ISOMAse
International Society of Ocean, Mechanical and Aerospace Scientists and Engineers

Journal of Ocean, Mechanical and Aerospace
-Science and Engineering-
30th March 2024. Vol.68 No.1
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March 30, 2024

Design of Air Blast Freezing System Using Cascade Refrigeration R290/R32 System with Capacity 5kg

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Paper History

Received: 27-December-2023
Received in revised form: 03-January-2024
Accepted: 30-March-2024

ABSTRACT

Indonesia is a maritime country that has an abundance of marine catches. In 2022, the production of marine catches reached 24.85 million tons, while the export amount was 1.221 million tons. This is due to the limited technology that can extend the freshness of marine catches. Based on this problem, a cooling system was designed in the form of an ABF that can freeze marine catch products. The Air Blast Freezing (ABF) system is designed at an air temperature of -40°C using a cascade refrigeration system. The working fluid used is R290/R32 hydrocarbon, which has very low GWP and ODP so it is safe for the environment and the earth's ozone layer. The results obtained show that the cooling load is 444.037 Watts, the LTC compressor power and HTC compressor power are 116.19 Watts and 205.98 watts. The designed air blast freezing system has a surface area of LTC evaporator of 2.670 m^2 and HTC condenser of 4.780 m^2. The calculated capillary pipe length is 1.94 m for HTC and 1.51 m for LTC, the COP of the ABF system is 2.774.

KEYWORDS: *Air blast freezing, Cascade refrigeration System, Design.*

NOMENCLATURE

Q_{fresh}	Fresh Load
$Q_{freezing}$	Freezing Load
Q_{frozen}	Frozen Load
m	Mass Product
Cp	Specific Heat Capacity
T_{Fresh}	Temperature Fresh
$T_{Freezing}$	Temperature Freezing
T_{Frozen}	Temperature Frozen
R_{total}	Thermal Resistance
h_{out}	convection heat transfer coefficient
h_{in}	convection heat transfer coefficient
A	Surface Area
k_{Alm}	thermal conductivity of aluminium
$k_{pu.foam}$	thermal conductivity of polyurethane foam
k_{ss}	thermal conductivity of stainlesstell
L	Lenght
$T_{ambient}$	Temperature ambient
T_{evap}	Temperature evaporator
P	Fan power
f	Electric motor power factor coefficient
Q_{trans}	Transmission Load
Q_{fan}	Fan Load
Q_{cond}	Condenser Load
$Q_{evap.LTC}$	Evaporator Load LTC
$Q_{evap.HTC}$	Evaporator Load HTC
$W_{comp.LTC}$	Power Input Compressor LTC
$W_{comp.HTC}$	Power Input Compressor HTC
$Q_{cond.LTC}$	Condenser Load LTC
$Q_{cond.HTC}$	Condenser Load HTC
h_{1-8}	Enthalpy
$\dot{m}_{A-B}$	Mass flow rate
COP	Coefficient of Performance
T_{out}	Temperature Out
T_{in}	Temperature In
ΔT_1	Temperature Difference
ΔT_2	Temperature Difference
ΔT_{lm}	Log meat temperature difference
v_m	Velocity
ρ	Density
Re	Reynold Number
v	Viscosity
Nu	Nusselt Number
Pr	Prandlt Number
N_{tube}	Number of Tube
N_{fin}	Number of Fin
A_{fin}	Surface Area of Fin
A_{tube}	Surface Area of Tube

1.0 INTRODUCTION

Indonesia is the largest archipelago in the world. Stretching from Sabang to Merauke, Indonesia has 17,499 islands with a total area of approximately 7.81 million km^2. Of the total area, 3.25 million km^2 is ocean and 2.55 million km^2 is Exclusive Economic Zone. Only about 2.01 million km^2 is land. With the vastness of the existing sea area, Indonesia has enormous marine and fisheries potential [1]. The potential of Indonesia's marine and fisheries economy is very diverse and is one of the most important sectors in the country's economy. Indonesia has great potential in producing various types of fish, shrimp, mollusks and other aquatic products thanks to the vast marine area and diversity of aquatic ecosystems. The main aquatic products in Indonesian waters include tuna, freshwater fish, shrimp, squid, and shellfish. In addition, coral reefs in Indonesian waters support the richness of marine ecosystems and are also the habitat of various types of fish and other marine life [2].

Fishery export commodities with the largest volume in 2021 include Shrimp, Seaweed, Tuna, Skipjack, Squid, Cuttlefish, Octopus, Gulama and Reeve's Croaker [3]. Meanwhile, the fishery export commodities with the largest value in 2021 are Shrimp, Tuna, Skipjack, Squid, Cuttlefish, Octopus, Crab, and Seaweed. Based on the value, shrimp is the highest export commodity both in volume and value in 2021 with a volume of 250,715,434 kilograms, and a value of USD 2,228,947,835 [3]. Based on the data obtained, the production of fisheries and marine products in Indonesia reached 24.85 million tons in 2022, the Ministry of Maritime Affairs and Fisheries targets fisheries production to reach 30.37 million tons in 2023 [4]. Marine capture fisheries production by main commodities include skipjack, tuna, tuna, shrimp, and others. In addition, around 69.69% of fish production throughout Indonesia comes from 3 provinces, namely West Nusa Tenggara, West Papua, and Southeast Sulawesi. In the first quarter of Q3/2022, fish production has reached 17.76 million tons, or around 68% of the year's production target [4], [5].

Problems in export activities, especially fishery and marine products that rot due to the development of microorganisms include contamination [6]. Some types of bacteria or microorganisms that can make fish and other marine catches rot include Pseudomonas putida, Klebsiella pneumoniae, Shewanella algae, Buttiauxella agrestis, Aeromonas sp, Pseudomonas sp, Edwardsiella sp, and Staphylococcus sp [6]. Microorganisms are a serious problem and can affect product quality and freshness. Microorganisms such as bacteria, molds, and yeasts can multiply rapidly at higher temperatures, causing spoilage and product deterioration [7].Therefore, to prevent the growth of microorganisms, marine catches are frozen. Marine catches are frozen by quik freezing system at -18°C to -52°C, then stored at temperatures below -17°C to last up to 6 months [8], [9].

Several studies related to air blast freezing have been conducted, one of which is Syaka designing an air blast freezing system using R22. The evaporator temperature is -30°C and the cooling chamber is -22.4°C [10]. Syaka designed a cascade refrigeration system using R22/R32. The results show the evaporator temperature of -40°C and cooling chamber -28°C, design and test COP of 1.418 and 1.018, respectively [11]. Bai, et al. (2020) [12] conducted experiments on the Joule-Thomson refrigeration system by mixing R170 and R290 refrigerants on system performance. The results show that the concentration of the mixture has a significant impact on system performance. The lowest freezing temperature, fastest cooling rate, and minimum daily energy consumption of 3.612 kWh were obtained at the optimal R170 concentration of 35%. [12]. Bai et al. (2021) [13] conducted a performance analysis on cascade refrigeration system with the addition of Ejector. In their research, an ejector-enhanced two stage cascade refrigeration cycle using R600a/R32/R1150 ternary blends was proposed for the application of -80°C freezing. The results show that the ternary blend of R600a/R32/R1150 has an optimum mass fraction ratio of 0.45/0.2/0.35 to the maximum COP, the COP value increased by 4.9% [13].

Han & Gokoglu [14] investigated the effect of freezing and thawing methods on the physical, chemical and sensory characteristics of red shrimp (*Aristaeomorpha foliacea*). The freezing method of red shrimp was divided into three including air blast freezing, still freezing and cryogenic freezing. Freezing red shrimp for 30 days at -18°C, it was found that the freezing and thawing method with air blast freezing can maintain the physical, chemical, and sensory properties of shrimp better than other methods [14].

Mowafy, et al. [15] conducted a study on the effect of freezing rate on Medjol dates. The Air Blast Freezing system was used to investigate the effect of freezing rate at three different freezing temperature settings (-20, -25, and -30°C) on Medjool quality parameters. Texture profile analysis tests were conducted on fresh and thawed fruits to determine the properties of the fruits, which were affected by freezing rate. The highest freezing rate (4.35°C/min) was the best in maintaining color, TSS, and EL close to fresh Medjool levels. The results can help in designing and operating date freezing systems and maintaining the properties of dates under frozen conditions [15]. Martin, et al. [16] designed evaporator and condenser in vacuum freez drying for rice seeding. Obtained the results Minimum temperature when freezing -10.2 °C with actual COP 2.224, Maximum temperature in secondary drying 36.2 °C, with actual COP 2.1 [16].

The Environmental Protection Agency (EPA) released a proposed rulemaking outlining its strategic approach to eliminate the use of high-GWP HFCs in new commercial air conditioning and refrigeration systems. This rulemaking is an integral part of the American Innovation in Manufacturing (AIM Act), which instructs EPA to reduce hydrofluorocarbon (HFC) production and consumption by 85% by 2036. Under this rulemaking, the EPA proposed a 700 GWP limit for most new comfort cooling equipment, including chillers, starting January 1, 2025. This came as a surprise to many in the HVAC industry, as the EPA was expected to propose a 750 GWP limit for most refrigeration equipment. Comfort cooling equipment, as well as the January 1, 2024 transition date for chillers, aligns with the HFC phase-out in California [17].

Based on related research and the problem of spoilage of marine catches, an air blast freezing system using a cascade refrigeration system was created. The cascade refrigeration system is specifically designed for freezing at very low temperatures, one of which is the freezing of marine catch products. This system is designed at a temperature of -40°C to freeze seafood, so R290 refrigerant is used for High Temperature Cycle with a boiling point of -42.1°C and R32 for Low Temperature Cycle with a boiling point of -51.7°C. -51,7°C. Cooling is done by circulating cold air at a temperature of -40°C to maintain the quality of marine catch products so that they still have a high selling value, so as to encourage Indonesia's economic growth in marine catch export activities.

2.0 METHODS

The implementation method of the Air Blast Freezing design starts with studying the literature to determine the required parameters, including the initial design parameters and the parameters to be sought. After that, identifying existing problems to fulfill the design objectives or to formulate problems that arise during the design process. After that, the results are put together and analyzed to get some conclusions.

The design of the air blast freezing system consists of designing the LTC evaporator cooling load, HTC evaporator cooling load, air blast freezing system, LTC evaporator surface area and HTC condenser surface area. The air blast freezing system uses a cascade refrigeration system, a cascade refrigeration system is a multistage system where two cycles operate at two different heat levels, where the condenser from the low pressure side is cooled by the evaporator from the high pressure side. The evaporator on the high pressure side will unite with the condenser on the low pressure side in a heat exchanger.

The design of the air blast freezing system uses R290 and R32 with -42.1°C and -53.15°C respectively, so R290 is used as refrigerant in HTC and R32 for LTC. Assumptions taken when designing this cascade refrigeration system include [11]:

1. Evaporating temperature LTC -40°C
2. Evaporating temperature HTC -5°C
3. Temperature difference of cascade heat exchanger 5 °C (evaporator HTC -5 °C and condenser LTC 0 °C)
4. R290 compressor pressure 15 bar.
5. R32 compressor pressure 9 bar.
6. ABF chamber wall thickness 2mm, 130mm and 2mm using stainless steel, polyurethane foam and aluminum respectively.
7. The cooling load comes from 5kg marine catch products, fan load and transmission load.
8. Product specific heat capacity 3.65 kJ/kg.K, product latent heat 1675 kJ.
9. Freezing time 3 hours.
10. The thermal conductivity of aluminum, polyurethane foam and stainless steel are 150 W/m°C, 0.022 W/m°C and 14.4 W/m°C.

2.1 Cooling Load of LTC Evaporator

The cooling load of LTC evaporator consists of product cooling load and transmission load, evaporator load. Product load is the load to freeze the seafood from ambient temperature to freezing temperature of -18°C-(-25°C). Transmission load is the load from the surrounding environment that enters the ABF system. Evaporator fan load is the heat load from the evaporator electric motor. The cooling load of the LTC evaporator can be calculated using the equation in Table 1.

2.2 Cooling Load of HTC Evaporator

HTC evaporator cooling load consists of LTC condenser load and transmission loads, evaporator load can be calculated using the equation in the Table 2.

Table 1: LTC cooling load calculation parameters

No	Parameter	Formula
1	Fresh Load	$Q_{fresh} = m \times Cp \times (T_{fresh} - T_{freezing})$
2	Freezing Load	$Q_{freezing} = m \times h_{lt}$
3	Frozen Load	$Q_{frozen} = m \times Cp \times (T_{freezing} - T_{frozen})$
4	Transmission Load	$R_{total} = \frac{1}{h_{out}A} + \frac{L}{k_{Alm}A} + \frac{L}{k_{pu.foam}A} + \frac{L}{k_{ss}A} + \frac{1}{h_{in}A}$ $Q_{trans} = \frac{T_{ambient} - T_{evap}}{R_{total}}$
5	Fan Evaporator Load	$Q_{fan} = P \times f$

Table 2: LTC cooling load calculation parameters

No	Parameter	Formula
1	LTC condenser load	$Q_{cond} = \dot{m} \times \Delta h$
2	Transmission Load	$R_{trans} = \frac{1}{h_i A} + \frac{L}{kA} + \frac{1}{h_o A}$ $Q_{trans} = \frac{T_{ambient} - T_{evap}}{R_{trans}}$

2.3 Air Blast Freezing System

The air blast freezing system uses a cascade refrigeration system. The cascade refrigeration system is a two-level refrigeration system, where the first level is a low temperature cycle and the second level is a high temperature cycle. The LTC condenser will unite with the HTC evaporator into a cascade heat exchanger. The cascaded refrigeration cycle can be seen in Figure 1 and 2.

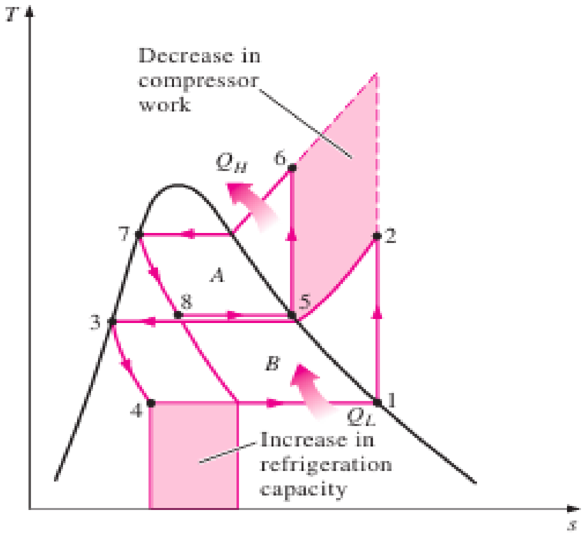

Figure 1: T-s diagram for cascade refrigeration system

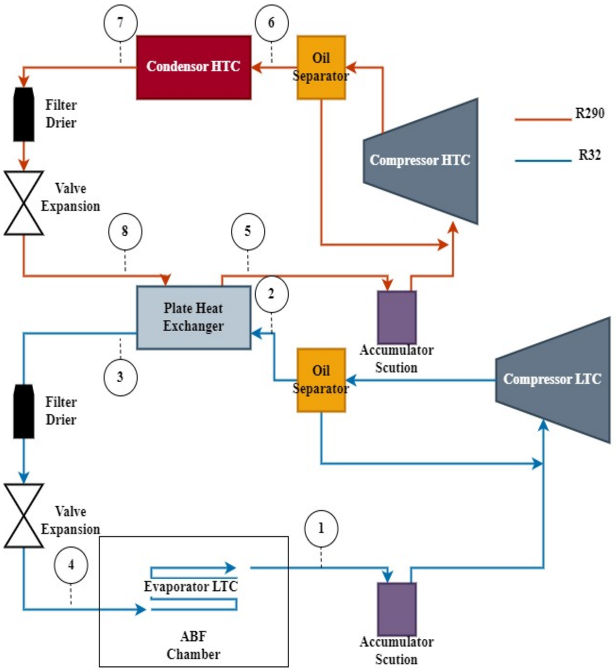

Figure 2: Schematic air flas freezing used cascade refrigeration system

The mass flow rate of each cycle, work input to the compressor, cascade heat exchanger, and heat transfer rate of the condenser were calculated using the balance equation. As a result of the analysis, the following equations were used:

Mass balance,

$$\sum_{in} \dot{m} = \sum_{out} \dot{m}$$

Energy balance,

$$\dot{Q} - \dot{W} = \sum_{out} \dot{m}\, h - \sum_{in} \dot{m}\, h$$

Several parameters were determined to determine the enthalpy, temperature and pressure values at each point in the cascade refigeration cycle. The system design parameter of air blast freezing is depicted in Table 3. To determine the mass flow rate, compressor power and condenser power can be calculated using the equation in the Table 4 [18].

Table 3: Design parameters of air blast freezing system

NO	Properties	Symbol	Value	Unit
1	LTC evaporator temperature	$T_{evap.LTC}$	-40	°C
2	LTC compressor pressure	$P_{comp.LTC}$	8	Bar
3	LTC cooling load	$Q_{evap.LTC}$	439.71	Watt
4	HTC evaporator temperature	$T_{evap.HTC}$	-5	°C
5	HTC compressorpressure	$P_{comp.LTC}$	15	Bar
6	HTC cooling load	$Q_{evap.HTC}$	893.88	Watt

Table 4: Design parameters of air blast freezing system [18]

No	Parameter	Formula
1	Mass flow rate of refrigerant A	$\dot{m}_B = \frac{Q_{evap.LTC}}{h_1 - h_4}$ $\dot{m}_A = \frac{Q_{evap.HTC}}{h_5 - h_8}$
2	Compressor power	$W_{comp.LTC} = \dot{m}_B \times (h_2 - h_1)$ $W_{comp.HTC} = \dot{m}_A \times (h_6 - h_5)$
3	Condenser load	$Q_{cond.LTC} = \dot{m}_B \times (h_2 - h_3)$ $Q_{cond.HTC} = \dot{m}_A \times (h_7 - h_8)$
4	*Coefficient of Performance* (COP)	$COP = \frac{Q_L}{W_{comp.LTC} + W_{comp.HTC}}$

2.4 Design of Heat Exchanger (Evaporator and Condenser)

The design of the heat exchanger is carried out using the logarithmic mean temperature difference (LMTD) method, after determining the cooling load on the heat exchanger [18].

Table 5: Design parameters of air blast freezing system

No	Parameter	Formula
1	Rate of heat transfer in heat exhanger	$Q = U \times A_s \times \Delta T_{lm}$
2	Rate of heat transfer in heat exchanger	$Q = \dot{m} \times C_p \times (T_{in} - T_{out})$
3	Outlet temperature	$T_{out} = T_{in} - \frac{Q}{\dot{m} \times C_p}$
4	Temperature difference	$\Delta T_1 = T_{h.in} - T_{c.out}$ $\Delta T_2 = T_{h.out} - T_{c.in}$
5	Log meat temperature difference	$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1/\Delta T_2)}$
6	Overall heat transfer cofficient	$U = \frac{1}{h_i} + \frac{1}{h_o}$
7	Velocity	$v_m = \frac{\dot{m}}{\rho \times A_c} = \frac{\dot{m}}{\rho \times \frac{\pi d^2}{4}}$
8	*Reynold Number*	$Re = \frac{v_m \times D_h}{v}$
9	*Nusselt Number*	$Nu = 0{,}023 Re^{0.8} Pr^{0.4}$
10	Heat transfer coefficient	$h = \frac{k}{Dh} Nu$
11	Surface area of heat exchanger	$A_s = \frac{Q}{U \times \Delta T_{lm}}$

Evaporator fin and tube calculations are based on surface models of finned tubes, circular tubes, and continuous fins (ST 3/8-0.8T) [10], [19]. Some equations in calculating the number of tubes, number of fins, fin surface area and tube surface area, to tube length can be seen in Table 6 [10].

3.0 RESULTS AND DISCUSSION

The design of Air Blast Freezing has been carried out by calculating the cooling load of marine catch products. The LTC evaporator is designed at a temperature of -40°C and HTC evaporator is designed at -5°C. For the cooling load of LTC evaporator is the load of seafood, transmission load and evaporator fan load. For HTC cooling load is LTC condenser load and transmission load.

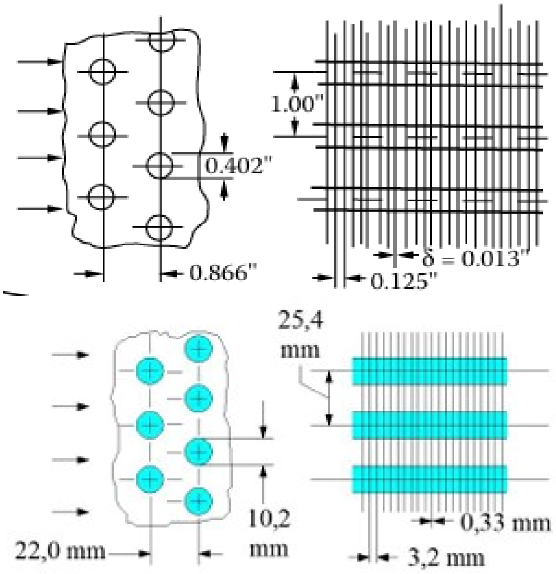

Figure 3: Surface 8.0-3/8T

The product load is the load to freeze seafood at a temperature of -18°C to 25°C. Transmission load is the load from the surrounding environment that enters the ABF system. Evaporator fan load is a heat load that comes from the evaporator electric motor. Furthermore, based on the calculation results of the casade refrigeration system design model in Table 6, and the CAD software was used to obtain the length and diameter of the capillary pipe that functions as an expansion device in both Low Temperature Circuit (LTC) and High Temperature Circuit (HTC).

The design parameter result of air blast freezing system is depicted in Table 7. The calculation result of cascade refrigeration system design shows in the Table 8. That can be seen in Table 8, the result of cooling load is 444.037 Watts. The result of high temperature cycle is 687.897 Watts. Therefore, the LTC compressor power and HTC compressor power are 116.19 Watts and 205.98 Watts. The design result of the air blast freezing system has a surface area of LTC evaporator of 2.670 m^2 and HTC condenser of 4.780 m^2 to support the freezing process quickly and evenly. The capillary calculation of pipe length is 1.94 m for HTC and 1.51 m for LTC.

Table 6: Design parameters of air blast freezing system [10]

No	Parameter	Formula
1	Number of tube	$N_{tube} = \left(\frac{L_3}{ST} \times \frac{\frac{L_2}{SL}+1}{2}\right) + \left(\left(\frac{L_3}{ST} - 1\right) \times \left(\frac{\frac{L_2}{SL}-1}{2}\right)\right)$
2	Number of fin	$N_{fin} = \frac{L_1}{P_f}$
3	Surface area of fin	$A_{fin} = 2\left[L_2L_3 - \left(\frac{\pi {d_0}^2}{4}\right)N_t\right]N_f + 2 \times L_3 \times t \times N_f$
4	Surface area of fin	$A_{tube} = \pi d_0[L_1 - tN_f]N_t + 2\left[L_2L_3 - \left(\frac{\pi {d_0}^2}{4}\right)N_t\right]$
5	Total surface area	$A_{total} = A_{fin} + A_{tube}$
6	Ratio of fin/tube surface area to total area	$\varphi = \frac{A_{fin}}{A_{total}}$ $\varphi = \frac{A_{tube}}{A_{total}}$

Table 7: Design parameters of air blast freezing system results

No		Parameter	Result
1	LTC evaporator load	Product load	273.379 Watt
		Fan load	40.023 Watt
		Transmission load	53.021 Watt
		Total load	366.425 Watt
		Safety Factor (1,2)	439.710 Watt
2	HTC evaporator load	LTC condenser load	560.235 Watt
		Transmission load	61.138 Watt
		Total load	621.37 Watt
		Safety Factor (1,1)	683.511 Watt
3	Cascade refrigeration system	LTC mass flow rate	0.002035 kg/s
		Enthalpy	State 1 = 273.4 kJ/kg
			State 2 = 330.5 kJ/kg
			State 3 = 55.2 kJ/kg

			State 4 = 55.2 kJ/kg
		HTC mass flow rate	0.002562 kg/s
		Enthalpy	State 5 = 482.5 kJ/kg State 6 = 562.9 kJ/kg State 7 = 214 kJ/kg State 8 = 214 kJ/kg
		COP	2.774
4	LTC evaporator	Total surface area	2.670 m^2
		Surface area of fin	2.467 m^2
		Surface area of tube	0.2022 m^2
		Number of fin	21
		Number of tube	25
		Tube lenght	6.7599 m
5	HTC condenser	Total surface area	4.780 m^2
		Surface area of fin	4.414 m^2
		Surface area of tube	0.366 m^2
		Number of fin	52
		Number of tube	45
		Tube lenght	12.114 m

Table 8: Calculation results of cascade refrigeration system design

	Qevap (Watt)	Qcond (Watt)	Wcomp (Watt)	ṁ (kg/s)	COP
Low Temperature Cycle	444.037	560.235	116.198	0.002035	2.774
High Temperature Cycle	687.897	893.881	205.984	0.002562	
	Surface Area (m^2)	Surface Area of Fins (m^2)	Surface Area of Tube (m^2)	Tube Diameter (mm)	Number of Tube (m)
Evaporator LTC	2.670	2.467	0.2022	0.009525	6.7599
Condenser HTC	4.780	4.414	0.366	0.009525	12.11
	Diameter (mm)			Lenght (m)	
Valve Expansion HTC	1.24			1.94	
Valve Expansion LTC	1.12			1.51	

4.0 CONCLUSION

The outlined air blast freezing design shows the overall design. The results show that the cooling load is 444.037 Watts. So, the LTC compressor power and HTC compressor power are 116.19 Watt and 205.98 Watt. The designed air blast freezing system has a surface area of LTC evaporator of 2.670 m^2 and HTC condenser of 4.780 m^2 to support the freezing process quickly and evenly. The calculated capillary pipe length is 1.94 m for HTC and 1.51 m for LTC. The Coefficient of Performance (COP) of 2.774 shows good efficiency in converting power into cooling. Overall, this design shows harmony between energy efficiency, heat exchange capacity, and overall performance of the air blast freezing system.

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