الجمهورية الجزائرية الديمقراطية الشعبية

PEOPLE’S DEMOCRATIC REPUBLIC OF ALGERIA

وزارة التعليم العالي والبحث العلمي

Ministry of Higher Education and Scientific Research

جامعة أبي بكر بلقايد – تلمسان –

University Aboubakr Belkaïd– Tlemcen –

Facultyof TECHNOLOGY

DISSERTATION

Submitted in Candidacy for the Degree of MASTER

In: Mechanical Engineering

Speciality: Energetics

By: MANONOSE Owen Tatenda

Subject

Parametric thermo-environmental study of a Vapour Compression Refrigeration System

Board of Examiners:

Pr SAÏM Rachid	University of Tlemcen	President
Dr ALIANE Abd-Ennour	University of Tlemcen	Supervisor
Pr SELADJI Chakib	University of Tlemcen	Examiner

Academic Year: 2020-2021

Table of Contents

ملخص

الهدف من هذه الأطروحة هو إجراء دراسة بيئية حرارية حدودية لنظام تبريد يعمل بضغط البخار. نناقش التكنولوجيا المستخدمة في أنظمة التبريد والتي تحتوي على أنواع مختلفة من المبخرات والضاغطات والمكثفات وصمامات التمدد.

نلقي نظرة على دورة ضغط البخار القياسية والتعديلات المفيدة الممكنة لجعلها أكثر كفاءة وخفض تكاليف التشغيل. تحليل سبع مبردات : R134a؛ R410a؛ R407C؛ R404A؛ R152a و R40.

تم تصميم برنامج لتحديد المبرد الأكثر كفاءة والأكثر احترامًا للبيئة وأيضًا لاكتشاف تلك الأكثر اقتصادا في التشغيل. تعتمد المحاكاة التي تم إجراؤها والنتائج التي تم الحصول عليها على برنامج لحل المعادلات الهندسية EES.

كلمات مفتاحية: تبريد بضغط البخار، مبرِّد، عوامل النجاعة، EES.

Abstract

The aim of this dissertation is to do a parametric thermo-environmental study of a vapour compression system (VCRS). We discuss the technology used in VCRS ranging from different types of evaporators; compressors; condensers and expansion devices. We look at the standard vapour compression cycle and possible beneficial modifications to make it more efficient and reduce cost of operation. Analysis of seven refrigerants which include R134a; R410A; R407C; R404A; R152a; R290 and R40, is done to find which one perform better, more efficient, and to outline the most environmentally friendly and also to find out which ones are the most economic to operate. The simulation done and results obtained are based upon engineering equation solver (EES) software.

Keywords: Vapour Compression Refrigeration, Refrigerant, Performance Parameters, EES

Résumé

L'objectif de cette thèse est de faire une étude paramétrique thermo-environnementale d'un système de réfrigération à compression de vapeur (SRCV). Nous discutons de la technologie utilisée dans un SRCV allant de différents types d'évaporateurs ; compresseurs ; condensateurs et détendeurs. Nous examinons le cycle à compression de vapeur standard et les modifications bénéfiques possibles pour le rendre plus efficace et réduire les coûts d'exploitation. L'étude du système avec sept réfrigérants dont le R134a, R410A, R407C, R404A, R152a, R290 et R40 est faite pour trouver celui qui est le plus performant, le plus efficace, et le plus respectueux de l'environnement et aussi pour découvrir ceux qui sont les plus économiques à exploiter. La simulation effectuée et les résultats obtenus sont basés sur un logiciel de résolution d'équations techniques (EES).

Mots-Clés : Réfrigération à compression de vapeur, Réfrigérant, Paramètres de performance, EES

LIST OF FIGURES

CHAPTER I

CHAPTER II

CHAPTER III

LIST of TABLES

I. General Introduction

The study, invention and development of new methods of preservation of food and drinks and perishables has been going on as long as human beings have been in existence.

Among other methods employed include salting and drying. Fish and animal meat could be stored this way for a considerable period of time and provide food security for the household. The demand for fresh food, fresh meat and fresh milk however meant people were to resort to other methods like icing giving birth to refrigeration. Appreciating the need for technological development, extensive and great efforts are focused, applied and concentrated on the market and the needs of people.

In the domain of refrigeration appreciating the need for sustainable methods is of great importance. Some refrigerants that were once in use have been totally banned and replaced by safer refrigerants.

In as much as it is important to enjoy luxury and comfort, provide more fresh food on the table and benefit financially from the selling refrigeration systems the knowledge of environmental protection is important.

In chapter 1 we will present the state of art of art of cold production of Vapour Compression Refrigeration System (VCRS). We evaluate energy availability, use and demand in refrigeration systems and we evaluate and appreciate advancements in technology, detailing the devices, main components and instruments used in VCRS.

In chapter 2 we will present the fundamental thermodynamics involved in VCRS. We look at the heat exchangers commonly used with their benefits and limitations. We demonstrate an awareness of environmental concerns and impacts of refrigeration systems and ongoing research on refrigerants to minimise or eliminate the global warming problem and ozone depletion.

In chapter 3 we will present the different refrigerants and carry out a parametric thermo-environmental study on their behaviours in relation to temperature changes of the evaporator and condenser. We will also establish conclusions on their efficiencies, cost of operation and environmental friendliness.

Brief history

A brief history timeline of development of refrigeration and air-conditioning:

- In 1823, Michael Faraday discovered that certain gases under constant pressure will condense when they cool.
- In 1834, Jacob Perkins, an American, developed a closed refrigeration system using liquid expansion and then compression to produce cooling.
- In 1842, Florida physician John Gorrie placed a vessel of ammonia atop a stepladder and let the ammonia drip, which then vaporized and produced a cooling effect.
- . In 1858, a French inventor, Ferdinand Carré, developed a mechanical refrigerator using liquid ammonia in a compression machine that produced blocks of ice.
- Sulfur dioxide was also used in the Audiffren-Singrün refrigeration machine patented in 1894 by a French priest and physicist, Father Marcel Audiffren.
- In 1902, Willis Carrier, the "father of air-conditioning," designed a humidity control to accompany a new air-cooling system.
- The Guardian Refrigerator Company developed a refrigerator they called "the Guardian." General Motors purchased Guardian in 1919 and developed the refrigerator they named Frigidaire.
- In 1928, Paul Crosley introduced an absorption-type refrigeration machine so that people could have refrigeration in rural areas where electricity was scarce.
- In 1939, the Copeland Company introduced the first successful semi hermetic (Copelametic) field-serviceable compressor.
- In 1974, two professors from the University of California, Sherwood Rowland and Mario Molina, presented the "ozone theory."
- 1990 (November, United States of America)—President George H. W. Bush signed the Clean Air Act amendments that initiated production freezes and bans on certain refrigerants.
- 1992 (July)—The EPA (Environmental Protection Agency, United States of America) made it against the law to intentionally vent CFC and HCFC refrigerants into the atmosphere.

Refrigeration is a complex topic that covers a wide range of areas. Refrigeration relates to the cooling of substances to:

- preserve and transport food products,
- produce ice,
- aid in the manufacturing of many commercial products, and
- aid in medical research.

In addition, refrigeration plays vital roles in many other industrial, commercial, and residential applications. Air-conditioning, a form of refrigeration, refers to space heating, cooling, dehumidifying, humidifying, air filtering, exhausting, ventilating, and improving overall indoor air quality for those in the occupied space [1].

Chapter I: State of the art of cold production

I.1 Introduction

Refrigerators and Heat Pumps

A refrigerator is a device used to transfer heat from a low- to a high-temperature medium. They are cyclic devices. Figure I.1 shows the schematic of a vapour-compression refrigeration cycle (the most common type). A working fluid called *refrigerant* enters the compressor as a vapour and is compressed to the condenser pressure. The high-temperature refrigerant cools in the condenser by rejecting heat to a high-temperature medium (at T_H). The refrigerant enters the expansion valve as liquid. It is expanded in an expansion valve and its pressure and temperature drop. The refrigerant is a mixture of vapour and liquid at the inlet of the evaporator. It absorbs heat from a low-temperature medium (at T_L) as it flows in the evaporator. The cycle is completed when the refrigerant leaves the evaporator as a vapour and enters the compressor [2].

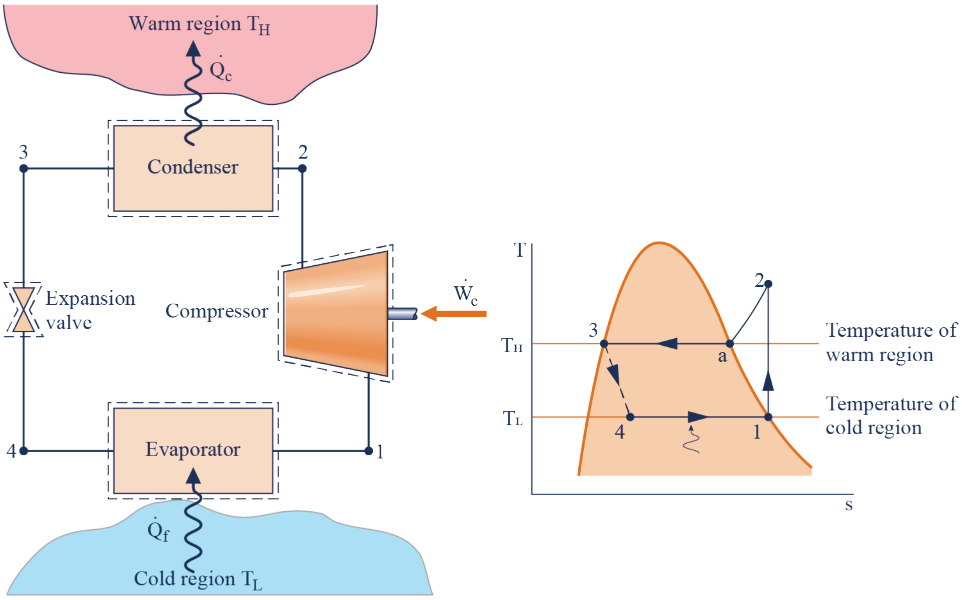


Figure I. 1: Vapour compression refrigeration cycle

I.2 State of the art

Heating Ventilation and Air-conditioning and Refrigeration are very pivotal in our daily lives. Some of the uses and applications include transportation of perishables like milk, storage of meat, food and drinks in supermarkets and home and industry air-conditioning for better working conditioning and comfort. The progress of technology over the years has ensured the research into new methods, analysis and development of more efficient vapour compression refrigeration system.

I.2.1 The First Law of Thermodynamics

It is simply known that thermodynamics is the science of energy and entropy and that the basis of thermodynamics is experimental observation. In thermodynamics, such observations were formed into four basic laws of thermodynamics called the zeroth, first, second, and third laws of thermodynamics. The first and second laws of thermodynamics are the most common tools in practice, because of the fact that transfers and conversions of energy are governed by these two laws, and in this chapter, we focus on these two laws.

The First Law of Thermodynamics (FLT) can be defined as the law of conservation of energy, and it states that energy can be neither created nor destroyed. It can be expressed for a general system as the net change in the total energy of a system during a process is equal to the difference between the total energy entering and the total energy leaving the system [2]:

$$E_{in} - E_{out} = E_{system} \tag{I.1}$$

Based on the appreciation of these laws we can study the refrigeration systems, come up with reasonable results and understand how we can better develop the refrigeration system technology.

I.2.2 Refrigeration System Components

There are several mechanical components required in a refrigeration system. In this part, we discuss the four major components of a system and some auxiliary equipment associated with these major components. These components include condensers, evaporators, compressors, refrigerant lines and piping, refrigerant capacity controls, receivers, and accumulators.

Major components of a vapour-compression refrigeration system are as follows:

- compressor,
- condenser,
- evaporator, and
- throttling device.

In the selection of any component for a refrigeration system, there are a number factors that need to be considered carefully, including:

- maintaining total refrigeration availability while the load varies from 0% to 100%,
- frost control for continuous performance applications,
- variations in the affinity of oil for refrigerant caused by large temperature changes, and oil migration outside the compressor crankcase,
- selection of cooling medium: (i) direct expansion refrigerant, (ii) gravity or pump recirculated or flooded refrigerant, or (iii) secondary coolant (brines, e.g. salt and glycol),
- system efficiency and maintainability,
- type of condenser: air, water or evaporatively cooled,
- compressor design (open, hermetic, semi hermetic motor drive, reciprocating, screw or rotary),
- system type (single stage, single economized, compound or cascade arrangement),
- selection of refrigerant (note that the type of refrigerant is basically chosen based on operating temperature and pressures) [2].

I.2.3 Energy use and availability

Electricity consumption in Africa, on both a total and a per-person basis, is relatively low, but has tremendous growth potential. In 2019, with a population of 1.3 billion people, Africa had nearly four times the population of the United States, and Africa's population is expected to grow to 2.4 billion by 2050. Yet, with an average net electricity generation of about 600 kilowatt-hours (kWh) per person per year—less than 6% of the United States average per person—Africa generated only 804 terawatthours (TWh) of net electricity in 2019, 20% of the United States total that year. [3]

I.2.4 Increase in energy demand

It is true that rapid industrialization has led to unprecedented growth, development and technological advancement across the globe. It has also given rise to several new concerns. Today global warming and ozone layer depletion on the one hand and spiralling oil prices on the other hand have become main challenges. Excessive use of fossil fuels is leading to their sharp diminution and nuclear energy is not out of harm's way. In the face of imminent energy resource crunch there is need for developing thermal systems which are energy efficient. Thermal systems like refrigerators and air conditioners consume large amount of electric power.

So avenues of developing energy efficient refrigeration and air conditioning systems with nature friendly refrigerants need to be explored [4].

I.2.5 The economy and environmental impact of refrigeration

The output of refrigeration systems has been increasing rapidly in recent decades and refrigeration systems become more important for people's daily lives. For example, room air conditioners used in China increased by about 15% per year in the past 10 years, and nowadays the use of air conditioners consumes a lot of electricity, amounting up to 40% of the total electricity consumption in the summer in some cities like Shanghai. Therefore, it is important to make the design process of refrigeration systems more efficient and the product performance better. Computer simulation is one of the valuable means to accomplish this target. The following conventional method is still used for

designing refrigeration systems: to determine the required performance object of a product at first, then to estimate the working conditions, and to calculate the structural parameters at last. This process is very straightforward and quite easy to be understood. However, the actual performance of the product might obviously deviate from the required one because there is no accurate model used in the design process. In order to make the products have the desired performance, the processes of developing prototypes, testing their performance and modifying their structures have to be repeated many times, which will increase the cost and delay the design process.

The requirements for simulation at least include:

(1) stability,

(2) rapidness and

(3) accuracy.

These three requirements may conflict with each other, and then a compromise

has to be made [5].

Refrigeration and air conditioning play a major part in the world economy. In the United Kingdom, it accounts for around 15% of the total electrical energy consumption at a cost of £2500 million per year. The environmental impact of refrigeration systems can be reduced by operation at higher efficiencies and reduction of refrigerant leakage. All refrigeration systems have the potential to leak because pressures in the system are usually many times higher than atmospheric. Loss of refrigerant from industrial and commercial refrigeration systems can occur:

- due to gradual leakage from joints or seals, and can remain undetected for long periods of time, until sufficient refrigerant has been lost to adversely affect the operation of the refrigeration system;
- through catastrophic damage which can occur when mechanical failure such as accidental rapture of a pipe or joint takes place and results in a significant loss of refrigerant charge in a short period of time and
- during servicing when some refrigerant can be accidentally vented to gain access to a section of pipe or a given piece of equipment for repair [6].

I.2.6 Heating ventilation and air-conditioning HVAC load calculations

HVAC load calculations are the foundation upon which the HVAC system design is built. Therefore, it is imperative that the HVAC system designer accurately calculate the peak heating and cooling loads for the project in order to properly design the HVAC system [7].

Same applies for refrigeration systems in order to know the size or type of compressor mathematical calculations and analysis are necessary to minimise money lost in fabrication process.

I.3 Vapor compression refrigeration system VCRS

I.3.1 Why do we use the term "compression"?

The **Vapour Compression Refrigeration Cycle involves four components:** compressor, condenser, expansion valve/throttle valve and evaporator. It is a compression process, whose aim is to raise the refrigerant pressure, as it flows from an evaporator. The high-pressure refrigerant flows through a condenser/heat exchanger before attaining the initial low pressure and going back to the evaporator [8].

Advantages

The advantages of vapour compression refrigerator are its

1. capability of removing large quantities of heat with a small mass flow of refrigerant,
2. high efficiency, arguably one of the most efficient refrigeration systems at the macroscale, producing high COP, and
3. the capability of achieving sub-ambient temperature without injecting additional pumping energy at the cold junction that too must be removed

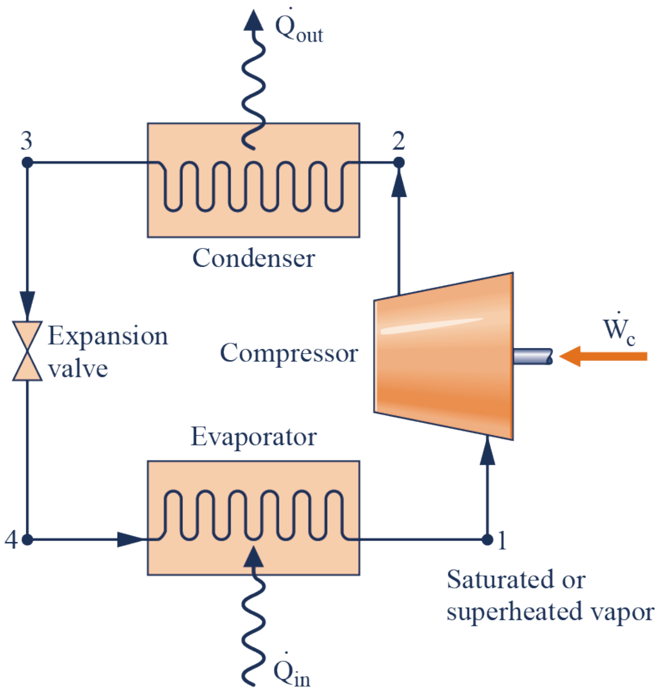


Figure I. 2: Components of a vapor-compression refrigeration system

Disadvantages

Unfortunately, vapour compression refrigerators typically perform less efficiently as their sizes become smaller [9].

I.3.2 The evaporator

The evaporator in a refrigeration system is responsible for absorbing heat into the system from whatever medium is to be cooled. This heat- absorbing process is accomplished by maintaining the evaporator coil at a lower temperature than the medium to be cooled.

I.3.2.1 Types of evaporators

a. Bare pipe evaporator

Numerous types of evaporators are available, and each has its purpose. The first evaporators for cooling air were of the natural- convection type. They were actually bare pipe evaporators with refrigerant circulating through them, **Figure I.3**. This evaporator was used in early walk-in coolers and was mounted high in the ceiling. It relied on the air being cooled, falling to the floor, and setting up a natural air current [1].

b. Forced-draft evaporator

Design trends in the industry have always been toward smaller, more efficient equipment, *Figure 4* [1].

c. Stamped evaporator

The *stamped evaporator* was one of the first designs to create a large pipe surface. It consisted of two pieces of metal stamped with the impression of a pipe passage through it, *Figure I.5* [1].

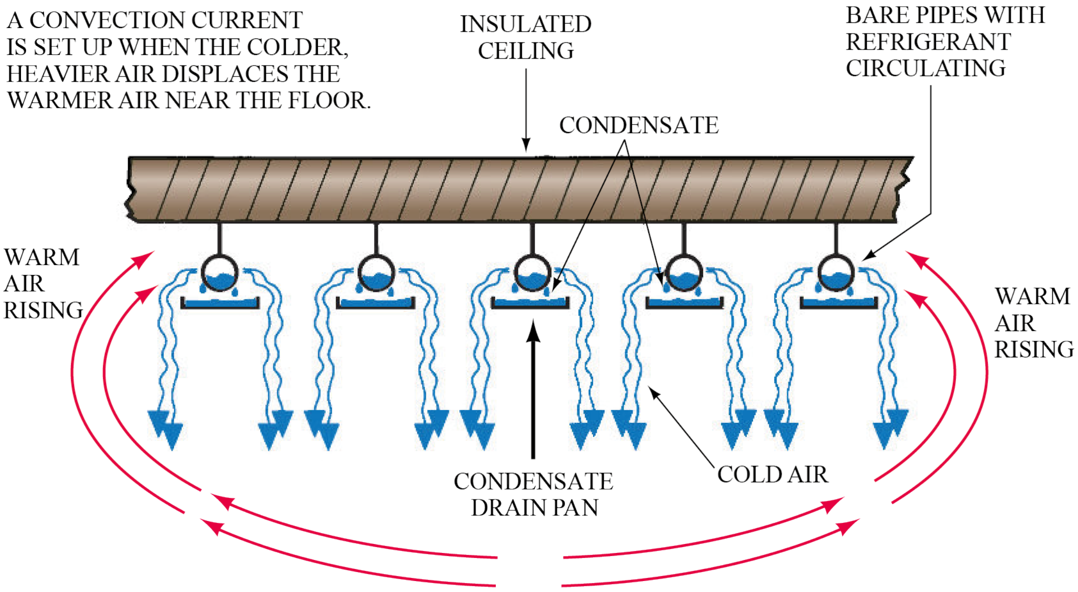
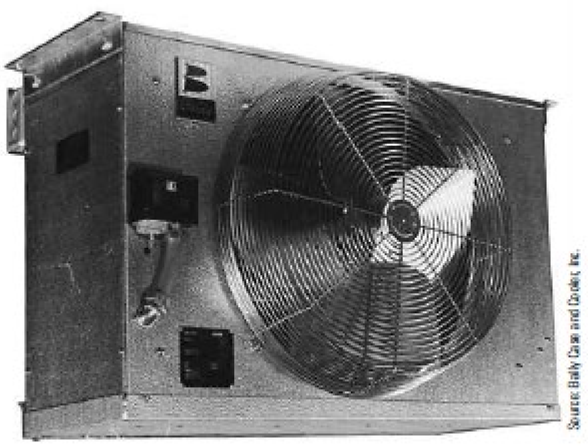
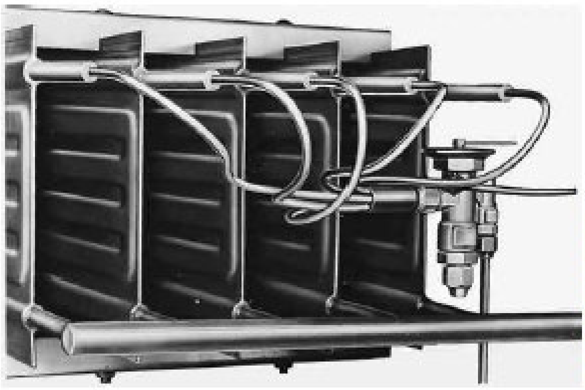


Figure I. 3: Bare pipe evaporator



Source: Bally Case and Cooler, Inc.

Figure I. 4: Forced-draft evaporator



Courtesy Sporlan Valve Company

Figure I. 5: Stamped evaporator

Courtesy Ferris State University Photo by John Tomczyk

Figure I. 6: A finned-tube evaporator for a medium-temperature

d. Finned-tube evaporator

A pipe with fins attached, called a *finned- tube evaporator*, is today used more than any other type of heat exchanger between air and refrigerant. This heat exchanger is efficient because the fins are in good contact with the pipe carrying the refrigerant. Figure I.6 shows an example of a finned- tube evaporator.

I.3.3 The condenser

The condenser is a heat exchange device similar to the evaporator; it rejects from the system the heat absorbed by the evaporator. In the first passes of the condenser the heat is rejected from a hot, superheated vapour. The middle of the

condenser rejects latent heat from saturated vapour and liquid, which is in the process of changing phase to a 100% saturated liquid. The last passes of the condenser reject heat from subcooled liquid. This further sub-cools the liquid to below its condensing temperature. In fact, the condenser performs three main functions on the refrigerant flowing through it.

They are in order of occurrence:

1. Desuperheating the vapours
2. Condensing vapours to liquid
3. Subcooling the liquid

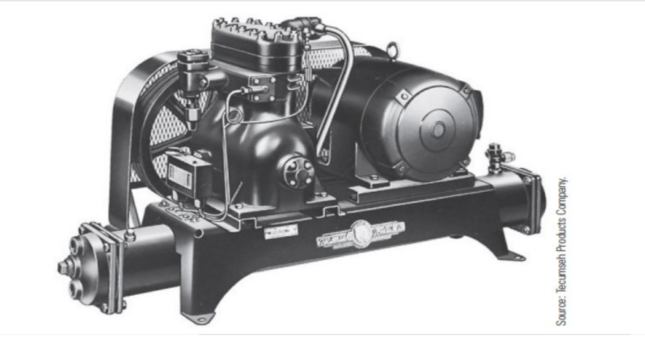
The greatest amount of heat is absorbed in the system when the refrigerant is at the point of changing state (liquid to a vapour). The same thing happens, in reverse, in the condenser. The point where the change of state (vapour to a liquid) occurs is where the greatest amount of heat is rejected. The condenser operates at higher pressures and temperatures than the evaporator and is often located outside. The same principles apply to heat exchange in the condenser as in the evaporator. The materials a condenser is made of and the medium used to transfer heat make a difference in the efficiency of the heat exchanger.

Types of condensers

I.3.3.1 Water-cooled condenser

The first commercial refrigeration condensers were water-cooled. Compared with modern water-cooled devices, these condensers were crude, Figure I.8**.** Water-cooled condensers can operate at much lower condensing temperatures. Because water has a higher specific heat and density than air, water-cooled condensers are more efficient than air-cooled condensers. Water-cooled equipment comes in several styles.

Three of the most common are the tube within a tube (double tube), shell and coil, and shell and tube.



Source: Tecumseh Products Company.

Figure I. 7: an early water-cooled condensing unit

I.3.3.2 Tube-within-a-tube condenser [1]

The tube-within-a-tube condenser comes in two styles: the coil type and the cleanable type with flanged ends, **Figure I.10.** The HVAC/R industry refers to these condensers as tube within a tube, double tube, and co-axial. The tube within a tube that is fabricated into a coil is manufactured by slipping one pipe inside another and sealing the ends in such a manner that the outer tube becomes one container and the inner tube becomes another container.

The flanged condenser can be cleaned by removing the flanges. Removal of the flanges opens only the water circuit, not the refrigerant circuit.

I.3.4 Compressors

A compressor is one of the four essential components of the basic vapour compression refrigeration system; the others are the condenser, evaporator, and expansion device. The compressor circulates refrigerant through the system and increases refrigerant vapour pressure to create the pressure differential between the condenser and evaporator. The chapter describes the design features of several categories of commercially available refrigerant compressors. There are two broad categories of compressors: positive displacement and dynamic.

Positive-displacement compressors increase refrigerant vapour pressure by reducing the volume of the compression chamber through work applied to the compressor's mechanism. Positive-displacement compressors include many styles of compressors currently in use, such as reciprocating, rotary (rolling piston, rotary vane, single screw, twin screw), and orbital (scroll, trochoidal).

Dynamic compressors increase refrigerant vapour pressure by continuous transfer of kinetic energy from the rotating member to the vapour, followed by conversion of the energy into a pressure rise. Centrifugal compressors function based on these principles [10].

Source: Noranda Metal Industries, Inc.

Figure I. 8: A pipe within a pipe condenser

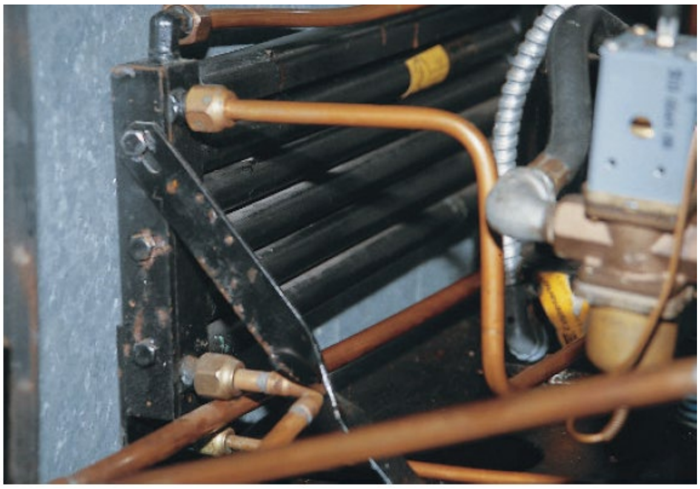


Figure I. 9: A flanged condenser

Courtesy Copeland Corporation

Figure I. 10: Reciprocating compressor

The amount of gas pumped by the compressor will always be less than the physical displacement of the pistons in the cylinders. Volumetric efficiency (VE) accounts for all the losses affecting the flow rate of the compressor [11].

Types of compressors

Five major types of compressors are used in the refrigeration and air-conditioning industry. These are the reciprocating, screw, rotary, scroll, and centrifugal [1].

I.3.4.1 Reciprocating compressor

Reciprocating compressors are positive displacement machines and are among the most widely used compressors because of their range of sizes and designs. Reciprocating compressors range from fractional tonnage units to hundreds of tons of refrigeration capacity in a single unit.

Reciprocating compressors are generally classified according to type of drive, motor accessibility, type of piston, number and arrangement of cylinders, valve construction, method of lubrication, and capacity control [12].

I.3.4.2 Rotary compressors

Rotary compressors are also positive displacement machines but because of the rotary motion of their compressing mechanism, they operate smoother than reciprocating compressors. The three general designs of rotary compression mechanisms in common use today are the rolling piston, the rotating vane, and the screw type [12].

Figure I. 11: Rotary compressor

I.3.4.3 Screw compressor

The other type of rotary compressor is the screw compressor, which is generally used on systems 50 tons or larger. This type of compressor uses two helically grooved rotors to compress the refrigerant vapour. The rotors intermesh to progressively reduce the space inside the cylinder and reduce the volume of refrigerant vapour and increase its pressure. As the rotors turn, vapour from an inlet port at the suction end of the screw cylinder enters the space between the rotors. The rotors continue to turn and close off the suction port. The screw action then forces the vapour to the discharge end and compresses it against a discharge plate. At a given point, the rotating screws uncover discharge ports in the discharge plate and the compressed vapour is forced out into the discharge line. Capacity control on the screw compressor is done by a slide valve in the housing wall underneath the rotors. The slide valve is hydraulically operated. When the system calls for a slowing of the refrigeration process the valve is opened allowing some vapour to recirculate in the cylinder without being compressed [12].

I.3.4.4 Centrifugal compressor

Centrifugal compressors are high-capacity machines moving large volumes of vapour and can't be economically built for small capacity systems. A positive displacement compressor is usually more economical below 100 tons. The centrifugal compressors used in HVAC refrigeration start about 80 tons and go to several thousand tons. The larger the capacity the more advantageous the centrifugal compressor becomes. Centrifugal compressors, centrifugal fans and centrifugal pumps are all members of the same family of machines where the pumping force is based on impeller size (wheel size for fans) and rotating speed [12].

I.3.4.5 Scroll compressor

The concept of compressing a gas by turning one scroll against another around a common axis isn't new. Scroll compressor technology has been around for 100 years, but it did not become commercially available and cost-effective until the mid 1980s. Today, it is becoming even more fine-tuned and is available in many more applications [1].

I.3.5 Expansion device

The **expansion device**, often called the metering device, is the fourth component necessary for the compression refrigeration cycle to function. The expansion device is not as visible as the evaporator, the condenser, or the compressor. Generally, it is concealed inside the evaporator cabinet and not obvious to the casual observer. The device can be either a valve or a fixed-bore [1].

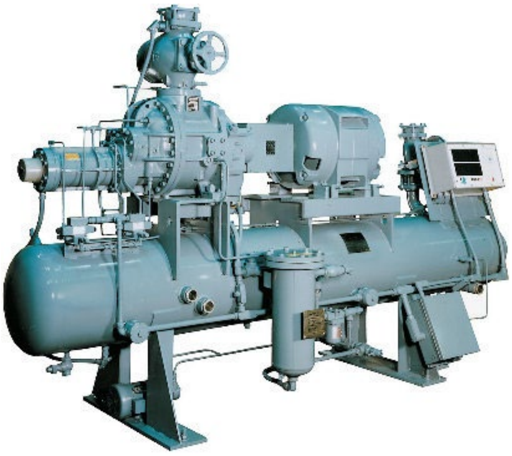


Figure I. 12: Screw compressor

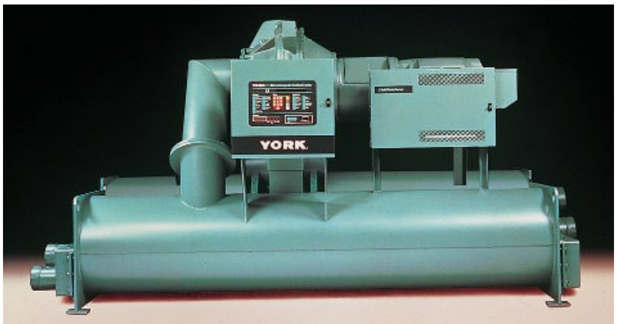


Figure I. 13: Centrifugal compressor

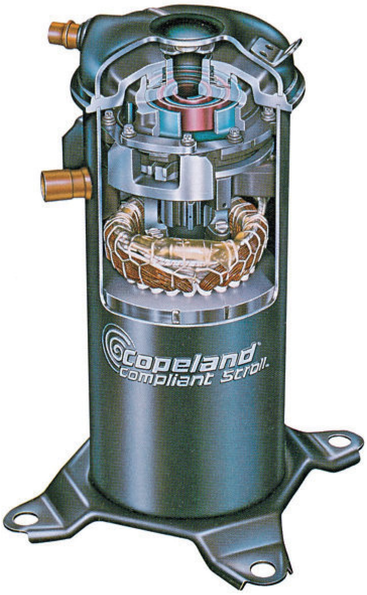


Figure I. 14: Scroll compressor

(A) (B) (C)

Figure I. 15: Three metering devices. (A) Thermostatic expansion valve. (B) Automatic expansion valve. (C) Capillary tube with liquid-line drier.

I.4 Conclusion

We research and find out the energy availability differences between the developed world like China, USA and Europe, and Africa is very huge. Much work needs to be done in Africa to harness the enormous energy potential and bring it to fruition. Energy demand and in refrigeration is one of the highest taking about 20% of the overall energy use in both industrial and domestic uses. We hope that more research development and advancement in technology will bring more efficient devices and instruments.

The different types of compressors, evaporators, condensers and expansion devices have been developed and realised to suit different uses and purposes. With more progress we are bound to realise more advanced refrigeration in the near future.

Chapter II: Thermodynamics of mechanical vapour compression refrigeration

II.1 Introduction

Temperature can be thought of as a description of the level of heat and also may be referred to as heat intensity. Heat level and heat intensity should not be confused with the amount of heat, or heat content. As a substance receives more heat, its molecular motion, and therefore its temperature, increases [1].

Many gases at low pressure, that is atmospheric pressure and below for water vapour and up to several bar for gases such as nitrogen, oxygen and argon, obey simple relations between their pressure, volume and temperature, with sufficient accuracy for engineering purposes.

II.1.1 The Carnot Refrigeration Cycle

The Carnot cycle is a theoretical model that is useful for understanding a refrigeration cycle.

As known from thermodynamics, the Carnot cycle is a model cycle for a *heat engine* where the addition of heat energy to the engine produces work. In some applications, the Carnot refrigeration cycle is known as the *reversed Carnot cycle* (Figure II.1). The maximum theoretical performance can be calculated, establishing criteria against which real refrigeration cycles can be compared [2].

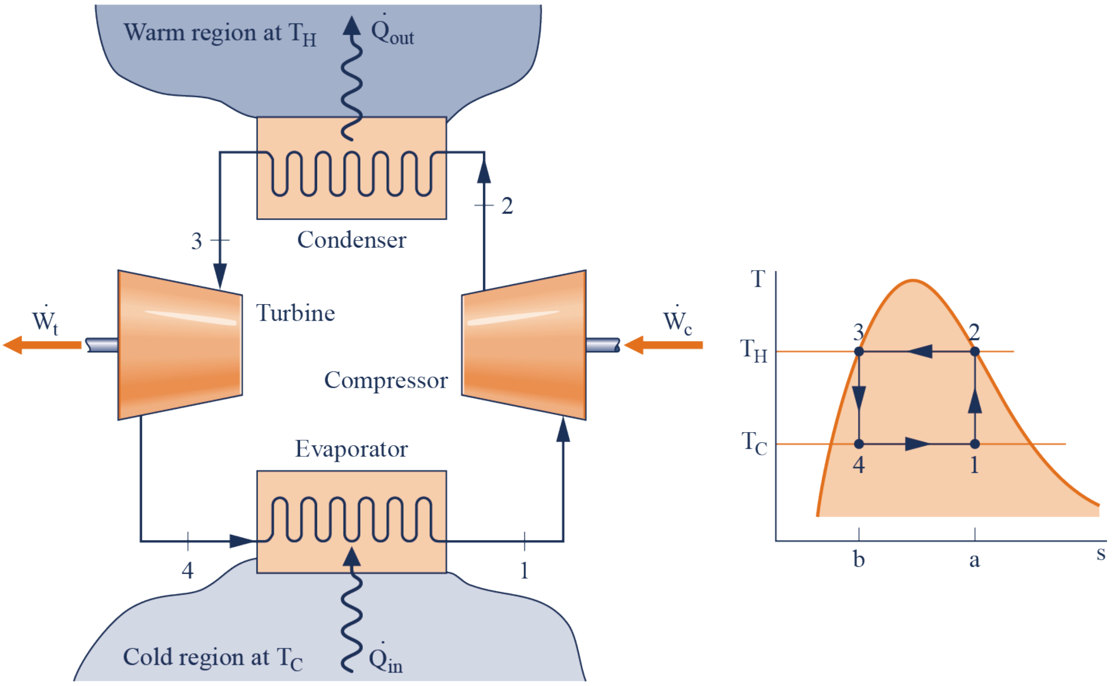


Figure II. 1 : T-s diagram of the Carnot refrigeration cycle

The following processes take place in the Carnot refrigeration cycle as shown on a temperature–entropy diagram in Figure II.1:

- (1–2) is the ideal compression at constant entropy, and work input is required. The temperature of the refrigerant increases.
- (2–3) is the rejection of heat in the condenser at a constant condensation temperature, T_H.
- (3–4) is the ideal expansion at constant entropy. The temperature of the refrigerant decreases.
- (4–1) is the absorption of heat in the evaporator at a constant evaporation temperature, T_L.

The refrigeration effect is represented as the area under the process line 4-1, as follows:

$$Q_L = T_L(s_1 - s_4) \tag{II.1}$$

The theoretical work input (e.g., compressor work) for the cycle is represented as the area within the cycle line 1–2–3–4–1, as follows:

$$w = (T_H - T_L)(s_1 - s_4) \tag{II.2}$$

The heat rejection rate during the process 2-3 in the condenser is

$$P_{23} = q_m\left(h_2 - h_3\right) \tag{II.3}$$

where q_m is the steady mass flow rate of the refrigerant. The fluid enthalpies at the entrance and exit are h_2 and h_3 respectively.

The heat absorption rate during the process 4-1 in the evaporator is:

$$P_{41} = q_m\left(h_4 - h_1\right) \tag{II.4}$$

The fluid enthalpies at the entrance and exit are h_4 and h_1 respectively.

Applying the energy balance equation to the cycle, the network input is:

$$P_{net} = P_{23} - P_{41} \tag{II.5}$$

The coefficient of performance of the *refrigeration* cycle 1-2-3-4, the purpose of which is to absorb heat from the *cold* region, is given by

$$COP_{ref} = \frac{P_{41}}{P_{net}} \tag{II.6}$$

If the main purpose of the cycle is to supply heat to the hot region, then the cycle 1-2-3-4 is called a *Carnot heat pump* cycle and its coefficient of performance is given by:

$$COP_{hp} = \frac{P_{23}}{P_{net}} \tag{II.7}$$

II.2 Standard Vapour Compression Cycle

The construction of a practical refrigerating plant operating on the Carnot refrigeration cycle with a vapour as the working fluid has been hampered by a number of practical difficulties.

In the case of a reciprocating compressor, liquid refrigerant may get trapped in the space between the head of the piston and the cylinder head, causing valve damage. Ideally, there should only be dry vapour at the end of the compression process. But this may not be the case in practice because droplet evaporation requires a finite time. Moreover, lubricant from the walls of the cylinder may be carried away by liquid refrigerant, accelerating wear. Due to these reasons, the compression process in actual refrigeration plants is carried out in the *dry* vapour region [13].

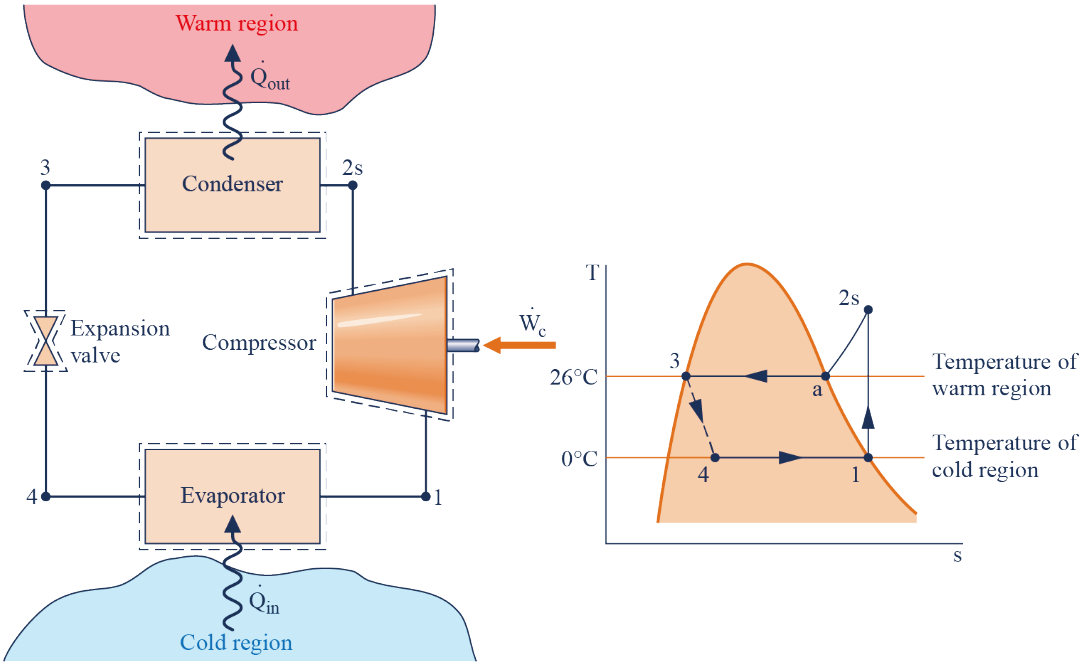


Figure II. 2: Ideal Vapor-Compression Refrigeration Cycle

In the Carnot refrigeration cycle, the expansion process 3-4 occurs isentropically in the vapour-liquid mixture region. It is difficult to implement this process practically because of the effects of droplets, and the carryover of the lubricant. Also, the work output of the expander or turbine is only a small fraction of the work required by the compressor. For these reasons the expansion of the working fluid from the condenser pressure to the evaporator pressure is carried out in an *expansion valve*. Ideally, the enthalpy of the refrigerant is constant during this irreversible throttling process. We have indicated the expansion process by a broken line 3-4 in the *T-s* diagram. The increase in fluid entropy during 3-4 is due to the irreversible nature of the expansion process. Most practical refrigeration systems operate on the modified cycle 1-2-3-4, shown in Fig. II.3, called the *actual vapour compression* cycle [13].

II.2.1 Analysis of the Standard Vapour Compression Cycle

Consider the vapour compression cycle shown in Fig. 20. Apply the steady flow energy equation to each of the processes, neglecting the kinetic and potential energy of the fluid.

The *heat rejection rate* in the condenser during process, 2s-3 is:

$$P_{2s3} = q_m(h_{2s} - h_3) \tag{II.8}$$

where q_m is the steady mass flow rate of the refrigerant [13].

II.2.2 Actual Vapour Compression Cycle

There are a number of differences between the *standard* vapour compression cycle, 1-2s-3-4, and the *actual* cycle 1-2-3-4, shown on the *T-s* diagram in Fig. II.3. Some of these differences are due to practical reasons while others are intentional. The fluid pressure drops in the condenser and the evaporator are unavoidable. These pressure drops increase the overall pressure difference across the compressor, which in turn, increases the required work input to the compressor.

In the standard cycle, the liquid entering the expansion valve at 3 is just saturated. In actual practice, however, subcooling the liquid slightly is found to be advantageous. In the case of the common form of expansion valve, known as the *capillary tube*, the presence of any vapour at the entrance to the tube could cause flow blockage. Subcooling ensures that only liquid enters the expansion valve. It is also desirable to slightly superheat the vapour to ensure that no liquid drops are present in the vapour entering the compressor. In some practical refrigeration systems superheating of the vapour is carried out in a counter-flow heat exchanger using the saturated liquid leaving the condenser. The liquid leaving the heat exchanger is subcooled.

The compression process in the actual cycle is not isentropic as assumed in the standard cycle. This difference could be readily accounted for by defining the *isentropic efficiency* of the compressor as the ratio of the isentropic work input to the actual work input [13].

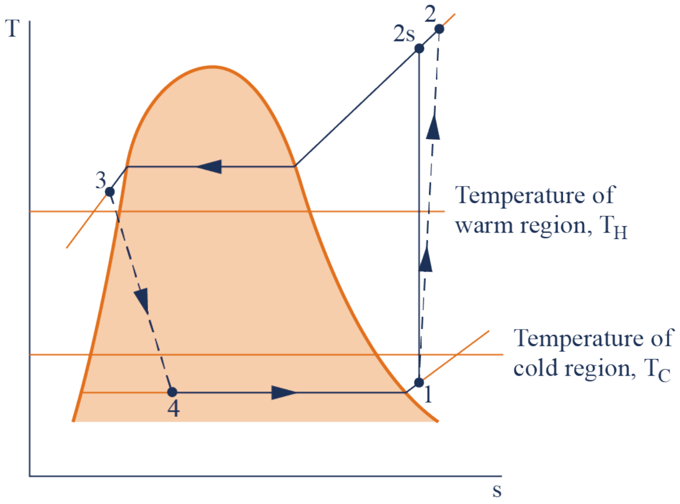


Figure II. 3: T–s diagram of an actual vapor-compression cycle

The differences between the standard cycle and the actual cycle mentioned above, relate mainly to the *internal* processes of the vapour compression cycle. There are also two important *external* factors that affect the performance of the actual refrigeration cycle. For the refrigerant to absorb heat from the cold space in the evaporator, and to reject heat to a heat sink in the condenser, there has to be finite temperature differences. These temperature differences constitute external irreversibilities, and they lower the COP of the actual cycle in comparison to the standard cycle.

II.3 Modifications to the Standard Vapour Compression Cycle

The standard vapour compression refrigeration cycle functions efficiently when the evaporating temperatures are relatively high. However, when the evaporator temperature is lowered, the required compressor power input increases significantly. Consequently, the COP of the cycle decreases. Furthermore, as the evaporator temperature is lowered, the compressor displacement, which is proportional to the size of the compressor, and the discharge temperature, increase. Multi-stage compression with inter-cooling can mitigate some of these detrimental effects at low evaporator temperatures [13].

II.3.1 Two-stage compression with flash inter-cooling

A modified vapour compression cycle with two-stage compression and flash inter-cooling is shown schematically and the *T-s* diagram of the cycle is depicted in Figure II.4 [14].

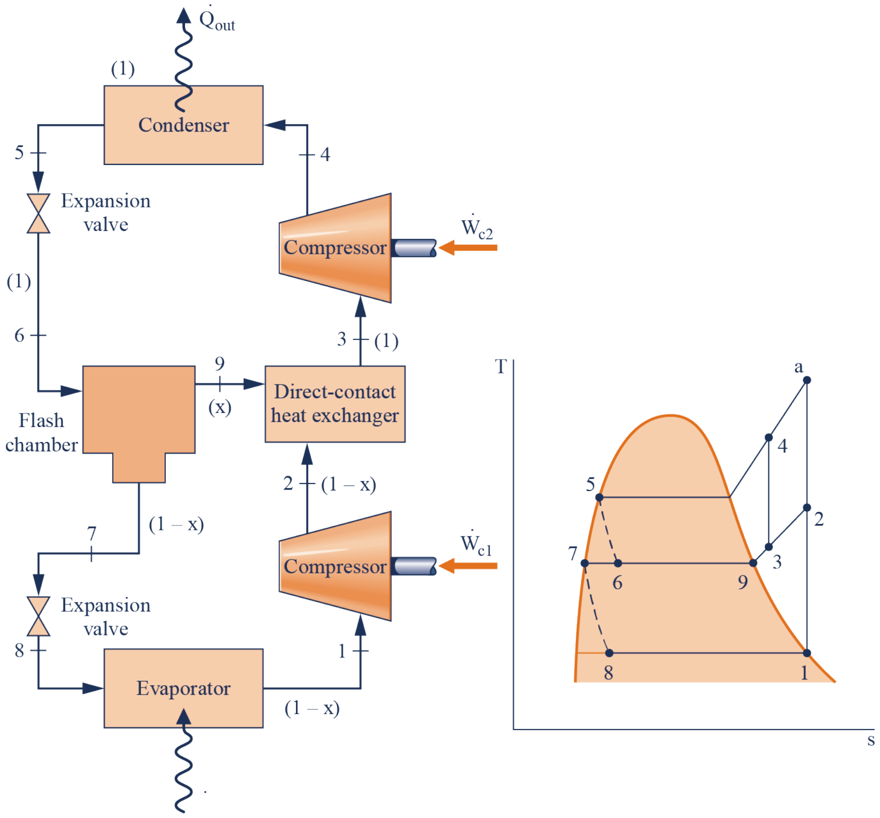


Figure II. 4: Figure II.4: Two-stage compression with flash inter-cooling cycle

II.3.2 The Combined Cycle

Some valuable modifications that could be carried out on a vapour compression cycle (VCC) to demonstrate an environmental awareness and appreciate the need to reduce operational costs of the refrigeration system is the use of a combined cycle.

Figure II.5 shows the arrangement of the combined cycle. It consists of an ejector refrigeration sub-cycle (ERSC) and a vapour compression sub-cycle (VCSC) as illustrated in Fig.II.5. In the ERSC, water is used as the refrigerant. The use of water has an obvious cost advantage. The VCSC uses HFC-134a, since this refrigerant has small specific volume at normal evaporator temperatures, and therefore, its use reduces the size and cost of the compressor. Furthermore, Hz0 and HFC- 134a conform to all foreseeable ozone preserving regulations. The connection between the two sub-cycles is at the intercooler, which serves as the “evaporator” for the ERSC and as the “condenser” for the VCSC. Its working temperature Ti is set between the condenser temperature T_C, and the evaporator temperature T_E, of the combined cycle [14].

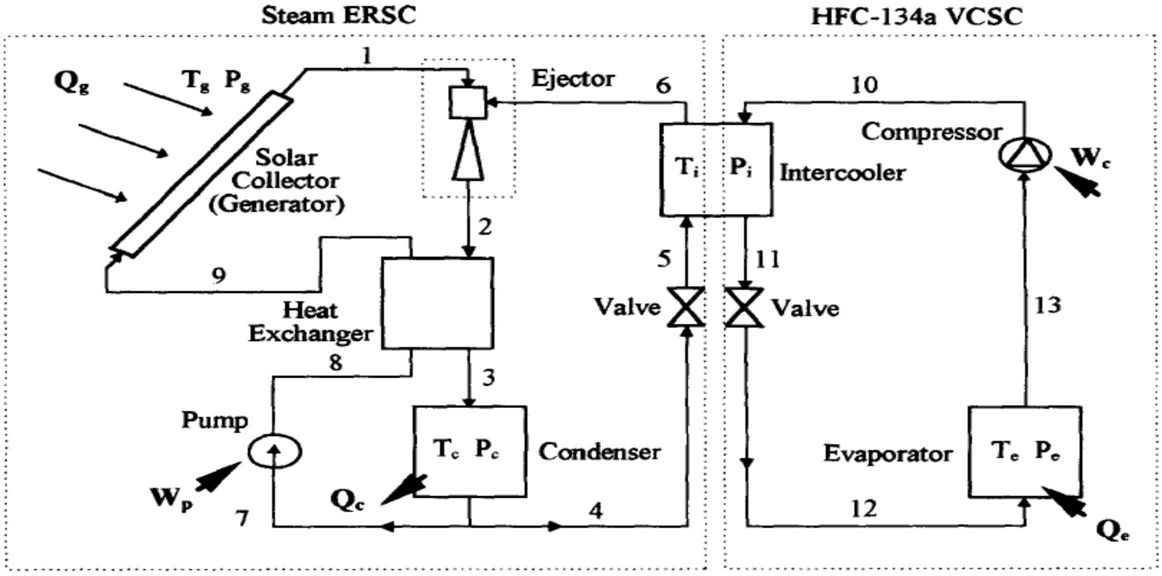


Figure II. 5: The combined cycle

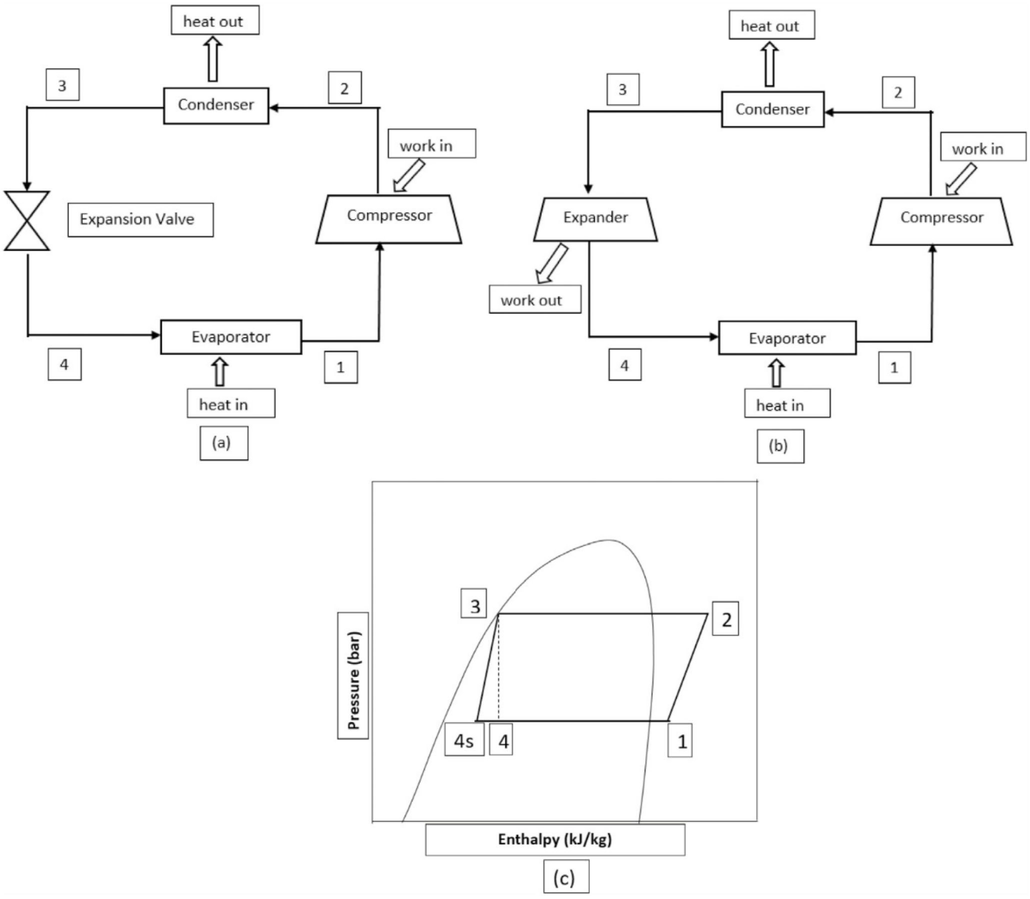


Figure II. 6: Schematics and idealized pressure-enthalpy diagrams of a vapour compression refrigeration cycle

II.3.3 Expanders and their performance in vapour compression refrigeration systems.

An expander can be thought of as a compressor operating in reverse. It takes in high-pressure fluid and expands the fluid gradually to a lower pressure to produce energy. The energy is typically in the form of torque, which can be used to reduce the load of the compressor motor or to generate electricity through a generator. The concept of using one in a refrigeration system dates from the early 1900s and they are sometimes mentioned in basic thermodynamic textbooks, but their use has usually not been considered to make economic sense (Horst, 1911). They were considered more seriously with the introduction of the CO_2 transcritical refrigeration cycle, which suffers a large throttling loss due to the extremely large operating pressure difference (Lorentzen & Pettersen, 1993; Lorentzen, 1994). Since then, the concept has gained more attention. This is visible in recent refrigeration and compressor conferences, where there have been an increasing number of presentations on expanders.

[15]

II.4 Environmental concerns

II.4.1 Refrigerant Issues

A refrigerant is any chemical compound that is capable of going through phase changes in order to absorb or release heat. Early refrigerants, developed in the 1920s and 1930s for use in vapour compression cycle refrigeration applications (e.g., R-11, R-12, and R-503), were predominately chemical compounds made up of *chlorofluorocarbons* (CFCs). While stable and efficient in the range of temperatures and pressures required for heating, ventilating, and air-conditioning (HVAC) use, any escaped refrigerant gas was found to be long-lived in the atmosphere. In the lower atmosphere, the CFC molecules absorb infrared radiation and, thus, contribute to atmospheric warming. Once in the upper atmosphere, the CFC molecule breaks down to release chlorine that destroys ozone and, consequently, damages the atmospheric ozone layer that protects the earth from excess ultraviolet (UV) radiation. The manufacture of CFC refrigerants in the United States and most other industrialized nations was eliminated by international agreement in 1996. Researchers found that modifying the chemical compound of CFCs by substituting a hydrogen atom for one or more of the chlorine or fluorine atoms resulted in a significant reduction in the life of the molecule, thereby reducing the negative environmental impact it may have. These new compounds, called *hydrochlorofluorocarbons* (HCFCs), were used in HVAC refrigeration systems such as R-22 and R-123. While HCFCs have reduced the potential environmental damage by refrigerants released into the atmosphere, the potential for damage has not been totally eliminated. Again, under international agreement, this class of refrigerants is slated for phase-out for new equipment installations by 2020, with total halt to manufacturing and importing mandated by 2030/2040, as summarized in Table II.1. A third class of refrigerants, *hydrofluorocarbons* (HFCs), are not regulated by international treaty, are considered, at least for the interim, to be the most environmentally benign compounds, and are now widely used in HVAC refrigeration systems. However, HFCs can contribute to increased greenhouse gas levels, and both the Kyoto Protocol (1997) and the Paris Agreement (2016) call for reducing use of these refrigerants. HVAC refrigeration equipment has undergone a transition in the use of non-HCFC refrigerants, including R-410A, R-407C, and R-134A, and further transitions are expected as the search for an environmental benign refrigerant continues [31].

II.4.2 Tackling global warming problem due to refrigerants

Table II. 1: Implementation of HCFC Refrigerant Phaseout in the United States

January of year	PHASEOUT OF HCFC-22	PHASEOUT OF HCFC-123
2020	All production/import of HCFC-22stops. Significant recycling required to provide refrigerant for servicing	Refrigerant production reduced to 0.5% of1989 level end of new equipment usingHCFC-123. Significant recycling required to provide refrigerant for servicing.
2030	By this date, it is anticipated that noHCFC-22 equipment will remain in-service.	All production/import of HCFC-123 stops. Significant recycling required to provide refrigerant for servicing
2040	Not applicable.	By this date, it is anticipated that no HCFC-123 equipment will remain in service.

When an evaporator-heat exchanger assembly develops a refrigerant leak and the compressor has operated after the refrigerant escaped, air and moisture have

entered the system. To protect the system, it must be flushed with liquid refrigerant and evacuated. Proper procedure must be followed to make sure the

flushing refrigerant does not escape into the atmosphere [32].

Great caution should be exercised in objects or instruments used and how they are used during manual defrosting of household refrigerators in order not to cause any damage to the evaporator loop which may result in leak of refrigerant into the atmosphere. Sharp objects like knives should never be used**.**

Recently, the ozone depleting potential (ODP) and global warming potential (GWP) have become the most important criteria in the development of new refrigerants apart from the refrigerant CFCs and HCFCs, both of which have high ODP and GWP, due to the their contribution to ozone layer depletion and global warming. In spite of their high GWP, alternatives to refrigerant CFCs and HCFCs such as hydro fluorocarbon (HFC) refrigerants with their zero ODP have been preferred for use in many industrial and domestic applications intensively for a decade. HFC refrigerants also have suitable specifications such as non-flammability, stability, and similar vapour pressure to the refrigerant CFCs and HCFCs. The problems of the depletion of ozone layer and increase in global warming caused scientists to investigate more environmentally friendly refrigerants than HFC refrigerants for the protection of the environment such as hydrocarbon (HC) refrigerants of propane, isobutene, n-butane, or hydrocarbon mixtures as working fluids in refrigeration and air-conditioning systems. Although HC refrigerants have highly flammable characteristics (A3) according to the standards of ASHRAE as a negative specification, they have not only several preferable specifications such as zero ozone depletion potential, very low global warming, non-toxicity, and higher performance than other refrigerant types but also high miscibility with mineral oil and good accordance with the existing refrigerating systems. They are used in many applications with attention being paid to safety of the leakage from the system as for other refrigerants in recent years [33].

II.4.2.1 The nanofluids

Thermal systems like refrigerators and air conditioners consume large amount of electric power. So, avenues of developing energy efficient refrigeration and air conditioning systems with nature friendly refrigerants need to be explored. The rapid advances in nanotechnology have led to emerging of new generation heat transfer fluids called nanofluids. Nanofluids are prepared by suspending nanosized particles (1-100nm) in conventional fluids and have higher thermal conductivity than the base fluids. Nanofluids have the following characteristics compared to the normal solid liquid suspensions.

- higher heat transfer between the particles and fluids due to the high surface area of the particles
- better dispersion stability with predominant Brownian motion
- reduces particle clogging

- reduced pumping power as compared to base fluid to obtain equivalent heat transfer.

Based on the applications, nanoparticles are currently made out of a very wide variety of materials, the most common of the new generation of nanoparticles being ceramics, which are best split into metal oxide ceramics, such as titanium, zinc, aluminium and iron oxides, to name a prominent few and silicate nanoparticle, generally in the form of nanoscale flakes of clay. Addition of nanoparticles changes the boiling characteristics of the base fluids. Nanoparticles can be used in refrigeration systems because of its remarkable improvement in thermophysical and heat transfer capabilities to enhance the performance of refrigeration systems. In a vapour compression refrigeration system, the nanoparticles can be added to the lubricant (compressor oil) [4].

II.4.3 Refrigerant Mixtures

Theory of refrigerant mixtures

The use of refrigerant mixtures is becoming of great interest due to the phase-out of pure halogenated refrigerants. Very limited pure fluids are having suitable properties to provide alternatives to the existing halogenated refrigerants. The mixing of two or more refrigerants provides an opportunity to adjust the properties, which are most desirable. The three categories of mixtures used in refrigeration and air conditioning applications are azeotropes, near azeotropesand zeotropes [34].

II.4.4 Technical difficulties with mixed refrigerants

Very few pure refrigerants have properties closer to the existing halogenated refrigerants. Refrigerant mixtures are the only choice to replace the halogenated refrigerants. However, the refrigerant mixtures are having following technical difficulties to replace the existing pure halogenated refrigerants.

- Zeotropic refrigerant mixtures are having high temperature glide due to the difference in boiling point of their components.
- Under leakage conditions, the zeotropic mixtures could cause problems in the refrigeration controls (pressure controls) due to their composition shift.
- Owing to the effect of temperature glide in evaporator, it is difficult to locate the thermostat in the evaporator to control the refrigeration system.
- Use of zeotropic refrigerant mixtures in low temperature refrigeration systems will form uneven frost formation in evaporator coils, which results in the loss of evaporator performance.
- Usually, the refrigerant mixtures exhibit lower heat transfer coefficient in both condensers and evaporators due to its non-linear behaviour.

- Non-linear behaviour of zeotropic refrigerant mixtures creates an ambiguity in design and selection components of the system.
- Low volatile component that is miscible with lubricant (like R600a or R600) is required to carry the lubricant oil to the compressor. Use of
- such low volatile component in refrigerant mixture leads to more composition shift.
- Zeotropic refrigerant mixtures require an increased heat exchange area to achieve the desired capacity.
- Conventional method of heat exchange design (LMTD and NTU) is not valid for refrigerant mixtures, which requires correction factor.
- The zeotropic mixtures may get change in their composition under leakage conditions, which affects the performance of the system.
- Non-isothermal behaviour of refrigerant mixtures in condensers and evaporators during phase change leads to the formation of pinch points, which affects the effectiveness of condensers and evaporators.
- Mixed refrigerants require liquid line receiver (in liquid line) and suction line accumulator (in the vapour line) to accommodate the non-linear behaviour of refrigerant mixtures.
- It is difficult to control the capacity of the system, due to the non-linear behaviour of zeotropic refrigerant mixtures.
- Owing to change in running composition of zeotropic mixtures, the pressure, capacity and temperature get changed inside the system, which
- affects the overall system performance.
- HC refrigerants mixtures are identified as the good substitutes to replace the halogenated refrigerants. But HC refrigerant mixtures are highly flammable in nature.
- The zeotropic mixtures should be transferred in liquid condition to retain the composition.
- Zeotropic refrigerant mixtures are not suitable for automobile air conditioners due to its
- frequent leakage.
- Zeotropic mixtures have strong deviation from ideal evaporation processes of a pure fluid, which makes errors in thermal design of evaporators [34].

II.4.5 Future research needs

Based on the extensive literature reviewed on refrigerant mixtures, it was observed that refrigerant mixtures are going to replace the halogenated refrigerants in future. The suitability of new refrigerant mixtures in the existing refrigeration system requires further research in the following areas:

- Reliability of refrigerant compressors working with environment-friendly alternatives.
- Wear studies on refrigerant compressors working with new refrigerant mixtures.

- Refrigerant–lubricant interaction of new refrigerant mixtures.
- Exergy optimization of refrigeration system working with new refrigerant mixtures.
- Development of a new user-friendly lubricant is necessary to replace the existing synthetic lubricant.
- Development of a new method for heat exchanger design is required to accommodate the nonlinear variation of new refrigerant mixtures during phase change.
- Development of new refrigeration system with low refrigerant inventory is required.
- The environmental properties, flammability and safety issues of new refrigerant mixtures.
- Start up and shunt down (dynamic) characteristics of new refrigerant mixtures.
- Phase change characteristics of new refrigerant mixtures.
- Development of simplified correlations for predicting the properties of refrigerant mixtures.
- Thermo economic optimization of vapour compression refrigeration system working with new refrigerant mixture.
- Clean development mechanism in refrigeration and air-conditioning sector working with new refrigerant mixtures [34].

II.5 Conclusion

The analysis of the thermodynamics involved in the ideal Carnot reverse cycle, actual refrigeration cycle and modifications applied permit us to appreciate the need to develop more efficient refrigeration cycles. In the same light we also uphold the introduction of natural resources like solar and water which are cleaner, cheaper and environmentally friendly. We have seen due to energy losses that we cannot realise 100% efficiency in a VCRS. There is a lot of ground to cover in research for more efficient mechanical cycles, heat exchangers and environmentally friendly and safe to use refrigerants.

Chapter III: Thermo-environmental parametric study of a vapour compression refrigeration system (CALCULATIONS)

III.1 Introduction

In this chapter we will learn, assess and study the environmental friendliness of different refrigerants. We also consider operational effectiveness of several refrigerants under different and variable thermodynamic parameters like pressure and temperature. The refrigerants analysed and studied reside in the data base of the Engineering Equation Solver (EES) software.

Since the invention of synthetic refrigerants in 1928 by Thomas J Midgeley, it meant that, from a several number or several options of refrigerants available, the most common and the most used became the chlorofluorocarbons (CFC) and hydrofluorocarbons (HCFC) refrigerants. However, scientists discovered that these conventional refrigerants have very high Ozone Depletion Potential (ODP) and when released into the atmosphere, contribute significantly to the destruction of the ozone layer and produce damaging effects on the global environment.

Even though CFCs and HCFCs were effectively; fruitfully and successfully introduced and were practical in terms of production; manipulation and use in refrigeration systems, there was a downside to them. In the adjustment, modification and enhancement of their stability, an increase in ODP value would result. The focus had to be sharply, radically or quickly shifted towards hydrofluorocarbons HFCs which carry or bear a null value of ODP.

Refrigeration applications are one of the major emitters of greenhouse gases. The systems employ high Global Warming Potential (GWP) refrigerants as their working fluids. They contribute to greenhouse gases emissions in two ways indirectly through the generation of electricity used to power the systems and directly through the leak of high GWP refrigerants from the system during repair, charging and normal operation. The percentage of direct emissions and indirect emissions differs and depends on the GWP of the refrigerant, the rate of leak and the emission factor of the electricity generation plant. According to Mylona et al.; Mota-Babiloni et al., averagely, direct emissions have been estimated to account for about 35% of the total emissions from refrigeration systems while larger share of the emissions (65%) is indirect through energy consumption. Also, it has been estimated that 2% of total equivalent CO2 emissions are caused by the direct release of refrigerants while the indirect release is about ten times the direct release putting the total contributions of refrigeration sector to global warming at approximately 20%.

When we analyse the different refrigerants presented in the table above, we notice that they all bear zero ODP value. This means that these substances are not just potential refrigerants to be used as replacements but they don't destroy the ozone layer cover, which is a very important aspect and quality.

Table III. 1: Environmental and physical properties of the studied refrigerant mixtures

Refrigerant	**R134a**	**R410A**	**R407C**	**R404A**	**R152a**	**R290**	**R40**
Ozone Depletion Potential ODP	0	0	0	0	0	0	0
Global Warming Potential GWP	1430	2088		3922	124	3	
Critical Point Temperature (C)	101,1	72,13	86,03	72,05	113,15	96,7	
Critical Point Pressure (MPa)	4,1	4,926	4,629	3,729	4,496	4,248	
Critical Density (kg/m3)	511,9	488,9	484,2	486,54			
Liquid Phase Density (kg/m3 at 25C)	1206,7	1062			899		
Vapour Phase Density (kg/m3 at 25C)	32,4	4,12	43,77	65,27			
Molar Mass (kg/kmol)	102	72,6	86,2	97,6	66,051	44	50,488
Latent heat of Vaporisation at atmospheric pressure (kJ/kg)	94,28	120	256,29	199,61			

However, the GWP of R134a, the most commonly used refrigerant in Vapour Compression Refrigeration System VCRS is worryingly high of 1430 times that of CO_2. Compounds like R152a and R290 however have very promising values of 124 and 3 respectively which are very sustainable.

III.2 Thermodynamic model

Considering the thermophysical properties and thermodynamic properties like critical point temperature, critical point pressure and vapour phase density, all the other refrigerants follow R134a closely meaning they could potentially replace it in the future. The following performance parameters which are necessary for the selection of good alternative refrigerants are considered in this study: discharge temperature, compression pressure ratio, cooling capacity, energy efficiency in terms of Coefficient of Performance (COP) and Specific Power Consumption (SPC) and other parameters. These performance parameters were computed using Eqs. (III.1) – (III.13).

The *pressure ratio* (P_R), also referred to as the compression ratio or system pressure ratio is a dimensionless parameter.

- condensing pressure (P_2) is the same as compressor discharge pressure
- evaporating pressure (P_1) is also the same as compressor suction pressure.

$$P_R = \frac{P_2}{P_1} \tag{III.1}$$

The compression power $\dot{W}_c$ determines the rate at which the system consumes electrical energy.

$$\dot{W}_c = \dot{m}\left(h_2 - h_1\right) \tag{III.2}$$

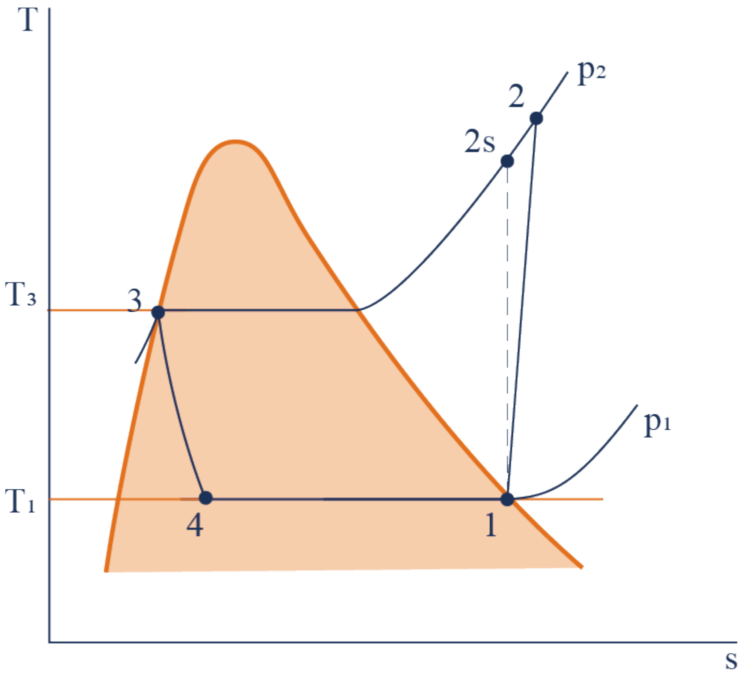


Figure III. 1: Schematics and idealized pressure-enthalpy diagrams of a vapour compression refrigeration cycle

where the rate of refrigerant flow is given by $\dot{m}$, the enthalpy at the exit of the evaporator, h_1 the enthalpy at the exit of the compressor in a real cycle, h_2.

The heating effect of the cycle Q_c represents the rate at which the system supplies energy to the heat pump, where h_3 is the enthalpy at the exit of the condenser

$$\dot{Q}_c = \dot{m}\left(h_2 - h_3\right) \tag{III.3}$$

The refrigerating effect of the cycle Q_f represents the rate at which the system removes heat energy from system where the enthalpy h_4, is found at the entrance of the evaporator

$$\dot{Q}_f = \dot{m}\left(h_1 - h_4\right) \tag{III.4}$$

The energy efficiency of the system is determined using the term *Coefficient of Performance* (COP) and is computed as the ratio of refrigerating effect ($\dot{Q}$) with $\dot{Q}_c$ for condensation (heating effect, heat pump) and $\dot{Q}_f$ for evaporation (cooling effect, refrigerator), to the work input through the compressor ($\dot{W}_c$):

$$COP_{hp} = \frac{\dot{Q}_c}{\dot{W}_c} \tag{III.5}$$

$$COP_{r} = \frac{\dot{Q}_f}{\dot{W}_c} \tag{III.6}$$

The ideal energy efficiency of the system is expressed in terms T_c condenser temperature and T_f evaporator temperature, where $COP_{carnotpc}$ results from heating effect and $COP_{carnotir}$ results from cooling effect.

$$COP_{Carnot-hp} = \frac{T_c}{T_c - T_f} \tag{III.7}$$

$$COP_{Carnot-r} = \frac{T_f}{T_c - T_f} \tag{III.8}$$

The global efficiency of the system is expressed as shown below, where equation (III.9) shows global efficiency of a heat pump and equation (III.10) shows global efficiency for a refrigerator.

$$E_{hp} = \frac{COP_{hp}}{COP_{Carnot-hp}} \tag{III.9}$$

$$E_{r} = \frac{COP_{r}}{COP_{Carnot-r}} \tag{III.10}$$

We can also calculate the isentropic efficiency from the equation below, where h_{2s} is the enthalpy at the exit of the compressor in an ideal cycle, h_2 is the enthalpy at the exit of the compressor in a real cycle and h_1 is the enthalpy at the exit of the evaporator

$$\eta_c = \frac{h_{2s} - h_1}{h_2 - h_1} \tag{III.11}$$

The *Specific Power Consumption* (*SPC*), also known as power per ton of refrigeration, is a useful indicator of the energy performance of the system which is expressed as:

$$SPC = 3.5\frac{\dot{W}_c}{\dot{Q}_f} \tag{III.12}$$

The *Volumetric Cooling Capacity* (*VCC,* kJm $^{-3}$) is the refrigerating effect per unit volume of refrigerant at the inlet of the compressor. It is a value calculated from the vapour density at the compressor's inlet and the refrigerating effect (Q_f, kJkg $^{-1}$):

-where, ρ_1 = density of the refrigerant at the inlet of the compressor (kgm $^{-3}$).

$$VCC = \rho_1 \dot{Q}_f \tag{III.13}$$

III.3 Parametric study

These equations constitute the elements a steady-state thermodynamic model that has been transcribed under EES, *Engineer Equation Solver* and adopted to study and compare the behaviour of a VCRS tested with several HFC selected refrigerants. In a first step the dependence of the pressure, the enthalpy of vaporization and the specific volume of the Saturated Liquid Temperature of the different refrigerants were compared with that of the R134a. For this purpose, a temperature range from -20 °C to 40 °C. In a second step, the influence of the evaporating temperature on the performance parameters is presented considering a temperature range from -20 °C to 0 °C. The study concerns also the effect of condensing temperature on the presented performance parameters for 30 °C to 60 °C.

III.3.1 Saturation pressure vs Saturated Liquid Temperature

The figure III.2 shows the variation of the saturation pressure as we travel along the values of the evaporator or the saturated liquid temperature. As shown in the figure the saturation pressure increases exponentially with increasing evaporator temperature. For evaporator temperature of 10 ^{0}C saturation pressure is about 250 kPa for R152a and R40, while it's around 1000kPa for R410A, which four times more. We note that R152a and R40 exhibit similar characteristics to R134a, meaning that they can be suitable alternatives for R134a in this case.

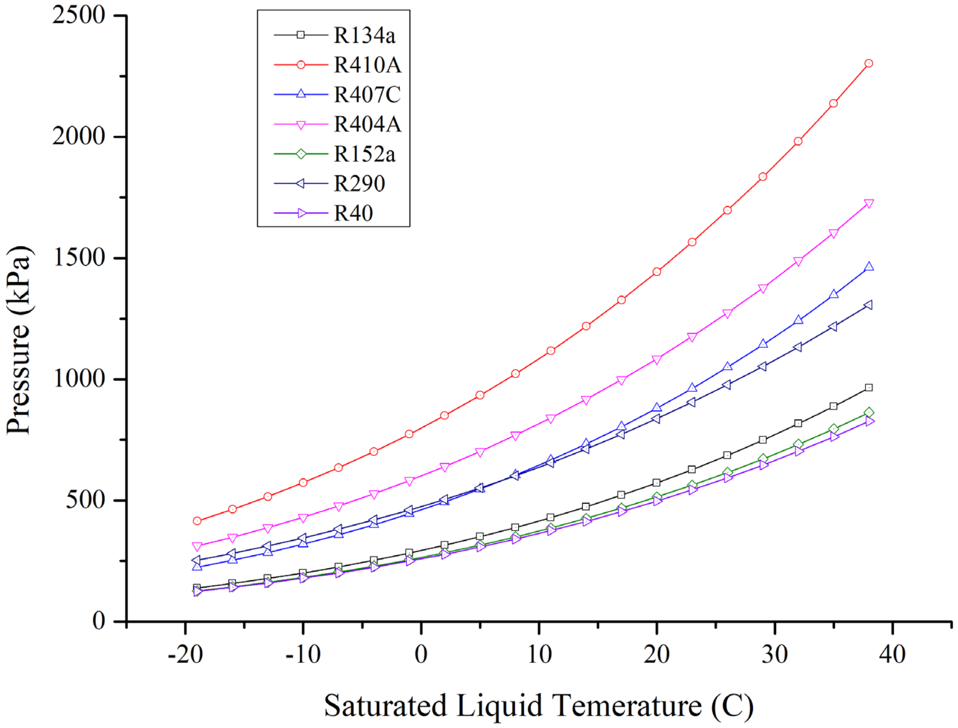


Figure III. 2:Saturation pressure vs Saturated Liquid Temperature

III.3.2 Enthalpy of vaporization vs SLT

The amount of energy or enthalpy that must be added to a refrigerant to change a kilogram of that refrigerant to gas decreases as values of evaporator temperature proceed to the right as shown in the figure III.3. When the refrigerant's temperature is increased it takes less energy to change 1kg of that refrigerant vapour. Considering the evaporator temperature of -10^{0}C R407C (enthalpy of vaporization) is about 175kJ/kg and R40 (enthalpy of vaporization) is found to be around 425kJ/kg, which is more than 2 times greater. This means R407C vaporises much more easily. We notice that the behaviour of R404A is the closest to R134a, which makes it the most comparable alternative to R134a.

III.3.3 Specific volume vs SLT

The curves shown in the figure III.4 show the variation of specific volume at the evaporator outlet to the evaporator temperature. The quantity of gas in m3 formed when 1kg of refrigerant evaporates decreases with increasing evaporator temperature. This influence refrigerator system components sizes. At evaporator temperature of 10^{0}C we see that R407C (specific volume) is approximately 0,025 m^3/kg while R40 (specific volume) is about 0,125 m^3/kg. This is about 5 times more gas produced when R40 evaporates. R40 has largest volumes produced, R407C has the smallest. In systems we use R134a; R404A and R290 may also be employed to use.

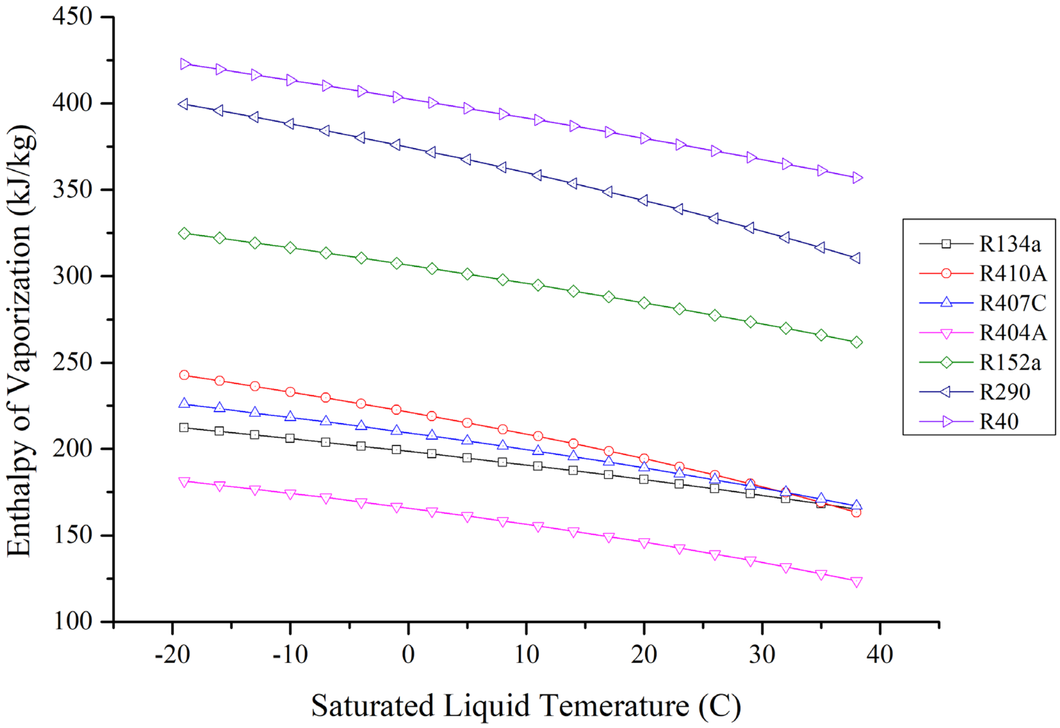


Figure III. 3 : Enthalpy of vaporization vs SLT

III.3.4 Pressure ratio vs Evaporating temperature

The figure III.5 illustrates the change in pressure ratio versus evaporator temperature. As shown on the figure above the ratio of the absolute discharge pressure leaving the compressor to absolute suction pressure entering compressor descends as evaporator temperature rises. When evaporator temperature is 0^0C, R290(pressure ratio) is around 3 while R407C(pressure ratio) is about 4, which is greater by a factor of “one”. Greater compression ratios mean that the compressor has to perform more work to reach the discharge pressure, which makes it heat up and may become less efficient. R410A, R404A and R290 exhibit the lowest compression ratios and therefore are the best alternatives.

III.3.5 Discharge temperature vs Evaporating temperature

Discharge temperature as a function of evaporator temperature gently slops downwards as evaporator temperature evolves to the right. As can be seen on figure III.6 at evaporator temperature of -10^0C, R410A (discharge temperature) is around 35^0C while R404A (discharge temperature) is about 160^0C, which may be too high for normal operation. Excessive discharge temperature may cause fatigue on the valves and thermal stress of the lubricant. R404A and R290 have marginally big discharge temperature in the range of 120^0C to 170^0C. R410A has notably small discharge temperature in the range 20^0C to 40^0C.

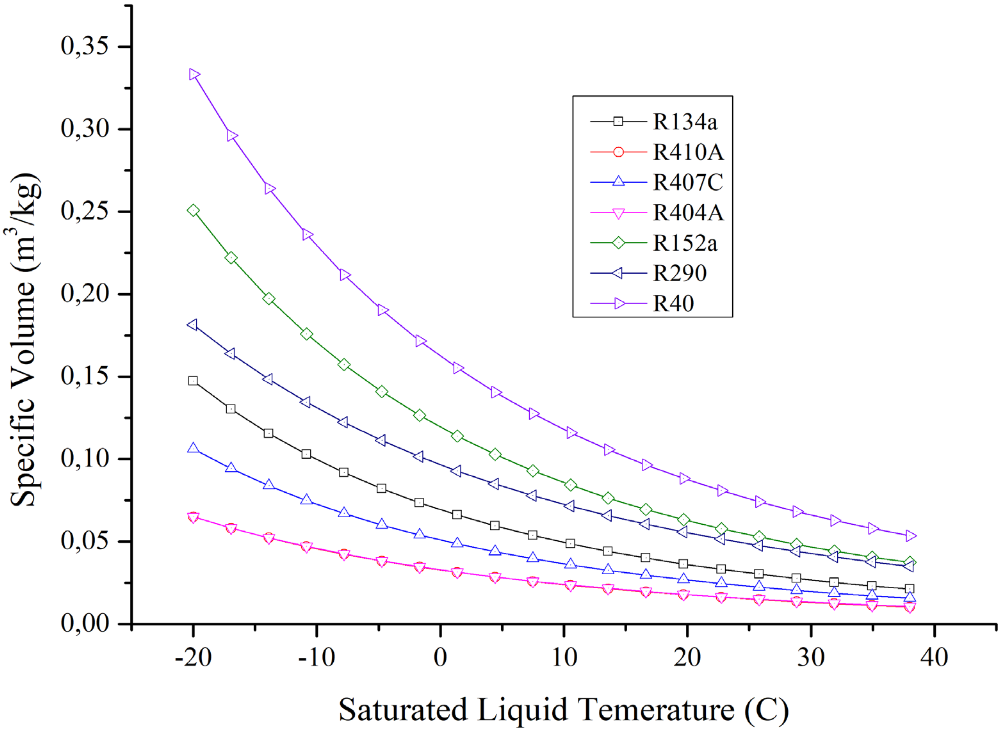


Figure III. 4 : Specific volume vs SLT

III.3.6 COP vs Evaporating temperature

The curves shown above illustrate the relationship of COP versus evaporator temperature. For evaporator temperature -10^0C we have R407C (COP) of about "1" while R410A (COP) is around 3,25, which is clearly 3,25 times greater. Ratio of useful cooling to power input increases with rising evaporator temperature. This is so because from **figure** (**pressure, P vs enthalpy, h**) as evaporator temperature goes up, ($h_1 - h_4$) increases while ($h_2 - h_1$) decreases, hence COP increases. R410A shows clearly the highest COP about 0,5 greater than the rest. R410A reduces operation cost of the plant.

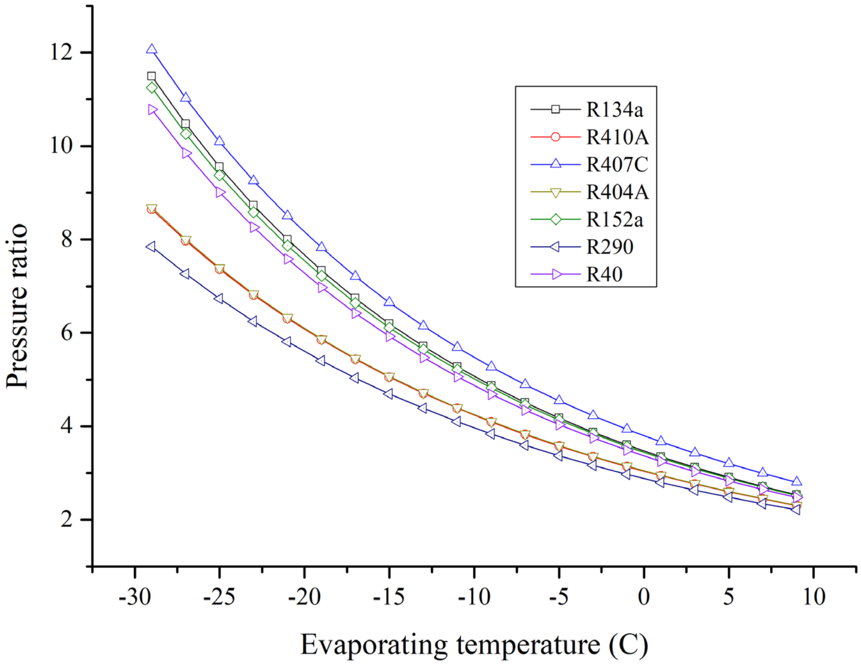


Figure III. 5 : Pressure ratio vs Evaporating temperature

III.3.7 Specific Power Consumption

Figure III.7 illustrates the evolution of power drawn by the refrigeration system as electricity for example, per ton of refrigeration. At evaporator temperature of -10^{0}C the values of R410A(specific power consumption) is 1kW/TR while for R407C(specific power consumption) is about 3,75kW/TR and it's 3,75 times greater. Specific power consumption gently goes down as the evaporator temperature increases. We note that R410A has notably low specific power consumption for each ton of refrigeration.

III.3.8 Volumetric Cooling Capacity vs Evaporator temperature

The amount of energy absorbed per m^3 of refrigerant vapourised in the evaporator rises proportionally to the evaporator temperature. While evaporator is at -10^{0}C we note that R152a VCC and R134a VCC is around 1500kJ/m^3 while for R410A(VCC) is about 4500kJ/m^3, which is 3 times greater. R410A absorbs the most heat energy among the seven refrigerants considered, followed by R404A.

III.4 Effect of condensing temperature

When we compare saturation pressure; enthalpy of vaporisation; specific volume; pressure ratio; discharge temperature at the evaporator outlet; coefficient of performance; specific power consumption; volumetric cooling capacity; mass of carbon dioxide produced as well as operation costs, considering condenser temperature in place of evaporator temperature we note that the resulting curves are completely opposite.

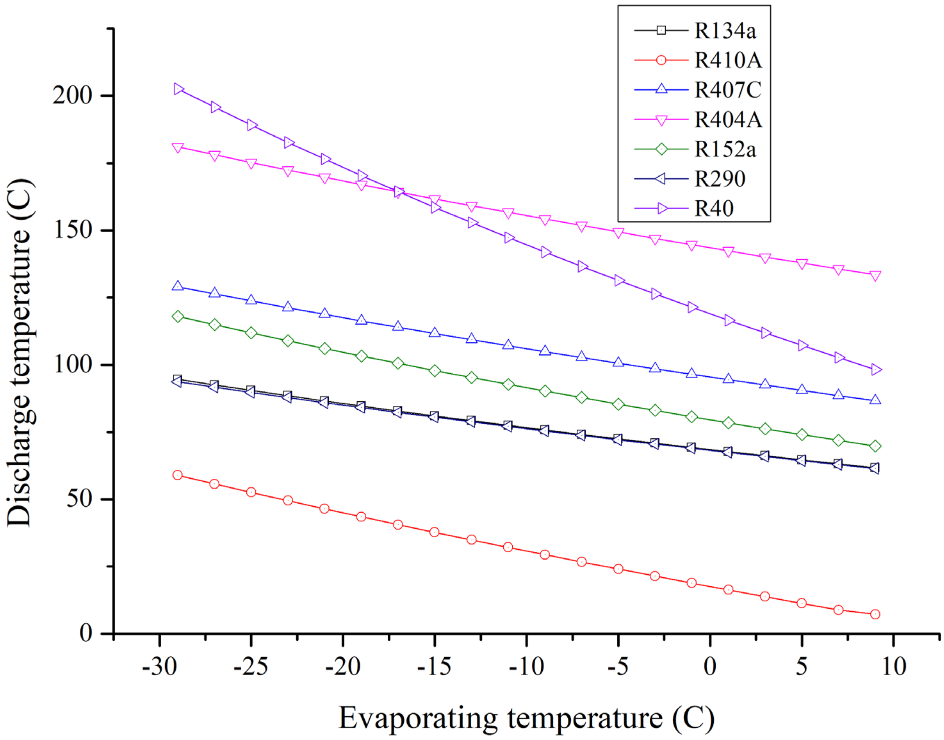


Figure III. 6 : Discharge temperature vs Evaporating temperature

The condenser temperature graphs are mirror images of evaporator temperature curves coming from the fact that as the evaporator is performing the refrigeration process the condenser is acting as the heat rejecter.

This happens simultaneously allowing the process of refrigeration to work continuously otherwise the refrigerant would become too warm to absorb more energy and cooling process would stop.

III.3.9 Mass of Equivalent released CO_2 vs Evaporating temperature

From the figure III.9 we note that the mass of carbon dioxide emissions reduce as evaporator temperature becomes more positive. When evaporator temperature is -10^0C R134a(mass of CO2) is around 5000 kg while R407C(mass of CO2) is about 15000 kg, which 3 times greater. R134a has the least greenhouse gas emission. Most carbon dioxide emission evolves indirectly from burning of fossil fuels, coal and natural gas for electricity generation.

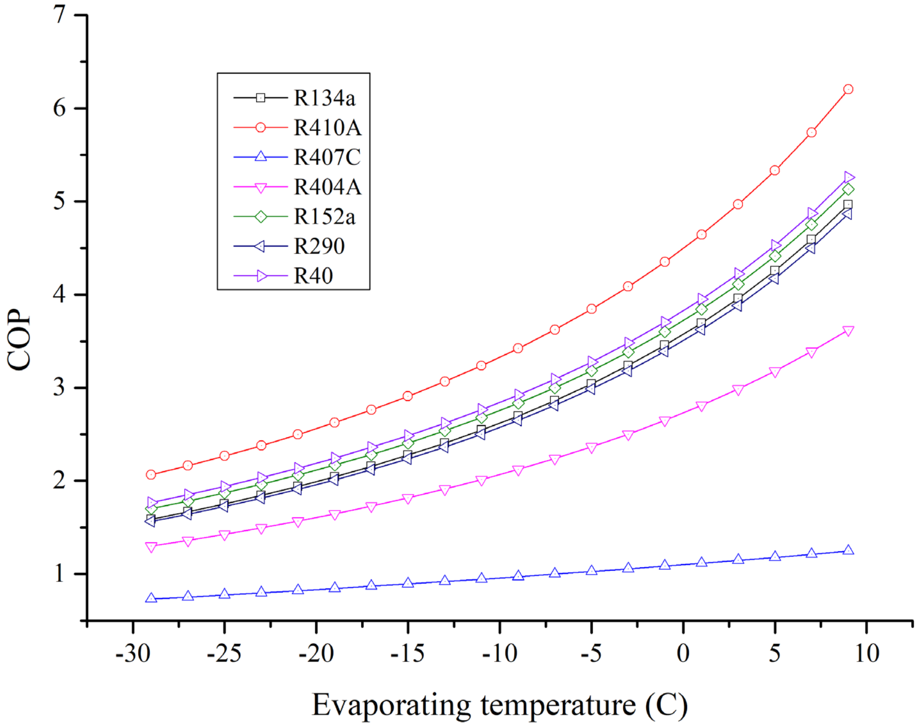


Figure III. 7 : COP vs Evaporating temperature

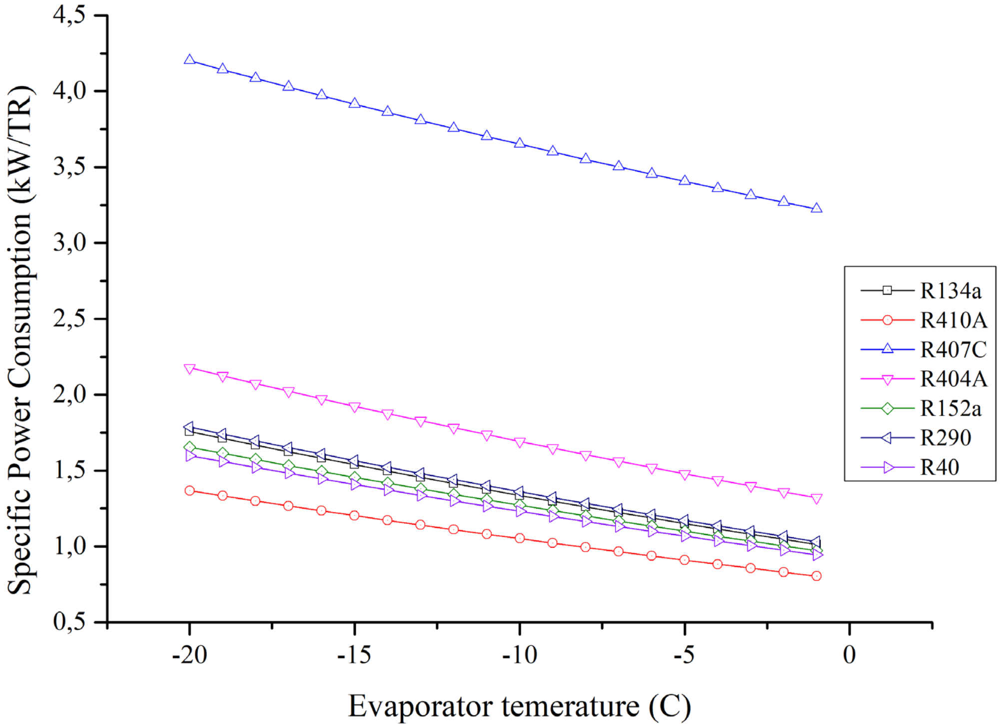


Figure III. 8 : Specific Power Consumption vs Evaporating temperature

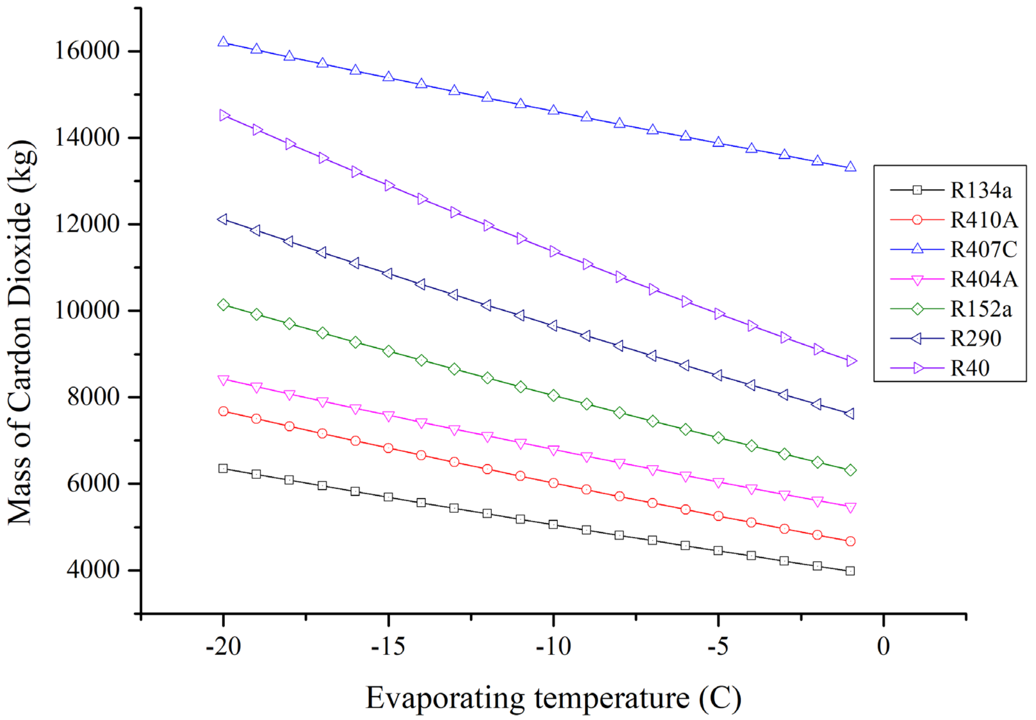


Figure III. 9 : Mass of Equivalent released CO_2 vs Evaporating temperature

III.3.10 Cost of OP vs Evaporating temperature

Operation cost is mainly affected by the efficiency of the system and operating conditions. When evaporator temperature is -10^{0}C R134a (cost of operation) is around 5000 dinars while R407C (cost of operation) is about 15000 dinars, which 3 times more expensive, figure III.10. R134a again exhibits the lowest operation cost trend as we increase the evaporator temperature. As evaporator temperature becomes more positive the cost of operation decreases. This makes practical sense because as the temperature of evaporation increases less power is drawn by the system.

When we compare saturation pressure; enthalpy of vaporisation; specific volume; pressure ratio; discharge temperature at the evaporator outlet; coefficient of performance; specific power consumption; volumetric cooling capacity; mass of carbon dioxide produced as well as operation costs, considering condenser temperature in place of evaporator temperature we note that the resulting curves are completely opposite.

The condenser temperature graphs are mirror images of evaporator temperature curves coming from the fact that as the evaporator is performing the refrigeration process the condenser is acting as the heat rejecter.

This happens simultaneously allowing the process of refrigeration to work continuously otherwise the refrigerant would become too warm to absorb more energy and cooling process would stop.

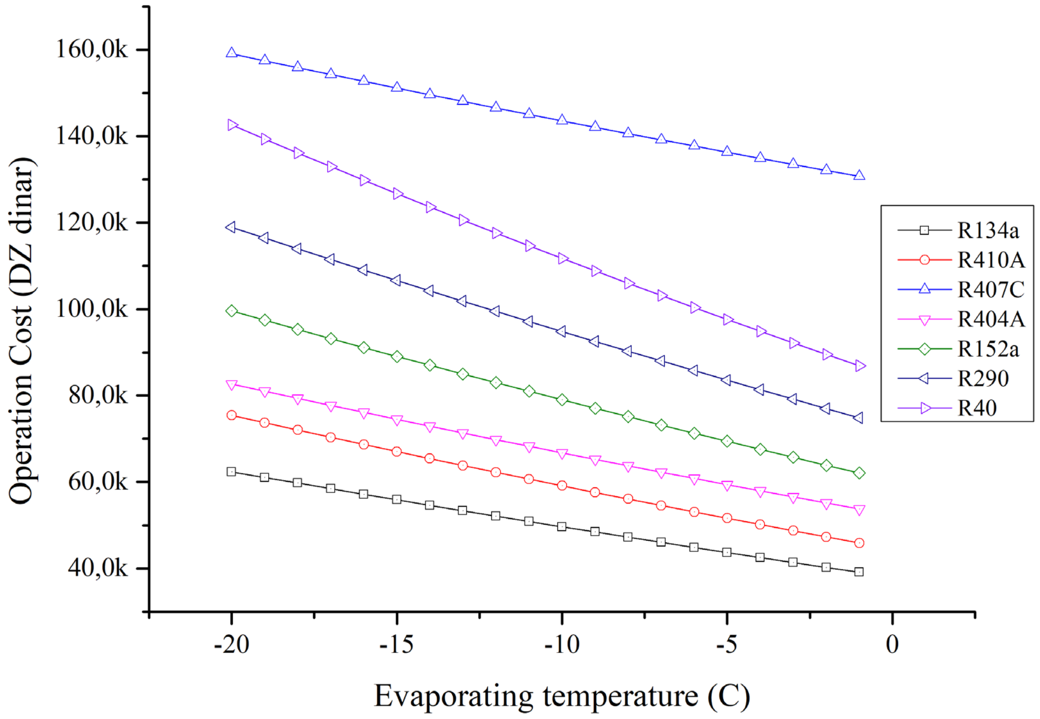


Figure III. 10 : Cost of operation vs Evaporating temperature

III.4 Effect of condensing temperature

When we compare saturation pressure; enthalpy of vaporisation; specific volume; pressure ratio; discharge temperature at the evaporator outlet; coefficient of performance; specific power consumption; volumetric cooling capacity; mass of carbon dioxide produced as well as operation costs, considering condenser temperature in place of evaporator temperature we note that the resulting curves are completely opposite.

The condenser temperature graphs are mirror images of evaporator temperature curves coming from the fact that as the evaporator is performing the refrigeration process the condenser is acting as the heat rejecter.

This happens simultaneously allowing the process of refrigeration to work continuously otherwise the refrigerant would become too warm to absorb more energy and cooling process would stop.

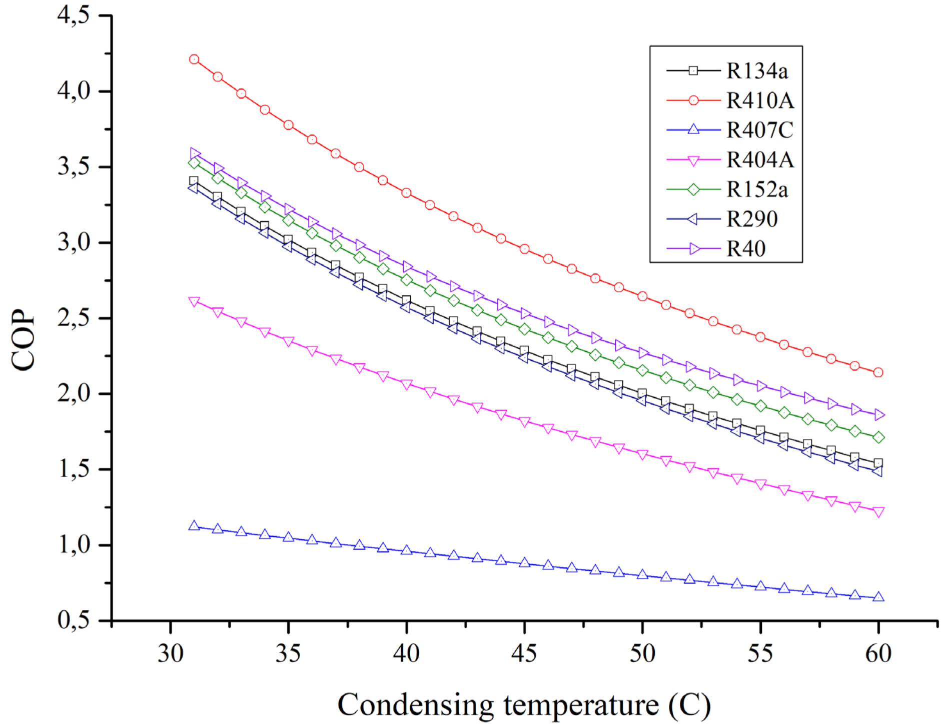


Figure III. 11 : COP vs Condensing temperature

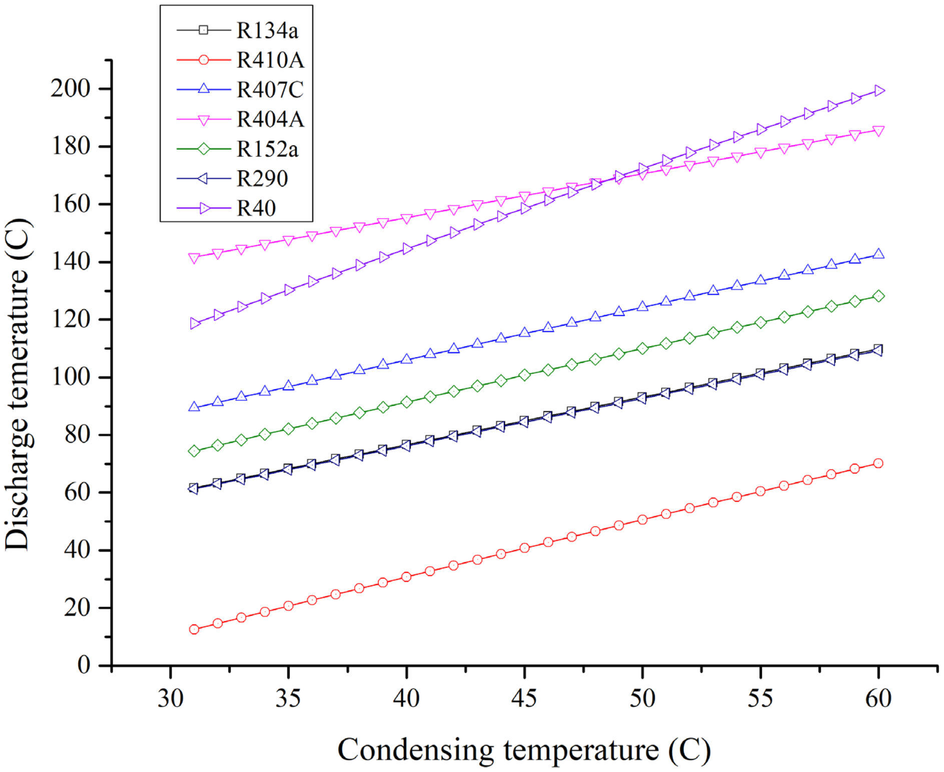


Figure III. 12 : Discharge temperature vs Condensing temperature

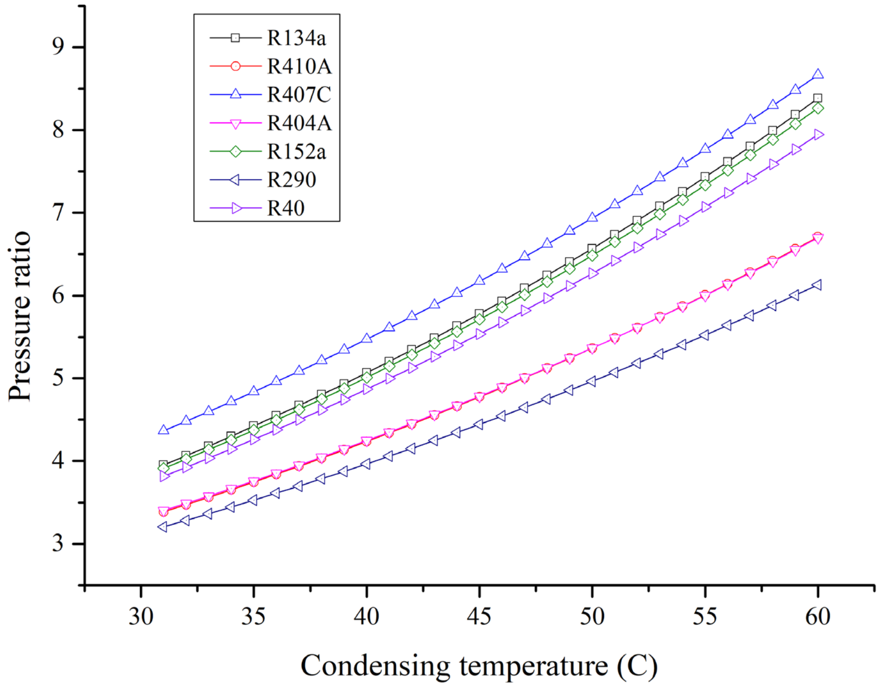


Figure III. 13 : Pressure Ratio vs condensing temperature

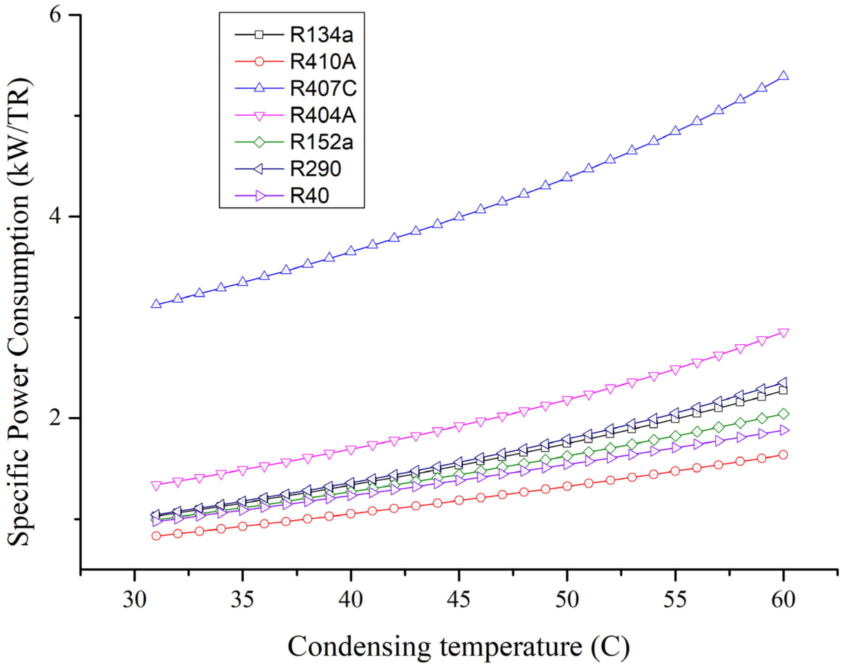


Figure III. 14 : SPC vs Condensing temperature

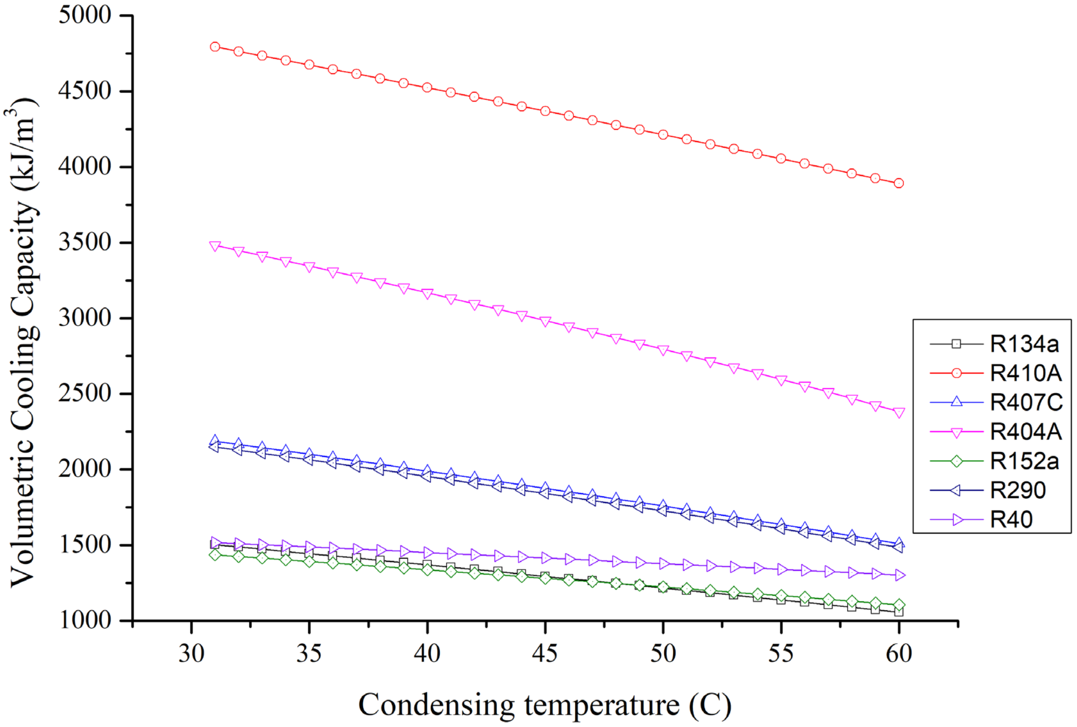


Figure III. 15 : VCC vs Condensing temperature

III.4 Conclusions

As we have several refrigerants available, we study and look into the ones with no ozone depletion potential (ODP) and low global warming potential (GWP less than 200), which can bring the best performance; reduce operation costs and adhere to the environmental safety guidelines. According to the investigations done the following conclusions can be made:

1) Saturation pressure-evaporator temperature relationship of R152a and R40 are closest to R134a, therefore could work as alternatives in systems where R134a is used. Even better the saturation pressures of R152a and R40 are lowest making them the most efficient in this case.

2) When it comes to enthalpy of vaporisation R410A; R404A and R134a have very close similarities with gaps of about 30 and 25 kJ/kg respectively between them, meaning they could work as alternatives to each other. R407C shows the lowest enthalpy of vaporisation which makes it the best alternative available.

3) Considering specific volume-temperature curves it is clear that R40 has the poorest performance about 0,05 m3/kg above the rest while R407C showed the most excellent specific volume making it the most suitable option.

4) Looking at pressure ratio-temperature graphs of the seven refrigerants, R410A; R404A and R290 show the most excellent values. When a compressor is working on any of these three substances there is less work of compression and therefore less heating up, therefore works more efficiently.

5) Discharge temperature-evaporator temperature relationship proves that R404A and R290 perform extremely poorly with most values above 120 ^{0}C. R410A turns out to be the best option with the lowest discharge temperature.

6) Investigating coefficient of performance COP-temperature curves, R410A leads the rest by a factor of about 0,5 followed by R407C which is close to R152a; R134a and R290. R404A is clearly the best available refrigerant.

7) Specific power consumption-temperature graphs prove that R410A had the least power consumption followed closely by R40; R153a; R134a and R290. R404A is higher with about 0,4 kW/TR but R407C is extremely high with a difference of about 2kW/TR from the rest. R410A is undeniably the best alternative.

IV General conclusion

Although Africa is still lagging behind in terms of energy availability especially in the form of electricity there is a lot of potential in the availability of the energy resource. It is estimated that in Africa an average person uses less than 10% of kilowatt-hours per year of an individual who lives in the United States.

However, Africa is blessed and is rich with natural resources which are yet to be exploited to their full potential and could see an increase in energy availability for processes like refrigeration for preservation of food products and provide food security.

The technology of refrigeration equipment since the 1800s has seen many great inventions and practises of refrigeration methods that allow food products to stay cool and preserved for long periods of time at very low cost.

The theory, science, mathematics and thermodynamics have also greatly improved with modifications being done to the original standard vapour compression refrigeration cycle to improve efficiency and reduce costs of operation. Among interesting areas of research include use of solar as a source energy and water as a refrigerant. Synthetic refrigerants remain the best heat carriers in pipes or ducts and heat exchangers.

In our study we discovered that the amounts of carbon dioxide emitted for operating R134a; R410A and R404A where the least and therefore these three could be the most environmentally friendly. However, as we also noted for example R134a(GWP) =1430 is extremely high and presence a danger should R134a leak into the atmosphere.

On a practical level R134a, R410A and R404A cost less to operate therefore present the best economic option among the refrigerants considered. R410A and R404A did not perform well considering saturation pressure at the evaporator outlet and enthalpy of vaporisation. Now this leads us to conclude that even though at present we have to pick the best option among the available refrigerants we need to appreciate the need to research for more efficient, cost effective and more environmentally friendly refrigerants

References

[1] J. Tomczyk, E. Silberstein, B. Whitman et B. Johnson, Refrigeration and Air Conditioning Technology, 2016.

[2] I. Dincer et M. Kanoglu, Refrigeration systems and applications, John Wiley & Sons, 2010.

[3] «International Energy Agency,» [En ligne]. Available: https://www.iea.org/. [Accès le February 2021].

[4] S. N et P. MJ, «Experimental studies on a vapour compression system using nanorefrigerants,» International Journal of Engineering, Science and Technology, 2011.

[5] (. Geno-Liang Ding, «Recent developments in simulation techniques for vapour-compression refrigeration systems,» International Journal of Refrigeration, pp. 1119-1133, 2007.

[6] T. S.A et G. I.N, «Fault diagnosis and refrigerant leak detection in vapour,» International Journal of Refrigeration, p. 680–688, 2005.

[7] W. Larsen et Angel, HVAC Design Sourcebook, The McGraw-Hill Companies, October 2011.

[8] «The Vapor Compression Refrigeration Cycle, Step By Step,» [En ligne]. Available: https://www.araner.com/blog/vapor-compression-refrigeration-cycle. [Accès le February 2021].

[9] J.Yeom, S. M.A et T.Singh, «Reference Module in Materials Science and Materials Engineering,» Micro-Coolers, 2017.

[10] ASHRAE, Heating, Ventilating,and Air-conditioning SYSTEMS AND EQUIPMENT, 2012.

[11] H. G F, T. A R et W. T C, REFRIGERATION,AIR CONDITIONING AND HEAT PUMPS Fifth Edition, Elsevier Ltd, 2016.

[12] S. C. Sugarman, HVAC Fundamentals Second Edition, The Fairmont Press,, 2007.

[13] N. E. Wijeysundera, principles of heating, ventilation and air-conditioning, with worked examples, Nihal E Wijeysundera, (2016), World Scientific Publishing Co.Pte. Ltd., 2016.

[14] D.-W. SUN, «SOLAR POWERED COMBINED EJECTOR-VAPOUR COMPRESSION CYCLE FOR AIR CONDITIONING AND REFRIGERATION,» pergamon, 1997.

[15] M. Anarghya Ananda, S. Alison, N. Stuart et F. Mitsuhiro, «A review on expanders and their performance in vapour compression refrigeration systems,» International Journal of Refrigeration, 2019.

[16] [En ligne]. Available: https://www.industryupdate.com.au/sites/default/public/imported_products/22947. [Accès le February 2021].

[17] [En ligne]. Available: https://4.bp.blogspot.com/-1AxP_4aTwmM/WNxcsYfO8VI/AAAAAAAAAEA/ZSUc9fVEi_8ONzELQmACvAj_OhzPND1TwCLcB/s1600/U3%25E9%2592%259B-2.jpg. [Accès le February 2021].

[18] [En ligne]. Available: https://www.apexgroup.eu/admin/uploads/products/coils/03.%20Finned%20Tubes.jpg. [Accès le February 2021].

[19] [En ligne]. Available: https://www.researchgate.net/profile/Uzair-Mir/publication/343111890/figure/fig2/AS:915840723611651@1595364852876/A-close-up-view-of-a-heat-exchanger-tube-bundle.jpg. [Accès le February 2021].

[20] [En ligne]. Available: https://heatexchanger.co.in/wp-content/uploads/2018/02/finned-tube-heat-exchanger.jpg. [Accès le February 2021].

[21] [En ligne]. Available: https://chemicalengineeringworld.com/wp-content/uploads/2020/02/collage54-1024x538-1.jpg. [Accès le February 2021].

[22] [En ligne]. Available: https://chemicalengineeringworld.com/wp-content/uploads/2020/02/collage51-1024x538-1.jpg. [Accès le February 2021].

[23] [En ligne]. Available:]https://chemicalengineeringworld.com/wp-content/uploads/2020/02/collage54-1024x538-1.jpg. [Accès le February 2021].

[24] [En ligne]. Available: https://image.slidesharecdn.com/shellandtubeheatexchangersthe-160106140650/95/selection-of-shell-and-tube-heat-exchanger-sthe-19-638.jpg?cb=1452089397. [Accès le March 2021].

[25] [En ligne]. Available: https://www.ipieca.org/media/2448/heat_exchangers_-_figure_5_-_schematic_of_a_plate_and_frame_heat_exchanger_0.gif?width=500&height=279.76190476190476. [Accès le February 2021].

[26] [En ligne]. Available: https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcTnNCTi4UD_9htudXZtu4QUf1uxLiIrjKeNgQ&usqp=CAU. [Accès le February 2021].

[27] «Ekin Industrial/ MIT Industrial,» [En ligne]. Available: https://www.ekinendustriyel.com/plate-heat-exchanger/what-is-plate-heat-exchanger/?gclid=EAIaIQobChMI4c-kw4eL8QIVisx3Ch1hngrMEAAYASAAEgJTR_D_BwE. [Accès le March 2021].

[28] «Industrial-in,» [En ligne]. Available: https://industrialin.com/heat-exchanger. [Accès le March 2021].

[29] [En ligne]. Available:]https://www.researchgate.net/profile/Gilles-Flamant-2/publication/278695521/figure/fig6/AS:325153230737413@1454533979645/Spiral-heat-exchanger-courtesy-of-Alfa-Laval.png. [Accès le February 2021].

[30] S. Ibrahim et M. M. Salah-eddine, Université Aboubakr Belkaïd Tlemcen, faculté de technologie, memoire, etude parametrique des échanges externes de chaleur d'une machine à absorption, Tlemcen, Algeria, 2017/2018.

[31] H. W. S. III et A. F. Spach, Analysis and design of heating, ventilating and air-conditioning systems, second edition, Taylor & Francis Group, LLC, (2019).

[32] R. Miller et M. R. Miller, Air-conditioning and refrigeration, The McGraw-Hill Companies, Inc., 2006.

[33] D. AS et W. S, «A performance comparison of vapour compression refrigeration system using various alternative refrigerants,» International Communications in Heat and Mass Transfer, p. 1340–1349, 2010.

[34] C. M. a. S. J. M Mohanraj, «A review on recent developments in new refrigerant mixtures for vapour compression based refrigeration air-conditioning and heat pump units,» *INTERNATIONAL JOURNAL OF ENERGY RESEARCH,* p. 647–669, 2010.

[35] G.-L. Ding, «Recent developments in simulation techniques for vapour-compression refrigeration systems,» 2007.