, air conditioning, etc.
iv. Transportation: The specific application of exergy is found in the transportation of fuel.
v. Economy: The use of exergy analysis helps in the design and analysis of energy systems, especially thermodynamics, with economies to achieve optimal designs.

VII. CONCLUSION

The study examined the applications of energy and exergy thermodynamic analysis to cascade refrigeration systems for minimizing energy losses. The energy and exergy losses at various system components were detected for optimization and overall efficiency. Classes of cascade refrigeration system designs were discussed for selecting the most economically viable type based on applications. The physicochemical properties of refrigerants were enumerated for achieving the desired cold temperature. An energy-efficient system for the handling and delivery of food and biomedical storage spaces. gas compression, petroleum-based products used in oil and gas manufacturing, electricity production, carbon sequestration, and the cold storage of biological cells are made possible by the review's findings. It was determined that a multi-stage refrigeration cycle could easily be constructed to supply the low temperature needed for factory operations. Equations were used in the review to propose potential methods of detecting system losses and calculating energy consumption in a two-stage vapor compression refrigeration system. As a result, the system's total energy-exergy efficiency was upgraded. Coefficients of performance were computed for a range of efficiency characteristics.

The review findings provided the following specific results:

i. Various classes of cascade refrigeration systems were stated, enumerated, and characterized on the basis of operation modules.
ii. The mechanical design of cascade refrigeration system components was carried out theoretically coupled applications.
iii. The physiochemical properties and significance of refrigerants in refrigeration systems were sequentially stated for application selection.
iv. The special applications of cascade refrigeration systems in solving real-life problems and their indispensability for advanced technological research to meet specific needs were elucidated.
v. A thermodynamic tool was employed to evaluate the system coefficient of performance and refrigerating effects for enhancing plant performance criteria.
vi. An energetic tool was utilized to identify, quantify, and evaluate system inefficiencies and energy losses. This helped in achieving optimal design concepts and system reliability.
vii. Techniques for eliminating energy losses, improving efficiency, and optimizing the processes of systems were analyzed through formulae.
viii. A theoretical approach was utilized to identify energy site losses, minimize possible energy destruction, optimize process operations, and ensure optimal machine performance.
ix. System model design and building techniques were mapped out (utilizing equations) for cascading optimal performance and zero energy destruction to achieve the desired ultra-low temperature.

Nomenclature

Symbol	Parameter	Units
I	Irreversibility	
η_x	Exergetic efficiency in percentage	%
s_1	Specific entropy of the refrigerant at	kJ/kg-

	the compressor outlet	K
s_2	Specific entropy of the refrigerant at the evaporator outlet	kJ/kg-K
s_3	Specific entropy of the refrigerant at the condenser outlet	kJ/kg-K
s_4	Refrigerant specific entropy at the expansion valve evaporator inlet	kJ/kg-K
h_1	Specific enthalpy of the refrigerant at the outlet of the evaporator	kJ/kg
h_2	Specific enthalpy of the refrigerant at the outlet of the compressor	kJ/kg
h_3	Specific enthalpy of the refrigerant at the outlet of the condenser	kJ/kg
h_4	Specific enthalpy of the refrigerant at the inlet of the evaporator	kJ/kg
W_{comp}	Compressor power input	Kw
Q_{cond}	Heat transfer rate at the condenser	Kw
Q_E	Heat transfer rate through the boundary at T_{evaps}	Kw
$\dot{m}$	refrigerant mass flow rate	kg/s
V	Volume flow rate	m^3/s
$\dot{m}$ i	Mass flow rate	kg/s
σ_τ	Tangential stress	Pa
V	Specific volume	m^3/kg
A_i	Inner area of the pipe	m^2
V_r	Velocity of the refrigerant in the pipe	m/s
S_y	Yield strength	Pa
P_i	Inside pressure	Pa
r_o	Outer radius	M
r_i	Inner radius	M
N	Factor of safety	

References

[1] Cirera, J., Carino, J. A., Zurita, D. and Ortega, J. A. (2020). Improving the energy efficiency of industrial refrigeration systems by means of data-driven load management. Molecular diversity preservation international (MDPL), Switzerland, 8, 1106.

[2] Bhavesh, P., Surendra, S. K. and Bhumik, M. (2016). Thermodynamic modeling and parametric study of a Two Stage Compression Absorption Refrigeration System for Ice Cream Hardening Plant. International Conference on recent advancements in Air conditioning and Refrigeration, Bhubaneswar, India, 10-12.

[3] Oginni, O. T., Bolaji, B. O., Oyelaran, O. A. (2023). Design and Building of a Two-Stage Cascade Refrigeration System for Storage of Blood Plasma. FUOYE Journal of Engineering and Technology (FUOYEJET), 8(3), http://doi.org/10.46792/Fuoyejet.v8i3.1060

[4] Kasi, P. and Cheralathan, M. (2021). Review of cascade refrigeration systems for vaccine storage. Journal of Physics: Conference Series, 2054:012041. https://doi.org/ 10.1088/1742-6596/2054/1/012041.

[5] Mota-Babiloni, A., Mastani, J. M., Navarro-Esbrí, J., Mateu-Royo, C., Barrag´an- Cervera, A, and Amat-Albuixech, M. (2020). Ultralow-temperature refrigeration systems: Configurations and refrigerants to reduce the environmental impact. International Journal of Refrigeration, 111, 147–58.

[6] Ghulam, R., Nilesh, K., Neha, P., Ashwini W. and Renuka, D, (2017). Cascade Refrigeration System for Blood Storage, Dr. D. Y. Patil Institute of Technology, Pimpri,Pune / Savitribai Phule Pune University, India.

[7] Mate, A., Panhale, P., Shinde, V. and Mane, P. (2017). Design and development of cascade refrigeration system. International Research Journal of Engineering and Technology (IRJET), 4, 2395 -0056

[8] Darwin, R. B., Syaka, W. S. and Muhammad, B. (2019). Characteristics study of two-stage cascade refrigeration system design for household air blast freezing. International Journal of Mechanical Engineering and Technology (IJMET), 10, 1804-1813.

[9] Mouneer, T A., Elshaer, A. and Aly, M. (2021). Novel Cascade Refrigeration Cycle for Cold Supply Chain of COVID-19 Vaccines at Ultra-Low Temperature -80°C Using Ethane (R170) Based Hydrocarbon Pair. World Journal of Engineering and Technology, 9, 309-336; doi: 10.4236/wjet.2021.92022.

[10] Park, H., Kim, D. H. and Kim M. S. (2013). Thermodynamic analysis of optimal intermediate temperature in R134a-R410A cascade refrigeration systems and its experimental verification. Applied Thermal Engineering, 54, 319-327.

[11] Udroiu, C. M., Mota-Babiloni, A., Espin´os-Est´evez, C. and Navarro-Esbrí, J. (2022). Energy-efficient technologies for ultra-low temperature refrigeration. Annual Conference, Smart and Sustainable Technology for Resilient Cities and Communities, Springer Singapore, 10, 309.

[12] Mishra, R. S. (2017). Thermal modeling of three stage vapour compression cascade refrigeration system using entropy generation principle for reducing global warming and ozone depletion using ecofriendly refrigerants for semen preservation. International Journal of Engineering and Innovation, 1, 22-28.

[13] Tao, B., Yu, L., Gang, Y. and Jianlin, Y. (2020). Performance Analysis of an Ejector Enhanced Two-Stage Auto-Cascade Refrigeration Cycle for Low Temperature Freezer. Journal of Thermal Science, 6, 1-12.

[14] Mingzhang, P., Huan, Z., Dongwu, L., Yan, Z., Youcai, L. and Guangrui, B. (2020). A Review of the Cascade Refrigeration System. Energies 2020, Vol.13; doi:10.3390/en13092254 www.mdpi.com/journal/energies

[15] Oginni, O. T., Bolaji, B. O., Oyelaran, O. A., Fadiji, E. A., Ige, A. M., & Yinka, A. (2023). Thermodynamic Performance Analysis of Cascade Vapour Refrigeration System Using Different Refrigerant Pairs : A Review. Adeleke University Journal of Engineering and Technology (AUJET), ISSN: 2714 – 2450, 6, (1), 132 – 145.

[16] Alhamid, M.I., Nasruddin, Darwin, R.B.S. and Lubis, A. (2013). Characteristics and COP Cascade Refrigeration System Using Hydrocarbon Refrigerant (Propane, Ethane and CO2) at Low Temperature Circuit (LTC). International Journal of Technology, 4, 112-120. https://doi.org/10.14716/ijtech.v4i2.125

[17] Bai, T., Lu, Yu., Yan, G. and Yu, J. (2021). Performance Analysis of an Ejector Enhanced Two-Stage Auto-Cascade Refrigeration Cycle for Low Temperature Freezer. *Journal of Thermal Science*, 30, 2015 - 2026.

[18] Bisht, V. S. and Pratihar, A. K. (2014). Thermodynamic analysis of actual vapour compression system with R22 and its eco-friendly alternatives refrigerants. International Journal of Advance Research in Science and Engineering IJARSE, 3(3), 2319-8354.

[19] Leonardo, A. M., Guillermo, V. O. and Gaudy, P. B. (2018). Computer-aided simulation of the energetic efficiency of a two-stage cascade cooling system cycle. International Journal of Applied Engineering Research, Indian, 13, 11123-11125.

[20] Joybari, M. M., Hatamipour, M. S., Rahimi, A., and Modarres, F. G. (2013). Exergy Analysis and Optimization of R600a as a Replacement of R134a in a Domestic Refrigerator System. International Journal of Refrigeration, 36(4), 1233–1242.

[21] Mohan, C. (2014). Exergy analysis of vapour compression refrigeration system using R12 and R134a as refrigerants. International Journal of Student Research in Technology and Management, 2, 134-139.

[22] Mondragon, L., Ochoa, G. V., and Botia, G. P. (2018). Computer-Aided Simulation of the Energetic and Exergetic Efficiency of a Two Stage Cascade Cooling Cycle. International Journal of Applied Engineering Research, 13(13), 11123-11128.

[23] Aktemur, C., Ozturk, I.T. and Cimsit, C. (2021). Comparative Energy and Exergy Analysis of a Subcritical Cascade Refrigeration System Using Low Global Warming Potential Refrigerants. Applied Thermal Engineering, 184, Article ID: 116254, https://doi.org/10.1016/j.applthermaleng.2020.116254

[24] Abdullah, A. (2012). Effect of evaporator temperature on vapor compression refrigeration system. Alexandria Engineering Journal, 50, 283–290.

[25] Tan, H., Xu, L., Yang, L., Bai, M. and Liu, Z. (2023). Operation performance of an ultralow-temperature cascade refrigeration freezer with environmentally friendly refrigerants R290-R170. Environmental Science and Pollution Research, 30, 29790-29806.

[26] Mogaji, T. S. Awolala, A., Ayodeji, O. Z., Mogaji, P. B. and Philip D. E. (2020). COP enhancement of vapour compression refrigeration system using dedicated mechanical subcooling cycle. Nigerian Journal of

Technology (NIJOTECH), 39, 776 – 784.
[27] Ustaoglu, A., Kursuncu, B., Alptekin, M. and Gok, M. S. (2020). Performance Optimization and Parametric Evaluation of the Cascade Vapor Compression Refrigeration Cycle Using Taguchi and ANOVA Methods. Applied Thermal Engineering, 180, Article ID:115816.https://doi.org/10.1016/j.applthermaleng.2020.115816
[28] Rui, S., Zhang, H., Zhang, B. and Wen, D. (2016). Experimental Investigation of the Performance of a Single-Stage Auto-Cascade Refrigerator. Heat and Mass Transfer, 52, 11-20. https://doi.org/10.1007/s00231-015-1577-4
[29] Jinkun, Z., Shengjian, L., Qin, W. and Dahong, L. (2018). Optimization analysis on the performance of an auto-cascade absorption refrigeration system operating with mixed refrigerants. International Journal of low-carbon Technologies, 13, 212-217.
[30] Roy, R. and Mandal, B.K. (2020). Thermo-Economic Analysis and Multi-Objective Optimization of Vapour Cascade Refrigeration System Using Different Refrigerant Combinations: A Comparative Study. Journal of Thermal Analysis and Calorimetry, 139, 3247-3261, https://doi.org/10.1007/s10973-019-08710-x
[31] Wang, H., Song, Y. and Cao, F. (2020). Experimental Investigation on the Pull-Down Performance of a -80°C Ultra-Low Temperature Freezer. International Journal of Refrigeration, 119, 1-10; https://doi.org/10.1016/j.ijrefrig.2020.04.030
[32] Bolaji, B. O. (2014). Influence of Subcooling on the Energy Performance of Two Eco-friendly R22 Alternative Refrigerants. Journal of Science and Technology, 34, 73- 83.
[33] Mishra, R. (2014). Thermodynamic performance evaluation of multi-evaporators single compressor in vapor compression refrigeration systems for reducing ozone depletion. International journal of advance research and innovation, 2, 325- 332.
[34] Mota-Babiloni, A., Makhnatch, P. and Khodabandeh, R. (2017). Recent investigations in HFCs substitution with lower GWP synthetic alternatives: Focus on energetic performance and environmental impact. International Journal of Refrigeration, 82, 288-301.
[35] Roy, R., Mandal, B. K. (2019). Thermo-economic analysis and multi-objective optimization of vapour cascade refrigeration system using different refrigerant combination. Journal of Thermal Analysis and Calorimetry, 3, 231 - 242.
[36] Seyitoglu SS., Dincer, I. and Kilicarslan, A. (2010). Energy and exergy analysis of hydrogen production by coal gasification. International Journal of Hydrogen Energy, 42, 2592-2600.