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“Study of the comparison of the exergy and energy analyses of the CO_2/NH_3 and CO_2/R134a cascade refrigeration system to be used in supermarkets”

A thesis submitted to the department of Mechanical and chemical Engineering (MCE), Islamic University of Technology (IUT), in the partial fulfillment of the requirement for degree of Bachelor in Technical Education with specialization in Mechanical Engineering.

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It is hereby declared that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma

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We seek excuse for any errors that might be in this report despite of our best efforts.

ABSTRACT.

Various techniques are being researched to refrigerate our stored products at a desired temperatures in supermarkets. In this report, via the exergy and energy analyses, the CO_2/NH_3 and CO_2/R134a cascade refrigeration systems were compared to determine which of the system suited best the supermarket application. The coefficient of performance (COP) was calculated as a measure of the energy analysis while on the other side the sum of the individual exergy destructions in each of the components which is equivalent to the total exergy destruction was a measure of the exergy analysis. The cascade refrigeration comprised of two refrigeration systems connected in series in which one of the system will in lower temperature circuit (LTC) while the other will be in the higher temperature circuit. The cooling space temperature and cooling capacity employed in this report were -40°C and 40 kW. In both the exergy and energy analyses the temperature at the LTC evaporator and condenser, cascade condenser temperature difference and HTC condenser were varied individually to obtain the desired results. The analyses result showed that CO_2/NH_3 cascade refrigeration system was more efficient than the CO_2/R134a system as it had lower values for the total exergy destruction and higher COP values. Furthermore, in both cascade systems maximum exergy destruction occurred in the condenser followed by the compressor.

NOMENCLATURE.

COP	Coefficient of performance.
HTC	Higher temperature circuit.
LTC	Lower temperature circuit.
T	Temperature.
m	Mass flow rate.
P	Pressure.
Q	Time rate of heat transfer.
η	Efficiency.
h	Enthalpy.
φ	Exergy produced.
E	Exergy destroyed

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1. Introduction.

1.1 Background.

The use of synthetic refrigerants such as CFC`s and HCFC`s dominated the refrigerant market for decades thanks to their efficacy and safety features. Being precarious to the environment, several measures have been introduced on their usage (Sawalha, 2008)[1]. In the 1970s, after decades of dissipating about a million tons of these refrigerants into the air each year, scientists came to know that CFC isn't harmless after all. CFC is slowly accumulated into the stratosphere, where it's eventually destroyed by the sun's ultraviolet rays. When the chemical bonds are broken, the chlorine atoms moves freely, and they become a catalyst that decompose unstable ozone molecules (O_3) into oxygen molecules (O_2). The chlorine isn't consumed in the reaction, so it continues ruining ozone for years. This is a big deal, because the ozone in the stratosphere acts like a blanket that protects all living things on the planet from the Sun's ultraviolet radiation. With all these discoveries, governments all over the world signed a treaty to ban the production of CFC and HCFC. Being prohibited, scientists turned their attraction towards the natural refrigerants like ammonia and carbon dioxide. Though they are flammable and toxic modern technology have been developed to minimize these defects.

Most supermarkets rely on the vapor compression refrigeration cycle to cool the products in a supermarket. In the supermarkets in Cape town, South Africa refrigeration accounts for 60% of the total energy. With the population increasing, the number supermarkets are also soaring to meet the demand of the citizens. The products needs to be kept cool at temperatures between -5 to -40°C. Using single stage refrigeration will be expensive on the long run because there is a huge difference between the temperature of the cooling space and the temperature of the environment. To solve these problems cascade systems have been determined to be the panacea. CO_2/NH_3 cascade is the most analyzed. (Carlos, Rodrigo, Daniel, Ramon, & Enrique, 2014) [2] worked on the experimental evaluation of R134a/ CO_2 cascade refrigeration systems. (Aminyavari, Najafi, & Rinaldi, 2014) [3] worked on the energetic, exergetic, environmental (3E) analyses of the CO_2/NH_3 cascade refrigeration system. (Lorentzen, 1994) [4] worked on the revival of CO_2 as a refrigerant. (Perales, 2006) [5] performed the parametric evaluation for the CO_2/NH_3 cascade system for supermarket refrigeration in laboratory environment.

1.2 History of refrigeration.

From the second law of thermodynamics (Clausius) it is impossible to transfer heat from a region cold potential to cold potential. This can only be done if some external work can be done. To defy this law scientists coined the mechanism of refrigeration. The heat movement is done thanks to the mechanical work within the refrigerator but other means like magnetic, electrical and laser can also be employed as replacement to the mechanical work.

Refrigeration has myriad application in industries, automobile, supermarkets, hospitals, households and many others. Refrigeration has a tremendous impact in the lifestyle of our society. The antiquated forms of refrigeration can be traced back from the ancient civilizations. Back at the time, people used to collect the ice from snow during winter to cool their products. The aim of cooling was not at first directed towards food. The Greeks used to manufacture beverages so used the ice they collected to cool and preserve the beverages. The use of collected ice was not only method. The Egyptians came out with another means. They transferred boiled water in jars, then placed in top of the roofs during the night to cool the water. The exterior part of the jar was moisturized and due to evaporation, the water was able to be cooled. This is still used in some villages in Africa which do not have access to electricity. This is technique was in a sense better than the ice collection because to collect ice you had to wait the winter season, whereas every night you can be able to cool your drink no matter the season.

In the USA in the 1830`s the indigenes used collect the ice from their ice stores with the aid of saw to cut the ice. But it was later reported that this method was dangerous and not safe. With the increase of products from farms it was necessary to discover a means to store them. With this ice became a marketable product and its consumption escalated in major cities like New York and Boston from about "12000 to 100000 tons and 6000 to 85000 tons respectively" (from wikipedia). The rise in the consumption of the ice became a catalyst for the advent of artificial refrigeration. Artificial refrigeration originated from Scotland where the Professor William Cullen build a small refrigeration machine which boiled diethyl ether and absorbing air from the environment. Unfortunately this method was of no us even though it created a small amount of ice. Scientists then reflected on the use evaporation to cool things. Professor Benjamin Franklin and John Hadley conducted some experiments with some conclusions that when highly volatile substances like alcohol are evaporated, objects can be cooled beyond water`s freezing point. With this other methods like vapor compression and gas absorption refrigeration system were given birth and are now used in industries.

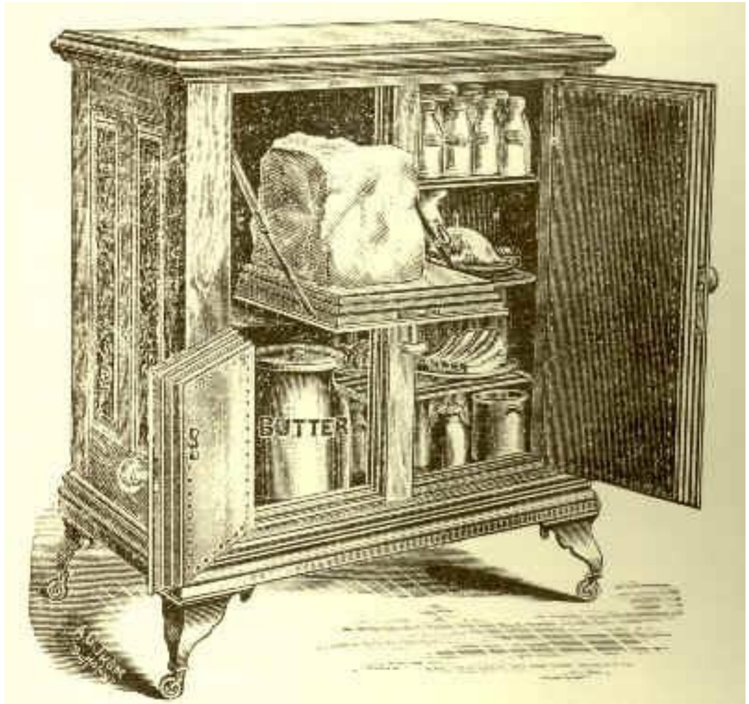

Figure 1: An Ice Box used to store some commodities.

Figure 2: Ice production.

1.3 Refrigerants.

Early mechanical refrigeration system employed some natural refrigerants such as ammonia, methyl chloride and Sulphur dioxide. Being, toxic and flammable sulfur dioxide and methyl chloride rapidly disappeared from the market with the introduction of CFCs. These refrigerants had the benefits of being non-flammable and non-toxic. They were used in refrigerators, air conditioners, automobiles. But later it was realized that their high Ozone

Depletion Potential (ODP) and Global Warming Potential (GWP) had devastating effects on our planet. Leakage of these refrigerants into the environment depletes the ozone layer and bring about global warming. Having being noticed two conferences prohibited the use of these refrigerants.

- **Montreal Protocol.**

With the rise of awareness regarding global warming the world leaders organized a conference in Montreal in September 1987. The main aim of this gathering was to project a plan in which the use of ozone depletion substances will be phased out. This was called the Montreal Protocol and some of its features are mentioned below:

- The use of CFC`s should be relinquished by 1996 in developed countries.
- The use of CFC`s should be removed by 2010 in developing countries with freeze in 1999 and progressive reduction after. Developed countries would have to phase out HCFC`s before 2030. Developing countries will have an extra 10 years to achieve that goal.
- Global warming being a threatening issue to be considered. Though other substances are responsible, CFC`s has a significant global warming potential to cause an impact.

- **Kyoto protocol.**

One of the major goals of the Kyoto protocol is to eliminate substances that are responsible for global warming. R134a being one of them, utilized as a house hold refrigerator was identified as a replacement to R-12 due to its zero ozone depletion potential. But it is not as ideal as expected since it has a global depletion potential of 1300 which is extremely high. Leakage of R-134a into the atmosphere will result in the packing of greenhouse gases thus affecting the atmosphere adversely. Hence it was included among the six refrigerants to be extracted out of the market in the near future under the Kyoto protocol. Following this scientists came back towards natural refrigerants as the modern technology can harness the defects of these refrigerants.

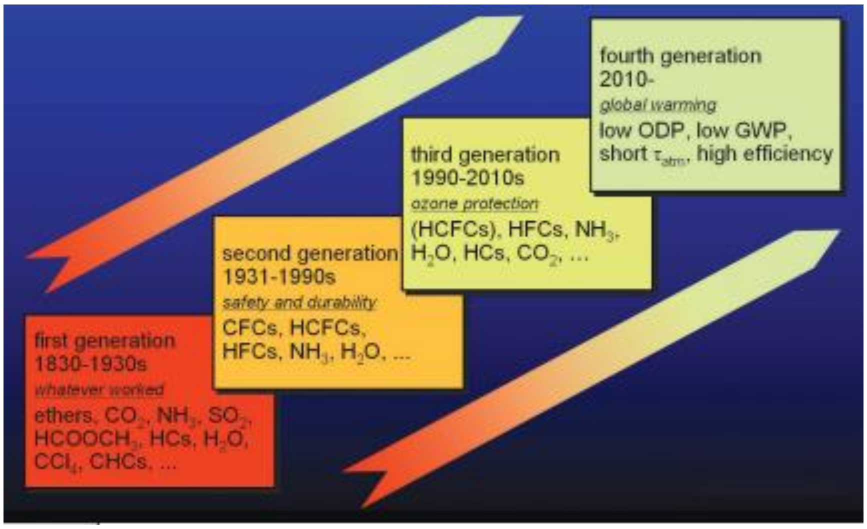

Figure 3: Diagram illustrating the evolution of refrigerants.

With all the restrictions being decided at these conferences, the refrigerants should be careful selected. The refrigerator`s operating temperature has an impact on the thermal efficiency. Some other factors like the size, design, initial and operating cost, serviceability, and reliability makes a balance on the refrigerant to be chosen for a particular application. As a result of environmental threats like global warming and ozone depletion and their connection to the refrigerants used, the choice for a refrigerant has become a global concern and care must be taken about it if our planet is to be free. The following requirements are to be followed for the selection of a refrigerant of a particular application.

- Thermo- dynamic and thermos physical properties.
- Environmental and safety properties.

Thermo-dynamic and thermo-physical properties.

- **Suction pressure:** To prevent the leakage of the refrigerant out of the system, the suction pressure should be beyond the atmospheric pressure. The higher suction pressure the smaller the compressor`s displacement.
- **Discharge pressure:** To permit the light construction of major components like the compressor and the condenser, the discharge pressure should be low as possible.
- **Pressure ratio:** To enhance the volumetric efficiency and reduce the power consumption the power ratio should be kept low.
- **Latent vaporization:** The latent heat of vaporization should be significant as possible for the mass flow rate per unit cooling capacity to be small.
- **Isentropic index of compression:** To minimize the temperature rise during the process of compression, the index of compression should be low.
- **Liquid specific heat:** For the extent of sub-cooling to be large to result to minute amount of flash at the evaporator, the liquid specific should be kept low.
- **Vapor specific heat:** To minimize the degree of superheating its value should be large as possible.
- **Thermal conductivity:** To attain higher heat transfer coefficients, the thermal conductivity in the vapor as well as in the liquid phase should be high.

- **Viscosity:** Minimization of the frictional pressure drops is needed for the efficient operation of the refrigeration system. Thus the viscosity should be as low as possible.

Environmental and Safety properties.

- **Ozone depletion potential (ODP):** Following the resolution from the Montreal protocol, non- zero ODP refrigerants such as R-11 and R-12 are to be eliminated from the refrigerants market. Refrigerants containing chlorine like CFC`s and HCFC`s and bromine have been banned because the ODP is dependent on the presence of these halogens.
- **Global warming potential (GWP):** Refrigerants such as R-134a despite having an ODP having of zero have an enormous GWP. Thus it has been planned to regulate the use of such refrigerants in future.
- **Total Equivalent Warming Index (TEWI):** The direct discharge of the refrigerants (as a result of its release in the atmosphere) and the indirect emission due to energy consumption as contributors to global warming is considered by the factor TEWI. Thus from this point of view with a minimum TEWI are given consideration.
- **Flammability:** For the safety of the refrigeration system it is required for the refrigerants to be non-flammable and non-explosive. A meticulous care should be taken to handle a system with flammable refrigerants. For this reason ASHRAE categorized the refrigerants into six safety groups that is A1 to A3 and B1 to B3. A1 refrigerants are the least flammable whereas B3 refrigerants are the most hazardous ones.

fluid	Boiling point (^0C)	Critical temperature (^0C)	Critical pressure(bar)	ODP/	GWP (100 years)	oil	flam
R12	-29	100.9	40.6	0.9	8100	mineral	no
R22	-40.8	96.2	49.8	0.055	1500	mineral	no
			Pure HFCs				
R23	-82.1	25.6	48.2	0	12000	ester	no
R32	-51.6	78.4	58.3	0	650	ester	yes
R125	-48.5	68.0	36.3	0	2500	ester	no
R143a	-47.6	73.1	37.6	0	4300	ester	yes
R134a	-26.5	101.1	40.7	0	1200	ester	no
R152a	-25.0	113.5	45.2	0	140	ester	yes
			HFC mixtures				
R407C[3]	-44.0	86.8	46.0	0	1600	ester	no
R410A[2]	-50.5	72.5	49.6	0	1900	ester	no
R404A[2]	-46.4	72.1	37.4	0	3300	ester	no
			Natural refrigerants				
R290(propane)	-42.1	96.8	42.5	0	<20	mineral	yes
R600a(isobutene)	-11.7	135.0	36.5	0	<20	mineral	yes
CO_2(R744)	-56.6@ 5.2bars	31.0	73.8	0	1	PAG	no
R717(ammonia)	-33.3	132.2	113.5	0	0	mineral	yes

Table 1: The SHERPHA project showing the environmental impact and properties of refrigerants.

1.4 Some refrigerants used in supermarkets.

Several refrigerants are used in the supermarket but in this report we will consider only we will work with:

- **R-134a.**

  Coined more than 20 years ago, to have features which are alike to R-12, it was the first non-ozone depletion refrigerant to be brought in the market. It is appropriate for medium and high temperature applications for which R-12 was employed. As a result of his high critical temperature and low hose permeability it became popular in the automotive air conditioning industry. Some of the house hold refrigerators use R-134a as a refrigerant. R-134a has the advantage to be a single component refrigerant, thus no glides can be expected. The con related to this refrigerant is that it has a capacity inferior to that of R-22. To use this refrigerant tubes within the heat exchangers and other components of the refrigeration system, should enlarged to lower the pressure drops and maintain a considerable efficiency. With the aggregation of the greater displacement of the compressor, this system is more costly compared to R-22. Comparing R-134a heat transfer coefficient with that of R-22, it has a lower value compared to the later. Thus design an effective refrigeration system which will replace R-22, sufficient time and money will be needed. But in larger commercial system where we have the use of larger screw compressor or centrifugal system, R-134a may offer a better solution compared to R-11 and R-12 which commonly used before been banned.

- **Ammonia (NH_3).**

  Ammonia is famous in large industrial plants. Being a halogen free refrigerant, it has a zero ozone depletion potential (ODP) as well as a zero global warming potential (GWP). Despite the fact of possessing the features mentioned above, it is considered as hazardous refrigerant due to its toxicity which limits its use in large industrial refrigeration applications. Ammonia performance can be compared to R-22, in large systems. Being easily obtainable and available at low cost, employing ammonia in commercial system requires some challenges to be surpassed. Higher discharge pressure are common with ammonia. Furthermore, as the oils are immiscible with oil, the oil management becomes a concern. Though it has a small mass flow rate which is advantageous in commercial system, it easily corrodes copper material thus steel should be employed as the refrigerant lines and the copper winding in the compressor should be insulated from the gas. Ammonia if not properly managed in commercial applications might lead to accidents as to its toxicity and flammability.

- **Carbon Dioxide (CO_2).**

  The application of carbon dioxide as a refrigerant has been considered for various small refrigeration systems. R-744 is the ASHRAE formula for carbon dioxide. Being non-flammable, having a low toxicity, easily available and having a low cost, carbon dioxide can be considered as an eco-friendly refrigerant. This is why 100 years back they used as refrigerants. Thermodynamically not efficient compared to HCFC`s, they have good heat transfer properties and can easily adjust to cycle modifications. Carbon dioxide performance is dependent upon the high heat transfer and the inclusion of an auxiliary heat exchanger. It has a positive vapor pressure at temperature below -35°C making it to be utilized in low temperature circuits of cascade refrigeration systems. Due to this high vapor pressure some modification is required in the compressor the compressor shell, valves, rings, terminal, and seals, as well as the pressure-relief valve and the condenser to be used in the system. The large pressure brings in some challenges in the static and dynamic seals of the compressor. This renders the system to be expensive as money is required for designing a system which be free all these defects. In real situations though the efficiency of the compressor is low, it should be fairly high theoretically. Microchannel heat exchangers are a necessity and a suction heat exchanger is a most. Nowadays carbon dioxide are mostly used in cascade refrigeration systems alongside refrigerants like ammonia and R-134a. They are employed in lower temperature circuits due to the fact they have a positive vapor pressure even at low temperatures preventing its leakage to the atmosphere.

2. Vapor Compression Refrigeration Systems.

2.1 Brief Description of the Vapor Compression Refrigeration System.

We are all aware it is possible to transfer heat from hot region to a cold. This process occurs without the help naturally that is without the employment of an external agent. But to do the reverse we require an external work. And here comes refrigerators which are devices capable of transferring heat for a low temperature zone to a higher temperature zone. They are cyclic devices which operates with working fluid called refrigerants.

They various types of refrigeration systems but our main concern here is the vapor refrigeration cycle. In this system the refrigerant undergoes a change of phase. It is a popular method for air conditioning of buildings and automobiles. It is also widely used in domestic and commercial refrigerators, large-scale warehouses for chilled or frozen storage of foods and meats, refrigerated trucks and railroad cars, and a host of other commercial and industrial services. Oil refineries, petrochemical and chemical processing plants, and natural gas processing plants are among the many types of industrial plants that often utilize large vapor-compression refrigeration systems. The vapor compression cycle is widely used in refrigeration systems, including refrigerators, refrigeration air conditioning, freezers, and auto air conditioners. Though R-22 and R-12 are popular, they are being eradicated from the market due to its contribution in the depletion of the ozone layer.

The vapour compression and refrigeration system is the most popular and widely used refrigeration using Liquid or Refrigerant as its medium of cycle. This kind of system have four main component that complete the system cycle. These are; Compressor, Condenser, Expansion Valve and Evaporator.

The system cycle of this vapor compression refrigeration system start at a Compressor chamber, the refrigerant enters the compressor at a low vapor and low temperature, then the refrigerant is compressed which increases the level of fluid pressure and temperature, as a result the fluid leaves the Compressor at high pressure and temperature and enters the second stage of refrigeration.

When the liquid leaves the Compressor at high pressure and temperature, it enters the Condenser where the liquid is cooled, heat is rejected therefore the vapor liquid is then converted into liquid due to the decrease in temperature that was rejected and cooled by the condenser but the pressure remain the same. Then the liquid enters or passed through the Expansion Valve, the liquid expands which results in low pressure or reduces the pressure the liquid, so now the liquid has low temperature and pressure, in other words the liquid is at low temperature and low pressure state.

Finally, the low temperature and low pressure refrigerant passes through the Evaporator where it absorbs the remaining heat of the refrigerant from the cold chamber and converted it into vapor and emitted the vapor in a cold state and this completes the Vapor Compression Refrigeration Cycle.

2.2 Main components of the vapor refrigeration compression system.

There are 4 main components in a mechanical refrigeration system. Any components beyond these basic 4 are called accessories. The compressor is a vapor compression pump which uses pistons or some other method to compress the refrigerant gas and send it on its way to the condenser. The condenser is a heat exchanger extracting heat from a highly pressurized and hot refrigerant eliciting the refrigerant to be condensed. The liquid refrigerant is then routed to the metering device. The flow of the refrigerant is been hampered by this device deviating it to a small hole leading to a pressure drop. The pressure drop causes the drop in the boiling point of the liquid refrigerant which eases its evaporation. Thus the evaporation of the liquid refrigerant takes in the evaporator. Here the liquid refrigerant being at a higher pressure than atmospheric absorbs heat ambient environment. The refrigerant is redirected toward the compressor and cycle continues.

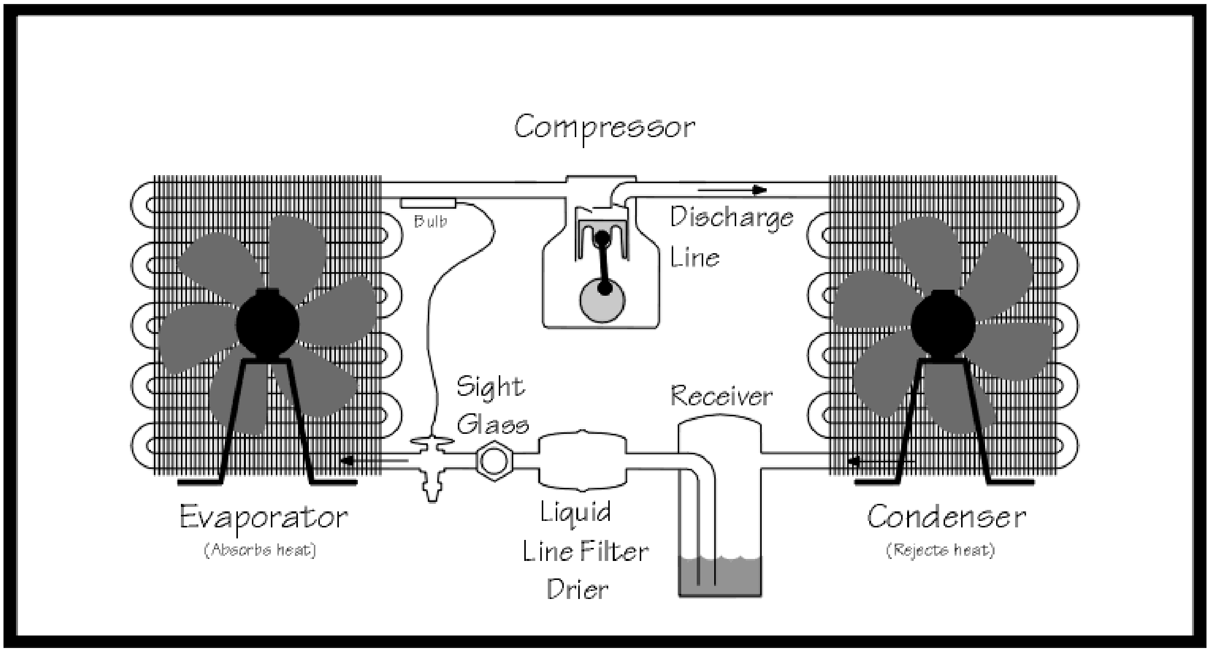

Figure 5: Diagram showing the main components of the vapor refrigeration system.

- **Condenser:** The condenser is responsible for a creating a milieu through which heat will be transferred from the compressed refrigerant to the ambient environment. Its appearance is not difference is not different for that of the evaporator. They operate under the same principle which is transfer of heat. But it differs from the evaporator as it function is to condensate hot compressed refrigerant for its evaporation in the evaporator. For a significant heat transfer to take place the refrigerant temperature should be above that of the ambient air that is carried from zone and relocated in another zone as suggested by the principle of refrigeration. The compressor aids in this process of condensation as it is responsible for the creation of a force which drives the refrigerant around a loop thus making it easy to transfer heat from one place to another. Liquefaction of the refrigerant generates heat which is in turn removed by the condenser. Water-cooled as well as air-cooled condenser can be used in the refrigeration system. The latter is more popular. The construction of the condenser comprises of tubing with external fins. The tubes are placed in such a way as to encourage the maximum possible heat transfer by enlarging the surface area of the tubes. The flow of heat is speeded by the use of heat of fan which increases the chance of heat to be liberated by the condenser.

Figure 6: Diagram showing the condenser of a refrigerator system.

- **Compressor:** To maintain the flow of the refrigerant in a loop which is to be transferred to condenser for the condensation the compressor is needed. The refrigerant from the evaporator has a low pressure so the compressor raises the pressure as well as the temperature of the refrigerant. The type compressors used in the refrigeration system either be a rotary, reciprocal or centrifugal. Of all the types mentioned above the reciprocal compressor is more used which is kind of similar to the automobile engine as it consists of a piston cylinder system in which there is a suction and delivery system. the piston here moves in a reciprocating manner that is as it moves downward , the refrigerant is sucked into the cylinder and while moving in the reverse direction it squeezes the compressor thereby raising its temperature and pressure. One of the inconveniences is heat is generated during the process and at high pressure humongous amount if heat can be generated. This can lead to a failure of the compressor itself consequently have adverse effects on the refrigeration system. Thus depending on the application of the refrigeration system a suitable compressor is to be chosen for its efficient operation.

Figure 7: Diagram illustrating the compressor of a system.

- **Evaporator:** The liquid refrigerant arrives liquid refrigerant whose temperature and pressure has been lowered. The goal of refrigeration is to transfer heat from a cold zone to a high temperature zone. The evaporator plays this primordial task of expunging the unwanted heat from the cold space with the help of the refrigerant rendering our refrigerator space. Following this liquid refrigerant is converted to vapor completing the process of evaporation. The air from which the heat is absorbed is generated by a fan. The construction of the evaporator is not dissimilar to that of the compressor. It comprises of fins as well as tubing. The material of these tubes are of high thermal conductivity which will be helpful for a remarkable heat transfer. Metals such as aluminum and cooper are useful to serve this purpose. It is also to be noted that the evaporation takes place at a low pressure. This pressure depends on

- The degree to which heat is extracted from the air by the liquid refrigerant.
- The extent to which the vapor refrigerant at low pressure is moved to the compressor.

Figure 8: Diagram illustrating the evaporator of the system.

- **Expansion valve:** The liquid refrigerant from the condenser still have a high pressure resulting from the compressor. The job of the expansion is to lower this pressure of the liquid refrigerant so as to facilitate the evaporation process in the evaporator. Within the valve there is an orifice through which the refrigerant is forced. As the refrigerant enters the orifice its pressure is reduced. The expansion has the responsibility of regulating the amount of refrigerant entering into the evaporator. The most used types of expansion valves are:

- Capillary tubes.
- Automatic expansion valves.
- Thermostat expansion valves.
- Low side float valves.
- High pressure float valves.

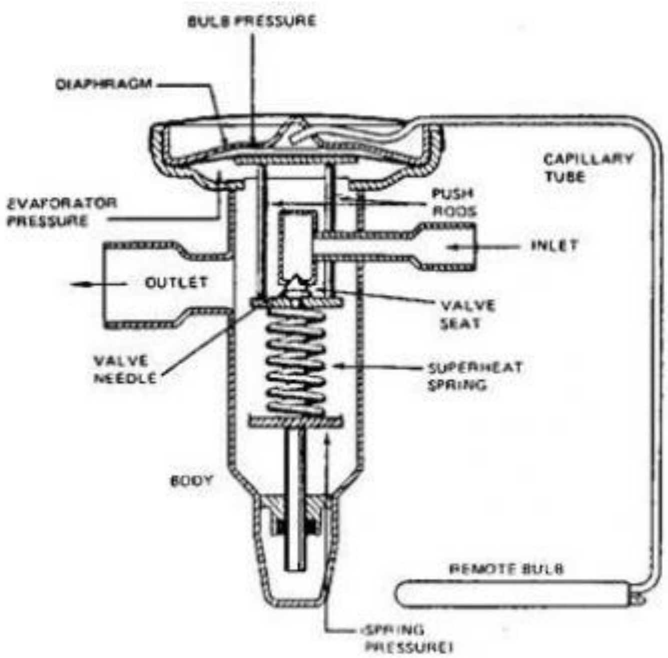

Figure 9: Schematic diagram of the thermostat expansion valve.

2.3 Cascade refrigeration system.

To hamper the decomposition of the food items it is desirable to conserve them at low temperatures. This hampers the growth of bacteria which is responsible for food spoilage. Refrigeration can meet this need. But not all refrigeration system can satisfy this condition. To be specific single stage refrigeration system can produce low temperatures. And the food needs to be conserved at extremely low temperatures. Cascade refrigeration system can be panacea to this problem. In this configuration more than one refrigeration system can be combined in series in order to obtain the desired temperature to conserve products. One of the refrigeration is located the higher temperature circuit and the other is located in the lower temperature circuit. According to the Nissin refrigeration and engineering ltd low temperatures from -40 to -80°C can be obtained. But this design tends to be inefficient when refrigerants of the same kind are used in both systems. To take advantage of the cascade system, it is advised to use different refrigerants in both refrigeration system. This enhances the efficiency of the system. For example in this report CO_2/NH_3 and $CO_2/$R134a cascade refrigeration system.

Some of the advantages of cascade refrigeration system, are outlined below:

- The higher temperature and lower temperature circuit are favored by some features such as temperatures. This helps in saving energy.
- Easy repair.
- Running cost is cheap.
- It can be ran at a low temperature.

3. Energy and Exergy Analysis.

3.1 Energy Analysis.

The energy analysis is based on the first law of thermodynamics which states that which states that energy is neither created nor destroyed but converted from one form to another. The energy analysis is made possible by the energy balance. Analysis of the energy balance will result would reveal the use of energy in different parts of the process and allow to comparing the efficiency and process parameters with the currently achievable values in the most modern installations (Ahamad, R., & Masjuki, 2011) [6]. Thermodynamic processes releases huge amount of heat energy to the atmosphere. Heat transfer between the system and surrounding environment takes place at a finite temperature difference which is a major source of irreversibility. Irreversibility causes the system to degrade. These losses can be evaluated using the energy analysis. Energy analysis is still the most common used method in thermal systems. Energy analysis is measured in refrigerators using the coefficient of performance (COP). It is the ratio of the useful refrigeration to the net work done. It is desirable to obtain a high COP as it implies that refrigerator only requires a small amount of work.

3.2 Exergy Analysis.

The world population is in need of energy to tackle the economic crisis going on and as well offer sanitation, increase health benefits and the reduction of pollutants decimating our environment. New sources of energy are being discovered every day in different parts of the world. Estimating the amount of energy usable is cardinal. What we really need to know is the work potential of the source that is the amount of energy we can extract from the source. This is known as exergy which can also termed availability. It is the maximum useful work that can be obtained as a system undergoes a process between two specified states. Scientists and engineers have been using exergy analysis to improve the functioning of processes and systems.

Although being new in the scientific world, its origin can be traced back for almost 200 years. The idea of maximum of energy was brought forth by Carnot . Rudolph Clausius with his second law of thermodynamics laid the bases of exergy and exergy analysis. But the term ‘exergy’ was coined by the German scientist Zoran Rant to denote the useful energy. Josiah Williard Gibbs who played an important role in thermodynamics. One of the most of the remarkable one was methods for ameliorating the second law of thermodynamics. These work enabled the second law analysis to be employed in real systems in the modern era.

In actual processes, energy is lost as a result of irreversibilities and the entropy of the system increases. Exergy analysis is relevant for identifying and quantifying both of exergy destruction within a process due to irreversibility (cannot be used to work and should be possibly eliminated) and the exergy losses e.g. the transportation of exergy to the environment. Exergy destruction is neglected in the evaluation of a system according to energy balance of first of thermodynamics. These energy inefficiencies help to highlight the areas of energy

improvement potentials within a system and also from the impact on the environment. The energy analysis is mostly used in thermal systems and it follows the first law of thermodynamics which talks about the conversation of energy. But it gives no information on how, where, and how much the system performance is degraded. To bring about the optimum performance of the system and identify the sites of exergy destruction exergy analysis is used.

The exergy is widely used in different systems. It has been found that major exergy losses have been caused in the refrigerator – freezer followed by air conditioner, washing machine, fan, rice cooker, iron, VCD/VCR/DVD player, and about 21% of total losses are caused by the refrigerator-freezer and 12% of the total losses are caused by the air conditioner (Ahamad, R., & Masjuki, 2011)[6]. So, it indicates that a major part of exergy losses in the energy sector is caused in the vapor compressor system (refrigerator and air conditioner, 33%). Refrigerators are widely use domestically. In the past halogenated refrigerants where used in our refrigerators. But this latter was a major contributor to the global warming and it usage was banned. Following this scientists were urged to conduct researches to bring about new ecologically friendly refrigerants. Based on different researches different refrigerants will yield results due to the exergy analysis and can thus be used to determine the optimum parameters of the refrigerants and improving the overall system. Energy and exergy analyses need some mathematical formulations for the simple vapor compression refrigeration cycle. In the vapor compression system, there are four major components: evaporator, compressor, condenser, and expansion valve. External energy (power) is supplied to the compressor and heat is added to the system in the evaporator, whereas in the condenser heat rejection is occurred from the system. Heat rejection and heat addition are dissimilar to different refrigerants, which cause a change in energy efficiency for the systems. Exergy losses in various components of the system are not same. A temperature and pressure are denoted by T_0 and P_0, respectively. Exergy is consumed or destroyed due to entropy created depending on the associated processes. To specify the exergy losses or destructions in the system, thermodynamic analysis is to be made.

4 Mathematical modelling.

A schematic diagram of the CO_2/NH_3 and CO_2/R134a refrigeration cycle which has been used in this study is show in figure 8 and 9.

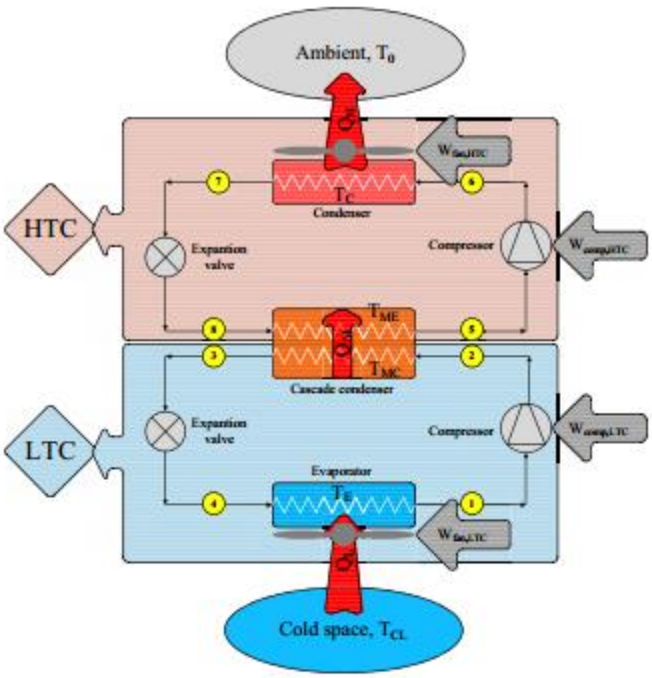

Figure 10: Schematic diagram of the CO_2/NH_3 refrigeration cycle.

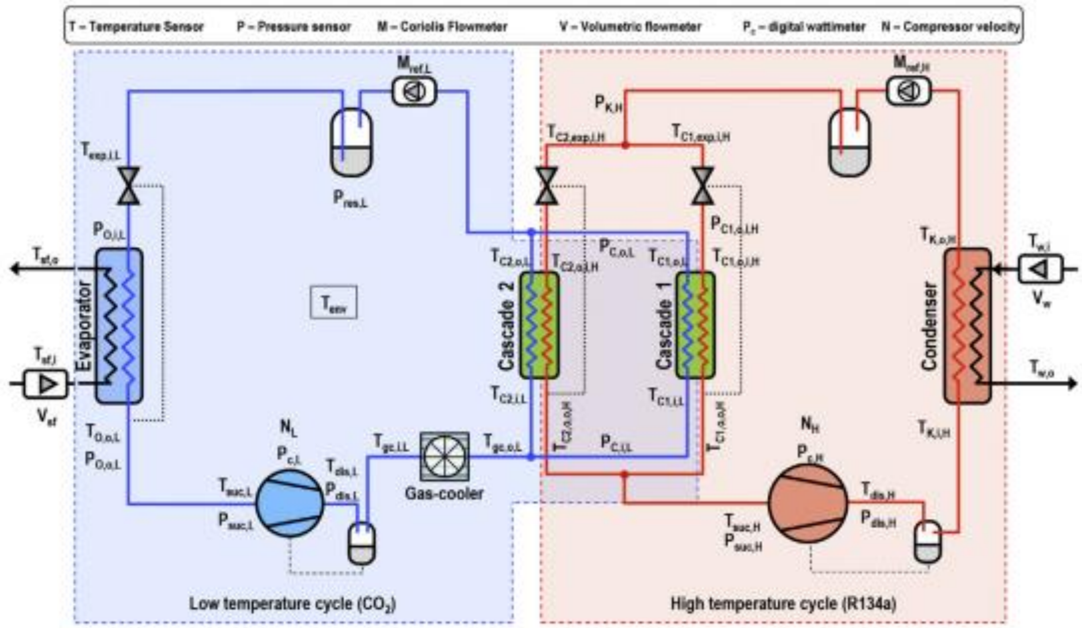

Figure 11: Schematic diagram for the CO_2/R134a refrigeration cycle.

The system consists of two circuits, the high temperature circuit (HTC) and the low temperature circuit (LTC). Ammonia and R134a were used as refrigerants in the HTC circuits meanwhile carbon dioxide was used in the LTC. Each refrigeration system comprises of an evaporator, compressor, condenser and expansion valve. In both refrigeration systems two circuits were thermally coupled to each other via a cascade refrigeration system which serves as a condenser for the LTC and evaporator for the HTC.

The evaporator in the LTC absorbs the cooling load, $\dot{Q}_L$ from the cooling space at the evaporator temperature T_E meanwhile the condenser at HTC dissipates the heat of $\dot{Q}_H$ at the temperature of the condenser T_C to the environment which is at a temperature of T_0. The heat transfer in the cascade condenser is equivalent the sum of the heat absorbed by the evaporator in the LTC and the work input of the compressor. In a similar way the heat rejected by the condenser in the HTC is equal to the sum of the heat absorbed by the evaporator in the HTC and work input of the compressor in the HTC. $\dot{m}_L$ and $\dot{m}_H$ are the mass flow rate used in the LTC and HTC respectively.

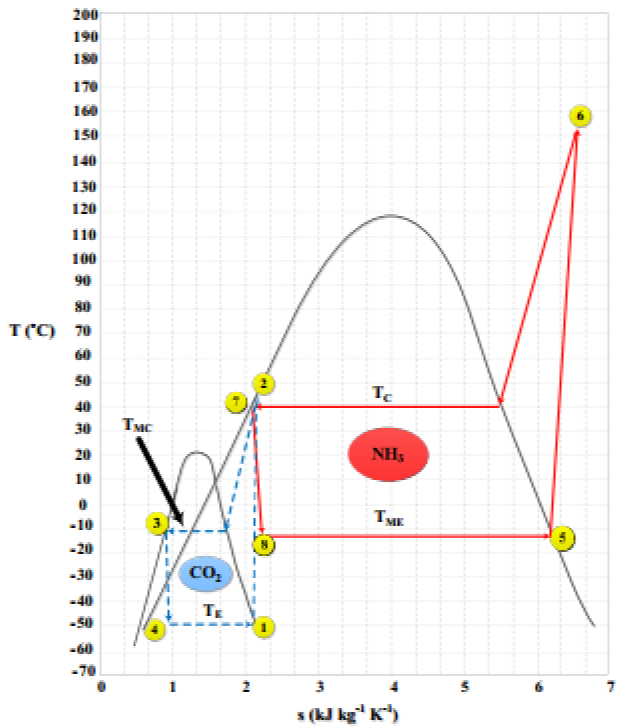

Figure 12: T-S of the CO_2/NH_3 refrigeration cycle

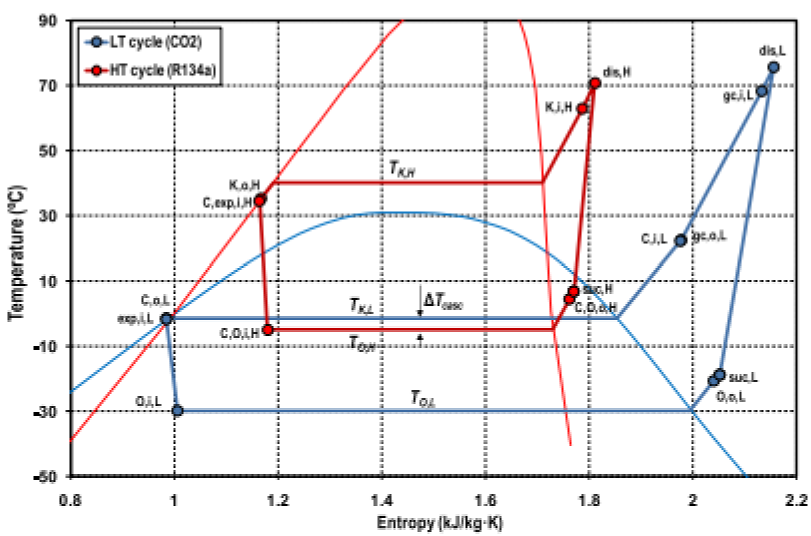

Figure 13: T-S diagram for the CO_2/R134a refrigeration cycle.

4.1 Energy Analysis.

The heat absorbed by the LTC evaporator from the cooling space is

$$\dot{Q}_L = \dot{m}_L(h_1 - h_4) \quad (1)$$

The isentropic efficiency of the compressor is assumed as

$$\eta_{is} = 1 - (0.004 \times r_p) \quad (2)$$

The mechanical and electrical efficiencies, η_m and η_e respectively were assumed to be 0.9.

The compression power of the LTC compressor due to energy balance is

$$\dot{W}_{LTC} = \frac{m_L(\dot{h}_{2s-h1})}{\eta_m \times \eta_e \times \eta_{is}} = \frac{m_L(\dot{h}_{2-h1})}{\eta_m \times \eta_e} \quad (3)$$

It was assumed the expansion process is isenthalpic so

$$h_3 = h_4 \quad (4)$$

$$h_7 = h_8 \quad (5)$$

The rate exchanged of heat between the LTC and the HTC in the cascade condenser is

$$\dot{m}_L(h_2 - h_3) = \dot{m}_H(h_5 - h_8) \quad (6)$$

The heat energy dissipated by the condenser to the ambient is

$$\dot{Q}_H \dot{=} \dot{m}_L(h_7 - h_6) \quad (7)$$

The power of the compressor in the HTC is

$$\dot{W}_{HTC} = \frac{m_L(\dot{h}_{6s-h5})}{\eta_m \times \eta_e \times \eta_{is}} = \frac{m_L(\dot{h}_{6-h5})}{\eta_m \times \eta_e} \quad (8)$$

$$\text{Coefficient of performance} = \frac{\dot{Q}_L}{\dot{W}_{LTC}+\dot{W}_{HTC}} \quad (9)$$

4.2 Exergy analysis.

Physically the exergy can be determined by

Specific exergy at any state,

$$\varphi = \dot{m}\,[(h - h_0) - T_0(s - s_0)] \quad (10)$$

The exergy destroyed in the LTC evaporator is,

$$\dot{E}_{D\ evap+fan} = (\varphi_1 - \varphi_4) - \dot{Q}_L\,(1 - \frac{T_0}{T_{CL}}) + \dot{W}_{evap\ fan} \quad (11)$$

Exergy destroyed in the LTC evaporator is,

$$\dot{E}_{D\ LTC\ comp} = (\varphi_2 - \varphi_1) + \dot{W}_{LTC} \quad (12)$$

The exergy destroyed in the LTC expansion valve is,

$$\dot{E}_{D\ LTC\ exp} = (\varphi_3 - \varphi_4) \quad (13)$$

Exergy destroyed in the cascade system is

$$\dot{E}_{D\ cas} = (\varphi_2 - \varphi_3) - (\varphi_8 - \varphi_5) \quad (14)$$

Exergy destroyed in the HTC evaporator is,

$$\dot{E}_{D\ HTC\ comp} = (\varphi_5 - \varphi_6) + \dot{W}_{HTC} \quad (15)$$

The exergy destroyed in the HTC expansion valve is,

$$\dot{E}_{D\ HTC\ exp} = (\varphi_7 - \varphi_8) \quad (16)$$

The exergy destroyed in the condenser

$$\dot{E}_{D\ cond} = (\varphi_6 - \varphi_7) - \dot{Q}_H\,(1 - \frac{T_0}{T_0}) + \dot{W}_{cond\ fan} \quad (17)$$

Total exergy destruction is,

$\dot{E}_{D\ Total} = \dot{E}_{D\ evap+fan} + \dot{E}_{D\ LTC\ comp} + \dot{E}_{D\ LTC\ exp} + \dot{E}_{D\ cas} + \dot{E}_{D\ HTC\ comp} + \dot{E}_{D\ HTC\ exp} + \dot{E}_{D\ cond}$. (18)

Cooling capacity, T_{CL}	40 kW
Ammonia/R134a condensing temperature	30°C
Carbon dioxide evaporating temperature	-50°C
Carbon dioxide condensing temperature	-5°C
Cascade condenser temperature difference	10°C
Ambient temperature	25°C
Cooling space temperature	-40°C
Work of the condenser fan	2.33 kW
Work of the evaporator fan	0.523 kW

Table 2: Characteristics of basic system.

Ammonia/R134a condensing temperature, T_C	30°C < T_C < 50°C
Carbon dioxide evaporating temperature, T_E	-50°C < T_E < -35°C
Carbon dioxide condensing temperature, T_{ME}	-10°C < T_{ME} < 5°C
Cascade condenser temperature difference T_{MC}	5°C < T_{MC} < 10°C

Table 3: Temperature variations.

5 Results and discussion.

The following results were obtained from the energy and exergy analyses of the CO_2/NH_3 and CO_2/R134a refrigeration systems.

$T_{evap\ CO2}$	$\dot{E}_{DECO2}$	$\dot{E}_{D\ CompCO2}$	$\dot{E}_{D\ expCO2}$	$\dot{E}_{D\ CAS}$	$\dot{E}_{D\ compNH3}$	$\dot{E}_{D\ expNH3}$	$\dot{E}_{D\ condNH3}$	$\dot{E}_{D\ Total}$	COP
-50°C	2.92	17.46	2.975	2.97	14.28	5.33	24.05	69.33	1.35
-45°C	0.85	16.11	2.02	3.21	12.73	5.33	24.05	64.28	1.43
-40°C	0.311	11.43	1.06	1.63	11.89	5.33	24.05	55.47	1.77
-35°C	0.184	9.39	0.59	1.16	9.40	5.33	24.05	50.10	2.15

Table 4: Illustrating the exergy destruction varying the evaporator temperature at LTC

$T_{cond\ CO2}$	$\dot{E}_{DECO2}$	$\dot{E}_{D\ CompCO2}$	$\dot{E}_{D\ expCO2}$	$\dot{E}_{D\ CAS}$	$\dot{E}_{D\ compNH3}$	$\dot{E}_{D\ expNH3}$	$\dot{E}_{D\ condNH3}$	$\dot{E}_{D\ Total}$	COP
-10°C	2.39	14.65	1.44	1.41	17.95	5.66	42.23	85.73	1.34
-5°C	2.92	17.46	2.975	2.97	14.28	5.33	24.05	69.33	1.35
0°C	2.98	19.11	3.81	3.13	12.88	3.9	23.09	68.90	1.29
5°C	3.83	25.19	4.29	3.3	11.21	3.32	13.69	49.83	1.24

Table 5: Illustrating the exergy destruction varying the condenser temperature at LTC

$T_{cond\ NH3}$	$\dot{E}_{DECO2}$	$\dot{E}_{D\ CompCO2}$	$\dot{E}_{D\ expCO2}$	$\dot{E}_{D\ CAS}$	$\dot{E}_{D\ compNH3}$	$\dot{E}_{D\ expNH3}$	$\dot{E}_{D\ condNH3}$	$\dot{E}_{D\ Total}$	COP
30°C	2.92	17.46	2.975	2.97	14.28	5.33	24.05	69.33	1.35
35°C	2.92	17.46	2.975	4.19	16.74	4.29	48.64	86.86	1.18
40°C	2.92	17.46	2.975	4.79	19.92	2.80	87.86	127.33	1.07
45°C	2.92	17.46	2.975	4.99	22.2	3.33	105.33	147.35	0.99

Table 6: Illustrating the exergy destruction varying the condenser temperature at HTC

ΔT	$\dot{E}_{DECO2}$	$\dot{E}_{D\ CompCO2}$	$\dot{E}_{D\ expCO2}$	$\dot{E}_{D\ CAS}$	$\dot{E}_{D\ compNH3}$	$\dot{E}_{D\ expNH3}$	$\dot{E}_{D\ condNH3}$	$\dot{E}_{D\ Total}$	COP
10°C	2.92	17.46	2.975	2.97	14.28	5.33	24.05	69.33	1.35
9°C	2.92	17.46	2.975	4.28	13.4	3.9	47.19	92.1	1.30
7°C	2.92	17.46	2.975	3.94	12.5	2.95	38.04	80.78	1.96
5°C	2.92	17.46	2.975	7.06	4.19	1.04	34.94	70.975	1.41

Table 7: Illustrating the exergy destruction varying the cascade condenser temperature difference

$T_{evap\ CO2}$	$\dot{E}_{DECO2}$	$\dot{E}_{D\ CompCO2}$	$\dot{E}_{D\ expCO2}$	$\dot{E}_{D\ CAS}$	$\dot{E}_{D\ comp134}$	$\dot{E}_{D\ exp134}$	$\dot{E}_{D\ cond134}$	$\dot{E}_{D\ Total}$	COP
-50°C	0.94	17.46	2.975	3.82	29.3	1.2	37.23	92.93	0.8
-45°C	2.195	14.2	1.92	2.08	27.63	1.2	37.23	86.46	0.91
-40°C	1.59	10.17	1.02	1.12	25.97	1.2	37.23	78.3	0.99
-35°C	2.76	8.26	0.94	0.5	25.97	1.2	37.23	76.88	1.05

Table 8: Illustrating the exergy destruction varying the evaporator temperature at LTC

$T_{condCO2}$	$\dot{E}_{DECO2}$	$\dot{E}_{D\ CompCO2}$	$\dot{E}_{D\ expCO2}$	$\dot{E}_{D\ CAS}$	$\dot{E}_{D\ comp134}$	$\dot{E}_{D\ exp134}$	$\dot{E}_{D\ cond134}$	$\dot{E}_{D\ Total}$	COP
-10°C	2.29	14.27	1.59	3.19	31.5	1.69	37.45	91.98	0.81
-5°C	0.94	17.46	2.97	3.82	29.3	1.26	37.23	92.98	0.8
0°C	1.12	19.49	4.05	4.18	27.17	0.83	33.7	90.54	0.78
5°C	2.02	22.18	1.13	4.61	25.25	0.34	32.81	88.34	0.77

Table 9: Illustrating the exergy destruction varying the condenser temperature at LTC

$T_{cond134}$	$\dot{E}_{DECO2}$	$\dot{E}_{D\ CompCO2}$	$\dot{E}_{D\ expCO2}$	$\dot{E}_{D\ CAS}$	$\dot{E}_{D\ comp134}$	$\dot{E}_{D\ exp134}$	$\dot{E}_{D\ cond134}$	$\dot{E}_{D\ Total}$	COP
30°C	0.94	17.46	2.97	3.82	29.3	1.2	37.23	92.78	0.8
35°C	0.94	17.46	2.97	4.38	17.62	0.84	12.61	56.66	1.16
40°C	0.94	17.46	2.97	3.92	17.41	1.4	7.9	51.86	1.06
35°C	0.94	17.46	2.97	3.23	18.6	1.94	7.67	49.44	1.0
ΔT	$\dot{E}_{DECO2}$	$\dot{E}_{D\ CompCO2}$	$\dot{E}_{D\ expCO2}$	$\dot{E}_{D\ CAS}$	$\dot{E}_{D\ comp134}$	$\dot{E}_{D\ exp134}$	$\dot{E}_{D\ cond134}$	$\dot{E}_{D\ Total}$	COP
10°C	0.94	17.46	2.97	3.82	29.3	1.2	37.23	89.05	0.81
7°C	0.94	17.46	2.97	2.45	13.01	0.47	10.458	45.2	1.06
5°C	0.94	17.46	2.97	2.15	10.51	0.23	6.69	40.81	1.30

Table 10: Illustrating the exergy destruction varying the condenser temperature at HTC and cascade condenser temperature difference.

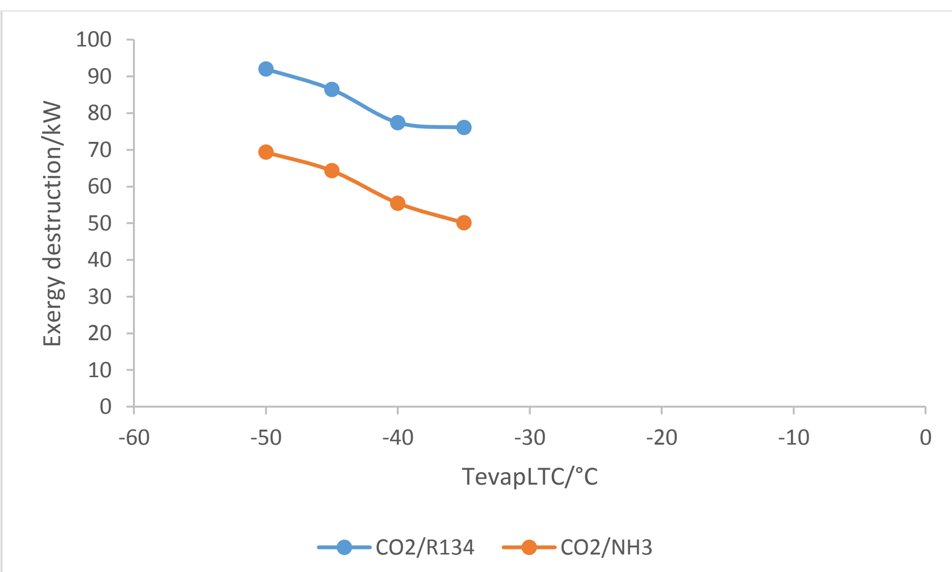

Figure 14: Variation of the exergy destruction in the LTC evaporator.

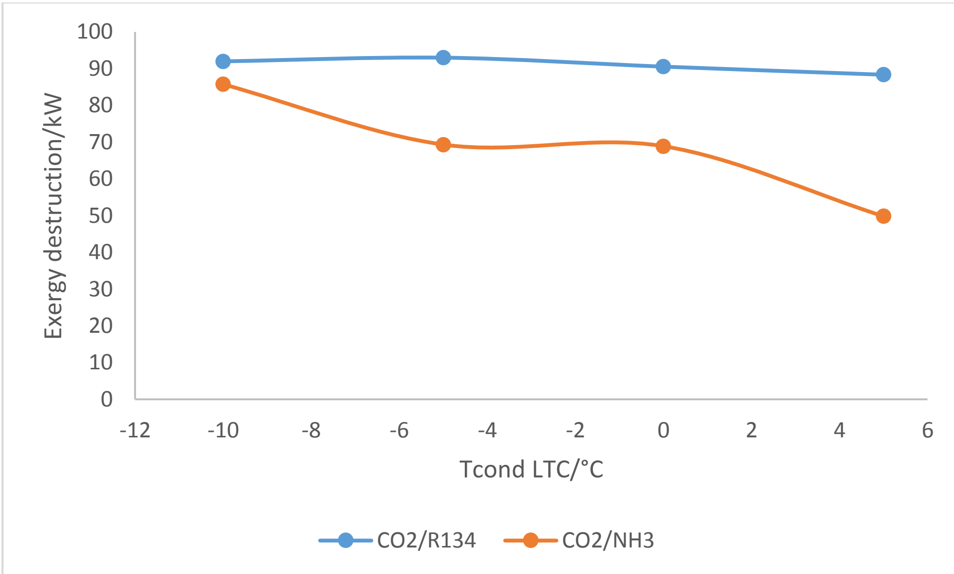

Figure 15: Variation of the exergy destruction in the LTC condenser.

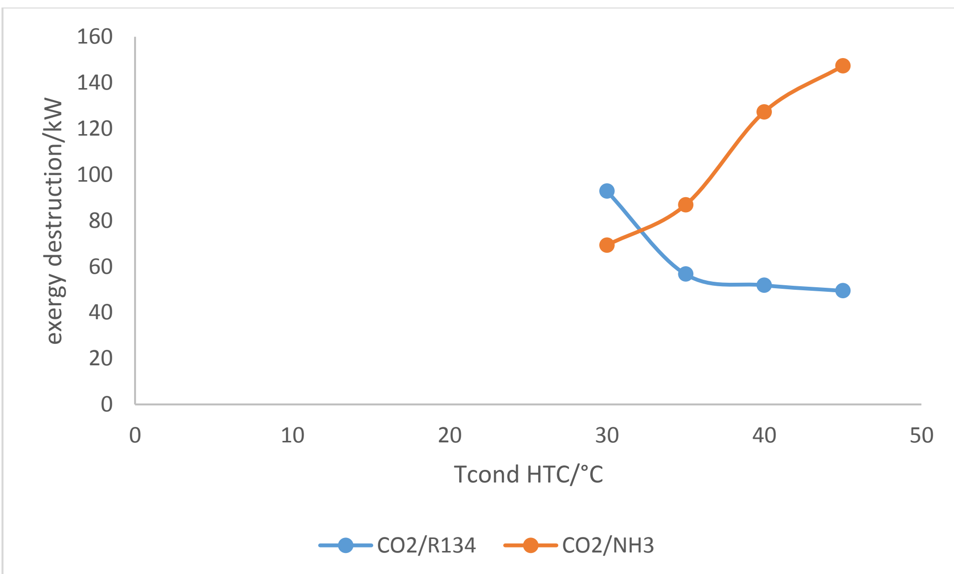

Figure 16: Variation of the exergy destruction in the HTC condenser.

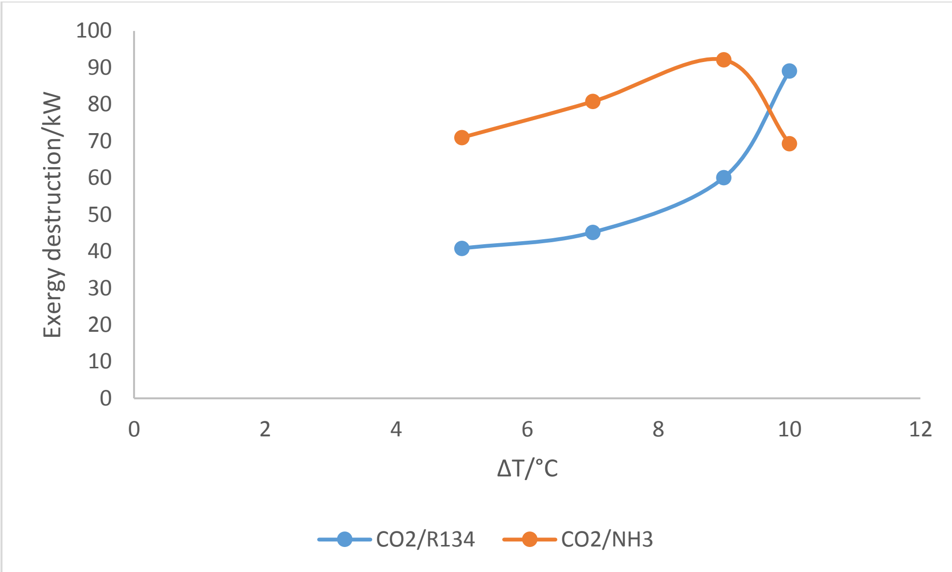

Figure 17: Variation of the exergy destruction in the cascade condenser temperature difference.

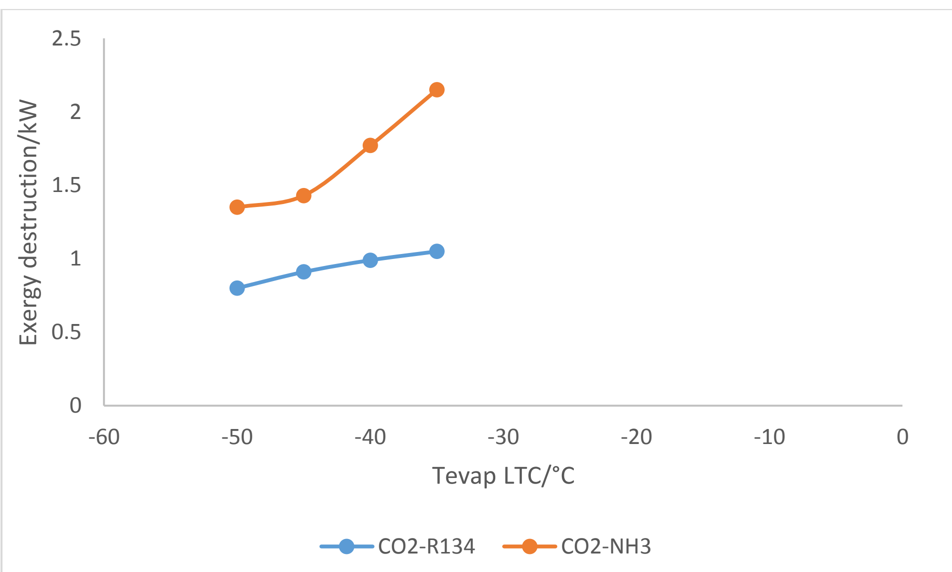

Figure 18: Variation of the COP in the LTC evaporator.

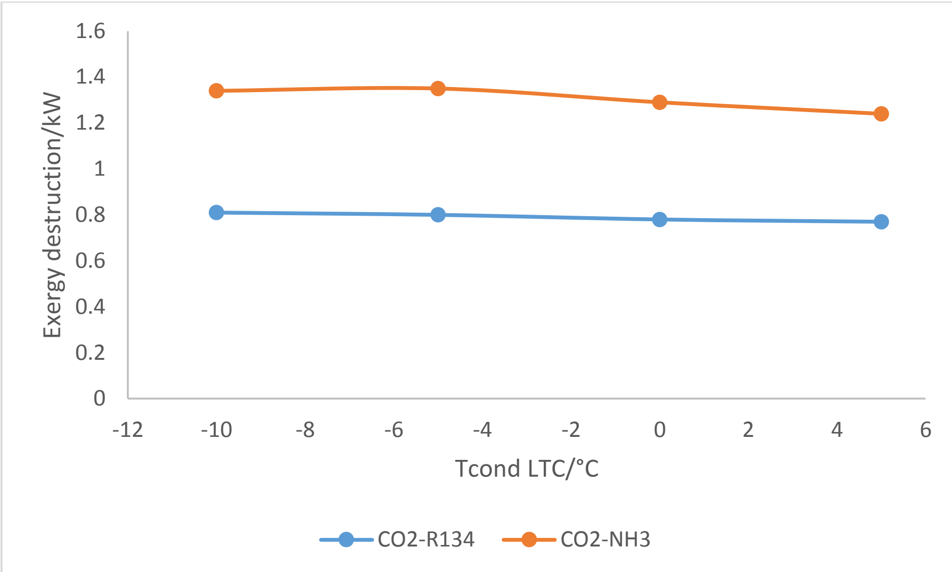

Figure 19: Variation of the COP in the LTC condenser.

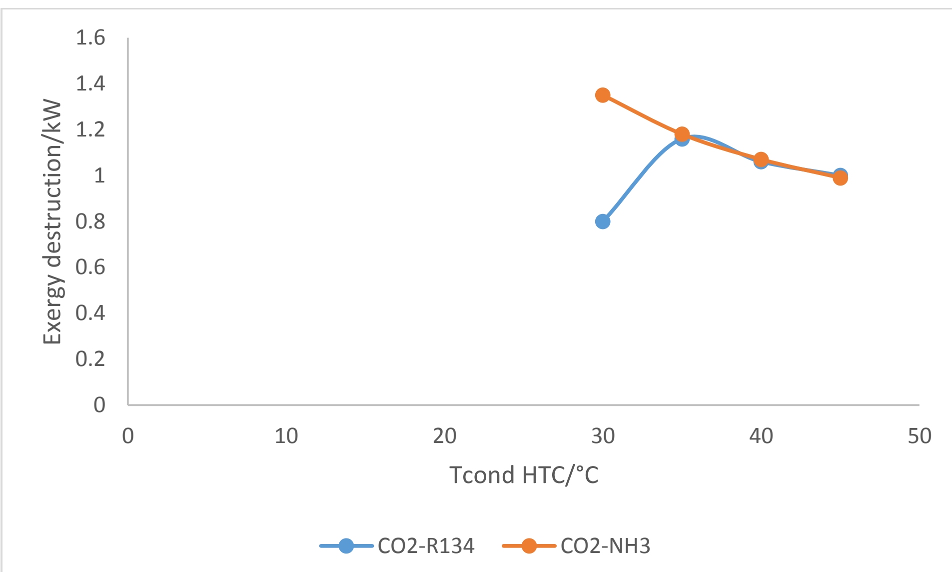

Figure 20: Variation of the COP in the HTC condenser.

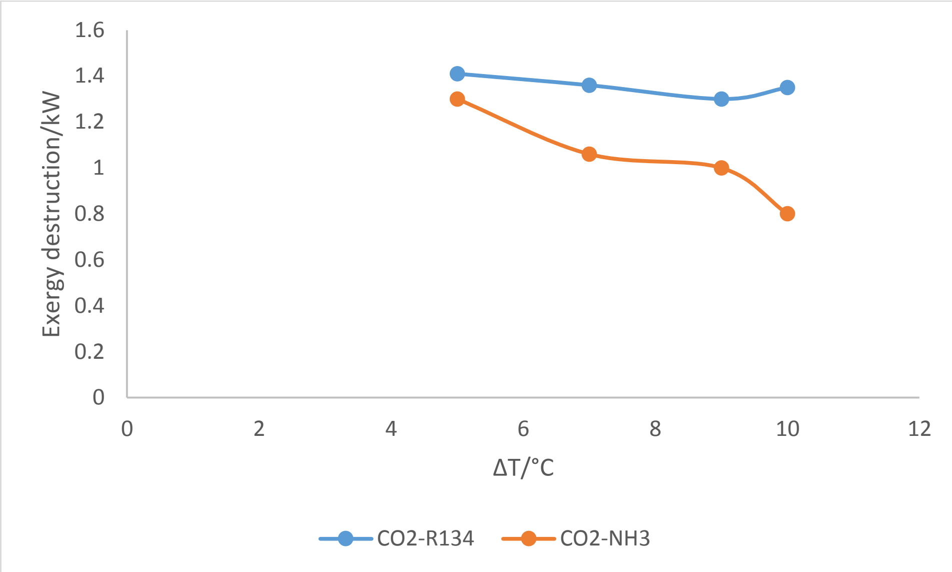

Figure 21: Variation of the cascade condenser temperature difference.

To measure the exergy destruction of both systems a prototype with the specific design conditions shown in Table 2 was utilized. Figure 12 outlines the exergy destruction in the LTC condenser for both the CO_2/R134a and CO_2/NH_3 cascade refrigeration system. Both follow the same trend as the exergy destruction decreases with increase in temperature. In figure 13 there is a slight decrement in the exergy destruction in the LTC condenser of the CO_2/R134a as the CO_2/NH_3 system also exhibit a downward trend with increase in temperature. In figure 14 there is an elevation of the exergy destruction with increase in temperature in the CO_2/NH_3 system in contrast to the CO_2/R134a system which continues diminishing. Both systems exergy destruction in the cascade condenser in figure 15 soar with temperature but in the CO_2/NH_3 system exergy destruction reaches a peak value before decreasing again. In both systems the more exergy is destroyed in the condenser followed by the compressor. The highest exergy destruction seen at the HTC condenser which is 147.35 kW.

Figure 16 illustrates the COP variation in the LTC evaporator for both systems. There is a 59.25% increase in COP in the CO_2/NH_3 system compared to a 31.25% increase in the CO_2/R134a system. In figure 17 the COP in the LTC condenser in both system is almost constant. In figure 18 the COP in the CO_2/NH_3 system increases in contrast to the COP in the CO_2/R134a system which decreases with increase in temperature when the HTC condenser in taken into consideration. Finally in the last figure there is a 4.4% decrease in the COP of the CO_2/NH_3 system meanwhile there is a 60.5% decrease in the COP of the CO_2/R134a system.

6 Conclusion.

In this report we tried to compare the exergy and energy analysis of the CO_2/NH_3 and CO_2/R134a cascade refrigeration system which could be employed in the supermarket. With the world population gradually increasing with time, there is a greater need to preserve the food items. Freezing the food items do not kill the bacteria but rather render it active from reproducing and affecting the quality of products. The inconvenience of freezing is that the product loses its freshness. From the ice collection to the artificial refrigeration used nowadays the advent of technology has played a significant role in the evolution of refrigeration. To attain much lower temperatures more than one refrigeration has to be connected in series. This configuration is termed as cascade refrigeration system. Some supermarkets use this configuration to preserve their products. The analysis was based on the mathematical model using the design specifications outlined in the literature. From the results in the table the exergy destruction in the CO_2/NH_3 system has higher values compared to the CO_2/R134a system in all major components of the refrigeration system with the exception in the HTC condenser where the maximum exergy destruction values are observed in the CO_2/NH_3 system. Furthermore the COP values in the CO_2/NH_3 system is higher than those in the CO_2/R134a for all major components of the refrigeration system. Following this investigations we can finalize that the CO_2/NH_3 system is more efficient than the CO_2/R134a system because less exergy is being dissipated and the COP values are higher. Thus it will be a better alternative for a supermarket.

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