INVESTIGATING THE APPLICATION OF ENVIRONMENTALLY FRIENDLY SOLUTIONS IN REFRIGERATION APPLICATIONS OF UGANDA

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ABSTRACT

The earliest refrigerants used were R40, R764, R717, R290 and R600a but these had drawbacks of flammability, toxicity, unpleasant smell as well as posing a danger of leakage through the shaft seals of compressors. In 1931, these were replaced by CFCs and HCFCs due to safety and reliability concerns. However in 1986, CFCs and HCFCs were confirmed to have an ozone depleting effect hence their use was discouraged under the Montreal Protocol. Manufacturers responded to this call by introducing HFCs on the market with no ozone depleting effect. However, nowadays, there is immense pressure to shift to natural refrigerants after the discovery that the emission of these substances to the atmosphere contributes to at least 20% of the greenhouse gas emissions. The use of synthetic refrigerants has led to the breakdown of stratospheric ozone molecules and emission of greenhouse gases to the atmosphere leading to global warming and global climate change. Today, there is increasing pressure from legislators, business partners and consumers to seek for new methods to achieve cooling that does not depend on global warming working fluids. Therefore, companies are tasked to rethink established solutions and implement environmentally friendly yet economically sensible technologies to seize their individual eco-advantage. For that matter, the use of refrigerants free of ozone depleting and global warming characteristics in Heating, Ventilating and Air Conditioning continues to take a central role in measures to reduce greenhouse gas emissions. This study aims at investigating the application of environmentally friendly solutions in refrigeration applications of Uganda with the main emphasis on natural refrigerants. This has been accomplished by ascertaining the current status of refrigeration in Uganda as well as modeling and simulation of the available systems and comparison of the results with those of recommended systems.

A field study has been carried out in order to assess the current status of refrigeration in the country i.e. the refrigerants used and the type of systems currently installed. It has been found out that synthetic refrigerants predominate and the systems installed are single stage vapor compression systems.

Operating parameters of these installed systems have been measured such as evaporating and condensing temperatures, compressor power demand and mass flow of the refrigerant. Models of the systems were developed using EES software and the efficiencies of the systems determined. Furthermore, models have been proposed for each sector using appropriate natural refrigerant and the efficiencies determined. Comparisons were then made with installed systems and it has been found that natural refrigerants offer a promising solution in the refrigeration industry of Uganda and hence should be adopted for energy, safety and environmental issues. However, for this transition to be realized there is need to create awareness in industry as well as government taking the lead in the development of a phase out plan with support from industry and research organizations. There is need to have rewards in form of tax waivers for those companies that comply and penalties to those who fail to comply.

Keywords: Environmentally, friendly, refrigeration, applications, Uganda
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LIST OF ABBREVIATION

CFC: Chlorofluorocarbons
COP: Coefficient of Performance
DRC: Democratic Republic of Congo
EER: Energy Efficiency Ratio
EES: Engineering Equations Solver
EU: European Union
FAO: Food and Agricultural Organization
GWP: Global Warming Potential
HC: Hydrocarbons
HCFC: Hydrochlorofluorocarbons
HFC: Hydrofluorocarbons
HVAC&R: Heating, Ventilating, Air Conditioning and Refrigeration
IIR: International Institute of Refrigeration
IPCC: Intergovernmental Panel on Climate Change
LCCP: Life Cycle Cost Performance
MEMD: Ministry of Energy and Mineral Development
MoH: Ministry of Health
NEMA: National Environment Management Authority
ODP: Ozone Depleting potential
PAG: Polyalkylene Glycol
POE: Polyol Ester
PVE: Poly Vinyl Ether
TEWI: Total Equivalent Warming Impact
TR: Tons of Refrigeration
UAE: United Arab Emirates
UBOS: Uganda Bureau of Statistics
UIA: Uganda Investment Authority
UNBS: Uganda National Bureau of Standards
UNEP: United Nations Environmental Program
USA: United States of America
VAR: Vapor Absorption Refrigeration
VCR: Vapor Compression Refrigeration
WHO: World Health Organization
1.0: INTRODUCTION

1.1: Background

Refrigeration is defined as the transfer of heat from a lower to a higher temperature region. This is accomplished by the use of refrigeration devices such as refrigerators, heat pumps, automotive air conditioners and residential/commercial air conditioners (Cengal et al., 1998). Refrigerating engineering is the technology associated with the creation and maintenance of temperatures lower than the surroundings. It is the art of pumping heat from one body of a low temperature to one of higher temperature (Granryd et al., 2005). The main applications of refrigeration are in the handling, storage and supply of food products as well as climate control and air conditioning.

The transition to the use of environmentally friendly solutions in the refrigeration applications is of high importance worldwide. The earliest refrigerants used were sulfur dioxide (R764), methyl chloride (R40), ammonia (R717), propane (R290) and isobutane (R600a), but these had drawbacks of being flammable, toxic, had a strong smell as well as posing a challenge of leakage through the shaft seals of compressors (Pearson, 2001; Palm, 2007). Later on, chlorofluorocarbons (CFC) refrigerants were introduced to replace R764, R40 and R717. These became popular in the 1930s and dominated the domestic refrigerant market. However later on, it was discovered that the CFCs had an ozone depletion potential which led to a shift from CFCs to hydrochlorofluorocarbons (HCFC) and then hydrofluorocarbons (HFC) with no ozone depleting potential (Palm, 2007). However, there was strong advocacy for natural refrigerants, because the doubt about synthetic refrigerants was later confirmed by the realization that emission of these substances contributes to at least 20% of the greenhouse gases (IPCC, 2005).

According to Pearson (2005), there are five substances generally recognized as natural refrigerants in modern refrigeration i.e. air (R729), water (R718), ammonia (R717), carbon dioxide (R744) and hydrocarbons (HCs). R729 is used in variety of gas cycles, with no change of phase and can achieve reasonably low temperatures, but the low theoretical efficiency of the Brayton cycle and the difficulty of getting close to that ideal have limited its use. R718 has been used with large centrifugal and axial turbines in open systems but the low pressures, large swept volumes and evaporation temperature limit of 0°C place several restrictions on its use and make it fundamentally unsuited to smaller air conditioning systems, industrial cooling and freezing applications. R717, R744 and hydrocarbons have a broader range of applications and are used in more conventional systems.

Today, with the increasing pressure from legislators, business partners and consumers to push environmental issues up the agenda unlikely to subside anytime soon, companies are tasked to rethink established solutions and implement environmentally benign yet economically sensible technologies to seize their individual eco-advantage. The use of refrigerants free of ozone depleting and global warming characteristics in Heating, Ventilating, Refrigeration and Air Conditioning (HVAC&R) will continue to take a central role in measures to reduce greenhouse gas emissions. CFCs, HCFCs and HFCs are known for ozone depletion, greenhouse gas emission and ecologically unfriendly and for that matter natural refrigerants such as air, ammonia, carbon dioxide, water and groups of hydrocarbons stand ready as current and future solutions in residential refrigerators, commercial heat pumps, industrial waste energy recovery and global food logistics (Karamangil et al., 2010).

While the environmental and technological benefits of these natural refrigerants are being acknowledged in the refrigeration industry, only few studies have heard the industry’s voice on their economic prospects. The most commonly used natural refrigerants today are R717, R744 and hydrocarbons such as R290, R600a and R1270. Mixtures of ammonia and dimethyl ether (R273) have been developed as well as various hydrocarbon blends with optimized performance and safety properties. R729 and R718 are also used to a minor extent such as in absorption chillers and deep freezing applications. Given their non-toxicity and non-flammability in addition to their unbeatable environmental credential in combination with widest availability, these two...
have shifted again to the focus of research and development activities today. The natural refrigerants no longer in use today are R764 and R40.

Uganda is located in the Eastern region of East Africa and is bordered by Kenya, Tanzania, Rwanda, the republic of South Sudan and the Democratic Republic of Congo. It is a land locked country which lies between latitudes and longitudes 4.2°N and 1.5°S and 28°E and 35°W respectively. The country covers an estimated total area of 241,020 km² (UIA, 2006). According to UBOS (2006), the population of Uganda is estimated to be 28.4 million. In Uganda just like many other developing countries, it is difficult to characterize the refrigerating equipment used because data is extremely scanty and makes it difficult to provide an accurate picture of the overall situation. The main applications however are in cold storage and domestic refrigeration (Billiard, 1999; IIR, 2002). Unlike other countries; Uganda is privileged in that it largely requires no heating and cooling of buildings. This is because the country suffers no climatic extremes throughout the year, hence the need for heating and cooling is very rare. Thermal comfort is attained by taking advantage of natural ventilation and wearing appropriate clothing.

If synthetic refrigerants are to be substituted or if their use is to be constrained to applications where there is no technically and economically viable alternative, then it is essential that the chemicals used in their stead fast satisfy some fundamental requirements i.e. should not be less energy efficient than the fluids that they replace, must be proven safe for both the immediate neighborhood and the global environment, must be simple and cost effective to use, readily available and ideally must not require any significant new or unfamiliar technology (Robinson, 1998; Pearson 2008; Messineo, 2011).

1.2: Problem Statement

The use of CFC and HCFC refrigerants has led to the breakdown of stratospheric ozone molecules and global warming. A decrease in the ozone layer can significantly increase the incidence of skin cancer, eye damage, decreased crop yield and damage to forests and aquatic life. In addition, ozone depletion in the stratosphere can aggravate the photochemical pollution. On the other hand HFC refrigerants that would serve as potential replacements have a global warming effect. The greenhouse warming effect causes an increase in global temperatures and associated catastrophic effects such as rising sea level, changes in the amount and pattern of precipitation, increasing the frequency and intensity of extreme weather events, fluctuations in agricultural yields as well as glacier retreat. This in Uganda is evidenced by changes in seasons that have led to unpredictable wet and dry seasons that have significantly affected agricultural production and the economy at large since Uganda is an agricultural country.
Table 1.1: Environmental impact of selected refrigerants

<table>
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<th>Refrigerant</th>
<th>Type</th>
<th>ODP</th>
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<tr>
<td>R11</td>
<td>CFC</td>
<td>1</td>
<td>4680</td>
</tr>
<tr>
<td>R12</td>
<td>CFC</td>
<td>0.82</td>
<td>10720</td>
</tr>
<tr>
<td>R22</td>
<td>HCFC</td>
<td>0.06</td>
<td>1780</td>
</tr>
<tr>
<td>R134a</td>
<td>HFC</td>
<td>0</td>
<td>1410</td>
</tr>
<tr>
<td>R404A</td>
<td>HFC</td>
<td>0</td>
<td>3863</td>
</tr>
<tr>
<td>R407A</td>
<td>HFC</td>
<td>0</td>
<td>1770</td>
</tr>
<tr>
<td>R407B</td>
<td>HFC</td>
<td>0</td>
<td>2285</td>
</tr>
<tr>
<td>R407C</td>
<td>HFC</td>
<td>0</td>
<td>2075</td>
</tr>
<tr>
<td>R410A</td>
<td>HFC</td>
<td>0</td>
<td>2060</td>
</tr>
<tr>
<td>R290</td>
<td>Natural</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>R717</td>
<td>Natural</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>R1270</td>
<td>Natural</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>R744</td>
<td>Natural</td>
<td>0</td>
<td>1</td>
</tr>
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</table>

Source: Arias, 2011

1.3: Main objective
The main objective of this study is to investigate the application of environmentally friendly solutions in refrigeration applications of Uganda.

1.4: Specific objectives
1. Ascertain the current status of refrigeration in Uganda.
2. Develop computer models and determine the efficiencies of the systems.
3. Design and recommend an appropriate system solution for each sector using natural refrigerant.

1.5: Justification
According to Leck et al. (2010), as a result of global warming and global climate change, many business and industrial sectors as well as personal aspects of our lives have come under heavy scrutiny. There is immense pressure to find ways to decrease the impact of human activities on the environment. Energy generation and use is the major contributor to carbon dioxide emissions in the earth’s atmosphere. In addition, certain fluorinated gases that have been used for refrigeration and other beneficial purposes have been found to have direct global warming potentials much higher than carbon dioxide if they are released into the atmosphere (Cavallini et al., 2010; Palm, 2007). The benefits that refrigeration and air conditioning brings to our lives are highly desired hence need for an increased effort to find new methods to achieve cooling that does not depend on global warming (GWP) working fluids. According to Rogstam et al. (2010), it is now paramount from a business perspective that companies avoid criticism for contributing to global warming and global climate change. Natural refrigerants reduce direct emissions from high potential global warming gases, save costs and future proof the refrigeration industry in Uganda from upcoming legislation.
1.6: Scope
This study will look at the feasibility of application of environmentally friendly solutions in the refrigeration sector of Uganda but the main emphasis will be on natural refrigerants.
2.0: LITERATURE REVIEW

Refrigeration and air conditioning is used to cool products or a building environment. The refrigeration and air conditioning systems transfer heat from a cooler low-energy reservoir to a warmer high-energy reservoir. This is represented in the Figure 2.1 below;

![Figure 2.1: Schematic of a refrigeration system (Source: Arora, 2000)](image)

Depending on the applications, several options/combinations of air conditioning systems are available for use and these include air conditioning (for space or machines), split air conditioners, fan coil units in a larger system and air handling units in a larger system. On the other hand, the following refrigeration systems exist for industrial processes (e.g. chilling plants) and domestic purposes (refrigerators). These include; small capacity modular units of the direct expansion type similar to domestic refrigerators, centralized chilled water plants with chilled water as a secondary coolant for temperature range over typically 5°C. These can also be used for ice bank formation; brine plants which use brines as a lower temperature secondary coolant for typically sub-zero temperature applications which come as modular unit capacities as well as large centralized plant capacities; the plant capacities up to 50 tons of refrigeration (TR) are usually considered as small capacity i.e. 50-250 TR as medium capacity and over 250 TR as large capacity units. Large companies may have a bank of units, often with chilled water pumps, cooling towers as an offsite utility. The same company may also have 2 or 3 levels of refrigeration and air conditioning such as a combination of comfort air conditioning (20-25°C), chilled water system (8-10°C) and brine system (sub zero applications)(UNEP, 2006).

The two principle types of refrigeration plants found in industry are Vapor Compression Refrigeration (VCR) and Vapor Absorption Refrigeration (VAR). VCR uses mechanical energy as a driving force for refrigeration while VAR uses thermal energy as the driving force for refrigeration.

2.1: Vapor compression refrigeration systems

Compression refrigeration cycles take advantage of the fact that compressed fluids at a certain temperature have a tendency of getting colder when allowed to expand. If the pressure change is sufficiently high, then the compressed gas will become hotter than the source of cooling (ambient air) and the expanded gas will become cooler than the desired cold temperature. In this case, fluid is used to cool a low temperature
environment and reject heat to a high temperature environment. Vapor compression refrigeration cycles have two advantages. First, a large amount of thermal energy is required to change state of refrigerant from liquid to vapor hence extracting a lot of heat from the conditioned space. Secondly, the isothermal nature of the vaporization allows extraction of heat without raising the temperature of the working fluid to that of the substance to be cooled. This means that the heat transfer rate remains high, because the closer the working fluid temperature approaches that of the surroundings, the lower the heat transfer rate. The refrigeration cycle is shown in figure 2.2 below and consists of the following stages:

1-2: Low pressure liquid refrigerant in the evaporator absorbs heat from its surroundings, usually air, water or some other process liquid. During this process, it changes its state from liquid to gas and at the evaporator exit it is slightly superheated.

2-3: The superheated vapor enters the compressor where its pressure is increased. The temperature will also increase due to the fact that some of the energy put into the compression process is transferred to the refrigerant.

3-4: The high pressure superheated gas passes from the compressor into the condenser. The initial part of the cooling process (3-3a) de-superheats the gas before it is turned back into liquid (3a-3b). The cooling for this process is usually achieved by using air or water. Further reduction in temperature happens in the pipe work and liquid receiver (3b-4), so that the refrigerant liquid is sub cooled as it enters the expansion device.

4-1: The high pressure sub cooled liquid passes through the expansion device, which both reduces its pressure and controls the flow into the evaporator.

Figure 2.2: Schematic of the vapor compression refrigeration cycle (Source: Bureau of Energy Efficiency, 2004)
The condenser has to reject the combined heat inputs of the evaporator and the compressor. It should be noted that there is no heat loss or gain in the expansion device.

### 2.2: Vapor Absorption Refrigeration Systems

The vapor absorption refrigeration system consists of:

**Absorber:** Absorption of refrigerant vapor by a suitable absorbent or adsorbent, forming a strong or rich solution of the refrigerant in the absorbent / adsorbent.

**Pump:** Pumping of the rich solution and raising its pressure to the pressure of the condenser.

**Generator:** Distillation of the vapor from the rich solution leaving the poor solution for recycling.

The absorption chiller is a machine, which produces chilled water by using heat such as steam, hot water, gas, oil, etc. chilled water is produced based on the principle that liquid (refrigerant) which evaporates at a low temperature absorbs heat from its surroundings when it evaporates. Pure water is used as refrigerant and lithium bromide solution is used as absorbent. Heat for the vapor absorption refrigeration system can be provided by waste heat extracted from the process, diesel generator sets, etc. in that case absorption systems require electricity for running pumps only. Depending on the temperature required and the power cost, it may even be economical to generate heat/steam to operate the absorption system.

According to UNEP (2006), absorption refrigeration systems that use Lithium bromide and water as refrigerant have a coefficient of performance (COP) in the range of 0.65-0.70 and can provide chilled water at 6.7°C with a cooling water temperature of 30°C. Systems capable of providing chilled water at 3°C are also available. Ammonia based systems operate at above atmospheric pressures and are capable of low temperature operation (below 0°C). Absorption machines are available with capacities in the range of 10-1500 tons. Although the initial cost of absorption system is higher than that of a compression system, operational costs are much lower if waste heat is used (Karamangil et al., 2010). Below is a schematic representation of a vapor absorption refrigeration system;
According to Karamangil et al. (2010), VAR systems are attractive because they can employ natural refrigerants (water, ammonia, methanol, etc), and can be driven by waste heat, solar or geothermal energy and hence support to reduce fossil fuel consumption and for that matter, VAR systems are viewed as a convenient way to reduce greenhouse gas emissions by refrigeration systems. There are numerous occasions where air conditioning, which stipulates control of humidity of up to 50% for human comfort or for processes, can be replaced by a much cheaper and less energy intensive evaporative cooling. This concept is simple and is similar to that of a cooling tower. Air is brought in close contact with water to cool it to a temperature close to the wet bulb temperature. The cool air can be used for comfort or process cooling. The only disadvantage is that the air is rich in moisture. Nonetheless, it is an extremely efficient means of cooling at a very low cost. Large commercial systems employ cellulose filled pads over which water is sprayed. The temperature can be controlled by controlling the airflow and the water circulation rate. The possibility of evaporative cooling is especially attractive for comfort cooling in dry regions. Below is a schematic diagram of an evaporative cooler.
2.3: Refrigerants

According to Cavallini et al. (2010), there exists no perfect or ideal refrigerant. However, when choosing a refrigerant for a particular application, there are certain desirable properties and characteristics to look out for such as environmental aspects like Ozone Depletion Potential (ODP), atmospheric lifetime, Global Warming Potential (GWP), Total Equivalent Warming Impact (TEWI) and Life Cycle Climate Performance (LCCP) are one of the most important in selecting a refrigerant for a particular application so long as the thermophysical properties and safety are also appropriate. Some of these properties include;

- **Chemical**: Stable and inert
- **Health and safety**: Non-toxic, non-flammable
- **Environmental**: No ODP, minimal GWP, minimal TEWI and LCCP, short atmospheric lifetimes
- **Thermophysical properties**: Critical point and boiling point temperature appropriate for application, moderate liquid molar heat capacity, low liquid viscosity, high liquid thermal conductivity.
- **Miscellaneous**: Soluble with lubricants, high vapor dielectric strength, low freezing point, compatible with most materials, easy leak detection, low cost, readily available.

2.3.1: Natural Refrigerants

According to Pearson (2005), there are five substances generally recognized as natural refrigerants. These include R717, R744, R718, R729 and HCs. However of these, R717, R744 and HCs find greater use in conventional systems. Below are some of their properties;

2.3.1.1: Ammonia (R717)

R717 is a colorless gas at atmospheric pressure with zero ozone depletion and global warming potential as well as short atmospheric lifetime and doesn’t form any by-products or decomposition products with negative environmental impact. R717 is one of the oldest and well understood refrigerants and is widely used in industrial applications with reciprocating compressors where it is easier to implement safety measures. However, it is rarely used in comfort cooling or small refrigeration systems except in some Scandinavian countries where it is used in indirect systems when it is confined to the machinery room.

The good thermodynamical properties of R717 such as high latent heat of vaporization, high critical point temperature and low liquid molar heat capacity gives good thermodynamic efficiency in the ideal vapor compression cycle. The good thermodynamic properties together with its transport properties result in good heat transfer performance. It is compatible with some commonly used lubricants e.g. it is suitable for use with polyol ester (POE) and polyvinyl ether (PVE) lubricants and it has only limited applications with polyalkylene glycol (PAG) lubricants. Some of the inherent features of R717 are its large vapor superheat that results on compression. The use of R717 is restricted in certain applications and geographical regions due to its high toxicity and lower flammability characteristics and as a result, it is prohibited for use inside occupied spaces. However, this problem can be overcome by using R717 in conjunction with other refrigerants so as to isolate the ammonia charge such as in secondary systems, using advanced safety equipment, deploying containment casings, and ammonia absorption systems. R717 has a pungent smell that makes leaks easily detectable.

R717 is widely used as a refrigerant in industrial systems for food refrigeration, distribution warehousing and process cooling. However, it is not suitable for use in domestic refrigerators or air conditioning systems due to its incompatibility with materials commonly used in these systems, particularly copper, zinc and their alloys. Recently, it has been proposed for use in applications such as water chilling for air conditioning systems but yet to receive widespread acceptance (Pearson, 2008). Its flammability and toxicity limits its use in certain applications but if the requirements of the existing safety codes are followed, R717 systems can be reliable, efficient and safe, making them more attractive for large industrial refrigeration systems than fluorocarbon alternatives for which the costs of installation and operation are likely to be higher. R717 is not permitted for use in direct air conditioning systems for human comfort where the refrigerant containing
parts are in contact with the air being cooled but can be used as a refrigerant in chillers where the chilled water is pumped to air handling units. It should be noted that the toxic effect of R717 is dependent upon the level of concentration in the atmosphere and on the length of time the exposure lasts. The benefits of using R717 for water chilling applications include efficiency improvement of the system, which is in the range of 9-17% and significant improvement in heat transfer in heat exchangers (Hrnjak and Park, 2007) which presents an opportunity to make efficient chillers in small footprints, particularly when air cooled condensers are used. The major constraint identified with the use of this refrigerant is that components for small ammonia systems are scarce (Palm, 2007). However, continued development of these components i.e. electronic expansion valves, low charge evaporators and hermetic compressors would simplify the problem.

2.3.1.2: Carbon dioxide (R744)

R744 is a natural substance that plays an important role in many natural and industrial processes. In nature, R744 plays a role in photosynthesis and is one of the contributors to the global warming effect. In industry, R744 is used as dry ice for transport cooling, to generate the sparkling effect in some beverages, as a fire extinguisher and as a preservative (Danfoss, 2008).

R744 is colorless, odorless and also denser than air with a GWP of 1, R744 is a reference value for comparing a refrigerant’s direct impact on global warming. It has low toxicity and is non-flammable. According to Pearson (2001), it is even possible to imagine a system where the R744 charge is used as an extinguisher to assist fire fighters.

R744 as a refrigerant is sourced from a number of production methods as a by-product. Whilst it is non-toxic, if enough R744 builds up in an enclosed space, it will begin to displace oxygen and can cause asphyxiation to people in the vicinity over a certain period of time. With a long atmospheric lifetime, R744 does not lead to any by-product formation or decay products with serious environmental impact. When used as a refrigerant, R744 typically operates at higher pressure than fluorocarbons and other refrigerants. While this presents some design challenges, it can usually be overcome in systems designed to specifically use R744. It is compatible with some but not all commonly used refrigeration system lubricants, in particular, it is not suited for use with POE and PVE lubricants and only has limited applications with PAG lubricants. It is generally regarded as a cheap and easily available refrigerant (Cecchinato et al., 2008; SHECCO, 2012).

R744 is becoming very popular of recent for cooling applications at very low temperatures in supermarkets (Sawalha, 2007; Dopazo et al., 2008). The 3 main solutions where R744 is applied in supermarket refrigeration are indirect, cascade and transcritical systems. The indirect system with R744 as secondary fluid is used for low temperature applications where pressure levels are reasonably low and conventional components can be used. The cascade arrangement implies that a temperature difference exists in the cascade condenser which decreases the evaporation temperature on the high side and decreases its COP. Using R744 transcritical system solutions in supermarket refrigeration is gaining interest with several installations already running in several European countries. According to Sawalha (2007), the performance of R744 refrigeration systems strongly depends on operating conditions. However, the specific characteristics of low critical temperature and high operating pressure limit its applications and imply the implementation of different control strategies.
Figure 2.6: Phase diagram for R744 (Source: Danfoss, 2008)

Figure 2.6 shows the phase diagram for R744. The 3 phases i.e. solid, liquid and vapor are represented as colored areas. Phase change takes places when a process crosses a boundary between areas. At the boundary the two phases exist in equilibrium and properties such as temperature and pressure are dependant. Two important state points can be seen i.e. the triple point and the critical point. The triple point represents the condition where all the 3 phases can co-exist in equilibrium. At temperatures below the triple point, liquid cannot exist i.e. the triple point sets the lower temperature limit for any heat transfer process based on evaporation/condensation. At the other end of the vapor pressure curve, the critical point marks the upper limit for heat transfer processes based on evaporation/condensation. At temperatures and pressures higher than those at the critical point, there is no clear distinction between liquid and vapor i.e. there is a region extending indefinitely upward from and indefinitely to the right of the critical point, this region is called the fluid region and is bounded by dashed lines that don’t represent phase changes but conform to arbitrary definitions of what is considered liquid or vapor. The condition in the fluid region is referred to as the supercritical condition or gas condition.

It should be noted that all substances have a triple point and a critical point but unlike R744, for most substances used as refrigerants, the triple point and critical point exist for conditions that lie outside the region where they are normally used. Table 2.1 compares the critical pressure and temperature of a number of refrigerants. Typically refrigerants have critical temperatures above 90°C but some of the refrigerants often used nowadays (R404A, R410A and R744) have critical temperatures below that.

Table 2.1: Critical Properties of selected refrigerants

<table>
<thead>
<tr>
<th>Refrigerant</th>
<th>Critical pressure (bar)</th>
<th>Critical temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R22</td>
<td>49.9</td>
<td>96.1</td>
</tr>
<tr>
<td>R134a</td>
<td>40.6</td>
<td>101.1</td>
</tr>
<tr>
<td>R404A</td>
<td>37.3</td>
<td>72.0</td>
</tr>
<tr>
<td>R410A</td>
<td>49.0</td>
<td>71.4</td>
</tr>
<tr>
<td>R600a</td>
<td>36.4</td>
<td>134.7</td>
</tr>
<tr>
<td>R717</td>
<td>113.3</td>
<td>132.3</td>
</tr>
<tr>
<td>R744</td>
<td>73.8</td>
<td>31.0</td>
</tr>
</tbody>
</table>

Source: Danfoss, 2008
From Table 2.1, it can be seen that for R134a, the critical temperature is 101.1°C. This implies that for R134a heat rejection processes by condensation can be established at temperatures up to 101°C. This temperature is more than sufficient for rejecting heat to the atmosphere for almost all applications in refrigeration and air conditioning while for R744; the critical temperature is only 31.0°C. This means that for R744 heat rejection process by condensation can only be established at temperatures up to 31°C. This temperature is lower than necessary for rejecting heat to the atmosphere for many refrigeration applications.

According to Danfoss (2008), considering the temperature difference required in the heat exchanger, a practical upper limit for a heat rejection process based on condensation is reached at temperatures 5-10 K below the critical temperature. For many refrigeration applications, the ambient temperature normally exceeds 25°C, making it practically impossible to reject heat by condensing R744. The heat rejection process is therefore accomplished by means of a gas cooler.

### 2.3.1.3: Hydrocarbons

These have no ozone depleting potential and have an ultra low global warming impact; the groups of hydrocarbons do not form any by-products or decomposition products in the atmosphere. HC refrigerants can be used either in systems designed specifically for their use or as a replacement in a system designed for a fluorocarbon refrigerant making them a cost competitive solution even for developing countries. HC refrigerants can operate over a wide range of temperature down to evaporation temperature of -170°C (SHECCO, 2012). Because of their flammability, their use has been limited largely to systems in the petrochemical industry. However, their excellent thermophysical properties and favorable environmental characteristics have led to their much wider acceptance and use particularly in Europe in the residential and commercial sectors.

The main advantage of HC is their good environmental characteristics i.e. atmospheric lifetimes of weeks or months which results in lower GWP values for HC compared to halocarbons. This when coupled with attractive COP values for HC based systems leads to very good TEWI values for these systems. In addition to this, HC refrigerants have excellent thermophysical properties, are soluble in common lubricants, including mineral oils and are compatible with most materials used in the refrigeration systems i.e. possess similar properties and attributes as the halogenated hydrocarbons the industry is accustomed to requiring no changes in the system or components, also hydrocarbons can be expected to give similar performance as the synthetic refrigerants. Their main disadvantage is their flammability which can be mitigated and managed by carefully following and adhering to industry standards during design, operation, installation and servicing of hydrocarbon based refrigeration systems.

#### Table 2.2: Characteristics of natural refrigerants

<table>
<thead>
<tr>
<th>Refrigerant</th>
<th>Refrigerant Number</th>
<th>Chemical Formula</th>
<th>GWP (100 years)</th>
<th>ODP</th>
<th>Normal Boiling Point (°C)</th>
<th>Critical Temperature (°C)</th>
<th>Critical Pressure (bar)</th>
<th>Safety Group</th>
<th>Molecular Weight (g/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia</td>
<td>R717</td>
<td>NH₃</td>
<td>0</td>
<td>0</td>
<td>-33.3</td>
<td>132.4</td>
<td>114.2</td>
<td>B2</td>
<td>17/03/11</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>R744</td>
<td>CO₂</td>
<td>1</td>
<td>0</td>
<td>-56.6</td>
<td>31.1</td>
<td>73.8</td>
<td>A1</td>
<td>44.0</td>
</tr>
<tr>
<td>Propane</td>
<td>R290</td>
<td>C₃H₈</td>
<td>3.3</td>
<td>0</td>
<td>-42.1</td>
<td>96.7</td>
<td>42.5</td>
<td>A3</td>
<td>44.10</td>
</tr>
<tr>
<td>Isobutane</td>
<td>R600a</td>
<td>C₄H₁₀</td>
<td>4</td>
<td>0</td>
<td>-11.8</td>
<td>134.7</td>
<td>36.48</td>
<td>A3</td>
<td>58.12</td>
</tr>
<tr>
<td>Propylene</td>
<td>R1270</td>
<td>C₃H₆</td>
<td>1.8</td>
<td>0</td>
<td>-48</td>
<td>91</td>
<td>46.1</td>
<td>A3</td>
<td>42.08</td>
</tr>
<tr>
<td>Water</td>
<td>R718</td>
<td>H₂O</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>373.9</td>
<td>217.7</td>
<td>A1</td>
<td>18.0</td>
</tr>
<tr>
<td>Air</td>
<td>R729</td>
<td></td>
<td>0</td>
<td>0</td>
<td>-194.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>28.97</td>
</tr>
</tbody>
</table>

Source: SHECCO, 2012

According to Lee et al. (2006), R717 is a natural refrigerant commonly adopted to low temperature two stage refrigeration systems. The only disadvantages are its pungent smell, toxicity and moderate flammability as well
as large swept volume requirements at temperatures below 35°C causing air to leak into the refrigeration system leading to shorter term inefficiency and long term unreliability of the system. Therefore, a cascade system with R744 and R717 meets these requirements. According to Dopazo et al. (2008), R744/R717 cascade system uses R717 and R744 in the high and low temperature circuits respectively. Compared to R717 two stage refrigeration systems, the R744/R717 cascade refrigeration system has significantly lower charge amount of R717 and its COP exceeds that of a two stage system at lower temperatures. R744 has been used as a refrigerant in vapor compression systems for over 130 years, but only in the last decade have inventive minds and modern techniques found new ways to exploit the uniquely beneficial properties of this remarkable refrigerant. R744 system development was driven in the 19th century by the shortcomings of alternatives i.e. air cycle, ether, absorption and R717. It was impeded by lack of knowledge, lack of commercial awareness, lack of manufacturing capability and lack of concern for safety. However, of recent, manufacturing is easy to cope with the requirements and an increased level of safety awareness backed by appropriate international codes and legislation will help to make R744 a preferred choice for industrial systems in the near future (Pearson, 2005).

Since the critical temperature of R744 is lower than the heat rejection temperature of air conditioning and heat pump, the transcritical vapor compression cycle is applicable for R744 in air conditioning and heat pump systems. Compared with refrigerating cycle of conventional refrigerants, transcritical R744 refrigerating cycle has larger pressure difference between heat rejection pressure and evaporating pressure. So, its throttling loss is larger accordingly. The COP of transcritical R744 refrigeration cycle is much lower than ones of conventional synthetic refrigerants (Fangtian, 2010). In order to reduce throttling loss and increase COP, researchers have studied throttling mode and proposed several methods such as incorporating an expander, vortex or ejector instead of a throttling valve to reduce throttling loss for example, Liu et al. (2002), analyzed the COP of transcritical R744 refrigeration cycle with an ejector and found that the ejector could increase the suction pressure of compressor to reduce its work input. Daqing Li (2005) calculated the COP of transcritical R744 cycle with an ejector and found that the COP of the ejector expansion transcritical R744 cycle to be 16% more than the transcritical R744 cycle with throttling valve under typical operating conditions for air conditioning. Yitai et al. (2006) analyzed the transcritical R744 cycle with ejector and two evaporators and found its performance better.

2.4: Applications of Refrigeration in Uganda

There are various applications of refrigeration in Uganda. Below are some of the major sectors/industries that employ refrigeration on a large scale in Uganda;

2.4.1: Fish industry

The fisheries sector remains the second highest foreign exchange earner for Uganda. Investment in this sector is estimated at $200 million with employment of over 700,000 people (UIA, 2009). The fish products exported include fresh fish, chilled and frozen fish, dry/ smoked fish, fish maws, fish meal, fish oil, fish skins and live (ornamental) fish. According to UIA (2009), fresh fillets are the main fish products exported from Uganda accounting for 76% of the total quantity and 78% of the total value. The European Union is the major market for Uganda’s fish accounting for 75% of the total exports. The major importers are France, Belgium and Netherlands as shown in the table below. Uganda is the 5th fish fillet exporter to France ranking after vast fish suppliers such as China with a market share of 10.9%, Norway (9.8%), Chile (7.2%) and USA (6.3%). France continues to be an important fish market for Uganda given the escalating demand for fresh water fish particularly Tilapia and Nile perch.
Table 2.3: Top 10 destinations of Uganda's fish exports (tons)

<table>
<thead>
<tr>
<th></th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>France</td>
<td>19,876</td>
<td>35,219</td>
<td>34,584</td>
<td>27,634</td>
</tr>
<tr>
<td>Belgium</td>
<td>21,698</td>
<td>27,263</td>
<td>27,197</td>
<td>27,319</td>
</tr>
<tr>
<td>Netherlands</td>
<td>13,704</td>
<td>19,966</td>
<td>16,197</td>
<td>18,702</td>
</tr>
<tr>
<td>Israel</td>
<td>846</td>
<td>2,343</td>
<td>9,699</td>
<td>7,424</td>
</tr>
<tr>
<td>UAE</td>
<td>5,901</td>
<td>6,968</td>
<td>6,847</td>
<td>6,481</td>
</tr>
<tr>
<td>Spain</td>
<td>5,588</td>
<td>8,423</td>
<td>3,613</td>
<td>4,440</td>
</tr>
<tr>
<td>Hong Kong</td>
<td>1,605</td>
<td>3,184</td>
<td>3,178</td>
<td>4,177</td>
</tr>
<tr>
<td>Egypt</td>
<td>1,526</td>
<td>3,123</td>
<td>4,115</td>
<td>2,419</td>
</tr>
<tr>
<td>Italy</td>
<td>1,080</td>
<td>1,872</td>
<td>5,728</td>
<td>2,234</td>
</tr>
<tr>
<td>Japan</td>
<td>2,376</td>
<td>658</td>
<td>2,161</td>
<td>2,223</td>
</tr>
</tbody>
</table>

Source: UIA, 2009

The regional market for fish is also gradually rising with the return of peace in southern Sudan and eastern Democratic Republic of Congo (DRC). At regional level, Uganda exports fish to Kenya, Sudan, DRC and Rwanda. Although this sector is significant to the economy, its performance has been affected by increased depletion of fish stocks from the lakes due to overfishing and use of wrong fishing gear. There are over 350 species but the Nile perch (Lates niloticus) and Tilapia (Orechromis niloticus) remain the most important, contributing 46% and 38% of the total respectively (UIA, 2009). According to UIA (2009), the sector depends on natural water bodies which account for about 18% of Uganda's total surface area. Lake Victoria the largest tropical lake and the second largest fresh water lake in the world contributes 60% of the fish caught while other lakes like Kyoga and Albert contribute 16% and 15% respectively.

The sector is supported by 15 international airlines which offer significant cargo space to enable exportation of fish to Europe. Compliance with international quality standards in the sector is guaranteed by Uganda’s Department of Fisheries Resources, Uganda National Bureau of standards (UNBS), Food Science and Technology Research Institute, National Environment Management Authority (NEMA) and The Ministry of Health (MoH). Each processing factory is given an export quota and only the best quality fish are selected for export. Most fishing in the sector is done by small canoes using either paddle or outboard power. All factories have refrigeration trucks that transport fish from landing sites to processing plants. The plants adhere to standards of design and construction specified with EU hygiene directive.

2.4.2: Beef industry

The beef sector is one of Uganda’s success stories since the early 1990s. However, the sector is still dominated by small scale enterprises and agro-pastoralists often near the subsistence level. The sector is economically dominated by cattle, accounting for 60-70% of the sector turn over. Livestock is mainly concentrated in the southern and western part of the country, accounting for about 80% of all cattle. A distinct cattle corridor runs from the north-east to the south-west. The sector is becoming increasingly export oriented, spearheaded by the rapid growth in the export of hides and skins. An estimated 90% of the national cattle herd is kept under pastoral and mixed small holder farming systems. These extensive production systems are generally very low in productivity (UBOS, 2002). Commercial beef ranching is limited accounting for less than 10% of the national herd. The main sources of meat are the culled animals and excess steers in the various farming systems. The meat subsector is mostly very domestic and self sufficient with very limited exports.

The national livestock population increases at an average rate of 4% per annum and was estimated to comprise 6 million cattle, 1.1 million sheep, 6.6 million goats, 1.6 million pigs and nearly 30 million poultry (UIA, 2006). The indigenous breeds account for over 95% of the national herd/ flock. The Ankole long horned breed whose meat is low in cholesterol levels dominates the cattle population. The small East African
goat and the Mubende breed have the finest skin from a non-endangered animal on the world market. An estimated 90% of the national animal herd is kept under pastoral and mixed small holder farming. Animals are kept for both meat and milk, draught and as a saving mechanism. The off-take for milk is rather low. Commercial beef ranching accounts for less than 10% of the total herd and about the same share of beef supply. The beef sector is almost domestic and self sufficient with no exports or imports. According to UIA (2006), consumption of beef products both in absolute terms and per capita basis is very low in Uganda. However, prospects for increased demand, hence increased production are good as per capita purchasing power continues to increase.

The national cattle population over the last decade has experienced steady growth. This has been attributed mainly to increasing demand for beef by consumers and beef processing plants, better herd management, and adoption of improved breeds, improved animal health and support services. An average growth rate of 3.1% has been experienced over the last five years. This is evidenced in the table below;

Table 2.4: Livestock population (X 1000)

<table>
<thead>
<tr>
<th></th>
<th>1998</th>
<th>1999</th>
<th>2000</th>
<th>2001</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cattle</td>
<td>5,651</td>
<td>5,820</td>
<td>5,966</td>
<td>6,148</td>
</tr>
<tr>
<td>Sheep</td>
<td>1,014</td>
<td>1,044</td>
<td>1,081</td>
<td>1,108</td>
</tr>
<tr>
<td>Goats</td>
<td>5,999</td>
<td>6,180</td>
<td>6,396</td>
<td>6,620</td>
</tr>
</tbody>
</table>

Source: UBOS, 2002

Fresh beef is the most common beef product on the Ugandan market. It is most prevalent in rural and semi-urban areas where purchase of beef is made from roadside butcheries. The butchers are the ones responsible for buying the animals from the farmers or other middlemen. The price for the animal is determined by its age and weight. The meat sold in butcheries is fresh as no refrigeration facilities are used; in addition, the purchase of animals for slaughter is determined by the locality of the butchery and the absorption capacity of consumers. The lack of cooling capacities means that butcheries try not to have meat overnight as this will result in business losses. The rural market is characterized by perfect competition where butcheries determine the prices of their fresh meat downwards, especially when there is low demand in order to avoid losses that come with extra beef.

In metropolitan areas, consumers buy freshly cut meat that is cleaned and packed. This beef is more convenient for the various types of cooking it may be subjected to. Still with the relatively low prices of packed beef, consumers still show preference for beef products in butcheries. Products offered in butcheries also include minced meat, kigere and other internal organs such as intestines, kidneys, liver and the heart. The major reasons as to why consumers prefer fresh butchery beef is because for the same price, they can get a mixture of various body parts whereas packed meat does not offer this.

The quality of beef produced is very good largely due to the fact that there is a combination of local and exotic breeds; the grassland structure of both western and eastern Uganda is also suitable for beef production. Most of the beef produced in Uganda is from animals that rely on pasture for more than 80% of the feeding. This translates into good beef quality and with market support; benefits accruing from the players in the chain could exponentially rise. Beef sausages are a very important component of the beef market in Uganda. Companies like Farmers Choice and imperial Gourmet Limited are specializing in the production of beef sausages. Recently, other companies have entered the sausage industry and there is a variety of products on market. Tinned beef in Uganda is imported mainly from Denmark, Germany and South Africa. It is packed in 250 and 500 gram containers.

2.4.3: Dairy industry

The dairy sector currently contributes about 20% to the food processing industry. It is composed of indigenous, exotic and cross breeds. The exotic breeds include the Jersey, Holstein, Fresians, Guernsey, Ashyire and the Brown Swiss. The leading districts in dairy production are Mbarara, Moroto, Bushenyi, Kotido, Masaka, Mbale, Kabarole, Mukono, Ntungamo and Kamuli. The demand for milk in Uganda comes
from households, schools, hospitals, catering institutions, food and dairy processing plants. Demand for processed milk is estimated at 400 million liters per year and this is expected to increase. Uganda produces a variety of milk products but a substantial amount of processed milk products is also imported indicating that the domestic production is not sufficient to meet market demands. Most of the imported milk products are complex processed products such as milk powder of which a big component is for infants. These include NIDO, NAN, SMA, S26, etc mainly from Europe and South Africa. This has been attributed mainly to the fact that local milk producers and processors lack capacity both technically and financially to process milk to milk powder that can favorably compete with the imported varieties. Also, consumers purchase milk powder largely due to its proven quality and reputation.

The local market mainly produces fresh, pasteurized and UHT milk and a portion of both fresh and pasteurized milk is exported to regional markets with Rwanda and DRC being the leading destinations. In Uganda, the most commonly consumed milk products are unprocessed raw milk, domestically processed packaged milk (pasteurized and UHT) and boiled unprocessed milk. The most commonly produced dairy products include yoghurt, ghee, butter, cheese, ice cream and fermented milk. The pie chart below gives a summary of the consumption of dairy products in Uganda. Yoghurt has the biggest market share followed by ice cream while cream and fermented milk have the lowest.

![Pie chart showing consumption of dairy products in Uganda](image)

**Figure 2.7: Consumption of dairy products in Uganda (Source: FAO, 2003)**

### 2.4.4: Beer industry

In Uganda, 19.47 liters of pure alcohol are consumed per capita per year (WHO, 2004). This is nearly 4 times higher than the world average and 5 times higher than the African region average, making Uganda ranked 1 from 189 WHO member states in level of alcohol consumption. Uganda is abundantly supplied with alcoholic beverages from imported beer, wine and liquor to beer produced in factories in the country to informally produced beer and distilled liquor in local makeshift bars and homes. There are a variety of factory and locally produced beer in Uganda. Imported factory produced beer such as Heineken, Carlsberg, Amstel, Bavaria, Tusker and Guinness can be readily found in urban areas of Uganda. In addition, 11-13 million crates of beer are produced in Ugandan factories every year, contributing to about 10% of state revenue. The common brands are Bell lager, Nile Special lager and Club pilsner. Consumption of factory beer is largely urban, factory produced beer is mainly consumed in the urban areas by people who can afford the more expensive price while locally produced and home brewed alcoholic beverages predominate in the rural areas, but are also consumed in urban areas by low income earners who can’t afford factory made drinks. The major beer industries in Uganda are East African Breweries Limited in Luzira and Nile Breweries in Jinja.
2.4.5: Supermarkets

The major supermarkets in Uganda are Nakumatt, Game, Capital city shoppers, Tuskys and Uchumi. Two temperature levels are required for supermarket refrigeration i.e. medium temperature for chilled foods and low temperature for frozen foods. Product temperatures of around +3 °C and -18 °C are typical (Gavarrell, 2011; Sawalha, 2008). In such applications with a large temperature difference between the evaporator and condenser, two stage system solutions are more favorable and are mainly adapted for the two temperature level requirements of the supermarket. R744 is a promising refrigerant in supermarket refrigeration and offers opportunities for energy savings. R744 in supermarket refrigeration is applied in 3 main different system solutions i.e. indirect, cascade and transcritical (Sawalha, 2007).

According to Sawalha (2007), the indirect system solution with R744 as secondary fluid is used for low temperature applications where pressure levels are reasonably low and conventional components can be used although recently, components for R744 became more available which has paved way for installation of cascade and transcritical systems in commercial refrigeration.

i) Conventional R404A systems

The indirect system consists of a medium temperature stage and a low temperature stage. The secondary circuits on the evaporator and condenser side are connected to a single circuit consisting of a secondary refrigerant such as propylene glycol. The low temperature stage uses a refrigerant such as R404A. The sub cooler is installed after the condenser and lowers the enthalpy before the expansion valve. It is simply a heat exchanger connected to the brine loop. The supply temperature of the brine is approximately -8°C. The reduction in enthalpy increases the enthalpy difference between the inlet and outlet of the evaporator considering an isenthalpic expansion valve. This power is transferred to the brine loop and will be extracted by the chiller loop, which has a higher COP and for these reasons, the extra cost of the sub cooler in the freezer loop is justified.

In the freezers, R744 can be used as brine in the secondary circuit. In this case, the R744 in the secondary circuit is stored in a large tank in liquid form. R744 is preferable where the recommended maximum working pressure is about 40 bars, which is said to be higher than normal in a refrigeration system with conventional components. In such a system with R744 for freezer applications, the pressure level is about 12 bars.

The medium temperature stage uses R404A as the refrigerant. This stage has a sub cooler which is located after the condenser for the purpose of sub cooling the liquid out of the condenser. An electronic expansion valve is used on this medium temperature stage. In addition, an internal heat exchanger is connected to further sub cool the liquid coming out of the sub cooler and superheat in the compressor inlet.
According to Gavarrell (2011), the performance of the above system is evaluated as follows; the sub cooling of the liquid has energy cost and it is considered in the evaluation of the COP. Therefore, the energy consumption of the freezer compressor and the electrical cost of sub cooling are considered in the evaluation of the COP.

\[
\text{COP}_{\text{freezer}} = \frac{Q_{o,\text{freezer}}}{E_{\text{comp,freezer}} + \frac{Q_{o,\text{subcool}}}{\text{COP}_{\text{chiller}}}} \quad \text{Equation 2.1}
\]

This energy consumption is introduced since separate systems for each level are not used. There is coupling between the systems and hence the energy used by the chiller compressor to dissipate the \( Q_{o,\text{subcool}} \) in the chiller condenser needs to be taken into account in the corresponding COP. In order to accomplish this, \( Q_{o,\text{freezer}} \), \( E_{\text{comp,freezer}} \) and \( Q_{o,\text{subcool}} \) have to be known. The cooling capacity of the freezers is calculated using the equation below;

\[
Q_{o,\text{freezer}} = m_{\text{freezer}} \Delta h_{\text{freezer}} = m_{\text{freezer}} \left( h_{\text{out,cab,freezer}} - h_{\text{in,cab,freezer}} \right) \quad \text{Equation 2.2}
\]

The above expression holds for all freezers in each refrigeration system. In case of direct expansion in the freezer, the refrigerant state before the expansion valve is sub cooled liquid. Considering a throttling process in the expansion valve, \( h_{\text{in,cab,freezer}} \) is obtained using a pressure transducer and a thermometer before the expansion valve.

At the exit of the cabinet, the refrigerant is a superheated vapor with enthalpy \( h_{\text{out,cab,freezer}} \). Its value is also obtained with a thermometer and a pressure transducer using thermodynamic properties of the refrigerant. Also, there is need to evaluate the mass flow rate through the low temperature circuit \( m_{\text{freezer}} \). This can easily be done by using a mass flow meter such as coriolis flow meter, gas flow meter or liquid flow meter. The parameters and their instrumentation are summarized in the table below;
Table 2.5: Instrumentation used in evaluating performance of systems

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Instrumentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass flow of refrigerant</td>
<td>$m_{freezer}$</td>
<td>Mass flow meter</td>
</tr>
<tr>
<td>Enthalpy at inlet to cabinet</td>
<td>$h_{in,cab,freezer}$</td>
<td>Pressure, Temperature</td>
</tr>
<tr>
<td>Enthalpy at cabinet exit</td>
<td>$h_{out,cab,freezer}$</td>
<td>Pressure, Temperature</td>
</tr>
</tbody>
</table>

Source: Gavarrell, 2011

In order to calculate sub cooling from the medium temperature unit, the evaluation is as follows;

$$Q_o, subcool = m_{freezer} \cdot (h_{out,HE,subcool} - h_{in,HE,subcool}) \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \text{Equation 2.3}$$

The state of the refrigerant is a slightly sub cooled liquid and for this matter, its temperature has to be known, assuming a constant pressure in the heat exchanger. The parameters and instrumentation for the cooling capacity in the sub cooler are summarized below;

Table 2.6: Instrumentation used in evaluating performance of sub cooler

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Instrumentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass flow rate of refrigerant</td>
<td>$m_{freezer}$</td>
<td>Mass flow meter</td>
</tr>
<tr>
<td>Enthalpy at exit of sub cooler</td>
<td>$h_{in,cab,freezer}$</td>
<td>Pressure, Temperature</td>
</tr>
<tr>
<td>Enthalpy at inlet of sub cooler</td>
<td>$h_{in,HE,subcooler}$</td>
<td>Pressure, Temperature</td>
</tr>
</tbody>
</table>

Source: Gavarrell, 2011

Finally, the $E_{comp,freezer}$ is measured using a power meter. Once each term is known as well as the COP of the chiller which can be subsequently calculated, the COP of the freezer and the cooling capacity $Q_o, freezer$ can then be calculated. For the COP calculation in the medium temperature unit, $Q_o,chiller$, $E_{comp,freezer}$ and $E_{pump,brine}$ must be evaluated. This being an indirect system means that the useful cooling capacity is not in the medium temperature refrigerant loop but in the brine loop. The COP for the chiller can then be evaluated as follows;

$$COP_{chiller} = \frac{Q_o,chiller}{E_{comp,chiller} + E_{pump,brine}} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \text{Equation 2.4}$$

The power requirement by both the brine pump and the compressor can be measured with a power meter. On the other hand, $Q_o,chiller$ can be evaluated as follows;
\[ Q_{o,chiller} = m_{chiller} \Delta h_{chiller} = m_{chiller} (h_{out, evap, chiller} - h_{in, evap, chiller}) \] \hspace{1cm} \text{Equation 2.5}

### Table 2.7: Summary of instrumentation used for the chiller unit

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Instrumentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass flow in chiller</td>
<td>( m_{chiller} )</td>
<td>Mass flow meter</td>
</tr>
<tr>
<td>Enthalpy at exit of chiller cabinet</td>
<td>( h_{out, evap, chiller} )</td>
<td>Pressure, Temperature</td>
</tr>
<tr>
<td>Enthalpy at inlet of chiller cabinet</td>
<td>( h_{in, evap, chiller} )</td>
<td>Pressure, temperature</td>
</tr>
</tbody>
</table>

Source: Gavarrell, 2011

According to Gavarrell (2011), although the energy consumption by the pumps in the brine loop should be divided between each COP, it is considered only in the chiller COP because this energy consumption is negligible compared to that of the compressors. In addition, \( Q_{o,subcool} \) is smaller than \( Q_{cab,chiller} \) and for this reason, the energy consumption of the brine pumps is considered only in the \( COP_{chiller} \).

**Brine loop**

Figure 2.9 shows the brine loop. The thermodynamic analysis of the brine loop for the system is illustrated below;

![Brine loop diagram](image)

**Figure 2.9: The brine loop (Source: Gavarrell, 2011)**

The secondary refrigerant is normally propylene glycol although ethylene glycol and other fluids can be used. According to Gavarrell (2011), we could place the evaporator directly inside the cabinets and extract a refrigerant line, with a by-pass to the evaporator and connect with expansion with the freezer heat exchanger. But the main obstacle to this is to minimize the refrigerant charge as much as possible due to effects of climate change hence the need for an indirect brine loop. From this perspective, there is necessity for a slight reduction in system efficiency as a result of the need to maintain a lower evaporator temperature in the chiller loop than the temperature in systems without a brine loop, the electric power from the pump is a direct load to the chiller COP. The energy balance in this loop is therefore;

\[ Q_{o,chiller} = Q_{cab,chiller} + Q_{o,subcool} + E_{pump,brine} \] \hspace{1cm} \text{Equation 2.6}

**Coolant loop**

Figure 2.10 shows the coolant loop. The thermodynamic analysis of the coolant loop for the system is illustrated below;
Also, because of the need to reduce the refrigerant charge, there is a necessity to take advantage of heat recovery in the HVAC system. Outdoor air for space conditioning in the supermarket can be preheated with the heat rejection from the cooling system. The above equation did not account for the electric power by the fans and the pump in the coolant loop. This electric cost should be divided in the two COPs in proportion to the cooling capacity of each unit: \( Q_{o, freezer} \cdot Q_{cab, chiller} \). The total COP can be calculated using the equation below:

\[
COP_{tot} = \frac{Q_{o, freezer} + Q_{cab, chiller}}{E_{comp, freezer} + E_{comp, chiller} + E_{pump, brine}} \hspace{1cm} \text{Equation 2.7}
\]

In these systems, the primary refrigerant can be R404A in the freezer circuit and R407C in the chillers while the secondary refrigerant can be ethylene glycol or propylene glycol. The figure below reveals the needed instrumentation to assess the specified parameters. Other temperature sensors (inside rectangles) have been introduced that are needed to estimate the mass flow rate of the refrigerant incase the flow meters are not installed in the system.
ii) Transcritical systems

The use of R744 transcritical system solutions is gaining interest with several installations already in operation in different European countries (Sawalha, 2007). According to Gavarrell (2011), there are two main systems solutions i.e. booster system and a parallel arrangement as described below;

a) Booster system

![Figure 2.11: Instrumentation in a Conventional R404A indirect system for Supermarkets (Source: Gavarrell, 2011)](image)

![Figure 2.12: Schematic diagram of R744 booster system with a low pressure receiver (Source: Gavarrell, 2011)](image)

As mentioned earlier, there are two types of refrigeration circuits i.e. medium temperature circuit for the display cabinets of chilled foods and cold rooms and low temperature circuit for the frozen foods. In a
booster system, these two circuits are integrated in a circuit with a single condenser. There is also mixing of the state in the intermediate pressure reducing overheating in the output of the low temperature compressor.

One advantage of the booster system is that the medium and low temperature levels can be served by one unit and then a single control system package can be used which cuts the cost of the system. A second advantage is the use of a single refrigerant at medium and low temperatures. Because of its thermodynamic properties, it is more appropriate system for cold climates in countries such as Sweden, Denmark and Germany unlike hot climates where the annual consumption of R744 is higher than in conventional R404A systems. This can be attributed to a high heat sink temperature making the system to operate in the transcritical region.

This system is composed of two compressor stages, keeping both pressures and temperature levels. This pressure level is achieved by expanding to an intermediate pressure between the saturated pressure in the condenser and the saturated pressure in the medium temperature evaporator. The discharge of the low pressure compressor is connected to the suction line of the high stage compressor and the exit of the chiller cabinet, getting with the mix to reduce the superheat in the suction line of the high pressure compressor.

There are two outlets on the receiver vessel i.e. one at the bottom for the liquid that is to be introduced to the cabinets and evaporated and one at the top for vapor extraction to the gas bypass circuit. This vapor is first expanded in two parallel expansion valves to reduce its pressure and temperature. The resulting vapor liquid mixture in this line and the saturated liquid from the bottom of the receiver tank enter a counter flow heat exchanger where the liquid is sub cooled and the vapor-liquid mixture is heated and returned to the suction line of the high stage compressor.

After the heat exchanger, the liquid refrigerant flow is divided into two parts i.e. one leading to the medium temperature cabinets and one to the freezers. There, evaporation takes place after the refrigerant has passed through expansion valves. The refrigerant from the freezers is returned to the low stage compressors and mixes with the flow from the chillers at the compressor discharge as well as that from the receiver before being compressed to a heat sink level.

The installation of a heat exchanger is intended to recover the losses caused by this intermediate temperature. There are two main reasons for using a heat exchanger. First, when expanding the saturated vapor from the receiver to the suction side of the high stage compressor, the result will be a liquid–vapor mixture causing a risk of liquid droplets entering the high stage compressor that can lead to cavitation. Since this mixture will be mixed with the relatively hot discharge gas from the low pressure compressors, there is minimal risk of this happening and this is further abated by the use of a heat exchanger. Furthermore, from the slope of the saturated vapor line in the p-h diagram, the lower the receiver pressure, the higher the vapor quality at the inlet of the evaporators. This implies that a larger region of the evaporators will be filled with liquid which improves the heat transfer. All these modifications are aimed at increasing the system COP without compromising the safety of the compressor as well as not to increase the cost of regulation and control.

For a booster subsystem, it is important to evaluate the total COP, the COP freezer and the COP chiller. in order for this to be accomplished, there is need to distinguish the four different mass flows i.e. mass flows going through the chiller, freezer, condenser and the line joining the heat exchanger with the high pressure compressor. It is also important to notice that a unit mass flow is the total mass flow going through the high stage compressor and condenser. A mass flow balance for the system is therefore;

\[ m_{\text{condenser}} = m_{\text{chiller}} + m_{\text{freezer}} + m_{\text{hi.E}} \]

Equation 2.8

There are 4 pressure levels and mass flow rates in a booster system. The mass flow, pressure and temperature measurements allow power for each part of the system to be calculated. For the evaluation of the COP, only the capacities of the chiller and freezer are required. However, since the outlet state of the cabinets is superheated vapor, there is need to know the pressure and temperature for each line in order to obtain the enthalpy at exit.

The system design is aimed at producing a cooling effect in the chiller and freezer cabinets but once the system is in operation, the mass flow is determined by the cooling capacity needed in the cabinets. Therefore
using the mass flow balance and with the measurement of 3 mass flows, the refrigerant flow in the 3 different lines in the circuit can be determined by performing an energy balance at the heat exchanger. The cooling capacity in the freezer and chiller can be calculated by the following equations;

\[ \dot{Q}_{o,\text{freezer}} = \dot{m}_{\text{freezer}} \Delta h_{\text{freezer}} = \dot{m}_{\text{freezer}} \cdot (h_{\text{out,\text{cab,freezer}}} - h_{\text{in,\text{cab,freezer}}}) \quad \ldots \ldots \ldots \ldots \ldots \text{ Equation 2.9} \]

\[ \dot{Q}_{o,\text{chiller}} = \dot{m}_{\text{chiller}} \Delta h_{\text{chiller}} = \dot{m}_{\text{chiller}} \cdot (h_{\text{out,\text{cab,chiller}}} - h_{\text{in,\text{cab,chiller}}}) \quad \ldots \ldots \ldots \ldots \ldots \text{ Equation 2.10} \]

The instrumentation for the evaluation of the various parameters is similar to that of the indirect system. The power consumption by the compressor can be directly evaluated using a wattmeter. However, in order to determine the COP of the freezer and chiller circuits, there is need for the distribution of the power consumption by the high stage compressor since its purpose is to reject the heat absorbed in the medium and low temperature cabinets. Hence there is need to know which part of the electric power is absorbed by the low stage compressor goes to the refrigerant since it must be rejected by the condenser.

\[ \text{COP}_{\text{freezer}} = \frac{\dot{Q}_{o,\text{freezer}}}{E_{\text{comp,freezer}} + E_{\text{comp,chiller,freezer}}} \quad \ldots \ldots \ldots \ldots \ldots \text{ Equation 2.11} \]

\[ \text{COP}_{\text{chiller}} = \frac{\dot{Q}_{o,\text{chiller}}}{E_{\text{comp,chiller}} + E_{\text{comp,chiller,freezer}}} \quad \ldots \ldots \ldots \ldots \ldots \text{ Equation 2.12} \]

It is necessary to determine the enthalpy at the exit of the low stage compressor. The electric power in the high stage compressor due to the freezer is calculated as follows;

\[ \dot{Q}_{\text{cond,freezer}} = \dot{m}_{\text{freezer}} \cdot (h_{\text{out,\text{comp,freezer}}} - h_{\text{in,\text{cab,freezer}}}) \quad \ldots \ldots \ldots \ldots \ldots \text{ Equation 2.13} \]

\[ E_{\text{comp,chiller,freezer}} = E_{\text{comp,chiller}} \cdot \frac{\dot{Q}_{\text{cond,freezer}}}{\dot{Q}_{\text{cond,freezer}} + \dot{Q}_{o,\text{chiller}}} \quad \ldots \ldots \ldots \ldots \ldots \text{ Equation 2.14} \]

The total COP of the system is therefore calculated as shown below;
\[
COP_{\text{tot}} = \frac{Q_{\text{freezer}} + Q_{\text{chiller}}}{E_{\text{comp, freezer}} + E_{\text{comp, chiller}}}
\]

Figure 2.13: Instrumentation in R744 booster system (Source: Gavarrell, 2011)

The schematic diagram above shows the instrumentation of the R744 booster system. Two flow meters can be positioned in the liquid part due to the high density. In addition, the sensors are compact and of relatively low price. The mass flow in the bypass is calculated by performing an energy balance. Temperature sensors can be located in the compressor discharge line as well as the outlet from the evaporator to measure the useful superheat in the cabinets. The pressure levels of the system are also measured, the temperature in the vapor bypass of the intermediate receiver is measured too since it is necessary for the heat balance in the heat exchanger from which the mass flow in the bypass can be obtained.
b) Parallel arrangement

![Schematic of R744 parallel system solution](image)

Figure 2.14: Schematic of R744 parallel system solution (Source: Gavarrell, 2011)

This configuration is one of the possible system solutions when using refrigerant R744 in supermarket refrigeration. The system consists of two separate circuits with one meeting the cooling requirements of the medium temperature cabinets while the other covers the needs of the freezers. The system used in the freezers involves two stage compression since it is necessary to avoid high discharge temperatures while the medium temperature has only single stage compression. However, both systems use direct expansion causing the need for special design of the various system components that can withstand the high operating pressure.

In order to compare the various systems, there is need to evaluate the energy extracted from the cooling system, \(Q_o\) and the electric power consumption in the process:

\[
Q_{o,freezer} = m_{freezer} \Delta h_{freezer} = m_{freezer} (h_{out,cab,freezer} - h_{in,cab,freezer}) \quad \text{Equation 2.16}
\]

\[
Q_{o,chiller} = m_{chiller} \Delta h_{chiller} = m_{chiller} (h_{out,cab,chiller} - h_{in,cab,chiller}) \quad \text{Equation 2.17}
\]

The instrumentation needed to evaluate the terms in the above equations is as in the previous cases. The electric power consumption can be measured and the cooling capacity calculated. The COP for the chiller and freezer can then be evaluated as shown below;

\[
COP_{freezer} = \frac{Q_{o,freezer}}{E_{comp,freezer}} \quad \text{Equation 2.18}
\]

\[
COP_{chiller} = \frac{Q_{o,chiller}}{E_{comp,chiller}} \quad \text{Equation 2.19}
\]

The total COP is also calculated with the following equation;
The figure above shows the location of the sensors. Two flow meters can be located, one in each circuit, in the liquid part of the system due to the high density and the relatively compact and low price of the sensors. The temperature sensors have been located in the inlet and outlet of the compressor inside a rectangle. These sensors can be used in the estimation of the mass flow in the absence of a mass flow meter. Temperature sensors are also located in the evaporator outlet to directly measure the useful superheat in the cabinets. The pressure levels of the system are also measured and the power consumption by the compressor can also be measured directly with a power meter.

R744 transcritical systems look more promising in eco-friendly refrigeration and air conditioning especially in supermarket and automobile applications. In the past two decades, extensive research has been done on the operation of R744 transcritical system solutions. Sawalha (2007) used a computer simulation model to investigate the performance of two main system solutions for supermarket refrigeration i.e. centralized with accumulation tank at medium temperature level and parallel arrangement with two separate circuits for low and medium temperature levels and found out that for the ambient temperature range (10-40°C), the reference centralized system solution exhibited a higher COP of about 4-21% compared to the reference parallel system solution. He also noted that using two stage compression in the centralized system solution instead of single stage can result in a total COP of about 5-22% higher than that of the improved two stage parallel system. Furthermore, the two stage centralized system solution also gives the highest COP for the selected ambient temperature range.

Fangtian (2010) performed a comparative study on two R744 transcritical refrigeration cycles i.e. one with an ejector and the other with an expansion valve basing on theory from the first and second laws of thermodynamics. They investigated the effects of the entrainment ratio of the ejector, heat rejection pressure, outlet temperature of gas cooler and evaporating temperature on the COP and exergy loss. The results showed that an ejector unlike a throttling valve can reduce exergy loss by 25% and increase the COP by at least 30%. In addition, the critical entrainment ratio of the ejector, optimal heat rejection pressure and critical
outlet gas temperature of the gas cooler affects the COP greatly for the R744 transcritical cycle with an ejector.

On the other hand, Yang et al. (2004), performed a comparative study for two R744 transcritical refrigeration cycles with one having an expander and the other a throttling valve basing on theory from the first and second laws of thermodynamics and investigated the effects of evaporating temperature and outlet temperature of the gas cooler on the optimal heat rejection pressure, COP, exergy loss and exergy efficiency. It was found that in the throttling valve cycle, largest exergy loss occurred in the throttling valve of about 38% of the total cycle irreversibility while in the expander cycle, the irreversibility mainly comes from the gas cooler and compressor of approximately 38% and 35% respectively. Also, the COP and exergy efficiency of the expander cycle is on average 33% and 30% higher respectively compared to that of the throttling valve cycle. It was concluded that the optimal heat rejection pressure can be obtained for all operating conditions to maximize the COP. This study can prove to be of vital importance to provide a theoretical basis for optimization design and control of the R744 transcritical cycle with an expander.

Liao et al. (2000) also used a computer simulation model to optimize the COP of an R744 transcritical cycle for air conditioning and discovered that the COP varies nonmonotonically with heat rejection pressure. He also noted that a maximum COP occurs at an optimal heat rejection pressure and that the values of the optimal heat rejection pressure depend on the outlet temperature of the gas cooler, evaporation temperature and compressor performance. This study can be of significance for the design and control of transcritical R744 air conditioning and heat pump systems. Other researchers like Aprea (2009) used an experiment and a simplified model for a split system used for cooling air in residential applications to investigate an optimum heat rejection pressure and obtained an optimum working condition at various ambient temperatures. They found out that both the model and experimental results suggested that the heat rejection pressure optimization is a convenient method to improve the performance of an R744 split system.

Kim et al. (2007) performed an experimental evaluation of the performance of an R744 transcritical heat pump system for fuel cell vehicles considering heat exchanger arrangements and discovered that there was an improvement in heating capacity and COP of the system by 54% and 22% respectively when using preheated air through the radiator instead of cold ambient air.

Cavallini et al. (2005) carried out both an experimental and a theoretical investigation of the potential of improving the cycle efficiency through two stage compression with intermediate cooling of a two stage R744 transcritical cycle at typical operating conditions for air conditioning. Tests were run at fixed evaporation pressure, evaporator outlet superheating and gas cooler outlet temperature while varying the gas cooler outlet pressure in the range of 8-11 MPa. Parameters under investigation were the optimal gas cooler pressure for the application as well as the effect of the intercooler efficiency on cycle performance. A FORTRAN code which served for theoretical analysis was used for simulation of an improved two stage cycle and validated against experimental results. The results confirmed that an optimum upper cycle pressure that gives maximum energy efficiency occurs for transcritical operation with an improvement in the COP of about 25% for typical air conditioning applications.
iii) Cascade systems

In some industrial applications, the requirement for moderately low temperatures makes it impossible to use a single stage vapor compression cycle for these low temperature applications because of the large temperature difference between the evaporator and condenser. In addition, the compression ratio is also large which tends to compromise the compressor efficiency (Gavarrell, 2011). Instead, two stage or cascade systems are used for these low temperature applications. R717 is a natural refrigerant that is most commonly adopted in low temperature two stage refrigeration systems but it has disadvantages i.e. R717 is toxic, has a pungent smell, is moderately flammable and has relatively large swept volume requirements when the evaporating temperature falls below -35°C. Additionally, the evaporating pressure of R717 system is below atmospheric pressure when the evaporation temperature falls below -35°C causing air leakage into the system leading to short term inefficiencies and long term unreliability of the system which necessitates the use of a non toxic, non flammable and dense refrigerant with a positive evaporation pressure. A cascade system solution with R744 and R717 meets the above requirements and is usually employed in such circumstances (Pearson, 2001; Lee et al., 2006). In this configuration, the cascade cycle is a set of vapor compression cycles in which the condenser of the low temperature cycle is connected to the evaporator of a high temperature cycle via a heat exchanger or heat transfer loop.

For supermarket applications, two units in series are used having different refrigerants in each cycle in order to satisfy the requirement of each temperature and pressure interval. The refrigerant combinations normally used are R404A-R744, R717-R744, R290-R7444, R1270-R744 and R290-R744+R170 (Messineo, 2011; Bhattacharyya et al., 2005; Alhamid et al., 2010). The mass flow rate of the refrigerant in the two cycles is different and the mass flow rate is determined by the desired cooling capacity as well as the heat transfer rate in the heat exchanger.

An energy balance for the heat exchanger reveals that the mass flow rate in each cycle is determined by the changes in the enthalpy of each fluid as it flows through the heat exchanger. R744 is the refrigerant normally...
used in the low temperature stage while other refrigerants such as R404A, R717 and R290 are normally used in the high temperature stage. The major advantage of the system is that ordinary components can be used since the operating pressures are not very high.

The cooling capacity in the low temperature unit is calculated from the equation below;

\[ Q_{\text{freezer}} = m_{\text{freezer}} \Delta h_{\text{freezer}} = m_{\text{freezer}} (h_{\text{out,cab,freezer}} - h_{\text{in,cab,freezer}}) \]  
Equation 2.21

The energy consumption from compressors and pumps can be directly measured with a power meter. The variables that need to be known are;

\[ Q_{\text{chiller}} \cdot Q_{\text{freezer}} \cdot Q_{\text{cond,freezer}} \cdot E_{\text{comp,freezer}} \cdot E_{\text{comp,chiller}} \cdot E_{\text{pump}} \]

\[ Q_{\text{chiller}} = m_{\text{chiller}} \Delta h_{\text{chiller}} = m_{\text{chiller}} (h_{\text{out,cab,chiller}} - h_{\text{in,cab,chiller}}) \]  
Equation 2.22

The heat rejected in the low temperature condenser is calculated as shown below;

\[ Q_{\text{cond,freezer}} = m_{\text{freezer}} (h_{\text{out,comp,freezer}} - h_{\text{in,comp,freezer}}) \]  
Equation 2.23

\[ COP_{\text{freezer}} = \frac{Q_{o,\text{freezer}}}{E_{\text{comp,freezer}} + \frac{Q_{\text{cond,freezer}}}{COP_{\text{chiller}}}} \]  
Equation 2.24

\[ COP_{\text{chiller}} = \frac{Q_{o,\text{chiller}}}{E_{\text{comp,chiller}} + E_{\text{pump}}} \]  
Equation 2.25

For a throttling process, the enthalpy at the evaporator inlet is the same as the enthalpy of the line between the expansion valves and heat exchanger output. Since the state of the refrigerant is a subcooled liquid, there is need to measure the temperature and pressure to determine its enthalpy. In the outlet of the evaporator, the refrigerant is a superheated vapor i.e. pressure and temperature transducers can be used to determine its enthalpy at this point. The total COP of the system can be calculated as shown below;

\[ COP_{\text{tot}} = \frac{Q_{o,\text{cab,freezer}} + Q_{o,\text{cab,chiller}}}{E_{\text{comp,freezer}} + E_{\text{comp,chiller}} + E_{\text{pump}}} \]  
Equation 2.26

The energy balance in the brine loop is;
\[ Q_{chiller} = Q_{o, chiller} + Q_{cond, freezer} + F_{pump, brine} \]  

Equation 2.27

Figure 2.17: Instrumentation in Cascade system (Source: Gavarrell, 2011)

Da Silva et al. (2011) made a comparison of an R744 cascade refrigeration with R404A and R22 conventional systems for supermarkets whereby the refrigeration systems consisted of a cascade cycle i.e. R744/R404A with R744 for subcritical operation and R404A in the high temperature stage, the configuration consisted of a pump circuit for normal refrigeration and a direct expansion for deep freezing while the other system used R404A and R22 with direct expansion systems for both medium and low temperature refrigeration. The results showed that a cascade system presented a lower refrigerant charge which was less than half the refrigerant charge of the other systems hence resulting into a more economical environmentally benign solution.

Alhamid et al. (2010), performed an exergy and energy analysis of a cascade refrigeration system using an azeotropic mixture of R744 and R170 for low temperature applications i.e. biomedical cold storage application and noted that for a specific system and operating conditions that for both exergy and energy optimization methods, an optimal condensing temperature of a cascade condenser can be obtained. He further noted that an increase in the evaporating temperature increased the COP of the system and reduced the mass flow ratios while an increase in the cascade condenser temperature difference reduces both the COP and mass flow ratios. He further stated that using a multilinear regression method, the maximum COP, optimum mass flow ratio and the optimum evaporating temperature of the high temperature circuit of the cascade system can be obtained. Another researcher Dopazo et al. (2008) analyzed an R717/R744 cascade refrigeration system and the results of the COP and exergetic efficiency versus operating and design parameters that were obtained showed that with exergetic analysis and energy optimization, an optimum value of condensing R744 temperature is obtained. Messineo (2011) performed a thermodynamic analysis of an R717/R744 cascade refrigeration system and investigated the effects of the condensing, evaporating, superheating and sub cooling temperatures in both the low and high temperature circuits on the COP of the system. Results where then compared with those of the R404A two stage system and it was concluded that the R717/R744 cascade system offers an interesting alternative to the R404A two stage refrigeration system for low evaporating temperatures (-30°C—50°C) in commercial refrigeration for energy, security and environmental reasons.
2.4.6: Biomedical refrigeration

Biomedical preservation requires storing biological specimens like stem cells, sperm, blood and organs at storage temperatures of around -80°C. For long term storage of biological materials, temperatures below -120°C are generally considered against the effects of devitrification and crystallization (Alhamid et al., 2006; ASHRAE, 2006). The major hospitals in Uganda are Mulago national referral hospital, St. Francis hospital Nsambya, Mengo Hospital, Lubaga hospital and Kawolo hospital in Mukono, Lacor hospital in Gulu and Kitovu hospital in Masaka. Refrigeration in the health sector is mainly employed for preservation of dead bodies, Vaccine refrigeration, cold storage of drugs and for preservation of samples for experimental purposes.

2.5: Assessment of the Performance of Refrigeration Systems

According to Crown et al. (1992), the criterion below is used to assess the performance of refrigeration systems. In order to evaluate the performance of the systems, the following parameters have to be measured;

2.5.1: Tons of Refrigeration (TR): This is referred as tons of refrigeration or chiller tonnage. It is given by;

\[ TR = \frac{Q \cdot C_p \cdot (T_i - T_o)}{3024} \] ………………………………………………………………………………………………………… Equation 2.28

Where;

- Q = Mass flow rate of coolant (kg/h)
- \( C_p \) = Coolant specific heat (kcal/kg\(^\circ\)C)
- \( T_i \) = Inlet temperature of coolant to evaporator (\(^\circ\)C)
- \( T_o \) = Outlet temperature of coolant from evaporator (\(^\circ\)C)

1 TR of refrigeration is the amount of cooling obtained by one ton of ice melting in one day and is equivalent to 3024 kcal/h or 12,000 Btu/h or 3.516 kW.

2.5.2: Specific power consumption (kW/TR): The specific power consumption kW/TR is a useful indicator of the performance of a refrigeration system. By measuring the refrigeration duty performed in TR and the kW inputs, kW/TR is used as an energy performance indicator. In a centralized chilled water system, apart from the compressor unit, power is also consumed by the chilled water (secondary) coolant pump, the condenser water pump (for heat rejection to cooling tower) and the fan in the cooling tower. Effectively, the overall energy consumption would be the sum of;

- compressor power
- chilled water pump power
- condenser water pump power
- cooling tower fan power

The kW/TR or the specific power consumption for a certain TR output is the sum of;

- compressor kW/TR
- chilled water pump kW/TR
- condenser water pump kW/TR
- cooling tower fan kW/TR

2.5.3: Coefficient of performance (COP): The theoretical coefficient of performance, COP\(_{\text{carnot}}\), a standard measure of refrigeration efficiency of an ideal refrigeration system depends on two key system temperatures; evaporator temperature, \( T_e \) and condenser temperature, \( T_c \). COP is given as;
\[ \text{COP}_{\text{carnot}} = \frac{T_e}{(T_c - T_e)} \]  \hspace{1cm} \text{Equation 2.29}

This expression also indicates that higher COP\textsubscript{carnot} is achieved with higher evaporation temperatures and lower condenser temperatures. But COP\textsubscript{carnot} is only a ratio of temperatures, and does not take into account the type of compressor. Hence the COP normally used in industry is calculated as follows:

\[ \text{COP} = \frac{\text{Cooling effect (kW)}}{\text{Power input to compressor (kW)}} \]  \hspace{1cm} \text{Equation 2.30}

Where the cooling effect is the difference in enthalpy across the evaporator and is expressed as kW.

2.5.4: **Energy Efficiency Ratio (EER)**: Performance of smaller chillers and rooftop units is frequently measured in EER rather than kW/ton. EER is calculated by dividing a chiller's cooling capacity (Btu/h) by its power input (W) at full load conditions, the higher the EER, the more efficient the unit.
3.0: METHODOLOGY

3.1: Literature review

Information related to the project was collected from various sources which included the internet, relevant textbooks and brochures. Various stakeholders like National Environment Management Authority (NEMA), Ministry of Energy and Mineral Development (MEMD) among others were consulted as well.

3.2: Data Collection

A field survey was carried out in the industries that have installed operating refrigeration systems. This was done in order to ascertain the current status of refrigeration in Uganda as well as to know the operating conditions of the installed systems. A combination of data collection techniques were employed to obtain the relevant data for the study such as questionnaires and interviews. Data about the operating parameters of the systems was obtained by use of appropriate equipment and instrumentation such as a digital infrared thermometer for temperature measurement, pressure gauges for measurement of pressure at the low and high pressure side and a power meter for measurement of the compressor power demand. According to Gavarell (2011), the following instrumentation is deemed appropriate for evaluating the performance of refrigeration systems the instrumentation used is summarized below;

![Summary of Instrumentation used](image-url)
Table 3.1: Summary of instrumentation used

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Units</th>
<th>Instrumentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enthalpy of refrigerant</td>
<td>h</td>
<td>kJ/kg</td>
<td>Pressure gauge, Infrared digital thermometer</td>
</tr>
<tr>
<td>Compressor power</td>
<td>E</td>
<td>kW</td>
<td>Power meter</td>
</tr>
<tr>
<td>Mass flow rate of refrigerant</td>
<td>m</td>
<td>kg/s</td>
<td>Pressure gauge, Power meter</td>
</tr>
</tbody>
</table>

The above instrumentation was used to collect relevant data for the computer simulation modeling of the systems. The required data included; temperature and pressure at the suction and discharge line of the compressor, evaporation and condensing temperature and the mass flow rate of the refrigerant. However, as a result of failure to obtain the mass flow meter, it was necessary to know the enthalpy of refrigerant prior and after the compression process. With knowledge of the compressor power demand, the mass flow rate of the refrigerant was then calculated. Data collection involved a field survey in industry and below are some of the industries visited;

3.2.1: Fish industry

A field survey in the fish industry was carried out. The factories visited were IFTRA (U) Limited at Kanyanya, Ngege Fish Factory at Luzira and Uganda Fish packers at Nakawa. While in this industry, I was granted access to the cold rooms where the fish is kept under cold storage prior to export, the ice plant which makes ice for cold storage of fish during transportation in trucks and the vehicles which are used to transport the ice. Some of the pictures for this field visit can be found in appendix A.

3.2.2: Beer, Soft drinks and Dairy industry

There are two companies in the soft drink business of Uganda i.e. Crown beverages in Nakawa and century Bottling Company in Namanve. Century bottling Company was the company visited since I was denied access to Crown Beverages. At century bottling company, I was granted access to the company’s mechanical department which is the one responsible for distribution and servicing of the various cooler sizes.

In the beer industry, the two companies visited were Uganda Breweries in Luzira and Nile Breweries Limited in Jinja while in the dairy sector; the companies visited were Sameer Agriculture and Livestock Limited (SALL) at 5th street industrial area in Bugolobi and Jesa Farm Dairy in Busunju Wakiso district. While at the beer and dairy factories, I was granted access to the factory premises especially the production line and the mechanical workshops responsible for the servicing and distribution of coolers. The companies are the ones responsible for the procurement, distribution and servicing of these coolers with the assistance of refrigeration contractors. Some of the pictures for this field visit can be found in appendices B and C.

3.2.3: Supermarkets

The three major supermarkets visited were Nakumatt supermarket at Bukoto, Tusks supermarket at Makerere and Capital City shoppers at Ntinda. During the survey, I was granted access to the freezers and chillers installed. I also met the technical people responsible for servicing and maintenance of the refrigeration systems. Some of the pictures for this field visit can be found in appendix D.

3.2.4: Hospitals

Mulago hospital in Kampala was visited here. While at Mulago hospital, I was granted access to the mortuary unit, the engineering department, the drug storage unit (cold rooms) as well as the blood bank. The pictures for this field visit can be found in appendix E.
3.2.5: Automobile and Commercial Air Conditioning

The companies visited here were Thermocool, Africool, Toyota (Uganda) Limited and Spear motors Limited at Nakawa. At thermocool, I was taken to the various air conditioning units being serviced and maintained by the company i.e. commercial buildings in the city center, Ntinda, Kamwokya, Kololo, Nsambya and Bugolobi. At Africool, I had a chance to have a 3 hour discussion with their refrigeration engineer which was very helpful. While at Toyota (Uganda) Limited and Spear Motors Limited, I had chance to visit the companies’ garages and mechanical workshops from which I got access to their various refrigeration equipment used in mobile air conditioning.

3.3: Modeling and simulation of the systems

The recent technological trends in the refrigeration sector related to environmentally friendly solutions were studied and the solution fit for the refrigeration sector in Uganda was selected. Using data obtained during the field survey, computer models of the systems were developed using EES software and the system efficiencies determined using appropriate equations and assumptions. Calculations using computer simulation modeling were made to compare and evaluate performance of systems in the Ugandan conditions. Limitations and possibilities for the suggested environmentally friendly solutions have also been discussed. The modeling process was accomplished by carrying out a mass and energy balance for each of the system components using the equations below:

\[ \sum_{in} m = \sum_{out} m \]  
Equation 3.1

\[ Q - W + \sum_{in} \dot{m}h - \sum_{out} \dot{m}h = 0 \]  
Equation 3.2

Where:
- \( m \) - Mass flow rate of refrigerant (kg/s)
- \( h \) - Specific enthalpy of refrigerant (kJ/kg)
- \( Q \) - Heat flow in the system components (kW)
- \( W \) - Energy input to the system components (kW)
4.0: RESULTS AND DISCUSSIONS

4.1: Ascertaining the current status of refrigeration in Uganda

In the fish industry, the refrigerants used are R12, R22, R717 and R404A. R12, R22 and R717 are mainly used in the cold rooms where the fish is kept under cold storage at the company premises before being sent to the market. R404A is used in the ice making plants that produce ice for cold storage of fish during transportation to the market. The systems used are single stage vapor compression systems. The compressors used are positive displacement machines i.e. reciprocating and screw compressors of open design.

In the beer, soft drinks and dairy industry, the refrigerants used are R22, R404A, R717 and R134a. R22 and R404A are the refrigerants used in the milk processing factory while R717 is used in the beer processing. In addition to the installed systems at the factories used in the processing line, these companies have coolers that are similar to domestic refrigerators that are procured and distributed to the various retail centers like shops, groceries, kiosks, bars and supermarkets. It is the companies that are responsible for the procurement, servicing, repair and maintenance of these coolers. The systems are single stage direct vapor compression with various capacities. The models include FV 1000, FV 400, FV 200, FV 1200D which are manufactured by Frigorex as well as CVC 250 and Easy reach 100 Generic. The compressors used are reciprocating type of hermetic design.

In the meat industry, the refrigerant used is R134a with simple vapor compression systems having single stage compression. In supermarkets, the dominant refrigerants are R404A and R134a. R404A is used in large systems while R134a is used in small refrigerators used for storage and preservation of soft drinks, alcoholic drinks, ice cream, etc. In hospitals, R404A is the refrigerant mainly employed while in space conditioning of commercial buildings, R404A is the main refrigerant. R12, R406A and R134a are the refrigerants used in automobile air conditioning.

In summary, the refrigeration industry of Uganda is still relying on synthetic refrigerants i.e. CFCs like R12, HCFCs like R22 and HFCs such as R134a, R404A and R406A. However most of the applications use HFCs with R404A being the dominant refrigerant. Few applications use CFCs and HCFCs while natural refrigerants i.e. ammonia has the least applications.

Table 4.1: Summary of current status of refrigeration in Uganda

<table>
<thead>
<tr>
<th>Sector</th>
<th>Refrigerant</th>
<th>System type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automobile</td>
<td>R12, R22, R134a and R406A</td>
<td>Single stage, vapor compression</td>
</tr>
<tr>
<td>Beer</td>
<td>R717 and R134a</td>
<td>Single stage, vapor compression</td>
</tr>
<tr>
<td>Commercial</td>
<td>R22, R134a, R407C, R410A and R404A</td>
<td>Single stage, vapor compression</td>
</tr>
<tr>
<td>Dairy</td>
<td>R22, R134a and R404A</td>
<td>Single stage, vapor compression</td>
</tr>
<tr>
<td>Fish</td>
<td>R12, R22, R717 and R404A</td>
<td>Single stage, vapor compression</td>
</tr>
<tr>
<td>Health</td>
<td>R134a and R404A</td>
<td>Single stage, vapor compression</td>
</tr>
<tr>
<td>Meat</td>
<td>R134a</td>
<td>Single stage, vapor compression</td>
</tr>
<tr>
<td>Residential</td>
<td>R22 and R134a</td>
<td>Single stage, vapor compression</td>
</tr>
<tr>
<td>Soft drinks</td>
<td>R134a</td>
<td>Single stage, vapor compression</td>
</tr>
</tbody>
</table>
4.2: Develop computer models of installed systems and determine their efficiencies

The application of new system solutions must be verified against existing technologies by theoretical analysis which is an essential step in defining potential advantages, disadvantages and limitations in each solution. Models have been written using EES software which provides numerical solutions to a set of algebraic equations. The results obtained in each sector are presented in this chapter. During modeling the following assumptions were taken;

i) It is assumed that there is no superheating and sub cooling in the systems

ii) It is assumed that the isentropic efficiency of the compressor is 0.7

iii) It is assumed that a throttling process takes place in the expansion device

iv) Changes in kinetic and potential energy are assumed to be negligible

v) The cycle operates under steady state conditions

vi) There is negligible pressure and heat losses/gains between the piping and system components

4.2.1: Fish Industry

The system models generated using EES are as shown below;

![Figure 4.1: Schematic representation of the system](image)

Simulation of the above model yielded the following results;
Explanation

The process is represented on a schematic diagram as shown in Figure 4.1 and the process is drawn on an h-logP diagram as shown on Figure 4.2 above. From the results, the refrigerating capacity of the system is found to be 211.3 kW and the condensing capacity is 296.3 kW with the compressor requiring 85 kW of power for operation, giving a COP of 2.486. The low value of COP can be attributed to a large temperature difference between the evaporation and condensing temperatures, and hence a high pressure ratio.
necessitating a high compressor power requirement. Also, this can also be attributed to the absence of superheating as well as sub cooling in the system. Therefore, the COP of the system can be improved by employing a two stage system and by taking advantage of superheating and sub cooling in the systems. From the plots i.e. Figure 4.3, it can be seen that the COP and volumetric refrigerating effect increase with the evaporation temperature. More results can be found in appendix F where it can also be seen that the condensing capacity and refrigerating capacity also increase with evaporation temperature, while on the other hand, the refrigerant mass flow rate decreases as the evaporation temperature increases. When $T_2$ is increased from -30°C to -5°C, the refrigerating capacity increases by 67% while the condensing capacity increases by 54%, on the other hand, the COP increases by 80%.

4.2.2: Beer, soft drinks and dairy industries

Models of these systems were developed and simulated using EES software and the following results obtained:

![Figure 4.4: Schematic representation of the system](image-url)
Figure 4.5: h-logP diagram for the system

Figure 4.6: Variation of COP with $T_2$ and $q_v$

Explanation
The process is represented on the schematic diagram as shown in Figure 4.4 above and the system is represented on an h-logP diagram as shown in figure 4.5 above. From the simulation results, it can be seen that the refrigerating capacity is 3.079 kW and the condensing capacity is 3.824 kW and the compressor power consumption is 0.745 kW, resulting in a COP of the system of 4.132. The high value of the COP can
be attributed to a lower temperature difference between the evaporator and condenser (<40°C) and hence a lower pressure ratio hence the compression process can be accomplished by a small size of compressor. As was the case with the fish industry model, the plots i.e. Figure 4.6 COP and volumetric refrigerating effect increase with increase in evaporation temperature. Also, the plots indicate that the refrigerating capacity, condensing capacity also increase with the evaporation temperature while on the other hand, the mass flow rate of refrigerant decreases with increase in evaporation temperature (see appendix G). The COP of the system can further be improved by incorporation of superheating and sub cooling in the system. From the plots, it can be seen that when the evaporation temperature is increased from 1 to 10 °C, the refrigerating capacity increases by 40% and the condensing capacity by 35% while the COP increased by 41%.

4.2.3: Meat industry

The EES model for the meat industry was developed and simulated to yield the results shown below;

![Schematic representation of the system](image)

Figure 4.7: Schematic representation of the system
Figure 4.8: h-logP diagram for the process

Figure 4.9: Variation of COP with T₂ and qᵥ
**Explanation**

The model is represented on a schematic diagram in Figure 4.7 and the process is represented on an h-logP diagram as shown on Figure 4.8 above. From the results, the refrigerating capacity of the system is found to be 5.221 kW and the condensing capacity is 7.421 kW with the compressor requiring 2.2 kW of power for operation. The COP of the system is then 2.373. The low value of COP can be attributed to a large temperature difference between the evaporation and condensing temperatures, and hence a high pressure ratio necessitating a high compressor power requirement. Also, this can also be attributed to the absence of superheating as well as sub cooling in the system. Therefore, the COP of the system can be improved by employing a two stage system and by taking advantage of superheating and sub cooling in the systems. From the plots i.e. Figure 4.9, it can be seen that the COP and volumetric refrigerating effect increase with the evaporation temperature. Also, the condensing capacity and refrigerating capacity increase with evaporation temperature, while on the other hand, the refrigerant mass flow rate decreases as the evaporation temperature increases (see appendix H). From the plots, when the evaporation temperature increases from -30°C to -5°C, the refrigerating capacity increases by 77% and the condensing capacity by 54% while the COP increases by 80%.

### 4.2.4: Supermarkets

The EES model for the supermarket chillers has been developed and the results obtained as shown below;

![Figure 4.10: Schematic representation of the system](image-url)
Figure 4.11: h-logP diagram for the process

Figure 4.12: Variation of COP with $T_2$ and $q_v$

For the freezers, the model generated using EES and the results after simulation are shown below;
Figure 4.13: Schematic representation of the system

Figure 4.14: h-logP diagram for the system
The model is represented on a schematic diagram and an h-logP diagram i.e. Figure 4.10 and 4.11 and Figure 4.13 and 4.14 for the chiller and freezer units respectively. For the chiller, the refrigerating capacity is 133.3 kW, condensing capacity is 170.3 kW with a compressor power requirement of 37 kW, and the COP for the chiller unit is 3.603 which is a reasonable value. However, this value can still be improved by taking advantage of superheat and sub cooling in the systems. The plots i.e. Figure 4.12 and Figure 4.15 indicates that the COP and volumetric refrigerating effect increase with increase in evaporation temperature. Also, the refrigerating capacity and condensing capacity increase with evaporation temperature, while the mass flow rate of refrigerant decreases with increase in evaporation temperature (see appendix I).

For the freezer unit, the refrigerating capacity is 94.36 kW, condensing capacity is 137.4 kW and the compressor power requirement is 43 kW resulting into a COP of 2.194. The overall COP of the system was 2.846. The relatively low value of COP can be attributed to the high temperature difference between the heat source and the heat sink resulting into the need for a big compressor and hence low COP. However, it can be improved by use of a multistage system as well as incorporating superheat and sub cooling in the systems. The plots i.e. Figure 4.15 indicate that the COP and volumetric refrigerating effect increase with increase in evaporation temperature. Also, the refrigerating capacity and condensing capacity increase with evaporation temperature, while the mass flow rate of the refrigerant decreases with increase in evaporation temperature (see appendix J).

From the plots, when the evaporation temperature increases from 1°C to 10°C for the chiller unit, the refrigerating capacity increases by 39% while the condensing capacity increases by 67% and the COP by 42%. For the freezer unit, increasing the evaporating temperature from -30°C to -5°C, the refrigerating capacity increases by 71% while the condensing capacity increased by 42% and the COP by 71%.
4.3: Design and recommendation of an appropriate system solution for each sector

This section shows the proposed system solutions for each sector. From the simulation results shown above and the operating conditions for each system, the following environmentally friendly solutions have been proposed:

4.3.1: Fish and Meat industry

In the fish and meat industry, R717 two stage refrigeration with intercooling between compressor stages is deemed more appropriate because of the high temperature lift. Special care should be taken during design and installation due to the flammability and toxicity of the refrigerant.

![Diagram of the system]

Figure 4.16: Schematic representation of the system
Figure 4.17: h-logP diagram for the process
The system is presented on the schematic diagram in figure 4.16 and the h-log P diagram in figure 4.17 respectively. From computer modeling and simulation, the system has a COP of 2.885. The variation of COP with compressor power demand, refrigerant mass flow, evaporation temperature and condensing capacity are presented (see Figure 4.18 and appendix K). The plots show that when the COP increases from 2.5 to 4, the low stage compressor power demand increases by 52% and the high stage compressor increases by 59%, the mass flow rate of refrigerant increases by 2.3% and the evaporation temperature by 87% and the condensing capacity by 8%.

Figure 4.18: Variation of COP with m and T_E
4.3.2: Health sector (hospitals)

The system is presented on a schematic diagram as shown in figure 4.19 above. From the simulation results, it can be seen that with a cooling capacity of 50 kW, the system has a COP of 2.265. This value of COP is a fairly reasonable value and can be further improved taking advantage of superheating and sub cooling in the system and also by incorporating an expander/ vortex/ ejector to reduce the high throttling losses in the R744 circuit.

Figure 4.19: Schematic representation of a cascade system

Figure 4.20: Variation of COP with $T_E$ and $m_r$
Plots of variation of parameters such as mass flow ratio of refrigerant in the high to low stage, heat rejection in the cascade condenser, evaporation temperature and temperature difference in the cascade condenser have been made (see Figure 4.20 and appendix L). From the plots, an increase in the COP from 1.6 to 2.0 increased the mass flow of refrigerant by 8.6%, increased the heat rejection in condenser by 8.4% and a 45% increase in evaporation temperature.

4.3.3: Beer, soft drinks, dairy and residential sectors
In these industries/sectors, R134a coolers available should be retained for the time being since the smaller capacity systems available cannot operate efficiently and safely with natural refrigerants i.e. R717 cannot be used in these systems since it’s difficult to source components for small ammonia systems as well as posing a challenge of high hot gas temperatures after compression since these coolers are normally situated indoors. Also the flammability and toxicity nature of this refrigerant requires that the system components be situated in a well ventilated area and safe considerations should be taken into account during design, installation, operation and maintenance of such systems. Hydrocarbons on the other hand cannot be used due to their high flammability i.e. R717 and HCs would pose a severe health and safety hazard. However, R744 transcritical systems offer a promising solution but the main challenge is redesigning the systems to accommodate the high operating pressures, low critical temperature and high throttling losses in the systems for the systems to be considered reliable and cost effective.

4.3.4: Supermarkets

![Figure 4.21: Schematic representation of cascade system](image)

The system is presented in a schematic diagram as shown in figure 4.21 above. Simulation of the above model yielded a COP of 2.896.
The variation of operating parameters with COP has been presented in the plots shown above. The plots reveal that an increase in COP from 2.7 to 3.0 leads to decrease in mass flow rate of refrigerant in the high temperature circuit by 16% and an increase in mass flow of refrigerant in low temperature circuit by 28%. On the other hand, the same increment in COP leads to a drop in power demand by 58% and 13% in the low stage compressor and high stage compressor respectively as well as a 13% drop in brine pump power consumption (see Figure 4.22 and appendix M).

4.4: Comparison of the systems

From the modeling and simulation results, it can be seen that using an R717 two stage system in the fish and meat industry improved the COP by 16% and 22% respectively therefore an R717 two stage system should be adopted in these sectors for energy and environmental reasons.

In the beer, soft drinks, dairy and residential sectors, R134a coolers (refrigerators) available should be retained for the time being since the smaller capacity systems available cannot operate efficiently and safely with natural refrigerants i.e. R717 cannot be used in these systems because it’s difficult to source components for small ammonia systems as well as posing a challenge of high hot gas temperatures after compression since these coolers are normally situated indoors. Also the flammability and toxicity nature of this refrigerant requires that the system components be situated in a well ventilated area and safety considerations should be taken into account during design, installation, operation and maintenance of such systems. Hydrocarbons on the other hand cannot be used due to their high flammability and since safety requirements compliance is not mandatory especially in residential areas i.e. R717 and HCs would pose a severe health and safety hazard and since the use of even mildly flammable refrigerant requires compliance with safety standards and laws such as building codes and standards for equipment. However, R744 transcritical systems offer a promising solution but the main challenge is redesigning the systems to accommodate the high operating pressures, low critical temperature and high throttling losses in the systems for them to be considered reliable and cost effective.

In commercial refrigeration (supermarkets) and biomedical refrigeration, the R717-R744 cascade refrigeration system offers a promising solution. Using an R717-R744 cascade refrigeration system led to a 12% improvement in the COP, although not a big improvement when compared to the performance of existing
systems (conventional R404A) but with an additional advantage that the utilization of R744 (ODP=0, GWP=1) and R717 (ODP=0, GWP=0) is preferred in the light of more pressing environmental issues since they are natural substances and environmentally benign unlike synthetic refrigerants such as R404A (ODP=0, GWP=3863) and R134a (ODP=0, GWP=1410) currently used for commercial and industrial refrigeration. The R717-R744 cascade refrigeration system gives good safety guarantees since it is possible to confine the high pressure circuit containing R717 within the machine room or well ventilated area that is endowed with all safety devices provided for by the legislative safety standards and the fluid that circulates in the low pressure circuit located indoors (sales area) with human occupants is R744 which is non toxic and non flammable.

Therefore, in commercial refrigeration, with low temperature applications i.e. rapid freezing and storage of frozen products, the use of an R717-R744 cascade refrigeration system to replace conventional systems using R404A is certainly a valid application from an energy, safety and environmental point of view.

In the automobile industry and air conditioning of buildings, R134a should be retained for the time being since it’s more environmentally benign than the other available refrigerants i.e. R12, R22 and R406A. However, more environmentally benign refrigerants for this purpose include R152a and R744. R152a has similar properties like R134a with a GWP of less than 150 but the main challenge is the flammability of this refrigerant. R744 transcritical systems seem to offer a more attractive solution but the system cost, low efficiencies and service issues still pose a huge problem.
5.0: CONCLUSIONS

In this study, the investigation of environmentally friendly solutions in refrigeration applications of Uganda has been carried out. It was found out that synthetic refrigerants dominate the applications and the systems installed are simple vapor compression with single stage compression.

From computer simulation modeling, it has been noted that natural refrigerants offer a better performance than the synthetic refrigerants that they can replace i.e. higher efficiencies coupled with a null environmental burden makes them suitable for the refrigeration applications in Uganda, but the major challenges are safety, system modifications especially in systems that are to use R744, lack of technical expertise to design, install, operate and service the systems as well as failure to have a government policy to spearhead this transition. Therefore for the transition to be realized there is need to come up with legislation concerning the use of environmentally harmful refrigerants most especially the CFCs and HCFCs and penalties should be stipulated for those companies that fail to comply.

The results also show that the COP of the refrigeration systems is affected by parameters such as evaporation temperature, condensing temperature, mass flow rate of the refrigerant and the temperature difference in the heat exchanger in case of cascade systems, and for a given system, it is possible to determine the optimum operating conditions in terms of the above parameters. Simulation results show that an increase in evaporation temperature increases the COP of the system and decreases the mass flow ratios, whereas an increase in the condensing temperature results in a decrease in COP and an increase in refrigerant mass flow ratios. On the other hand, an increase in the temperature difference of the cascade condenser reduces both the COP and mass flow ratios.

Most companies visited had their systems managed by contractors who were external to the company and did not engage any of their staff in the design, installation and maintenance. Secondly, these companies did not have proper records of the system performance making it had to monitor their performance with time. Furthermore, industries/companies in Uganda seem not to appreciate the role of research in national development. Researchers are never attended to and sometimes they are denied access to the facilities or not accorded the necessary assistance required to accomplish their tasks i.e. some information is perceived to be sensitive which further complicates the study. This was evidenced in the beer industry, health sector, dairy and air conditioning.

The application of natural refrigerants in Uganda is very important and is a feasible option and efforts should be directed towards this transition in the next decade in order to save the environment from degradation. This will require strong cooperation from government, industry and academic institutions for this goal to be attained.
6.0: RECOMMENDATIONS

1. Companies need to realize that the synthetic refrigerants they are currently using are environmentally harmful and are bound to be phased out soon since their use is discouraged under the Kyoto and Montreal protocol and should start preparing themselves early enough for the transition from synthetic to natural refrigerants.

2. Companies need to appreciate the role of research towards national development. They should drop the mentality of looking at researchers as a burden but as people who are an asset to them since it’s the companies that benefit from the findings of the research. There is need for strong cooperation between industry and academic institutions.

3. Companies need to start employing technically competent people with a strong background in refrigeration and air conditioning who can best manage the systems and prepare a database of the systems performance so as to easily monitor the performance and for carrying out preventive maintenance on the systems.

4. In the systems currently installed, it is important to employ superheating and sub cooling as a measure of improving the COP. Also, in the design of new systems (in case of adoption), superheating and sub cooling are necessary to consider.

5. The proposed systems seem to offer a better performance when compared to the existing systems from an energy and environmental perspective and should be adopted although performing an economic analysis would give a better justification from an industrial point of view.

6. The Government of Uganda needs to come up with proper legislation to counter the effects synthetic refrigerants on the environment and should carry out regular inspections on the available systems to ensure compliance with the stipulated standards and penalties should be put in place for those companies that fail to comply.

7. The Government of Uganda needs to impose a total ban on the importation of CFCs and HCFCs in the country and needs to come up with a guideline for banning new installations and refilling of existing systems. This should be followed by a higher tax rate for importation of HFC refrigerants in the country.
REFERENCES


7.0 APPENDICES

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Figure 7.2: Fish trucks at Uganda Fish Packers
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Figure 7.5: Recording of measured data

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