Individual Analysis Project

EMS623U - Heat Exchange and Waste Minimisation

Name : Amir Mohammad Pousti

1. Abstract

Focussing their efficiency and sustainability, this report investigates the important part heat exchangers play in air conditioning systems. We investigate thermodynamic performance using R134a refrigerant in the vapor-compression cycle by means of entropy and exergy calculations, highlighting inefficiencies. Important results emphasise the heat transfer functions of the evaporator and condenser with suggestions to improve Coefficient of Performance (COP) and reduce energy loss follow from this. This work provides a framework for raising heat exchanger efficiency and sustainability for modern uses by including advanced materials and optimising system design.

Part I – Analysis of Heat Exchangers in Engineering Applications

1.1 - The system and how the system works

A heat exchanger is a device meant to move thermal energy or heat between two or more fluids [1]. By using heat exchangers, air conditioning systems efficiently control thermal energy transfer, hence maintaining comfortable indoor conditions. Air conditioners are part of a larger group of systems know as HVAC (Heating, Ventilation, and Air Conditioning) system. During the 1880s, air conditioners were only used for freezing meat and making ice, however in the early 1900s, a new idea was starting called cooling for comfort later changed to air conditioning [2]. Although there are 3 transfer methods for heat, conduction, convection and radiation, only are mostly conduction and convection are used for HVAC systems. While both transfer heat, they are done in very different ways. In conduction, there is vibrations and movement of the eletrons meaning it is strictly a diffusion process, while conduction is caused by differences in temperature within the fluid, moving the hot fluid to the cooler regions [3].

In homes, businesses, and factories as well, air conditioning is essential. In homes, it preserves a comfortable indoor temperature, especially in very hot or cold weather. For those with respiratory problems particularly it also controls humidity levels, so lowering the risk of mould affecting indoor air quality and health. It also provides filtered air, so reducing allergens, dust, and pollutants. In commercial settings, it not only guarantees employee productivity and customer satisfaction by creating comfortable environment but also assists in good preservation of goods. By keeping suitable temperature and humidity levels, air conditioning helps preserve perishable goods in stores, supermarkets, and restaurants as well as in storage buildings. Apart from other purposes, air conditioning guarantees machinery and equipment in the industrial environments run within safe temperature limits.

To effectively transfer heat, the refrigerant moves through an ongoing phase change cycle. The cycle is called the Refrrigeration cycle. This is where the, refrigerant absorbs heat from indoor air as it runs across the evaporator coil. This heat evaporates refrigerant into a low-pressure gas, cools and recirculates indoor air over the coil, so producing a comfortable environment.The compressor next compresses refrigerant gas, raising its temperature and pressure. Next the refrigerant is ready for heat rejection. High pressure, high temperature refrigerant passes through the condenser coil where heat is emitted to the outside air during condensation. Lost heat drives refrigerant to condense into a high-pressure liquid, so extracting heat from the system.Refrigerant runs across the expansion valve in final expansion. This process reduces its temperature and pressure, hence the liquid for the evaporator is low-temperature. By repeated cycle, the system preserves indoor cooling.

In an air conditioning system, the refrigerant is a crucial working fluid that helps heat to be transferred across the vapor-compression cycle. It is a chemical compound meant to phase change under specific pressures and temperatures. This results from its absorbing heat from the indoor environment and releasing it outside, so facilitating the cooling mechanism [6]. Strong thermal conductivity of a refrigerant guarantees effective heat transfer during evaporation and condensation. They also low enough boiling point to condense outside temperatures and evaporate inside ones. High latent heat of vaporisation enables refrigerant to absorb or release a lot of heat during phase transitions without appreciable temperature increase [6]. The main types of referigents used in air conditioners are Hydrofluorocarbon (HFC), Hydrofluorocarbon (HFC), Hydrofluoroolefin (HFO), Hydrochlorofluorocarbon (HCFC) and hydrofluoroethers (HFE).

The two laws of thermodynamics comes into effect in the cycle. The first law states that energy cannot be created or destroyed but can be transferred or converted [9]. This is seen in the the refrrigeration cycle as it is a closed cycle and the work done by the compressor adds energy to the refrigerant, enabling it to transfer heat from a cooler region to a warmer region. In a refrigeration cycle, heat is transferred against the empreturre gradient, from a region of high-temperature to a low-temperature, which is known as the second law [9]. The refrigeration cycle reverses this process and transfers heat from a low-temperature region to a high-temperature one.Additionally controlling the entropy changes is the second law. The entropy of the system reduces during heat rejection in the condenser; conversely, the entropy of the surroundings rises as heat is emitted, so guaranteeing total entropy of the system and surroundings increases.

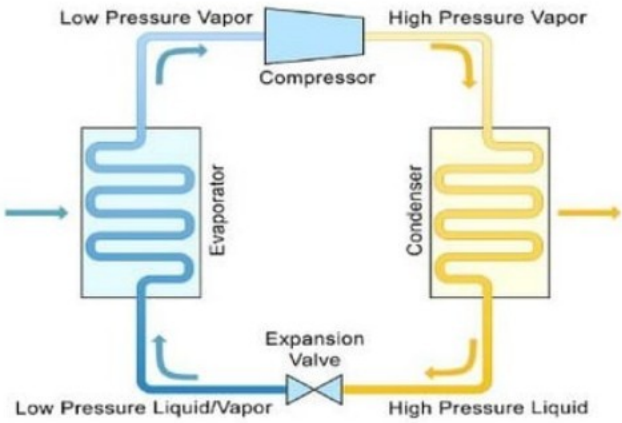

Figure 1. image of a refrigeration cycle [10]

As seen on figure 1, the refiration cycle consists of a 4 main components including the compressor, condenser, evaporator and a expantion valve [4]. A compressor is there to circulate the refrigerant through the cycle meaning it's the main part of the air conditioner. It creates high pressure and high-temperature gas through compressing the low-pressure refrigerant gas. the refrigerant compressed raises its temperature above the outside air so that it may release heat in the condenser [4]. It guarantees also continuous refrigerant flow through the system. The condenser takes in the heat from the compressor and the refrigerant releases heat to the surrounding environment [4]. Arriving at the condenser coils, the high-pressure, high-temperature refrigerant gas transfers heat to the outdoor air [4]. The refrigerant condenses into a high-pressure liquid as it cools. This process cools the refrigerant by removing heat, so preparing it for evaporator cooling of indoor air. [5]. The cold refrigerant absorbs heat from the indoor air passing over the evaporator coils once in the evaporator, where cooling occurs. The refrigerant evaporates and becomes a low-pressure gas as it absorbs heat [4]. Completing the cooling cycle, the chilled air that passes over the coils is then pushed back into the room. Moving air through the system is the blower responsibility. It guarantees that air moves across the evaporator coil to be cooled and then fills the indoor environment [5]. Drawing in warm indoor air and driving it across the cold evaporator coils to enable heat exchange cools the air. The use of ducts or vents are to bring the cool air back into the inside environment while also maintaining consistent cooling and effective system operation depend on constant airflow. Another component would be a expantion valve where the crucial point of transition between the low and high pressure sides of the air conditioning system.At this point, the valve lets the refrigerant expand, so lowering its temperature and pressure. This pressure drop gets the refrigerant ready for its next part in the cooling cycle. The low-temperature liquid refrigerant that results passes into the evaporator, where it absorbs heat from the indoor air, so facilitating the cooling cycle. [reference]

2.2 - The functions of the heat exchangers in the system

The critical components of an air conditioning system in charge of enabling heat transfer between the refrigerant and the surrounding environment are heat exchangers as they both directly affect the performance and efficiency of the system, as heat is rejected by the condenser and heat is absorbed by the evaporator.

The first heat exchanger is the condenser heat exchanger. The high-pressure, high-temperature refrigerant vapor releases its heat to the external environment in the condenser, so turning into a high-pressure liquid. During the evaporation phase, this process is necessary for releasing the heat absorbed from the indoor air. Usually made from copper tubing and aluminum fins, due to the copper being durable and corrosion-resistant, the copper has high thermal conductivity, which guarantees effective heat transfer and fits for outdoor surroundings.

The second heat exchanger is the evaporator heat exchanger. The heat absorbing phase, where the low-pressure, low-temperature refrigerant absorbs heat from the indoor air, so cooling the space, is done by the evaporator. This process gets the refrigerant from a liquid to a vapor so it is ready for compression. Blown over the evaporator coils by a fan, indoor air moves heat to the refrigerator. Assuming this latent heat of vaporization, the refrigerant transforms from liquid to vapor without significant temperature increase. Moisture in the warm, humid air condenses on the cold evaporator coil surface. While preventing mould and mildew growth, this dehumidification enhances indoor air quality and comfort. Usually, collected vapor is disposed of such that it does not damage systems.

2.3 - The types of the heat exchangers

There are 2 main types of heat exchangers used in air conditioning systems [11]. The first is finned tube heat exchangers. They are made of tubes usually copper surrounded by fins usually made of aluminum to maximize surface area as seen on figure 2. The refrigerant flows through the tubes. Heat is passed from the air to the refrigerant as air moves over the fins. The fins increased surface area helps release heat [12]. The fins increase the surface area, so enhancing the heat exchange rate. the robust design of the heat exchanger makes suitable for outdoor use in evaporators or condensers. there are lower manufacturing cost compared to complicated designs such as plate exchangers. However, it takes more space, which could be an issue in compact systems. Furthermore, the fins might covered with trash or dust, so limiting airflow and efficiency and calling regular cleaning [12].

The second type of heat exchanger is plate heat exchangers [11]. plate heat exchangers are made of stacked corrugated-surfaced plates to provide several fluid flow channels as seen on figure 3. the fluid flows in opposite directions between the adjacent channels. Two different fluids, the refrigerant and a secondary fluid, pass through alternate plates. as this occurs, the Heat moves across the thin plate from one fluid to the other [13]. the Corrugated plates allow for more turbulence to. be generated, so improving heat transfer. The modular design of stacked plates allow for good efficiency in a small footprint meaning it can babe. smaller then finned tube heat exchangers. In addition the modular plates can be broken down for cleaning and then rebuilt, which allows the efficiency not to be reduced. Also, plates made with precision raise manufacturing expenses meaning it will cost more then finned tube heat exchangers.

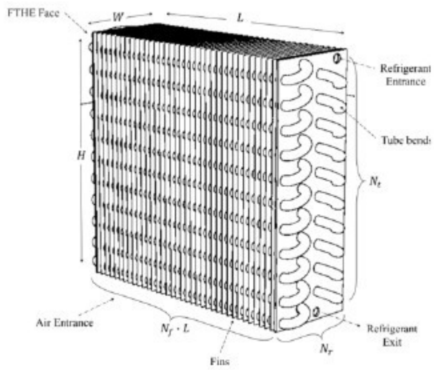

Figure 2. Diagram of Finned tube heat exchanger [14]

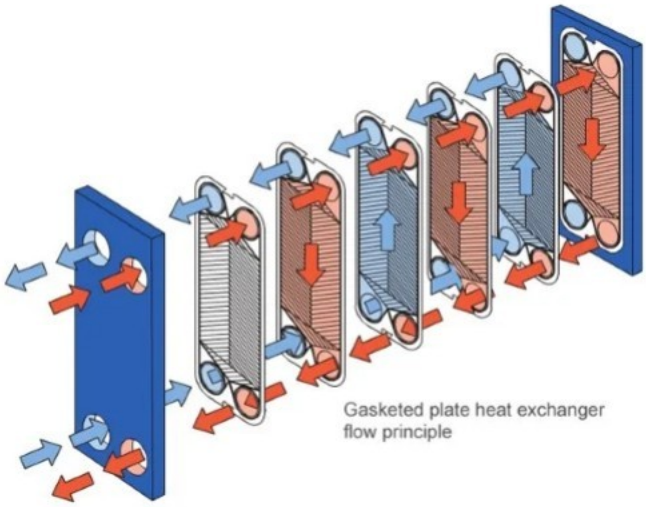

Figure 3. Diagram of Plate heat exchanger [15]

2.4 - The structure configuration, geometry, size, dimensions, and working conditions

Any air conditioner's most important aspect is refrigerants used, which also act as the working fluid allowing heat transfer during the refrigeration cycle. Refrigerants let the system keep a cool and comfortable indoor environment by through repeated phase changes absorbing heat during evaporation and releasing it during condensation. The referigrant, R134a is one of the most common one used. Due to its excellent thermodynamic characteristics of R-134a make it effective for air conditioners' heat absorption and rejection [17]. With minimal refrigerant volume, its high latent heat of vaporisation allows substantial heat transfer. Since R-134a has zero ozone depletion potential (ODP), it is safer for the ozone layer than more past refrigerants such R-22. moreover, because R-134a is non-corrosive, it is compatible with many materials, including copper and aluminium used in finned tube and plate heat exchangers [17]. It also runs effectively at moderate pressures, so simplifying system construction and lowering the demand for bigger heat exchanger designs.Many systems use R-134a since it is reasonably priced and readily available than more modern refrigerants [17]. However, Regular inspections of R-134a systems are required to prevent leaks, which otherwise might raise environmental impact and lower system efficiency.

Table 1. Working conditions of refrigeration cycle [16]

Mass flow rate (kg/s) $\dot{m}_r$			0.0315	
	P (kPa)	**T (°C)**	**h (kJ/kg)**	**s (kJ/kg·K)**
7. Evaporator inlet	526.47	16.51	274.7543	1.2592
6. Expansion valve inlet	1519.85	52.05	274.7543	1.246545
1. Evaporator outlet	409.07	20.55	414.3072	1.757734
2. Compressor inlet	388.43	20.32	414.5679	1.762456
3. Compressor outlet	2068	88.7	455.5975	1.77394
4. Condenser inlet	1559.34	81.48	455.5975	1.791496
5. Condenser outlet	1519.85	52.67	275.7345	1.249556

Using the data from Table 1 and the pressure-enthalpy diagram in Figure 4, R-134a's thermodynamic characteristics will be examined more closely to understand how it performs within the refrigeration cycle y applying the first order analysis. It enables us to examine what takes place in every cycle stage. Working with the enthalpy values at particular pressures allows us to determine the amount of heat the refrigerant absorbs in the evaporator, the amount it releases in the condenser, and the work the compressor must complete. With Eqs. (1,2 and 3) the heat transfer, $\dot{Q}$, can solved for each component [19].

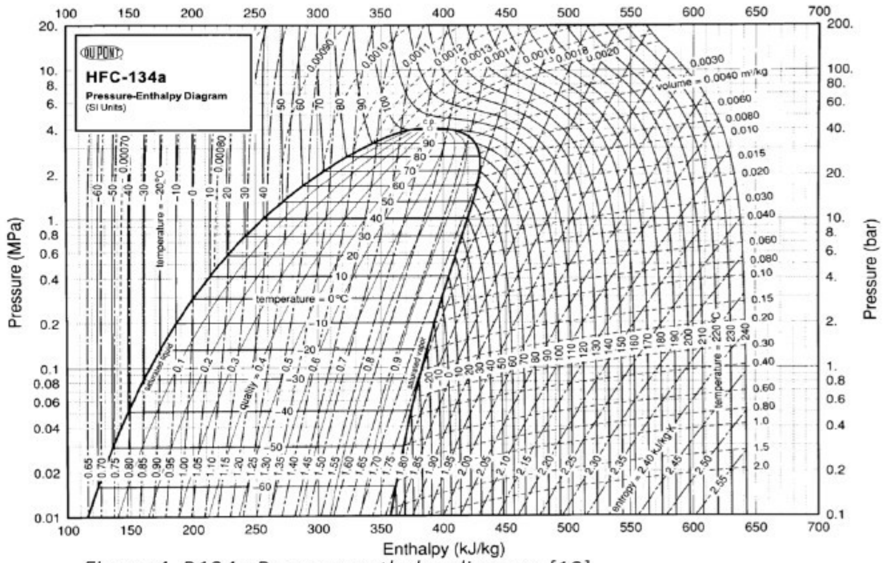

Figure 4. R134a Pressure enthalpy diagram [18]

$$\dot{Q}_{evap} = \dot{m}_r(h_1 - h_7) \tag{1}$$

$$\dot{Q}_{comp} = \dot{m}_r(h_3 - h_2) + \dot{W}_{comp} \tag{2}$$

$$\dot{Q}_{cond} = \dot{m}_r(h_5 - h_4) \tag{3}$$

Table 2. Calculated heat transfer of each stage of refrigeration cycle

	Heat Transfer (kW)
Evaporator	4.3959
Compressor	2.3264
Condenser	-5.6657

In table 2, the caclulated heat transfer of each component can be seen. In the evaporator, a heat transfer of 4.3959 kW is present from the indoor environment in the evaporator results from the refrigerant entering the evaporator at 274.7543kJ/kg leaving 414.3072kJ/kg. The refrigerant evaporates at a low pressure and temperature, so cooling the indoor air by means of this heat transfer. The. Compressor was assumed to have a 80% effiency. The compressor's heat transfer, compression of the refrigerant from a low pressure vapour to a high pressure vapour increases the system work.This energy input raises the temperature and pressure of the refrigerant, so ready for heat rejection in the condenser. The compressor was assumed to have an 80% efficiency. The negative sign of heat transfer in the condenser shows that heat is rejected from the refrigerant to the outdoor surroundings.The heat rejected comprises the work the compressor as well as the heat absorbed in the evaporator.

2. Part II – Exergy analysis & performance optimisation of heat exchangers for a thermal energy system

Exergy is the maximum amount of useful work a system can produce in interacting with its surroundings. It measures the system's capacity for work before it achieves equilibrium [20]. Exergy depends on the conditions of the system and the surroundings, usually taken to be at a reference state defined by ambient temperature, pressure, and chemical composition which is our refigrent [20]. First law of thermodynamics tells us that energy is conserved however, exergy is not. It can be consumed or destroyed, meaning the isn't a 100% efficiency. To solve the exergy, the entropy generation needs to be solved first. The entropy generation in a process is the total wasted energy resulting from inefficiencies [21]. For each components of the referigration cycle, the entropy generation can be solved using the Eqs. (4,5,6 and 7) below [19]. T_L is the 5 kelvin above the evaporator inlet tempreture and $T_h$is 5 kelvin above the condenser inlet tempreture.

$$\dot{S}_{evaporator} = \dot{m}_r (s_1 - s_7) - \frac{\dot{Q}_{evap}}{T_L} \quad (4)$$

$$\dot{S}_{compressor} = \dot{m}_r (s_3 - s_2) - \frac{\dot{Q}_{loss}}{T_0} \quad (5)$$

$$\dot{S}_{condenser} = \dot{m}_r (s_5 - s_4) - \frac{\dot{Q}_{cond}}{T_H} \quad (6)$$

$$\dot{S}_{expansion} = \dot{m}_r (s_7 - s_6) \quad (7)$$

Table 3. Calculated Entropy generation of each stage of refrigeration cycle

	Entropy Generation(kW/K)
Evaporator	0.030622371
Compressor	0.008355798
Condenser	0.001316863
Expansion	0.000398633

In table 3, we see the entropy generated in each stage of the cylce. In the evaporator stage, we can see the highest entropy generation of 0.030622371 kW/K. Knowing the evaporator absorb heat from the indoor environment, the larger temperature differences between R134a and air lead to greater irreversibilities and higher entropy generation. R134a goes from a liquid to vapor in the evaporator requiring a lot of heat input. The compressor can be seen to have the second highest entropy generation of 0.008355798 kW/K. This could be due to the compressor having moving parts within it meaning there is mechanical friction present leading to a generation of heat contributing to entropy generation. In a ideal situation, no entropy change should be present during the compression stage. The condenser has a lower entropy generation of 0.001316863 kW/K. Heat from R134a is rejected by the condenser into the outdoor air. The smaller temperature gradient compared to the outdoor air since the heat rejection process is controlled and the air is generally cooler than in the evaporator, so reducing the irreversibilities. Also, the condenser maximises heat exchange efficiency by using materials with high thermal conductivity and large surface area, so lowering entropy generation. The lowest value of entropy generation calculated was in the expansion valve with a value of 0.000398633 kW/K. Without doing work or exchanging heat with the surroundings, the expansion valve mainly lowers the pressure of R134a refrigerant. There is little entropy generation and this process is almost isenthalpic. this means that, the very fast expansion process reduces chances for irreversibility.

Following this, the exergy can be calculated through second order analysis. Often including irreversibilities and entropy generation into a review of a system's performance, second-order analysis highlights the quality or usefulness of energy. The exergy can be calculated through Eqs. (8,9,10,11 and 12) [19].

$$\Delta\psi_{condenser} = h_5 - h_4 - T_0 (s_5 - s_4) \quad (8)$$

$$\Delta\psi_{evaporator} = h_1 - h_7 - T_0 (s_1 - s_7) \quad (9)$$

$$\Delta\psi_{compressor} = h_3 - h_2 - T_0 (s_3 - s_2) \quad (10)$$

$$\psi_{expansion\ in} = h_6 - h_0 - T_0 (s_6 - s_0) \quad (11)$$

$$\psi_{expansion\ out} = h_7 - h_0 - T_0 (s_7 - s_0) \quad (12)$$

Table 4. Calculated Exergy of each stage of refrigeration cycle

	Exergy (KJ/kG)
Evaporator	-9.0850121
Compressor	37.6056454
Condenser	-18.283589
Expansion in	45.35650541
Expansion out	41.58341716
	97.17696687

Table 4 above shows the exergy values at each refrigeration cycle stage. The evaporator generated −9.085kJ/kg exergy. The negative exergy value shows that rather than generating it, the evaporator consumes exergy. Under low temperature and pressure, the refrigerant absorbs heat from the interior space in the evaporator. Considered low-quality energy, this heat cannot be straightly transformed into useful work. There is a phase change from liquid to vapor which calls for energy input. The exergy lowers here since no useful activity is carried out. The Compressor with a 37.606kJ/kg exergy came second. Because it compresses the refrigerant, the compressor adds useful energy (work) into the system, so having a positive exergy value. Compression raises the refrigerant's temperature and pressure, so enabling higher temperature rejection of heat in the condenser. then we could clearly see once more with a negative value of −18.284kJ/kg is the condenser. The condenser rejects heat to the environment, so extracting energy from the refrigerant. This heat rejection reduces exergy of the refrigerant. The negative exergy value suggests that, as the refrigerant moves its heat to the outdoor air, which has less potential to perform beneficial action. Then for the expansion inlet, a 45.357kJ/kg exergy was calculated. This is the refrigerant's exergy reaching the expansion valve. The refrigerant at this point is high-pressure liquid. The low entropy and higher pressure of the refrigerant compared to the evaporator account for the high exergy here. Then the exergy of 41.583kJ/kg was calculated for the expansion outlet. The refrigerant's pressure and temperature greatly drop once it passes the expansion valve. The drop in pressure reduces the capacity of the refrigerant to perform work, so causing exergy loss. Still, the refrigerant keeps enough exergy to absorb evaporator heat. This gives our total exergy for the cycle of 97.177kJ/kg. This shows the overall possibility for practical work in the cycle by showing the whole available exergy in the system.

The loss of exergy was then calculated also know as Exergy Destruction, using the equations below for reach component [19].

$$\dot{I}_{evaporator} = T_0\,\dot{S}_{evaporator} \tag{13}$$

$$\dot{I}_{compressor} = T_0\,\dot{S}_{compressor} \tag{14}$$

$$\dot{I}_{condenser} = T_0\,\dot{S}_{condenser} \tag{15}$$

$$\dot{I}_{expansion} = T_0\,\dot{S}_{expansion} \tag{16}$$

Table 5. Calculated Exergy destruction of each stage of refrigeration cycle

	Exergy Destruction (kW)
Evaporator	9.13005197
Compressor	2.491281124
Condenser	0.392622578
Expansion	0.11885228
	12.13280795

Table 5 shows the exergy destruction calculated from Eqs. (13,14,15 and 16). With a value of 9.130kW, the evaporator has the highest exergy destruction. At the lowest temperature in the cycle, the evaporator runs where irreversibilities from heat transfer. High entropy generation and exergy loss follow from a significant temperature difference between the refrigerant and the indoor air being cooled. With calculated value of 2.492kW, the compressor has the second-highest exergy destruction. Though mechanical and thermal inefficiencies result in exergy losses, the compressor adds work to the cycle. With value of 0.392 kW, the condenser has rather low exergy destruction when compared to the evaporator and compressor. Higher temperature heat rejection produces a smaller temperature gradient with the ambient air compared to the evaporator. With a value of 0.119kW, the expansion valve causes the lowest exergy destruction. The expansion process consists in a fast pressure drop without significant heat transfer.

Following this, we can work out the COP, coefficient of performance. Using Eqs. (17 and 18), the COP for the vapor compression system and the reversibility COP, COP_{rev}, can be calculated [19]. This allows the second law effiency, ε_c, to be calculated in Eq. (19) [19].

$$COP_c = \frac{\dot{Q}_{evap}}{\dot{W}_{comp}} \tag{17}$$

$$COP_{rev} = \frac{T_L}{T_H - T_L} \tag{18}$$

$$\varepsilon_c = \frac{COP_c}{COP_{rev}} \tag{19}$$

Table 6. Calculated COP (coefficient of performance)

	COP
Vapor compression cycle	4.251592143
Reversibility	4.535323946

The Vapour Compression Cycle has a calculated COP of 4.25159. This value, which takes real-world irreversibilities including friction, heat transfer across temperature differences, and compressor, evaporator, condenser, and expansion valve into account, so representing the actual COP of the refrigeration system. The Reversible Cycle has a COP of 4.5332. Calculated assuming an ideal process free of irreversibilities or losses, this is theoretically maximum COP for the system. Irreversibility causes the real COP to be less than the ideal performance, or reversible COP.

$$\varepsilon_c = \frac{4.251592143}{4.535323946} = 0.9374395627 \approx 93.74\%$$

Using Eq. (19), the second law effiency was calculated to be 93.74%. For a refrigeration cycle, this represents a good performance since the system makes use of 93.76% of the theoretically accessible exergy.

To improve, Begin with the evaporator, concentrate on lowering exergy destruction and raising efficiency to improve the COP and performance of the refrigeration system. Increasing the surface area of the evaporator, and minimising temperature gradients can improve heat transfer and lower irreversibilities. Regular maintenance, including refrigerant leak detection, helps to greatly lower mechanical and thermal inefficiencies by ensuring appropriate cooling and lubrication of the compressor. Larger coils, high-conductivity materials, improved airflow, and modest refrigerant subcooling for the condenser help to increase heat rejection efficiency.Giving the evaporator and compressor top priority will help to bring the real COP closer to the ideal and greatly lower energy consumption since they most contribute to exergy destruction.

References

1. Shah, R.K. and Sekulic, D.P. (2003). *Fundamentals of Heat Exchanger Design*. [online] Google Books. Available at: https://books.google.co.uk/books?hl=en&lr=&id=beSXNAZblWQC&oi=fnd&pg=PA1&dq=heat+exchanger&ots=NZKlnoe3RK&sig=atmvJ6oLY6cj5gnrJNJutXGVXqA&redir_esc=y#v=onepage&q=heat%20exchanger&f=false.

2. McDowall, R. (2007). *Fundamentals of HVAC Systems (SI)*. [online] Google Books. Available at: https://books.google.co.uk/books?hl=en&lr=&id=5L4fEQAAQBAJ&oi=fnd&pg=PP1&dq=what+are+hvac+systems&ots=dDwcdLlx4U&sig=5rkkw-FjEvmZeEbNfsjViYHpYGY&redir_esc=y#v=onepage&q=what%20are%20hvac%20systems&f=false.

3. Wendl, Michael. (2015). Theoretical Foundations of Conduction and Convection Heat Transfer. [online] Available at: https://www.researchgate.net/profile/Michael-Wendl/publication/280092363_Theoretical_Foundations_of_Conduction_and_Convection_Heat_Transfer/links/55a8189308aea3d0867c37a4/Theoretical-Foundations-of-Conduction-and-Convection-Heat-Transfer.pdf

4. Vedavarz, A., Kumar, S., Hussain, M.I. and Kumar Sunil (2005). *HVAC the Handbook of Heating, Ventilation and Air Conditioning for Design and Implementation*. [online] Available at: https://app-knovel-com.ezproxy.library.qmul.ac.uk/web/view/khtml/show.v/rcid:kpHVACTHH2/cid:kt008VX6PE/viewerType:khtml/root_slug:hvac-handbook-heating/url_slug:air-conditioning-systems?&b-toc-cid=kpHVACTHH2&b-toc-root-slug=hvac-handbook-heating&b-toc-title=HVAC%20-%20The%20Handbook%20of%20Heating%2C%20Ventilation%20and%20Air%20Conditioning%20for%20Design%20and%20Implementation&b-toc-url-slug=fundamentals&kpromoter=marc&view=collapsed&zoom=1&page=1

5. Sugarman, S.C. (2020). *HVAC fundamentals*. [online] Lilburn: Fairmont. Available at: https://app-knovel-com.ezproxy.library.qmul.ac.uk/web/view/khtml/show.v/rcid:kpHVACFE0L/cid:kt010WWYN5/viewerType:khtml//root_slug:hvac-fundamentals-3rd/url_slug:introduction-hvac-systems?b-toc-cid=kpHVACFE0L&b-toc-root-slug=hvac-fundamentals-3rd&b-toc-title=HVAC%20Fundamentals%20%283rd%20Edition%29&b-toc-url-slug=introduction-hvac-systems&kpromoter=marc&view=collapsed&zoom=1&page=1.

6. Hundy, G.F., Trott, A.R. and Welch, T.C. (2008). *Refrigeration and Air-Conditioning*. [online] Google Books. Available at: https://books.google.co.uk/books?hl=en&lr=&id=BuWLtqjv4kwC&oi=fnd&pg=PP1&dq=air+conditioner+refrigerant&ots=sTP6m4u563&sig=EpjBdN7KoSMyYkU97VGOluJOSHU&redir_esc=y#v=onepage&q=air%20conditioner%20refrigerant&f=false.

7. Calm, J.M. (2008b). The next generation of refrigerants – Historical review, considerations, and outlook. *International Journal of Refrigeration*, [online] 31(7), pp.1123–1133. doi:https://doi.org/10.1016/j.ijrefrig.2008.01.013.

8. TSAI, W. (2005). Environmental risk assessment of hydrofluoroethers (HFEs). *Journal of Hazardous Materials*, 119(1-3), pp.69–78. doi:https://doi.org/10.1016/j.jhazmat.2004.12.018.

9. Frederick, G. and Mayhew, Y.R. (2006). *Engineering Thermodynamics*.

10. Super Radiator Coils (2021). *The 4 Main Refrigeration Cycle Components | The Super Blog*. [online] www.superradiatorcoils.com. Available at: https://www.superradiatorcoils.com/blog/4-main-refrigeration-cycle-components.

11. Lamanna, B. (2022). *Heat Exchangers in the HVAC/R Sector*. [online] www.carel.com. Available at: https://www.carel.com/blog/-/blogs/heat-exchangers-in-the-hvac-r-sector.

12. Basavarajappa, S., Manavendra, G. and Prakash, S.B. (2020). A review on performance study of finned tube heat exchanger. *Journal of Physics: Conference Series*, 1473, p.012030. doi:https://doi.org/10.1088/1742-6596/1473/1/012030.

13. L Wang, Bengt Sundén and Manglik, R.M. (2007). *Plate heat exchangers : design, applications and performance*. Available at: https://books.google.co.uk/books?hl=en&lr=&id=P3gTR8YHLHgC&oi=fnd&pg=PA1&dq=plate+heat+exchangers+&ots=5gDNHehE4p&sig=RQK2oUx0Sa1AV3GgMg1pzR0kmDE&redir_esc=y#v=onepage&q=plate%20heat%20exchangers&f=false

14. Siddiqui, M., Azam, M.A. & Ali, H.M. Parametric Evaluation of Condensate Water Yield from Plain Finned Tube Heat Exchangers in Atmospheric Water Generation. *Arab J Sci Eng* **47**, 16251–16271 (2022). https://doi.org/10.1007/s13369-022-06832-3

15. Alfalaval.co.uk. (n.d.). *How does a plate heat exchanger work?* [online] Available at: https://www.alfalaval.co.uk/products/heat-transfer/plate-heat-exchangers/gasketed-plate-and-frame-heat-exchangers/how-plate-heat-exchangers-work/.

16. Ersoy, H.K. and Bilir Sag, N. (2014). Preliminary experimental results on the R134a refrigeration system using a two-phase ejector as an expander. *International Journal of Refrigeration*, 43, pp.97–110. doi:https://doi.org/10.1016/j.ijrefrig.2014.04.006.

17. Satsangi, R., Dheeraj, A. and Kumar, S. (2018). *R134a Refrigerant in Vapour Compression Cycle: A Review Paper*. [online] Academia.edu. Available at: https://www.academia.edu/36827925/R134a_Refrigerant_in_Vapour_Compression_Cycle_A_Review_Paper.

18. HFC-134a Pressure-Enthalpy Diagram. (n.d.). Available at: https://www.pfri.uniri.hr/web/dokumenti/uploads_nastava/20180214_103058_kralj_R134a.pressure.enthalpy.si.pdf.

19. Bahman, A.M and Groll, E.A. (2016) Second-Law Analysis to Improve the Energy Efficiency of Environmental Control Unit.

20. Jørgensen, S.E. (2008). Exergy. *Encyclopedia of Ecology*, pp.1498–1509. doi:https://doi.org/10.1016/b978-008045405-4.00689-3.

21. Yaşar Demirel (2002). Using the second law of thermodynamics. *Elsevier eBooks*, pp.124–185. doi:https://doi.org/10.1016/b978-044450886-7/50006-0.

Second law analysis

evap $\dot{S}_{gen,evap} = \dot{m}_r (s_1 - s_7) - \frac{\dot{Q}_{evap}}{T_L}$

$T_L = 16.51 + 5 + 273.15 = 294.66$

$\dot{S}_{gen.evap} = 0.0315(1.2592 - 1.757734) - \frac{4.3959}{294.66}$

$= -0.030622\,37119$

Compressor

$\dot{S}_{gen,comp} = \dot{m}_r (s_3 - s_2) - \frac{\dot{Q}_{loss}}{T_0}$

$T_0 = 25 + 273.15$

$Q_{loss} = Q_{comp}$ ← assume

$\dot{S}_{gen\,comp} = 0.0315(1.77394 - 1.791496) - \frac{2.3264}{298.15}$

$= -8.35579\,7834 \times 10^{-3}$

Condenser

$\dot{S}_{gen\,condenser} = \dot{m}_r (s_5 - s_4) - \frac{Q_{cond}}{T_h}$

$T_h = 81.48 + 5 + 273.15 =$

$\dot{S}_{gen\,condenser} = 0.0315(1.249556 - 1.791496) - \frac{-5.6}{359.6}$

$= -1.31686\,2579 \times 10^{-3}$

expansion valve

$S_{gen\,expander} = \dot{m}(s_7 - s_6)$

$= 0.0315(1.2592 - 1.246545)$

$= 3.986325 \times 10^{-4}$

Second law effiency

Evaporator

$\Delta\psi_{evap,r} = h_1 - h_7 - T_0(s_1 - s_7)$

$= 414.3072 - 274.7543 - 298.15(1.757734 - 1.2592)$

$= -9.0850121$

Compressor

$\Delta\psi_{comp} = h_3 - h_2 - T_0(s_3 - s_2)$

$= 455.5975 - 414.5679 - 298.15(1.77394 - 1.76248)$

$= 37.656454$

condenser

$\Delta\psi = h_5 - h_4 - T_0(s_5 - s_4)$

$= 275.7345 - 455.5975 - 298.15(1.249556 - 1.791496)$

$= -18.283589$

expansion Valve

inlet

$\psi_{exp\,in} = h_6 - h_0 - T_0(s_6 - s_0)$

$h_0 = 424.523003125$

$s_0 = 1.900998\,15625$

$= 274.7543 - 424.52300312S - 298.15(1.246545 - 1.9009$

$= 45.35650541$

outlet

$\psi_{exp\,out} = h_7 - h_0 - T_0(s_7 - s_0)$

$= 274.7543 - 424.52300312S - 298.15(1.2592$
$- 1.9009$

$= 41.58341716$