Design and thermodynamic analysis of an Organic Rankine Cycle

Etudiants :

Marine   DALLE

Brieuc   PECOT

Hector SALLEZ

Enseignant-responsable du projet :

Muhittin CELEP

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Intitulé du projet : **Design and thermodynamic analysis of an Organic Rankine Cycle .**

Type de projet : **Numerical modeling**.

Objectifs du projet :

The aim of this project is to study an Organic Rankine Cycle through numerical modelling. Therefore, it will be very useful to study the working fluid and the components of the cycle.

Mots-clefs du projet *:*

Cycle, efficiency, modeling.

Table des matières

NOTATIONS, ACRONYMES

- T : Temperature (K)

- P : Pressure (Pa)

- h : Enthalpy (J/kg)

- s : Entropy (J/kg.K)

- v : Specific volume (m^3/kg)

- Cp : Specific pressure (J/kg.K)

- ṁ : mass flow rate (kg/s)

- W : Work (J/kg)

- Q : Heat (J/kg/s)

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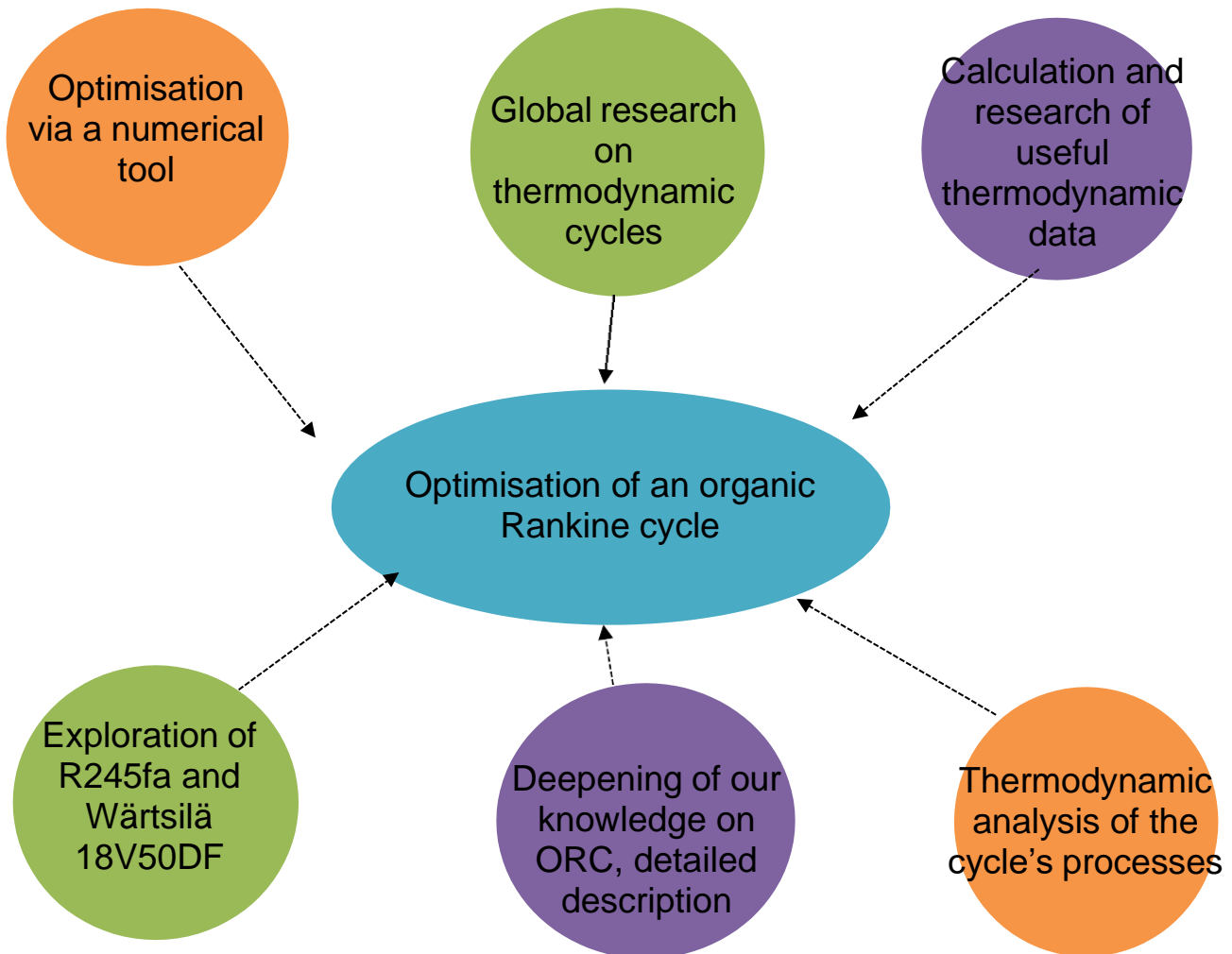
1. INTRODUCTION

1.1. Organisation

We will start this report by overseeing the work structure that we had during the semester, how we managed to organize ourselves.

At the beginning of the project, initial research on hydrogen and Organic Rankine Cycles (ORC's) has been led individually and then shared with the group. We then split the global subjects into different parts that would structure our project. As every piece of this report, the different subjects studied were linked and useful to one another for a better understanding of our whole work. Each person had to go further into precise and distinct branches such as thermodynamic data treatment, cycles understanding, numerical modelling... Each week, we were meeting up to assess our research and to find solutions to issues that we met, helped happily by our always really involve teacher, that we thank truthfully by the way. Finally, the writing of the report and its proofreading were carried out as a group.

Here you can see the global organization that we had, knowing that this is some kind of shortcut, the worktimes were indeed together, thus we were always helping each other's in our obstacles.

Optimisation via a numerical tool

Global research on thermodynamic cycles

Calculation and research of useful thermodynamic data

Optimisation of an organic Rankine cycle

Exploration of R245fa and Wärtsilä 18V50DF

Deepening of our knowledge on ORC, detailed description

Thermodynamic analysis of the cycle's processes

Marine DALLE: purple Brieuc PECOT: orange Hector SALLEZ: green

1.2. General introduction

Thermodynamics cycles are various, and all used for different purposes. They're basically a sequence of different thermodynamic processes, involving heat transfers and work. Meanwhile there is an evolution of the different variables within the system (temperature, pressure, enthalpy, entropy, and other state variables…) during the cycle. Eventually, they return to their initial state.Let's have a look at the most basic one: The Carnot Cycle. It is defined as an ideal reversible adiabatic (closed) cycle
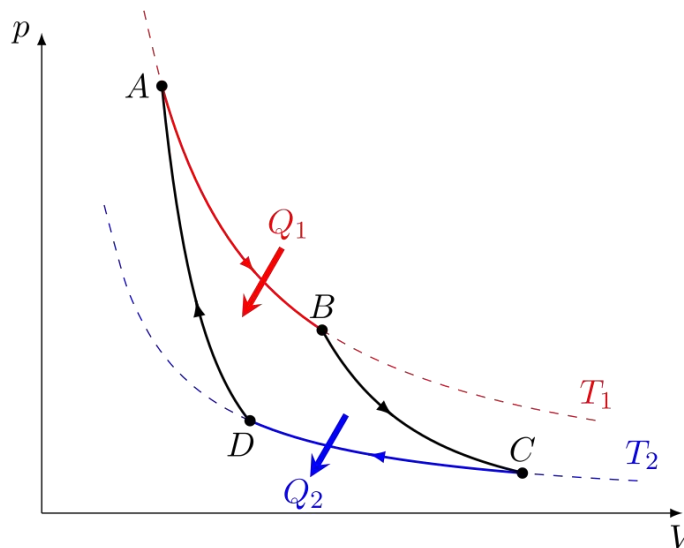

Figure 1 : P-V diagram of a Carnot cycle

So many thermodynamic cycles are known by almost everybody in everyday life, without being known as such. We could talk about the Otto cycle, which is basically the name of the cycle that runs into petrol/gasoline engines, or also diesel cycle for the engine of the same name. When we talk about these different cycles, the properties that make them independent from one another are the nature of the different processes inside of them (isobaric, isothermal, isentropic…). As we can see on the table below, the processes may be the same ones but in different order thus it will change the nature of the cycle and its use.

| cycle/process	compression	heat addition	expansion	heat rejection
external combustion power cycles				
carnot	isentropic	isothermal	isentropic	isothermal
stirling	isothermal	isochoric	isothermal	isochoric
Ericsson	isothermal	isobaric	isothermal	isobaric
internal combustion power cycles				
Otto (gasoline/petrol)	adiabatic	isochoric	adiabatic	isochoric
Diesel	adiabatic	isobaric	adiabatic	isochoric
Brayton	adiabatic	isobaric	adiabatic	isobaric
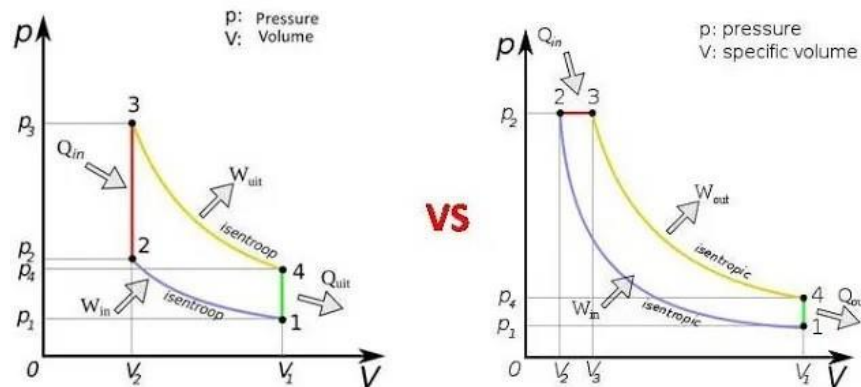
Figure 2 : Otto and Diesel cycles

To give a drawn example, as we can see on figure 1 right above, the biggest difference between both cycles is that heat addition is done at constant volume for the Otto cycle whereas it is at constant pressure for the diesel cycle. Depending on these differences, so many variables are changing from a cycle to one another.

We can also talk about de Brayton cycle. We can say that Brayton cycles are globally the same as basic fuel-based cycles, with the difference of having pressurized air as working fluid. With real Brayton cycle uses, we won't find a closed system but an open one. Whereas working fluid is cooled down so that it can be reused, the exhausted gases of the turbine (which is basically pressurized air), will be released in the air. Obviously, we could use it back and then it would be an ideal Brayton cycle, but why should we recycle it where we can just take some more air (assuming that we don't deteriorate air, which is kind of obvious, only oxygen will be used, moreover we could filter the hazardous gases such as nitrogen). This is this feature that is used in some conditions, such as aeronautical ones. Indeed, when it is used for aircraft propulsion, the gas turbine produces just enough power to drive the compressor and a small generator to power the auxiliary equipment. The high-velocity exhaust gases are responsible for producing the necessary thrust to propel the aircraft. On the following charts/scheme, we can see that these cycles are similar to the previous ones. The big difference is that there is a "q in" and a "q out", representing the energy brought and released from the system, which is relevant of an open system. Seeing that this cycle is composed of only 3 components and works thanks to air, a flying plane may be the perfect candidate for wearing this kind of devices.

Here we will talk about Rankine Cycles (RC). A short name for a vast family of cycles existing since 1859 thanks to the Engineer William J.M Rankine. Used throughout time in many ways, their presence is now ubiquitous. Special mention to the steam Rankine cycle since we have so many heat sources possible: biomass, thermal/solar/nuclear power plants, liquid fuel, coal… According to our times, we won't interest ourselves in the two latter, but in the Waste Heat Recovery (WHR) that will be defined later.
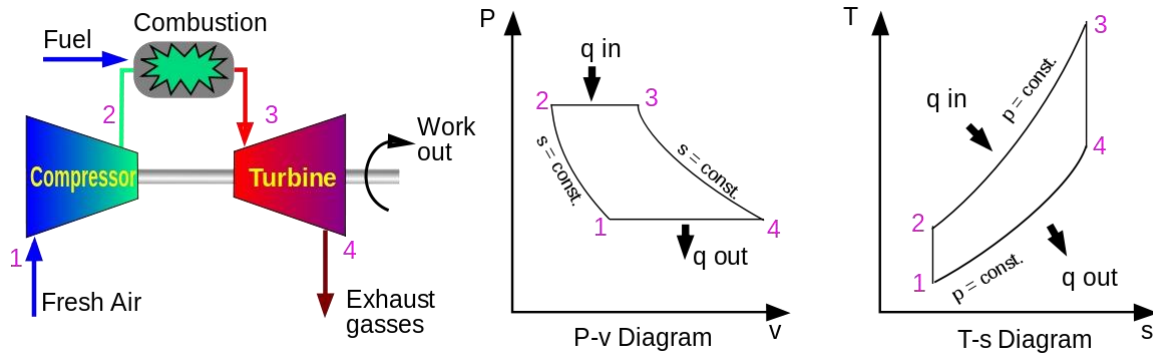
Figure 3 : Schema and diagrams of a Brayton cycle

During the 19th century, we took advantage of the thermodynamic analysis of basic RCs to design and begin to use Organic Rankine Cycles (ORC). A small difference in the type of working fluid used that leads to many possibilities and modifications of the cycle.

Our work during these few months consisted in designing the most efficient model of ORC working thanks to WHR with a particular heat source and organic fluid. We first had to understand the global idea around combining the thermodynamic data of both the fluid and the heat source. Then we had to work on the optimisation of the cycle to have a minimal amount of energy loss.

Most of our research were first based on a thesis [9] such as all of our choices were guided by the ones made in the thesis. The difficulty was for us that the calculations were done for a cycle more advanced than the one we chose to use, thus we had to work on all the math and the optimisation using Excel.

To be precise the analysis ran in the thesis is only about Regenerative Organic Rankine Cycle (RORC), a particular cycle that is laid out underneath:
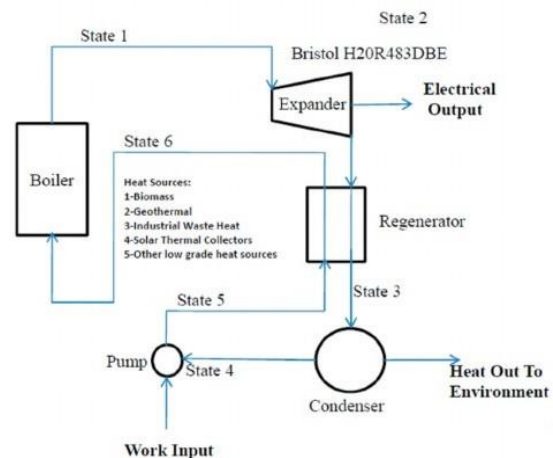
Figure 4 : RORC, description of a cycle

As you can see, there is one more device that is called a Regenerator, which is passed through by the working liquid twice in a cycle, following the study of the thesis would have then led us to the analysis of 6 different states of the liquid.

A regenerator is a type of heat exchanger where heat from the hot fluid is intermittently stored in a thermal storage medium before it is transferred to the cold fluid. In order to do this, the hot fluid is brought into contact with the heat storage medium, then the fluid is displaced with the cold fluid, which absorbs the heat. Basically, they can recover heat by

cycling it through heat sinks for example. A feature that could be used to recover heat from the Wartsila.

We then helped ourselves with some books [8][10], where precise calculus is done using water as working fluid, which permitted us once we had all the data's we needed for the R245fa to be sure of our results.

2. ORGANIC RANKINE CYCLES

2.1. Rankine cycles :

2.1.1. Generalities:

Rankine cycle is a cycle that turns heat energy into a mechanical one, using only four devices (Steam generator/boiler, turbine, condenser, pump). Therefore, RCs are usually connected to a generator to create electricity. Nowadays, the steam Rankine cycle is the most common once since it generates around 90% of the world electricity (Wiser, Wendell H., 2000). Though, those cycles used in the everyday life tends to be quite complex, leading us to our choice of talking about basic (organic) Rankine cycles. They are cycles that works in a closed loop where heat is supplied externally to a device (boiler, steam generator…) that will heat the water to produce steam.
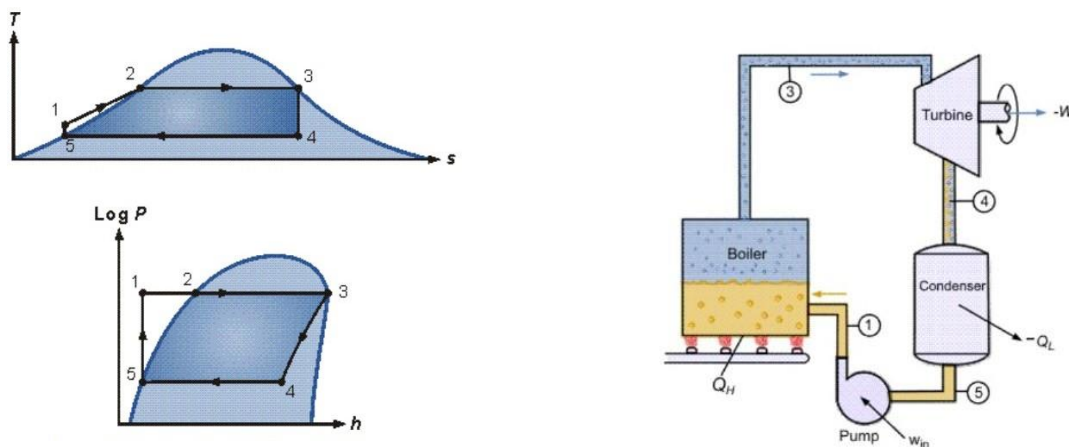
Figure 5 : Rankine Cycle description

Here we can see that the water goes through five distinct phases. Although it is a closed-cycle, thermodynamic analysis of Rankine Cycle starts always from the **compressor/pump**. First, the water **before compressor** is considered already at the saturated liquid phase which is then converted into compressed liquid. Then, by going through the **boiler,** it is converted into superheated vapor. Once the water is now steam, it

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will put in motion the **turbine** that will produce the researched electricity and cool down the vapor changing it to wet vapor. Thus, wet steam will return into liquid state throughout the **condenser**. Finally, the liquid will be treated by the **pump** once again to be pressurized as it needs to be for the boiler, and finally we did a whole cycle, that can be repeated again and again. These different states will be detailed thermodynamically speaking while explaining the ORC.
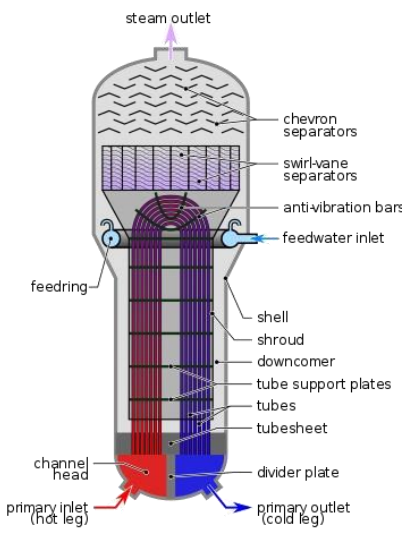
2.1.2.   Components:

- <u>A pump:</u>

The pump goal is basically to give pressure to our liquid, to give him speed, mass flow rate and so on …

- <u>A steam generator:</u>

Basically, a steam generator is used to take a fluid and turn it into steam. Here we can see the common design of one. On it, we can see two types of inlets/outlets because there's two types of fluid that are going through the device. First there's the fluid that is passing through all the cycle: which will be our organic fluid. This fluid will come in the "feeding water inlet" and go out by the steam outlet, once pressurized (thus heated). It is here called the feeding water inlet; in our case we could call it the feeding organic fluid inlet.

The second useful fluid will stay in a short circuit linked to the steam generator to bring a heat source in the device. it will pass through the primary inlet, tubes and go out by the primary outlet (to make it simple). Once cooled, this fluid passes through our heat source to e heated again, and so on.

- <u>A turbine generator:</u>
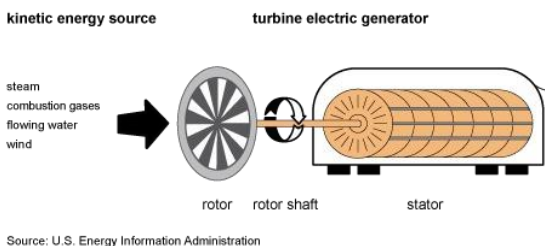
Here we can see basically how an electrical turbine's working. Basically, it just works by making a rotor turn, transferring this momentum to a rotor shaft, then once the kinetic energy is turned into mechanical energy, thanks to a stator, the mechanical energy will be turned into electricity.

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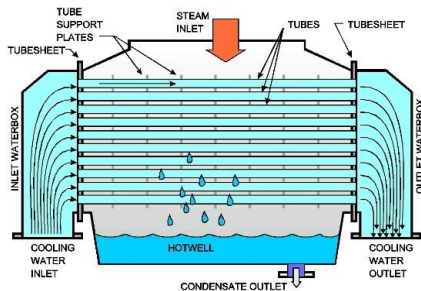
- A condenser:

A condenser is designed to transfer heat from a working fluid (e.g. water in a steam power plant) to a secondary fluid or the surrounding air. The condenser relies on the efficient heat transfer that occurs during phase changes, in this case during the condensation of a vapor into a liquid.

2.2.   Organic Rankine Cycles (ORC):

2.2.1.   *Working fluids:*

Even though it is not the most used for now, the ORC has many advantages compare to the steam RC. Indeed, using low temperature heat sources are not advantageous for those kinds of cycles, where it is for ORCs, which will lead them to be cheaper and more reliable technology. As ORCs preferred to utilise low/medium temperature heat sources, it allows us to think about natural or eco-friendly ways to heat the working fluid that won't be water anymore but some organic fluids.

To easily describe the working principle of the ORC, it's the same as the steam RC, but using fluids such as alkanes, aromatases, siloxane, and other fluids that you can see in the table below, instead of water inside of the cycle. The website "law insider" [11] gives us the following definitions: *Organic fluid means any substance or mixture thereof, which is liquid at standard conditions and contains carbon compounds that act as volatile organic compounds*. Also: *Organic fluid means a hydrocarbon based high molecular mass fluid with a liquid-vapour phase change that occurs at a lower temperature than the water-steam phase change.*

Both these definitions give us some of the aspects that will interest us in the theme of our cycles. Indeed, this low boiling temperature will be the first argument to use these fluids. Moreover, the molecular weight will allow us better thermodynamic performances. Precisely, we can see is in the thesis [9] "high superheating the working fluid is not necessary in order to avoid the erosion caused by moisture in the turbine blades", and the fact that we don't need to work on high pressure liquids means that we won't have to work with expansive turbine but more basic ones.

To resume: "an organic fluid can be considered a good candidate for an ORC system when it shows high latent heat of evaporation, high specific heat, positive or null slope of the vapor saturation curve, high thermal conductivity, low viscosity, chemical and thermal stability at high temperature, safety, and low environmental impact." (Sciencedirect.com) All these thermodynamics aspects may be encountered with organic fluids whereas water couldn't give us all these opportunities. Therefore, we understand that choosing the right fluid is crucial since it will affect the cycle thermodynamically and the whole project economically.

Underneath this paragraph, you can see a table that shows different examples of organic fluids that could fit right in an ORC use [7].

Fluid	Critical Temperature (°C)	Critical Pressure (kPa)	Density * (kg/m³)	Heat of Vaporization ** (kJ/kg)
R134a	101	4059	4.258	217
R227ea	102.8	2999	7.148	131.7
R245fa	154	3651	5.718	196
R123	183.68	3668	1464	170.6
R600	151.98	3796	2.441	358
Toluene	318.6	4126	862.2	361.3
Iso-butane	134.7	3640	2.44	165.5
Iso-pentane	187.2	3370	614.5	342.5
n-pentane	196.5	3364	620.8	358

* Density at Room Temperature (25 °C) 1 atm; ** Heat of Vaporization at 1 atm.

Figure 6 : Table of properties of different organic fluids

2.2.2. Their application and their current use

The use of ORC is widely spread in the world since decades to produce energy. As we understood right before, their main advantage is the possibility of being heated by low temperature heat sources. We find nowadays use in geothermal powerplants, biomass heat generator, solar thermal power sources or even waste heat recovery of already working devices. All of these has positive aspect for environment and usually economics. We can point out the fact that geothermal energy is renewable and totally natural, biomass greenhouse gases are fewer than when burning fossil fuels and that there is so much heat losses in factories today that using these as an energy source would be a real improvement (moreover when we see the low efficiency of some huge engines because of the heat losses).

The arguments given before could not be used with typical RCs because even if these aspects seem to be basic to consider that we are not talking about high temperatures here, more temperature around 200/400°C, that would be not sufficient for water-based cycle.

Here we can see a power plant by *Turboden* which is a producer of ORC based plants. These kind of companies shows us with about 400 plants installed around the world (2000 delivered) and 800 Mwe generated that, even though it is not wide expanded in our thoughts, ORC technology is an actual working science.

Figure 7 : ORC power plant by Turboden

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3. STUDY CASE: OPTIMISATION OF AN ORC IN A PURPOSE OF INDUSTRIAL WASTE HEAT RECOVERY

3.1. Waste heat recovery:

3.1.1. Definition and use:

As we talk about in the introduction, one way of bringing a heat source to our boiler in the case of ORCs is recovering the heat wasted by some already existing engines. We need to notice that this method allows us to generate power through an ORC without having to create a heat source to heat the working fluid, our final goal. In other words, this technic will have for real purpose to optimize and rise the efficiency of already working devices. When we see that efficiency of different gas/petrol engines is usually around 30/45%, using ORC based on WHR is not only a way of being "eco-friendly", but it could be a major source of energy if we were able to idealise the interested cycles. Moreover, in times where reducing the carbon-based emissions is a world spread purpose, it is important to underline that this is one solution to produce more energy and less waste, even more than that because with WHR, you reuse waste so that it becomes a heat source. Thus, we can say that technically, the already existing waste that is considered as being the normal can be reduced.

WHR is a spread method that has many applications. We talked about the ones in industry that are obvious with exhausted gases or high temperature liquids, but in fact, we can see WHR in all the industries that are transforming raw materials. Indeed, these processes usually generate a lot of heat that is destined to be wasted, so using this heat source provide a solution for wide range of utilisations in the whole world. We can talk about systems in Australia where sugar cane transforming processes generate loads of by-products that are used to heat, heat again and reheat water. We have also been brought to see projects of pulp and paper mills operating in the coldest parts of Finland where flue gas coolers are used to reheat water for other plant applications. Finally, we can say that this method fits perfectly in today's mentality of not creating new things but optimising what we know, in order not to use and exploit our planet

3.1.2. The Wärtsilä 18V50DF:

The Wärtsilä 18V50DF is said as being the example of fuel flexibility for an engine, indeed it can be used with natural gas, light or heavy fuel oil…The Wärtsilä 50DF is manufactured in configurations from 6 up to 18 cylinders giving 950/975 kW for each one and a total maximum mechanical output of 17,100 kW. The engine has a maximum thermal efficiency of 47%, higher than for any other gas engine. This last odd will be the one to optimize, even if it's considered as being one of the best efficiencies that we could hope, the 53 % wasted is an amount of energy that is crazy thinking about how productive the engine is.

Figure 8 : The Wärtsilä 18V50DF

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Many assumptions will have to be made for this kind of engines and to get any results, which is more relevant than trying not to put that many assumptions and just have nothing.

Assumptions:

- we will consider that all heat exchanges/transfers inside the whole process of recovery and of the cycle are "ideal", meaning that everything is well isolated and that there's no loss in the whole cycle.
- no pressure drops inside of the turbine, the heat exchanger and all the pipes. Moreover, all the components are considered with a full isentropic efficiency, which is one more time an "ideal" assumption.
- the specific heat capacity is considered constant for the exhaust gases and is given by the thesis that we're referring to, and that the rise in temperature in the pump will be neglected but it's work is included in the calculations.

3.2. R245fa: the fitting working fluid:

The Organic Rankine Cycle (ORC) works with the same principle as the Steam Rankine cycle, but organic fluids are used as working fluid instead of water in the ORC applications. Therefore, the choice of the working fluid is important. The working fluid should ensure that high thermal efficiency and high utilisation of the available heat source/sources are achieved in the ORC process. Additionally, the working fluid should be environment friendly, inexpensive, and meet the safety criteria.

Pentafluoro propane which has a chemical nomenclature; HFC 1,1,1,3,3 or as it is commonly known as R245fa, it is a type of dry fluid. It has zero Ozone Depletion Potential (ODP) and low Global Warming Potential (GWP) in comparison with most of the organic fluids that are convenient to use in the case of this study. Also, it is not hazardous and not flammable. So, it fulfils the safety criteria as well.

The fluid is very interesting in terms of boiling temperature and critical temperature; indeed, they are not too high so the energy we have to provide neither is. [8]

$$Boiling\,temperature : T_{eb}°=15,1°C \; ; \; Critical\,temperature\,T_c°=154,01°C$$

On the environmental side, we have to look at the Ozone Depletion Potential; this is an index that ranks the harmfulness of a chemical compound to the ozone layer and the Global Warming Potential; this index characterises the action of a chemical compound on the greenhouse effect. The reference molecule is CO2, which has a $GWP=1$ for well-defined periods, generally 100 years. The higher this index is, the more harmful the compound is.

$$GWP=1030 \; ; \; ODP=0$$

In addition, the gas is contained under pressure, it can explode under heat. Only experienced and properly trained persons should handle gases under pressure. It can cause asphyxiation in high concentrations. Symptoms may include loss of consciousness or motor skills.

Because of its high volatility, the product is unlikely to cause land or water pollution.

3.3.   Organic Rankine Cycle:

The ideal Rankine cycle has no internal irreversibility and consists of the following four processes:

1-2 Isentropic compression in a pump

2-3 Heat addition at constant pressure in a boiler

3-4 Isentropic expansion in a turbine

4-1 Constant pressure heat rejection in a condenser

The fluid enters the pump in state 1 as a saturated liquid and is isentropically compressed to the operating pressure of the boiler. The temperature of the fluid increases somewhat during this isentropic compression process. The vertical distance between states 1 and 2 on the T-s diagram is greatly exaggerated for clarity. The fluid enters the boiler as a compressed liquid in state 2 and exits as superheated steam in state 3. The boiler is essentially a large heat exchanger. The superheated steam in state 3 enters the turbine, where it expands isentropically and produces work by rotating the shaft connected to an electric generator. In this process, the pressure and temperature of the steam drops to the values of state 4, where the steam enters the condenser. In this state, the steam is usually a high-quality saturated liquid-steam mixture. The steam is condensed at a constant pressure in the condenser, which is essentially a large heat exchanger, rejecting the heat to the outside. The steam leaves the condenser as a saturated liquid and enters the pump.

Remembering that the area under the process curve in a T-s diagram represents the heat transfer for reversible internal processes, we can see that the area under the process curve 2-3 represents the heat transferred to the boiler water and the area under the process curve 4-1 represents the heat rejected into the condenser. The difference between the two is the network produced during the cycle. [9]

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4. CALCULUS AND REQUIRED DATA

4.1. Obstacles:

4.1.1. Software:

When we first imagined something about the project, the aim was to use a software able to design and to recreate the functioning of an organic Rankine cycle. Indeed, we just needed to understand how it works and maybe how to be able to create a software like this by ourselves. Moreover, the work could have been easier for us because it would have done the math for us, we could have more played around the selection of this or that organic fluid, comparing the different feats of them all. Such software is sadly expensive, and we couldn't even find a basic or trial version to emphasize our words.

Because of this, we tried to find a way to design, at least, the calculations and evolutions of thermodynamic parameters in the cycle. That is the reason why we thought of an excel file.

4.1.2. First Excel:

We had to do a numerical modelling for the project, so we created an excel where we made calculations to find the best efficiency of this cycle. Here are the digits that represent each step for the cycle and accordingly for the excel file.

1: Inlet pump

2: Inlet heat exchanger

3: Inlet turbine

4: Inlet condensor constant

For this first excel, we made assumptions such as Cp and Cv (specific heat capacity at constant pressure or volume), as well as the characteristics of the exhaust gases and the cooling water. To follow the rest of the explanations, please refer to the file. We set $T_2 A T_4$; we make calculations to find the $T_1 A T_3$:

$$m_e' C p_e (T_e, 2 - T_e, 1) - m_w' L_w - m_w' C p_w (T b_w - B2) m_w' C p_w + B2 = B3$$

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Then to calculate the efficiency: $efficiency = \dfrac{W_t - W_p}{Q_{add}} = \dfrac{usefull\,energy}{investment}$

Where useful energy is the difference in work between the work of the steam turbine and the work supplied by the pump. We need the Q and W thanks to:
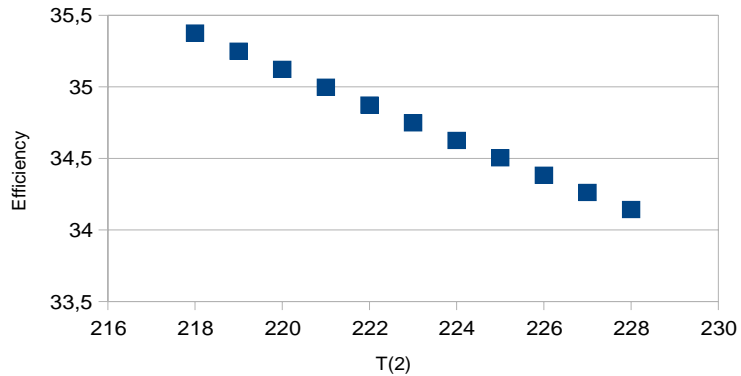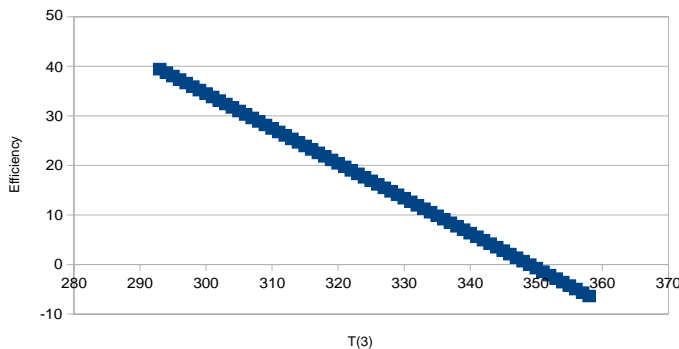

Figure 9 : T-Efficiency diagram, T(4) fixed

$$m_w^{'} C p_w (T b_w - B2) + m_w^{'} L_w + m_w^{'} C p_w (B3 - B2) = Q$$

$$W = mCp\,\Delta T$$

We vary $T_2 A T_4$ without exceeding the superheat temperature. The work of the pump is negligible compared to the work of the turbine. Then we vary $T3AT4$. Finally, we draw a graph representing the efficiency as a function of the temperatures. We notice that the lower the temperature is, the higher the efficiency is.

Figure 10 : T-efficiency diagram, T(2) fixed

Now, you may wonder why we said that this Excel file brought us obstacles we needed to overcome. In fact, throughout our research, we realised that many applications and many assumptions we made were not something accurate for our calculations. It appears that we needed to use a totally different method. Of course, we kept a few things, but still the major part had to be restart.

Now let's talk about our misunderstandings. As you probably noticed, we never use the pressure to calculate anything. That was our biggest mistake because we realised that it had an impact on everything, so we were forced to take pressure into account in our calculations. We also thought that entropy and enthalpy were not really useful but then, we understood that it was not true. It looks like the only equation we were using was $W = mCp\,\Delta T$ but in fact it is not that easy. In addition to this, we also did not mention the fact that the fluid could be sometimes saturated, superheated or even a mixture of gas and liquid. Indeed, we realised that the thermodynamic tables were very useful and that it was the solution of our mistakes.

After this first try, we knew what we needed to do so everything could be done faster, and we are going to explain you the process of the accurate calculations in the next part. All along the semester and the realisation of our project, we have been through many obstacles, and we tried many techniques for our calculations. Finally, and thanks to some reports we read, we came up with calculations that looked pretty accurate, even if there are still things that we did not resolve.

4.2. Devices

First, let's come back to our cycle. As four components are modifying the properties of our fluid at each step, we need to calculate every value to find a way to get the best efficiency. Indeed, in the end, we will try to find how we could modify some values to obtain the maximal efficiency. As explained in the part talking about the obstacles we have been through, some reports helped us in our research. You can find them in the appendix. Now let's recap the process we applied.

4.2.1. Pump

We will start from the inlet of the pump. The assumptions we will make about this device is that it is isentropic, and that the temperature is nearly constant. We will see later that we added a few Kelvins for the graph to be more easily readable. The pressures at the inlet and the outlet of this pump will now be the only parameters of the fluid set. Indeed, the rest will be determined thanks to calculus and reading of thermodynamic tables.

Another assumption is also that the fluid's state at the inlet is saturated liquid. Thanks to this, we can refer to the thermodynamic table of the R245fa to check the values of the other parameters. We made the technique that allowed the results to be as precise as possible. Indeed, thanks to the thermodynamic table, we drew a Pressure/Parameter graph for each parameter we wanted, it is to say temperature, enthalpy, entropy and specific volume. Then, we took the equation of the curve drawn and replaced it in our calculations sheet. This equation was either polynomial or exponential depending on the shape of the curve we had.

Here, you can see an example with a Pressure-Enthalpy diagram. We can notice the term "$\in 50\ kPa$" appearing; indeed, when we drew the curves, we noticed that it had a different shape in different pressure scales.
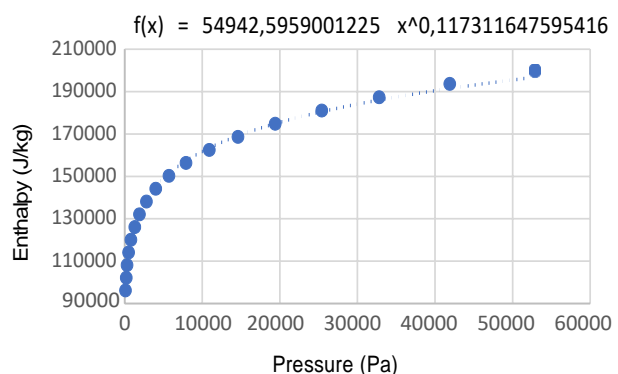

Figure 11 : P-h diagram, P < 50 kPa

That is the reason why more than one graph has been made for each parameter. Thanks to this, we can find very accurate values and optimize the most our calculations. The enthalpy below is calculated with P_1 replacing the x in the equation. Here, the values we are interested in are temperature, enthalpy, entropy, and specific volume.

When they are found, we must search for their evolution, and for their values at the outlet of the pump. As previously said, the temperature and entropy will remain the same and the specific volume will just help us to calculate h_2. (A letter is added after each parameter depending on the state where we are).

Indeed, a pump needs work to function. As we can see in the report of Yunus Cengel [8] this work coming in can be calculated with $W = v_1 (P_2 - P_1)$. Finally, we know that $W = \Delta h$ and more particularly, $h_2 = W_{pump, \in \lnot} + h_{\lnot}$.

4.2.2.   *Heat exchanger*

We now have everything we need to advance to the heat exchanger. As explained in the obstacles we went through, we first tried to calculate the change of values from the heat exchanger, but we realised that they were not all possible and that we also needed a thermodynamic table. First, we introduce the exhaust gas that will give us the heat added in the fluid. Thanks to a report written by Tihomir Mladenov Ruse ([9]), we can set the specific pressure (Cp) and the inlet and outlet temperatures of the exhaust gas.

Here, this gas will be water. We also choose a mass flow rate that will be modified to try to get the maximal efficiency. Then, the heat added is calculated thanks to $Q_{\lnot} = mCp (T_{\lnot} - T_{out})$. The main reason why we are doing this is that it permits us to calculate the enthalpy that will helps us to extract the other thermodynamic properties of the superheated working fluid from its thermodynamic table, such as temperature and entropy.

The outlet pressure of the heat exchanger is equal to its inlet because the process is isobaric. However, we do not know h3. That's where the heat added is interesting. As the work is null, $Q = \Delta h$ and so here, $h_3 = Q_{\lnot} + h_2$

Now we have everything, we can refer to the table and find the value of T_3. Then, we take the other table where the entropy is written, and we do the same for s_3 now we have the temperature. We have everything we wanted, and we can move on to the turbine.

4.2.3. Turbine

The turbine brought the first problem we did not resolve. However, we still manage to do something even if it could be a bit inaccurate. Indeed, the assumptions we first made about the turbine was that it was isentropic. It meant that $s_4=s_3$ and the state of the fluid at the outlet of the turbine was thus a dry gas. We can also say that it is a saturated mixture. From that point, the process is the same as for the pump except that we have to deal with saturated vapour and saturated liquid. Therefore, I will explain step by step how we dealt with this saturated mixture.

- Condenser assumed isobaric and isothermal: $T_4=T_1 \text{A} P_4=P_1$

- Yunus Cengel [8] tells us that $h_4=h_f + x\, h_{fg}$, with $h_{fg}=h_g - h_f$ We write f for the value of the saturated liquid and g for the saturated gas.

- Then, we find h_f and h_g thanks to the graphs we drew based on thermodynamic tables of our liquid, in its saturated liquid or vapour form.

- The x in the equation is the fraction of gas in the mixture. Its value is ($s_4 - s_f ¿/s_{fg}$ [8] and we used the same way to get the entropies as for the enthalpies in the last bullet. As you know, we are dealing with a saturated mixture so this x need to oscillate between 0 and 1. However, during our calculations and despite many tests, this x has always been greater than 1 and that is a problem. We are thus forced to consider that the state of the fluid at the outlet of the turbine is not (always) a saturated mixture but still superheated vapour. It does not change the outlet pressure, but we cannot say anymore that it is isothermal and isentropic.

So you guess that we now have to consider our fluid as superheated vapour at the outlet of the turbine. Here is the steps that are going to be applied to calculate the thermodynamic parameters of the fluid in this case.

- We need to use the thermodynamic table of superheated vapour. As we have to determine s_4, h_4 and T_4, we first have to find one of them to use the table.

- Our assumption will be to say that $s_4=0,98 ¿ s_3$ because the entropy is not varying a lot no matter the case.

- Finally, h_4 and T_4 can be easily found on the thermodynamic table.

- The calculus of the work is the same for the 2 ways, it is to say $W =h_4 - h_3$ We just have h_4 that will change depending on the situation.

4.2.4. *Condenser*

For the condenser, we have nothing to do because we already have the values at its inlet and its outlet as the cycle is now completed. The only thing we could do is calculate the heat going out of the cycle through this condenser, but it does not intervene in the efficiency, so it is useless.

4.3. Efficiency

Now we have everything, we can calculate the efficiency in order to see how we could manage to find the maximal one. To begin, we can determine the efficiency in the case of a Carnot cycle with our values. It gives us $\mu_{Carnot} = (1 - T_1/T_3) * 100$. Of course, the following efficiencies that will be calculated have to be lower than the Carnot one. We talk about efficiencies in plural because there are 2, as we have the case of a saturated mixture and of superheated vapour at the outlet of the turbine. The calculus will be the same, it is to say $\mu_{eff} = (1 - (h_4 - h_1)/Q_i) * 100$, and h_4 is not the same depending on if $x > 1 \vee x \in 1$.

Finally, you can see that we can only modify the pressures around the pump and the mass flow rate of the exhaust gas. Thanks to this, it is easy to play with these parameters with the aim to get the maximal efficiency. This part will be explained to you when talking about the excel file in the next part.

4.4. Excel manipulation

When doing calculations, the most useful free software that is easy to manipulate is excel. That is why we decided to work only thanks to it. It helped us to put the tables and to check in it when we needed data. To be more understandable, the excel file will be recap through a flowchart and some information will be added.
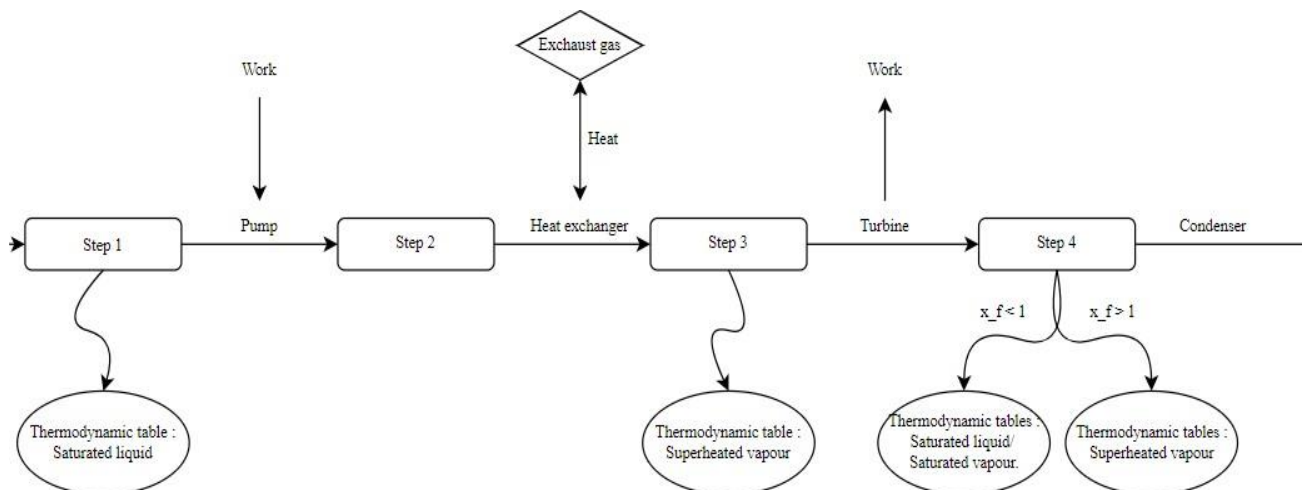

Figure 12 : Flowchart of the excel manipulation

As you can see on this flowchart, the round boxes represent the sheets in the excel file and the squared boxes are the different steps of the process. Now, let's add some information about each operation.

The process has been different when the fluid was superheated vapour. In fact, 2 parameters are necessary to find another one, so a graph would be useless. Unfortunately, the only way to do it is to use a function that research the value corresponding to the 2 other parameters that we already know. For example, this is how a superheated vapour thermodynamic table for our fluid looks like :

Temp (C)	P bar	Temp (K)	P (Pa)											Superheat (C) - Enthalpy
				0	5	10	15	20	25	30	35	40	45	
-100	0	173,15	0	335895	338994	342142	345339	348584	351879	355224	358619	362065	365561	

Figure 13 : Small part of the thermodynamic table of superheated R245fa

The unit of the enthalpy is J/kg in this table

As you see, there are many possibilities and choices. This is also why we need to use several thermodynamic table only for superheated vapour. Indeed, there is one for the enthalpy and another for the entropy.

There is still something that disturb our final results. Indeed, when we look through a table to find a value. If the reference we used is not written in the table, excel will select the closest value to the one we have. Therefore, we could set different values but still find the same results as the closest value of each of them is exactly the same. We will mention this problem once again later. Still, this is the best method we found for this application. We also made basic operations such as a repetition of boxes when a parameter is constant through a device for example

We also respected some limited factors during our calculations. Indeed, the fluid had a critical temperature that had not to be exceeded. Temperatures also needed to be lower or higher than the boiling temperature of the fluid depending on its state. Moreover, efficiency can not be higher than the Carnot efficiency. A lot more conditions were also there not to let the heat coming in from the gas being equal to zero, or the work produced by the turbine being negative. All these conditions restricts a lot the values we could use and modify when we were trying the get the maximal efficiency.

4.5. Graphs

After all these calculations, we may not forget the aim of our project. Find a way to obtain the maximal efficiency and maybe also comparing our results with others we found from our researches. Of course, we used graph because it shows well evolution of parameters when we modified values. We made two, the first one to see how a T/S diagram looks like depending on the conditions we have. It gives us this.
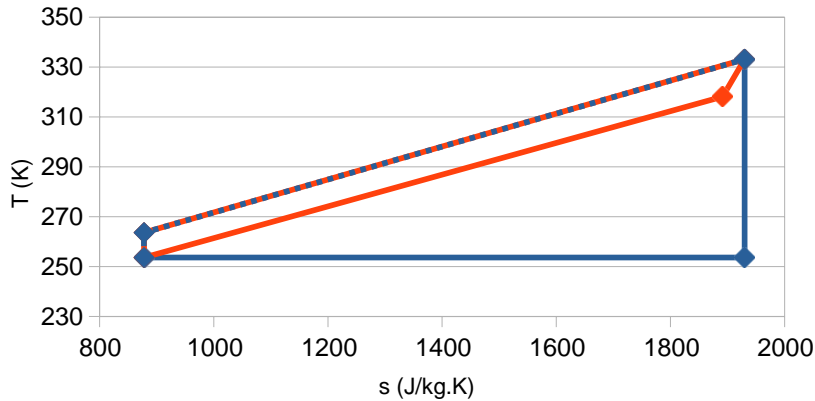
INSTITUT NATIONAL DES SCIENCES APPLIQUEES DE ROUEN
Département Sciences et Techniques Pour l'Ingénieur
avenue de l'Université - 76801 Saint-Etienne-du-Rouvray - tél : +33 (0)2 32 95 97 00 - fax : +33 (0)2 32 95 98 60

On this diagram, the first step is represented by the point at the bottom left corner. As said in the title, the blue line is the T/S diagram if we take x smaller than 1 at the outlet of the turbine. The red represents the same thing for x greater than 1. Of course, these curves have been made according all the assumptions we made.

Figure 14 : T-S diagram, red line : x_f > 1, blue line : x_f < 1

In reality, we know that it would not be that straight and that accurate. The only thing we have not respected is the fact that T_1 has to be equal than T_2. Here, we added 10° to T_2 in order to see the 4 points separated.

Finally, we can see that the diagram is almost the same as the ideal one presented at the beginning of the report. The state are not mentioned on this diagram and that is what is distinguishing them.

This second diagram is the last step of our project. Indeed, we came to something where we could modify some parameters to get the maximal efficiency. When we gather nearly everything, it gives us this diagram. As said before, the only thing we can modify is the pressures at the outlet and inlet of the pump (same as at the inlet of the pump). We can also play with the mass flow rate to find the best efficiency for each pressure. Finally, we tried different values to have a curve that seemed at least accurate.

Turbine inlet (Pressure bar)	Energetic efficiency (%)	mass flow rate (exhaust gas)
18	26,06	0,996
15	25,08	0,983
13	24,96	0,948
11	24,25	0,939
9	23,86	0,902
7	23,35	0,896
5	22,48	0,855

Figure 15 : Table of thermodynamic parameters

We can see that it is roughly linear. We do not guess it when we see this table but the interval of mass flow rate where the efficiency found is accurate is not that huge. Indeed, we needed to take care that the efficiency was not higher than the Carnot one. Other parameters could also change with these modifications, and they were becoming wrong so we could not use the informations we had at that time. Then, because of the superheated vapour where we were picking the values in the table, we found the same efficiencies for different pressures, as explained in the part about the excel.

Finally, to make a quick analysis of the diagram, we can say that the efficiency increases when the pressure becomes higher. However an average of 25% is still pretty low and we could think of a way to optimize the amount of work produced.

MD2M

Turbine inlet Pressure (bar)	Energetic efficiency (%)
11,7	33,8
5	30,3

Even, if we compare with different fluids, we notice that the efficiency if much higher. The difference may either come from the fluid but also probably from our calculations.

MDM

Turbine inlet (Pressure bar)	Energetic efficiency (%)
14,5	30,4
13	29,7
11	29,3

Figure 16 : Thermodynamic parameters of other fluids

5. CONCLUSION :

Throughout this project, we managed to optimise the efficiency of the cycle through numerical analysis using Excel. The use of Excel was complicated but because our teacher is well-trained on this calculation tool, he explained to us the different functions to be implemented to perform our calculations. Moreover, this could be used to design more efficient energy generator devices, or optimise those that are already working. This method could be reused and generalised to reduce energy losses, thus limiting natural outcomes. This numerical modelling was a success because the efficiency obtained is correct even if it is still pretty low, but we could think of a way to optimise the amount of work produced.

This group work allowed us to apply our scientific knowledge learnt throughout our course, but also to work in a group. As a result, we were able to share our ideas, our points of view. While working on this project, we were able to develop a lot of knowledge in many areas that were unknown to us before. The use of Excel and all its features was a challenge, but we managed to use it well. Moreover, each of us was always willing and available to meet and exchange our research. Moreover, this project allowed us to realise what the reasoning and approach of an engineer consisted of. We pooled the thinking of all the members of the group towards a common goal, which is also one of the most important tasks we must acquire in order to build the identity of the engineers we will be tomorrow.

Finally, it would be interesting to improve the performance obtained by changing the working fluid. We can also study another cycle and compare it with this one, looking for example at its environmental impact as well as its efficiency.

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7. APPENDICES

7.1. Table of thermodynamic properties of R245fa

Masse molaire	g/mol	134,05
Point de fusion	°C	-102,1
Point d'ébullition (sous 1,013 bar)	°C	15,13
Densité du liquide saturé à 25°C	kg/m³	1339
Densité de la vapeur au point d'ébullition	kg/m³	5,960
Tension de la vapeur à: 25°C 50°C	bar	1,48 3,44
Température critique	°C	154,0
Pression critique	bar	36,51
Densité critique	kg/m³	516
Chaleur latente de vaporisation au point d'ébullition	kJ/kg	196,05
Conductivité thermique à 25°C Liquide Vapeur sous 1,013 bar	W/m.K	0,088 0,013
Tension de surface à 25°C	10⁻³N/m	13,63
Viscosité à 25°C Liquide Vapeur sous 1,013 bar	10⁻³ Pa.s	0,401 0,01
Chaleur spécifique à 25°C Liquide Vapeur sous 1,013 bar	kJ/(kg.K) kJ/(kg.K)	1,322 0,920
Ratio Cp/Cv à 25°C sous 1,013 bar		1,101
Inflammabilité dans l'air		Ininflammable
Point éclair		Néant
Classification NF-EN 378-1 ASHRAE		B1 B1
Potentiel d'action sur l'ozone	(R11 = 1)	0
GWP Selon IPCC-AR4/Selon IPCC-AR5	(CO₂ = 1)	1030/858

7.2. First Excel

Etape	T(K)	P (bar)	H(kJ/kg)	Cp(kJ/(kg*K))	Cv(kJ/(kg*m^3))	m(kg/s)
2	225	5,00E+00	220	1,322	0,92	20
3	423,86913767	5,00E+00	550	1,322	0,92	20
4	300	3,00E-02	511	1,322	0,92	20
1	199,075416036	3,00E-02	219	1,322	0,92	20

Etape	Q (kW)	W (kW)		Exhaust gases (Assumption)	Cooling water (Assumptions)
2 -> 3 (Heat exchanger)	7505,448	0	m (kg/s)	28,2	25
3 -> 4 (Turbine)	0	-3275,1	Cp (kJ/(kg*K))	1,05	4,19
4 -> 1 (Condenser)	-2668,446	0	T°in (K)	673	293
1 -> 2 (Pump)	0	685,446	T°out (K)	363	350

Efficiency	34,5036565439

Fluid	R245fa
Tc (K)	427,01
Tb (K)	288,3
Pc (bar)	3,65E+01
Latent heat (kJ/kg)	196,05