UNIVERSITY “POLITEHNICA” OF BUCHAREST
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MASTER’S THESIS

COLD TECHNIQUES IN CIVIL ENGINEERING

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Bucharest June 2013

Summary

The main objective of this master thesis is the analysis of two different cold techniques that are used in civil engineering.

First of all, the two different techniques, cooling the concrete and the ground freezing method, will be described with all their important characteristics: manufacturing process, application of the two methods in real cases, working process, etc.

After that, it will be designed the two different vapor compression refrigeration systems that remove the heat produced for both cold technique applications in civil engineering. The design of the refrigeration system will be presented as the calculation method that is necessary to obtain all the different values that defines the two constructive solutions.

The next point that this project will study is the choice of one of these technologies and its calculation method, for doing the constructive solution's analysis. For doing this chapter, it will be used the software proportionated for the University "Politehnica" of Bucharest, "Engineering Equations Solver".

Finally, the last point that this project will study is the analysis of the refrigeration system if different refrigerants are used. In this last chapter it will be chosen the constructive solution and the most advanced refrigerant and it will be studied the difference of using ecological refrigerants or the synthetics freons types.

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1. Glossary

$\dot{Q}_0$	*Cooling power*	p_0	*Evaporating pressure*
$\dot{Q}$	*Heat flux*	p_c	*Condensing pressure*
$\dot{m}$	*Mass flow rate*	**Q**	*Heat load*
η_s^{cp}	*Compressor isentropic efficiency*	**q**	*Specific mass heat load*
c	*Volumetric heat capacity*	q_0	*Specific cooling power*
COP	*Coefficient of Performance*	**s**	*Specific entropy*
GFM	*Ground Freezing Method*	**t/T**	*Temperature ºC/ K*
GWP	*Global Warming Potential*	t_0	*Evaporating temperature*
h	*Specific enthalpy*	t_c	*Condensing temperature*
k	*Thermal conductivity*	**VCRS**	*Vapor Compression Refrigeration System*
l	*Specific mechanical work*	**vl**	*Expansion valve*
L	*Length*	**x**	*Title (quality) of saturated vapor*
l.b.	*Liquid bottle*	**X**	*Mass fraction*
ODP	*Ozone Depletion Potential*	ΔT	*Temperature difference*
Pcp	*Mechanical consumption*	τ	*Time*
p	*Pressure*	**f**	*frigorific*
2s	*Entropy constant*	**sc**	*Subcooling*
cd	*Condenser*	**sh**	*Overheating*
reg	*regenerative*	**t**	*thermic*
cp	*compressor*	**w**	*Water*

2. Foreword

2.1. Origin of the project and motivation

This project is born from the collaboration between the University “Politehnica” of Bucharest and the University “Politècnica” of Catalonia. This collaboration started with the request of the author to perform an Erasmus at the UPB and, after being conceded, with the application for course the master’s thesis in the department of thermodynamic, engines, thermal and refrigeration equipments. This fact caused the exchange of mails between the Prof. Gheorghe Popescu and the author and it finished with the agreement for a collaboration to perform the project introduced below.

When thinking about different types of applications that has a relation in industrial engineering, the first ones that come to mind probably will not be the refrigeration systems and the structural fields. This is one of the most important reasons for doing this project; link these two fields of study.

2.2. Previous requirements

Before doing this project it was completely necessary to delve into a field totally unknown for the developer of the project (refrigeration systems). In addition, the study of the program that will be used in this project (EES) was required.

3. Introduction

3.1. Main aim

The main aim of this project is the comparative analysis of two different constructive solution that are used in two different of the considered cold technique applications in civil engineering. After choosing one of them, the next objective will be to determine which refrigerant is better for the refrigeration system and, besides, study the difference between a ecological refrigerant and a synthetic one.

3.2. Scope

This project will study just two different refrigeration systems, the single and the double stage vapor compression refrigeration system (VCRS). In addition, for the single stage VCRS will be studied two different constructive solutions while for the two stage VCRS only one.

For the refrigerants, it only will be analyzed the behavior in a refrigeration system for the most used in the industry. These refrigerants that will be studied are the ammonia (R717, the best of the ecological ones), and different types of Freon, like R134a and the family R400.

4. Two cases of study

4.1. First case of study: cooling concrete

4.1.1. History

The word concrete comes from the Latin word "concretus" (meaning compact or condensed) the perfect passive participle of "concrescere", from "con-" (together) and "crescere" (to grow).

On a human time-scale, lime mortars were used in Greece, Crete, and Cyprus in 800 BC, and the Romans used concrete extensively from 300 BC to 476 AD, a span of more than seven hundred years.

During the Roman Empire, Roman concrete was made from quicklime, pozzolana and an aggregate of pumice. Its widespread use in many Roman structures, a key event in the history of architecture termed the Roman Architectural Revolution, freed Roman construction from the restrictions of stone and brick material and allowed for revolutionary new designs in terms of both structural complexity and dimension.

Modern structural concrete differs from Roman concrete in two important details. First, its mix consistency is fluid and homogeneous, allowing it to be poured into forms rather than requiring hand-layering together with the placement of aggregate, which, in Roman practice. Second, integral reinforcing steel gives modern concrete assemblies great strength in tension, whereas Roman concrete could depend only upon the strength of the concrete bonding to resist tension.

Another important date was in 1849 when reinforced concrete was invented by Joseph Monier. In 1889 the first concrete reinforced bridge was built, and the first large concrete dams were built in 1936, Hoover Dam and Grand Coolee Dam. [1]

Figure 1: a. Roma pantheon b. pont du Gard

Ancient additives

Concrete additives have been used since Roman and Egyptian times, when it was discovered that adding volcanic ash to the mix allowed it to set underwater. Similarly, the Romans knew that adding horse hair made concrete less liable to crack while it hardened, and adding blood made it more frost-resistant.

Modern additives

In modern times, researchers have experimented with the addition of other materials to create concrete with improved properties, such as higher strength or electrical conductivity.

4.1.2. Concrete manufacturing process

The manufacture process of concrete is fairly simple. First, the cement (usually Portland cement) is prepared. Next, the other ingredients, aggregates (such as sand or gravel), admixtures (chemical additives), any necessary fibers, and water are mixed together with the cement to form concrete. The concrete is then shipped to the work site and placed, compacted, and cured.

Preparing Portland cement

The limestone, silica, and alumina that make up Portland cement are dry ground into a very fine powder, mixed together in predetermined proportions, preheated, and calcined (heated to a high temperature that will burn off impurities without fusing the ingredients).

Next, the material is burned in a large rotary kiln at 1400 degrees Celsius. At this temperature, the material partially fuses into a substance known as clinker.

The clinker is then cooled and ground to a fine powder in a tube or ball mill. A ball mill is a rotating drum filled with steel balls of different sizes (depending on the desired fineness of the cement) that crush and grind the clinker. Gypsum is added during the grinding process. The final composition consists of several compounds: tricalcium silicate (Ca_3SiO_5), dicalcium silicate (Ca_2SiO_4), tricalcium aluminate ($Ca_3Al_2O_6$) , and tetracalcium aluminoferrite ($Ca_4Al_2Fe_2O_{10}$).

Mixing

The cement is then mixed with the other ingredients: aggregates (sand, gravel, or crushed stone), admixtures, fibers, and water. Aggregates are pre-blended or added at the ready-mix concrete plant under normal operating conditions. The mixing operation uses rotation or stirring to coat the surface of the aggregate with cement paste and to blend the other ingredients uniformly. A variety of batch or continuous mixers are used.

Transport to work site

Once the concrete mixture is ready, it is transported to the work site. There are many methods of transporting concrete, including wheelbarrows, buckets, belt conveyors, special trucks, and pumping. Pumping transports large quantities of concrete over large distances through pipelines using a system consisting of a hopper, a pump, and the pipes.

Placing and compacting

Once at the site, the concrete must be placed and compacted. These two operations are performed almost simultaneously. Placing must be done so that segregation of the various ingredients is avoided and full compaction with all air bubbles eliminated can be achieved. Whether chutes or buggies are used, position is important in achieving these goals. The rates of placing and of compaction should be equal; the latter is usually accomplished using internal or external vibrators.

Curing of concrete

Once it is placed and compacted, the concrete must cured before it is finished to make sure that it doesn't dry too quickly. Concrete's strength is influenced by its moisture level during the hardening process: as the cement solidifies, the concrete shrinks. If site constraints prevent the concrete from contracting, tensile stresses will develop, weakening the concrete. To minimize this problem, concrete must be kept damp during the several days it requires to set and harden.

4.1.3. Main physical properties of concrete

In this point it will be explained the most important physical properties of concrete. Concrete has been used along the time because is a material that works very well under compression stress. For this reason concrete has become one of the most important materials in the construction field.

On the other hand, concrete is a bad material when the intention is to resist tensile stress. That is the reason why the reinforced concrete is used.

An important parameter that depends of the concrete’s composition the following one:

- Density: 2240 - 2400 kg/m^3

About the different strength that concrete is able to support, it is important to remark that this values depend of concrete’s composition. However, the normal values of these parameters are the ones shown below. [2]

- Compressive strength: 20 - 40 MPa
- Flexural strength: 3 - 5 MPa
- Tensile strength: 2 - 5 MPa

This values confirm that concrete is a good material just for compression stress as it was explained previously.

In addition, there are some other important parameters that probably will not be needed but that are useful to know.

- Modulus of elasticity: 14000 - 41000 MPa
- Coefficient of thermal expansion : 10^{-5} ºC^{-1}
- Shear stress: 6 – 17 MPa.
- Specific heat capacity: 0.75 kJ/kg K

4.1.4. Considerations for cooling concrete

In order to do this project it is necessary to establish some criteria and some restrictions for the correct study of concrete's harden. First of all, this project will consider all the calculations for the construction of a dam that will be chosen in the following chapter. The dimensions and the amount of concrete will be decided in the moment that the structure is defined.

The second one is that it is necessary to establish which concrete will be used and which its internal composition is.

The last criterion is defining the amount of water that will be necessary for the correct concrete's hardening and the temperature of this water before and after being cooled. For doing this it will be necessary to explain from where the water comes from (a river, the sea, etc).

4.2. Second case of study: ground freezing method

4.2.1. History

Artificial ground freezing was the brainchild of German scientist F. Hermann Poetsch, who first patented his "Method of and Apparatus for Sinking Shafts through Quicksand" in 1883. Its first use in the United States was for the Chapin Mine Company in Iron Mountain, where freezing was performed to a depth of 100 feet (30,48 meters).

The technique met with great success throughout Europe, and became relatively common where the project could bear the cost of constructing the massive refrigeration plant required. However, it would be more than 60 years before the second U.S. ground freezing application was completed to aid the sinking of a 765-feet (233,172 meters) deep shaft at the Potash Company of America's Carlsbad, mine.

These days, ground freezing is common worldwide and its use has extended to encompass a range of civil and environmental applications as is showed in Figure 2. However, providing groundwater control and excavation support for shaft sinking remains the primary application. In fact, for deep shafts, no better method has yet been established. Brine freezing is typically used for large, longer-term applications where project schedule permits a freeze formation period measured in weeks and months.

Central Artery/Tunnel, Boston, MA
In the largest project of its kind ever undertaken in the USA, mass freezing stabilized complex, obstruction-laden soils for jacking of three, massive box tunnels beneath live rail tracks for the I-90/92 approach to the Fort Point Channel crossing.

City Water Tunnel No. 3, New York, NY
Brine freezing to depths ranging between 75 and 130 feet from ground surface, for construction of deep, vertical access shafts rising through glacial deposits and water-bearing sands above bedrock. Scheduled to be completed in 2020, City Water Tunnel No. 3 will eventually span more than 60 miles, and represents the largest capital construction project in New York City's history.

Figure 2: examples of GFM

4.2.2. Ground freezing process

The ground freezing process converts pore water into ice by the continuous circulation of a cryogenic fluid within a system of small diameter, closed-end pipes installed in a pattern consistent with the shape of the area to be treated

Figure 3. The frozen pore water acts as a bonding agent, fusing together particles of soil or rock

Freeze pipes are typically installed vertically in the soil and connected in series-parallel. The coolant is pumped down a drop tube to the bottom of the freeze pipe and flows up the annulus, withdrawing heat from the surrounding soil. When the soil temperature reaches 0°C, ice begins to form around the pipes in the shape of vertical, elliptical cylinders. As the cylinders gradually enlarge with time, they interconnect to form a continuous wall.

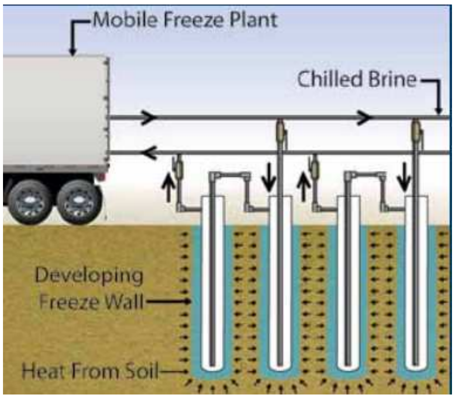

Figure 3: pipes operation

Once the frozen wall reaches design thickness, the freeze plant is typically operated at a reduced rate to maintain the condition.

Unlike other groundwater cut-off and excavation support techniques, ground freezing is a minimally invasive technique that requires only limited physical penetration into the ground and propagates thermally, rather than by displacement. The ground remains largely undisturbed during freeze pipe installation and the freezing process and, in most instances, reverts to its original state once freezing is discontinued. [3]

4.2.3. Types of Ground Freezing

Brine freezing

Brine freezing is typically used for large, longer-term applications where project schedule permits a freeze formation period measured in weeks and months. Chilled calcium chloride brine is the most common cooling agent. It is cooled typically to temperatures between -15°C and -25°C and pumped down a drop tube to the bottom of the freeze pipe, then flows up the annulus, withdrawing heat from the soil. The brine is returned to the refrigeration plant, where it is chilled and recirculated.

Refrigeration plants can be regulated to re-circulate brine over a relatively wide and controllable range down to approximately -35°C .With proper placement of the freeze pipes and careful design of the brine delivery piping, a brine freeze will provide relatively even and consistent cooling effort in the ground. Typically, the cooler temperatures are desirable for freeze formation and warmer temperatures are desirable for maintenance of the freeze.

Liquid nitrogen freezing

Liquid nitrogen, which acts more quickly than brine, has been used effectively for emergency situations in disturbed, displaced, and loss ground conditions where detailed soil delineation cannot practically be performed in a timely manner, and on smaller projects such as where the freeze is required to be maintained for a short period of time. Although the per-day cost is greater than with circulated brine, the accelerated freeze formation time makes this method very competitive.

The liquid nitrogen is stored in an insulated pressure vessel, which is refilled periodically from special over-the-road tank trucks. The liquid is conducted to the drop tube in the freeze pipe, boils rapidly, and the exhaust gas is vented to the atmosphere.

Figure 4: pipes with liquid nitrogen

Soils suitable for ground freezing

Ground freezing can be accomplished in all soils and in pervious or fissured rock, and is cost-effective where both support of excavation and groundwater cut-off are required and the ground improvement must be provided at significant depth. However, its applicability and cost effectiveness increases in difficult, disturbed or sensitive ground.

Figure 5: effective soil range by application

Peripheral Freezing

The general intent of the creation of a frozen containment structure, or peripheral freezing, is to minimize the amount of frozen ground to be excavated. The frozen wall, of appropriate thickness and strength, is constructed primarily outside of the excavation limits but terminates a short distance inside the future excavation surface so that the freshly exposed face remains frozen and may be insulated before significant melting begins.

Vertical peripheral freezing for excavation support and groundwater control during deep shaft construction is the primary application, with numerous projects completed across North America. Other tunneling related applications include horizontal peripheral freezes for sewer and utility line installations, and frozen-arch canopies to prevent ground loss or mitigate settlement during excavation.

Mass Freezing

Under certain circumstances, it may be desirable to completely freeze large volumes of soil. Such mass freezing may be justified where:

- A more homogenous ground condition is desired, such as to permit a hard rock TBM to pass through a mixed ground condition.
- Ground control in difficult subsurface conditions is crucial to the success of a project.

- The excavation of frozen ground provides a greater degree of overall safety of the operation. No geologic cut off is present within reasonable depth below subgrade at a proposed shaft location. In this case, the use of ground freezing may necessitate a mass freeze to create an artificial bottom seal.

4.2.4. Considerations for the GFM

For the correct study of the ground freezing method it will be necessary to specify where the tunnel will be done. Depending of this, the soil's composition will be different and it will be necessary to use more or less pipes. In addition, depending of the diameter and the length of the tunnel longer pipes or with a bigger diameter will be needed.

Finally, another important parameter will be how many time it will be necessary to make the tunnel because if it is needed just a few days it will be necessary to use a liquid with more cooling power, like the liquid nitrogen.

4.3. Refrigeration systems applied to both cases of study

The refrigeration systems span different zones and depending where is located the requirements of the project one or another type of constructive solution will be required and the same with the refrigerant used.

The following diagram explains the different work zones of the different applications and where are located the two different cases of study (GFM and concrete cooling).

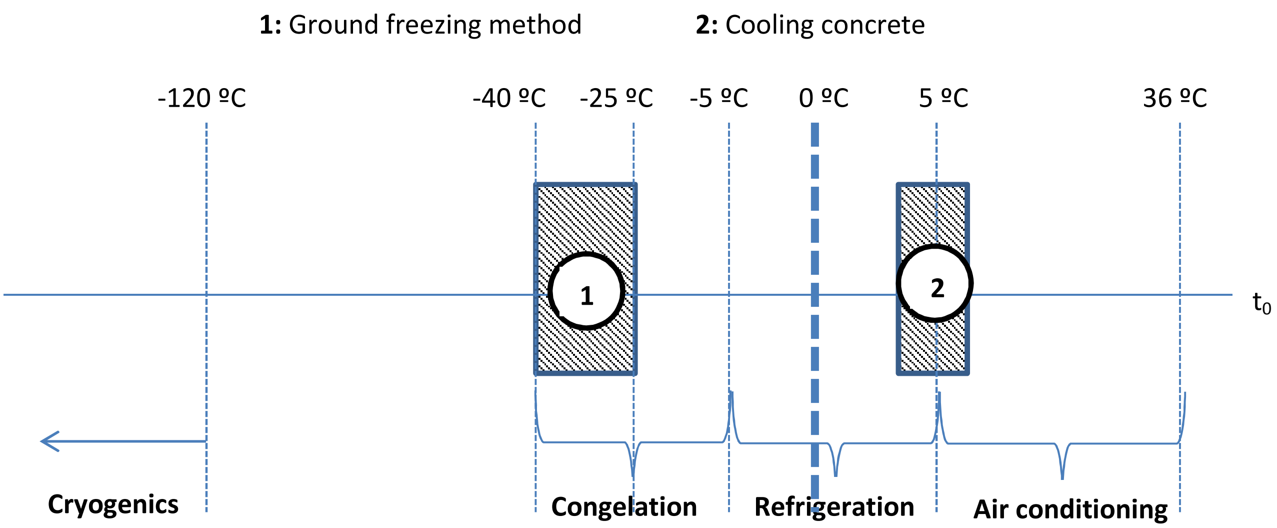

Figure 6: different zones of work. 1 GFM / 2. Cooling concrete

To obtain water at approximately 5 ºC to use in the concrete technology (refrigeration zone) it is recommended to use a one stage vapor compression refrigeration system. For the GFM (congelation zone), to obtain the necessary temperature for freeze the water in the soil, it must be used the two stage vapor compression refrigeration system.

4.3.1. Concrete refrigeration system

For cooling concrete, the rank of temperature where the VCRS usually works is between the 4 ºC and 6 ºC. For this reason, the constructive solution that usually is used for cooling the water that concrete needs is one of the more simples, the vapor compression refrigeration system with a single stage.

For the correct modeling of this refrigeration system, it will be necessary to determine approximately the different parameters that are needed to design it. The most important ones that must be known about the case of cooling concrete are the mass flow $\dot{m}$ and the temperature t_0. With these two parameters it is possible to calculate the cooling power $\dot{Q}_0$ and start the design of the constructive solution.

For an approximate value of these parameters it will be used: for cooling water from 16 ºC to 1,5 ºC in 90 minutes it is needed a VCRS with $\dot{Q}_0$ = 2450 kW**;** that means that the $\dot{m}_w$ is about 144 t/h. [4]

The application that this project studies needs to cool water from 20 to 5 ºC, so if it is used the same $\dot{m}_w$, it will be necessary a cooling power of 2512 kW.

This values will be very useful for calculate the constructive solution, but the exactly values and the explanation of how can be obtained will be explained in the following chapter where a specific location and building for both cases will be established. Knowing the location of the buildings and its structure and dimensions, it will be easy to define these parameters.

4.3.2. GFM refrigeration system

This method is located in the zone of congelation, between -40 ºC and -25 º C. As it is a zone completely different from the first case (cooling concrete) the constructive solution that this method needs has some differences from the one explained previously.

The main difference between this VCRS and the previous one is that the first one has only one stage while the one for this application (ground freezing method) might use two stages.

Even if it is possible that the ground freezing method uses a refrigeration system with only one stage; the thermal losses would be around the 60 %. Obviously, these losses are too big and this fact would mean that it would have a lot of economic losses.

For this reason, the most used constructive solution of VCRS is the one with two stages.

Before calculate the constructive solution an approximate value will be given as a reference. For the Fürth subway tunnel (Germany) it was necessary a refrigeration plant consisted of two two-stage freezing aggregates, each with a cooling power of 465 kW. Calcium chloride brine cooled down to -40 ºC was used as a refrigerant. [5]

This tunnel has a diameter of 6,6 m. and a length of 56 meters. It used 23 pipes with the same length of the tunnel and it took 28 days to complete the operation.

4.4. Refrigerant restrictions.

4.4.1. History and evolution of refrigerants.

A refrigerant is a substance used in a heat cycle usually including, for enhanced efficiency, a reversible phase transition from a liquid to a gas.

The use of all type of refrigerants where allowed until the 1987, when the Montreal protocol was signed. This protocol intended to protect the ozone layer and phasing out the production of numerous substances believed to be responsible for ozone depletion. As a consequence of this protocol, all the substances with a high ozone depletion potential (ODP) were phasing out. The main refrigerants affected were the Chlorofluorocarbons (CFCs) and Hydrochlorofluorocarbons (HCFCs) such as R11, R12 R14…R502.

The problem of the refrigerants mentioned before was the chlorine which was causing the ozone layer when it reacts with the ozone O_3. For this reason, the chlorine was removed from the refrigerants and gave way to the second generation of refrigerants, the Hydrofluorocarbons (HFCs). The first HFC was R134a, having a null ODP and a few years later other HFCs have been used, such as (R152, R404A, R407C, R410A etc.), obtained by blending different CFCs and HCFCs, which had a low ODP, with R134a, leading to the "third generation" of refrigerants.

In 1997, the second big protocol was signed, the Kyoto's protocol. This protocol putted some restrictions to these gases that produced the global warming, specifically these ones with a Global Warming Potential (GWP) higher than 20. As a consequence of these restrictions, the use of HFCs refrigerants was drastically restricted.

The result of the signature of these two protocols was the necessity of create a new refrigerant with a null ODP and a lower GWP. These new refrigerants (fourth generation) were a mixture of HFCs and PFCs and they had a low GWP or also new pure refrigerants like the Fluoroalkene (HFOs). However, there was another solution besides the fourth generation of refrigerants, the ones called natural refrigerants, like the ammonia R717 (NH_3) and the CO_2.

4.4.2. Refrigerants for both cases of study

As it was explained in the previous points, depending of which refrigerant uses the VCRS the parameters obtained will be different. For the first case (cooling concrete) the most common refrigerant is the ammonia, a natural refrigerant with excellent properties. For the second one (GFM) the most common ones are the brine and the liquid nitrogen.

The ammonia is an excellent refrigerant because of his boiling temperature (-27 ºC at atmospheric pressure) and his latent heat of vaporization (1400 kJ/kg at 1 atm.). On the other hand, although is a good refrigerant, it is toxic, corrosive and pollutant. For these reason the refrigerating system must be very safe.

5. Constructive solution and calculation method

Once in the previous chapter has been explained in which consists the two methods that will be studied during this project; the cooling of concrete and the ground freezing method (GFM), it is turn to explain the different constructive solutions that have been adopted for both cases of the considered cold technique applications in civil engineering.

The main objective of this chapter is to explain the different steps that permit the calculation of all the parameters of a Vapor Compression Refrigeration System (VCRS) that will be necessary for compare and choose the method that will be studied in this project.

5.1. History and origins of VCRS

The American inventor Oliver Evans, acclaimed as the "father of refrigeration," invented the vapor-compression refrigeration machine in 1805. Heat would be removed from the environment by recycling vaporized refrigerant, where it would move through a compressor and condenser and would eventually revert back to a liquid form in order to repeat the refrigeration process over again. However, no such refrigeration unit was built by Evans.

In 1834, Jacob Perkins modified Evans' original design, building the world's first refrigerator and filing the first legal patent for refrigeration using vapor-compression. John Gorrie, an American doctor from Florida, invented the first mechanical refrigeration unit in 1841, based on Evans' original invention to make ice. Gorrie's mechanical refrigeration unit was issued a patent in 1851. In 1853, Alexander C. Twining of Cleveland, Ohio patented an early vapor-compression refrigerator that was fully capable of producing a ton of ice per day.

In 1856, James Harrison developed an ice making machine using ammonia and an ether compressor. Ferdinand Carré of France developed a more complex system in 1859. [6]

5.2. First case: cooling concrete

For the correct calculation of the different parameters that perform the constructive solution for the first case of study (cooling concrete) it will be necessary define some generalities that are essentials for the correct development. These generalities are the determination of the concrete's structure, which will be the location of the building and define its structure.

5.2.1. Generalities

5.2.1.1. Type of concrete and manufacturing process

For the first case of study, cooling concrete, first of all it will be explained the manufacturing process and which is the concrete's composition. There are so many types of concrete, but in this project will be studied the concrete that uses the Portland cement.

The reason of study this type of concrete is that, nowadays, is one of the most used and its manufacturing process is not so complicated.

Manufacturing process

To produce concrete, the first step is to make the Portland cement. For doing this, it is necessary to crush into small pieces the limestone ($CaCO_3$). After this, the crushed limestone is mixed with clay, sand and iron ore until is obtained a homogeneous product.

The mixture is putted into a rotary cylindrical kilns (they can grow to 6 meters in diameter and 180 feet long) where it becomes warmer. The mixture enters for the top of the cylinder and is distributed throughout the cylinder due to the rotation and tilt of the cylinder. At the bottom, fuel is injected and burned, which produces enough heat for produce the mixture reaction. This stage can last up to two hours.

As the mixture down the cylinder, it progresses through four stages of transformation. Initially, the water present in free state evaporates. Then, the decomposition happen bound water and CO_2, a process called calcination. The third stage is called clinkering, period during which is formed calcium silicate. Finally, the last stage is cooling the mixture.

The resulting product is known as clinker, and is a mixture of four main components that will be described below. The Clinker is cooled and mixed with small quantities of plaster and finally get Portland cement. [7]

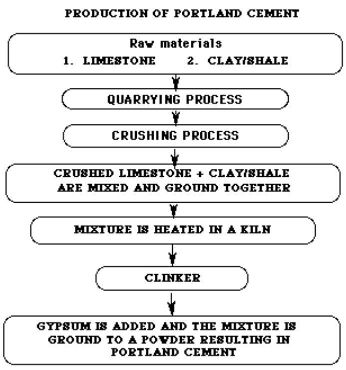

Figure 7: manufacturing process Portland cement

It is important to know the percentage of the different components that form the Portland cement. This percentage is showed in the following tables:

Clinker composition

Clinker Compound	Weight Percentage	Chemical Formula
Tricalcium silicate	50	Ca_3SiO_5
Dicalcium silicate	25	Ca_2SiO_4
Tricalcium aluminate	10	$Ca_3Al_2O_6$
Tetracalcium aluminoferrite	10	$Ca_4Al_2Fe_2O_{10}$
Gypsum	5	$CaSO_4.2H_2O$

Table 1: clinker composition [7]

Protland cement composition

Cement	Weight Percentage %	Chemical formula
Calcium oxide	61-67	CaO
Silicon dioxide	19-23	SiO_2
Aluminum oxide	2.5-6	Al_2O_3
Ferric oxide	0-6	Fe_2O_3
Sulfate	1.5-4.5	

Table 2: Portland cement composition [7]

Once the Portland cement is produced, to obtain concrete it is necessary to mix it with some aggregates (gravel and sand) and water.

During the Portland cement elaboration some different reactions occur. These reactions are very important to know for the well development of this project because they indicate the amount of heat that is necessary to remove. [7]

The two most important reactions that produce most of the heat are the following ones:

Tricalcium silicate + Water--->Calcium silicate hydrate + Calcium hydroxide + heat

$$2\ Ca_3SiO_5 + 7\ H_2O \dashrightarrow 3\ CaO.2SiO_2.4H_2O + 3\ Ca(OH)_2 + 173.6kJ$$

Dicalcium silicate + Water--->Calcium silicate hydrate + Calcium hydroxide +heat

$$2\ Ca_2SiO_4 + 5\ H_2O \dashrightarrow 3\ CaO.2SiO_2.4H_2O + Ca(OH)_2 + 58.6\ kJ$$

However, these reactions occur in different moments during the concrete's hardening and the duration of both reactions are very different. The first exhotermic reaction happens when the concrete is placed, for the first 15 minutes. The amount of heat that this reaction emits is very high.

On the other hand, even the second exhotermic reaction produces an amount of heat lower than the first one, this reaction take place along 32 hours approximately.

The following graphic shows the amount of heat that the concrete emits during its hardening.

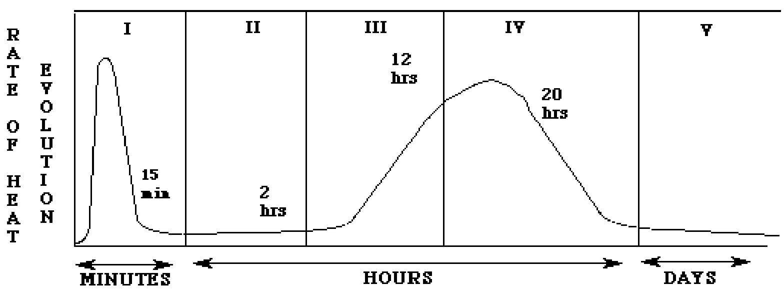

Figure 8: heat evolution [7]

The stage I, hydrolysis of the cement compounds, occurs rapidly with a temperature increase of several degrees. The first stage of the heat evolution starts with an exothermic reaction that stops at the 15 minutes it has started. As it was explained before, during this stage the reaction emits a big amount of heat.

Stage II is known as the dormancy period. The evolution of heat slows dramatically in this stage. The dormancy period can last from one to three hours. During this period, the concrete is in a plastic state which allows the concrete to be transported and placed without any major difficulty. This is particularly important for the construction trade who must transport concrete to the job site.

It is at the end of this stage that initial setting begins. In stages III and IV, the concrete starts to harden and the heat evolution increases due primarily to the hydration of tricalcium silicate. Stage V is reached after 3 hours. The slow formation of hydrate products occurs and continues as long as water and unhydrated silicates are present.

5.2.1.2. Type of construction and location

As in every project, there must be an specific application for the method that is studied that allows estimate the different parameters and permits the reader of the project have a better idea of the dimensions of this project.

For this project, it has been chosen a type of construction that is very common around the world and for sure all people have seen in their lives, a dam. To be more specific, the dam that will be studied in this project is a real dam that was built in 1967 at la "Pobla del Benifassar" (Valencia). This dam controls a reservoir located in the river Senia and provides with water to all surrounding cities and the growing fields along all the months of the year.

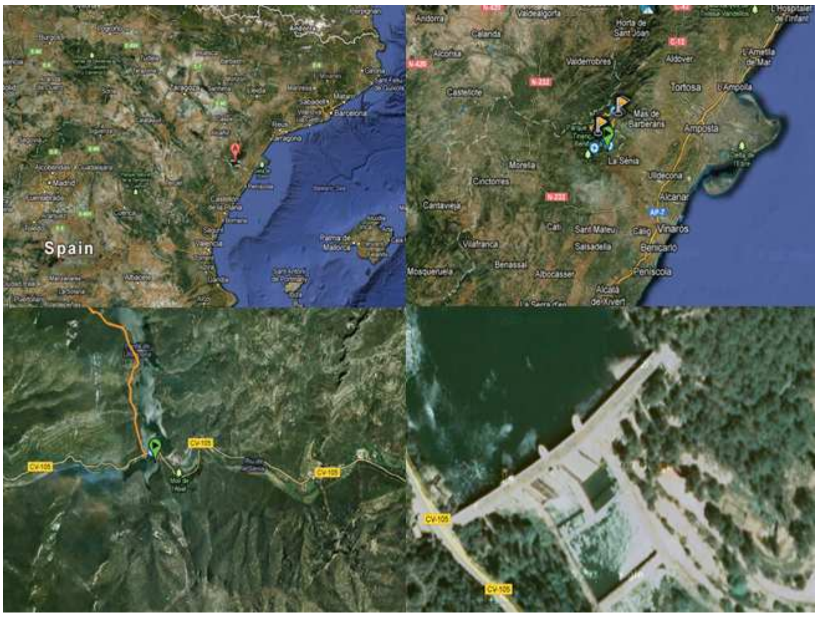

Figure 9: localization of the dam

To perform the constructive solution for cooling water it is necessary to know the dimensions of the dam and the amount of concrete that was used in its construction. To have an idea about the dimensions of the construction it was needed a total amount of 129000 m^3 of concrete, or 296700000 kg of it (the concrete's density is around 2300 kg/m^3). [8]

Figure 10: dam's structure and reservoir formed by the dam [8]

A big advantage about the placement of this construction is that, as it was explained previously, is located in the river Senia. This fact allows that the water needed for cooling the concrete can be taken from the same river. In addition, the temperature of the river is approximately the same during the year, so it will be taken as a temperature of the river 20 ºC.

However, the river's temperature is too high to cool the concrete correctly. For this reason it will be needed a VCRS that cool the water from the 20 ºC until 5ºC.

5.2.1.3. Parameters for the design of a VCRS

Thanks to the graph that shows the evolution of the heat along the different days while the concrete is hardening, it is possible to calculate the amount of heat that will be needed to remove by the VCRS. Using the tables with the composition percentage that have been showed before and the total amount of concrete that will be needed it is possible

However, to make easier the calculation of heat removed from the concrete, the hypothesis that the different reactions take place simultaneously is made.

First of all, it is necessary to calculate the heat for the different stages where the exothermic reaction occurs. For the first case the amount of heat is the following one:

$$\frac{173.6kJ}{2\ mol\mathbf{Ca3SiO5}} \cdot \frac{1mol\mathbf{Ca3SiO5}}{228\ grams\ \mathbf{Ca3SiO5}} = 0{,}38\ kJ/g \quad \frac{58.6kJ}{2\ molCa2SiO4} \cdot \frac{1molCa2SiO4}{172\ grams\ Ca2SiO4} = 0{,}17\ kJ/g$$

$Q_{dev} = \sum q_i \cdot X_i$ = 0.38·0.5+0.17·0.25 = 0.2325 kJ/g concrete (5.1)

$$Q_{tot} = Q_{dev} \cdot g\ concrete = 0{,}2325 \frac{kJ}{gconcrete} \cdot 2{,}967x10^{11} gconcrete = 68982750000\ kJ \quad (5.2)$$

As in this period the reaction takes place along 15 minutes:

$$\dot{Q}_{tot} = \frac{Q_{tot}}{\tau} = \frac{Q_{tot}}{15min \cdot \frac{60s}{1min}} = 76647500\ \mathrm{kW} \quad (5.3)$$

If the same procedure is done for the second most important reaction, which occurs during 32 hours,the amount of heat that will be necessary to remove is:

$$Q'_{tot} = 0.8 \cdot Q_{tot} = 0.186 \frac{kJ}{kgconcrete} \quad \dot{Q}_{tot} = \frac{Q'_{tot}}{\tau} = \frac{Q_{tot}}{32h \cdot \frac{3600s}{1h}} = 479046{,}875\ kW \quad (5.4)$$

For the correct cooling of concrete it will be necessary the continuous supply of water that will be used. This water can be supplied for trucks (if it is not a big construction) or from rivers. For this project the water used will be extracted from the nearest river, which temperature is around the 20 Celsius degrees, and, obviously, it will be necessary to cool (and filtrate) the water before use it for cooling the concrete.

The main objectives of the following chapters will be the analysis and design of the VCRS that will cool the water from the 20 ºC (river) to 5 ºC (water's for cooling concrete). In addition, normal VCRS in one stage that are used for cooling concrete have a mass flow around 60 t/h. With these two parameters it is possible to calculate the cooling power of a VCRS and estimate in how many parts will be necessary for build the dam.

$$\dot{Q}_0 = c_W \cdot \Delta T_W \cdot \dot{m}_W = 4{,}1868 \frac{kJ}{kg \cdot K} \cdot (20ºC - 5ºC) \cdot \frac{60t}{h} \cdot \frac{1000kg}{t} \cdot \frac{1h}{3600s} = 1046{,}7\ kW$$

(5.5)

With all this specifications it is possible to perform a design of the VCRS in one stage, but it will be designed after the choosing between the two different cases of study.

The second method of calculation is based in the following graph and explained with more precision in the table. [9]

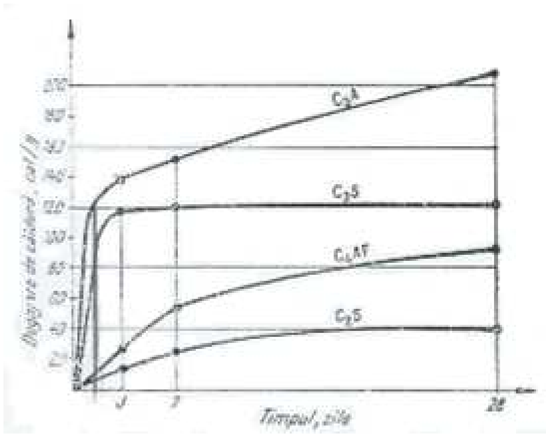

Figure 11: heat emitted by component- time [9]

Cement Compound	Weight Percentage	Chemical Formula	Heat (cal/g)
Tricalcium silicate	50 %	C_3S	120
Dicalcium silicate	25 %	C_2S	15
Tricalcium aluminate	10 %	C_3A	140
Tetracalcium aluminoferrite	10 %	C_4AF	25
Gypsum	5 %	$CaSO_4.2H_2O$	

Table 3: heat for every concrete component

Following the same steps that were done previously it is possible to obtain the cooling power for this method.

$Q_{dev} = \sum q_i \cdot X_i = 120 \cdot 0{,}5 + 15 \cdot 0{,}25 + 140 \cdot 0{,}1 + 25 \cdot 0{,}1 =$ 80,25 cal/g concrete (5.6)

$$80{,}25 \frac{cal}{gconcrete} \cdot \frac{4{,}1868J}{1cal} = 336 \frac{J}{gconcrete}$$

$$Q_{tot} = 336 \frac{J}{gconcrete} \cdot 2{,}967x10^{11} gconcrete = 99691200000\ kJ \qquad (5.7)$$

$$\dot{Q}_{tot} = \frac{Q_{tot}}{\tau} = \frac{99691200000\ kJ}{3day \cdot \frac{24h}{1day} \cdot \frac{3600s}{1h}} = 384611{,}11\ kW \qquad (5.8)$$

In the following table it is showed the values of the cooling power for the different methods and in how many parts the dam must be built if it is done with a VCRS in one stage with a mass flow of 60 t/h or 100 t/h

Method	Method 1	Method 1'	Method 2
Cooling power (kW)	76647500	479046,875	384611,11
Parts (60 t/h)	73207	458	368
Parts (100 t/h)	43924	275	221

Table 4: parts needed for every method

Looking the previous table the first conclusion that can be made is that is very difficult to determine the exact amount of heat that the concrete emits during its hardening. There are several things that influence on the amount of heat, like could be the concrete's composition, the air temperature, etc. and for this reason the results of the cooling power are so different depending of the method used.

However, as the time needed to build the dam is one of the most important factors that determine its construction; it has been chosen that the constructive solution has a water mass flow of 100 t/h. That means that the cooling power of the VCRS will be approximately 1750 kW.

5.2.2. One stage refrigeration system

For the first case of study (cooling concrete) two different constructive solutions will be studied. The first one will be the constructive solution that uses an overheating and subcooling, while the second one will be the constructive solution that uses only the overheating of the vapor and a liquid bottle.

Before establish the calculation method for the VCRS in one single stage, it is important to have the basic parameters that will allow calculating the constructive solution.

- $\dot{Q}_0$: cooling power.
- River's temperature.
- Water's temperature for cooling the concrete.
- Temperature increase for subcooling.
- Temperature increase for overheating.

The diagram of temperature variation, in case of a pure substance is isotropic. For the correct exchange of heat between the refrigerant and the cooling water for the concrete, there is a little variation of the temperature between both fluids. [10]

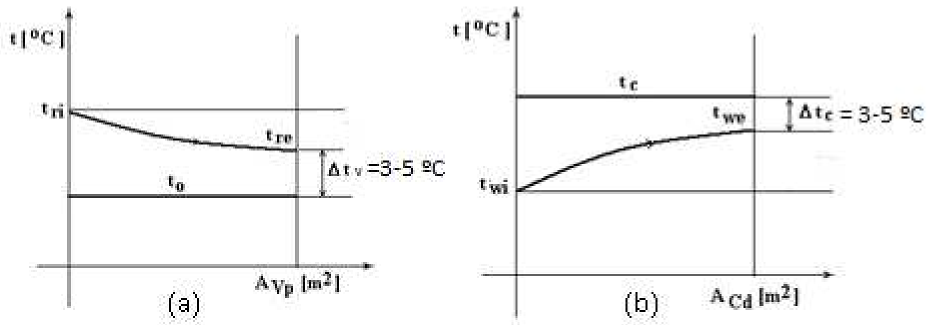

Figure 12: temperature variation evaporator (a) and condenser (b) [10]

With these variations of temperature it is possible to calculate the value of the t_0 and t_c and, knowing the refrigerant that the VCRS will use, it is possible to calculate the values of the pressure p_o (when x=1) and p_c (when x=0).

5.2.3. First constructive solution

As it was explained previously, the first constructive solution uses an overheating and a subcooling, that protects the cylinder and increases the value of q_0. The thermal cycling that is below shows the subcooling (sr) and the overheating (si).

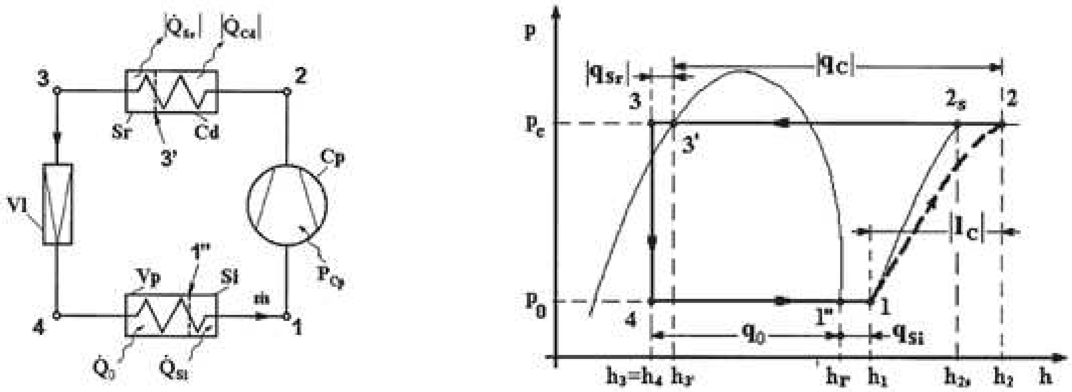

Figure 13: const. scheme and theoretical therm. cycle one stage VCRS [11]

Calculation of characteristic points

Point 1''

In this point, the pressure (p_0) is known and the hypothesis that the vapor is saturated is done (x=1). With these two parameters is possible to calculate all the others (entropy, enthalpy…).

Point 1

At the same pressure (p_0), the refrigerant experiments an overheating to prevent drops of liquid into the cylinder compressor. For this reason the temperature t1 is $t_1 = t_0 + \Delta t_{sh}$ where the value of $\Delta t_{sh} \in (10 \div 25)º$ for the refrigerants R and for the ammonia $\Delta t_{sh} \in (10 \div 15)º$

With the two parameters calculate (t_1 and p_0), the other parameters are easy to obtain. One of the parameters that are important to note is the specific volume because it is an essential parameter to measure the cylinder.

Point 2s

This is a theoretical point, where the hypothesis that the entropy is constant along the process is made. That means that $s_{2s} = s_1$ and the pressure of work is p_c. With this information and knowing all the time which refrigerant uses the VCRS, the point is defined.

Point 2

Obviously, the efficiency of the compressor is not 100% (because the compression is not isentropic and there are some losses). For this reason it will be necessary to calculate which efficiency has the compressor and determinate the point 2.

For calculate the efficiency:

$$\eta_s^{cp} = \frac{|l_1|}{|l_{cp}|} < 1 \qquad \text{where } \eta_s^{cp} \in (0{,}7 \div 0{,}95)$$

$$\eta_s^{cp} = \frac{|l_1|}{|l_{cp}|} = \frac{T_1(p_a)}{T_1(p_r)} = \frac{T_0}{T_c} < 1 \qquad \eta_s^{cp} = \frac{h_{2s}-h_1}{h_2-h_1} \rightarrow h_2 = h_1 + \frac{h_{2s}-h_1}{\eta_s^{cp}} \quad (5.10)$$

With the enthalpy h_2 and the pressure p_c all the other parameters that conforms the point 2 can be calculated.

Point 3'

This point corresponds at the state of the refrigerant after passing for the condenser. In this point the pressure still being p_c and the other important parameter that allow to calculate all the values is the title, because after passing for the condenser, the refrigerant is in a state of saturated liquid (x=0).

Point 3

In this point, the refrigerant experiments a subcooling that increases the value of q_0 and in this way is diminished the irreversible negative influence on the effectiveness of cold rolling process cycle

Knowing that the decrease of the temperature $\Delta t_{sc} \in (4 \div 10)$ for the refrigerants R and the ammonia it is possible to calculate the value of t_3: $t_3 = t_c - \Delta t_{sc}$

With the value of the temperature and the pressure this point is totally defined.

Point 4

The last point corresponds to the one after the expansion valve. This process occurs at a constant enthalpy, what means that h_3=h_4 and the pressure of this point is p_0 again. After this, all the other parameters can be calculated easily. In addition, the title of the refrigerant is a very important parameter and it must be lower than 0,2.

Specific energy exchange

$q_0 = h_{1''} - h_4$ $\quad q_{sh} = h_1 - h_{1''}$ $\quad |l_c| = h_2 - h_1$ $\quad |q_{cd}| = h_2 - h_{3'}$ $\quad q_{sc} = h_{3'} - h_3$ (5.11)

Determination of the mass flow rate of refrigerant

As there is only one circuit, there will be only one mass flow.

$$\dot{Q}_0 = \dot{m}_0 \cdot q_0 \rightarrow \dot{m}_0 = \frac{\dot{Q}_0}{q_0} \qquad (5.12)$$

Determination of energy flux exchanged

$$P_{cp} = \dot{m}_0 \cdot |l_c| \quad \dot{Q}_{sh} = \dot{m}_0 \cdot q_{sh} \quad |\dot{Q}_{cd}| = \dot{m}_0 \cdot |q_{cd}| \quad |\dot{Q}_{sc}| = \dot{m}_0 \cdot |q_{sc}| \quad (5.13)$$

Energy balance

$$\sum \dot{Q} = \sum P \rightarrow \dot{Q}_0 + \dot{Q}_{sh} - |\dot{Q}_{cd}| - |\dot{Q}_{sc}| = -P_{cp} \quad (5.14)$$

Coefficient of Performance

$$COP_f = \frac{\dot{Q}_0}{P_{cp}} \qquad COP_t = \frac{|\dot{Q}_{cd}|}{P_{cp}} \qquad COP_{cog} = \frac{\dot{Q}_0 + |\dot{Q}_{cd}|}{P_{cp}} \quad (5.15)$$

5.2.4. Second constructive solution

A second constructive solution for a single stage VCRS which uses as a refrigerant the ammonia is the one that is shown below.

The main difference between this VCRS and the previous one is that this one doesn't use a subcooling for increase the q_0. This one uses a liquid separator increasing the amount of heat that can be extracted for the VCRS as it is showed in Figure 14.

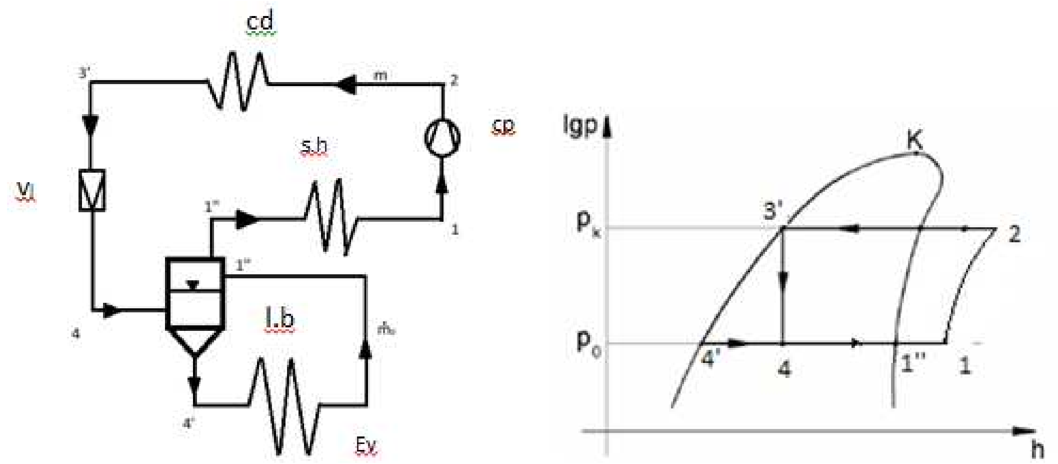

Figure 14: const. scheme and theoretical therm. cycle one stage VCRS with l.b.

Calculation of characteristic points

As the first points of this constructive solution are exactly the same than in the previous one, the points 1'', 1, 2s, 2 and 3' will not be explained again. To know the procedure the only thing necessary is to consult the previous point.

Point 4

The point 4 corresponds to the one after the expansion valve. This process occurs at a constant enthalpy, what means that $h_{3'}=h_4$ and the pressure of this point is p_o again. After this, all the other parameters can be calculated easily.

Point 4'

As a result of the liquid tank, the refrigerant in the point 4 is separated in saturated liquid and saturated vapor. The point 4' corresponds at the saturated liquid and using the pressure p_0 and the title x=0 it is possible to calculate all the different parameters.

One of the most significant difference between the constructive solutions that uses a subcooling and the one that uses a liquid bottle is that while the first one the value of q_0

depends of the grade of subcooling, for the second one this value will be always the maximum. This is because in the bottle there is saturated liquid what causes that q_0 is the difference between the enthalpy when the title of the refrigerant is 1 and when is 0 (vapor and liquid saturated).

Specific energy exchange

$q_0 = h_{1''} – h4'$ $\quad q_{sh} = h_1 – h_{1''}$ $\quad |l_c| = h_2 – h_1$ $\quad |q_{cd}| = h_2 – h_{3'}$ (5.16)

Determination of the mass flow rate of refrigerant

As a difference from the other constructive solution with a single stage VCRS that was explained previously, in this one there is two different mass flow. The $\dot{m}_0$ can be calculated as before (5.12) while the mass flow that circulates in the evaporator must be calculated doing an energetic balance in the liquid tank.

$$\sum \dot{H}_i = \sum \dot{H}_o \rightarrow \dot{m}_0 \cdot h_{1''} + \dot{m}_2 \cdot h_4 = \dot{m}_0 \cdot h_{4'} + \dot{m}_2 \cdot h_{1''}$$

$$\dot{m} = \frac{h_{1''} - h_{4'}}{h_{1''} - h_4} \cdot \dot{m}_0 \quad (5.17)$$

Determination of energy flux exchanged

$$P_{cp} = \dot{m} \cdot |l_c| \qquad \dot{Q}_{sh} = \dot{m} \cdot q_{sh} \qquad |\dot{Q}_{cd}| = \dot{m} \cdot |q_{cd}| \quad (5.18)$$

Energy balance

$$\sum \dot{Q} = \sum P \rightarrow \dot{Q}_0 + \dot{Q}_{sh} - |\dot{Q}_{cd}| = -P_{cp} \quad (5.19)$$

The coefficient of performance can be calculated like in the 5.15

5.3. Second case: GFM

5.3.1. Limitations of a single stage VCRS

There are several key parameters which, when are exceeded in the design, another type of constructive solution is required. Below are mentioned some of them:

- Compression ratio: usually one stage systems operate on values of 6 to 7.
- Evaporation temperature: for one stage VCRS the evaporation temperatures don't reach the -35 °C or if they reach this temperature they will not do with great efficiency.
- Economical criterion: there is an equation that allows calculating if the one stage VCRS is economically viable. $\lambda_{min} = \lambda_0 \cdot \lambda_p \cdot \lambda_T \cdot \lambda_e \geq 0.65$

    - λ_0: theoretical coefficient of flow
    - λ_p: coefficient which account for losses in the suction pressure
    - λ_T: flow coefficient that takes into account the change in temperature of the refrigerant at the suction passage (93%).
    - λ_e: flow coefficient that takes into account the lack of sealing of the cylinder (96%).

If the value of λ_{min} is not equal or higher than 0.65 that means that use a one stage VCRS is not economically viable. [12]

- Pressures criterion: as it is obvious, the atmospheric pressure is 1 bar. For this reason, it is necessary that p_0 has a value of 1 or slightly above. If it doesn't happen, a depression occurs that tends to crush the component (it would be necessary large thicknesses to resist it).
- Oil temperature criterion: if the compressor temperature reaches the 140 ºC, the oil that circulate with the refrigerant may lost its properties as a consequence of the high temperature.

5.3.2. Description of the GFM project

The second case of study is the performance of a subway tunnel in the city of Fürth (german) and it was made on 2001 using the GFM technique. Two 1300 meters long, single-track tunnels connecting the Stadthalle and Klinikum stations were constructed as part of the extension of the U1 subway line in the German town Fürth (Bayer).

The tunnels cross mostly competent rock with the exception of the Rednitz valley close to the Stadthalle station. Here the tunnel line is located in sand and passes through a length of 56 m beneath a block of historical buildings which are sensitive to surface settlement and are built on water bearing ground. The line section before the building block was excavated in an open cut, which formed a temporary starting work pit for the abovementioned tunnels.

Artificial ground freezing was chosen as an auxiliary measure in order to allow a safe crossing of the valley before reaching the rock formation and avoiding water ingress in the tunnel, as well as inadmissible settlements of the buildings.

The subsequent parts of the tunnels through rock were driven conventionally. Since only the permeable layers needed to be frozen, the freeze pipes were installed in the upper part of the tunnels. Twenty-three freeze pipes with an outer diameter of 89 mm were utilized. To be on the safe side, the first freeze pipes were placed within the competent rock, near its upper boundary.

The location of the interface between the competent rock and the sand deposits or weathered rock was determined on site with ram sounding resistance tests prior to the installation of the freeze pipes. Due to project requirements, the alignment of both tunnels has a slight vertical and horizontal curvature. The boreholes of the freeze pipes also have to follow the same curvature, according to the project contract. To ensure that deviations from the theoretical locations do not exceed 25 cm at any point along the freeze pipes, the boreholes were constructed using the horizontal directional drilling method.

After each 4.66 m, the length of the rod pieces, the position of the end of the borehole was measured and the direction for the next stroke corrected. Since in all of the boreholes were kept within the tolerances, no additional boreholes were necessary. The end of the freeze pipes was embedded at a depth of at least 1.0 meters in the competent rock.

5.3.3. Parameters for the design of a VCRS

As it was mentioned previously, the part of the tunnel where it was used the GFM had a dimensions of 6,6 meter of diameter and 56 meters of length. However, all the calculation will be done for the construction of only one of the two tunnels.

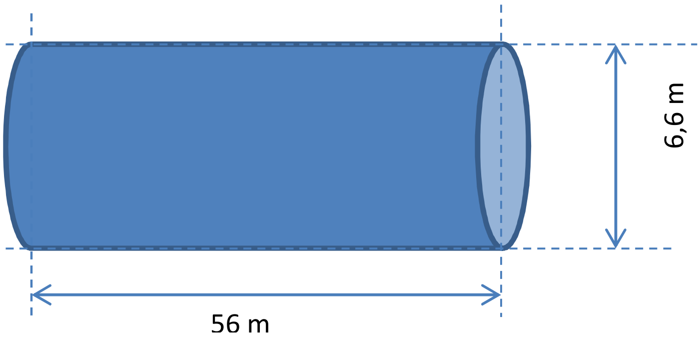

Figure 15: tunnel dimensions

It means that the total volume of the tunnel where the ground freezing method will be used is:

$$V = \frac{\pi \cdot \emptyset^2}{4} \cdot L = 1916\, m^3 \quad (5.20)$$

To perform this tunnel, it was necessary to freeze and perforate the soil with the following properties:

Material	ρ (density kg/m^3)	k (W/m·K)	c_v (MJ/m^3·K)
Soil	1,70	2,20	2,78
Rock	2,00	2,00	2,40

Table 5: parameters of the soil [5]

However, as it was mentioned in the first point, the soil composition is 50% rock and 50 % sediments and weathered rock. So, the ground freezing method will be needed only for the sediment part, because it is the only one where is more difficult to perform the hole. [5]

For this reason, the total volume that will be needed to freeze is 958 m^3.

As it is shown in the following graph, Figure 16, the temperature of the soil or a deep of 9 meters is 14 ºC.

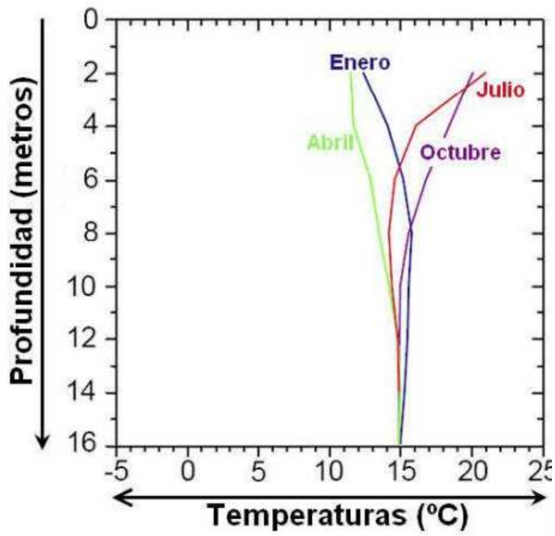

Figure 16: temperature soil – deep

To perform the constructive solution of a VCRS it is necessary to determine the amount of heat that will be needed to remove.

$$Q_{tot} = V \cdot c \cdot \Delta T = 958m^3 \cdot 2780 \frac{kJ}{m^3 \cdot K} \cdot \left(14ºC - (-35ºC)\right) = 130498760\ kJ \quad (5.21)$$

Finally,

$$\dot{Q}_0 = \frac{Q_{tot}}{\tau} \quad (5.22)$$

With all the parameters determined, depending in how many days the tunnel must be done, one cooling power or another will be necessary. In the table below is possible to appreciate the cooling power depending of the hours required for the drilling.

t (h)	$\dot{Q}_0$ (kW)	t (h)	$\dot{Q}_0$ (kW)	t (h)	$\dot{Q}_0$ (kW)
6	6042	**20**	1812	**72**	503
10	3624	**24**	1510	**96**	377,5
16	2265	**48**	755	**120**	302

Table 6: cooling power-time

The two-stage refrigeration system consists of forcing the circulation of the refrigerant gas through two stages, called high and low pressure. These two stages take place inside a special compressor called dual-stage compressor.

5.3.4. Constructive solution

The two-stage refrigeration system consists of forcing the circulation of the refrigerant gas through two stages, called high and low pressure. This contrivance is necessary in order to achieve lower temperatures of evaporation from a single compressor without increasing the compression ratio.

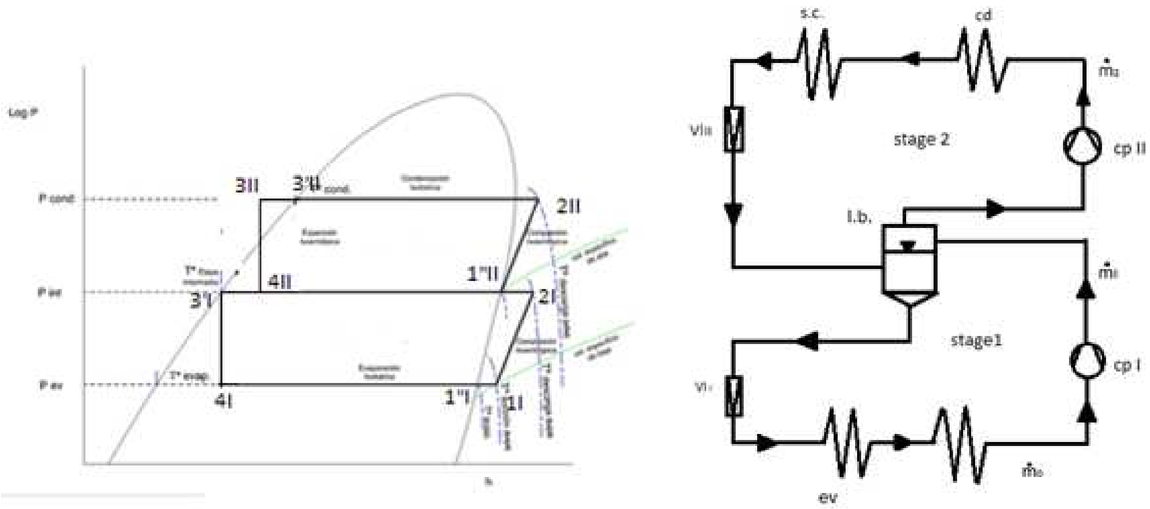

Figure 17: const. scheme and theoretical therm. cycle two stage VCRS

Calculation of characteristic points

The calculation of the different point will be done with an specific notation that identify if the point corresponds to the first stage (I) or to the second one (II).

First stage

Point 1_I''

In this point the pressure (p_0) is known and the refrigerant is saturated vapor (x=1). With these two parameters is possible to calculate all the others (entropy, enthalpy…).

Point 1_I

At the same pressure (p_0), the refrigerant experiments a overheating to prevent drops of liquid into the cylinder compressor. For this reason the temperature t_{1_I} is $t_{1_I} = t_0 + \Delta t_{sh}$ where the value of $\Delta t_{sh} \in (10 \div 25)^{o}$ for the refrigerants R and for the ammonia $\Delta t_{sh} \in (10 \div 15)^{o}$.

With the two parameters calculate (t_{1_I} and p_0), the other parameters are easy to obtain.

Point $2s_I$

This is a theoretical point, where the hypothesis that the entropy is constant along the process is made. That means that $s_{2sI} = s_{1I}$ and the pressure of work is p_i. With this information and knowing all the time which refrigerant uses the VCRS, all the values of this point can be calculated.

Point 2_I

$$\eta_s = \frac{|l_1|}{|l_{cp}|} < 1 \text{ where } \eta_s \in (0{,}7 \div 0{,}95)$$

$$\eta_{sI}^{cp} = \frac{|l_1|}{|l_{cp}|} = \frac{T_1(p_a)}{T_1(p_r)} = \frac{T_0}{T_i} < 1 \qquad \eta_{sI}^{cp} = \frac{h_{2sI}-h_{1I}}{h_{2I}-h_{1I}} \rightarrow h_{2I} = h_{1I} + \frac{h_{2sI}-h_{1I}}{\eta_{sI}^{cp}} \quad (5.23)$$

With the enthalpy h_{2I} and the pressure p_i all the other parameters that conforms this point can be calculated.

Second stage

Point 1_{II}''

In this point, the pressure (p_i) is known and the refrigerant is saturated vapor (x=1). With these two parameters is possible to calculate all the others (entropy, enthalpy…).

Point $2s_{II}$

This is a theoretical point, where the hypothesis that the entropy is constant along the process is made. That means that $s_{2s} = s_1$ and the pressure of work is p_c. With this information and knowing all the time which refrigerant uses the VCRS, all the values of this point can be calculated.

Point 2_{II}

$$\eta_s = \frac{|l_2|}{|l_{cp}|} < 1 \text{ where } \eta_s \in (0{,}7 \div 0{,}95)$$

$$\eta_{sII}^{cp} = \frac{|l_2|}{|l_{cp}|} = \frac{T_1(p_a)}{T_1(p_r)} = \frac{T_i}{T_c} < 1 \qquad \eta_{sII}^{cp} = \frac{h_{2sII} - h_{1II}}{h_{2II} - h_{1II}} \rightarrow h_{2II} = h_{1II} + \frac{h_{2sII} - h_{1II}}{\eta_{sII}^{cp}} \quad (5.24)$$

With the enthalpy h_{2II} and the pressure pc all the other parameters that conforms this point can be calculated.

Point 3_{II}'

This point corresponds at the state of the refrigerant after passing for the condenser. In this point the pressure still being pc and the other important parameter that allow to calculate all the values is the title of the refrigerant, because after passing for the condenser, the refrigerant is in a state of saturated liquid (x=0).

Point 4_{II}

The last pint corresponds to the one after the expansion valve. This process occurs at a constant enthalpy, what means that $h_{3II}=h_{4II}$ and the pressure of this point is p_i again. After this, all the other parameters can be calculated easily. In addition, the title of the refrigerant is a very important parameter and it must be lower than 0,2.

Point 3_I'

As a result of the liquid tank, the refrigerant in the point 4 is separated in saturated liquid and saturated vapor. This point 3' corresponds at the saturated liquid and it is possible to calculate all the different parameters using the pressure p_0 and the title x=0.

Point 4_I

The last pint corresponds to the one after the expansion valve. This process occurs at a constant enthalpy, what means that $h_{3'I}=h_{4I}$ and the pressure of this point is p_i again. After this, all the other parameters can be calculated easily. In addition, the title of the refrigerant is a very important parameter and it must be lower than 0,2.

Specific energy exchange

$$q_0 = h_{1''I} - h_{4'I} \qquad q_{sh} = h_{1I} - h_{1''I} \qquad |l_{c1}| = h_{2I} - h_{1I}$$

$$|l_{c2}| = h_{2II} - h_{1''II} \qquad |q_{cd}| = h_{2II} - h_{3II'} \qquad |q_{sc}| = h_{3'II} - h_{3II} \quad (5.25)$$

Determination of the mass flow rate of refrigerant

As a difference from the other constructive solution of a single stage VCRS that was explained previously, in this one there is two different mass flow. The $\dot{m}_0$ can be calculated as before (5.12) while the mass flow that circulates in the evaporator must be calculated doing an energetic balance in the liquid tank.

$$\sum \dot{H}_i = \sum \dot{H}_o \rightarrow \dot{m}_0 \cdot h_{2I} + \dot{m} \cdot h_{4II} = \dot{m}_0 \cdot h_{3I'} + \dot{m} \cdot h_{1II''}$$

$$\dot{m} = \frac{h_{2I} - h_{3I}}{h_{1II''} - h_{4II}} \cdot \dot{m}_0 \qquad (5.26)$$

Determination of energy flux exchanged

$$P_{cp1} = \dot{m}_0 \cdot |l_{c1}| \qquad P_{cp2} = \dot{m} \cdot |l_{c2}| \qquad \dot{Q}_{sh} = \dot{m}_0 \cdot q_{sh}$$

$$|\dot{Q}_{sc}| = \dot{m} \cdot |q_{sc}| \qquad |\dot{Q}_{cd}| = \dot{m} \cdot |q_{cd}| \qquad (5,27)$$

Energy balance

$$\sum \dot{Q} = \sum P \rightarrow \dot{Q}_0 + \dot{Q}_{sh} - |\dot{Q}_{cd}| - |\dot{Q}_{sc}| = -P_{cp1} - P_{cp2} \qquad (5.28)$$

Coefficient of Performance

$$COP_f = \frac{\dot{Q}_0}{P_{cp1}+P_{cp2}} \qquad COP_t = \frac{|\dot{Q}_{cd}|}{P_{cp1}+P_{cp2}} \qquad COP_{cog} = \frac{\dot{Q}_0+|\dot{Q}_{cd}|}{P_{cp1}+P_{cp2}} \quad (5.29)$$

5.4. Choosing the application that will be studied

In the previous points was showed the two different constructive solutions for both cases of study. Now, it is time to choose one of them to continue with the project and the analysis of the VCRS if different refrigerants are used.

The method to decide consists in a few criteria that have a determinate value which is related with the importance of the topic. Every case will have a scoring about the topic and the one with the total score higher will be the one studied.

One of the most important qualities that must have the project is that it has to be easy to develop. This means that it is possible to study all the different points which the project is related. Developing the project like this, it will become a complete project where all the parts are well explained and, in fact, easy to understand for non-specialized people.

On the other hand, it shocks that the less important points are the external support and if it is easy to find information about the case of study. This is because nowadays, with internet and all the external support that the world is provided with, it is easy to find any information.

In the following table it is possible to observe the different topics, with their relevance and the total score for both cases of study.

SCORING		CONCRETE		GROUND FREEZING METHOD	
Knowledge about the topic	3	4	12	1	3
Easy to find information	2	5	10	3	6
Interest	3	3	9	5	15
Easy to develop	4	4	16	3	12
External support	2	2	4	1	2
Relation with structural field	4	4	16	3	12
Total			67		50

Table 7: choosing the best alternative

Using this method, the clearly candidate is the alternative of cooling concrete. The difference between both cases is enough significant to choose the first case (cooling concrete) as the one which this project will study about.

So, as a conclusion, the chosen one is the case of cooling concrete with its corresponding one stage constructive solution.

6. Comparative analysis of a single stage VCRS

In this chapter will be determined which one of the two constructive solutions for a single stage VCRS that were explained in the chapter 5.2 is better for cooling concrete. All the parameters that define a VCRS will be the same for both cases with the exception of the subcooling degree (only one of the constructive solutions uses it).

In addition, it will be studied how the different constructive solutions work if they use different refrigerants. The different refrigerants that the VCRS will use are: the ammonia (R717) as a natural refrigerant, and the freons, concretely, the family of R400 (R404A, R407C and R410A) and the R134a as the synthetic ones.

Finally, it will be studied which one of the refrigerants is better comparing the values of the COP, P compressor, mass flow, and making sure that they comply with the restrictions.

6.1. Refrigerants

In the chapter 4.4 was explained the evolution of the refrigerants along the years and the necessity of use new refrigerants that respects the Montreal’s protocol and the Kyoto’s protocol. Now, before study the behavior of the different refrigerants in the one stage VCRS, it will be explained these refrigerants and their properties.

6.1.1. Ammonia (R717)

Ammonia or azane R717 is a compound of nitrogen and hydrogen with the formula NH_3. It is a colorless gas with a characteristic pungent smell what causes that the leaks are easily detectable.

Some great advantages that presents this compost is that does not deplete the ozone (ODP = 0) and does not contribute to climate change (0 GWP). This is one of the most important characteristics of the natural refrigerants.

Its density being 0.589 times that of air, boils at −33.3°C, and freezes at −77.7°C to white crystals at a pressure of 1 atmosphere. For this reason ammonia must be stored under high pressure or at low temperature.

Ammonia and oil do not mix well, so keeping oil in the compressor is less difficult. In addition, ammonia is miscible with water, so it is easily diluted, and easily washed away. On the other hand, ammonia doesn't mixt with copper, so the pipes that will use the constructive solution must be of another material.

Toxicity

Ammonia is toxic and corrosive, so personal protective equipment must be used when working with ammonia. If the ammonia mixes with air, it will burn. As it is toxic, equipment rooms must be well ventilated and safety measures must be taken when is manipulated.

The toxicity of ammonia solutions does not usually cause problems for humans and other mammals, as a specific mechanism exists to prevent its build-up in the bloodstream. Ammonia even at dilute concentrations is highly toxic to aquatic animals, and for this reason it is classified as dangerous for the environment.

In the following table is presented the table that shows the health effects depending of the concentration of ammonia in ppm (parts per million).

ppm	Effect	ppm	Effect
5	Average odor threshold	**1700**	Coughing
100-200	Eyes irritated	**2400**	Threat to life after 30 min exposure
500 and below	No permanent eye damage	**5000 vapor**	Full body chemical suit is required
300	Immediate throat irritation	**5000 liquid**	Second degree burns and blisters

Table 8: ammonia's toxicity

Properties

- Molecular weight: 17.03 g/mol
- Liquid density (1.013 bar at boiling point) : 682 kg/m3
- Latent heat of vaporization (1.013 bar at boiling point) : 1371.2 kJ/kg
- Heat capacity at constant pressure (c_p) (1.013 bar and 15 °C): 0.037 kJ/(mol.K)
- Heat capacity at constant volume (c_v) (1.013 bar and 15 °C): 0.028 kJ/(mol.K)
- Thermal conductivity (1.013 bar and 0 °C): 22.19 mW/(m.K)

6.1.2. R134a

1,1,1,2-Tetrafluoroethane is an inert gas used primarily as a "high-temperature" refrigerant for domestic refrigeration and automobile air conditioners. Tetrafluoroethane, when compressed as inside gas duster cans, is a clear liquid which boils when exposed to atmospheric pressure at room temperature.

In addition, its environmental effects are acceptable with an insignificant ozone depletion potential (ozone layer), a significant global warming potential (GWP = 1430) and negligible acidification potential (acid rain).

Toxicity

Contact of 1,1,1,2-tetrafluoroethane with flames or hot surfaces in excess of 250 °C may cause vapor decomposition and the emission of toxic gases including hydrogen fluoride and carbonyl halides. Its gaseous form is denser than air and will displace air in the lungs. This can result in asphyxiation if excessively inhaled. This is what contributes to most deaths by inhalant abuse.

Aerosol cans containing 1,1,1,2-tetrafluoroethane, when inverted, become effective freeze sprays. Under pressure, 1,1,1,2-tetrafluoroethane is compressed into a liquid, which upon vaporization absorbs a significant amount of thermal energy. As a result, it will greatly lower the temperature of any object it contacts as it evaporates. This can result in frostbite when it contacts skin, as well as blindness upon eye contact.

Properties

- Molecular weight: 102.03 g/mol
- Liquid density (1.013 bar and 25 °C): 1206 kg/m3
- Boiling point (1.013 bar): -26.6 °C
- Heat capacity at constant pressure (c_p) (1.013 bar and 25 °C): 0.087 kJ/(mol.K)
- Latent heat of vaporization (1.013 bar at boiling point) : 215.9 kJ/kg

6.1.3. Family R400

One of the properties that characterize the family R400 is that these refrigerants have a zeotropic performance. The zeotropic blends boil out at different pressure but at the same temperature. As the blend changes phase, more of one component will transfer to the other phase faster than the rest.

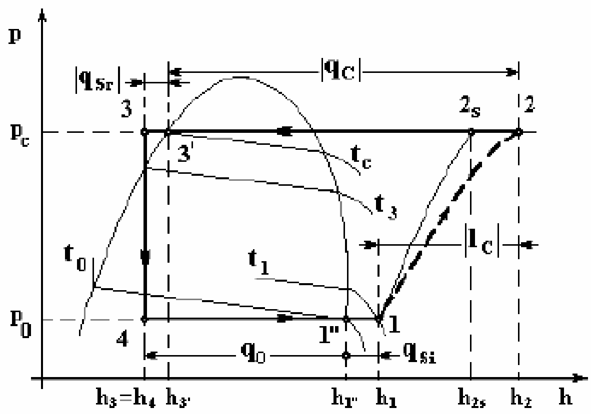

Figure 18: zeotropic blends p-h diagram [12]

6.1.3.1. R404A.

R404A is a near zeotropic refrigerant blend obtained by mixing R125, R143A and R134A pure substance in 44, 52, 4 mass fractions.

Properties

- Molecular Weight 97.6
- Boiling Point, C -46.5
- ODP 0
- GWP 3260
- Latent heat of vaporization 165,3 kJ/kg

6.1.3.2. R407C

R-407C or CH2F2/CHF2CF3/CF3CH2F is a mixture of hydrofluorocarbons used as a refrigerant. It is a zeotropic blend of difluoromethane (R-32), pentafluoroethane (R-125), and 1,1,1,2-tetrafluoroethane (R-134a). Difluoromethane serves to provide the heat capacity, pentafluoroethane decreases flammability, tetrafluoroethane reduces pressure

Properties

- Molecular Weight 86.2: kg/kmol
- Latent heat of Vaporization: 183.2 kJ/kg
- Boiling point (1.013 bar): -43.9 ºC
- ODP 0
- GWP 1.526

6.1.3.3. R410A

R-410A, sold under the trademarked names Forane 410A, Puron, EcoFluor R410, Genetron R410A, and AZ-20, is a zeotropic, but near-azeotropic mixture of difluoromethane (CH2F2, called R-32) and pentafluoroethane (CHF2CF3, called R-125), which is used as a refrigerant in air conditioning applications.

Environmental effects

Unlike alkyl halide refrigerants that contain bromine or chlorine, R-410A (which contains only fluorine) does not contribute to ozone depletion, and is therefore becoming more widely used, as ozone-depleting refrigerants like R-22 are phased out. However, it has a high GWP (2088 times the effect of carbon dioxide), similar to that of R-22. [14]

Properties

- Molecular Weight: 72.6
- Boiling point: -48.5 ºC
- Latent heat of vaporization 220,8
- ODP: 0
- GWP: 2088

To have an idea about the zeotropy of the family R400, in the table below is showed the difference of pressure for the two temperatures between will work the constructive solutions for cooling concrete.

Refrigerant	Temperature	p (x = 0) bar	p (x = 1) bar	ΔP (bar)
R404A	T_0 = 1 ºC	6,341	6,234	0,107
	T_c = 40 ºC	18,33	18,17	0,16
R407C	T_0 = 1 ºC	5,852	4,714	1,138
	T_c = 40 ºC	17,37	15,19	2,18
R410A	T_0 = 1 ºC	8,242	8,217	0,025
	T_c = 40 ºC	24,16	24,1	0,06

Table 9: zeotropy family R400

As it is possible to appreciate in the previous table, the refrigerant R410 A is near an azeotropic refrigerant, followed by the R404 A. On the other hand, the refrigerant R407C is totally zeotropic.

To prevent the zeotropic effects which consequence is that the refrigerant boils at different pressure, for the calculation of all the parameters of the constructive solution, it will be done the hypothesis that the boiling pressure is:

- For the temperature t_0, the pressure will be the one that corresponds when the title of the refrigerant is 1.
- For the temperature t_c, the pressure will be the one that corresponds when the title of the refrigerant is 0.

Doing this hypothesis, the assumption that the power consumption of the compressor is the maximum possible is done.

6.2. Parameters

For doing a comparative analysis it is necessary establish some parameters that must be used for the calculation of the two constructive solutions. These parameters that have been defined previously are:

- $\dot{Q}_0 = 1750kW$
- t_0= 1 ºC
- t_c = 40 ºC
- Overheating degree= 10 ºC
- Subcooling degree = 5 ºC

Once these parameters have been defined, with the program EES (see in the appendix 1 and 2) is possible to obtain all the values that conform the constructive solution the parameters are calculated.

One of the most important parameters that are interesting to study is the coefficient of performance (COP) that indicates the ratio of the cooling provided over the electrical energy consumed. As it was showed in the previous chapter, for refrigeration systems this coefficient can be calculated with the formula $\mathrm{COP_f} = \frac{\dot{\mathrm{Q}}_0}{\mathrm{P_{cp}}}$. In addition, it will be studied also the COP regenerative for both constructive solutions.

6.3. Comparison between the two constructive solutions

The first step to determine the best constructive solution and the refrigerant that have the objective of cooling concrete, is determine which of the two possible solutions showed before is better adapted to the requirements.

To achieve this objective, it will be used the graphics below that show the performance of the two constructive solutions for the different refrigerants (it is possible to see the graphics in the appendix 3).

In the first graphics can be appreciate the values of the COP, Pcp and the mass flow for the different refrigerants.

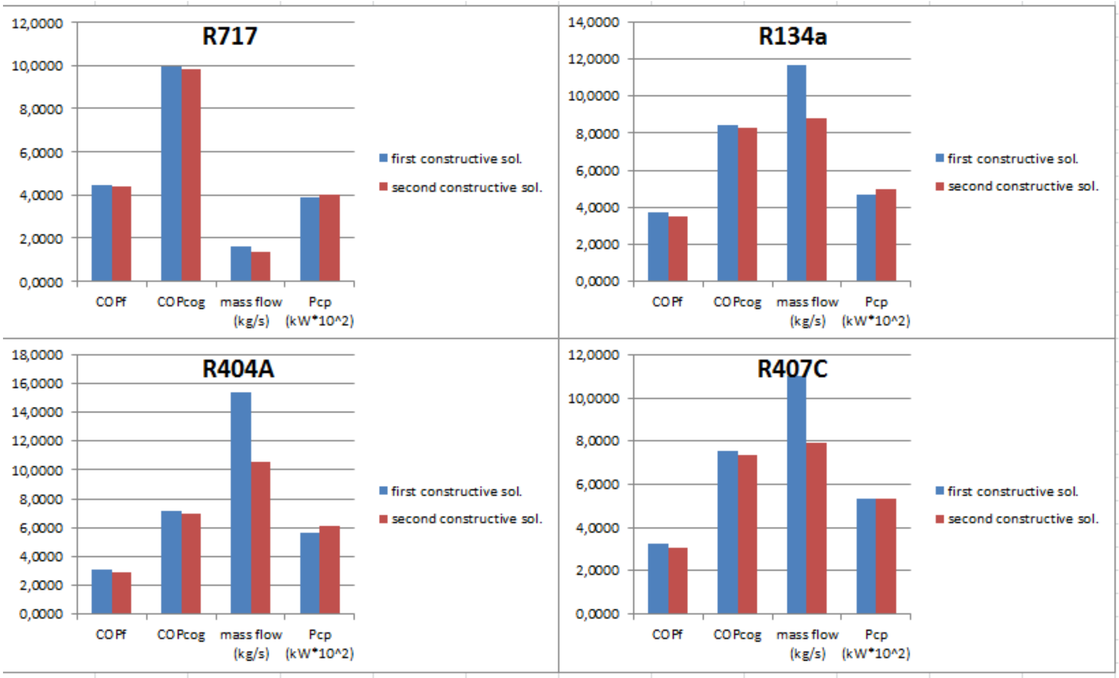

Figure 19: graphs COP/mass flow/Pcp-refrigerants

Looking these graphs several observations and conclusions can be done. The first refers to the coefficient of performance, which is very similar for both constructive solutions, being a little less for the second one.

From the standpoint of consumption (Pcp), the results are very similar too. However, the second constructive solution has a power consumption a little bit higher than the first one.

Finally, the parameter that is most different between the two possibilities is the mass flow. As it can be observed in the graph, there is a several reduction of the mass flow that is required for the second VCRS (as exception the ammonia). The explanation for this decrease is that for the constructive solution that uses the bottle of liquid the value of q_0 is always the maximum possible (this value corresponds at the difference between the liquid saturated and the vapor saturated).

For this reason, if it is acceptable a decrease of the COP, the second constructive solution there will have an important saving of the mass flow required.

As a conclusion, for the ammonia both constructive solutions are very similar, but, if the Freon is used as a refrigerant, the second constructive solution is better.

6.4. Comparison of the different refrigerants

Once the best constructive solution has been chosen, it is time to analyses the performance of the different refrigerants and choose the one that results better for the objective of cooling concrete. The refrigerants that will be studied are the ammonia, the R134a and the family of R400 (R404A, R407C and R410A).

As in the previous point, to analyze the results of the performance of the different refrigerants it will be used some different graphs where is easy to appreciate the significant difference between using one or another refrigerant.

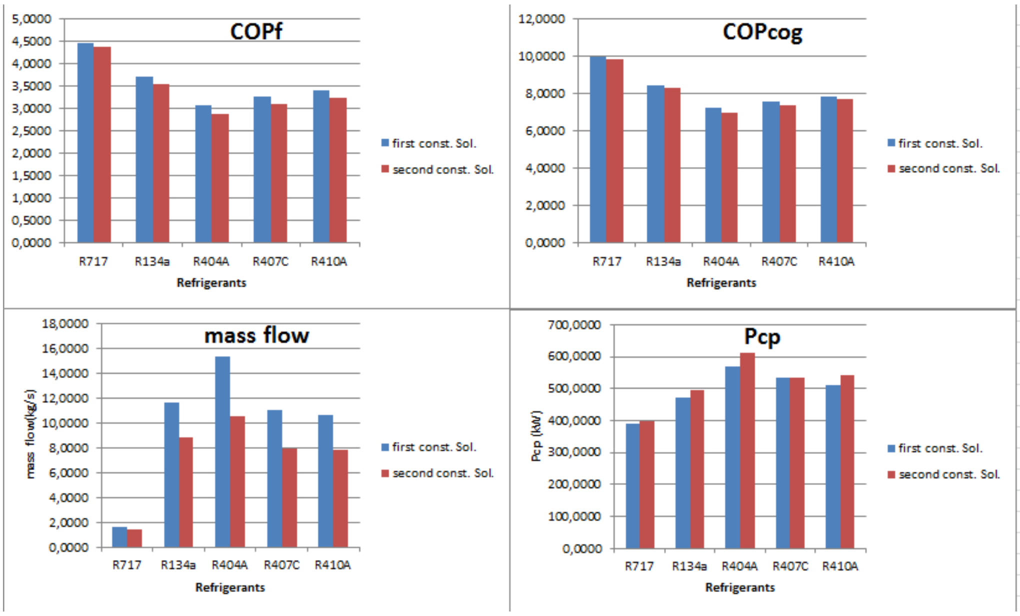

Figure 20: COPf / COPreg/ mass flow/ Pcp-refrigerants

The first conclusion that can be done just looking on the graph is that the ammonia has the higher coefficient of performance and the lowest consumption of energy. Just with this results it would be easy choose the ammonia as the best refrigerant. However, where it can really appreciate that the ammonia is the best refrigerant is in the mass flow ($\dot{m}_0$).

Looking at the graph of the mass flow it is possible to see that the quantity of refrigerant that is needed if the constructive solution uses ammonia is 4 times less than with the others. This is consequence of the latent heat of vaporization, as the ammonia's is around the 1400 kJ/kg while for the other ones is around the 200 kJ/kg.

On the other hand, there are some restrictions that the refrigerant must accomplish and that have been mentioned previously.

The first one is that the title after the expansion valve must be lower than 0,2 (only for the first constructive solution because for the second one it is always 0). This is to assure that the refrigerant uses as much of his cooling capacity.

The second one is that the temperature of the discharge of the compressor must be lower than 140 ºC or the oil will lose its properties as a lubricant.

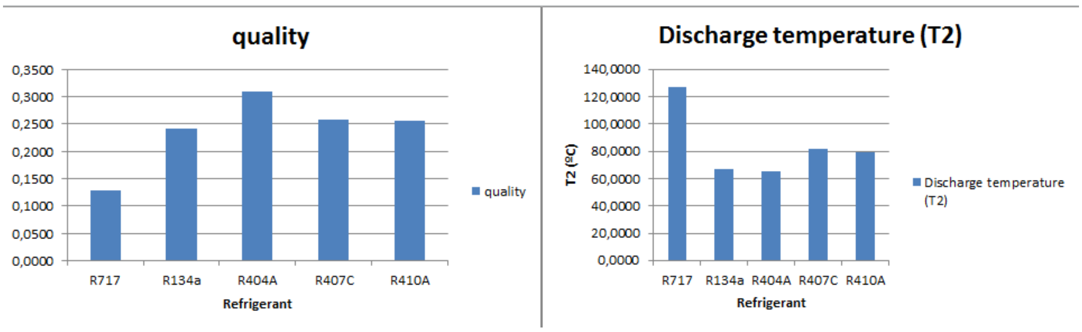

Figure 21: a. title- refrigerant; b. discharge temperature – refrigerants

for the constructive solution with sh and sc

Looking at the graph, only the ammonia accomplish both restrictions because , although all of the refrigerants have a discharge temperature lower than 140 ºC, only the ammonia has a title lower than 0,2.

For all the reasons that have been explained, it is possible to conclude that the ammonia is the best refrigerant for VCRS with a high COP.

Conclusions

After intensive research and applying diverse methods, a constructive solution for a VCRS for cooling concrete has been designed in the course of this project. The first important point is that depending of the VCRS finality; different types of constructive solution are required. This situation has caused that along the history different constructive solutions have been used, like single stage with subcooling, overheating, liquid bottle or double stage with liquid bottle, double cascade, etc.

About the difference between using a single stage VCRS with subcooling or liquid bottle, it has been demonstrated with the program "Engineering Equations Solver" that the constructive solution that uses a liquid bottle is better. The reason of this affirmation is based in the less consumption of mass flow rate (Figure 19 and Figure 20) that requires the constructive solution with a liquid bottle respect the constructive solution that uses the subcooling.

Analyzing the use of different refrigerants in the two constructive solutions, the most important conclusion that can be made is that the ammonia is the best refrigerant (Figure 20 and Figure 21a). The reason is that the latent heat of vaporization is seven times more than the other refrigerants (around 1400 kJ/kg) and, as a consequence, the mass flow required when the ammonia is used as a refrigerant is 4 times less than with the R134a or the family R400.

In addition, the ammonia as an ecological refrigerant has a null ODP and a GWP, and for this reason and the ones mentioned previously, it will be never possible give up with the use of the ammonia as a refrigerant, even if it has some drawbacks like the highest discharge temperature (Fig. 21b and toxicity).

Finally, considering the zeotropic refrigerants of R400 family, the results presented in Fig. 20 show that R410A is the best one, having the highest coefficient performance and the lowest mass flow rate.

Appreciations

I would like to express my deep appreciation to my advisor, Professor Gheorghe Popescu, for giving me valuable suggestions, especially in the field of Refrigeration systems. Very special and kind thanks to my professor, Horatiu Pop, for giving me useful recommendations, above all during the first days of my Erasmus and teaching me with the EES program.

June 2013

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Appendices

Appendix 1 – Calculation program EES for the one stage VCRS with overheating and subcooling.

Appendix 2 - – Calculation program EES for the one stage VCRS with overheating and liquid bottle.

Appendix 3 - Results of the EES programs.

Appendix 1.

"CALCULUL TERMIC IFV 1 TREAPTA CU SUBRACIRE SI SUPRAINCALIRE"
"DATELE DI INTRARE"
"Temperatura de vaporizare - evaporating temperature" t_0=1 [C]
"Temperatura de condensare - condensing temperature" t_c=40 [C]
"Puterea frigorifica - cooling capacity" Q_dot_0=1750 [kW]
"Gradul de subracire - subcooling" deltat_sr=5
"Gradul de supraincalzire - superheating"DELTAt_si=10

"DETERMINAREA MARIMILOR DE STARE IN PUNCTELE CARATERISITCE ALE CICLULUI TERMODINAMIC - STATE PARAMETERS"

"Determinarea presiunii de vaporizare - evaporating pressure"
p_0=Pressure(ammonia;T=T_0;x=1)
"Determinarea presiunii de condensare - condensing pressure"
p_c=Pressure(ammonia;T=T_c;x=0)

"Punctul 1´´"
p_1´´=p_0
t_1´´=t_0
h_1´´=Enthalpy(ammonia;T=T_0;x=1)
s_1´´=Entropy(ammonia;T=T_0;x=1)
v_1´´= Volume(ammonia;T=T_0;x=1)

"Punctul1"
p_1=p_0
t_1=t_0 + DELTAt_si
h_1=Enthalpy(ammonia;T=T_1;p=p_1)
s_1=Entropy(ammonia;T=T_1;p=p_1)
v_1= Volume(ammonia;T=T_1;p=p_1)

"Punctul 2s"
p_2s=p_c
s_2s=s_1

h_2s=Enthalpy(ammonia;s=s_2s;p=p_2s)
t_2s=Temperature(ammonia;s=s_2s;p=p_2s)
v_2s=Volume(ammonia;s=s_2s;p=p_2s)

"Punctul 2"
"Randamentul izentropic al comprimarii" eta_s=(t_0+273,15)/(t_c+273,15)
h_2=(h_2s-h_1´´)/eta_s+h_1
p_2=p_c
s_2=Entropy(ammonia;h=h_2;p=p_2)
v_2=Volume(ammonia;h=h_2;p=p_2)
t_2=Temperature(ammonia;h=h_2;p=p_2)
"Punctul 3´"
p_3´=p_c
t_3´=t_c
h_3´=Enthalpy(ammonia;x=0;p=p_3´)
s_3´=Entropy(ammonia;x=0;p=p_3´)
v_3´=Volume(ammonia;x=0;p=p_3´)

```
"Punctul3"
p_3=p_c
t_3=t_3´-DELTAt_sr
h_3=Enthalpy(ammonia;t=t_3;p=p_3)
s_3=Entropy(ammonia;t=t_3;p=p_3)
v_3=Volume(ammonia;t=t_3;p=p_3)
"Punctul 4"
h_4=h_3
p_4=p_0
t_4=t_0
s_4=Entropy(ammonia;h=h_4;p=p_0)
v_4=Volume(ammonia;h=h_4;p=p_0)
x_4=Quality(ammonia;h=h_4;p=p_0)
"DETERMINAREA SCHIMBURILOR ENERGETICE SPECIFICE"
"Puterea frigorifica specifica"
q_0=h_1´´-h_4
"caldura preluata in procesul de supraincalzire"
q_si=h_1-h_1´´
"Lucrul mecanic necesar antrenarii compresorului - compressor work input (consumption)"
l_c=h_2-h_1
"Sarcina termica specifica a condensatorului - condenser thermal load"
q_c=h_2-h_3´
"Caldura cedata in procesul de subracire - heat rejected in subcooling"
q_sr=h_3´-h_3
"DETERMINAREA DEBITULUI MASIC DE AGENT FRIGORIFIC - REFRIGERANT MASS
FLOW RATE"
m_dot_0=Q_dot_0/q_0
"DETERMINAREA SCHIMBURILOR ENERGETICE"
"Fluxul de caldura preluat in procesul de supraincazire . heat flux received in superheating"
Q_dot_si=m_dot_0*q_si
"Puterea necesara antrenarii compresorului - compressor power input (consumption)"
P_cp=m_dot_0*l_c
"Fluxul de caldura ceat la nivelul condensaorului - puterea condensatorului - heat flux rejected
in the condenser"
Q_dot_c=m_dot_0*q_c
"Fluxul de caldura cedat in procesul de subracire - heat flux rejected in subcooling"
Q_dot_sr=m_dot_0*q_sr
"VERIFICAREA-PRINCIPUL I - BILANT ENERGETIC - ENERGY BALANCE"
m_s=Q_dot_0+Q_dot_si+P_cp
m_d=Q_dot_c+Q_dot_sr
epsilon=(m_s-m_d)/m_s*100
"DETERMINAREA COEFICIENTULUI DE PERFORMANTA - COEFICIENT OF
PERFORMANCE"
COP=Q_dot_0/P_cp
COP_cog=(Q_dot_0+Q_dot_c)/P_cp
```

Appendix 2.

"CALCULUL TERMIC IFV 1 TREAPTA CU reservoir de liquide de liquid SI SUPRAINCALIRE"
"DATELE DI INTRARE"
"Temperatura de vaporizare - evaporating temperature" t_0=1 [C]
"Temperatura de condensare - condensing temperature" t_c=40 [C]
"Puterea frigorifica - cooling capacity" Q_dot_0=1750
"Gradul de supraincalzire - superheating"DELTAt_si=10

"DETERMINAREA MARIMILOR DE STARE IN PUNCTELE CARATERISITCE ALE CICLULUI TERMODINAMIC - STATE PARAMETERS"

"Determinarea presiunii de vaporizare - evaporating pressure"
p_0=Pressure(R407C;T=T_0;x=1)
"Determinarea presiunii de condensare - condensing pressure"
p_c=Pressure(R407C;T=T_c;x=0)

"Punctul 1´´"
p_1´´=p_0
t_1´´=t_0
h_1´´=Enthalpy(R407C;T=T_0;x=1)
s_1´´=Entropy(R407C;T=T_0;x=1)
v_1´´= Volume(R407C;T=T_0;x=1)

"Punctul1"
p_1=p_0
t_1=t_0 + DELTAt_si
h_1=Enthalpy(R407C;T=T_1;p=p_1)
s_1=Entropy(R407C;T=T_1;p=p_1)
v_1= Volume(R407C;T=T_1;p=p_1)

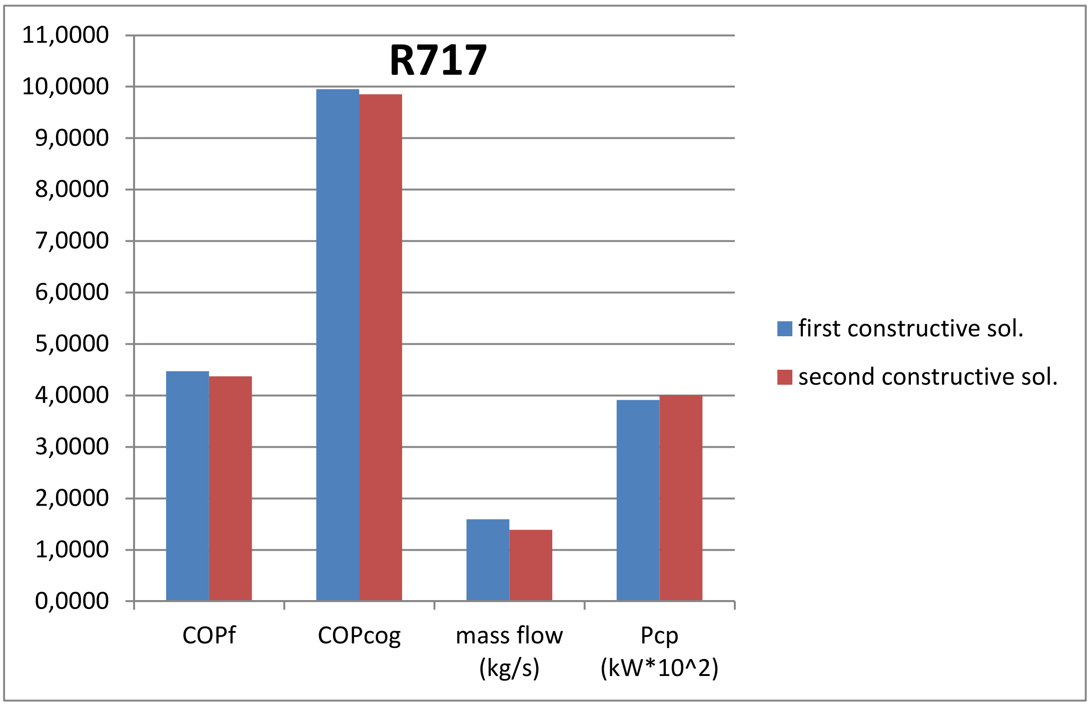
"Punctul 2s"
p_2s=p_c
s_2s=s_1

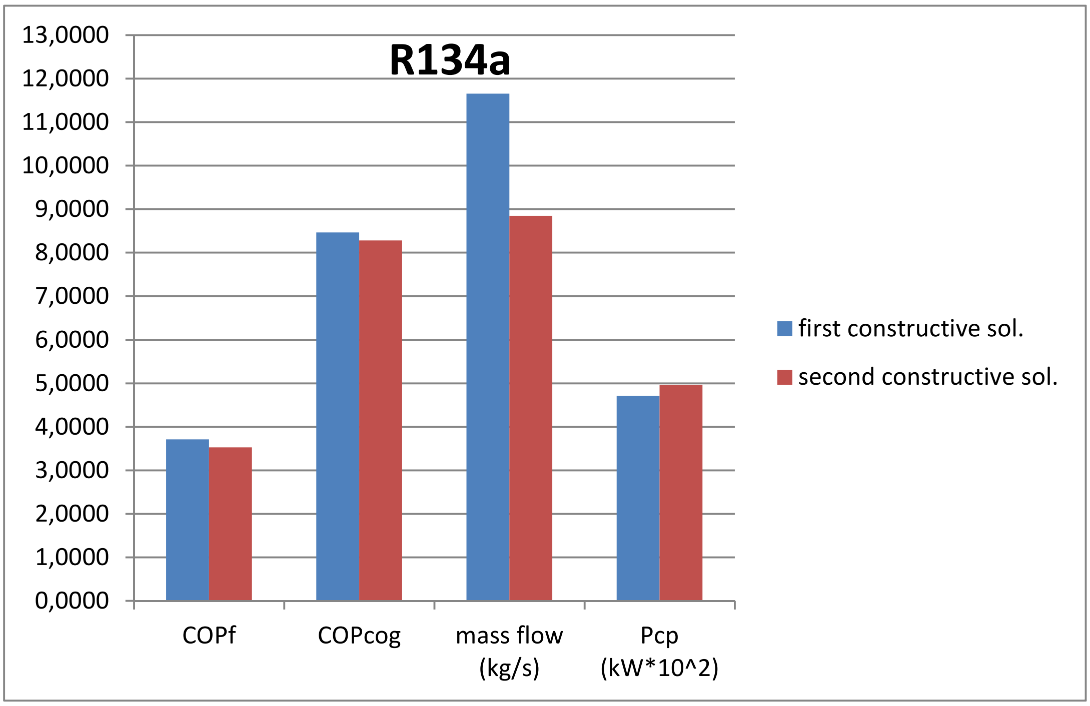
h_2s=Enthalpy(R407C;s=s_2s;p=p_2s)
t_2s=Temperature(R407C;s=s_2s;p=p_2s)
v_2s=Volume(R407C;s=s_2s;p=p_2s)

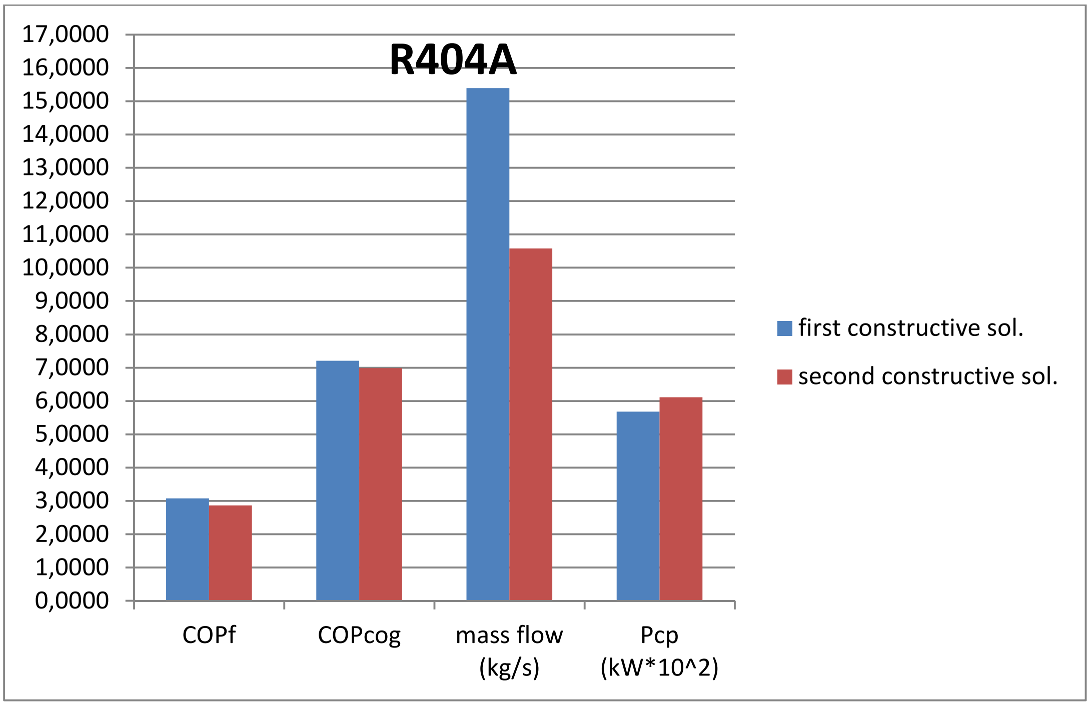
"Punctul 2"
"Randamentul izentropic al comprimarii" eta_s=(t_0+273,15)/(t_c+273,15)
h_2=(h_2s-h_1´´)/eta_s+h_1
p_2=p_c
s_2=Entropy(R407C;h=h_2;p=p_2)
v_2=Volume(R407C;h=h_2;p=p_2)
t_2=Temperature(R407C;h=h_2;p=p_2)
"Punctul 3´"
p_3´=p_c
t_3´=t_c
h_3´=Enthalpy(R407C;x=0;p=p_3´)
s_3´=Entropy(R407C;x=0;p=p_3´)
v_3´=Volume(R407C;x=0;p=p_3´)
"Punctul 4 "

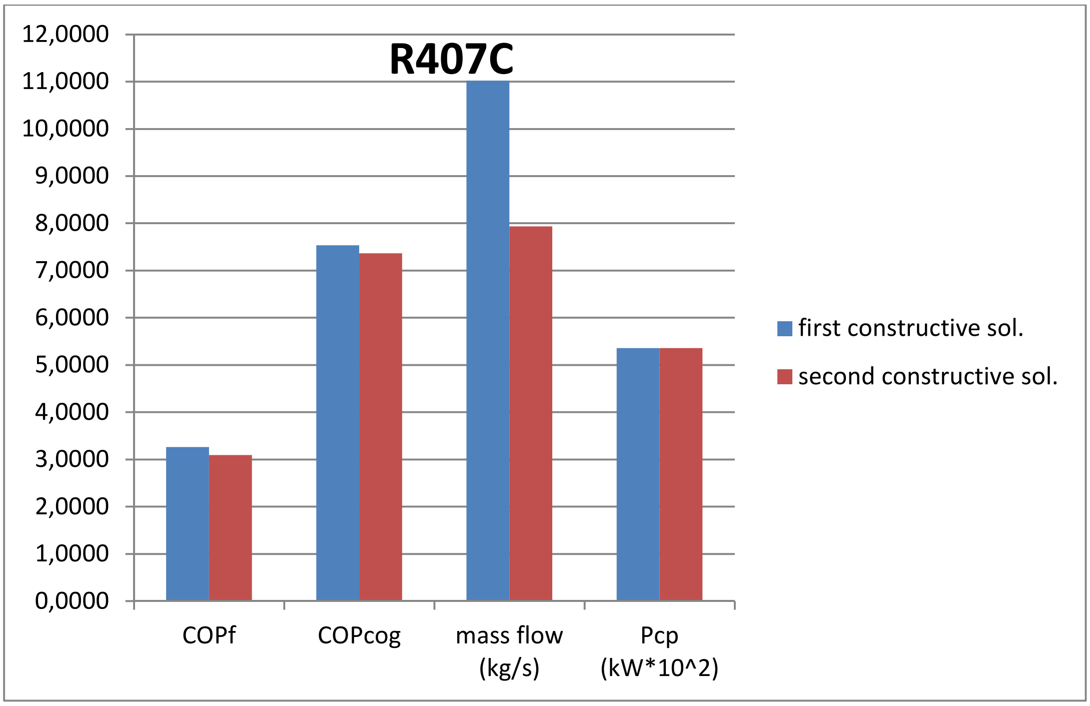
```
h_4=h_3´
p_4=p_0
t_4=t_0
s_4=Entropy(R407C;h=h_4;p=p_0)
v_4=Volume(R407C;h=h_4;p=p_0)
x_4=Quality(R407C;h=h_4;p=p_0)
"Punctul 4´"
p_4´=p_0
t_4´=t_0
s_4´=Entropy(R407C;x=0;p=p_0)
v_4´=Volume(R407C;x=0;p=p_0)
h_4´=Enthalpy(R407C;x=0;p=p_0)

"DETERMINAREA SCHIMBURILOR ENERGETICE SPECIFICE"
"Puterea frigorifica specifica"
q_0=h_1´´-h_4´
"caldura preluata in procesul de supraincalzire"
q_si=h_1-h_1´´
"Lucrul mecanic necesar antrenarii compresorului - compressor work input (consumption)"
l_c=h_2-h_1
"Sarcina termica specifica a condensatorului - condenser thermal load"
q_c=h_2-h_3´

"DETERMINAREA DEBITULUI MASIC DE AGENT FRIGORIFIC - REFRIGERANT MASS FLOW RATE"
m_dot_0=Q_dot_0/q_0
m_dot=((h_1´´-h_4´)/(h_1´´-h_4))*m_dot_0
"DETERMINAREA SCHIMBURILOR ENERGETICE"
"Fluxul de caldura preluat in procesul de supraincazire . heat flux received in superheating"
Q_dot_si=m_dot*q_si
"Puterea necesara antrenarii compresorului - compressor power input (consumption)"
P_cp=m_dot*l_c
"Fluxul de caldura ceat la nivelul condensaorului - puterea condensatorului - heat flux rejected in the condenser"
Q_dot_c=m_dot*q_c

"VERIFICAREA-PRINCIPUL I - BILANT ENERGETIC - ENERGY BALANCE"
m_s=Q_dot_0+Q_dot_si+P_cp
m_d=Q_dot_c
epsilon=(m_s-m_d)/m_s*100
"DETERMINAREA COEFICIENTULUI DE PERFORMANTA - COEFICIENT OF PERFORMANCE"
COP=Q_dot_0/P_cp
COP_cog=(Q_dot_0+Q_dot_c)/P_cp
```

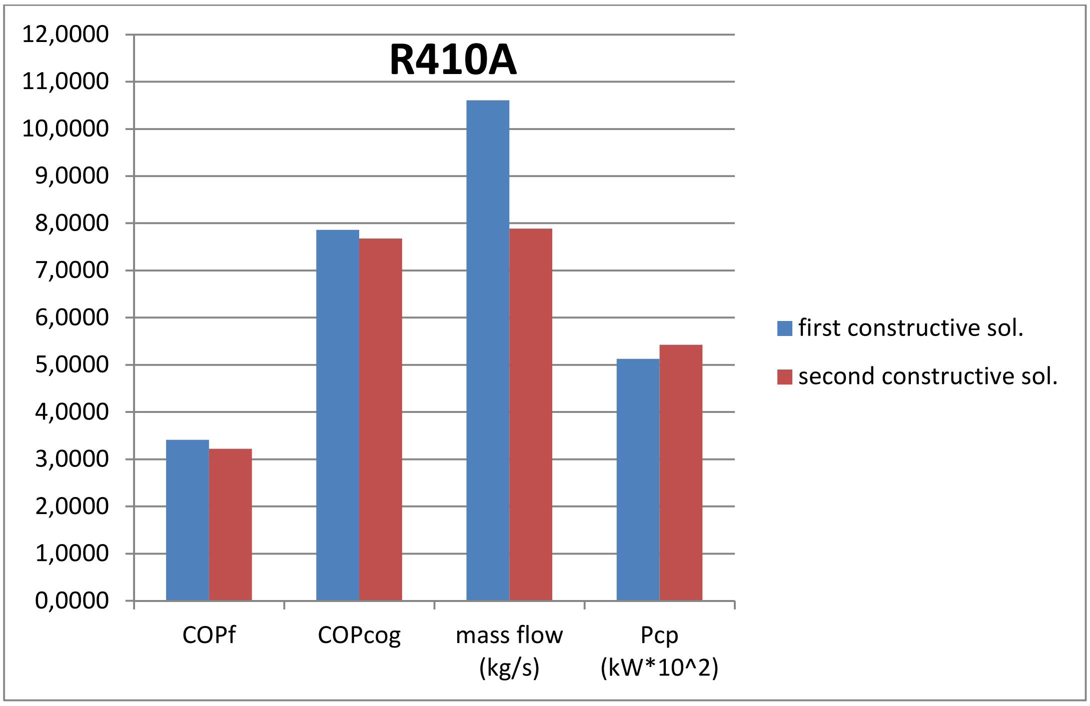
Appendix 3.

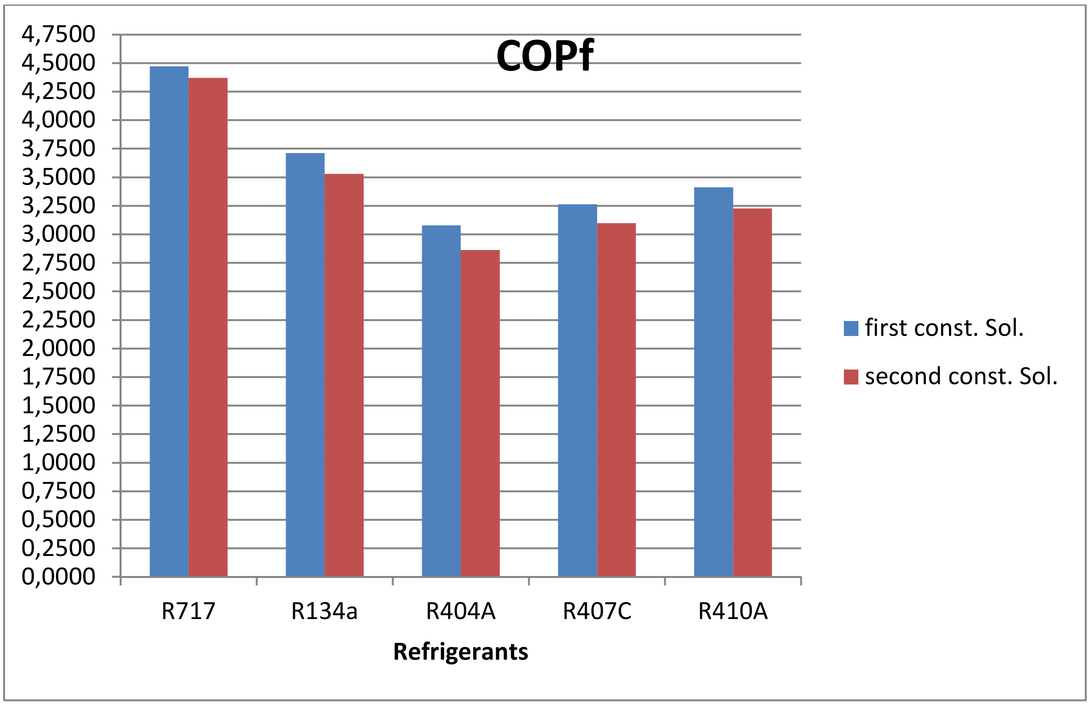

R717
11,0000
10,0000
9,0000
8,0000
7,0000
6,0000
5,0000
4,0000
3,0000
2,0000
1,0000
0,0000
COPf
COPcog
mass flow (kg/s)
Pcp (kW*10^2)
first constructive sol.
second constructive sol.

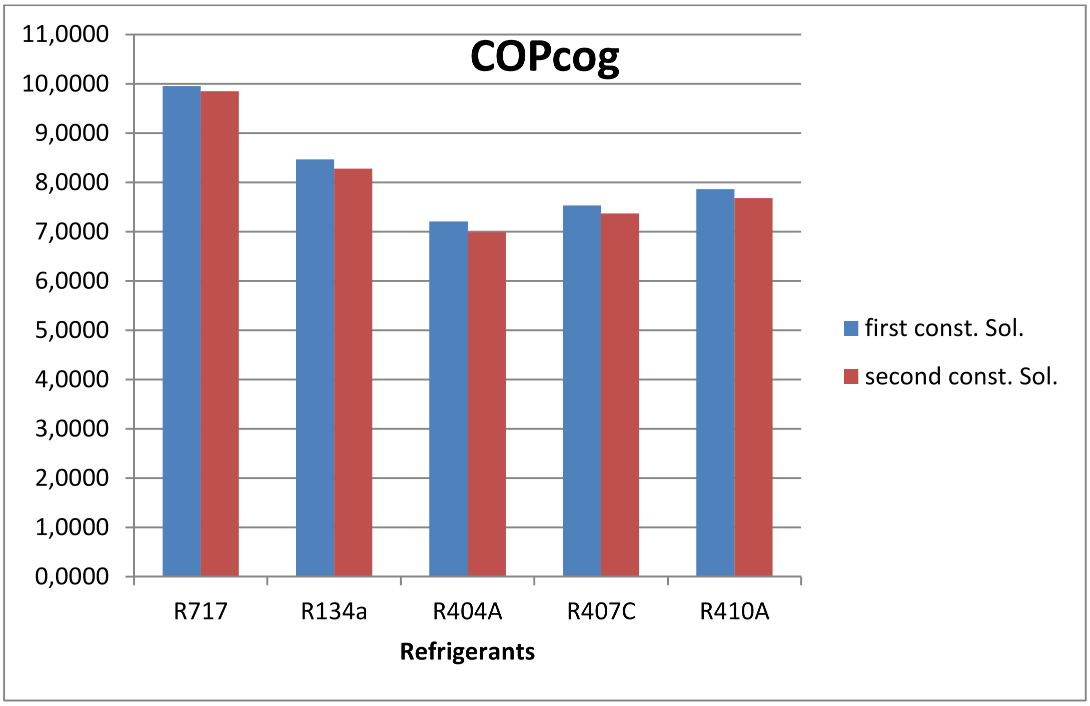

R134a
13,0000
12,0000
11,0000
10,0000
9,0000
8,0000
7,0000
6,0000
5,0000
4,0000
3,0000
2,0000
1,0000
0,0000
COPf
COPcog
mass flow (kg/s)
Pcp (kW*10^2)
first constructive sol.
second constructive sol.

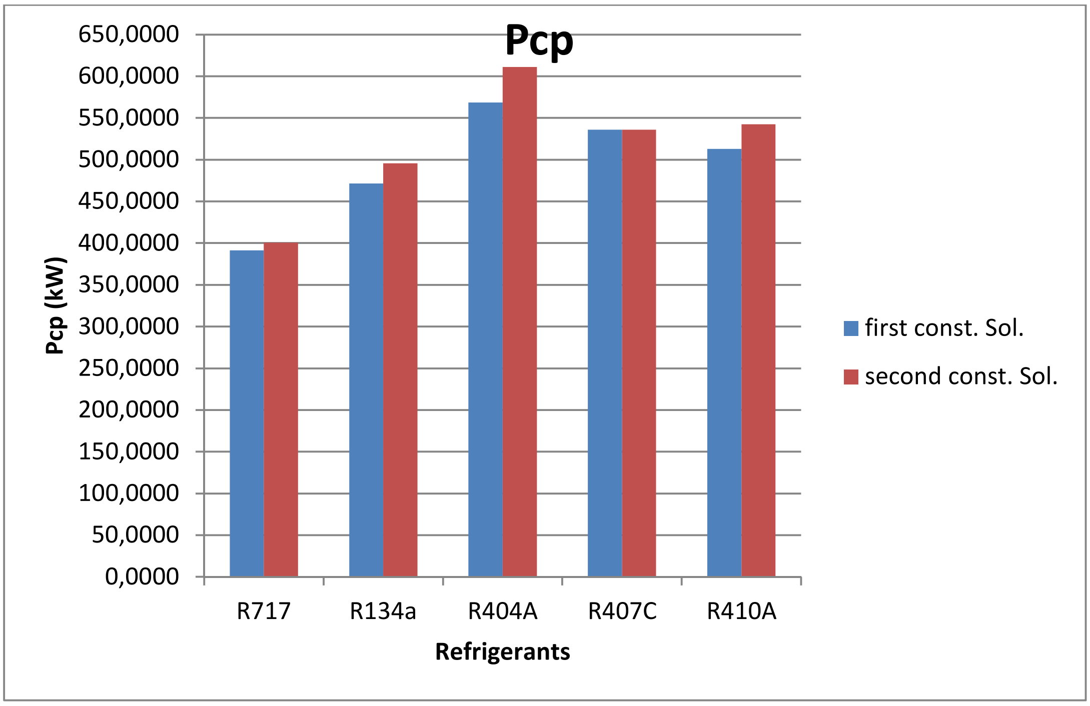

R404A
17,0000
16,0000
15,0000
14,0000
13,0000
12,0000
11,0000
10,0000
9,0000
8,0000
7,0000
6,0000
5,0000
4,0000
3,0000
2,0000
1,0000
0,0000
COPf
COPcog
mass flow (kg/s)
Pcp (kW*10^2)
first constructive sol.
second constructive sol.

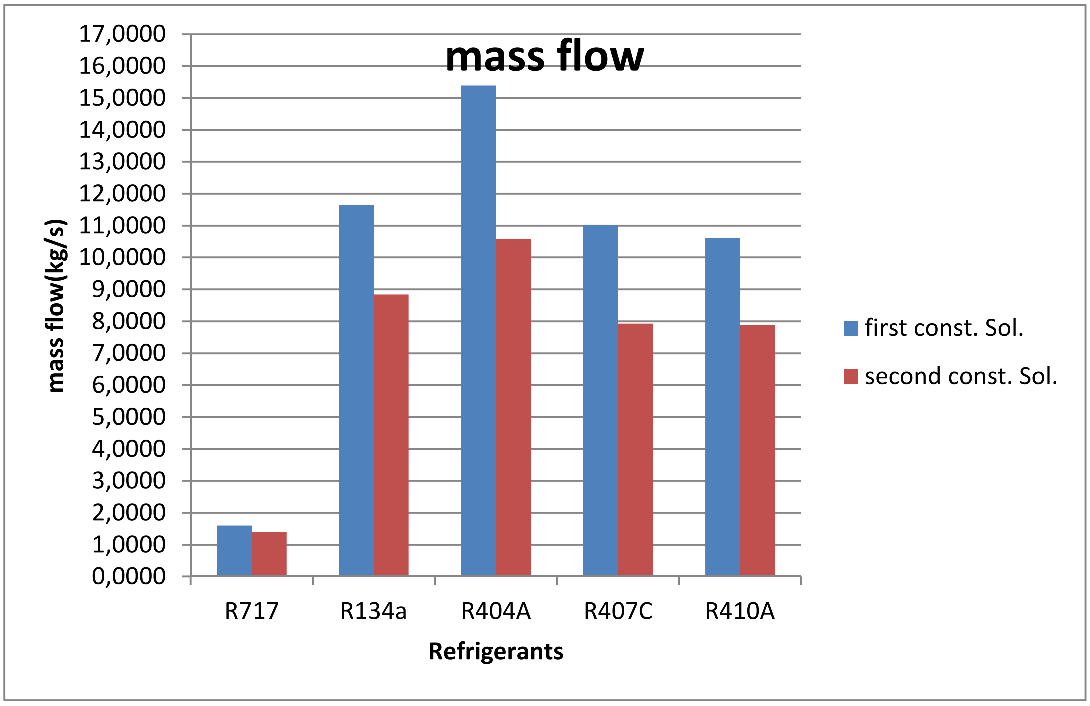

R407C
12,0000
11,0000
10,0000
9,0000
8,0000
7,0000
6,0000
5,0000
4,0000
3,0000
2,0000
1,0000
0,0000
COPf
COPcog
mass flow (kg/s)
Pcp (kW*10^2)
first constructive sol.
second constructive sol.


R410A
12,0000
11,0000
10,0000
9,0000
8,0000
7,0000
6,0000
5,0000
4,0000
3,0000
2,0000
1,0000
0,0000
COPf
COPcog
mass flow (kg/s)
Pcp (kW*10^2)
first constructive sol.
second constructive sol.


COPf
4,7500
4,5000
4,2500
4,0000
3,7500
3,5000
3,2500
3,0000
2,7500
2,5000
2,2500
2,0000
1,7500
1,5000
1,2500
1,0000
0,7500
0,5000
0,2500
0,0000
R717
R134a
R404A
R407C
R410A
Refrigerants
first const. Sol.
second const. Sol.


COPcog
11,0000
10,0000
9,0000
8,0000
7,0000
6,0000
5,0000
4,0000
3,0000
2,0000
1,0000
0,0000
R717
R134a
R404A
R407C
R410A
Refrigerants
first const. Sol.
second const. Sol.


Pcp
650,0000
600,0000
550,0000
500,0000
450,0000
400,0000
350,0000
300,0000
250,0000
200,0000
150,0000
100,0000
50,0000
0,0000
Pcp (kW)
R717
R134a
R404A
R407C
R410A
Refrigerants
first const. Sol.
second const. Sol.


mass flow
17,0000
16,0000
15,0000
14,0000
13,0000
12,0000
11,0000
10,0000
9,0000
8,0000
7,0000
6,0000
5,0000
4,0000
3,0000
2,0000
1,0000
0,0000
mass flow(kg/s)
R717
R134a
R404A
R407C
R410A
Refrigerants
first const. Sol.
second const. Sol.