FUOYE Journal of Engineering and Technology, Volume 8, Issue 3, September 2023 ISSN: 2579-0617 (Paper), 2579-0625 (Online)

Design and Building of a Two-Stage Cascade Refrigeration System for Storage of Blood Plasma

[1]Olarewaju T. Oginni, [2]Bukola O. Bolaji, and [2]Olatunde A. Oyelaran
[1]Department of Mechanical Engineering, Bamidele Olumilua University of Education, Science and Technology, Ikere-Ekiti, Nigeria
[2]Department of Mechanical Engineering, Federal University Oye-Ekiti, Nigeria
oginni.olarewaju@bouesti.edu.ng|bukola.bolaji@fuoye.edu.ng|ajani.oyelaran@gmail.com

Received: 11-JUN-2023; Reviewed: 05-AUG-2023; Accepted: 11-AUG-2023
http://doi.org/10.46792/fuoyejet.v8i3.1060

ORIGINAL RESEARCH

Abstract- Daily life-saving transfusions rely on the usage of blood products in clinical and research settings. With its proteins used for replacement treatment, human blood plasma serves as the main source for a variety of therapeutic transfusions. During the COVID-19 pandemic, plasma-based therapy was one of the treatment modalities used to treat infectious infections and as a source of neutralizing antibodies in patients. The speciality of transfusion medicine was adversely impacted and faced a stockpile shortage because plasma must be quickly frozen within six hours of collection in order for its proteins and coagulation components to be of the optimum quality. As a result, the cascade refrigeration system is an innovative technology that can provide the required ultra-low freezing temperature and maintain the same temperature in storage for plasma management. The paper concentrated on the design and construction analysis of a two-stage cascade refrigeration system for quick freezing time, and storing plasma proteins at extremely low temperatures to prolong their limited shelf life in a sensitive, temperature-controlled storage system. The choice of refrigerants R404A and R410A is made for high temperature and low temperature circuits which are carefully selected based on study and analysis of the characteristics of different refrigerants for short-term freezing. The ultra-low temperature evaporator is achieved using a blend of two vapour compression refrigeration cycles thermally connected by a heat exchanger to produce a freezing temperature of -35 ^{0}C. For analysis, the system was charged with various weights of plasma weighing between 1 kg and 4 kg for two hours and a half hour and kept at a temperature of -35 ^{0}C. The system's dependability and practicality for extending plasma shelf life were assessed. After 72 hours of temperature-controlled storage, the results showed 75% efficiency and a negligible (0.4) plasma quality drop.

Keywords- Controlled-Temperature, Design, Quality, Rapid Freezing, Shelf-life

◆

1 INTRODUCTION

Low-temperature technology is a branch of cryogenics and refrigeration for deep storage of samples by petrochemicals, pharmaceuticals, and other biological samples. For preservation of biobanking samples, proteins, deoxyribonucleic acid, vaccines, antibodies, small molecules, enzymes, and other biological materials, ultra-low temperature refrigeration is a critical necessity in all research fields, businesses, and domestic uses. Perishable food items, food processing, storage, and transportation are all preserved by keeping them at low temperatures, which is one of the most significant uses of refrigeration (Bolaji, 2016).

The cascade refrigeration system, an energy-efficient cycle that lowers running costs for attaining quick freezing and maintaining optimum storage temperature, is the most promising technology in low-temperature applications. It functions in sub-zero conditions and has frozen cabinets with an evaporation temperature that ranges from -18°C to -35°C. When it comes to heat-sensitive goods, such vaccines and blood products, which need to be stored safely and require a powerful refrigeration system, the cascade system offers numerous solutions. The system condenses the other major refrigerant, which is working at the target evaporator, using one of the refrigerants. (Bijaksana, 2019).

For example, in the medical field, cascade refrigeration technology is used in blood banks for the preservation of plasma, vaccinations, bone banks, and other biological fluids. Keeping vaccinations that are heat-sensitive at the proper temperature is important but sometimes challenging due to the lack of ultra-low temperature cold storage. Due to its numerous advantages in meeting human everyday requirements and scientific sectors including medicine, biology, business, agriculture, and industry, the applications of this machine have lately attracted the interest of both academia and industry (Mouneer *et al*., 2021) and (Bolaji and Huan, 2014b).

Several essential drugs and vaccines require a constant cold chain from the time of creation till the time of inoculation to maintain their integrity. When vaccines are maintained at low temperatures, the risk of bacteria growing inside the vaccine and reducing its effectiveness is decreased (Rabbani *et al*., 2017). It is difficult to deliver vaccinations to every region of the world. A sequence of painstakingly scheduled operations must be carried out in temperature-controlled environments in order to store, handle, and transport these life-saving supplies (Mouneer *et al*., 2021; Ratio, 2018). But a variety of diseases and infections brought on by human plasma transfusion need immediate attention, more research, and technical breakthroughs. Therefore, the slow processing of fresh plasma and the subpar temperature control, especially during times of power outages in Nigeria, are the driving forces behind the necessity for this study to design a quick model management for safe transfusion delivery in an emergency.

---

*Corresponding Author

Section B- MECHANICAL/MECHATRONICS ENGINEERING & RELATED SCIENCES
Can be cited as:
Oginni, O.T., Bolaji, B.O., and 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 (FUOYE**JET**), **8(3), 329-335.**
http://doi.org/10.46792/fuoyejet.v8i3.1060

© 2023 The Author(s). Published by Faculty of Engineering, Federal University Oye-Ekiti.
This is an open access article under the CC BY NC license. (https://creativecommons.org/licenses/by-nc/4.0/)

2 CHALLENGES RELATED TO PLASMA STORAGE

Blood and blood products must be accessible in sufficient and secure quantities, as well as safe transfusion services and effective use of blood components in disease detection, treatment, and prevention (Tu *et al.*, 2020; Rabbani *et al.*, 2017). One of the therapeutic modalities used to treat infectious disorders in COVID-19 was plasma-based therapy. (Rabbani *et al.*, 2017) and (Gao et al., 2020; Selvnes *et al.*, 2021). But the reasons for the shortage, which led to a lack of blood products and posed a significant global problem in transfusion medicine, were a lack of planning, international safety concerns regarding plasma importation, difficulties with plasma administration, and a problem with frozen plasma within 8 to 24 hours of collection (Gauthier & Griffin 2014).

2.1 TWO-STAGE CASCADE REFRIGERATION SYSTEM

Two independently operating single-stage refrigeration systems are connected in series to create a cascade system (Oginni *et al.*, 2023): a lower system that maintains a lower evaporating temperature and creates a refrigeration effect, and a higher system that runs at a higher evaporating temperature. The heat generated by the condenser in the lower system is extracted by the evaporator in the upper system through a cascade condenser that connects these two independent systems. When a very large temperature range between low and high temperatures is necessary, the cascade cycle is utilized. The COP of a refrigeration cycle is enhanced by cascade. Additionally, choosing refrigerants with progressively decreasing boiling points will allow for adequate evaporator and condenser pressures throughout two or more temperature ranges (Bijaksana, 2019; Bolaji & Huan, 2012).

2.2 STUDIES ON CASCADE REFRIGERATION SYSTEM

R404A and R22 were used to design and build a two-stage cascade refrigeration system for use at high and low temperatures, respectively. Before the refrigerant was introduced to the throttling device, a heat exchanger was used to physically connect compressor's inlet and throttling device's intake in order to superheat and pre-cool the refrigerant entering the compressor. By doing this, the system was able to have a higher COP and last longer (Selvnes *et al.*, 2021; Tsatsaronis & Morosuk, 2018). Pan *et al.*, (2020) and Subramani & Prakash, (2011) work was built on simulation of a two-stage cascade refrigeration system model as well as model's validation and evaluation utilizing information from experiments. Following the design of the two-stage cascade refrigeration system R22/R32, an experiment was carried out to collect operational data that would be used to validate and rate the system's constituent parts. The two-stage cascade refrigeration system was created to provide simulation the appropriate temperature and pressure. The results of the experiment revealed that the COP value was 1.018 at the evaporator temperature of -40 °C.

2.3 SYSTEM WORKING PRINCIPLE

A cascade refrigeration system's parts are schematically depicted in figure 1 along with the system itself. It comprises of a cascade condenser that thermodynamically connects two stages of lower temperature (pressure) cycle and higher temperature (pressure) cycle. The Low Temperature Compressor, High Temperature Compressor, Condenser, Evaporator, Cascade Condenser (Heat Exchanger), and Throttling Devices for Low Temperature Cycle and High Temperature Cycle are the major elements of the Cascade System (Martins *et al.*, 2012).

The low pressure and low temperature cycle refrigerant are isentropically compressed during processes 1 and 2. The refrigerant of a higher temperature and pressure receives heat as it passes through a cascade condenser (processes 2–3). In order to create the required refrigerating effect, it expands in the throttling device (process 3–4) and then moves on to the evaporator (process 4–1). The refrigerant is compressed in the upper stage using a high temperature cycle compressor (processes 5–6), and it then passes through a condenser where it rejects heat (processes 6–7). It travels via a throttling mechanism (processes 7 and 8) where it expands isentropically, and then continues on to a cascade condenser where heat transfer between two refrigerants occurs (Rangel *et al.*, 2022; Selvnes *et al.*, 2021).

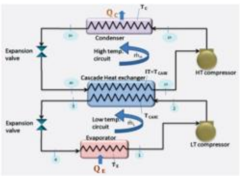

Fig. 1: Schematic Diagram of a Simple Cascade Refrigeration System

2.4 CASCADE REFRIGERATION CYCLE OPTIMIZATION

Mouneer *et al.*, (2021) experimentally investigated the pull-down performance of a −80 °C ultra-low temperature freezer. The study concluded that the volumetric efficiency of high temperature cycle compressor deteriorated more obviously during the pull-down process, and had higher potential for performance improvement compared with that of low temperature cycle. According to Raphael *et al.*, (2020), the research optimized the performance of a vapour compression cascade refrigeration cycle by considering the statistical analysis methods, Taguchi and ANOVA approaches. They concluded that the coefficient of performance and exergy efficiency within the range of the operating parameters in the evaluation were found to be 3.274% and 37.63%. In a further study to optimize the performance of cascade refrigeration system, Mouneer *et al.*, (2021) proposed a novel ternary mixture, R600a/R23/R14, for ARC systems for −83 °C applications. The results demonstrated the feasibility of the proposed R600a/R23/R14 ternary mixture as an environmental benign alternative for Auto-Refrigeration cascade systems. ting conditions.

2.5 INFLUENCE OF REFRIGERANT TYPES ON CASCADE REFRIGERATION CYCLES

A theoretical study on a modified vapour compression refrigeration cycle with zeotropic mixture R170/R290 for freezers was conducted with the potential advantages for ultra-low temperature application in the freezers. Martins *et al.*, (2012) presented the thermodynamic performance of R170/R290 mixture on a heat pump bench test in an

© 2023 The Author(s). Published by Faculty of Engineering, Federal University Oye-Ekiti.

This is an open access article under the CC BY NC license. (https://creativecommons.org/licenses/by-nc/4.0/)

attempt to substitute R22, the result revealed that the coefficient of performance and capacity of R290 were up to 15.4% higher and 7.5% lower, respectively than those of R22 for two conditions. In a similar work, Oginni et al., (2023) presented a comparative analysis of thermodynamic performance of cascade refrigeration systems for refrigerant couples R41/R404A and R23/R404A to discover whether R41 is a suitable substitute for R23. It was noticed that the theoretical analysis indicates that R41/R404A is a more potential refrigerant couple than R23/ R404A in the cascade refrigeration system. R22 refrigerant was mainly used in air conditioners and deep freezers etc. R22 has ozone depletion potential (ODP) of 0.034. The global warming potential (GWP) of R22 is 1700 and atmospheric life time of 12 years. The replacements of R22 are R407C and 410A having zero ozone depletion potential. Although, R22 has very low ozone depletion potential but high global warming potential. The replacements of R22 are R407C and 410A (Bolaji & Huan, 2012).

Summarily, refrigerants are often evaluated in terms of their suitability for use in a specific application. A substance is a useful refrigerant (or a mixture of substances) if it satisfies a set of different criteria. Firstly, having suitable chemical, physical and thermodynamic properties for a specific system and working conditions and secondly, should be safe to use, including environmentally safe. However, Mahmood *et al*., (2021 and Mogaji *et al*., (2020) study helped to find out the best refrigerants and appropriate operation parameters. It is found in the study that cascade condenser, compressor and refrigerant throttle valve are the major source of exergy destruction. The analysis has been realized by means of mathematical model of the refrigeration system

2.6 THE BLOOD PLASMA AND ITS COMPONENTS

Plasma is the liquid portion of blood that is essential for the components of blood to circulate through the body known as blood plasma, appears light-yellowish or straw-coloured. It consists of water and its dissolved constituents including proteins like albumin, fibrinogen and globulins. Plasma is mostly water that is absorbed from ingested food and fluid by the intestines. The heart pumps them around the body as blood by way of the blood vessels. Plasma constitutes 55% of blood's total volume and the remaining 45% are RBC, WBC and platelets that are suspended in the plasma. It contains 91% to 92% of water and 8% to 9% of solids include glucose, hormones, proteins, mineral salts, fats, vitamins, waste products, clotting factors, immunoglobulins, carbon dioxide. The remaining 45% of blood mainly consists of red and white blood cells and platelets. The protein concentration in plasma/serum is approximately 60 – 80 mg/mL of which about 50 – 60 % are albumins and 40 % globulins (10 – 20 % immunoglobulin). Each of these has a vital role to play in keeping the blood functioning effectively. It is the proteins that have been the focus of interest for transfusion medicine,(Mouneer *et al*., 2021; Rabbani *et al*., 2017). Blood plasma is a yellowish liquid as shown in figure 2.

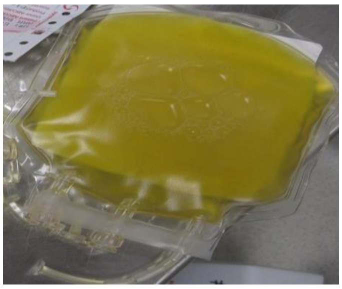

Fig. 2: The Human Fresh Frozen Plasma

2.6.1 Physio-Chemical Properties of Blood Plasma

Table 1 characterised the physiochemical properties of blood plasma ranging appearance, heat capacity, boiling and melting points, freezing and storage temperatures among others (Rabbani *et al*., 2017).

Table 1. Physiochemical Properties of Blood Plasma.

Properties	Values
Appearance	Barely yellow to dark yellow
Specific heat capacity above freezing point	3.93J/g-^{0}C
Specific heat capacity below freezing point	2.0 J/kg
Latent heat	307 J/kg
Melting point	-0.568 – 0.512 ^{0}C
Boiling point	Approximately 0.158 ^{0}C
Density	1025 Kg/m^3 or 1.025g/ml
Freezing point	At -0.59 ^{0}C
Storage temperature	-18 C or colder
Protein's content	It is 7% protein
Mineral salts	It contains 1% mineral salts
Water content	91% to 92% amount of water

3 METHODOLOGY

3.1 DESIGN CYCLE ANALYSIS

The following assumptions were made to simplify the thermodynamic analysis:

i. All components were assumed to operate at a steady state.
ii. The changes in the kinetic and potential energy of the working fluids across each component are negligible.
iii. The heat loss and pressure drop in the component-piping network are negligible.
iv. All throttling devices are at constant enthalpy (isenthalpic).
v. The heat transfer process in the heat exchangers is at constant pressure (isobaric).

3.1.1 Design Parameters

Figure 3 shows the computer aided design of both the refrigerating chamber with the suspended plasma, whereas figure 4 is the constructed two-stage cascade refrigeration system developed for quick freezing of the fresh plasma. All the components of the refrigeration system were arranged in compact form as a unit for transit purpose and portability. The unit is separated into two as shown. One sub-unit is the evaporator (cooling box) mounted directly on the system components arrangement in the same support frame to minimize space.

© 2023 The Author(s). Published by Faculty of Engineering, Federal University Oye-Ekiti.
This is an open access article under the CC BY NC license. (https://creativecommons.org/licenses/by-nc/4.0/)

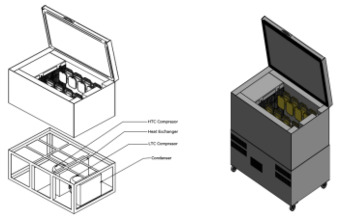

Fig. 3: Design Drawing and System Solid Works

Fig. 4: System and Blood Plasma Assembly

3.2 REFRIGERANT SELECTION

The selection of R410A and R404A refrigerants in this study is purposely targeted rapid freezing and storing blood plasma proteins for shelf-life increase. The following factors were considered among others such as better mass flow rate, high refrigerating effect, high discharge pressure, short time for low-temp. attainment, better C.O.P, affordability (cheap) and availability and existing refrigeration components favour R410A and R404A. (Bolaji & Huan, 2012, 2014a). In many industries and medical sectors, the time to achieve the desired temperature is paramount utmost. Refrigerants R410A and R404A were chosen for rapid homogeneous freezing and storing fresh blood plasma in terms of refrigerating Effect and Discharge Pressure, R410A is slightly better than that of R22, achieving low-temperature in short time, R404A is recommended for domestic refrigeration purpose, R410A is preferred over R22, mass flow rate, R404A is better when compared with R410A and R22 and thermodynamic properties for all refrigerants, R410A is widely used refrigerant (System, 2014).

3.3 CYCLE ANALYSIS

3.3.1 Determination of Heat Load

A. Heat Conducted through the Walls of Evaporator

The wall heat gain load or the wall leakage load is a measure of the heat flow rate by conduction through the walls of refrigerated space from the outside to the inside. The quantity of heat conducted through the walls of evaporator mainly depends on the temperature difference between the inside and outside of the chamber, their thermal resistance, thickness and surface area. Thus, in this design, the followings are maintained:

Ambient product temperature, T_{AP} = 35 ^{o}C = 308 K
Frozen plasma temperature, T_{FP} = -35 ^{o}C = 238 K

Change in temperature, $\Delta T = T_{AP} - T_{FP} = 70$ K

$A_{ins} = \{[(1.03 \times 0.65) + (1.03 \times 0.50) + (0.65 \times 0.50)] \times 2\}$ m^2

$A_{ins} = 3.02$ m^2 Lemboye *et al*., (2015) (1)

$$\dot{Q} = UA\Delta T \quad (2)$$

$$\dot{Q}_{cond} = (0.314 \times 3.02 \times 70) \text{ W}$$

$$\dot{Q}_{cond} = 0.0664 \text{ kW} \quad (3)$$

The quantity of heat conducted, Q_C, through the walls of the evaporator in three hours of steady operation is estimated as follows:

$$Q_{cond} = \dot{Q}_{cond}\, t \quad (4)$$

$$Q_{cond} = 717.12 \text{ kJ} \quad (5)$$

B. The Product Heat Load

The heat emitted from the product to be stored is very important in case of cold storages. The product load for the system is the total mass of the blood plasma (250ml) and its bag each.

The cooling chamber is designed to take in 16 pieces of blood plasma bags at a time.

$$m_{tp} = 0.256 \times 16 = 4.1 \text{ kg} \quad (6)$$

Therefore, the capacity of the evaporator (cooling chamber load on isolation) is 4.1 kg of blood plasma bags. In other to determine the product load (Q_{prod}) of the cascade system, the load to be considered in the cold storages are divided into three groups via;

i. Chilling Load Above Freezing, Q_c

This is the heat gained in cooling the blood plasma from 30℃ to -0.59 ℃ (blood plasma starts freezing at -0.59 ℃).

$$Q_c = m_{tp}\, c_p\, \Delta T_1 \quad (7)$$

$$Q_c = 573.46 \text{ kJ} \quad (8)$$

ii. Cooling Load Below Freezing, Q_{bf}

This is the heat gained in further cooling from -0.59℃ to -35℃.

$$Q_{bf} = m_{fp} \times c_{fp} \times \Delta T_2 \quad (9)$$

$$Q_{bf} = 282.16 \text{ kJ} \quad (10)$$

iii. Freezing Load, Q_f

This is the heat gained in changing the phase of blood plasma from -0.59℃ to freeze plasma (latent heat of freezing).

$$Q_f = m_{fp} L_{fp} \quad (11)$$

$$Q_f = 1258.70 \text{ kJ} \quad (12)$$

Therefore, the product heat load of the cascade system, Q_{prod} is calculated as follows:

$$Q_{prod} = Q_c + Q_f + Q_{bf} \quad (13)$$

$$Q_{prod} = 195.77 \text{ W} \quad (14)$$

C. Infiltration Heat Gain

The infiltration air is the air that enters a refrigerated chamber through cracks and opening of doors. This is caused by temperature difference between the inside and outside air, cooler sizes.

$$Q_{inf} = m_{inf}\, C_a\, (T_o - T_i) \quad (15)$$

$$= 1.55 \text{ W} \quad (16)$$

D. Packaging Heat Gain

Packages might be made of plastic, steel, wood, glass, or any other material with a low specific heat, often accounting for more than 10% of the weight of the goods. Each 250 g of liquid plasma is placed in a plastic bag, which is then suspended using a hanger.

$$Q_{pk} = m_{pk}\, C_{pk}\, (T_o - T_i) \times 10^3 \quad (17)$$

$$Q_{pk} = 4.25 \text{ W} \quad (18)$$

© 2023 The Author(s). Published by Faculty of Engineering, Federal University Oye-Ekiti.
This is an open access article under the CC BY NC license. (https://creativecommons.org/licenses/by-nc/4.0/)

http://doi.org/10.46792/fuoyejet.v8i3.1060

E. Service Load

The amount of heat added by the system operations as lighting, opening and the like is called service load. The service load is dealt with collectively and assumed to be 1% of heat from the other two sources. Hence, the service load, Q_{serv} is given by;

$$Q_{\text{serv}} = (Q_{cond} + Q_{prod} + Q_{inf} + Q_{pk}) \text{ x } 1 \quad (19)$$

$$Q_{\text{serv}} = 9.19 \quad (20)$$

3.3.2 Total Heat Load

This is the summation of all the heat loads, Q_T as given by

$$Q_T = Q_{cond} + Q_{prod} + Q_{inf} + Q_{pk} + Q_{\text{serv}} \quad (21)$$

$$Q_T = 927.88 \text{ W} \quad (22)$$

For the factor of safety, we take 40%

$$Q_{TCL} = Q_T + Q_T \text{ x SF} \quad (23)$$

$$= 1.299 \text{ kW} \quad (24)$$

However, refrigeration system is rated by the amount of heat it would remove within a certain defined time. Considering the time to absorb the above heat load to be 3 hours, the refrigeration capacity, Q_{Ref} for the system is estimated thus;

$$Q_{\text{Ref}} = 1.299 \text{ kW} \quad (25)$$

3.3.3 Compressor Size

The required compressor size to produce the refrigerating capacity of 1.299 kW for three hours daily is approximately 2hp (1 hp compressor each). The Evaporator and Condenser were selected and bought based on this compressor capacity (Lamboye *et al.*, 2015).

3.3.4 Design of Evaporator

The refrigeration capacity is calculated by using equation 26 taking u = 0.04345 kW/m²K

$$Q_{\text{Ref}} = UA\Delta T = 1.299 \text{ kW} \quad (26)$$

3.3.5 Design of LTC Condenser (cascade condenser)

The heat rejected by LTC condenser, Q_{CL} is defined by

$$Q_{CL} = \dot{m}_L (h_2 - h_3) \quad (27)$$

$$Q_{CL} = 1.726 \text{ kW} \quad (28)$$

3.3.6 Design of HTC Condenser

The heat rejected by HTC condenser, Q_{CH} is defined by equation 29

$$Q_{CH} = \dot{m}_H (h_6 - h_7) \quad (29)$$

$$Q_{CH} = 1.954 \text{ kW} \quad (30)$$

3.3.7 Fabrication and Assembly of the Machine

The components were bought and fixed appropriately when the cooling load and the operating conditions are determined based on design calculations. The piping networks for easy flow were made of copper tube and brazed together with the aid of sivrons. Circuit breakers were used as a safety device over load and current fluctuation. Thermocouples were mounted on the evaporator to display the evaporator temperatures as the device works. The compressors were installed inside the same casing below the evaporator in the same unit with the respective condenser using bolts and nuts. Other components such as the expansion valves and filters were fixed by welding as showed. All the components of the refrigeration system were arranged in compact form as a unit for transit purpose and portability. The unit is separated into two as shown in figure 3. One sub-unit is the evaporator (cooling box) mounted directly on the system components arrangement in the same support frame to minimize space as presented in figure 4.

The machine was evaluated on no load and charged with varying loads ranging 1 kg to 4 kg until the system attained -35 ⁰C. The frozen plasma was kept at same temperature while quality assessments were made at regular interval of 18 hours. The result was analysed using refractometer.

4 RESULTS AND DISCUSSION

The results from the design analysis at varying operating conditions of the system using dissimilar refrigerants R410A and R404A are as presented in Table 2.

Table 2. Results of the Various Design and Performance Analysis of VCRS

Cycle	LTC	HTC
Refrigerating Effect (kJ/kg)	180.7	-
Mass flow rate (kg/s)	0.007	0.016
Compressor Pressure Ratio	6.199	2.069
Compressor Work (kJ/kg)	59.4	14.46
Compressor Power (kw)	0.427	0.226
Compressor Power (hp)	0.57	0.30
Cycle COP	3.04	7.66
Revered Cycle COP	4.49	10.18
System Efficiency (%)	67.7	75.25
Heat Rejection (kw)	-	1.73

In Table 2, the design performance analysis of a two-stage cascade refrigeration system is compared. The system's efficiency in both cycles is 75.25% (HTC) and 67.7% (LTC). In comparison to the HT cycle, the LT cycle performed 59.4 kJ/kg of compressor work. While the mass flow rate was lower at LT (0.00719 kg/s) than HT (0.0156 kg/s), the system refrigerating impact is 180.7 kJ/kg. Performance cycle coefficients for LTC and HTC are 3.04 and 7.66, respectively.

A. Coefficient of Performance, COP_{cas}

The coefficient of coefficient of performance for the whole system, COP_{cas} is calculated as given by equation 31.

$$COP_{cas} = \frac{R_e}{W_{CL}+W_{CH}} \quad (31)$$

$$COP_{cas} = 2.45 \quad (32)$$

A coefficient of performance of 2.45 implies that, 3 kW of air-cooling power is achieved for every kW of electricity consumed by the system's compressor (input power). It is well known that when the refrigerated space temperature drops, the cascaded system's performance coefficient falls.

B. Isentropic Efficiency, $\eta_{isentropic}$

The isentropic efficiency of the system is estimated as follows:

$$\eta_{isentropic} = \frac{W_{rev}}{W_{actual}} x 100\% \quad (33)$$

$$\eta_{isentropic} = 58.5\ \% \quad (34)$$

© 2023 The Author(s). Published by Faculty of Engineering, Federal University Oye-Ekiti.
This is an open access article under the CC BY NC license. (https://creativecommons.org/licenses/by-nc/4.0/)

http://doi.org/10.46792/fuoyejet.v8i3.1060

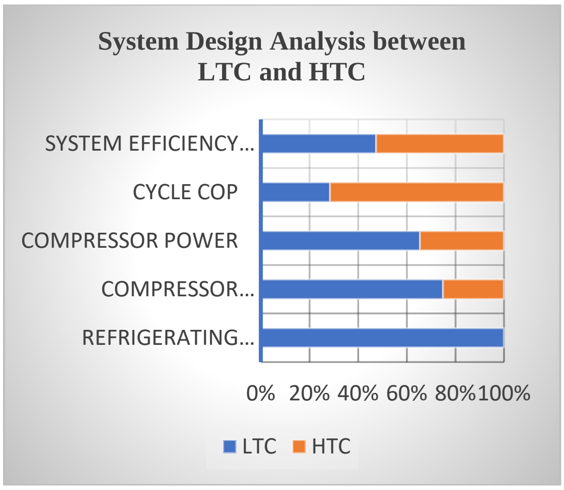

Fig. 5: Graph of Design Parameters between LTC and HTC

Figure 5 depicted the link between the design criteria and the performance evaluation at different phases of low temperature and high temperature circuits. While the mass flow rate is larger at high temperature circuit (HTC) than low temperature circuit (LTC), the graph demonstrates that the refrigerating effect only occurs at the LTC. Comparatively speaking, the LTC does more work than the HTC due to higher compressor pressure ratios. HTC has 75.25 percent system efficiency, whereas LTC has 67.7 percent. The implication is that the design system achieves the intended goal.

Table 3. Quality Variation of Frozen Plasma for 72 Hours

Mass (kg)	Time (hr)	Proteins (%)
1	18	100
2	36	99
3	48	99.4
4	72	99.60

The data in Table 3 demonstrated a clear correlation between plasma mass and the time it takes to freeze. It is known that coagulation factors are present in plasma both before and after it has been frozen at a very low temperature and stored under regulated temperatures. Even after 72 hours of processing and storage at -18 °C, the results show that the plasma proteins have undergone no change.

5 CONCLUSION AND RECOMMENDATION

The paper described the design and construction of a two-stage vapour compression refrigeration cycle specifically intended for the quick and homogenous freezing of 4.0 kg of fresh blood plasma between 35 ^{0}Cand -35 °C while maintaining its quality and viability. The apparatus assisted in maintaining the product's quality during temperature-controlled storage, and the fast-deep-freezing application consequently increased the product's short shelf-life for a continuous life-saving transfusion. The uniqueness of the work is in the deep-freezing procedure used to preserve fresh plasma protein for 72 hours following a two and a half-hour period of freezing. This is the first of its type, with the same high standards of quality at power outage. The work produced the following practical results over existing devices:

i. Development of a refrigeration system for the quick processing and management of fresh blood plasma at collection.
ii. Effective plasma proteins safety post-production by rapid homogenous freezing and storage.
iii. Achieving low temperatures quickly utilizing readily accessible and reasonably priced different refrigerants.
iv. The availability of temperature-controlled, heat-sensitive storage systems.

NOMENCLATURE

Q_{cond} is the heat transferred by conduction [kJ]
t is the time in second [s]
m_{tp} is the total mass of loaded plasma [kg]
C_p is the specific heat capacity of plasma above freezing [kJ/kgK]
ΔT_1 = temp. change in cooling plasma to 0.59 °C [K]
$\Delta T_1 = t_{ap} - t_{fp}$ is change in chilling temperature [K]
t_{ap} is the entering blood plasma temperature [K]
t_{fp} is the freezing blood plasma temperature [K]
m_u is unit mass of a plasma bag [K]
m_{fp} is mass of the frozen product [K]
C_{fp} is specific heat of frozen plasma below freezing [KJ/kgK]
ΔT_2 is the temperature change in cooling plasma [K]
m_p is the blood plasma mass [kg]
C_e is the evaporator capacity [m^3 & kg]
$T_o = t_{ap,}$ is the ambient temperature [K]
$T_1$is the LTC evaporator inside temperature [K]
W_{Rev} is the reversible work input
W_{actual} is the actual work input
R_e is the heat absorbed from evaporator [kW]
($W_{CL} + W_{CH}$) is the total input work to the system [kJ]
Q_{CH} is the quantity of heat rejected by the HTC condenser [KW]
$\dot{m}_H$ is the mass flow rate of the HTC refrigerant [kg/s]
($h_6 - h_7$) is the heat rejected by HTC [kJ/kg]
$\dot{m}_H$ is the mass flow rate of the HTC refrigerant [kg/s]
ρ_l is the density of refrigerant [kg/m^3]
Q_{CL} is the quantity of heat rejected by the LTC condenser [kW]
$\dot{m}_L$ is the mass flow rate of the LTC refrigerant [kg/s]
($h_2 - h_3$) is the heat rejected by LTC [kJ/kg]
Q_{pk} is the packaging heat load [W]
m_{pk} is the mass of product [kg]
C_{pk} is the packaging material specific heat [J/kg ^{0}C]
T_O is the outside temperature [°C]
T_i is the temperature of the refrigerated space [°C]
x is the thickness of copper tube[m]
k is the thermal conductivity of insulator [kW/mK]
h_i is the inside convection coefficient [kW/m^2K]
h_o is the outside convection coefficient [kW/m^2K]
U is the overall heat transfer coefficient [kW/m^2K]
A is the surface area through which heat is being transferred [m^2]
ΔT is the change in temperatures between outside and inside [K]
m_{inf} is the mass of in-flow air [kg]
ρ is the air density [kg/m^3]
C_a is the specific heat of the air [J/kg °C]
V_f is the volumetric flow rate of infiltrated air [m^3/s]
T_o is the outside temperature [°C]
T_i is the inside temperature [°C]
m_{fp} is the total mass of the freezing plasma [kg]
L_{fp} is the latent heat of plasma changing to freezing plasma [kJ/kg]
C_p is the specific heat capacity of plasma above freezing [kJ/kgK]
U is the overall heat transfer coefficient measured [W/m^2K]
A is the surface area of the insulator measured [m^2]
ΔT is the temperature difference across the walls [K]

© 2023 The Author(s). Published by Faculty of Engineering, Federal University Oye-Ekiti.
This is an open access article under the CC BY NC license. (https://creativecommons.org/licenses/by-nc/4.0/)

t_{ap} is the outside temperature (ambient) of plasma [K]
t_{fp} is the inside/refrigerated space temperature [K]
$\dot{Q}_{cond}$ is the rate of heat transfer by conduction [W]
V is the volumetric flow rate [m^3/s]
$\dot{m}_L$ is the mass flow rate of the LTC refrigerant [kg/s]
ρ_l is the density of refrigerant [kg/m^3]
x is the thickness of the layer of the wall (insulator) [m]
k is the thermal conductivity of the material [W/Mk]
h_i is the convection heat transfer coefficient of inside air [W/m^{2}K]
D_e is the depth of load space inside the evaporator

REFERENCES

Bijaksana, M. (2019). Characteristics study of two-stage cascade refrigeration system design for household air blast freezing. 10(01), 1804–1813.

Bolaji, B. O. (2016). Theoretical analysis of the energy performance of three low global warming potential hydro-fluorocarbon refrigerants as R134a alternatives in refrigeration systems. March. https://doi.org/10.1177/0957650913507252

Bolaji, B. O., & Huan, Z. (2012). Computational analysis of the performance of ozone-friendly R22 alternative refrigerants in vapour compression air- conditioning systems . February 2015. https://doi.org/10.5277/EPE120404

Bolaji, B. O., & Huan, Z. (2014a). Energy performance of eco-friendly R152a and R600a refrigerants as alternative to R134a in vapour compression refrigeration system. August.

Bolaji, B. O., & Huan, Z. (2014b). Performance Investigation of Some Hydro-Fluorocarbon Refrigerants with Low Global Warming as Substitutes to R134a in Refrigeration Systems.April. https://doi.org/10.1134/S1810232814020076

Gao, L., Shi, X., & Wu, X. (2020). Applications and challenges of low temperature plasma in pharmaceutical field. Journal of Pharmaceutical Analysis. https://doi.org/10.1016/j.jpha.2020.05.001

Gauthier, C., & Griffin, G. (2014). Landmarks in animal-based research and key moral. September 2005.

Lemboye, K. T., Layemi, A. T., Oduntan, K., Akintunde, M. A. and Dahunsi, O. A. (2015). Developing a two-stage cascade compressor arrangement for ice block production. *Journal of Machinery Manufacturing and Automation, World Academic Co. Limited, Hong Kong, Vol.* 4(2) pp. 10 -16.

Mahmood, R. A., Ali, O. M., & Noor, M. M. (2021). Review of mechanical vapour compression refrigeration system part 2 : performance challenge School of Mechanical and Electrical Engineering , University of Southern Queensland Faculty of Mechanical & Automotive Engineering Technology , Universiti Malaysia Pahang. 26(3), 119–130. https://doi.org/10.2478/ijame-2021-0039

Martins, L. N., Fábrega, F. M., & Angelo, J. V. H. (2012). Thermodynamic performance investigation of a trigeneration cycle considering the influence of operational variables. 42(August),1879–1888. https://doi.org/10.1016/j.proeng.2012.07.584

Mogaji, T. S., Awolala, A., Ayodeji, O. Z., Mogaji, P. B., & Philip, D. E. (2020). COP Enhancement of vapour compression refrigeration system using dedicated mechanical subcooling cycle . 39(3), 776–784.

mouneer, T. A., Elshaer, A. M., & Aly, M. H. (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. 309–336. https://doi.org/10.4236/wjet.2021.92022

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. 6(1), 130–142.

Pan, M., Zhao, H., Liang, D., Zhu, Y., Liang, Y., & Bao, G. (2020). A review of the cascade refrigeration system.Energies,13(9).https://doi.org/10.3390/en13092254

Rabbani, G., Karma, N., & Patil, N. (2017). Cascade Refrigeration System " For Blood Storage ." 2(6), 20–23.

Rangel, V. B., Almeida, A. G. S., Almeida, F. S., & Duarte, L. G. da C. (2022). Cascade Refrigeration System for Low Temperatures Using Natural Fluids. Revista Foco, 15(1), e295. https://doi.org/10.54751/revistafoco.v15n1-013

Raphael, A., Conceição, S., Almeida, F. S., Gustavo, L., Gabriel, A., & Almeida, S. (2020). Optimization of cascade refrigeration system to achieve lower temperatures 1 introduction The depletion of the ozone layer caused by the use of synthetic fluids. 5,1-20.https://doi.org/10.21575/25254782rmetg2020vol5n81397

Ratio, C. (2018). Single Stage , Compound , Cascade and Booster Systems and Inter- stage Cooling Methods. March, 11–18.

Selvnes, H., Allouche, Y., Manescu, R. I., & Hafner, A. (2021). Review on cold thermal energy storage applied to refrigeration systems using phase change materials. Thermal Science and Engineering Progress, 22(December 2020), 100807.https://doi.org/10.1016/j.tsep.2020.100807

Subramani, N., & Prakash, M. J. (2011). Experimental studies on a vapour compression system using nanorefrigerants. 3(9), 95–102.

System, D. A. (2014). Energy Consumption of Solar-assisted Internally Cooled / Heated Liquid ScienceDirect Energy Consumption of Solar-assisted Internally Cooled / Heated Liquid Desiccant Air-conditioning System in Hong Kong.December.https://doi.org/10.1016/j.egypro.2014.12.277

Tsatsaronis, G., & Morosuk, T. (2018). Exergy analysis of cascade refrigeration system working with refrigerant pairs R41-R404A and Exergy analysis of cascade refrigeration system working with refrigerant pairs R41-R404A and R41-R161. https://doi.org/10.1088/1757899X/377/1/012036

Tu, Y., Chien, C., Yarmishyn, A. A., & Lin, Y. (2020). A Review of SARS-CoV-2 and the Ongoing Clinical Trials.

© 2023 The Author(s). Published by Faculty of Engineering, Federal University Oye-Ekiti.
This is an open access article under the CC BY NC license. (https://creativecommons.org/licenses/by-nc/4.0/)