Techno-economic Analysis of Cascaded Vapour Compression Refrigeration System

Atishay Singhai (20D170010), Rohit Gedam (20D170012),
Shadab Ansari (20D170023), Pranav Limaye (20D170028)
Course Project – Part 3

Abstract

An important phase in the development of any project is the techno-economic analysis (which may best be done in parallel with the budgeting and component selection phases). The following report aims to conduct a techno-economic analysis of a cascade vapour compression refrigeration system, proposed and explored earlier in this report.

The cascade heat exchanger in between the cycles will also be sized and modelled in detail. Cost functions from existing research have been used to estimate the cost of all the individual components, while adjusting for cost indices for their respective years.

Keywords: heat exchanger modelling, ht Python library, techno-economic analysis, cost functions, performance improvement

1. Introduction

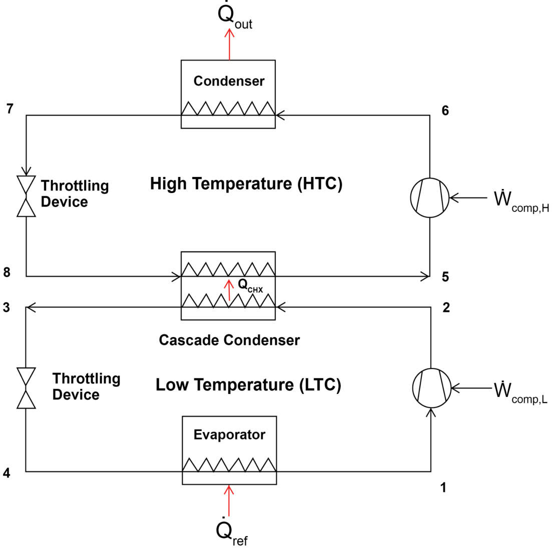
The system (represented in Fig 1) employs two vapour compression refrigeration cycles (represented in Figure 2(a)) with two different refrigerants: R23 in the LTC and R1234ze(E) in the HTC. The LTC operates between the temperatures -65 ℃ and +33.5 ℃, and the HTC between -33 ℃ and +51.1 ℃. Both cycles are idealised, except for the isentropic efficiencies of the compressor which have realistic values of 0.6 and 0.75 for the LTC and HTC respectively.

The methodology and results of its simulation (done using "CoolProp" on Python) have been described earlier in this report; and those results will be used during the current techno-economic analysis and modelling. The selected components have been described in Table 1, and possibly suitable models have been proposed for purchase in Table 2. As mentioned in that previous report, this system is to be used for the purpose of cooling the components of high performance computers, and suitable assumptions have been made accordingly.

Table 1: Component types

Path	Component	Type
1-2	Compressor (LTC)	Hermetic Sealed Reciprocating[1]
2-3	CHX (as LTC Condenser)	Brazed Plate Heat Exchanger[2]
3-4	Expansion Valve (LTC)	Thermostatic[3]
4-5	Evaporator (LTC)	Fin-type Microchannel[1]
5-6	Compressor (HTC)	Hermetic Sealed Reciprocating[1]
6-7	Condenser (HTC)	Micro Plate Heat Exchanger[1]
7-8	Expansion Valve (HTC)	Thermostatic[3]
8-5	CHX (as HTC Evaporator)	Brazed Plate heat exchanger[2]

Fig 1: System Schematic



2. Methodology

2.1 Sizing of Cascaded Heat Exchanger

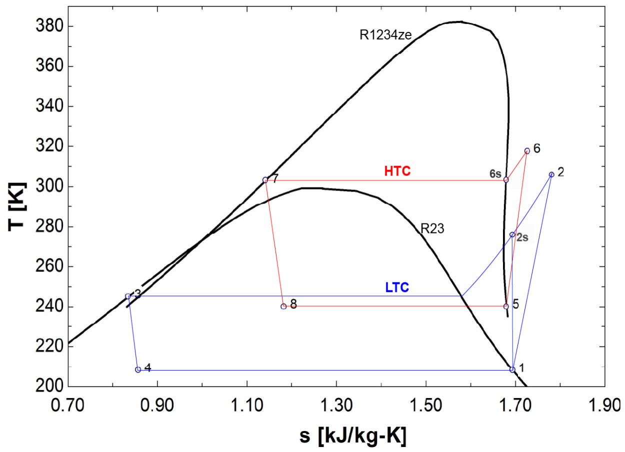


Fig 2(a)

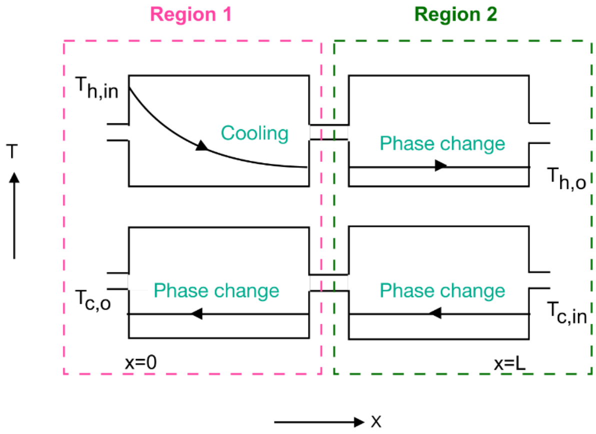


Fig 2(b)

Fig 2: (a) T-s curve (generated on EES) (b) Discretised CHX schematic (generated on Apple Pages)

From the T-s curve, the CHX (of counter-flow type) can be sensibly divided into two discrete regions.

(i) Isobaric cooling (of pure gas) in LTC and phase change (partial evaporation) in HTC

(ii) Phase change (complete condensation) LTC and phase change (complete evaporation) in HTC

Using energy balance for Region 1, the quality at its endpoint on the HTC side ($Q_{R1H,o}$) can be determined.

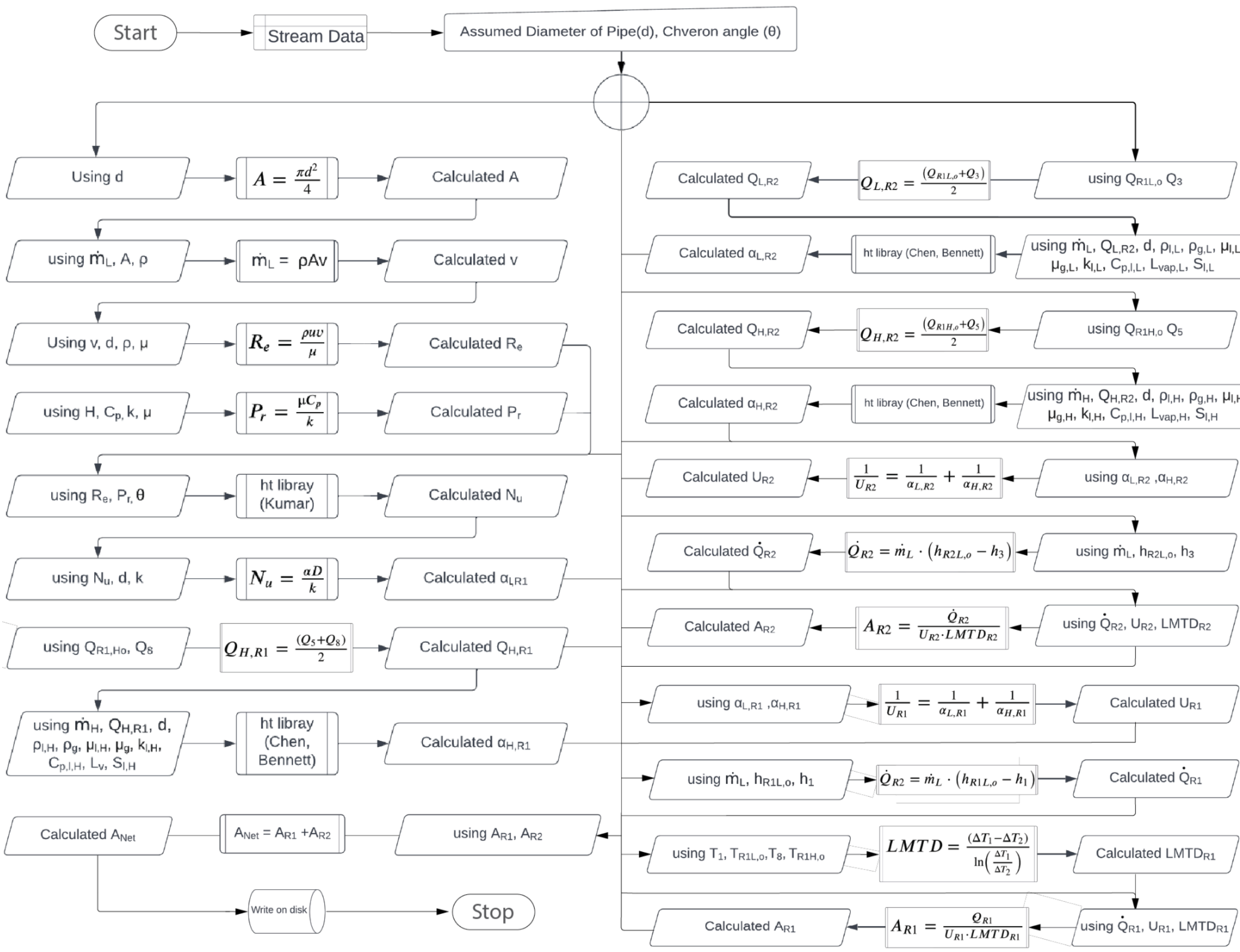
Assumptions:

1. To calculate the Nusselt number in LTC Region 1, the refrigerant temperature was assumed to be the average of the temperatures of Region 1 endpoints.
2. To calculate heat transfer coefficients on the HTC side in Region1 and both sides in Region 2, the qualities of refrigerants were assumed to be the averages of the qualities of respective Region endpoints.
3. The thermal resistance of the bulk material of all the heat exchangers (between their respective pairs of fluids), including their piping, were assumed to be negligible. Fouling resistances were also neglected.
4. The system was assumed to be perfectly thermally insulated from the environment except at the HTC condenser (which rejects heat to the ambient atmosphere) and at the LTC evaporator (which extracts heat from the refrigerated space).
5. In the brazed plate heat exchanger, pipe diameter and chevron angle for the plate were assumed to be 4 cm and 45° respectively.
6. In the cascade heat exchanger, it was assumed that the boiling in the HTC channels can be approximated as climbing film boiling[4] rather than nucleate boiling (though some nucleation might be required at the walls near the entrance to initiate the boiling process). Correspondingly, the condensation in the LTC channels was approximated as falling film condensation.

Calculations:

The correlations used for determining heat transfer coefficients in any thermodynamic system are heavily dependent on the system conditions, the types of processes involved, the materials and fluids being used, and the assumptions made during calculations. The “ht” Python library[5] is a comprehensive open-source collection, consisting of modules providing heat transfer functions, for a large variety of processes and systems. Its official manual provides detailed documentation of every single correlation (even citing the research papers in which they were determined). Thus, a multi-module Python program (available here on Github) In accordance with the system assumptions, the Chen-Bennett correlation[6] was used for determining α on both sides of Region 2, and on the HTC side of Region 1. The Kumar correlation[7] was used for determining Nu (and later α via Equation 4) on the LTC side of Region 1. Both of these correlations required flow-specific properties, which were determined using the “CoolProp” Python library and some analytical calculations. Next, U was determined for both regions, followed by LMTD, and the required area.

Figure 3: Flowchart for calculation of area of CHX



Note:

Here, $\dot{Q}$ represents the heat transfer rate in the heat exchanger, and Q represents the quality of refrigerant.

Values for all the ρ, μ, K, σ, and C_p were determined using the CoolProp library, at a particular state.

As h represents specific enthalpy, α represents the convective heat transfer coefficient (to avoid confusion).

All other symbols and notations are the same as mentioned in the nomenclature.

Equations Used

1. $\dot{m} = \rho A v$
2. $R_e = \frac{\rho v D}{\mu}$
3. $P_r = \frac{\mu C_p}{k}$
4. $Nu = \frac{\alpha D}{k}$
5. $A_{net} = A_{R1} + A_{R2}$
6. $\frac{1}{U} = \frac{1}{\alpha_1} + \frac{1}{\alpha_2}$
7. $\dot{Q} = \dot{m} \cdot (h_o - h_i)$
8. $\dot{Q} = U \cdot A \cdot LMTD$
9. $LMTD = \frac{(\Delta T_1 - \Delta T_2)}{ln(\frac{\Delta T_1}{\Delta T_2})}$;

   where,

   $\Delta T_1 = T_{h,i} - T_{c,o}$ and

   $\Delta T_2 = T_{h,o} - T_{c,i}$
10. $Q_{mixed\ region} = \frac{Q_{endpoint\ 1} + Q_{endpoint\ 2}}{2}$
11.

2.2 Component models

Table 2: Chosen Components

Components	Specific Model Name
Brazed Plate Heat Exchanger (CHX)	Danfoss, BPHE B3-052[10]
Evaporator	Danfoss, H62(L)-EZU[11]
Condenser	Danfoss, H622L-CX[10]
Throttle Valve LTC	Danfoss, TGE series[3]
Throttle Valve HTC	Danfoss, TGE series[3]
Compressor LTC	J & Hall International HSS series[13]
Compressor HTC	J & Hall International HSS series[13]

This heat exchanger model was chosen on the basis of its type, number of plates, and exchanger area. The evaporator and condenser models were also chosen on the basis of their type and their exchanger area. The throttle valve model was chosen on the basis of its inlet and outlet pressures. The compressor model was chosen on the basis of its capacity and rated evaporator temperature. However, the suggested refrigerants for the throttle valve and the compressor aren't the ones being used in this cascade refrigeration system, so certain adjustments might have to be made to achieve the same performance and reliability.

2.3 Cost Analysis of System

Table 3: Cost Function for different Components

Components	Cost function in ₹ (C_k), 2022
Brazed Plate Heat exchanger (CHX)	$56380.5 \times A_{BPHE}^{0.8}$ [14]
Evaporator	$131874 \times A_{evap}^{0.89}$ [15]
Condenser	$131874 \times A_{cond}^{0.89}$ [15]
Compressor	$959791.6 \times W^{0.46}$ [15]
Throttle Valve	$10808.6 \times \dot{m}$ [15]
Refrigerant R23	$2000 \times m$ [16]
Refrigerant R1234ze(E)	$8517.61 \times m$ [17]

*Conversion rates used (as of 21:00, October 15, 2022): $1 = ₹82.42 & €1 = ₹80.12

For simplicity, the specific heat flux for the LTC evaporator was assumed to be 10^6 W/m^2, as per the application of electronics cooling[8]. This also matches the assumption made previously in this report. The price of connecting pipes was neglected in comparison to the prices of the other cutting-edge components.

Using, $Indexed\ Cost\ of\ Acquisition = Original\ Cost\ of\ Acquisition \times \frac{CII\ of\ the\ Given\ Year}{CII\ of\ the\ Base\ Year}$, the cost functions listed in Table 3 have already been adjusted for the current year (2022).

3. Results and discussion

Table 4: Table of results for the cascaded heat exchanger

Parameters	Region 1	Region 2
Rate of heat transfer (kW)	12.39	42.16
Overall heat transfer coefficient ($kW/m^2 K$)	6.71	2.19
Logarithmic mean temperature difference (K)	23.77	5 (overlap temperature)
Area (m^2)	0.14	4.75

Thus, total area of the CHX = 4.89 m^2, for a total rate of heat transfer rate = 54.55 kW

Table 5: Results of system cost analysis

Component	Cost in ₹ (2022)
Brazed Plate Heat exchanger (CHX)	261861.19
Evaporator (LTC)	8608.41
Condenser (HTC)	16764.23
Compressor for LTC	3767773.43
Compressor for HTC	5257644.25
Throttle Valve for LTC	2831.01
Throttle Valve for HTC	5965.24
Refrigerant R23	24000
Refrigerant R1234ze(E)	194717.97

Total Capital Cost = ₹ 9540165.73

3.1 State of the Art Literature Review

The proposed system is useful for a very specific set of operations and focuses mainly on the refrigeration objective; so the cost is not a rigid factor during the decision. There are more efficient models available but their temperature ranges do not go that low, So, the trade-off is between Cost and COP. The literature which we have reviewed has been cited earlier in the previous report.

4. Optimisation/Suggestion

The performance of a refrigeration system is evaluated in terms of COP (the ratio between refrigeration effect and the net work input). The COP of a vapour compression refrigeration system can be improved either by increasing the refrigeration effect or by reducing work input given to the system.

- As per a parametric study performed against ambient temperature, depicted in "*Fig 4" of this report*, the overall COP can be improved by decreasing the ambient temperature near the HTC condenser.
  - This can be ensured by using a fan to facilitate forced convection of any heated air away from the condenser, drawing cooler air back in.
  - Moreover, the condenser could be placed away from any direct and diffused sunlight.
  - If possible, the project site could be shifted to a place with a naturally colder climate.
- The throttling process in vapour compression refrigeration is an irreversible expansion process; one of the main factors responsible for exergy loss in the cycle. It occurs due to the production of flash vapours

due to some practically spontaneous boiling. This reduces the cooling capacity of the refrigerant which must be counteracted with a larger evaporator size. This problem can be eliminated by adopting multi-stage expansion (with the removal of flash-vapours after each stage of expansion).[19]

- The isentropic efficiency of the compressors and the evaporator temperature of the upper cycle have a considerable impact on the performance of the overall system. Thus, the possibility of using more isentropically efficient compressors should be considered.
- Adjustments may be considered at the project site which allows the cooling temperature near the evaporator to be increased from -65 ℃ to something more easily achievable. This will not only reduce the desired refrigeration effect but also reduce the required work input (in fact, depending on the project constraints, this might be more preferable even at a lower system COP).

5. Conclusion

Thus, this report quantifies the technical and economic performance of a cascaded vapour compression refrigeration system of the previously proposed configuration, under certain feasible assumptions, and using cost functions which were developed by previous researchers. The main objective, the detailed modelling of the cascaded heat exchanger, has been especially successful, reporting a required exchanger area of 4.89 m^2. This analysis has significantly built upon the analysis which was described in the earlier report. Moreover, components roughly matching the requirements of this system have been proposed for purchase.

6. Nomenclature

Abbreviations

COP	Coefficient of performance
CHX	Cascade heat exchanger
HTC/H	Higher temperature circuit
LTC/L	Lower temperature circuit
CP2	Course Project Part 2
CII	Cost of Inflation Index

Symbols

h	Specific enthalpy (kJ/kg)
d	pipe diameter (m)
θ	Chevron Angle (degrees)
R_e	Reynolds Number (unitless)
P_r	Prandtl Number (unitless)
N_u	Nusselt Number (unitless)
α	convective heat transfer coefficient (W/(m^2 K))
k	Thermal conductivity (W/(m·K))
C_p	Specific heat capacity (J/(kg °C))
$\dot{m}$	Mass flow rate (kg/s)
Q	Quality (unitless)
$\dot{Q}$	Rate of heat transfer (kW)
A	Area(m^2)
U	Overall Heat Transfer Coefficient (W/(m^2°C))
T	Temperature (℃)
LMTD	Logarithmic mean temperature difference (°C)
$\dot{W}$	Work input of a compressor (kW)

Greek symbols

ρ	density (kg/m^3)
σ	Surface Tension (N/m)
μ	Dynamic Viscosity (Ns/m^2)
v	velocity (m/s)
Δ	Difference between 2 quantities
η	Efficiency (as a fraction between 0 and 1)

Subscripts and superscripts

1, 2…	Stream numbers
O	Output of Region 2 in Fig 2(b)
R1	Region 1
R2	Region 2

References

1. Coggins, C.L., 2007. Single-and multiple-stage cascaded vapor compression refrigeration for electronics cooling (Doctoral dissertation, Georgia Institute of Technology).
2. (2015) *Brazed plate heat exchangers*, Alfalaval. Available at : https://www.alfalaval.in/products/heat-transfer/plate-heat-exchangers/brazed-plate-heat-exchangers/ (Accessed: October 15, 2022).
3. *Danfoss.com*. Available at: https://assets.danfoss.com/documents/196911/AD135086437198en-000601.pdf (Accessed: October 15, 2022).

4. Hewitt, G.F. (2011) *Evaporators*, *THERMOPEDIA™*. Begel House Inc. Available at: https://dx.doi.org/10.1615/AtoZ.e.evaporators (Accessed: October 15, 2022).
5. Caleb Bell (2016-2021). ht: Heat transfer component of Chemical Engineering Design Library (ChEDL) Available at: https://github.com/CalebBell/ht. (v1.0.1, Accessed: October 15, 2022).
6. Bennett, D.L. and Chen, J.C., 1980. Forced convective boiling in vertical tubes for saturated pure components and binary mixtures. AIChE Journal, 26(3), pp.454-461.
7. Kumar, H., 1984, July. The plate heat exchanger: construction and design. In Institute of Chemical Engineering Symposium Series (Vol. 86, pp. 1275-1288). Leeds, UK: Pergamon.
8. ht documentation: https://ht.readthedocs.io/en/latest/ht.conv_plate.html (Accessed: October 15, 2022).
9. ht documentation: https://ht.readthedocs.io/en/latest/ht.boiling_flow.html (Accessed: October 15, 2022).
10. *Brazed plate heat exchanger Type B3 range, Danfoss*. Danfoss Climate Solutions. Available at: https://assets.danfoss.com/documents/161428/AI364239153110en-000101.pdf (Accessed: October 15, 2022).
11. (2020) *Economic and environmental savings in chillers and heat pumps, Danfoss.* DCS (CR). Available at: https://assets.danfoss.com/documents/157095/AD228186437325en-000501.pdf (Accessed: October 15, 2022).
12. *Micro Plate heat exchanger, MPHE H62L-CX 021H9014*, *Danfoss.* Available at: https://store.danfoss.com/en/Climate-Solutions-for-cooling/Heat-Exchangers/Plate-Heat-Exchangers/Micro-Plate-Heat-Exchangers/Micro-Plate-heat-exchanger%2C-MPHE-H62L-CX/p/021H9014 (Accessed: October 15, 2022).
13. *Semi-hermetic refrigeration compressor HSS series*, Direct Industry. J&E Hall International. Available at: https://www.directindustry.com/prod/j-e-hall-international/product-39777-305324.html (Accessed: October 15, 2022).
14. Arsenyeva, O., Orosz, Á. and Friedler, F., 2021. Retrofit Synthesis of Industrial Heat Exchanger Networks with Different Types of Heat Exchangers. *Chemical Engineering Transactions, 88*, pp.613-618.
15. Roy, R. and Mandal, B.K., 2019. Thermo-economic assessment and multi-objective optimization of vapour compression refrigeration system using low gwp refrigerants. In 2019 *8th International Conference on Modeling Simulation and Applied Optimization (ICMSAO)* (pp. 1-5). IEEE.
16. *Refrigerant Gas, Ganesh Enterprises.* Available at: https://www.ganeshenterprises.org/refrigerant-gas.html (Accessed: October 15, 2022)
17. *10R1234ZE, URI.* United Refrigeration INC. Available at: https://www.uri.com/refrigerants-and-chemicals/refrigerants/gases/r1234/10r1234ze-zid10R1234ZE-product (Accessed: October 15, 2022).
18. Vaartstra, G., Zhang, L., Lu, Z., Díaz-Marín, C.D., Grossman, J.C. and Wang, E.N., 2020. Capillary-fed, thin film evaporation devices. *Journal of Applied Physics*, 128(13), p.130901.
19. Mishra, R.S., 2019. Methods for improving thermodynamic performances of vapour compression refrigeration systems. *Int. J. Res. Eng. Innovat.*, 3(05), pp.291-297.