Master of Science in Mechanical Engineering

Master Thesis

Analysis of a vending machine refrigeration system with propane (R290)

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11, December 2018

Prima di mostrare il mio lavoro di tesi, desidero ringraziare tutti coloro che hanno reso possibile il raggiungimento di questo traguardo:

La mia famiglia, in particolare mia madre e mio padre,
per il loro instancabile sostegno morale ed economico;

Alberto Spinoglio CEO di SandenVendo Europe S.p.A.,
per avermi permesso di seguire questo progetto ed aver creduto in me;

Daniele Barbierato di SandenVendo Europe S.p.A.,
per avermi trasmesso la passione ed una parte del sapere sulla refrigerazione;

Professor Masoero il relatore di questa tesi di laurea,
per l'aiuto e la disponibilità dimostratemi durante il periodo di tirocinio e tesi;

Infine, questo lavoro di tesi lo voglio dedicare a tre persone importanti: ai miei nonni che sono e saranno il mio esempio di vita, e a Valeria che riesce sempre a sopportarmi e mi è sempre vicina.

Abstract

The history of refrigerants has been decided by Montreal and Kyoto protocols. The first one was designed with the aim to reduce the production and consumption of ozone depleting substances, including the HCFCs refrigerants. The second one paved the way to the European regulation F-gas and the international Kigali amendment to the Montreal protocol, which established a timetable to phase down the production and usage of HFCs gases. Both these refrigerants will be banned in a few years in function of their greenhouse contribution, evaluated by using a measure called GWP level (Global Warming Potential).

Consequently, the world-wide refrigeration and food and drink vending machine sector is working toward the developing of a new refrigeration system which could adopt refrigerants with a low GWP level. Currently, in domestic and commercial refrigeration, the whole of possible refrigerant solutions includes natural gases like propane (R290), isobutane (R600a) and carbon dioxide (R744), or chemical mixture as R1234yf.

Among these refrigerants SandenVendo Europe S.p.A., a leader company in food and drink vending machine sector, has decided to design a new refrigeration system which adopts propane. This choice has two main reasons: first, propane is a natural gas which does not affect global warming; secondly, if used according on the international regulations, it assures a performant and reliable vending machine.

The purpose of this thesis is to present the SandenVendo Europe propane refrigeration system and subsequently analyse its performance compared with R404A vending machine. After an introduction that aims to describe history and characteristics of refrigerants, the most important European and international regulations that govern the flammable refrigerants adoption are presented.

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CHAPTER 1

1 Introduction

1.1 Vending machines

Vending machines cover nowadays an important function in our ordinary life. We only need to think that during a common break at school or at work people usually use a vending machine to have a coffee, a snack or a cold drink. They are usually located in hospitals, work break rooms and generally in most of public and private places.

Among the several types of existing vending machines, the most common are the following ones: coffee, snack and drink, ice-cream, cigarettes, pharmacy products, candy and gumball, money exchange, and ticket machines. Moreover, global market is now seeing the rise of specialized vending machines that sell non-traditional products: an example is the pizza vending machine, that was first created in Italy and is now spreading into United Kingdom [1]. As there is an huge variance among all the products that could be offered by a vending machine, so the internal mechanic system is not the same: some machines use a refrigeration system, while other kinds of machines do not need it. Vending machines that need to keep the products inside at a specific temperature are snack, drink and pharmacy ones.

In 2018 during the Venditalia (an Italian benchmark trade fair for international Vending that is held in Milan every two years), Conifida, an Italian association that takes care of vending market, shew some important data about the Vending trade. These data showed that during 2017 vending market has been registered an increase of product sales; in particular coffee covered the 55 per cent, cold drinks the 19.7 percent and snack the 15.5 per cent of total sales [2].

Typically, in coffee, snack and drink vending market, vending service is provided by companies (that are called operators) who buy the machines from the producers and place them in public or private premises. These companies provide complete maintenance and service, as well as products, usually without any cost for the premise owner, except sometimes for a service charge.

Figure 1.1 shows a model of snack and drink vending machine produced by SandenVendo Europe S.p.A., one of the leader industries in vending machines sector. The system that is most commonly used to move the product from the back to the front of the shelf is a small electric motor that turns a spiral where the products are inserted. Some companies choose a different system that use shelves with a low slope that make the product move by its self, so the electric motor with spiral is avoided.

Figure 1.1 *– SandenVendo Europe S.p.A. snack and drink vending machine* [3]

Nowadays vending market is being witness of a global run to create smart and sustainable vending machines, with the final aim to satisfy the client demand. For example, we can think about new machines that lead clients to pay with credit card or with an app installed on their phone. What is more, new technologies that can help service companies have been introduced: a programme that send them a message when a certain product is finished, or another one that can make statistics about which are the best seller products.

With regard to the increasingly importance of a more sustainable market, the ideas that can lead to a real change are the reduction of machine energy consumption and the employment refrigerant gasses that do not produce pollutions.

1.1.1 SandenVendo Europe S.p.A.

Vending machines which are object of this thesis are produced by SandenVendo Europe S.p.A.. This European company forms part of the Japanese multinational SandenVendo, a corporation that operates as one of the leader companies in the vending machine market.

Figure 1.2 *– SandenVendo Europe S.p.A. logo*

The SandenVendo story begins in 1937, when a company initially called "Vendo" was founded in Kansas City (Missouri), U.S.A. In the '60s it opened branches offices in Germany, France, Belgium and Spain, and finally set up a production facility in Coniolo (AL), Italy. Later on, in 1988 Vendo became part of the Sanden Corporation and it was renamed as SandenVendo in 2005.

The Japanese Sanden Corporation is a global expert in thermodynamics technologies supplying products for the automotive, vending and living & environment business sectors. Under its Management Policy "to create corporate values for the environment", the company is working on harmonizing environmental preservation and business activity by setting the environment as a core business objective.

Nowadays SandenVendo counts more than 500 thousand vending machines produced, 282 Billion Yen annual revenue in 2016, 54 business locations in 23 countries. The company participated as vending machine official partner in five Olympic Games and in the last Soccer World Championship in Sochi in 2018 [3].

Figure 1.3 shows the three main vending machines produced by SandenVendo Europe S.p.A. On the left-hand there is the G-Drink, in the centre the G-Coffee and on the right-hand the G-Snack.

Figure 1.3 *– Three kind of vending machine produced by the SandenVendo Europe S.p.A. respectively from the left-hand: G-Drink, G-Coffee and G-Snack*

1.2 Refrigeration history

The necessity to store perishable foods is a problem that has been existing since the stone age, when primitive men used cold caverns to keep fresh both meat and vegetables. To going on time, before fridge and freezer invention, people used cellar to keep food and drink cold and of good quality. Humans had to wait until the '800s, when the refrigerant gases were discovered, to see the first fridge of the story.

A refrigerant is a chemical or natural compound that can readily absorb and release heat thanks to its phase changes from liquid to gas and vice versa. Thanks to this property, refrigerants were adopted as working fluid for the refrigeration systems. **Figure 1.4** represents schematically the evolution over time of refrigerants employed in refrigeration industry.

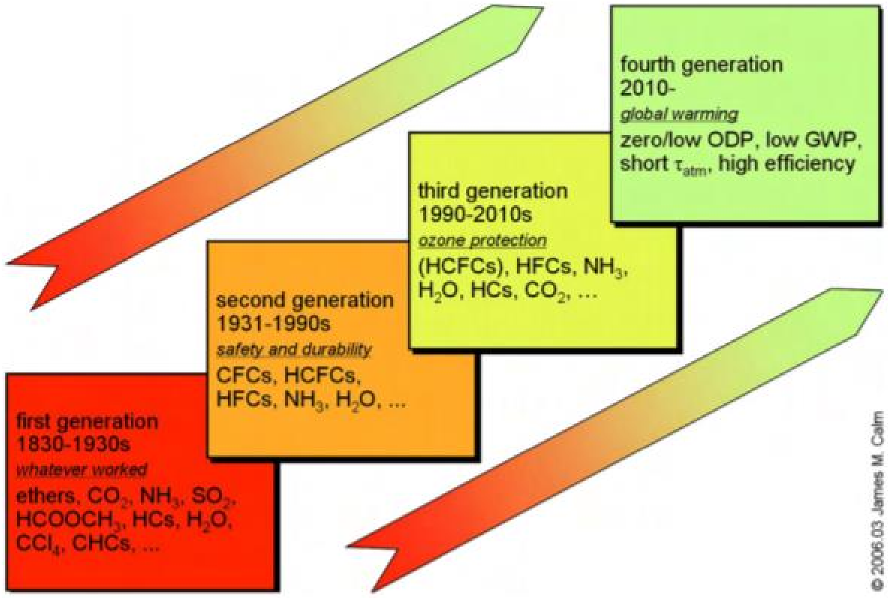

Figure 1.4 *– Refrigerants progression in history* [4]

1.2.1 First refrigerants generation – Discover

During the 19th century, thanks to Gay Loussac, Faraday and Boyle, liquid evaporation was discovered as having the property to cool down something, and Carnot developed the first refrigeration cycle theory. These innovations brought Perkins to create the first refrigeration system of the story in 1834. Perking system was a closed circuit that comprised modern vapor-compression system components (compressor, condenser, expansion device and evaporator) and used as working fluid the ethyl ether [5].

Between the 19th and the 20th century, natural gases like water, ethyl ether, ammonia and carbon dioxide were adopted as refrigerants. Among these gases, ammonia was the most used even if it is toxic, because carbon dioxide require high working pressure and ethyl ether is high flammable [6].

1.2.2 Second refrigerants generation – Safety

As time went on, to prevent dangers caused by natural refrigerants, like toxicity and flammability, the biggest refrigeration companies pooled their forces to develop a new chemical class of refrigerants: chlorofluorocarbons (CFCs). This refrigerant is a single molecule made up of fluorine, chlorine and carbon atoms. CFCs gas does not separate out for the change of pressure and temperatures and only ultraviolet light can break their chemical bonds. This aspect is very important because it simplifies the refrigeration systems design thanks to its stability at different conditions [6].

CFC gases were principally adopted in the refrigeration industry (in particular R11, R12 and R502) and in the spray industry, as liquid gas need to expel the liquid contained inside. [7]

1.2.3 Third refrigerants generation – Ozone protection

In 1974 two scientists, Rowland and Molina, discovered an important CFCs characteristic that changed their utilization. Ones that these refrigerants had spilled out from the spray or if there were leakages in the refrigeration systems, they reach stratosphere and their chemical bonds are destroyed by the photolysis (light-initiated decomposition) through ultraviolet rays.

When chemical bonds break up, chlorine atoms drift freely and become a catalyst that breaks unstable ozone molecules (O_3) into oxygen molecules (O_2). Chlorine is not consumed during the reaction, so it can continue ruining ozone for years. This fact represents a big deal, because stratospheric ozone is the shield that protects all living things on the planet from ultraviolet radiations. [8]

What happened after this worrying discover was a difficult period for the refrigeration world. This trouble was due to the prohibition to produce refrigeration systems with CFCs gases to avoid getting worse the ozone conditions. What is more, refrigeration industry was really penalised because it has focused its effort to develop the performance of CFC machines for many years.

In 1987 the first international agreement, called Montreal Protocol, was signed: it established a progressive CFCs reduction of 50 per cent of its production and consumption before 1999. As a consequence, during the ‘90s conferences to find out a solution for the CFC gases started to be undertook. Due to the alarming reports about the stratospheric ozone situation, in 1991 in London a stop of CFC production until 2000 was decided. After this conference other meetings that aimed to anticipate the London decision and to select other new refrigerants to use took place. CFCs end in Europe was finally determined in 1994 with the new Regulation 3093/94, that established the definitive stop of their production before the 31^{sr} December 1994 [6].

A useful measure that was applied to simplify the measurement required by the Montreal Protocol and its amendment was the Ozone Depletion Potential (ODP). ODP provides a relative measure of the expected impact on ozone per unit mass emission of a gas as compared to that expected from the same mass emission of CFC-11 (R11) integrated over time [9].

Montreal Protocol also regulates the entrance in the market of the third generation of refrigerant: hydrochlorofluorocarbon (HCFCs) and hydrofluorocarbon (HFCs).

HFCs refrigerants do not contribute to ozone depletion since they do not contain chlorine. Among those, the most used are R134a, R404A, R407, R507 and R410A.

At the contrary, HCFCs are less stable gases and contain less chlorine than CFCs thanks to the presence of hydrogen. In this way HCFCs molecules have shorter atmospheric lifetimes than CFCs and deliver less reactive chlorine to the stratosphere where the ozone layer was found. When HCFCs are oxidized in the troposphere, chlorine that is released typically combines with other chemicals to form compounds that dissolve in water and ice and are removed from the atmosphere by precipitations. Thus, chlorine from HCFCs does not reach the stratosphere and does not contribute to ozone destruction. However, a certain portion of HCFC molecules released to the atmosphere will reach the stratosphere and here they will be destroyed by photolysis (by sun ultraviolet rays): thus, the chlorine released in the stratosphere can participate in ozone depleting reactions as chlorine liberated from the photolysis of CFCs, however in lower proportion [10].

The most used HCFCs gases were the R22 and R123.

1.2.4 Fourth refrigerants generation – Global warming

Even if HCFCs gases contain a very low chlorine quantity respect to CFCs, they were view as a temporary replacement for CFCs. In fact, Montreal Protocol limited consumption (defined as production plus imports less exports and specified destruction) of HCFCs in steps in 1996 (freeze at calculated cap), 2004 (65% of cap), 2010 (25%), 2015 (10%), and 2020 (0.5%) with full consumption phase out by 2030 in non-Article 5 countries (mostly developed). For the Article 5 countries (developing countries) the phase out is provided for the 2040 [11].

The discontinuation of the employment of CFC and HCFC brought the industries to the actual condition: the utilization of HFCs, mixtures thereof and natural refrigerants.

Unfortunately, the very successful response to ozone depletion stands in sharp contrast to the deteriorating situation with climate change, as depicted in **Figure 1.5**. Certainly, global warming does not depend only on the refrigeration industry, but there are studies that declared that around 10-15 per cent of global greenhouse emissions (GHG) comes out from refrigerators and air conditioners. Approximately one third of these emissions is due to refrigerant leakage [12].

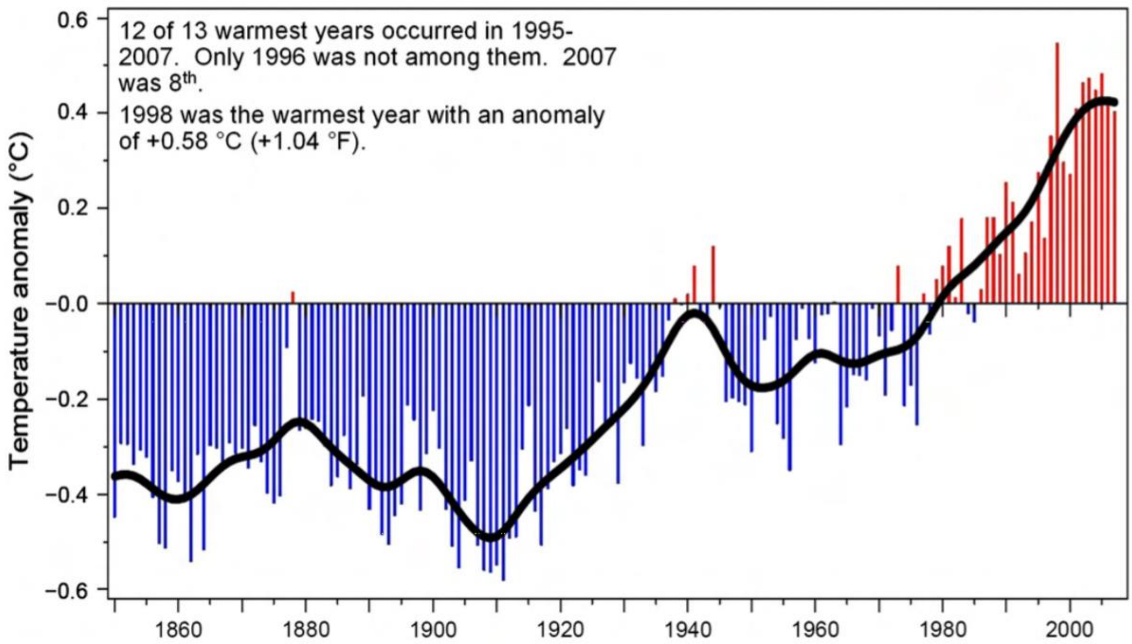

Figure 1.5 *– Global temperature rise. Analyses of three rings, coral reefs, ice cores and other indicators show the 1990s to be the warmest decade in the last millennium and the 20th century to be its warmest century* [4]

Climate changing became rapidly a big problem and governments started to take care about it. In 1998, during Kyoto Mondial conference, pursuant to the United Nations Frame-work Convention on Climate Change (UNFCCC), Kyoto Protocol was defined. It set binding targets for greenhouse gas emissions based on calculated equivalents of the following gases:

- Carbon dioxide (CO_2)
- Methane (CH_4)
- Nitrous oxide (N_2O)
- Hydrofluorocarbon (HFC)
- Perfluorocarbons (PFCs)
- Sulphur hexafluoride (SF_6).

Kyoto Protocol aims to reduce the GHG emissions of these gases of about 5 per cent during the period from 2008 to 2012, setting 1995 as the base year for HFCs, PFCs and SF_6 , while 1990 for the other gases (Article 3 of the Kyoto Protocol) [13].

Since that moment many countries have implemented Kyoto Protocol by imposing taxes and recent more stringent measures (either adopted or proposed) at regional, national, state, and municipal levels.

The measure that is generally used to define the gas environmental impact is Global Warming Potential (GWP). It was developed to allow comparisons of the global warming impacts of different gases. Specifically, it is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO_2). There are three periods of time that could be used, 20, 100 and 200 years, but for the GWPs evaluation 100 years is usually used. The value of ODP and GWP values of the CFCs, HCFCs, HFCs, natural gasses and hydrofluoroolefin (HFOs) are shown in

Table 1.1 [14].

***Table 1.1** – Ozone Depletion Potential and Global Warming Potential values for the principal refrigerants used in refrigeration [15]*

Refrigerant	ASHRAE denomination	ODP	GWP	GWP weight
CFC	R12	1	10900	High
	R502	0.33	4657	High
HCFC	R22	0.055	1810	Medium
	R123	0.06	77	Low
HFC	R32	0	675	Medium
	R143a	0	1430	Medium
	R404A	0	3922	High
	R407C	0	1774	Medium
	R410A	0	2088	Medium
	R507A	0	3985	High
HFO	R1234yf	0	4	Low
	R1234ze	0	6	Low
Natural	R170 (Ethane)	0	6	Low
	R290 (Propane)	0	3	Low
	R600a (Isobutane)	0	3	Low
	R717 (Ammonia)	0	0	Zero
	R744 (Carbon dioxide)	0	1	Low
	R1150 (Ethylene)	0	4	Low
	R1270 (Propylene)	0	2	Low

In 2006, the European parliament approved the Regulation (EU) No 842/2006 that set the time steps that would ban the fluorochemical (also called F-Gas) refrigerants. Later, in 2014, the European union substituted the previous Regulation (EU) No 842/2006 with the new Regulation (EU) No 517/2014 [16]. This new regulation is more restrictive than the previous one: it briefly introduces quota that limits the quantities of HFCs that producers or importers can put on the market and describe how to deal with hydrochlorofluorocarbon gases.

F-gas Regulation brought to the development of the fourth refrigerants generation: HFO and HFCs mixture with low GWP. In parallel to these two gas families, natural refrigerants as Propane (R290), Ammonia (R717), Carbon dioxide (R774) etc. continued to exist, with their characteristics that were already known. It is very important to underline that F-gas Regulation is valid at European level.

Another decision was taken after Kyoto in October 2016 through the Kigali amendment: adding to the Montreal Protocol the phase-down of the production and consumption of HFCs. It was ratified by 56 parties and these are classified as Article 5 (developing countries) and Non-Article 5 (developed countries) countries. In **Table 1.2** is shown the HFCs phase down [17][18].

Table 1.2 *– Kigali HFCs phase down for Article 5 and Non-Article 5 countries* [18]

	Non-Article 5		**Article 5**	
Baseline year	2011, 2012 & 2013		2020, 2021 & 2022	
Step 1	2019	10%	2029	10%
Step 2	2024	40%	2035	20%
Step 3	2029	70%	2040	30%
Step 4	2034	80%	2045	85%
Step 5	2036	85%		

An important aspect is that the U.S. do not ratify the amendment and currently they have not taken a decision about the HFCs phase down.

1.3 Classification and use of refrigerants

1.3.1 Refrigerants denomination

The ANSI/ASHRAE 34-2016 Standard 34 describes a shorthand way of naming refrigerants. At the beginning of the name there is an “R” that stand for refrigerant. After the first letter there are three or four numbers: the first on the left identifies the component that the gas comes from, the other ones compose a combination series that identifies better the kind of gas [19].

- Serie R000 : derived compounds from methane. Ex. R50 is the methane;
- Serie R100 : derived compounds from the ethane. Ex. R170 is the ethane;
- Serie R200 : derived compounds from the propane. Ex. R290 is the propane;
- Serie R300 : derived compounds from the butane. The butane is called R600 to avoid series problem;
- Serie R400 : zeotropic mixture, the temperature change during the phase change at constant pressure (glide). Ex. R410A, the last letter identifies the different concentration by weight;
- Serie R500 : azeotropic mixture, the temperature does not change during the phase change at constant pressure;
- Serie R600 : organic compounds. Ex. R601 is the pentane;
- Serie R700 : inorganic compounds with molar mass lower or equal to 99 atomic mass unit. Ex R744 is the carbon dioxide;
- Serie R1000 : unsaturated inorganic compounds. In the case of isomers in the propane series (R1200) are added at the end two letters. Ex. R1234yf;
- Serie R7000 : inorganic compound with a molar mass higher than 99 atomic unit mass.

In addition to the nomenclature there is the safety classification, which differentiates refrigerants basing on their toxicity and flammability level. This classification is composed by a letter and a number [20]. The letter could be:

- "A": signifies refrigerants for which toxicity has not been identified at concentrations less than or equal to 400 [ppm];
- "B": signifies refrigerants for which there is evidence of toxicity at concentrations below 400 [ppm].

While digit identifies the flammability level:

- "1": non-flammable, it indicates refrigerants that do not show flame propagation when tested in air at 60 [°C] and 101.3 [kPa];
- "2": lower flammability, it indicates refrigerants having a lower flammability limit of more than 0.10 [kg/m^3] at 60 [°C] and 101.3 [kPa] and a heat of combustion of less than 19 [kJ/kg];
- "2L": it is a sub classification of class 2 refrigerants which present a maximum burning velocity less than or equal to 10 [cm/s] when tested at 23 [°C] and 101.3 [kPa];
- "3": higher flammability, it indicates refrigerants that are highly flammable as defined by a lower flammability limit of less than or equal to 0.10 [kg/m^3] at 21 [°C] and 101.3 [kPa] or a heat of combustion superior than or equal to 19 [kJ/kg].

In

Table 1.1 are presented the safety classification of the principal refrigerants used in refrigeration.

Table 1.3 *– Toxic and flammability classification of the principal refrigerants used in refrigeration* [21]

ASHRAE denomination	**Denomination**	**Safety classification**
R717	Ammonia	B2
R744	Carbon dioxide	A1
R290	Propane	A3
R600a	Isobutane	A3
R134a		A1
R404A		A1
R1234yf		A2L
R1234ze		A2L

It is important to know that an A2L refrigerant is classified as “lower flammability”, so it must be used only in those refrigeration systems that are designed by considering refrigerant flammability risk. An A2L refrigerant must not be used to substitute a non-flammable refrigerant without a full risk assessment and necessary modifications [22].

1.3.2 Current refrigerant gases application

The aim of this chapter is to describe which are the typical refrigerants used up to 2018 in the refrigerant industry. In **Figure 1.6** is represented a statistic, referred to the first quarter of 2018, provided by the European Commission about the sectorial distribution of refrigerants in Europe. It is possible to see that the commercial refrigeration covers the 17.1 per cent of the total refrigerants consumption.

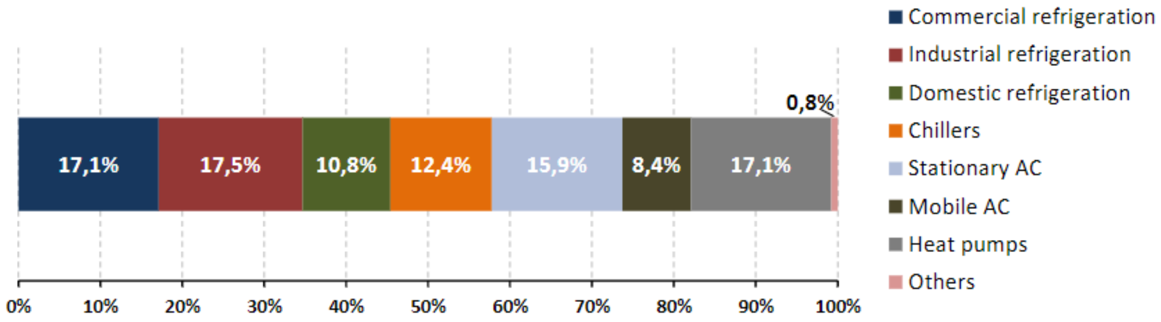

***Figure 1.6** – Sectorial distribution of refrigerants* [23]

The refrigerant gases used nowadays could be a substance or mixture both are used in the refrigeration industry to exchange heat. Refrigerant mixtures are created to satisfy needs that refrigerants on their own are not able to satisfy.

There are two families among the mixtures: azeotropic (R4xx) and zeotropic (R5xx) mixtures. To understand which is the difference between these two gases, the gas behaviour has to be defined. During the boiling process for a refrigerant two temperatures are defined:

- Saturated liquid temperature (bubble point temperature): it identifies the temperature which leads a liquid refrigerant to first begin to boil. Instead, in the condensing process, the bubble point temperature is when all refrigerant condensed and became liquid;
- Saturated vapor temperature (dew point temperature): it identifies the moment when the last drop of liquid refrigerant has boiled. Instead, in the condensing process, the saturated vapor temperature (dew point) is the temperature at which the refrigerant vapor first begins to condense.

At constant pressure, the difference between the saturated vapor temperature and the saturated liquid temperature is referred to as the "temperature glide" of the refrigerant [24]. It is measured in Kelvin.

It is possible to see the temperature glide in zeotropic mixtures. At the contrary, azeotropic mixtures behaviour is the same as water behaviour: they evaporate and condense at one temperature, so the glide temperature is 0 [K].

At the end of the presentation of all the existing refrigerants, I am going to speak about the HFCs refrigerants, that are the most used, and their application sector according to Linde (a world leading company gases supplier) [25]:

- R134a (GWP 1430) is an extremely common refrigerant, and it is used in a wide range of refrigeration and air conditioning applications, including medium and high temperature refrigeration (both domestic and commercial), residential & light air conditioning, automotive air conditioning and industrial applications such as centrifugal chillers. It is also a common component in many HFC refrigerant blends and is used in some propellant applications. It will be banded from 2022;
- R404A (GWP 3922) and R507A (GWP 3985) are HFCs mixtures that are widely used in low and medium temperature refrigeration applications, such as those used in commercial refrigeration. Whilst they have become the widely accepted alternative to CFC R502, they are coming under greater scrutiny due to its high Global Warming Potential, leading to an increased focus on lower GWP alternatives such as R407A, R407F and R442A. They will be banded from 2020;
- R407A (GWP 1774) is an HFC blend that is suitable for use in low and medium temperature refrigeration applications, such as those used in commercial refrigeration. It is an ideal retrofit solution for many existing R404A and R507A systems, offering a substantially lower carbon footprint due to its lower GWP, and improved energy efficiency. It will be banded from 2022;
- R410A (GWP 2088) is an HFC blend designed for new R22 applications. It operates at higher pressures than many other refrigerants, and so cannot be used to retrofit R22 systems. Systems designed for R410A can take advantage of its ability to use smaller components, making it a key refrigerant for domestic and light air conditioning equipment. R410A has low glide also makes it suitable for some centrifugal compressors, and it can operate in low temperature applications. It will be banded from 2022.

Concerning the natural refrigerants, the most commonly used are:

- R717 (Ammonia) has been used in industrial applications since the 1930s and is generally acknowledged as being the most efficient refrigerant. It has a low boiling point and is favoured because it is a highly energy efficient refrigerant which also has minimal environmental impact, having zero ODP and zero GWP. Its problem is that is toxic and it is classified as low flammability (safety classification B2), for this reasons refrigeration system that use ammonia are located far from public locals;
- R600a (Isobutane) has low environmental impact and excellent thermodynamic performance and it is now the refrigerant gas of choice in domestic and small commercial refrigerators. It is non-toxic but has high flammability (safety classification 3), with zero ODP and GWP equal to 3.

It has to be said that in addition to the natural refrigerant cited above, R290 (Propane) and R714 (CO_2) should be mentioned. These two gases are not currently so much used in the market, because the components that they required are more expensive compared to the other gases, even if efficiency is comparable and, in some case, even better. However, thanks to the F-Gas Regulation, in a few years these gases will able to substitute the HFCs gases.

1.3.3 Common vending machines working gas

Among all refrigerants discussed in Chapter 1.3.2, the refrigerant mostly used in the vending machines sector are R134a and R404A; some companies like SandenVendo Europe use also CO_2. These two gases assure the absence of safety problems because they are non- toxic and non-flammable. In this way there are no limit charge and the IEC 60079 explosive atmosphere standards could not be followed.

The refrigerant is chosen in function of two factors: temperature application and heat load. With regard to temperature, we have to differentiate positive temperature (snack and drink vending machines) in which R134a is preferred, and negative temperature (ice-cream vending machine) where R404A is generally used. Considering vending machines dimensions the required heat load becomes very important, so in case of a big snack machine the refrigerant that it is used is R404A.

It is very important to underline that the gases already described belonged to the HFCs family and they are subjected to the F-Gas Regulation (described in Chapter 2.1). More precisely R404A will be expired in 2020 while R134a will be banned in 2022. For this reason, vending machine producers are developing new refrigeration systems with different refrigerants. Currently possible solutions are natural gases like propane (R290) or hydrofluoroolefin (HFO) gases like R1234yf, but due to their flammability classification, respectively A3 and A2L, both these refrigerants require to follow the explosive atmosphere standards.

Thanks to the CO_2 vending machine production, SandenVendo Europe is ready for the F-Gas requirements. Unfortunately, this machine will not be produced, mainly because the company that sold CO_2 compressors to SandenVendo Europe will not produce them anymore.

Consequently, SandenVendo Europe decided to design a new vending machine refrigeration system with a non-HFCs refrigerant. They analysed all the possible solutions and they decided that R290 (propane) would be the best refrigerant for their future vending machine. SandenVendo Europe S.p.A will be the first vending machine company in the world that has designed, certificated and patented a new refrigeration system that use as working fluid the R290.

1.4 How does refrigeration system work

In vending machines, the refrigeration system does not generally differ to those that are used in other sectors of refrigeration industry. This chapter is going to present the main components of a refrigeration system and the most important characteristics of each one.

Refrigeration systems are composed by four main components: compressor, condenser, throttling valve and evaporator. **Figure 1.7** shows a generic refrigeration working cycle in a pressure-volume diagram; the principal phases are highlighted.

- 1 – 2 : Compression;
- 2 – 3 : Condensation;
- 3 – 4 : Expansion;
- 4 – 1 : Evaporation.

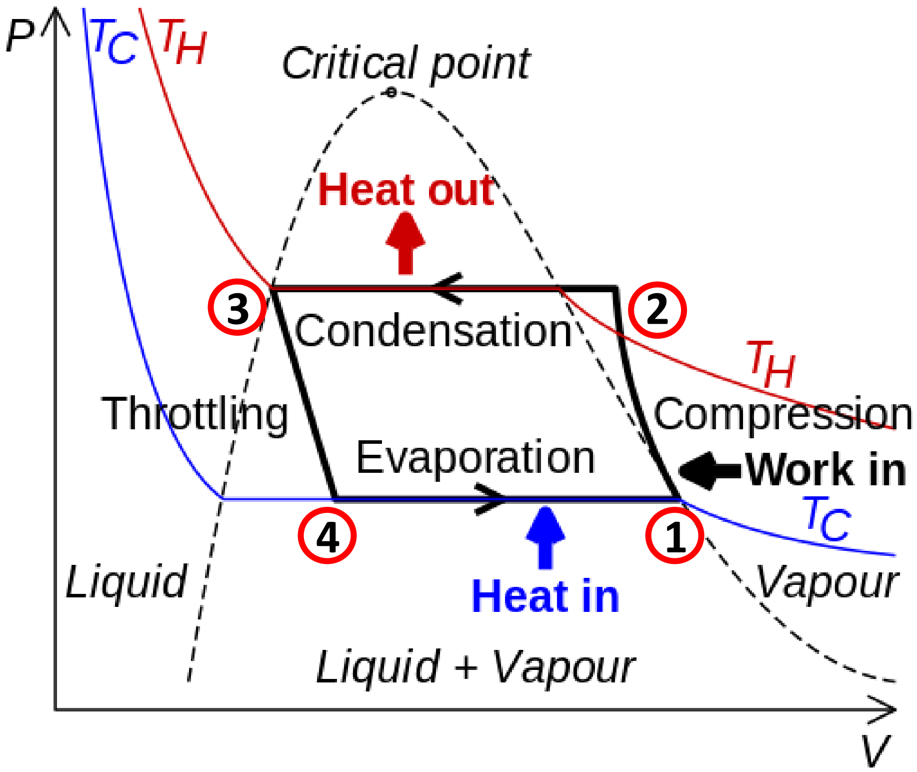

***Figure 1.7** – A generic refrigeration working cycle* [26]

1.4.1 Compressor

The compression phase is represented in **Figure 1.7** (point 1 to 2). During this phase the compressor sucks vapor that comes from the evaporator and compresses it to the condenser, increasing its pressure and temperature and decreasing its volume. These two pressure levels set the temperature at which the refrigerant exchanges heat thanks to the phase change.

When we have to design a compressor there are some fundamental aspects to keep in mind. First of all, the refrigerant must not have any liquid particles at the compression suction to avoid compressor damage. To prevent this problem, as soon as the refrigerant comes out from the evaporator it is heated in order to make its last liquid parts evaporate. Secondly, it is important to choose the right oil to lubricate the compressor mechanical components among all the different existing oils, since each one is compatible with a certain refrigerant. In addition to the oil selection, it has to be always guaranteed oil presence and its return into the compressor. In the end, compressor must not overheat to avoid significant efficiency drops and to extend compressor life.

Compressors are divided into three categories:

- Hermetic: electric motor and compressor are confined in a single outer welded steel shell, so they can operate in an isolated environment. Since the motor takes place in the refrigerant circuit, the efficiency of hermetic compressor-based systems is not so high because the heat dissipated by the motor and compressor becomes part of the system load. On the other hand, air and dust do not have the possibility to enter inside and dirt the lubricant and moving parts. Material compatibility must be ensured between the electrical windings, refrigerant and oil. What is more, when this compressor stops working, it has to be completely replaced, because a hermetic system cannot be opened;
- Open: compressor and electric motor are completely separated components. This design can assure a high thermal efficiency because the electric motor can dissipate its heat to the environment, and an open system also allows parts replacement when a problem occurs. A disadvantage is that this design often requires maintenance;
- Semi-hermetic: it is a unit that features elements of both designs.

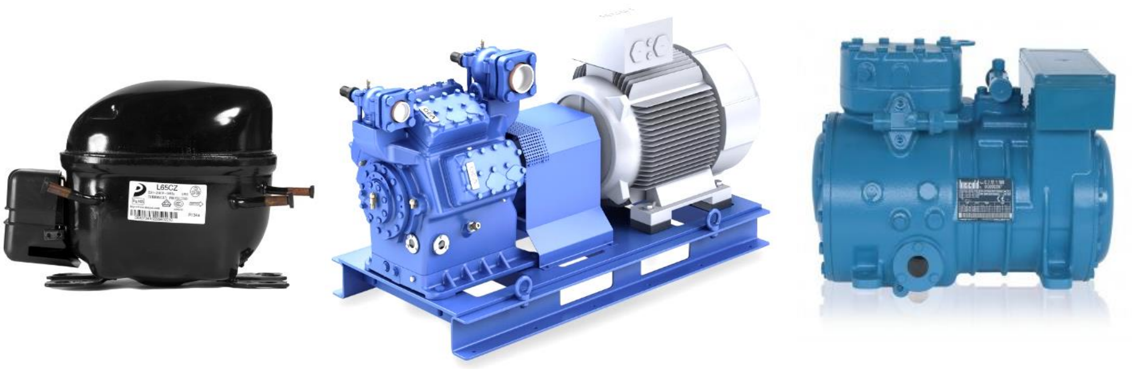

Figure 1.8 *– From the left-hand side: hermetic compressor, open compressor and semi-hermitic compressor*

Hermetic compressors are the most used in domestic and in some commercial refrigeration thanks to their small dimension, simple design and low maintenance. At the contrary, the semi-hermetic and open options are used when high power is required.

In the market there are several types of hermetic compressors which differ in the compression system that they use. Here below the compressors that are most commonly used in domestic and commercial refrigeration are listed:

- Reciprocating compressors: they have a cylinder that contains a piston that moves up and down which is connected to the connection rod and the crank; there are two laminar valves that let the gas enter and exit. Vapours from the suction line are moved through the intake valve inside the cylinder thanks to the depression created by piston downward motion. When the piston moves upward, it compresses refrigerant vapours which are then pushed through the exhaust valve that will be opened by refrigerant high pressure. Not all the compressed refrigerant leaves the cylinder: in fact, reciprocating compressors leave a small amount of compressed gas in the cylinder because touching the head or valve plate is not practical for the piston. This mechanical system is also used in automotive sector but after the compressor the combustion phase is added. Reciprocating compressor weakness are:
  - Production of considerable vibrations and a noisy compressor due to the alternative motion;
  - Inconvenience of regulating outer pression or mass flow rate with by-pass or other methods;
  - Need of a high starting torque to contrast its internal friction;
  - Low efficiency due to its internal friction and leakages from valves.

  By the way, the reciprocating compressor is mainly used for low power domestic and commercial refrigeration and when a compact compressor is required.

Figure 1.9 *– A hermetic reciprocating compressor* [27]

- Scroll compressors: they have one fixed scroll which remains stationary and another moving scroll coupled to the motor, that rotates through the use of swing link. Vapours enter through refrigerant inlet that is located close to the outer scroll inside the space between the two scrolls. After the suction phase the compression chamber gets smaller thanks to the outer scroll motion, and trapped refrigerant is compressed. The maximum pressure is reached when the compression chamber reaches its minimum volume, then the refrigerant is pumped out through outlet port located in the centre of the scroll. These suction, compression and discharging processes are continuously repeated and are shown in **Figure 1.10**. Scroll compressor advantages include smaller dimensions and lower weight than reciprocating compressors of same capacity. They also are characterized by very high efficiency at the design compressor ratio, even if it decreases at different working conditions. They are mainly use for high cooling capacity and their best feature is a smooth and quiet operation thanks to its fewer moving parts and less torque variation compared to the reciprocating compressors.

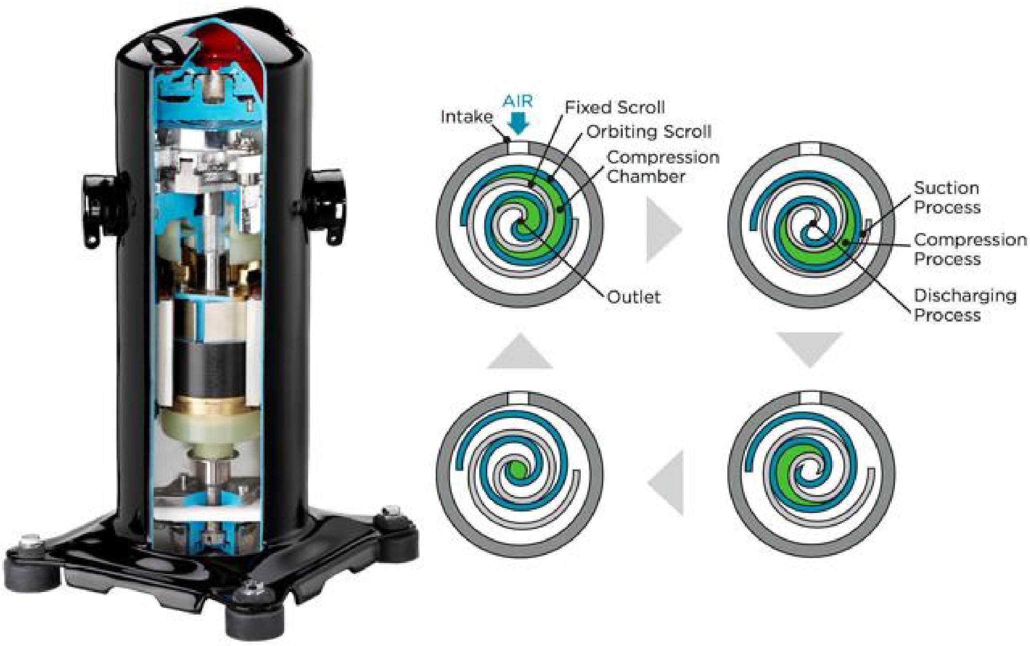

Figure 1.10 *– A hermetic scroll compressor with a scroll system detail* [28]

- Rotary vane compressors: they consist of a cylindrical casing, two openings - one suction and one discharge - and a rotor positioned eccentrically respect to the casing. Compression occurs by refrigerant flowing into the chamber where, due to eccentric rotation, there is a reduction in the desired volume. A detail of this compressor is shown in **Figure 1.11**. This compressor is used to substitute low cooling capacity reciprocating compressor when vibrations and noises are not desired. Recently, to satisfy high cooling capacity a second rotor that revolves in counter rotating directions has been added to this compressor in the same shaft. This feature grants a wider range of applications making this compressor suitable for the commercial and industrial markets, and it is preferred to the more expensive scroll compressors.

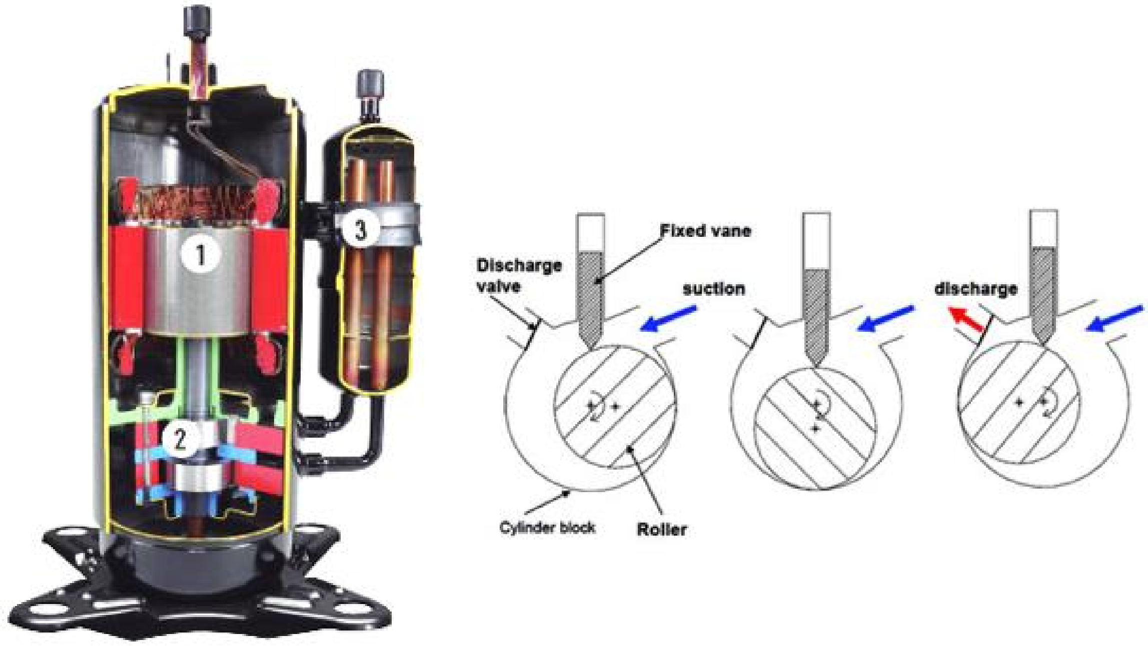

Figure 1.11 *– A twin hermetic rotary vane compressor with rotary system detail* [29]

1.4.2 Throttling valve

The throttling valve realizes the isenthalpic refrigerant expansion that makes the refrigerant cool down thanks to the transformation of pressure energy into friction. This component is located between the condenser and the evaporator and in the pressure-volume diagram shown **Figure 1.8** is represented by the evolution from point 3 to 4.

The simplest and most economic throttling valve is called capillary tube. It is a copper pipe with a small internal diameter (diameter 0.5 to 1.5 [mm] and length 1.5 to 6 [m]) that connects the condenser to the evaporator. This solution entails a difficult design because there are no specific mathematic formulas: for this reason the selection of the right capillary tube is only possible with experience and by doing tests. The two parameters that assure the achieving of a determined pressure drop are length and diameter. A bad design can occur in one of the following situation:

- Small diameter or short tube: it creates resistance to the liquid passage, in this way not all the liquid generated by the condenser can pass through the capillary tube and it remains inside the condenser;
- Big diameter or long tube: it tries to pass more liquid than the condenser can condense, as a result through this capillary tube will enter also vapor. Due to the fact that vapor tends to occupy a higher volume than liquid, it follows that the liquid flow through the tube is reduced.

Both situations decrease refrigeration system cooling capacity and its efficiency. A well design capillary tube can work within pressure range by varying refrigerant mass flow rate that pass through itself. This pipe tubes can be found on small, high-volume commercial systems such as household refrigerators, but can also be used for larger systems if the operating conditions are relatively stable.

Due to the small diameter, the capillary tube is vulnerable to clogging, which is why a filter drier and filter are normally mounted before the inlet. It is very important to select the right filter to avoid that it has too fine texture such a way that could happen high pressure losses or that particles block the refrigerant passage.

It is very useful to cool down the refrigerant in the capillary tube to obtain a subcooled liquid by heating the refrigerant that is sucked by the compressor, in order to avoid liquid suction. The subcooled liquid helps to obtain more liquid in the evaporator inlet and in doing so, there will be more cooling capacity thanks to the evaporation of more liquid. This application lead to an efficiency increase but the vapor heated does not exceed a certain temperature to avoid that at compressor outlet refrigerant has a temperature too high.

A possible solution to realize what is already described is shown in **Figure 1.12**, where the capillary tube is in rolled out onto the suction line.

Figure 1.12 *– Capillary tube rolled out onto the compressor suction line*

When a variable cooling capacity is needed, it is possible to control the refrigerant passage and the pressure drop between condenser and evaporator, by using a throttle valve instead of the capillary tube. The throttling valve commonly used in refrigeration are floating ball valve and thermal expansion valve. The first valve is mainly used for full liquid evaporator, this type of evaporator requires a certain height of the liquid level, which is guaranteed by the floating ball valve. While the other valve controls the refrigerant flow into the evaporator through controlling the degree of superheat of refrigerant in the evaporator outlet. The thermal expansion valve is widely used in those application where a continuous temperature control is required, like for example in air conditioning applications.

1.4.3 Evaporator and condenser

The same heat exchanger that is used to condense the refrigerant could be adopted to evaporate it, with a difference in the location of this device into the refrigeration cycle. As it is shown **Figure 1.7**, if we install the heat exchanger after the compressor we obtain the refrigerant condensation (points 2 to 3) while if it is located after the throttling valve it is able to evaporate the refrigerant (points 4 to 1).

The devices are designed in order to exchange latent heat at constant pressure and temperature between environment and refrigerant. For a more detailed description, during the condensation phase the refrigerant in vapor phase at high pressure coming from compressor releases latent heat to the environment to change its phase into liquid. The condensation phase is very important because it determines the liquid amount that will be used by the evaporator, and consequently the evaporator cooling load. With regards to the evaporation phase, refrigerant in liquid phase at low pressure coming from the throttling valve acquire latent heat from the environment to change its phase into vapour. The evaporator is the item that let air conditioning system to cool down air or it allows to keep a low temperature inside the fridge.

Usually after the condenser is added a filter with inside particular salts which absorb the moisture residual in the refrigeration system after has been produced. And being a close cycle, the moisture is all removed during the first refrigeration system cycles.

In vending machine, domestic and some commercial applications, the finned tube heat exchanger which is shown in **Figure 1.13** is commonly used. This heat exchanger is mainly applied in cheap applications that involve a considerable amount of heat transfer from a hot fluid to a colder fluid. Usually are added one or more fans in order to increase the heat exchange by convection.

Figure 1.13 *– Finned tube heat exchanger* [30]

The heat exchange offered by finned tube heat exchanger is mainly provided by convection, thanks to the speed of a fluid that enters between two fins, and radiation, while a small contribute comes from conduction between air and tube walls. Usually it is air that passes-through fins and it is moved by fans. As it is possible to see in **Figure 1.13**, heat exchanger is composed by copper tubes where refrigerant flows in, and fins that are attached to them. The advantage of this configuration is the increased heat exchange surface area thanks to the addiction of fins that contribute to exchange more heat. The flow arrangement is a mix between cross-flow, due to the perpendicular fluids travel, and counter-flow, because fluid flow starts and finishes at opposite ends. What it is just described is schematically represented in **Figure 1.14**.

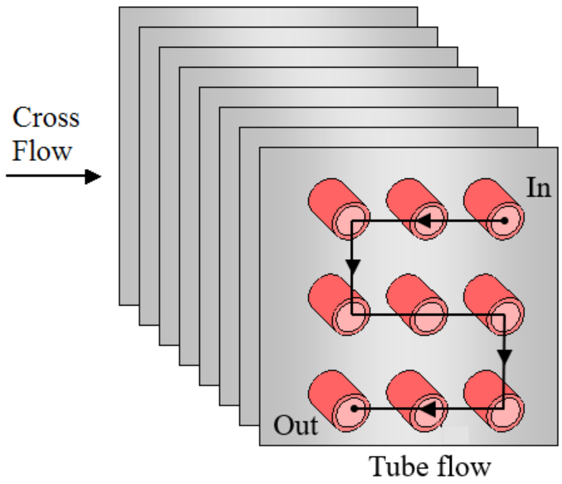

Figure 1.14 *– A schematic finned tube heat exchanger flow arrangement*

During the design phase heat exchanger dimensions should be defined according to request of heat exchange. The parameters that the engineers have to define are the following ones: type and number of tubes, consequently tubes diameter and their pitch, fins type (corrugated, plat, louvered etc.) and fin pitch. The design of this type of heat exchanger is complicated because it needs a good mathematical model that could approximate air flow and refrigerant phase change, which consider properties variation like pressure drop, mass flow rate and density of both fluids. For this reason, finned tube heat exchange is currently being investigated, and for its design data that have been obtained in tests are applied.

The space between two fins allows heat exchange to both condenser and to evaporator. For this reason, a periodic control shall be provided by removing dust or other objects that could obstacle air inlet/outlet that it is formed by heat exchanger normal operation. This control can assure liquid condensation in the condenser and a designed cooling capacity in the evaporator. Another important aspect is the ice formation between evaporator fins, that mainly depends on external air humidity and evaporator temperature. The solution of this problem needs the planning, after some working cycles, of other cycles in which the refrigerant that is pumped by the compressor goes directly to the evaporator: in this way ice melts and the evaporator can work again in design condition.

The rate which heat transfer can occur at depends on three factors: the temperature difference between the two fluids, the heat transfer coefficient between each fluid and the tube wall, and the surface area which each fluid is exposed to.

1.4.4 CO_2 refrigeration system

Carbon dioxide (also called R744) is a gas that meets the demand for a natural refrigerant with low global warming impact, non-toxicity and non-flammability. However, it presents challenges in both its application and handling. The main aspect that influences the CO_2 application is its critical point, that occurs at 72.8 [bar] and 31 [°C]. This characteristic means that, depending on the climate conditions, the system condensing temperature and pressure could be higher than the critical point.

Critical point is the condition at which the liquid and gas densities are the same. When this point is overpassed, the refrigeration system works transcritical and the gas cannot condense into liquid phase: this is the case at standard conditions for CO_2. For this reason, the heat exchanger cannot be called condenser: it is called gas cooler, since it does not exchange latent heat. At the contrary, other gasses like R404A always work subcritical because the condensing temperature is lower than the critical point (e.g., in case of R404A 72 [°C] and 35.7 [bar]) [31].

The single stage transcritical system is represented in **Figure 1.15**. The refrigerant discharged from the compressor (from point 1 to 2) flows into the gas cooler where heat is removed (from point 2 to 3). The refrigerant is cooled down but, since it is above the critical point, it does not condense in this part of the system (from point 3 to 4). Then, the refrigerant passes through the expansion device (from point 4 to 5) and it starts condensing when its pressure drops below the critical point. The saturated refrigerant then flows into the evaporator (from point 5 to 6) where evaporates and superheats (from point 6 to 1). Finally the fluid goes inside a liquid separator and then it is drawn back into the compressor.

Generally, CO_2 refrigeration cycle works subcritical or transcritical depending on the ambient temperature if it is above or below the critical point. The Mollier chart in **Figure 1.15** shows two R744 refrigeration systems: subcritical when the condensation temperature is lower than 31 [°C] and transcritical when the gas cooler exit temperature is higher than 31 [°C]. This aspect strongly affects working pressure, for this reason in commercial application where the ambient temperature change in time is better to use the thermal expansion valve. Whereas in those spaces where the temperature is controlled is more convenient to use the capillary tube. The difference between these two systems is on efficiency, if the system works in transcritical, it can provide lower cooling capacity than subcritical operation, because there is less liquid that evaporates.

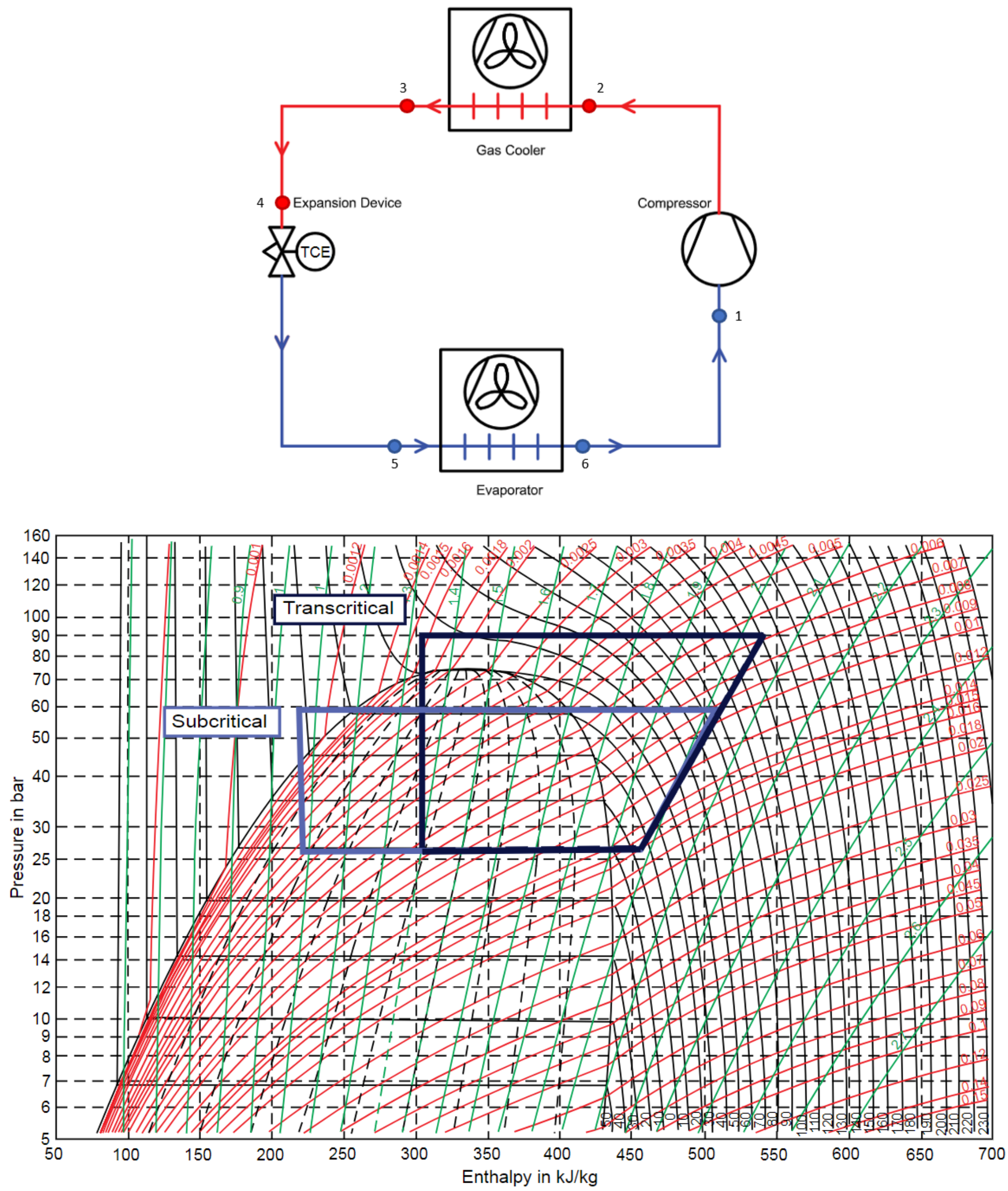

Figure 1.15 – *CO_2 transcritical working cycle scheme and Mollier representation of a CO_2 transcritical and subcritical systems* [31]

The usage of CO_2 as refrigerant presents some advantages concerning the refrigeration system performance. High density (up to five times than R404A) and low compression ration lead R744 system to be characterized by very high volumetric cooling capacity, high isentropic efficiency and a low refrigerant charge. At the same time, the main disadvantages are related to system functioning, that requires to increase tubes thickness and all components have to be designed to handle high-pressure operation. Finally, CO_2 refrigeration system efficiency is strongly affected by the ambient temperature, which has to be controlled to reach high efficiencies [31].

Figure 1.16 shows the CO_2 vending machine transcritical working cycle tested in climate chamber. We can see CO_2 working pressure that starts from 28 [bar] and rises to 97 [bar], while its temperature at compressor delivery is 110 [°C].

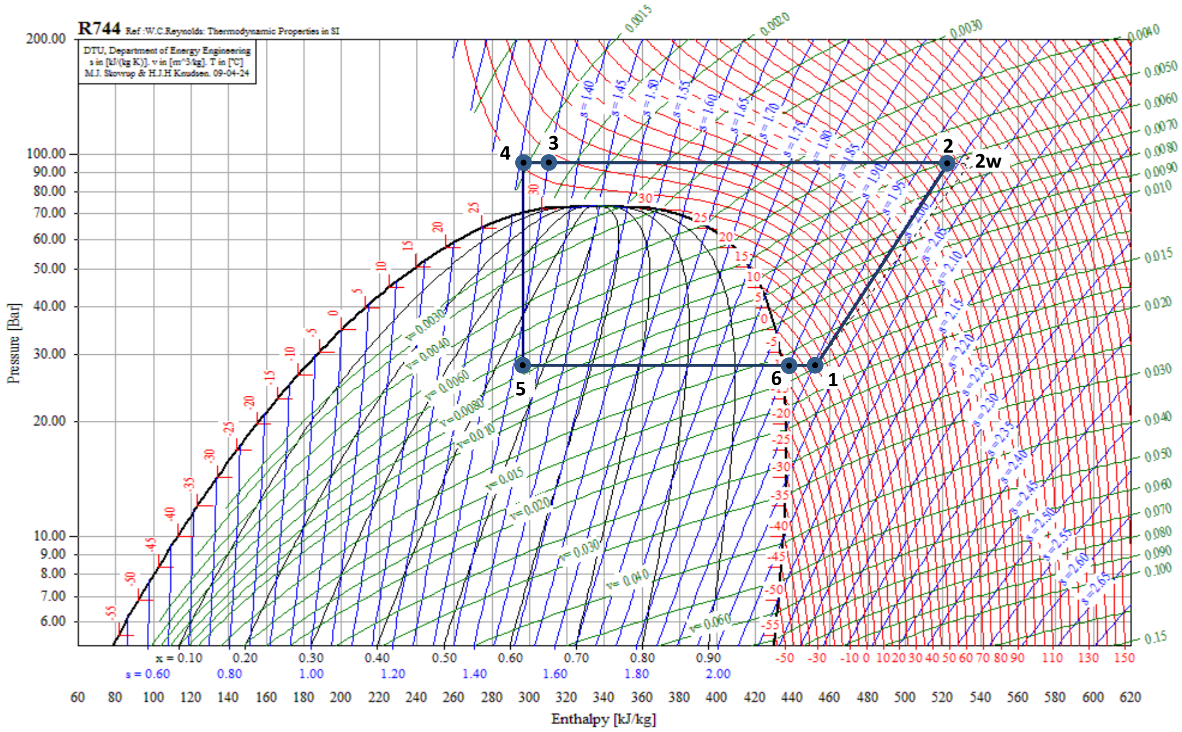

Figure 1.16 – *CO_2 vending machine transcritical working cycle tested in climate chamber*

1.4.5 R404A refrigeration system

R404A is an HFCs refrigerant widely used in refrigeration sectors because it can provide high cooling capacity and good performance. Furthermore, it has a high critical point (72 [°C] and 35.7 [bar]) that let refrigeration system works always subcritical, and it is non-flammable and non-toxic. Thanks to these properties it results easy to handle and to apply. However, R404A has a high GWP level (3922) and according to F-gas Regulation it will be banned from 2020.

Figure 1.17 represents R404A vending machine working cycle. The refrigerant discharged from the compressor (from point 1 to 2) flows into the condenser where latent heat is removed and the refrigerant is condensed (from point 2 to 3). After that the refrigerant is subcooled in order to increase the liquid phase that will evaporate inside the evaporator (from point 3 to 4). Then, the refrigerant passes through the expansion device (from point 4 to 5) and it starts condensing when its pressure. The refrigerant then flows into the evaporator (from point 5 to 6) where it evaporates and superheats (from point 6 to 1) and finally it is drawn back into the compressor.

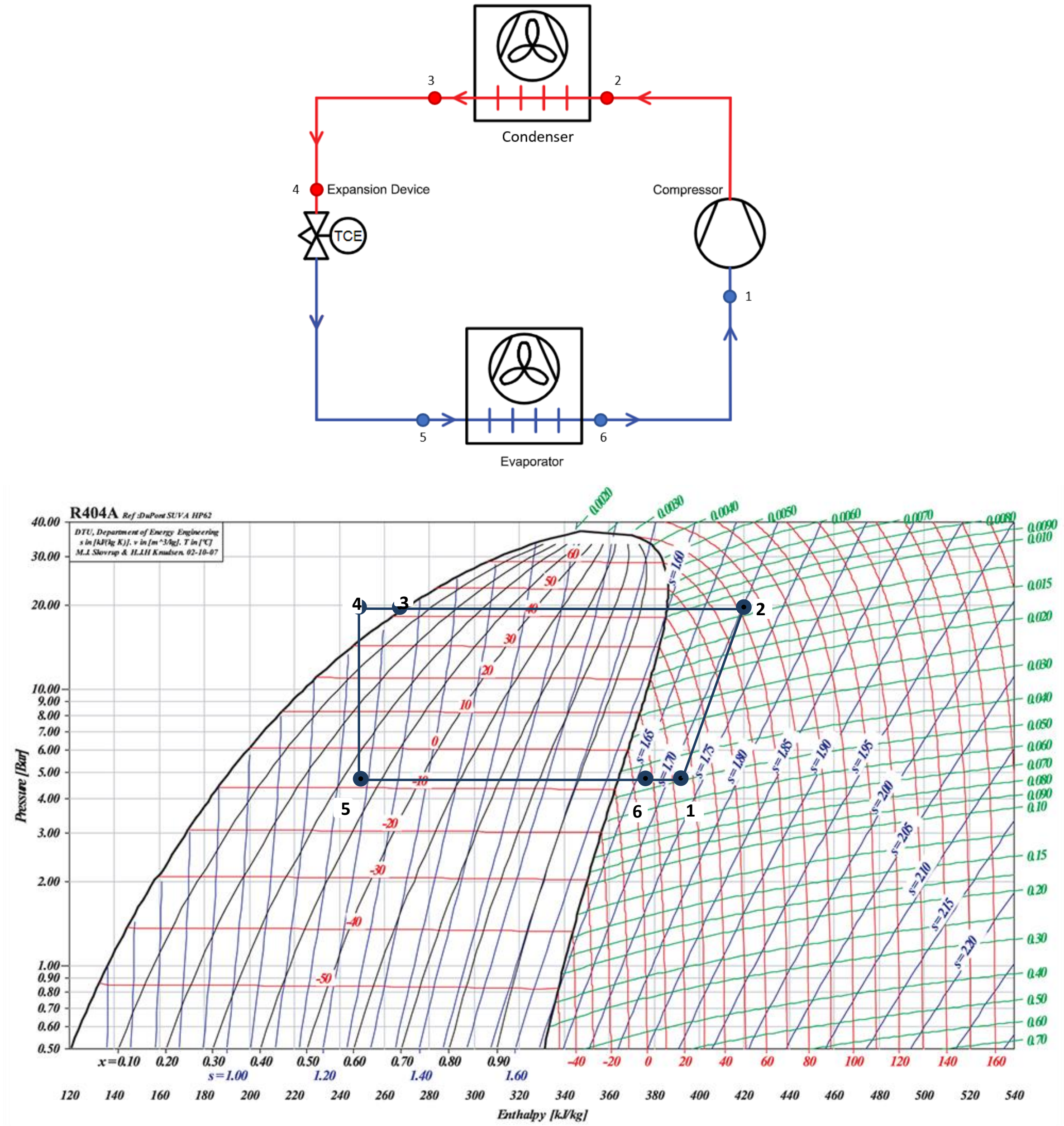

***Figure 1.17** – R404A vending machine working cycle and its representation in the Mollier diagram*

From **Figure 1.17** it is possible to see R404A working pressure that starts from 4.5 [bar] and rises to 20 [bar], while its temperature at compressor delivery is 71 [°C].

CHAPTER 2

2 Aim, material and methods of the thesis

The F-gas Regulation guided the refrigerant trend towards to alternative refrigerants and in more detail to flammable refrigerants compared to previous ones as HCFCs. Currently, with regards to domestic and commercial refrigeration, the possible choice is among three families: hydrocarbons, HFO and carbon dioxide. Hydrocarbons, defined as high flammable, are now widely used in small integral systems as well as in some larger systems. HFOs, such as R1234yf, are characterized by a lower flammability; they were firstly adopted in automotive sector but are now being introduced in other applications. Finally CO_2, a natural and non-flammable refrigerant, finds more application in commercial sector due to its high operation pressures.

The refrigerants that is currently used by SandenVendo Europe in their vending machines are R134a, adopted for small vending machines, R404A, used for big and for negative temperature vending machines, and R744 (CO_2), that is a perfect R404A substitute if we want a natural refrigeration system. Among these refrigerants, R404A and R134 will be banned by the F-gas Regulation (respectively from 2020 and 2022), and consequently R744 is the only one that could be used.

CO_2 vending machine refrigeration system, as explained in chapter 1.4.4, presents some disadvantages that lead SandenVendo to stop CO_2 vending machine production:

- Efficiency is strongly affected by ambient temperature. Since R744 has its critical point at low temperature 31 [°C] and at high pressure 72.8 [bar], its working cycle could be subcritical or transcritical depending on ambient temperature. The refrigeration system works subcritical when it is possible to condensate the gas, i.e. the condensation temperature is lower than 31 [°C]. On the other hand, the transcritical system cannot condense the gas because it is not possible to reach the condensation temperature.
  The difference between these two systems is the liquid amount inside the evaporator, which determines the evaporator cooling capacity and the refrigeration system efficiency. Since the subcritical system, thanks to the possibility to condense the gas, can provide more liquid than the transcritical one, is more efficient.

- Operating pressure are very high. Subcritical system has lower working pressures (between 50 and 65 [bar]) if compared to transcritical system (between 90 and 100 [bar]), but they are still higher than pressures of other refrigeration systems. The high working pressures are necessary to deal with carbon dioxide, but unfortunately create a lot of noise due to vibrations generated by the compressor.

In addition to the technical aspects, there is also an economic reason that brought SandenVendo to stop CO_2 vending machines production. This decision regards the reciprocating CO2 compressor produced by Sanden, which compressor has been out of production since the beginning of 2018. Currently there is one CO_2 reciprocating compressors suppliers and is around three times more expensive than the previous compressor.

In doing so, SandenVendo Europe decided to design a new refrigeration system which uses a refrigerant consistent with F-gas Regulation. Among all the possible solutions, the refrigerant selected is propane (R290).

R290 is a natural refrigerant which has a low GWP level equal to 3 and it does not contribute to ozone depletion, it is non-toxic, but it is classified as high-flammable (A3). This refrigerant has been already used in domestic and commercial applications, but it has never been used in vending machines since the numerous electric components that are located inside a vending machine could trigger a spark and consequently the gas explosion. For this reason, International Standards like IEC 60079 and IEC 60335, which explain how deal with electric components in explosive environments, and European standards like UNI EN 378, which specifies how to use refrigerants, shall be followed to design and create the new refrigeration system.

With the aid of these regulations and of the SandenVendo Europe engineers' experience the R290 vending machine prototype has been produced and consequently patented. Most of my internship at SandenVendo Europe was spent helping them with this deal, so the aim of this thesis is the evaluation of the propane refrigeration system performance in comparison to the R404A one.

2.1 Regulations

To the aim of the thesis is very important to explain the whole of regulations about the usage of propane in vending machines. The most important are:

- Among the European regulations, F-Gas Regulation (that aims to reduce the HFCs gases use) and UNI EN 378 (which describes how to adopt refrigerants in each sector)
- Among the international regulations, IEC 60079 and IEC 60335, that explain how to deal with electronic devices in explosive environments.

2.1.1 F-Gas Regulation No 517/2014

This regulation aims to reduce the HFCs refrigerants adoption in new refrigeration systems, because these gases contribute to greenhouse effect. It was approved by European Union in 2014, and in this thesis are descripted the most important points.

Article 3: In case of losses detected by the refrigeration circuit, the operator has the duty to have it repaired without undue delay. Furthermore, during installation, servicing, maintenance, repair or dismantling of the equipment, the refrigerators take precautionary measures to prevent gas leaks.

Article 4: The obligation to keep the system booklet and to periodically check the leakages no longer depends on the 3 kg charge threshold but varies according to the type of refrigerant: the most polluting ones (such as R404A, for example) must have booklet and be verified also for modest charges (just under 1.3 kg for the R404A). The cold rooms of trucks and refrigerated trailers are also included in these obligations. If the charge is in any case less than 3 kg (6 kg if the circuit is hermetically sealed) this obligation enters into force from 1 January 2017.

Moreover, the frequency of leakage checks is no longer established on the basis of the charge kg of the circuit, but on the basis of its pollution potential (kg charged per refrigerant GWP) as shown in

Table 2.1.

Table 2.1 *– Equipment control frequency*

Kind of equipment	Control frequency
Equipment that contains 5 tons or more, but less than 50 tons of $C0_2$ equivalent	At least every 12 months Or Where a leakage detection system is installed at least every 24 months
Equipment that contains 50 tons or more, but less than 500 tons of $C0_2$ equivalent	At least every 6 months Or Where a leakage detection system is installed at least every 12 months
Equipment that contains 50 tons or more, but less than 500 tons of $C0_2$ equivalent	At least every 3 months Or Where a leakage detection system is installed at least every 6 months

Article 6: Who sells F-gas keeps a register where he records:

- The quantity and type of fluorinated greenhouse gases installed;
- The quantities of fluorinated greenhouse gases added during installation, maintenance or servicing or due to leakage;
- Whether the quantities of installed fluorinated greenhouse gases have been recycled or reclaimed, including the name and address of the recycling or reclamation facility and, where applicable, the certificate number;
- The quantity of fluorinated greenhouse gases recovered;
- The identity of the undertaking which installed, serviced, maintained and where applicable repaired or decommissioned the equipment, including, where applicable, the number of its certificate;
- The leakages dates and results of the checks carried out under Article 3;

- If the equipment was decommissioned, the measures taken to recover and dispose of the fluorinated greenhouse gases.

Article 8: It is mandatory to recover F-gases also from cooling circuits of refrigeration units of trucks and refrigerated trailers.

Article 10: Operators must be trained and in function of the type of equipment and kind of work they have to get a certification. The certification programmes and training cover:

- Applicable regulations and technical standards;
- Emission prevention;
- Recovery of fluorinated greenhouse gases;
- Safe handling of equipment of the type and size covered by the certificate;
- Information on relevant technologies to replace or to reduce the use of fluorinated greenhouse gases and their safe handling.

Article 11: The purchase of HFC refrigerants is allowed only to certified companies or employing certified personnel. If an equipment that is not hermetically sealed pre-loaded with HFC gas is sold to end users only if the installation is performed by a certified company. It is also prohibited placing on market product and equipment listed in Annex III of the Regulation and here represented in **Figure 2.1**.

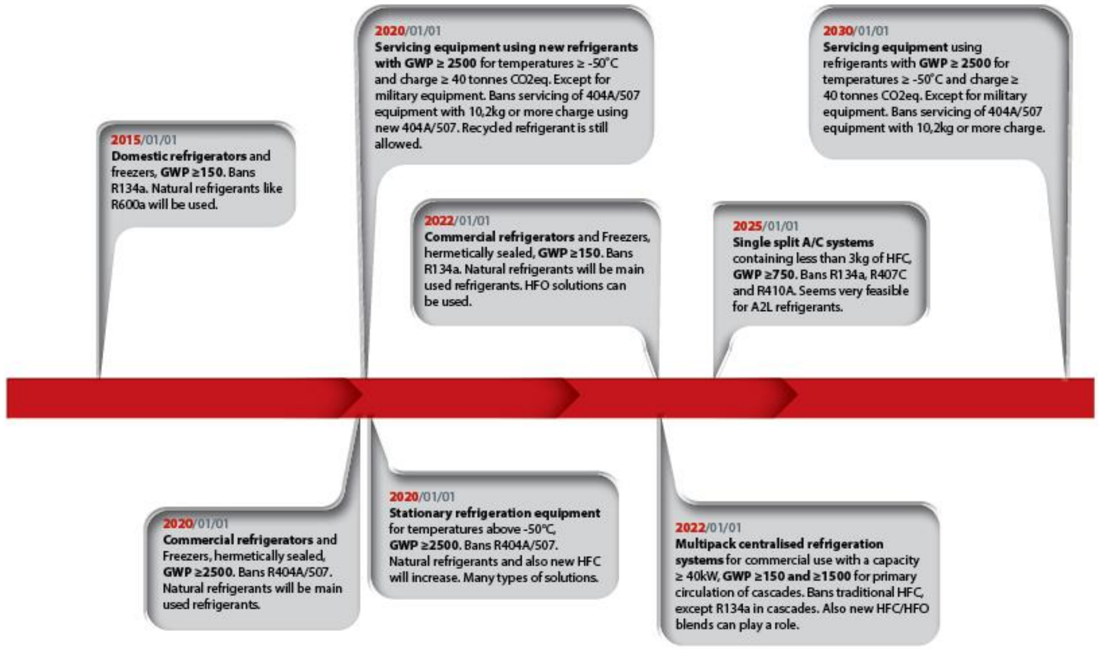

Figure 2.1 *– Placing on the market prohibitions referred to in Article 11 of the EU Regulation No 517/2014* [32]

Article 12: This article specifies a label that has to be applied to equipment that contains an HFCs gas (read the article for the exceptions). The following equipment if contains an HFCs gas they must have a label: heat pumps, fire protection equipment, electrical switchgear, aerosol, all fluorinated greenhouse gas containers, fluorinated greenhouse gas-based solvents and organic Rankine cycles. The label must contain the following requirements:

- A reference that the product or equipment contains an HFCs gases or that its functioning relies upon such gases;
- The accepted industry designation for the HFCs gases;
- The quantity expressed in weight and in CO_2 equivalent and the global warming potential of the HFCs gases;
- A reference that the fluorinated greenhouse gases are contained in hermetically sealed equipment;
- A reference that the electrical switchgear has a tested leakage rate of less than 0,1% per year;
- Adjacent to the service ports for charging or recovering the fluorinated greenhouse gas;
- On that part of the product or equipment that contains the fluorinated greenhouse gas.

Article 13: The ban on the use of HFCs with GWP equal to or greater than 2500 for the assistance or maintenance of refrigeration equipment with a refrigeration load size equal to or greater than 40 tonnes of CO_2 equivalent as of January 1, 2020.

Prohibition of the use of reclaimed HFCs with GWP equal to or greater than 2500 in the maintenance or servicing of existing refrigeration equipment with a refrigeration load size equal to or higher than 40 tons of equivalent CO_2 starting from January 1, 2030.

Prohibition of the use of recycled HFCs with GWP equal to or greater than 2500 in the maintenance or repair of existing refrigeration equipment, provided they have been recovered from such equipment from 1 January 2030. These recycled gases may be used exclusively by company that has carried out or on behalf of which the recovery has been carried out as maintenance or assistance.

Article 15: The beginning of the Regulation cite: "The Commission shall ensure that the quantity of hydrofluorocarbons that producers and importers are entitled to place on the market in the Union each year does not exceed the maximum quantity for the year in question calculated in accordance with Annex V.
Producers and importers shall ensure that the quantity of hydrofluorocarbons calculated in accordance with Annex V that that each of them places on the market does not exceed their respective quota allocated pursuant to Article 16 or transferred pursuant to Article 18".

From 2018 onwards, the maximum quantity referred to in Article 15 (5) shall be calculated by applying the percentages in **Figure 2.2** to the annual average of the total quantity placed on the market into the Union during period 2009 to 2012.

Years	**Phase down scheduled**
2015	100%
2016-17	93%
2018-20	63%
2021-23	45%
2024-26	31%
2027-29	24%
2030	21%

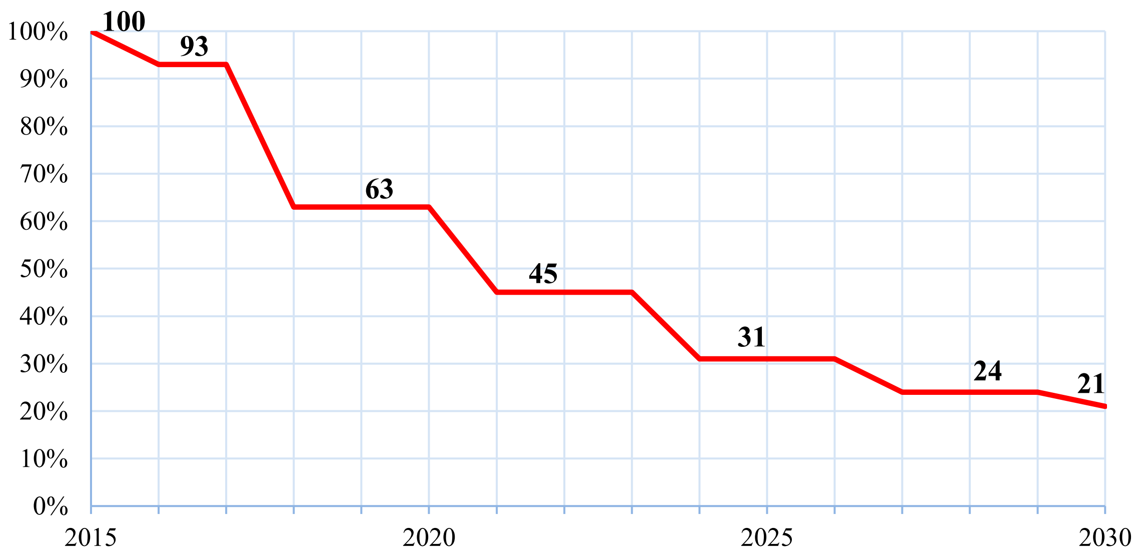

Figure 2.2 *– The phase down. It represents the percentage to calculate the maximum quantity of HFCs to be placed on the market and corresponding quota. These values comes from Annex V of the Regulation 517/2014 [16]*

These limitations are not applied to the following categories of HFCs:

- HFCs imported into the Union for destruction;
- HFCs used by a producer in feedstock applications or supplied directly by a producer or an importer to undertakings for use in feedstock applications;
- HFCs supplied directly by a producer or an importer to undertakings, for export out of the Union, where those hydrofluorocarbons are not subsequently made available to any other party within the Union, prior to export;
- HFCs supplied directly by a producer or an importer for use in military equipment;
- HFCs supplied directly by a producer or an importer to an undertaking using it for the etching of semiconductor material or the cleaning of chemicals vapour deposition chambers within the semiconductor manufacturing sector;
- HFCs supplied directly by a producer or an importer to an undertaking producing metered dose inhalers for the delivery of pharmaceutical ingredients.

Article 16: It describes the allocation of quotas for placing hydrofluorocarbons on the market. In the Annex VI is expressed the allocation mechanism as follow:

> *1. Determination of the quantity to be allocated to undertakings for which a reference value has been established under Article 16 (1) and (3)*
>
> Each undertaking for which a reference value has been established receives a quota corresponding to 89 % of the reference value multiplied by the percentage indicated in Annex V for the respective year.
>
> *2. Determination of the quantity to be allocated to undertakings that have submitted a declaration under Article 16 (2)*
>
> The sum of the quotas allocated under point 1 is subtracted from the maximum quantity for the given year set out in Annex V to determine the quantity to be allocated to undertakings for which no reference value has been established and which have submitted a declaration under Article 16 (quantity to be allocated in step 1 of the calculation).

2.1. Step 1 of the calculation

Each undertaking receives an allocation corresponding to the quantity requested in its declaration, but no more than a pro-rata share of the quantity to be allocated in step 1.

The pro-rata share is calculated by dividing 100 by the number of undertakings that have submitted a declaration. The sum of the quotas allocated in step 1 is subtracted from the quantity to be allocated in step 1 to determine the quantity to be allocated in step 2.

2.2. Step 2 of the calculation

Each undertaking that has not obtained 100 % of the quantity requested in its declaration in step 1 receives an additional allocation corresponding to the difference between the quantity requested and the quantity obtained in step 1. However, this must not exceed the pro-rata share of the quantity to be allocated in step 2.

The pro-rata share is calculated by dividing 100 by the number of undertakings eligible for an allocation in step 2. The sum of the quotas allocated in step 2 is subtracted from the quantity to be allocated in step 2 to determine the quantity to be allocated in step 3.

2.3. Step 3 of the calculation

Step 2 is repeated until all requests are satisfied or the remaining quantity to be allocated in the next phase is less than 500 tonnes of CO_2 equivalent.

3. Determination of the quantity to be allocated to undertakings that have submitted a declaration under Article 16 (4)

For the allocation of quotas for 2015 to 2017 the sum of the quotas allocated under points 1 and 2 is subtracted from the maximum quantity for the given year set out in Annex V to determine the quantity to be allocated to undertakings for which a reference value has been established and that have submitted a declaration under Article 16 (4).

The allocation mechanism set out under points 2.1 and 2.2 applies.

For the allocation of quotas for 2018 and every year thereafter, undertakings that have submitted a declaration under Article 16 (4) shall be treated in the same way as undertakings that have submitted a declaration under Article 16 (2).

Article 17: An electronic register is set up for quotas for placing HFCs on the market. The registration in the register is compulsory for:

- Producers and importers to which a quota for the placing on the market of hydrofluorocarbons has been allocated in accordance with Article 16 (5);
- Undertakings to which a quota is transferred in accordance with Article 18;
- Producers and importers declaring their intention to submit a declaration pursuant to Article 16 (2);
- Producers and importers supplying, or undertakings in receipt of hydrofluorocarbons for the purposes listed in Article 15 (2);
- Importers of equipment placing pre-charged equipment on the market where the hydrofluorocarbons contained in the equipment have not been placed on the market prior to the charging of that equipment in accordance with Article 14.

Article 18: It specifies how transfer of quotas and authorisation to use quotas for the placing on the market of hydrofluorocarbons in imported.

This Regulation has contributed to increase the HFC selling prices. The price developing is register by Öko-Recherche GmbH, an organisation dedicated to environmental research and monitoring, that shown the results at the European webinar taken on 29 May 2018. The average purchase prices of R134a, R410A and R404A, were under 2€/tCO_2e (tonne of CO_2 equivalent) in 2014, but jumped to between 7€/t CO_2e and 23€/t CO_2e in the first quarter of 2018. According to a forecast carried out by the same agency, the prices will rise to 35€/t CO_2e for the 2030 [23].

The European Commission with CITEPA (France) as project partner and nationals and EU associations decided to monitor the HFC prices and the effect of the phase down. It were established in the mid-2016 a survey from all level of the EU supply chain. They are included gas producers and distributors, service companies and the end user of refrigeration, air conditioning and heat pump (RACHP) sector. At the moment it is not compulsory and in the 2018 first quarter 71 companies participated voluntary.

The **Figure 2.3** represent the purchase prices behaviour, already described, for some HFC refrigerants at service company level.

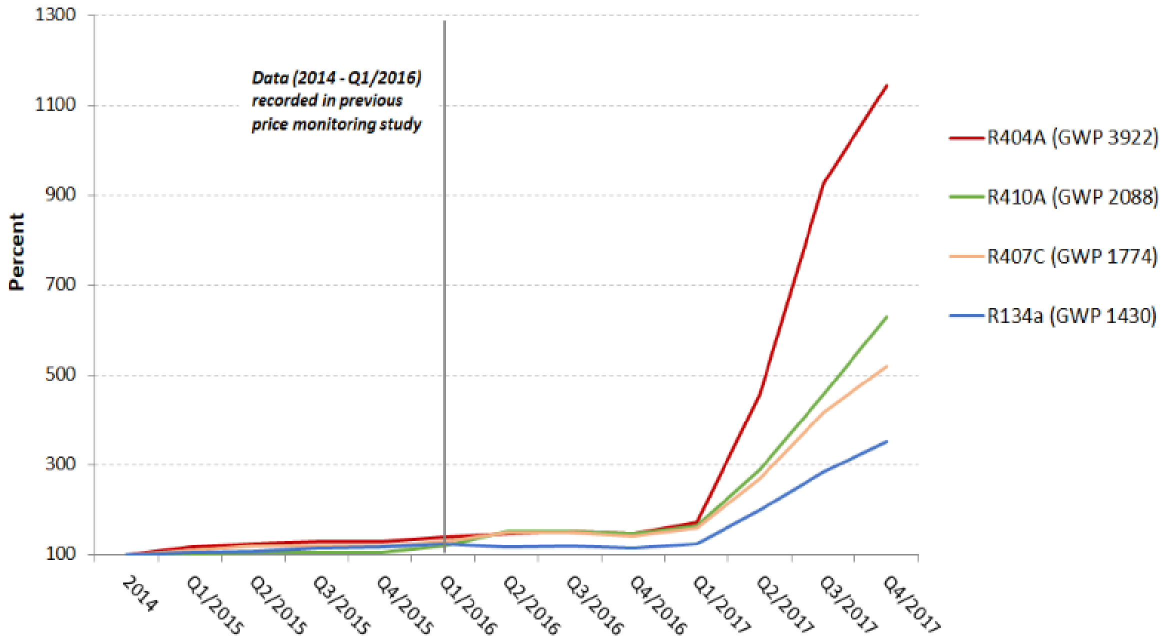

Figure 2.3 *– Development of purchase prices of various HFC refrigerants at service company level, indexed to 2014 prices (100 %)* [23]

2.1.2 UNI EN 378:2017 – "Refrigeration systems and heat pumps – Safety requirements and the environment"

This standard specifies the requirements for the safety of persons and property, provides guidance for environmental protection and establishes procedures for the operation, maintenance and repair of refrigeration systems and the recovery of refrigerant. The latest version of EN 378 is EN 378:2017 built on the previously published version EN 378:2008, which primarily incorporated new requirements for the newly established A2L refrigerant classification.

The standard applies to [33]:

- Commercial refrigeration;
- Industrial systems;
- Transportation refrigeration;
- Air-to-air conditioners and heat pumps;
- Chillers.

This Standard is divided into four parts. The first part is EN 378-1 that defines a classification for refrigeration systems in order to identify their hazard level and the refrigerant charge limit. The first classification, as shown in **Table 2.2**, concerns spaces where refrigeration systems are installed.

Table 2.2 *– Spaces classification where refrigeration systems are installed* [22]

Categories	General characteristics	Example
General occupancy A	Rooms, parts of buildings, building where: • People may sleep; • People are restricted in their movement; • An uncontrolled number of people are present or to which any person has access without being personally acquainted with the necessary safety precautions	Hospitals, courts or prisons, theatres, supermarkets, schools, lecture halls, public transport, hotels dwellings, restaurants
Supervised occupancy B	Rooms, parts of buildings, buildings where only a limited number of people may be assembled, some being necessarily acquainted with the general safety precautions of the establishment.	Business or professional offices, laboratories, places for general manufacturing and where people work.
Authorised occupancy C	Rooms, parts of buildings, buildings where only authorised people have access, who are acquainted with general and special safety precautions of the establishment and where manufacturing, processing or storage of material or product take place.	Manufacturing facilities, e.g. for chemicals, food, beverage, ice, ice-cream, refineries, cold stores, non-public areas in supermarkets.

With regards to the refrigerant charge limit, refrigerants must be dividend into flammable and non-flammable. If non-flammable refrigerants are used the limit charge is very high (e.g. R134a practical limit is 0.21 [kg/m^3][22]), while concerning flammable refrigerants the limit charge depends on where the system is installed:

- Machinery assigned in a busy space;
- Machinery with compressor, liquid receiver and an exchanger in an external or unoccupied space;
- Machinery with all components containing refrigerant fluid placed in an unoccupied or open space.

The limit charge evaluation could be calculated by applying following formula:

$$m_{max} = 2.5 \cdot LFL^{5/4} \cdot h_0 \cdot A^{1/2}$$

Where:

m_{max}: Allowable maximum charge in [kg];

LFL: Lower Flammable Limit in [kg/m^3];

h_0: Fixed height value [m];

A: Room area in [m^2].

It is possible to use the practical limit instead compute the previous formula. **Table 2.3** shows the Low Flammability Limits, practical limit and other properties of the most adopted flammable refrigerants.

Table 2.3 *– Low Flammability Limit, Autoignition temperature, Practical limit of the most adopted flammable refrigerants* [34]

Refrigerant	**Safety group**	**LFL [kg/m^3]**	**Auto ignition temperature [°C]**	**Practical limit [kg/m^3]**
R600a	A3	0.038	460	0.011
R290	A3	0.038	470	0.008
R1234yf	A2L	0.299	405	0.06
R32	A2L	0.307	648	0.061

E.g. for a vending machine that:

- uses as working fluid (propane),
- has a food area size (width x height x dept) of 0.9 [m] x 1.5 [m] x 0.7 [m],

the limit charge is evaluated by multiplying the practical limit by chamber volume, so the admissible refrigerant amount expressed in gram is 7.5 [g].

The second part EN 378-2 is applicable to the design, construction installation and test of refrigeration systems including pipes, components and materials.

In more detail, all components have to be tested by the producer or if it is not done they have to be tested before assembling them. Before charging the refrigeration system a ait-tightness is required.

Concerning A3 refrigerants, this regulation includes specifications for:

- Sealing of piping and ducting through walls;
- Doors and exits;
- Ventilation;
- Emergency mechanical ventilation;
- Explosion relief;
- Equipment inside the room;
- Alarms and leak detection systems.

The third part EN 378-3 concerns the installation site identification (open or close space and machinery rooms) and safety services requirements.

The last part EN 378-4 is focused on the refrigeration system maintenance, repair and recovery.

At present, discussions are underway on several issues that are especially relevant for natural flammable refrigerants that could not be addressed during the development process of EN 378:2016, such as [35]:

- Improved system measures, such as protection against mechanical impacts, prevention of fretting and minimisation of vibration and piping resonances;
- A minimum airflow rate, established from refrigerant type, charge amount and system characteristics, or airflow in response to an activated sensor, to prevent the formation of flammable mixtures.

2.1.3 IEC 60079 and IEC 60335

To sell a product in the market place there are international standards that must be followed, according to many regulations. Some of these guidelines are specific for a determined sector, while other ruled are generic and could be used for in several areas.

With regard to vending machines, there are some generic regulations that define which electric components to use and how to make electric connections, in order to build a safety vending machine. In addition to these regulations, since the refrigeration systems could adopt flammable coolant it must be followed regulations that deal with explosive atmospheres. For the aim of the thesis, in this section will be descripted the most important Standards to observe in explosive atmosphere.

The International Standards regarding all electrical, electronic and related technologies are prepared and published by IEC (International Electrotechnical Commission) [36]. These standards could be accepted, rejected or modified by the nations. With regards to Europe there is the CEN, the European Committee for Standardization, that takes decisions about the IEC Standards and deals with bringing together the National Standardization Bodies of 34 European countries. Moreover, CEN supports standardization activities in relation to a wide range of fields and sectors including: air and space, chemicals, machinery, etc. [37].

The International and European Standards regarding to the electric equipment installed in explosive atmosphere are almost identical. The regulations needed to design and check a propane vending machine are:

- IEC 60079-0:2017 standard specifies the general requirements for construction, testing and marking of electrical equipment and Ex Components intended for use in explosive atmospheres. This standard is supplement or modified by other standards which specify additional test, safety requirements and construction line guide for specific type of equipment and protection [38];
- IEC 60079-14:2013 contains the specific requirements for the design selection erection and initial inspection of electrical installations in or associated with explosive atmospheres. Electrical equipment and wirings should be located in non-hazardous areas. Where it is not possible to do this, it should be installed in area where an explosive atmosphere is least likely to occur. Where additional protection is required to meet other environmental conditions, for example, protection against ingress of water and resistance to corrosion, the method used shall not adversely affect the integrity of the equipment.

The requirements of this standard apply only to the use of equipment under standard atmospheric conditions as defined in IEC 60079-0. For other conditions additional precautions may be necessary and the equipment should be certified for these other conditions [39];

- IEC 60079-15:2017 specifies requirements for the construction, testing and utilisation for Zone 2 (the zone classification is descripted in IEC 60079-10) electrical equipment with type of protection “n”, electrical equipment with parts or circuits producing arcs or sparks or having hot surfaces which, if not protected in one of the ways specified in this standard, could be capable of igniting a surrounding explosive gas atmosphere. In this classification are included: non-sparking device “nA”, enclosed-break device “nC”, hermetically-sealed devices “nC”, non-incendive components “nC”, sealed devices “nC”, and restricted-breathing enclosures “nR” intended for use in explosive gas atmospheres [40];
- IEC 60335-2-75:2012 deals with the safety of electric commercial dispensing appliances and vending machines for preparation or delivery of food, drinks and consumer products, their rated voltage being not more than 250 [V] for single-phase appliances and 480 [V] for other appliances. Examples of appliances that are within the scope of this standard are bulk tea or coffee brewing machines, cigarette vending machines, hot and cold beverage vending machines, etc. This standard also deals with the hygiene aspects of appliances. In 2015 was approved an implement of this regulation the IEC 60335-2-75:2012/AMD1:2015 [41];
- IEC 60335-2-89:2010 specifies safety requirements for electrically operated commercial refrigerating appliances that have an incorporated compressor or that are supplied in two units for assembly as a single appliance in accordance with the manufacturer’s instructions. This Standard limits the maximum charge limit for A3 refrigerant used in commercial refrigeration to 150 [g]. There are two amendment that complete this regulation: AMD1:2012 and AMD2:2015, which introduced requirements for transcritical CO_2 systems [42].

  A Committee Draft for Vote (CDV) on IEC 60335-2-89, which was voted on and approved by national committees in July 2018, contains several modifications relevant for the use of flammable refrigerants in commercial refrigeration systems. Among these change it was proposed to increase from 150 [g] to approximately 500 [g] of A3 refrigerants per circuit [43].

There are two certifications that must be obtained for those electrical components that respect the regulations for explosive atmosphere, ATEX and IECEx. ATEX (Atmosphère Explosibles) is mandatory across Europe and involves all stages from the manufacture, through to the installation and use of the equipment. While the IECEx (International Electrotechnical Commission Explosive) is an international certification accepted in several countries to help build confidence in the safety of Explosive equipment. It also facilitates international trade of equipment and services for use in explosive atmospheres. Although there are some small differences between each certification, ATEX and IEC Ex are very similar. The main difference is the geographical location where the certification is recognised and accepted [44].

2.2 The propane vending machine

According to UNI EN 378, the regulation that provides the maximum refrigeration systems charge, the maximum allowed propane amount inside the vending machine product area is 7.5 [g]. Usually the refrigeration system charge that a vending machine needs is around a hundred or more grams, so to adopt propane as working fluid some electric components that comply with IEC 60079 and IEC 60335 should be used: for example, ATEX in Europe or IECEx in other nations. These certified components are more expensive than the traditional ones, because they are designed and manufactured to avoid spark and arc production while they work.

SandenVendo Europe decided to avoid the explosion risks by employing a refrigeration system that uses two operating fluids: propane for cooling area and glycol for product area. By dividing the two cameras, propane cannot enter into the product area, where refrigeration system leakages could lead to a very high risk of explosions, due to the presence of many electrical motors. **Figure 2.4** shows the R290 vending machine created by SandenVendo Europe.

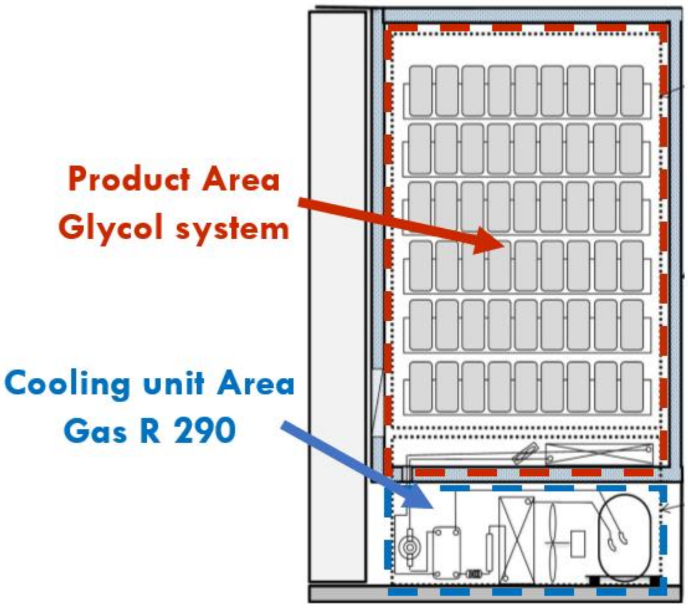

Figure 2.4 *– SandenVendo Europe propane vending machine presentation*

Inside the cooling area, glycol and propane act as working refrigerants: to make their use possible, compressor, condenser, filter, capillary tube, plate heat exchanger and pump are installed. Due to the propane application, this space is classified as Zone 2 by the IEC 60079-10 Standard. This means in this area explosive atmospheres could be present, but only rare situations or for brief periods. In this way, the certified electric components like ATEX or IECEx are not required, but the system must respect the IEC 60079-15 safety protection requirements.

With regards to the propane refrigeration system, it employs a hermetic reciprocating compressor suitable for medium back pressure (evaporating temperature between -20 [°C] and 10 [°C]) with cylinder capacity of 12.11 [cm^3], represented in **Figure 2.5**. It uses a CSIR motor (Capacity Start Inductive Run), which means that a condenser provides a high starting torque that the compressor starting needs, while during compressor normal functioning the inductive motor provides the required energy.

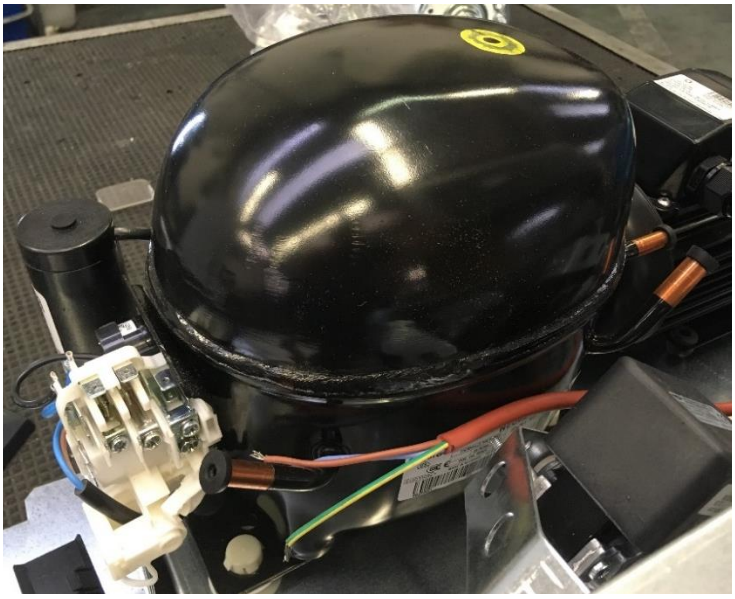

***Figure 2.5** – CSIR propane compressor*

Propane condensation phase is provided by the condenser shown in **Figure 2.6**. It is composed by 32 copper tubes with an outer diameter of 7.2 [mm], divided into 4 rows and 8 tubes per row. Aluminium corrugated fins are spread over 380 [mm] with a distance of 5 [mm] from a fin to the next one; they are 200 [mm] high and 91 [mm] wide. Air flow is provided by two fans of 500 [m^3/h] theoretical air mass flow rate and a diameter of 152 [mm] each.

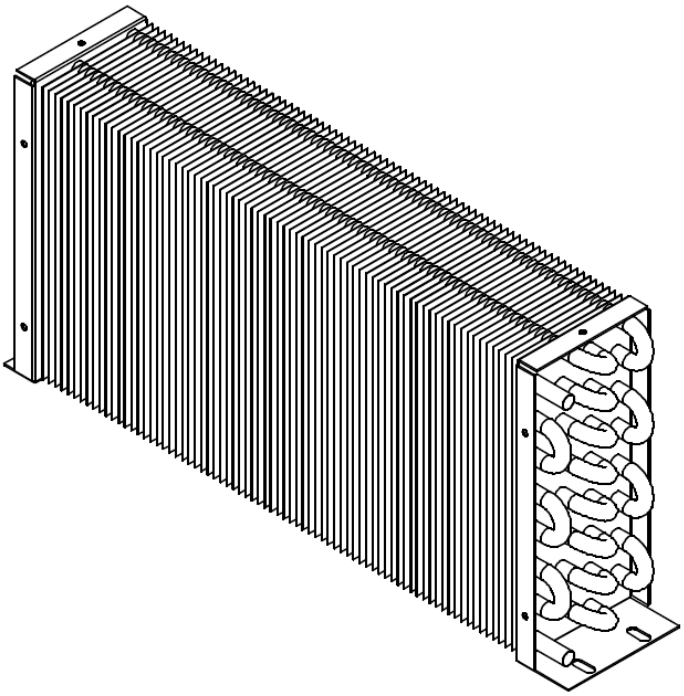

***Figure 2.6** – Condenser composed by 32 tubes divided into 4 rows and 8 tubes per row*

The gas expansion is obtained by the capillary tube, which through a pressure drop cools down the refrigerant. This capillary tube has an internal diameter equal to 1.24 [mm] and it is 2400 [mm] long. As it has been better explained in chapter 1.4.2, the capillary is rolled out onto compressor inlet line to obtain a better fluid cool down.

Finally, propane evaporates in a plate heat exchanger, which is used when heat exchange between two fluids, small dimensions and good thermal capacities are required. It is composed by 20 plates, which create 19 canals in which glycol and propane flow alternatively, for a total of 10 glycol canals and 9 propane canals. More precisely, these fluids exchange heat in counterflow and propane evaporates since it is heated up by glycol which instead is cooled down. **Figure 2.7** shows this heat exchanger on which propane enters from the down-left port and exits from the up-left port, while the glycol enters from the up-right port and exits from the down-right port.

***Figure 2.7** – Plate heat exchanger used to propane and glycol heat exchange*

Concerning the glycol system, Temper 30 is the operating glycol which presents all the determined properties that are required by the refrigeration system. When glycol temperature changes, it presents higher thermal capacity and excellent thermal conductivity in comparison to propylene glycol. Moreover, its density is quite constant when temperature decreases under 0 [°C] until its freezing point, that is reached at -30 [°C]. The principal thermal properties of Temper 30 are shown in **Table 2.4**.

Table 2.4 *– Temper 30 principal thermal properties*

Temperature [°C]	**Density [kg/m³]**	**Specific heat [kJ/kg K]**	**Thermal conductivity [W/m K]**	**Dynamic viscosity [mPa s]**
10	1181	3.102	0.473	2.76
0	1184	3.075	0.46	3.96
-10	1187	3.042	0.448	6.14
-20	1190	3.004	0.435	10.1
-30	1192	2.961	0.423	17.32

The pump showed in **Figure 2.8** sends glycol to the plate heat exchanger and after to the internal heat exchanger inside the product area. This application needs the use of the diaphragm pump suitable for glycol applications, which adopts a synchronous induction motor to increase glycol pressure inside the three chambers. At the pump end a fan is installed, with the aim to cool down the pump to avoid that the heat block temperature is reached. This pump respects the International Standard thanks to various characteristics: the inductive motor does not create arcs or sparks, the pump thermal-link is hermetically sealed and furthermore the pump temperatures that is reached are lower than the propane auto ignition temperature which is 470 [°C].

Figure 2.8 *– Diaphragm pump used for glycol*

Glycol absorbs products area heat through the finned tube heat exchanger that is represented in **Figure 2.9**. It is composed by 24 copper tubes with an outer diameter of 9.52 [mm]divided into 8 rows and 3 tubes per row. Aluminium corrugated fins are spread over 428 [mm], 65 [mm] high and 203 [mm] wide, with a differentiated step: at the air inlet for the first three rows fins are spaced by 11 [mm], while the other 5 rows fins are spaced by 5.5 [mm]. This is done to avoid ice formation at the air inlet of the heat exchanger which creates air flow problems until the air channels closure. Air flow is provided by three fans of 170 [m^3/h] theoretical air mass flow rate and a diameter of 116 [mm] each.

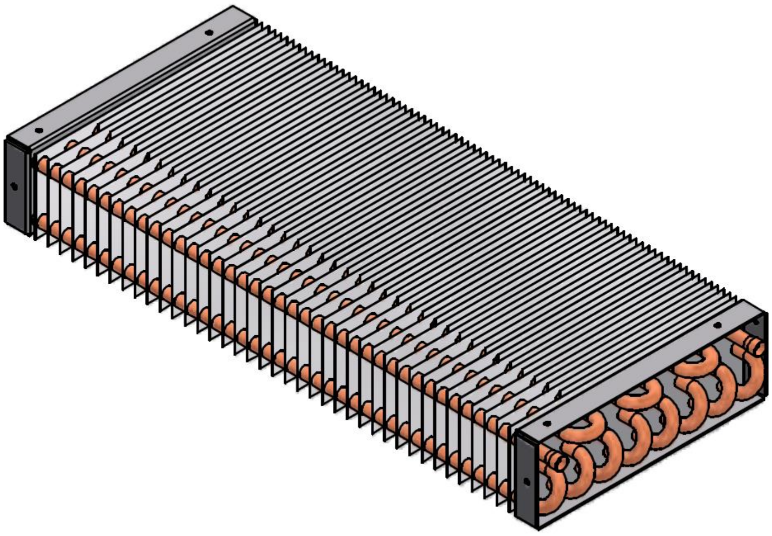

Figure 2.9 *– Product area finned tube heat exchanger composed by 24 tubes dived into 8 rows and 3 tubes per row*

2.3 Climate chamber

All vending machine prototypes are tested in a climate chamber in order to check how they work and to verify their performance. The vending machine model that is generally tested by SandenVendo Europe is G-Drink DV9 which contains 504 cans; it is composed by 7 shelves and 9 selection rows and for each selection there are other 8 cans.

There are two reasons why testing G-Drink DV9. The first one is related to the performance tests that SandenVendo clients require, especially for this kind of vending machine. These tests are very restrictive, and their aim is to reach the products temperature of 4 [°C] in a certain time, starting from a specific initial temperature. The other reason concerns the high cooling load that is required by this vending machine: consequently, if this vending machine pass all the tests, the same system could be applied to other vending machines that need a cooling load lower than this one.

When a vending machine prototype is tested, the refrigeration system is not installed inside the vending machine, as **Figure 2.10** shows. In this way it is easy to add or remove coolant and to substitute components, but the most important advantage is the possibility to change refrigeration system without moving the vending machine.

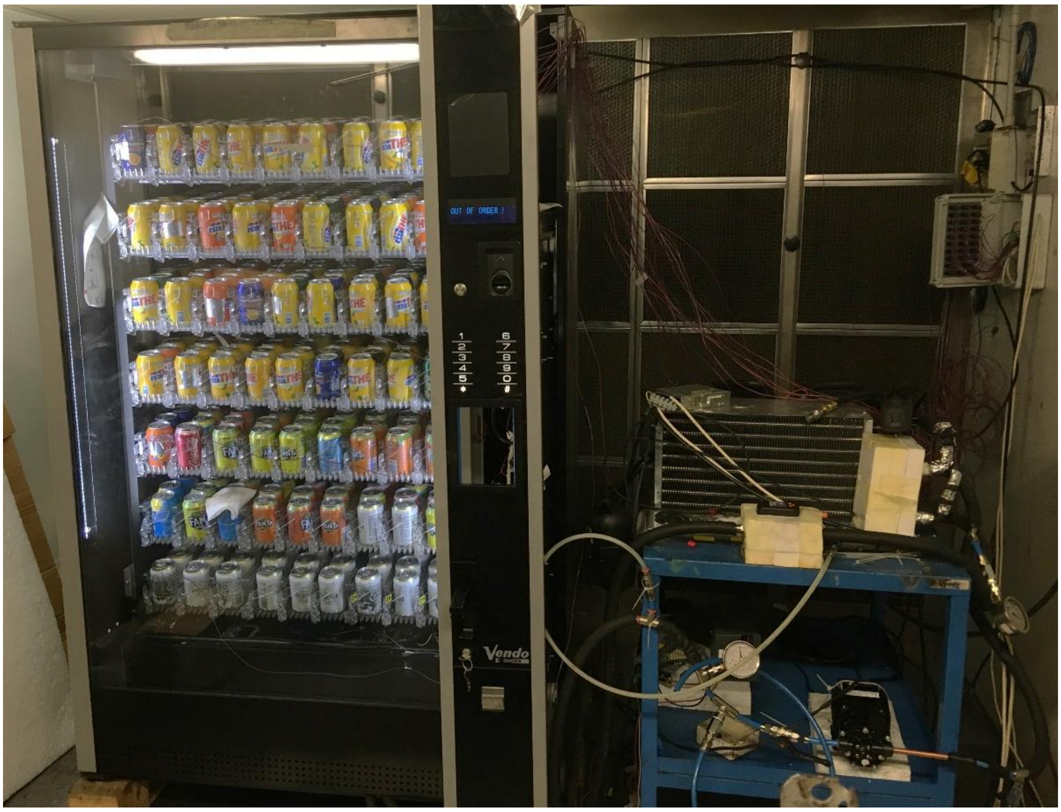

Figure 2.10 *– Propane vending machine prototype*

The aim of this thesis is to test the vending machine inside the climate chamber kept at 33 [°C] to evaluate its performance, when the refrigeration system works to maintain the internal products at a constant temperature of about 2 [°C]. The refrigeration system works stop-start; to explain it in more detail, it stops when the inlet air in the internal heat exchanger reaches 1 [°C] and restarts to cool down when the air temperature overpasses 3 [°C].

These tests have been made with the aid of two assists: on one hand, a system that records the vending machine electric consumption, on the other hands the presence of heat probes, which are positioned on the outer diameter of the copper connection tube and is covered by the insulation. Probes are installed on the most important vending machine parts:

- Products;
- Compressor inlet and outlet;
- Condenser exit;
- Filter;
- Evaporator inlet and outlet;
- Air entrance and exit in the evaporator.

To evaluate the glycol system efficiency of propane vending machines, a volume flow meter has been added and further heat probes have been installed on the evaporator glycol (inlet and outlet), on the pump glycol (inlet and outlet) and finally in the internal heat exchanger (inlet and outlet).

It is very important to show how products temperature is recorded, in order to obtain a reasonable product mean temperature. **Figure 2.11** shows how the heat probes position in the products is close to the glass that divides them form the external environment and far from the cold air nozzles, i.e. they are installed in product area critical points. In addition to these probes the products temperature has been recorded at vending machine corners in the last column, in order to verify that the last products are not frozen.

Figure 2.11 *– Heat probes position inside the product area*

It must be pointed out that during tests the working pressures of the propane refrigeration system could not be measured, because the prototype was already made without manometers and their addition would have been a waste of time. Regarding to the glycol system, working pressures are measured at the pump inlet and at the plate heat exchanger glycol outlet.

CHAPTER 3

3 Results

The propane vending machine has been tested when the refrigeration system works stop-start to maintain the product temperature constant at 2 [°C]. More specifically, the system stops when the heat exchanger inside the product area intake air at 1 [°C] and it restarts to cool down when the air temperature overpasses 3 [°C].

To obtain more reliable results, ten refrigeration system tests are made inside a climate chamber temperature of 33 [°C]. In this way, it is possible to compare the propane test with a previous one made by the same vending machine which adopts a R404A refrigeration system. After collecting all temperature data, an average among all the temperatures of each phase is calculated, without considering the starting cycle temperatures because they are very high and do not affect the refrigeration system efficiency.

Since it was not possible to detect the operating pressures, thermodynamic tables, Mollier diagrams and a computer program (that is called CoolPack) have been used. Moreover, R290 and R404A operating cycles do not consider pressure drops induced by components and pipes.

According to pressure levels, compressor outlet pressure has been evaluated by assuming that the condenser outlet temperature is the temperature at which the gas condenses at constant pressure. At the contrary, the compressor inlet pressure has been evaluated by considering the evaporator inlet temperature, that indicates the temperature at which the liquid evaporates at constant pressure. It is very important to keep in mind that for R290 refrigeration system the evaporation takes place into the plate heat exchanger.

Table 3.1 represents pressure and temperature data for the R290 (propane) and R404A refrigeration systems.

Table 3.1 *– Propane and R404A pressures and temperatures cycle data*

	R290	**R404A**

	Pressure [bar]	Temperature [°C]	Pressure [bar]	Temperature [°C]
Suction	3.14	-8.4	4.53	21.0
Delivery	14.7	72.7	18.5	70.8
Condenser outlet	14.7	43.2	18.5	40.5
Filter	14.7	41	18.5	38.7
Evaporator inlet	3.14	-12.9	4.53	-8.9
Evaporator outlet	3.14	-12.3	4.53	-3.7

Figure 3.1 shows the propane prototype working cycle in the Mollier diagram, according to the data represented in. The cycle has been simplified by showing the most important working points: from point 1 to 2 the compression phase takes place, after from 2 to 3 the gas is condensed, consequently from 3 to 4 the liquid is expanded to reach colder temperatures and finally all the liquid evaporates from 4 to 1.

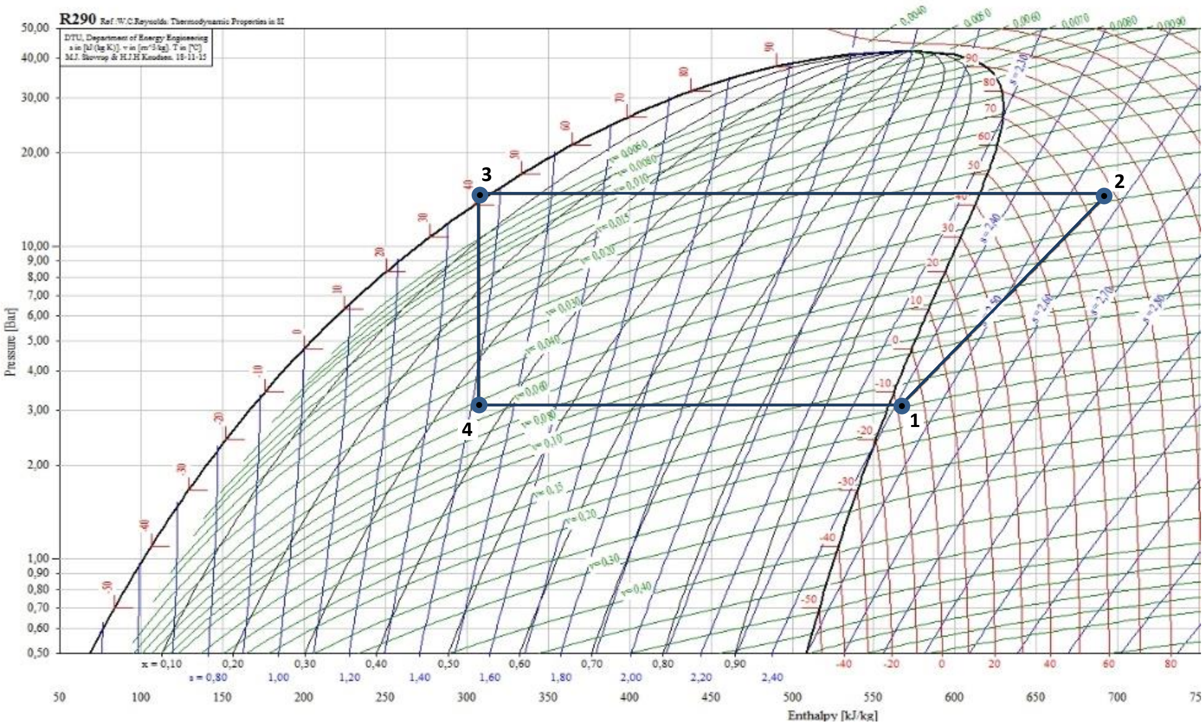

***Figure 3.1** – Propane refrigeration system working cycle represented in the Mollier diagram*

Once the propane working cycle is represented on the Mollier diagram, it is possible to determine cycle enthalpies that help to define the exchanged thermal powers. By dividing the evaporation enthalpy by the compression enthalpy, it is possible to determine the coefficient of performance (COP). The refrigeration systems COP usually exceeds 1 and higher COP equates to lower energy consumption. The evaporation and compression enthalpies for R290 and R404A refrigeration systems are represented in **Table 3.2**.

Table 3.2 *– Evaporation and compression enthalpies for R290 and R404A refrigeration systems*

	R404A	**R290**
Evaporation [kJ/kg]	106.5	252.4
Compression [kJ/kg]	42.1	126.3

As it was no possible to detect the cycle pressure drops and consequently the exact cycle enthalpies, the refrigeration system COP is evaluated through the ratio between evaporator cooling power and the electric power that is absorbed by the compressor. Thus, this COP does not consider the total vending machine electric consumption, but it aims to detect refrigeration system efficiency.

The cooling power through the evaporator is evaluated by the heat equation which describes the heat exchange between two fluids, by considering the total heat that is gained or lost by one fluid. The formula is the following:

$$Q = c_p \cdot dT \cdot v \cdot \rho$$

Where:

Q is heat power [W]

c_p is the specific heat capacity at constant pressure [J/kg·K]

dT is the change in temperature [K]

v is volumetric flow rate [m^3/h]

ρ is density [kg/m^3]

This formula requires the selection of a reference system. According to R290 refrigeration system, glycol has been selected, which gains heat from air, while for R404A refrigeration system the choice has been the air, which releases heat to the R404A.

Table 3.3 represents Temper 30 cycle mean temperatures at the plate heat exchanger inlet and outlet and internal heat exchanger inlet and outlet, and glycol mean volume flow rate evaluated at the plate heat exchanger outlet. In addition to glycol temperatures, Temper 30 density and heat capacity at constant pressure are evaluated from **Table 2.4Error! Reference source not found.**.

Table 3.3 *– Glycol temperature and volume flow rate data*

Plate heat exchanger inlet [°C]	-4.4
Plate heat exchanger outlet [°C]	-9.5
Internal heat exchanger inlet [°C]	-8.8
Internal heat exchanger inlet [°C]	-5.0
Volume flow rate [m^3/h]	0.1962

With regards to R404A refrigeration system, the air that circulates inside the product area, which is cooled down by the evaporator, is assumed to be dry air. This assumption is not possible to be verified, but we can assume it as true thanks to two conditions: on one hand, there is not a continuous air exchange; on the other hand, cold temperatures make water condense. **Table 3.4** shows R404A evaporator air inlet and outlet temperatures with respectively densities and specific heat capacities [45].

Table 3.4 *–R404A evaporator air inlet and outlet properties [45]*

	Temperature [°C]	**Density [kg/m^3]**	**Specific heat [J/kg·K]**
Air inlet	1.3	1.287	1005.6
Air outlet	-2.3	1.304	1005.5

The vending machine mean electric consumptions are represented in **Table 3.5**.

Table 3.5 *– R290 and R404A vending machines mean electric consumption*

	R290	**R404A**
Compressor [W]	483	522
Internal fans [W]	31	31
Condenser fans [W]	79	79
Lights and electronics [W]	30	30
Pump [W]	120	

The refrigeration system COP is calculated by applying the previous heat equation to obtain the evaporator cooling capacity and dividing it by the compressor electric consumption. The results are represented in **Table 3.6**.

Table 3.6 *– R290 and R404A refrigeration system COP*

	R290	**R404A**
Evaporator cooling capacity [W]	1006.2	646.7
Compressor electric consumption [W]	483	522
COP	2.08	1.24

Since R404A and R290 COPs refer to different cooling loads (the first one is provided to internal product while the other one is provided to glycol), it is necessary to consider the same cooling power for each vending machine. Furthermore, as R290 vending machine adopts a glycol pump in addition to the refrigeration system, its total power consumption is higher than the R404A one. In the end, the comparison of vending machines efficiencies needs to consider both the internal product cooling power and the total vending machine electric consumption.

To evaluate the air heat which glycol absorbs, the heat equation used before is applied, by considering the glycol temperature at the internal heat exchanger inlet and outlet showed in **Table 3.3**, and their respectively density and specific heat capacity from **Table 2.4**. Finally this thermal power is divided by the vending machine electric power found in **Table 3.5.**

Table 3.7 *– R290 and R404A vending machine efficiencies*

	R290	**R404A**
Internal evaporator cooling capacity [W]	748.3	646.7
Vending machine electric consumption [W]	743	662
Efficiency	1.01	0.98

CHAPTER 4

4 Discussion

To start analysing the functioning of two refrigeration systems, it is better to define R290 and R404A most important thermal properties and their values.

The first property is the latent heat which each refrigerant can provide. With regards to this characteristic, propane has an higher latent heat value than R404A: for example, at -10 [°C] R404A can produce 177.08 [kJ/kg] while propane can produce only 388.3 [kJ/kg] [46]. Consequently, propane refrigeration system has a lower refrigerant charge if compared with R404A.

Other important refrigerants properties that influence the refrigeration system efficiency are the saturated vapour density and volumetric capacity, where the first one influences the second one. In more detail, an high density implies high compression works but at the same time leads to compact compressors, thanks to high volumetric capacity. Speaking about this property, propane saturated vapour density is lower than the one of R404A; consequently this difference is equal if we consider the volumetric capacity, for instance at -10 [C] R290 values are 7.63 [kg/m^3] and 2962.7 [kJ/m^3] while at the same temperature R404A values are 21.74 [kg/m^3] and 3849.7 [kJ/m^3]. Even if R404A refrigeration system has a higher refrigerant charge, it adopts a compressor which have the same cylinder capacity as the R290 one, thanks to the high R404A volumetric capacity; however, R404A compressor has a higher electric consumption due to the high vapour density.

The most significant data that allows to compare how refrigeration systems work is the COP, which defines the refrigeration system efficiency through the ratio between cooling power and compressor electric consumption. According to **Table 3.6**, it is possible to see that COP is much higher for propane system than for R404A system. Since the compressor electric consumption does not present a significant diversity, the high COP difference is mainly dictated by the cooling power which refrigeration systems can provide, i.e. 1006 [W] provided by propane system against the 647 [W] by R404A system.

By analysing better the two systems, it can be noticed that the evaporation of gases happens in two different components: inside the plate heat exchanger for propane system and inside the finned tube heat exchanger for R404A system. Another important aspect that has to be underlined is that the plate heat exchanger is used to cool down glycol and is installed close to the compressor, while the fined tube heat exchanger is located inside the products area and cools down air for products. Therefore, in addition to the different conditions that these two components present, there is evidence that the plate heat exchanger can exchange a higher heat amount than the finned tube heat exchanger.

Since the R290 vending machine uses two refrigerants (propane and glycol), it is better to evaluate its efficiency by considering the cooling load provided by glycol and by considering the total vending machine electric consumption. In doing so, as shown in **Table 3.7** the two vending machine efficiencies are the same.

It must be specified that the obtained COP values are referred to the prototype functioning, while during the real vending machine work the COP could be lower. This is due to the refrigeration system position: in the prototype it is located outside the machine, while when the vending machine is produced it is installed at the vending machine bottom. The difference between these two working conditions is that when a vending machine is produced the refrigeration system components are close to one another, due to the loss of space. In this way, the air inlet channel of condenser is obstructed by other components and the refrigerant is not well cooled down by the condenser. As a consequence, the cooling power that the evaporator can provide is reduced and the same happens for the COP.

Moreover, during the refrigeration system cycle pressure drops occur and are induced by components and connection tubes. These pressure drops lead to a lower evaporating temperature and to a cooling power decrease due to latent heat reduction. In doing so, the refrigeration system COP is lower than the one calculated in **Table 3.6**.

It has to be said that the SandenVendo vending machines have to pass several very restrictive client tests, which require a high cooling load. For this reason, the compliance with all the tests has a price that has to be paid: a low vending machine efficiency.

CHAPTER 5

5 Conclusion

In conclusion, greenhouse gases emissions in the refrigeration and air conditioning sector are the result of manufacturing process, leakage and service over the operational life of the equipment and disposal at the end of the useful life of the equipment. Thanks to both F-Gas regulation and Kigali amendment, leakages and service greenhouse gases production will be significantly reduced.

The propane vending machine by SandenVendo Europe is a good solution to replace the polluting R404A vending machine from 2020. According to the ecological point of view, propane respects all the obligation that are required by the F-Gas regulation, i.e. it has an ODP value equal to 0 and a GWP level equal to 3.

We checked the propane vending machine performance by testing R290 and R404A refrigeration systems, both installed in the same vending machine. Finally, we obtained a COP value equal to 2 for propane refrigeration system and equal to 1.3 for R404A system. Whereas, if we consider the total electric consumption and the real cooling load, the two vending machine efficiencies are similar and equal to 1.

SandenVendo Europe future steps aim to the propane vending machine more competitive from 2020, by reducing its electric consumption and by increasing its efficiency.

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