Design of Auxiliary Power Unit (APU) for co-operation with a turboshaft engine

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NOMENCLATURE

$\dot{m}$	Refrigerant mass flow (kg/s)
$\dot{m}_{air}$	Air mass flow (kg/s)
$\dot{m}_{exh}$	Exhaust gases mass flow (kg/s)
P	Pressure (MPa)
T	Temperature (K)
h	Enthalpy (kJ/kg)
s	Entropy (kJ/kg·K)
Cp	Specific heat (kJ/kg·K)
ρ	Density (kg/m^3)
ε	Heat exchanger efficiency
ε'	Condenser efficiency
$\dot{W}_{turb}$	Turbine power (kW)
$\dot{W}_{pump}$	Pump power (kW)
$\dot{Q}_{12}$	Heat exchanger power (kW)
$\dot{Q}_{34}$	Condenser power (kW)
η_{ORC}	Organic Rankine Cycle efficiency
η_{pump}	Pump efficiency
η_{turb}	Turbine efficiency
m_{kero}	Kerosene mass (kg)
m_{ORC}	ORC mass (kg)
$\dot{m}_{kero}$	Fuel consumption (kg/h)
P_{GTD}	Engine power (GTD-350, kW)
m_{fuel}, m'_{fuel}	Specific Fuel consumption (kg/kW·h)
t, t'	Flight time (h)

1. MOTIVATION OF THIS PROJECT

This Master Thesis started as a purpose to take profit of the exhaust gases of an aircraft engine due to their very high temperature that is usually wasted by being thrown out in the atmosphere during flight. One way to recuperate this energy might be to use the **Organic Rankine Cycle** (ORC). This technology is very promising for its large number of applications. One of the fields to study is the **waste heat recovery**. For example, the ORC can be used as a small scale cogeneration plant on a domestic water heater in a little community, to take profit from industrial waste heat, exhaust gases from vehicles, etc. Other fields of study can be biomass-fueled power plants, geothermal plants etc.

The Rankine Cycle (RC) is a thermodynamic cycle which converts heat into work. The heat is supplied externally to a closed loop, which usually uses water as the working fluid. This cycle generates about 80% of all electric power used throughout the world (www.turboden.eu). The difference between RC and ORC is the working fluid. The ORC works with organic substances, for example, refrigerants. Using refrigerants in an ORC allows recovery of wasted heat from low temperature source medium. The research of refrigerants is now heavily explored and very motivating to learn how the technology and the chemistry can work together combined.

Talking about environmental aspects, offered by application of ORC to aircraft engines, is very tempting because the European Union has proposed to reach the year 2020 with ambitious targets in terms of climate and energy. These targets are called “20-20-20” (ec.europa.eu/clima/policies/package/index_en.htm), and they are:

- A 20% reduction in EU greenhouse gas emissions from 1990 levels.
- Raising the share of EU energy consumption produced from renewable resources to 20%.
- A 20% improvement in the EU's energy efficiency.

This aim of the project described herein was to design an auxiliary power unit for a small to mid-size helicopter machine in order to produce all or partial energy for on-board devices by exhaust heat recuperation. This would reduce the hot gas emissions and improve the global efficiency of the engine. In turn, the fuel consumption would be reduced and, in consequence, there would be less CO_2 emissions.

The section that comes below presents types of aircraft engines. Knowing this, will be an explanation of Auxiliary Power Units (APU) and how they are involved in the operation of an aircraft. One purpose of this project was to try to replace these engines

From presented previously, the concept of waste recuperation system will be introduced. How this system works with refrigerants, their different classifications and characteristics.

Finally, the final design will be presented, the selection of the refrigerant and all calculations relating to the cycle, as well as sensitivity and possible directions of research which can take this project.

2. AIRCRAFT ENGINES

2.1. Turboshaft engines

A turboshaft engine is a gas turbine engine which basically consists of three components: a compressor, a combustion chamber and a turbine. Firstly, the compressor elevates air pressure, the air is mixing with fuel, burns inside the combustion chamber generating heat and kinetic energy (exhaust gases) which is then converted into mechanical energy of the shaft by passing through the turbine. The kinetic energy is used to rotate the shaft that ,partially, gives power to the compressor to work. Turboshafts are usually used as engines to propel rotors in aviation helicopters.

A turboshaft engine, presented in Fig. 1, is usually made up of two major part assemblies: the 'gas generator' and the ‘power section’. The gas generator consists of the compressor, combustion chamber and one or more stages of a turbine. The power section consists of additional stages of turbines and the shaft output. The gas generator creates the hot expanding gases that are driven to the power section.

In most designs, the compressor and the turbine that share a single shaft are separated from the power section, so they can each rotate at different speeds, the independent turbine is called ‘free turbine’.

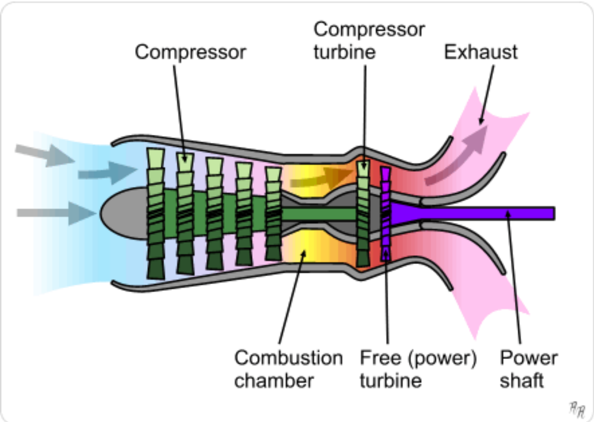


Fig. 1: A turboshaft engine

Below are examples of the most commonly used turboshafts along with their features and images have been extracted from Pratt & Whitney Canada webpage:

2.1.1. PW-200

This engine provides power ranging from 372 to 522 kW. This turboshaft is composed by three main rotating components. On the one hand, has single-state compressors driven by one single-stage turbine with a reverse flow combustor power a free, single-state power turbine. This turbine also delivers power to the main shaft by means of reduction gearbox. With this reduction and the engine accessories is obtained a compact design.

Examples of aircrafts which use this engine are: Eurocopter EC135, AgustaWestland A109 Grand, Bell 427 or Kazan Ansat. Table 1 shows the characteristics of the PW-200 series engines:

Tab. 1. Characteristics of the PW200 series engines

	Thermo Power Class* (kW)	**Mechanical Power Class*** (kW)	**Output Shaft Speed** (RPM)	**Diameter**** (m)	**Length**** (m)
PW206 Series	477	321 to 418	5900	0,5588	0,9 to 1,05
PW207 Series	545	425 to 485	6000 to 6240	0,5588	0,9 to 1,01

* Powers are approximate values at take-off. Available at sea level, standard day, static conditions, uninstalled.

** Dimensions are approximate values.

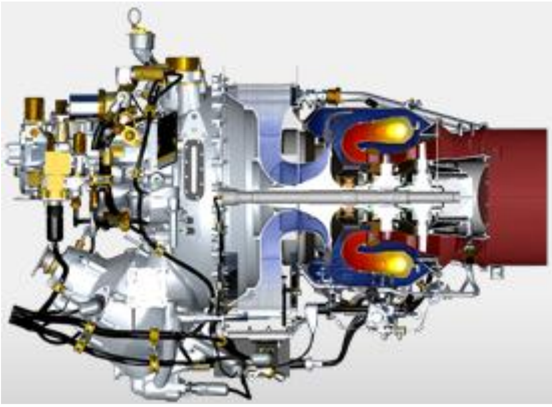


Fig. 2: PW-200 series

2.1.2. PT6T

This engine provides power ranging from 1341 to 1649 shaft kW. This turboshaft has been improved modifying its aerodynamic load and using new materials.

The configuration of PT6T configuration consists of two PT6A power sections coupled to a combining gearbox which allows both twin engines to operate as a single. The operation of each twin engines is with a two-shaft configuration consisting of a multi-stage compressor driven by a single-stage compressor turbine and an independent shaft coupling the power turbine to the output shaft through the combining reduction gearbox.

Examples of aircrafts which use this engine are: Agusta Bell Model 212, Bell CFUTTH CH-146 Griffon or Sikorsky S-58T. Table 2 shows the characteristics of the PT6T series engines.

Tab. 2. Characteristics of the PT6T series engines

	Thermodynamic Power Class* (kW)	**Mechanical Power Class*** (kW)	**Output Shaft Speed** (RPM)	**Height**** (m)	**Width**** (m)	**Length**** (m)
PT6T-9 Series	1673	1384	6600	0,825	1,1	1,68
PT6T-6 Series	1470	1400				
PT6T-3 Series	1342 to 1432	1342 to 1400***				

* Powers are approximate values at take-off. Available at sea level, standard day, static conditions, uninstalled.

** Dimensions are approximate values.

***The value of Mechanical power class should be lower than the thermodynamic power class because there are losses transforming power. The values are taken from Pratt & Whitney Canada.

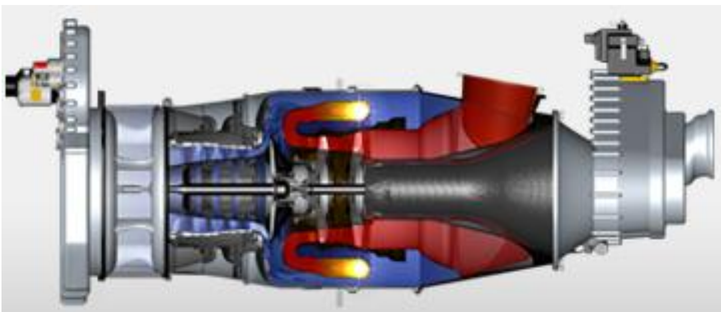


Fig. 3: PT6T series

2.1.3. PT6C

This engine provides power ranging from 894 to 1490 shaft kW. This turboshaft remains the PT6T configuration, consisting of two PT6A power sections coupled to a combining gearbox which allows both twin engines to operate as a single. The differences between PT6T is that has an advanced compressor and the efficiency of combustion and turbine has been improved. With these, the fuel consumption is lower and, in consequence, the emissions.

Examples of aircrafts which use this engine: Agusta Westland AW139, Dyncorp UH-1 Global Eagle, Eurocopter EC175. Table 3 below shows the characteristics of the PT6C series engines:

Tab. 3. Characteristics of the PT6T series engines

	Thermodynamic Power Class* (kW)	**Mechanical Power Class*** (kW)	**Output Shaft Speed** (RPM)	**Diameter**** (m)	**Length**** (m)
PT6C-67A	1447	1447***	30000	0,5842	1,4986
PT6C-67C	1253	821	21000	0,5842	1,4986
PT6C-67E	1324	970	21000	0,5842	1,4986

* Powers are approximate values at take-off. Available at sea level, standard day, static conditions, uninstalled.
** Dimensions are approximate values.
***The value of Mechanical power class should be lower than the thermodynamic power class because there are losses transforming power. The values are taken from Pratt & Whitney Canada.

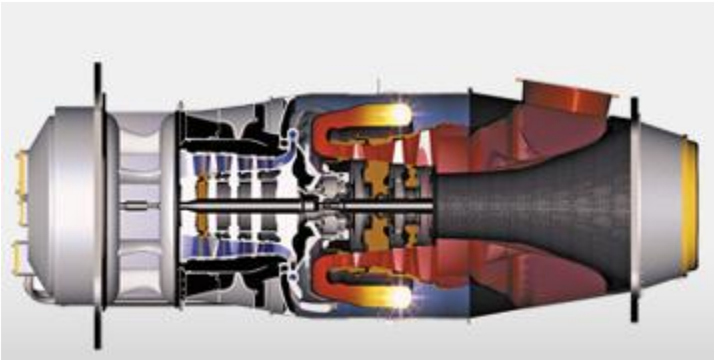


Fig. 4: PT6C series

2.2. Turbofan engines

The turbofan or fanjet is a type of air breathing jet engine that is widely used for aircraft propulsion. The incoming air is captured by the engine inlet. Some of the incoming air passes through the fan and continues on into the core compressor and then the burner, where it is mixed with fuel and combustion occurs. The hot exhaust passes through the core and fan turbines and then out the nozzle, as in a basic turbojet. The rest of the incoming air passes through the fan and bypasses, or goes around the engine, just like the air through a propeller. The air that goes through the fan has a velocity that is slightly increased from free stream. So a turbofan gets some of its thrust from the core and some of its thrust from the fan. The ratio of the mass-flow of air bypassing the engine core compared to the mass-flow of air passing through the core is referred to as the bypass ratio. The engine produces thrust through a combination of these two portions; engines that use more jet thrust relative to fan thrust are known as low bypass turbofans, while those that have considerably more fan thrust than jet are known as high bypass. Most commercial aviation jet engines in use today are of the high-bypass type, and most modern military fighter engines are low-bypass.

Since most of the air flow through a high-bypass turbofan is low-velocity bypass flow, even when combined with the much higher velocity engine exhaust, the net average exhaust velocity is considerably lower than in a pure turbojet. Engine noise is largely a function of exhaust velocity; therefore turbofan engines are significantly quieter than a pure-jet of the same thrust.

Since the efficiency of propulsion is a function of the relative speed of the exhaust to the surrounding air, propellers are most efficient for low speed flight, pure jet engine for high speed flight, while ducted fan engine configuration are a middle alternative. Turbofans are thus the most efficient engines in the range of speeds from about 500 to 1000 km/h, the speed at which most commercial aircraft operate. Turbofans retain an efficiency edge over pure jets at low supersonic speeds up to roughly Mach 1.6, but have also been found to be efficient when used with continuous afterburner at Mach 3 and above.

The vast majority of turbofans follow the same basic design, with a large fan at the front of the engine and a relatively small jet engine behind it. There have been a number of variations on this design, however, including rear-mounted fans which can easily be added to an existing pure-jet design, or designs that combine a low-pressure turbine and a fan stage in a single rear-mounted unit.

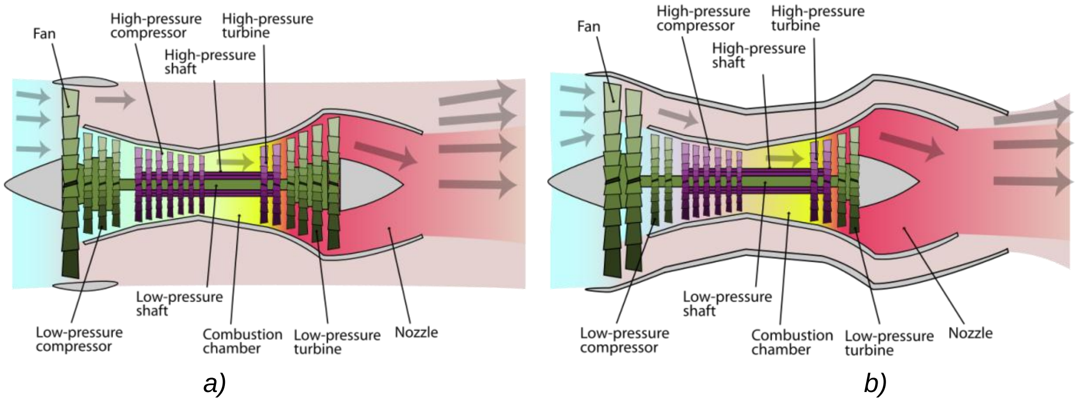


Fig. 5: A turbofan a) and a turbofan with bypass b)

Below are presented some examples of turbofans:

2.2.1. JT15D

The JT15D is a two-spool engine which is composed of six components: a single-stage high pressure centrifugal compressor driven by a single-stage high pressure turbine and a single-stage low pressure turbine driving a robust fan with wide-chord blades and compressor boost stage. The reverse-flow combustor has high efficiency, so the consumption is lower and the emissions also.

Examples of aircrafts which use this engine: Aerospatiale Corvette, Agusta S211, Hawker 400A/400XP or Cessna Citation I. Table 4 shows the characteristics of the PT6C series engines:

Tab. 4. Characteristics of the JT15D series engines

	Thermodynamic Thrust Class* (kN)	**Mechanical Thrust Class*** (kN)	**Diameter**** (m)	**Length**** (m)
JT15D-5 Series	15,135	13,577	0,69	1,54
JT15D-4 Series	11,129	11,129***	0,69	1,60
JT15D-1 Series	9,793	9,793***	0,69	1,50

* Thrusts are approximate values at take-off. Available at sea level, standard day, static conditions, uninstalled.
** Dimensions are approximate values.
***The value of Mechanical thrust class should be lower than the Thermodynamic thrust class because there are losses transforming power. The values are taken from Pratt & Whitney Canada.

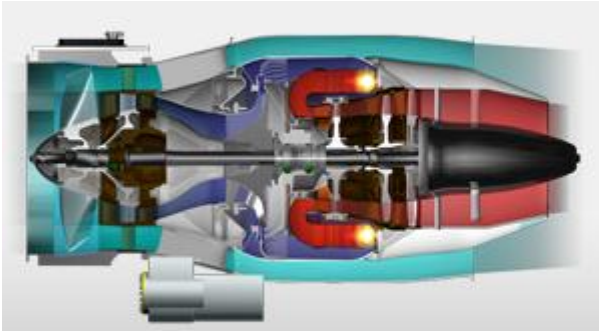


Fig. 6: JT15D series

2.2.2. PW300

The PW300 is a two-spool engine composed by a high pressure compressor with five stages. The compressor is driven by a cooled high pressure two-stage turbine. The fan is driven by a three-stage low pressure turbine. This engine has high efficiency in combustor, consequently, achieves low emissions and fuel consumption.

Examples of aircrafts that use this engine are: Bombardier Learjet Model 60, Cessna Citation Sovereign, Dassault F7X, Hawker 4000 or Gulfstream G200. Table 5 shows the characteristics of the PW300 series engines:

Tab.5. Characteristics of the PW300 series engines

	Thermodynamic Thrust Class* (kN)	**Mechanical Thrust Class*** (kN)	**Height**** (m)	**Width**** (m)	**Length**** (m)
PW308 Series	37,170	31,160	1,27	1,17	2,13
PW307 Series	33,386	28,498	1,19	1,04	2,18
PW306 Series	31,160	26,709	1,14	0,97	1,93
PW305 Series	26,264	20,922	1,14	0,91	2,06

* Thrusts are approximate values at take-off. Available at sea level, standard day, static conditions, uninstalled.

** Dimensions are approximate values.

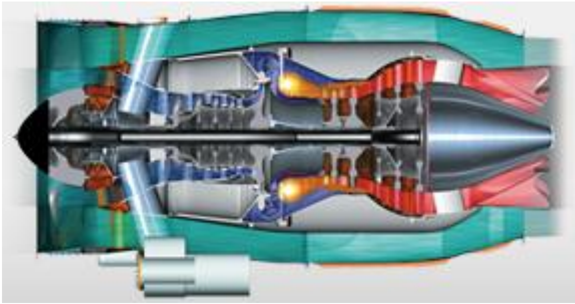


Fig. 7: PW300 series

2.2.3. PW500

This two-spool engine is composed by a three-stage high pressure compressor driven by a cooled high pressure turbine with a single stage. The two-stage low pressure turbine drives the fan. Models like P535 and PW545 incorporate a compressor boost driven by the fan. As the PW300, this engine has high efficiency in combustor, consequently, achieves low emissions and fuel consumption. The innovating exhaust mixer reduces fuel burn and noise levels.

Examples of aircrafts that use this engine are: Cessna Citation Bravo, Cessna UC-35 C/D or Embraer Phenom 300. Table 6 shows the characteristics of these engines:

Tab.6. Characteristics of the PW500 series engines

	Thermodynamic Thrust Class* (kN)	**Mechanical Thrust Class*** (kN)	**Height**** (m)	**Width**** (m)	**Length**** (Im)
PW545 Series	20,922	18,251	1,19	0,81	1,73
PW535 Series	18,251	15,135	0,97	0,74	1,69
PW530 Series	13,800	12,909	0,89	0,71	1,52

* Thrusts are approximate values at take-off. Available at sea level, standard day, static conditions, uninstalled.

** Dimensions are approximate values.

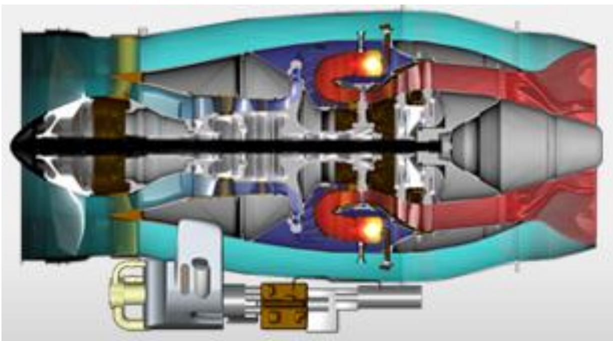


Fig. 8: PW500 series

2.2.4. PW600

This two-spool engine is composed by a two-stage high pressure compressor driven by a cooled high pressure turbine with a single stage. The low pressure turbine has only one stage drives the fan. As the PW300 and PW500, this engine has high efficiency in combustor, consequently, achieves low emissions and fuel consumption. PW600 uses the same exhaust mixer than PW500, obtaining reduction in fuel burn and noise.

Examples of aircrafts that use this engine are: Cessna Mustang, Eclipse 500 or Embraer Phenom 100 . The table 7 shows the characteristics of these engines:

Tab. 7. Characteristics of the PW600 series engines

	Thermodynamic Thrust Class* (kN)	**Mechanical Thrust Class*** (kN)	**Diameter**** (m)	**Length**** (m)
PW617F Series	9,126	7,924	0,45	1,26
PW615F Series	7,545	6,499	0,41	1,26
PW610F Series	5,342	4,229	0,36	1,17

* Thrusts are approximate values at take-off. Available at sea level, standard day, static conditions, uninstalled.

** Dimensions are approximate values.

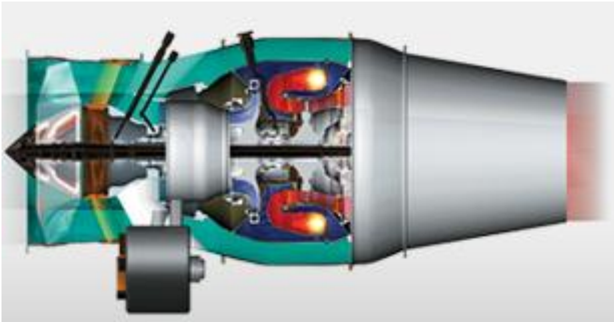


Fig. 9: PW600 series

3. AUXILIARY POWER UNIT (APU)

The APU is an independent jet engine installation and an element of the engine installed normally at the tail of the aircraft, in airplanes, and at the lower part after the cabin, in helicopters. This unit can provide to the aircraft:

- Electric power from shaft driven electricity generators;
- Pneumatic pressure for air conditioning and engine starting purposes;
- Hydraulic pressure for oil pumps.

Figure 10 is a scheme of how an APU works. The operation is similar to the aircrafts engines based on Brayton-Joule cycle. The air is compressed, after that, is mixed with fuel, burned, and the outgoing exhaust gases pass through the turbine. The intake fuel comes from the aircraft tanks; the quantity of it is controlled before the combustion. There are gates on the sides of the plane where the intake air enters as is shown in Fig. 11. Figure 12 shows the different thermodynamic processes done by the air inside the APU.

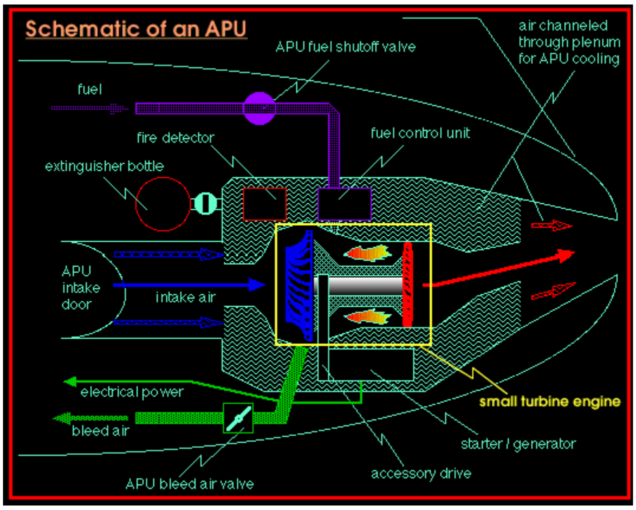


Fig. 10: APU's scheme inside an airplane

a) *b)*

Fig. 11: APU inlet a) and APU outlet b) for a commercial airplane

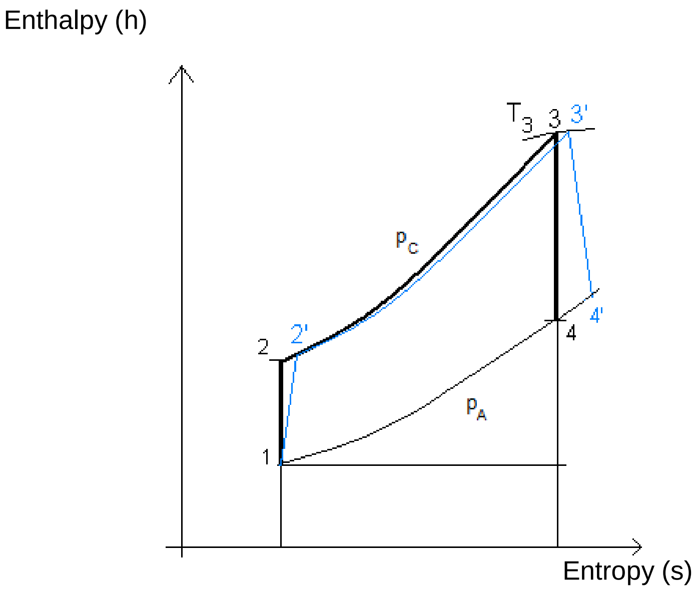


Fig. 12: A Brayton-Joule h-s diagram for air inside the APU

APU is an automatic engine, which normally runs at a governed speed of 100%. Some APUs have an idle facility that allows the engine to run at 85% of nominal RPM when no loads are applied. As it is an automatic engine, the fuel system must control the engine throughout the start and running phases of operation.

On most modern aircraft, the APU is also used in the air to provide air-conditioning during take-off and landing phases, or to back up the main engines in case of a generator or air system failure.

Although the APU is usually rated to run at the max cruise altitude of the aircraft it is fitted to, its ability to take load diminishes with altitude. As the major load on any APU is the air load it can be usual that the APU's ability to provide sufficient air for the aircraft is limited to 4500 - 6100 m.

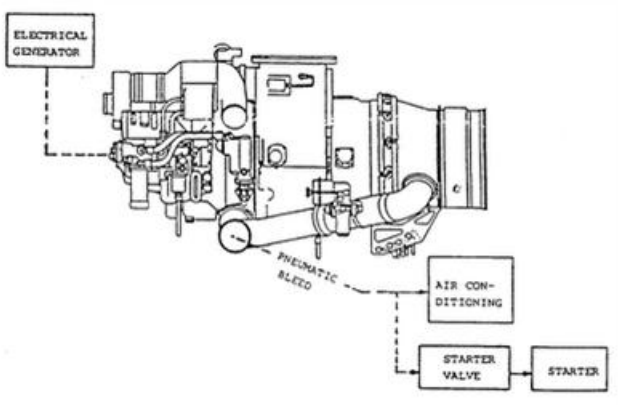


Fig. 13: An APU's scheme

The aim of the project will analyse possible alternatives to replace or augment APUs by other power generation systems. The APUs that are going to be studied will be the ones that are used in small aircrafts or helicopters, which give an average power of up to 75 kW. For example:

Tab. 8. Examples of APUs with weight and power given

(Auxiliary and ground power systems, Hamilton Sundtrand)

	Weight (kg)	Power (kW)
T62T2A1	32,21	70,87
T62T2B	34,02	70,87
T62T11	31,75	55,95
T62T16B/B1	34,02	55,95
T62T27	38,10	104,44
T62T40-1	39,46	41,776
Average	34,93	66,64

In the Tab. 8 are shown different models of APUs with their weight and the power given. Is important to know the weight because the analysis will have to consider how much power is lost and how much weight can be put back on the aircraft to maintain aircraft robustness and efficiency.

4. CONCEPT OF WASTE HEAT RECUPERATION SYSTEM ON BOARD AN AIRCRAFT

4.1. Introduction

The aim of this project is to test if is possible to replace the APU using a single turbine propelled by a coolant which takes profit of heat energy of exhaust gases. Normally, this energy is being thrown out to the atmosphere.

The first idea is to use the high temperature of the combustion gases making them go through a heat exchanger. It is intended that the substance, which circulates in counter current cycle to exhaust gas path, has a lower than upper source boiling point to increase its enthalpy and hence generate power through a turbine without having to add a compressor. Such approach requires a coolant fluid. With these conditions, the coolants seem to be the best option because they have low boiling point. Figure 14 presents the proposed scheme of the engine combined with heat exchanger and additional Brayton-Joule cycle designed to power the on-board accessories.

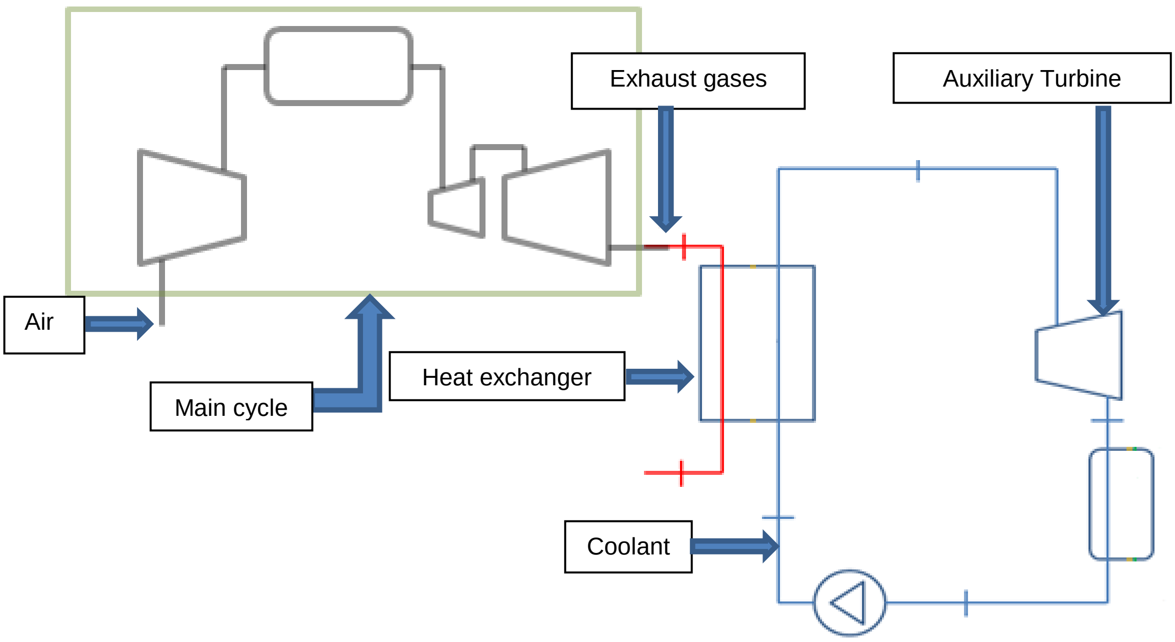


Fig.14: A proposed engine scheme an alternative to APU

As named before, the air goes through a Brayton-Joule cycle and the coolant is going to go via an Organic Rankine Cycle (ORC).

4.2. Organic Rankine Cycle (ORC)

Unlike the traditional steam-operated Rankine cycle, the organic Rankine cycle (ORC) uses a high molecular mass organic fluid. It allows heat recovery from low temperature sources such as industrial waste heat, geothermal heat, solar ponds, etc. The low temperature heat is given to a constant pressure fluid. The fluid is vaporized and then expanded in a vapor turbine that drives a generator, producing electricity.

In the **ideal** cycle, four processes can be identified (refer to Fig. 15 for control planes):

1. Isobaric evaporation (1 – 2): The refrigerant is vaporized at constant pressure inside the boiler receiving heat. This heat can be delivered by burning combustible or by heat recovery from other sources.

2. Isentropic expansion (2 – 3): The gases pass through the turbine which converts the thermal energy into mechanical and after into electric energy.

3. Isobaric condensation (3 – 4): The refrigerant is condensed until in saturated liquid state.

4. Isentropic compression (4 – 1): The pressure of the refigerant is raised until it reaches the value of turbine operation.

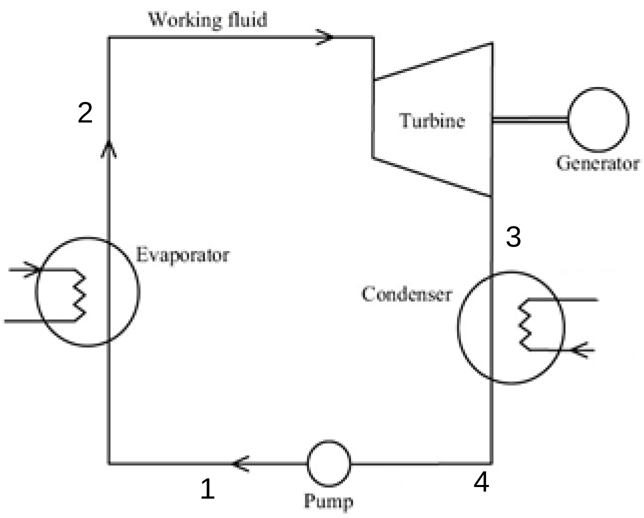


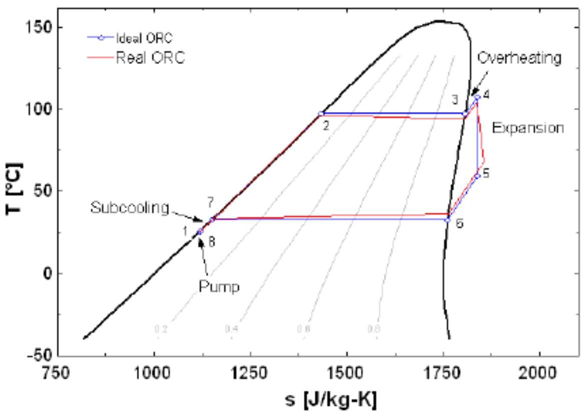
Fig.15: An Organic Rankine Cycle

In the **real** cycle, the presence of irreversibilities lowers the cycle efficiency. These irreversibilities mainly occur:

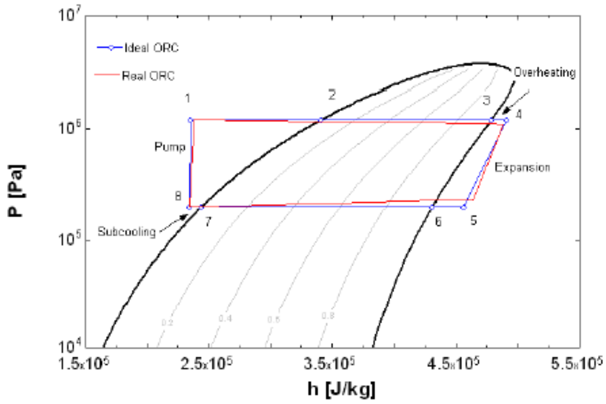
- During the expansion: Only a part of the energy recoverable from the pressure difference is transformed into useful work. The other part is converted into heat and is lost. The efficiency of the expander is defined by comparison with an isentropic expansion.

- In the heat exchangers (evaporation and condensation): The tortuous path taken by the working fluid in order to ensure a good heat exchange causes pressure drops, and lowers the amount of power recovered from the source.

- Inside the pump: Electromechanical losses and internal leakage lead to irreversibilities that transform a part of the useful work into heat.



a)



b)

Fig. 16: ORC a) T-s diagram and b) P-h diagram

5. REFRIGERANTS

5.1. Definition

"A substance, such as air, ammonia, water, or carbon dioxide, used to provide cooling either as the working substance of a refrigerator or by direct absorption of heat" (American Heritage Dictionary, 2013).

Refrigerants are the vital fluids in any refrigeration system. Any substance that changes from liquid to vapor and vice versa, can function as coolant, depending on the pressure range, temperatures and the working cycle (Joule-Brayton, Rankine, etc.) to make these changes.

There are a very large number of refrigerants that evaporate, but only a few are currently used. For example, since 1995 CFCs (chlorofluorocarbons) should have been replaced by others because they were one of the causes of the reduction of the Earth's atmospheric ozone layer. Most common CFC refrigerants are: R-11, R-22 or R-12 replaced by R-123, R-407C and R-134a respectively.

5.2. Identification of refrigerants

The refrigerants are identified by numbers after letter R, which means "refrigerant". The identification system has been standardized by ASHRAE (America Society of Heating, Refrigerating and Air Conditioning Engineers). In order to understand the abbreviations, it is necessary to be acquainted with the numbers and the names of refrigerants.

There are three types of refrigerants depending on their nature:

- Pure compounds - substances formed by a single type of molecules or component.

- Zeotropic blend - mixture of which the compositions of the vapor and the liquid phase at the vapor-liquid equilibrium state are never the same. These mixtures are obtained by mixing refrigerants.

- Azeotropic blend - mixture of which the compositions of the vapor and the liquid phase at the vapor-liquid equilibrium state are the same. These mixtures are obtained by mixing refrigerants.

The table 9 shows some examples of common refrigerants:

Tab.9. Commonly used coolants

Number	Chemical Number	Chemical formula	Type
50	Methane	CH_4	Pure compounds
123	2,2-dichloro - 1,1,1-Trifluoroethane	$CHCl_2CF_3$	Pure compounds
134a	1,1,1,2-Tetrafluoroethane	CH_2FCF_3	Pure compounds
717	Ammonia	NH_3	Pure compounds
718	Water	H_2O	Pure compounds
365mfc	R-365/227 (87/13)*	--	Pure compounds
407C	R-32/125/143a (23/25/52)*	--	Zeotropic blend
409A	R-22/124/142b (60/25/15)*	--	Zeotropic blend
507	R-125/143a (50/50)*	--	Azeotropic blend

* The numbers in brackets indicate the percentage of each component.

The meaning of the numbers is as follows:

- Adding 90 to the number gives three digits which stands for the number of carbon, hydrogen and fluorine atoms, respectively. For example, R-134a has 2 carbon atoms, 2 hydrogen atoms, and 4 fluorine atoms, an empirical formula of tetrafluoroethane.

- Remaining bonds not accounted for are occupied by chlorine atoms.

- A suffix of a lowercase letters a, b, or c indicates increasingly unsymmetrical isomers. In the case of R-134a, the suffix indicates that the isomer is unbalanced by one atom, giving 1,1,1,2-Tetrafluoroethane.

- As a special case, the R-400 series is made up of zeotropic blends and the R-500 series is made up of so-called azeotropic blends. The rightmost digit is assigned arbitrarily by ASHRAE.

5.3. Classification of refrigerants

Nowadays, refrigerants must be rated in terms of toxicity and flammability together. They are handled by many people, from manufacturer to distributor to consumer and must not represent any danger. Most synthetic refrigerants are not toxic, and the risk of dying inhaling them if there is some leak is very slight or nonexistent. However, there are some that are really harmful for people, even in small concentrations and with short time of exposure like R-717 or R-123. In high concentrations in the air, every refrigerant can cause suffocation, because it displaces the air and creates oxygen deficiencies. The same happens with flammability; the refrigerants vary extremely in their ability to burn or support combustion.

The current classification of refrigerants includes the two foregoing characteristics: the flammability and toxicity. Table 10 below shows this classification:

Tab.10. Classification of refrigerants based on flammability and toxicity (ASHRAE)

	Security group	
More flammability	A3	B3
Less flammability	A2	B2
No flame propagation	A1	B1
	Less toxicity	More toxicity

5.4. Thermodynamic Properties

To use a liquid as a refrigerant, the thermodynamic properties are very important to reach the objectives of this project.

The main reason for using the refrigerants is because they have a range used for reaching low temperatures by undergoing phase change between liquid and gas. In addition, the use of refrigerants fits rightly with the objective of trying to recover energy from the exhaust gases. The reason is that they do not need very high temperatures to reach the gas state.

Moreover, the difference of temperatures in the cycle is not very big; which means that the heat required to achieve the working temperature is lower. Further on, specific values of these properties will be given.

5.5. Other properties

The following properties are important in the choice of refrigerant and depend on the designed system:

- Should have no effect on other materials: The main materials that are used in refrigeration systems are: metals, elastomers and plastics. The use of the first group requires a focus on the corrosive effect that can be caused by the refrigerant. The second group can present expansion or contraction caused by the contact between the refrigerant and the elastomer. The plastics, in general, do not present any kind of inconvenience, but some refrigerants (R-11, R-12 or R-22) dissolve this material.

- Easy to spot when leaks: All refrigerants have a tendency to leak, and when this happens, the refrigerant selected should be easily detectable. At present, this is no longer a deficiency in any refrigerant, because several methods have been developed to detect any leakage of refrigerant. There are many factors that determine the trend of refrigerants to escape. Pressure, viscosity and density, are some of them. When these features are the same for different refrigerants, depends of the size of the crack. This means that through a crack of a small size, the refrigerant of low molecular weight would leak more easily than one with a higher molecular weight. If the crack is bigger than the higher molecular weight refrigerant, this will leak first because of heavier sedimentation on the bottom.

  There are many systems for detecting leakage of the coolant. For example: These are: dyes, bubble solutions, halide torches, electronic detectors (sniffers), ultrasonic detectors and fluorescent leak detectors (www.achrnews.com/articles/115576-refrigerant-leak-detection).

- Should be miscible with the oil: The miscibility of the oil and the refrigerant plays a very important role in the design of refrigeration systems. The miscibility of the oil with the refrigerant can be defined as the ability of these to be mixed. Although the function of the oil is to lubricate the moving parts of the compressor, can not be avoided that some oil leaks into the system with the refrigerant, even having an oil separator.

- Do not react with humidity: All refrigerants in varying amounts absorb humidity. In a cooling system, this amount should be kept below the maximum permissible limit, in order to operate successfully. Therefore, it is imperative to remove humidity from the system components during manufacture, and precautions are taken to avoid water vapor in the system during the installation procedure or service. Refrigerants and oils are supplied by the manufacturers, with very low humidity limits. One should make a great effort to keep humidity out of the cooling systems, for two main reasons:

    1. Excess moisture, such as "free water", can be frozen at low temperatures and restrict or stop the flow of refrigerant through the expansion valve or capillary tube.

    2. Excess water can react with refrigerant to form corrosive acid, which cause clogging, corrosion burns from the compressor, and in general, impairment of the cooling system.

- It must be a stable compound: In normal systems that are reasonably clean, dry refrigerant stability is not a problem. The majority of refrigerants have adequate stability for applications where they are used. This means that the temperatures and pressures which the coolant is going to work with do not affect its composition.

6. FINAL DESIGN

6.1. Elements description of waste heat recuperation system

The design of the heat recovery system has been based on studies of L. Jedrzejewski and P. Lampart from the University of Gdansk. The calculations will be presented in the next section. Figure 17 ORC is the base of this project and the scheme of the final design is:

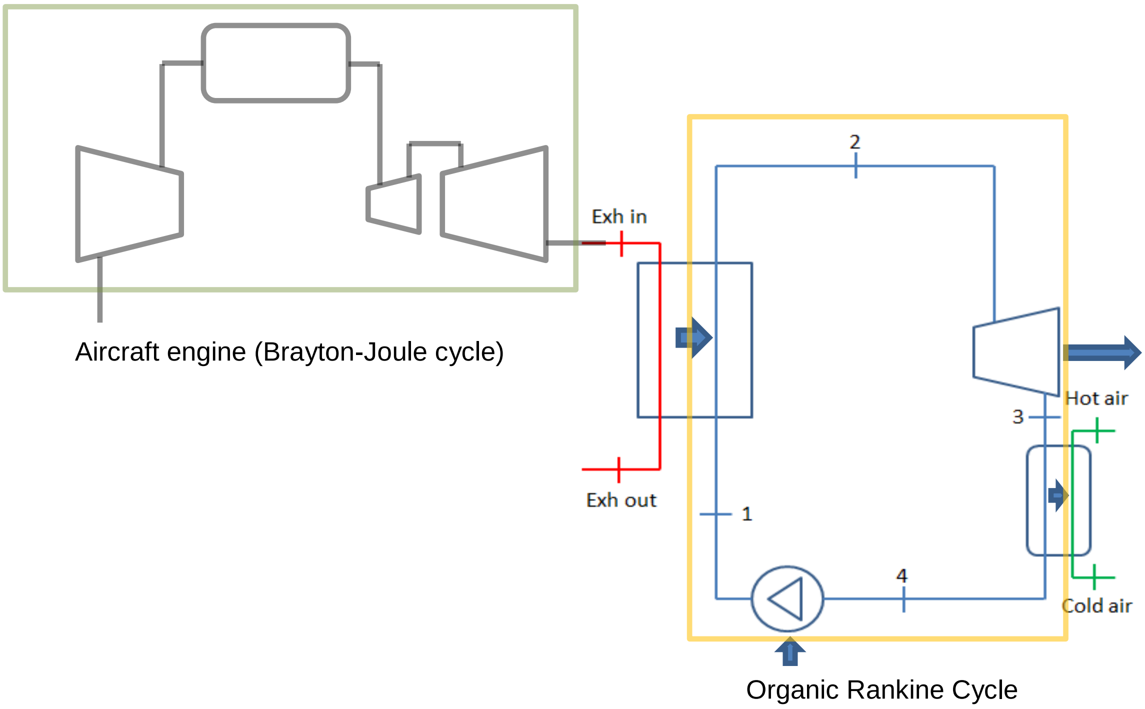


Fig. 17: Aircraft engine connected with the ORC heat recuperation system

As the fig. 17 presents, the exhaust gases from the aircraft engine, either a turbofan or turboshaft, are directed to go through a counter-current heat exchanger. In the other way a coolant is flowing to receive the heat energy from the exhaust gases. After being heated, the coolant changes its state and circulates through the ORC which has been described in section 3.2.

The elements of the fig. 17 are detailed below:

6.1.1. Turboshaft

A turboshaft engine the **GTD-350** from Polish helicopter WSK Mi-2R has been selected for calculations of exhaust gasses temperature level. This engine is composed of a compressor with seven-stage axial flow plus a single-stage centrifugal stage, a reverse flow combustion chamber and a single-stage compressor turbine plus two-stage power turbine. The main specifications of this engine are:

- Nominal Power: 300 kW at 40500 rpm
- Overall pressure ratio: 8:1
- Temperature downstream turbine (exhaust gas): 873 K
- Mass flow rate: 2,4 kg/s
- Pressure after turbine: 0,1 MPa

The mass flow and the temperature downstream from the free turbine are the values that are going to be important for the calculations of the ORC.

Figures 18 and 19 below present GTD-350:

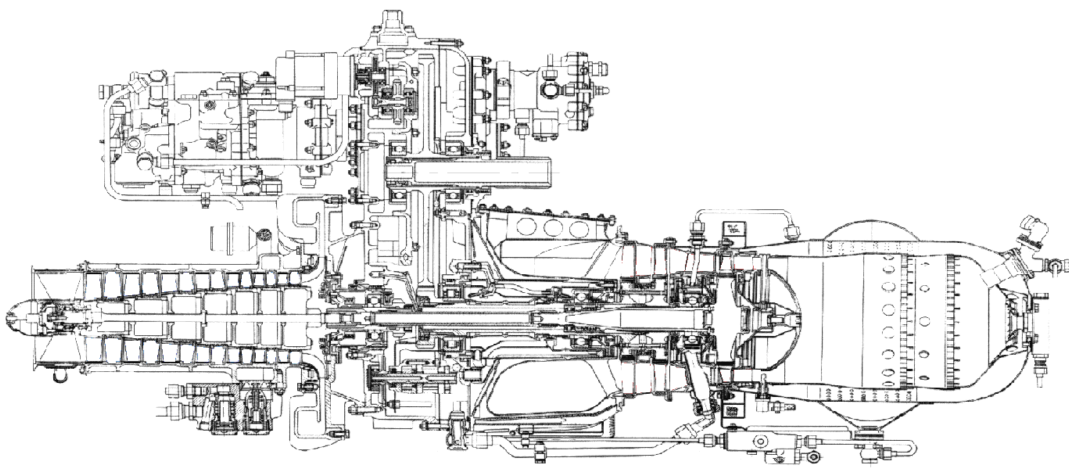


Fig. 18: Inside of a GTD-350

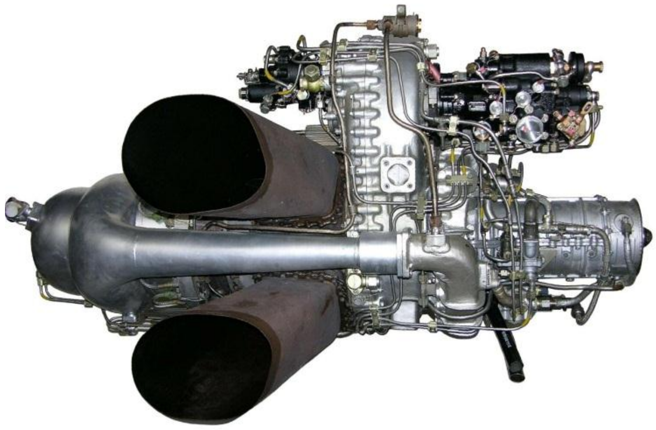


Fig. 19: A GTD 350

The GTD-350 uses a 10% of its maximum power (300 kW approximately) for auxiliary units (electric, pneumatic or hydraulic power).

6.1.2. Turbine in the ORC

The turbine is the ORC element that converts the heat energy from exhaust gases into mechanical energy. The turbine used in this design is a Tesla turbine. Opposite to classical bladed turbines where viscous effects in the flow are undesirable as a source of efficiency loss, these effects enable the rotation of the disc - a Tesla-turbine rotor. The rotor consists of up to a few dozens of thin disks locked on a shaft perpendicular to its axis of revolution. The supply of a Tesla turbine is accomplished by one or several nozzles discretely located along the circumference. The nozzles are tilted under a certain angle to the disk tangent. Working fluid flows between the disks spirally from the outer to inner radius and transfers energy to the rotating disks. The medium flows out in the axial direction through a number of holes in the disks situated near the turbine shaft. The efficiency of the Tesla turbine will be assumed as **0,3** to resemble as much as possible that used in studies of Gdansk University, *"Tesla friction type micro turbine for small-scale cogeneration"* by L. Jedrzejewski and P. Lampart. Figure 18 below shows an example Tesla turbine:

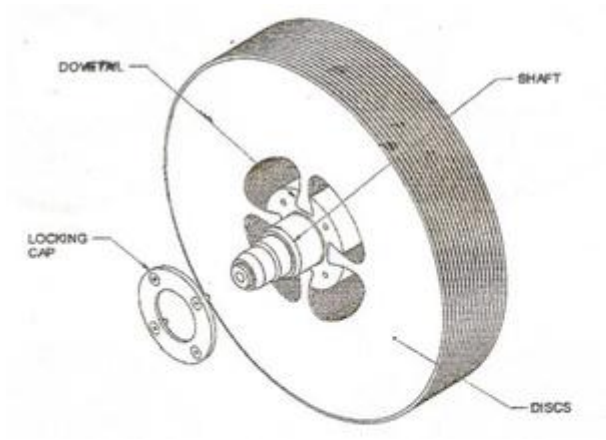


Fig. 20: A scheme of a Tesla turbine (Hicks Kenneth USA)

6.1.3. Evaporator

This element is very important to make the exchange of heat from exhaust gases to the coolant to ensure that the refrigerant first evaporates and subsequently overheats. Is very important to talk about the efficiency of this exchanger because is the way to obtain heat energy. In the computations it has been considered that there are no pressure drops in the coolant way and is shown how to calculate the efficiency of the evaporator. The reference heat exchanger used in this project is AlfaNova 52, from Alfa Laval Company. The reasons are: can be used as evaporator and as a condenser, has a compact design and can operate with the exhaust gases temperatures. The problem is that is necessary to adapt the size to our mass flow, because this model is too small.

6.1.4. Condenser

The operation of this element is very similar to the evaporator. The coolant flows through the condenser, where it gives away enough heat to go out in saturated liquid state. The condenser's efficiency has been assumed as 0,6, like the evaporator. The coolant inside the condenser is cooled by air from the atmosphere. The air circulation occurs in countercurrent manner. The temperature of air depends exclusively on the helicopter's flight altitude. The equation and values will be presented in the next section.

6.1.5. Pump

A pump is a device that moves fluids by mechanical action. Pumps are typically reciprocating or rotary type, and consume energy to perform mechanical work by moving the fluid. Pumps operate via many energy sources, including manual operation, electricity, an engine of some type, or wind power. The most common type of pumps used to move liquids through a pipe system are the centrifugal ones. This type of pumps is used to increase the pressure of the refrigerant. Figure 19 shows an example of a centrifugal pump:

Fig. 21: Centrifugal pump

6.2. Refrigerant's selection

As mentioned before, this project is based on the study of L. Jedrzejewski and P. Lampart from the University of Gdansk. The refrigerant used for the studies is called SOLKATHERM®SES36.

SOLKATHERM®SES36 is a fluid azeotropic mixture of the hydrofluorocarbon $CF_3CH_2CF_2CH_3$ (Solkane®365mfc-95%) and a perfluorinated polyether (PFPE-5%). Its intended use is in high-temperature applications, such as ORC systems and high-temperature heat pumps, but also cooling systems for machines and electronics, e.g. as indirect or immersion cooling systems.

SOLKATHERM®SES36 is compatible with most metals commonly used in refrigeration engineering. However, at high temperatures and/or pressures, reactions may occur with reactive metals such as zinc, aluminum and magnesium. Recommended sealants are neoprene and EPDM for the area of elastomers and PVC, PP and PS for the area of thermoplastics.

SOLKATHERM®SES36 main characteristics:

- It is a non-flammable liquid, but its vapors form flammable mixtures with air in the range 3,9% (Lower Flammability Limit) – 11,7% (Upper Flammability Limit). The Minimum Ignition Energy (MIE) of SOLKATHERM® SES36 is very high: 130mJ. For comparison, other reference materials have: methane 0,4mJ; R152a 0,35mJ; n-pentane 0,22mJ. Only strong electric discharges and naked flames have the energy to ignite SOLKATHERM®SES36 vapors.

- The flame does not propagate to the liquid phase. It is not listed as toxic substance. The ASHRAE classify this coolant as A1 - Non flame propagation and less toxic.

- It has a characteristic odor of 'solvent'. It can be detected by smell before it reaches large concentrations in air. Its vapors are heavier than air and have the tendency to disperse at ground level.

- It is colorless, it looks like water. It boils fast and at a relatively low temperature subtracting heat from the environment. In this, its behavior is similar to many other well-known solvents like alcohols or ethers.

- It is chemically stable. It is compatible with most construction materials.

- It is thermally very stable. Its first decomposition reactions occur in laboratory at 220°C. It has been proved in continuous operation conditions up to 190°C.

- Auto-ignition is at 580°C.

6.3. Estimated Weight of the installation

The weight of the system is a very important point to consider because if the system is very heavy the engine can consume more, making installation unprofitable. Taking the references named before, the fuel consumption can be estimated.

Components:

- Evaporator/Compressor: the model AlphaNova 52 weights 1,9+0,22*n kg (n is the number of plates). The weight supposed is 8 kg for each heat exchanger considering that each heat exchanger has as minimum 10 plates and adding a more weight because with AlphaNova 52 the mass flow which can pass through is less than necessary.
- Tesla turbine: the energy produced is less than 2 kW. The weight of the turbine is approximately 6 kg.
- Centrifugal pump: in order to the mass flow amount of refrigerant circulating in the cycle, the pump must be very large, more or less than about 3 kg (www.pakuya.com).

Finally, the weight of the installation is approximately 25 kg.

6.4. Environmental aspects

As to the environmental aspects, the main concerns include the ozone depletion potential (ODP), global warming potential (GWP) and the atmospheric lifetime (ALT). The ODP and GWP represent substance's potential to contribute to ozone degradation and globe warming. Due to environmental concerns, some working fluids have been replaced, such as R-11, R-12, R-113, R-114, and R-115, while some others are being replaced in 2020 or 2030 (such as R-21, R-22, R-123, R-124, R-141b and R-142b).

Alternative fluids are being found and applied, like SOLKATHERM®SES36. The alternatives are expected to retain the attractive properties and avoid their adverse environmental impact.

7. CALCULATIONS AND ANALYSIS

The calculations of this project have been done mainly with two programs: the Microsoft Excel and REFPROP, a certified application prepared by National Institute of Standards and Technology (NIST), a United States governmental body.

REFPROP is database software used in science research. REFPROP allows calculations of the properties of practically any fluids at different temperatures and pressures. These properties include thermodynamic properties such as density, enthalpy, entropy, etc., as well properties such as viscosity and conductivity. REFPROP has been used to calculate each state of the ORC refrigerants.

REFPROP does not have the SOLKATHERM®SES36 as one of the predefined mixtures because it is protected by patent, but as mentioned above, this refrigerant has a 95% composition of R-365mfc. Finally, the chosen refrigerant for calculations in REFPROP is R-365mfc.

7.1. Calculations

7.1.1. Organic Rankine Cycle calculations

The ORC analyzed is:

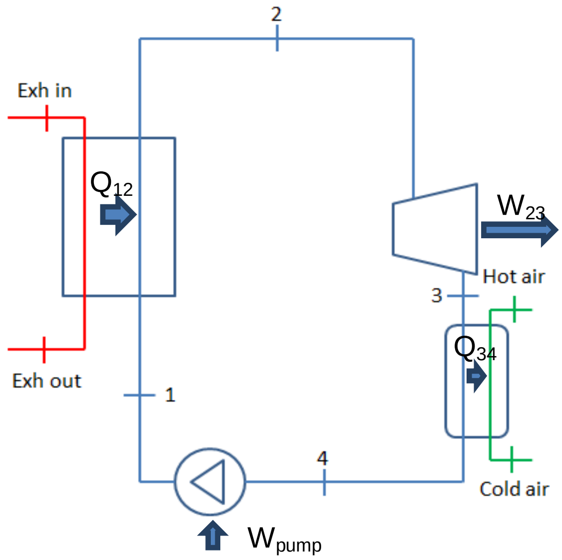


Fig. 22: Organic Rankine Cycle

The first step to make is to define states and values from the studies of the IMP Gdansk Turbine which this project is based on:

- Refrigerant mass flow $\dot{m}$ = 0,132 kg/s.
- Tesla turbine isentropic efficiency η_{turb} = 0,3.
- Max. pressure P_1=P_2=1,48 MPa.
- Min. pressure P_3=P_4=0,19 MPa.
- Inlet turbine temperature T_2= 416 K*****

*****This temperature value has been modified from the original one of the IMP Gdansk Turbine study (instead of 410 K) because at the pressure of 1,48 MPa the saturation temperature is 416 K. The Gdansk study has been performed in Fluent assuming perfect liquid conditions. At the very beginning the gas state is assumed in the saturation point.

With these values it is possible to start calculating all the states, the turbine power and delivered or received heat in the ORC to evaporate or condense the working fluid.

Thermodynamic properties in state 2 are:

Tab. 11: Thermodynamic properties of state 2

Temperature (K)	Pressure (MPa)	Liquid Density (kg/m³)	Vapor Density (kg/m³)	Liquid Enthalpy (kJ/kg)	Vapor Enthalpy (kJ/kg)	Liquid Entropy (kJ/kg-K)	Vapor Entropy (kJ/kg-K)	Liquid Cp (kJ/kg-K)	Vapor Cp (kJ/kg-K)
416,10	1,4800	930,22	90,809	414,96	533,55	1,6233	1,9083	1,8078	1,6198

The state 3 has to be calculated with the Tesla turbine isentropic efficiency. Assuming that s_2=s_{3s} and P_3=P_{3s}. The state 3s, considering the state change from 2 to 3s is isentropic, is completely defined and the values are:

Tab. 12: Thermodynamic properties of state 3s

Temperature (K)	Pressure (MPa)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/kg-K)	Cp (kJ/kg-K)
363,10	0,19000	9,8023	495,18	1,9083	1,1378

Having the coordinates of the point 3s and having the same pressure in state 3s than in 3, the state 3 will be defined with the equation below:

$$\eta_{turb} = \frac{h3-h2}{h3s-h2} \quad \text{(eq. 1)} \longrightarrow \quad h_3 = 522{,}039\ kJ/kg$$

Tab. 13: Thermodynamic properties of state 3

Temperature (K)	Pressure (MPa)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/kg-K)	Cp (kJ/kg-K)
386,40	0,19000	9,1112	522,04	1,9800	1,1682

At this point the thermal energy of the gases is transformed into mechanical energy. The amount can be calculated with the equation below:

$$\dot{W}_{turbine} = \dot{m} * (h_2 - h_3) \quad \text{(eq. 2)} \longrightarrow \quad \mathbf{\dot{W}_{turbine} = 1{,}519\ kW}$$

The value of 1,519 kW is the energy which can be delivered from 0,132 kg/s of working fluid. This power can be used for some systems in the airplane as for conditioning the cabin, electric devices, etc.

The next state (4) is after the condenser. It should be said that it is assumed that the condenser works (theoretically) at the pressure of P_3=P_4=0,19 MPa. This condenser works inside the countercurrent heat exchanger, where cold air is used until all the refrigerant is in saturation liquid state. Because of this, knowing refrigerant's pressure and the saturated liquid state the state 4 is defined with the coordinates of the table 14:

Tab. 14: Thermodynamic properties of state 4

Temperature (K)	Pressure (MPa)	Liquid Density (kg/m³)	Vapor Density (kg/m³)	Liquid Enthalpy (kJ/kg)	Vapor Enthalpy (kJ/kg)	Liquid Entropy (kJ/kg-K)	Vapor Entropy (kJ/kg-K)	Liquid Cp (kJ/kg-K)	Vapor Cp (kJ/kg-K)
332,07	0,19000	1181,2	10,973	281,79	460,48	1,2703	1,8084	1,4502	1,0994

The useful values of this table are the ones of the saturated liquid state. The heat power delivered to the cold air is:

$\dot{Q}_{34} = \dot{m} * (h_4 - h_3)$ (eq. 3) ⟶ $\mathbf{\dot{Q}_{34} = -31,713\ kW}$

This heat is negative so is taken away from the cycle.

The next step to follow is that the coolant has to go through the pump. For calculating state 1, it is necessary to know that the pump elevates the refrigerant pressure until it reaches the value of $P_2 = P_1$ = 1,48 MPa. This process is done by the pump with an isentropic efficiency of 0,7, (Kryllowicz W. 2013, professor at Institute of Turbomachinery, private conversation) . For calculating the next state it is necessary to apply the efficiency equation, but first it is necessary to know the ideal state 1s. It is assumed that the pressure $P_{1s} = P_1$ and $s_{1s} = s_4$ because of an isentropic change of state. The state 1s is defined as:

Tab. 15: Thermodynamic properties of state 1s

Temperature (K)	Pressure (MPa)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/kg-K)	Cp (kJ/kg-K)
332,49	1,4800	1184,9	282,78	1,2700	1,4457

With the ideal state 1s and applying the isentropic equation, all of the cycle is defined because the state 1 is the last to calculate:

$\eta_{pump} = \frac{h1s - h4}{h1 - h4}$ (eq. 4) ⟶ $h_1 = 283{,}20\ kJ$

Finally, with the state 1 defined, the whole cycle is defined:

Tab. 16: Thermodynamic properties of state 1

Temperature (K)	Pressure (MPa)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/kg-K)	Cp (kJ/kg-K)
332,78	1,4800	1184,2	283,20	1,2713	1,4463

The power that the pump needs to work is calculated as:

$\dot{W}_{pump} = \dot{m} * (h1 - h4)$ (eq. 5) $\longrightarrow$ $\dot{W}_{pump} = 0,1867\ kW$

This value is a 12,3% of the power delivered by the turbine, consequently, it must be considered for calculating the global efficiency of the ORC.

Having the state 1, it is time to calculate how much energy the refrigerant needs to be overheated until state 2:

$\dot{Q}_{12} = \dot{m} * (h2 - h1)$ (eq. 6) $\longrightarrow$ $\mathbf{\dot{Q}_{12} = 33,045\ kW}$

This heat energy has to be taken from the exhaust gases from the GTD-350 engine. With the heat value the efficiency of the ORC can be calculated as:

$\eta_{ORC} = \frac{\dot{W}_{23} - \dot{W}_{pump}}{Q_{12}} \cdot 100$ (eq. 7) $\longrightarrow$ $\boldsymbol{\eta_{ORC} = 4,03}\%$

The efficiency of the ORC means how much energy this cycle is taking from the exhaust gas thermal energy.

As a conclusion of the Organic Rankine Cycle:

$$\dot{W}_{turbine} = 1,519\ kW$$

$$\dot{Q}_{12} = 33,045\ kW$$

$$\dot{Q}_{34} = -31,713\ kW$$

$$\eta_{ORC} = 4,03\%$$

$$\dot{W}_{pump} = 0,1867\ kW$$

To confirm these results, SOLKANE® has own application that allows simulating an ORC with few inputs and calculates all the output parameters:

The input values are:

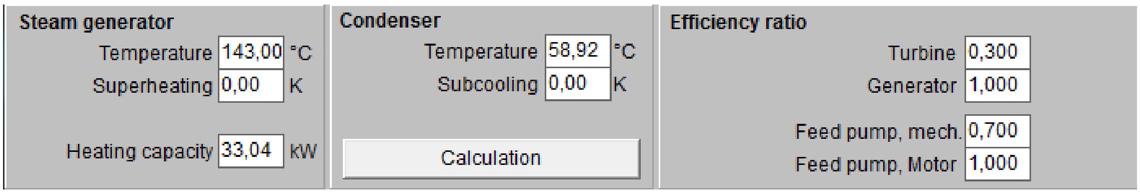


Fig. 23: Input values in SOLKANE® program

These values have to be calculated before as has been done. The temperature of the steam generator means the dew point at this pressure. The heating capacity is referred to the heat energy that the refrigerant receives through the evaporator. The condenser temperature has the same meaning that the steam generator one. Finally, the other inputs are elemental efficiencies of the cycle.

Once the data inputs have been filled, the program does the calculations of the coordinates and other parameters such as mass flow, cycle efficiency, the power delivered by the turbine, etc. The following figures show the results:

	p	t	v	h	s	x
Point	bar	°C	dm³/kg	kJ/kg	kJ/kgK	--
1	1,90	58,92	0,85	281,81	1,2708	0,00
2	14,81	60,00	0,85	283,37	1,2755	0,00
2´	14,81	143,00	1,08	414,88	1,6237	0,00
2´3´´m	14,81	143,00	6,04	475,31	1,7689	0,50
3´´	14,81	143,00	11,01	535,73	1,9141	1,00
3	14,81	143,00	11,01	535,73	1,9141	1,00
4s	1,90	93,01	102,97	497,05	1,9141	1,00
4	1,90	115,40	110,39	524,12	1,9858	1,00
4´´	1,90	58,92	91,09	458,21	1,8028	1,00
4 1´m	1,90	58,92	45,97	370,01	1,5368	0,50
1´	1,90	58,92	0,85	281,81	1,2708	0,00

Fig. 24: Thermodynamic states of R365mfc

Power	Simple Organic Rankine Cycle (ORC)		
Steam generator	33,04	Pressure ratio	7,80
Condenser	31,73	Pressure difference	12,91 bar
Turbine	1,52	Mass flow	130,9 g/s
Generator	1,52	Feed pump,	
Feed pump, complete	0,20	Volume flow	0,40 m³/h
		Efficiency ratio, complete	0,04

Fig. 25: Other properties from the ORC

As the fig. 25 shows, the values from SOLKANE® are similar to the results calculated above. SOLKANE® asks for temperatures of condenser and heat exchanger, efficiencies and the heating capacity of the evaporator. This means that Q_{12} has been took from REFPROP calculations. Table 17 presents values from both calculations:

Tab. 17: Values from REFPROP and SOLKANE®

	Calculations		
	Refprop and excel	SOLKANE®	Error (%)
Q_{34} (kW)	-31,713	-31,73	0,05
Q_{12} (kW)	33,045	33,045	--
$W_{turbine}$ (kW)	1,519	1,52	0,06
W_{pump} (kW)	0,1867	0,2	7,12
Efficiency	0,0403	0,04	0,74
Mass flow (kg/s)	0,132	0,1309	0,83

As the Tab. 17 presents, the error between both calculations is negligible except for the pump power, but a 7,12% does not represent too much of this power.

With all this information the plots of the cycle can be calculated. The plots are done by SOLKANE®.

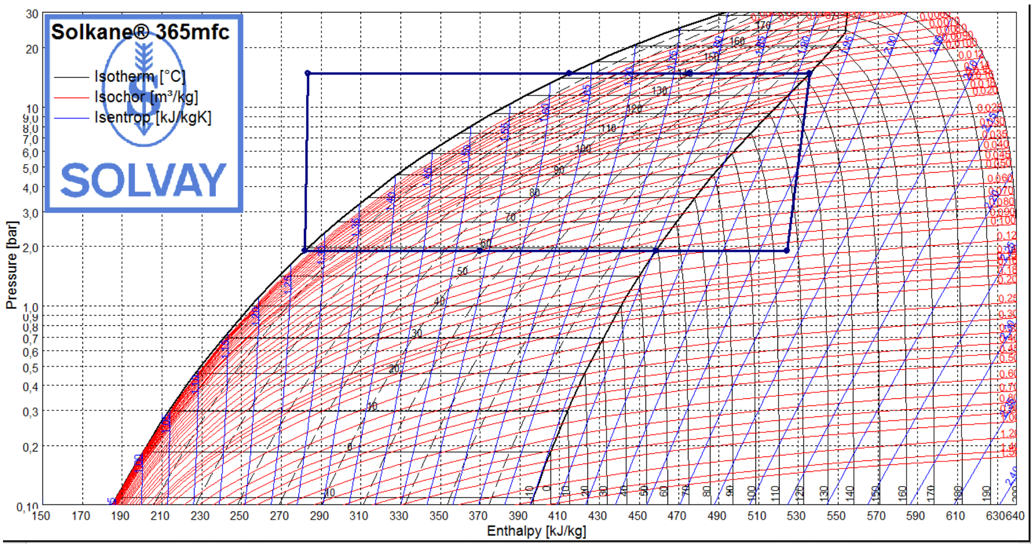


Fig. 26: p-h diagram

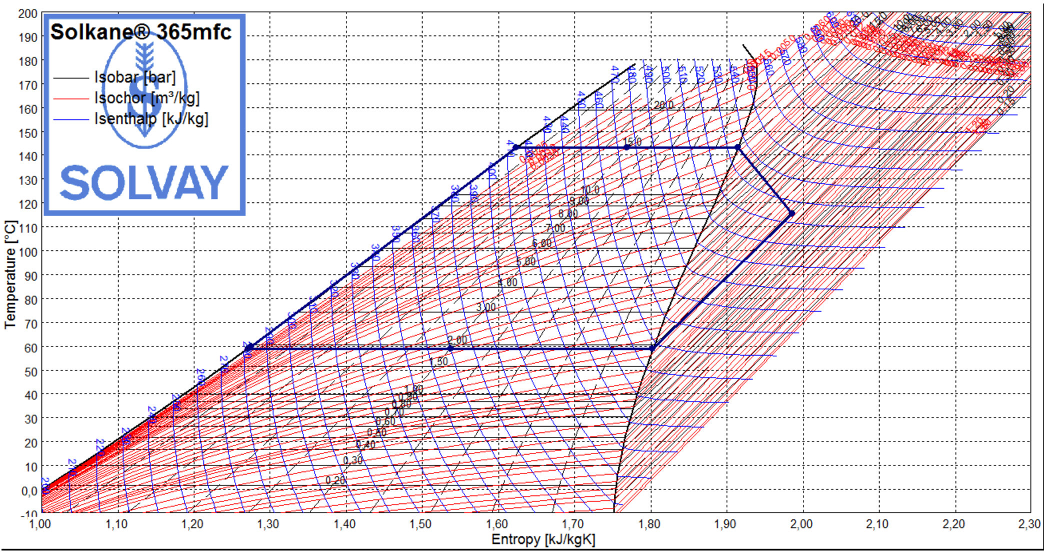


Fig. 27: T-s diagram

7.2. Analysis and validation

To compare the results obtained from the calculation based on own model, do not differ much from those simulated from “Investigations of aerodynamics of Tesla bladeless microturbines”, Piotr Lampart & Łukasz Jędrzejewski, Tab. 17 has been done which compares the results. If the difference is small, it can be determined that the simulation is valid.

Tab.18: Comparison between theoretical and simulated project

	Project		
	Moreno Gallart	Lampart et al.	
Tin (K)	416,1	410	
Pin (Mpa)	1,48	1,48	
Pout (Mpa)	0,19	0,19	
Mass flow (kg/s)	0,132	0,132	Error
Power (kW)	1,519	1,177	22,5%

First, one should note that the inlet temperature (T_{in}=416,1 K) of the turbine does not match the one of the simulated study (T_{in}=410 K). The T_{in}=416,1K has been chosen because it is the saturation temperature at P_{in}=1,48 MPa. This will increase the power delivered by the turbine, because the gas enthalpy state is greater than in wet steam. The reason of this change is because turbine does not work at high efficiency with liquid at the entrance.

The second parameter to talk about is the power delivered by the Tesla turbine. The differences between the calculation in the simulation and the own model are quite large. For calculating the power by the simulator, this program takes into account many variables: geometry, quantity of nozzles, losses, etc. In contrast, the theoretical project only considers the decrease of enthalpy. The 22,5% error is considerable and this is an obstacle to reach the validation objective.

Other way to compare the calculations of the theoretical and simulation projects is getting the inlet turbine temperature as T_{in}= 410 K in saturated state, with a P_{in}=1,313 MPa. Making the computations of with these values and changing other states as required, the results are:

Tab.19: Comparison between theoretical and simulated project (2)

	Project		
	Moreno Gallart	Lampart et al.	
Tin (K)	410	410	
Pin (Mpa)	1,313	1,48	
Pout (Mpa)	0,19	0,19	
Mass flow (kg/s)	0,132	0,132	Error
Power (kW)	1,428	1,177	17,58%

The results are closer to the simulated project. The global error comparing only turbine delivered powers is reduced by almost 5% with the other calculations.

Finally, there is other important factor to consider. The refrigerant chosen for comparing both projects is not SOLKATHERM®SES36, but R365mfc. It should be remembered that the SOLKATHERM®SES36 has a composition of 95% similar to R365mf. Not having the exact same thermodynamic states directly affects the calculations of any ORC element.

After the analysis and comparison between the data obtained in the theoretical calculation and the studies from “Investigations of aerodynamics of Tesla bladeless microturbines”, Piotr Lampart & Łukasz Jędrzejewski, this installation would be possible for providing electricity to one of the devices of the aircraft and trying to reduce the weight of the APU. One of the problems of this device is the low efficiency, besides adding weight to the aircraft. The installation needs improvements because, for example, pressure or heat losses are not considered.

7.3. Example calculations used in the own model

7.3.1. Exhaust gases calculations

The exhaust gases states are:

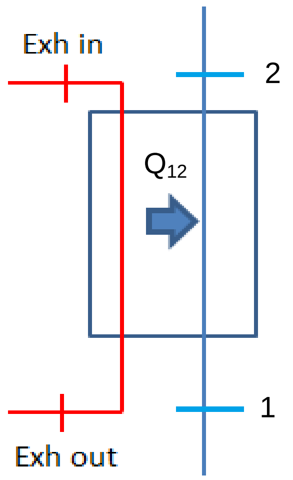


Fig. 28: Exhaust gases heat exchanger

The fig. 23 shows the scheme of the heat exchanger which involves the exhaust gases and the states 1 and 2 from the Organic Rankine Cycle. There are values known from the GTD-350 engine and Perry's Chemical Engineers' Handbook (8th edition 2008, McGraw-Hill Publishers) about the air + kerosene mixture:

- Temperature after turbine (Brayton-Joule cycle): T_{exh1} = 873 K.
- Mass flow after turbine: $\dot{m}_{exh}$ =2,4 kg/s.
- Heat exchanger efficiency: $\varepsilon = \frac{Texh1 - T2}{Texh1 - T1}$ = 0,85.
- $\lambda = \frac{AFR}{AFR_{stoich}} = 3$. The relation of 3 between AFR and AFR_{stoich} means that there is an excess air, 3 times more than the required, to ensure that the entire air-fluel mixture is burned.
- $Q_{12} = 33{,}05$ kW.

The first step to follow is to calculate the total heat which is delivered by the exhaust gases from the main cycle. Considering the heat exchanger efficiency equation:

$Q_{12} + \varepsilon \cdot Q_{exh12} = 0$ (eq. 8) $\longrightarrow$ $\mathbf{Q_{exh12} = -39{,}07\ kW}$

$Q_{exh12} = \dot{m}_{exh} \cdot Cp_{avg} \cdot (T_{exh2} - T_{exh1})$ (eq. 9)

Then, there are two unknown values, the Cp_{avg} and the Texh2. The Cp_{avg} is a given value for an average temperature values. This means that Cp_{avg} of the process is known by interpolating between two state temperatures, supposing the ΔT between T_{exh1} and T_{exh2} and after calculating the real value. Finally, with eq. 9, the T_{exh2} can be calculated. T_{exh2} = 858,94 K. The exhaust gases temperature after the evaporator is important for maintaining certain operation point.

7.3.2. Condenser system calculations

The condenser system is:

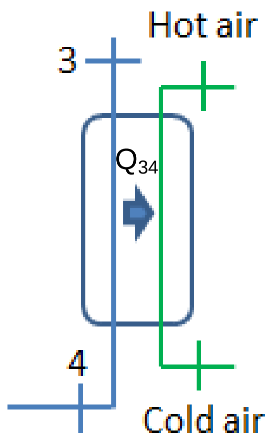


Fig. 29: Condenser system

The fig. 24 shows the scheme of the condenser which involves the states 3 and 4 and the air from the atmosphere. In this system the assumed and the known values are:

Assumed values:

- Flight altitude h = 2000 m (a helicopter flies between 1500 and 2500 m).
- Condenser efficiency: $\varepsilon' = 0{,}75$ (if the efficiency is not assumed in the condenser, one more value is needed, 0,75 is an average value for condensers in general).
- Temperature at sea level: T_{sea} = 288 K.
- Air mass flow: $\dot{m}_{air} = 1\ \mathrm{kg/s}$.

Known values:

- Air Inlet temperature: $T_{cold} = T_{sea} - \frac{6{,}5 \cdot h}{1000}$, this equation is from the International Standard Atmosphere (ISA). The air inlet temperature is T_{cold} = 275 K.
- The Cp_{air} value is calculated from tables. There is a very wide temperature range with the constant Cp_{air} and this value is Cp_{air} = 1,006 kJ/K·kg.

$Q_{con} + \varepsilon \cdot Q_{34} = 0$ (eq. 10) ⟶ $\mathbf{Q_{cond} = 23{,}78\ kW}$

$Q_{con} = \dot{m}_{air} \cdot Cp_{air} \cdot (Thot - Tcold)$ (eq. 11) ⟶ T_{hot} = 298,93 K

8. SENSITIVITY STUDY

In this study it is necessary to determine how the system changes by changing some of the more important input values. Some questions can be asked. For example, if the gas is overheated, how much will this affect the efficiency of the cycle? What if the efficiency of the heat exchanger will be increased? What about using other coolants and the influence of their thermodynamic properties on functionality of the designed ORC?

8.1. Overheating the working fluid

8.1.1. Overheating the working fluid 10 K

By earlier calculations, the power delivered by the Tesla turbine is 1,588 kW. The previous value of power was 1,519 kW, this means that increasing the inlet temperature 10 K the power has increased a 4,54%.

In this case, the heat exchanger has to transfer more heat energy. The energy in the first model was Q_{12} = 33,045 kW and with these values Q_{12}' = 34,88 kW (the heat received has increased by 5,55%). Looking at the heat exchanger efficiency, the efficiency has been reduced from 0,85 to 0,83. As the efficiency is calculated with ε equation, the value of the numerator is smaller than in the first calculations. Moreover, the T_{exh2} decreases more to give more heat energy to the refrigerant. This is logical because the efficiency has been calculated with the ε equation.

Other element affected by the temperature change is the condenser; the condenser needs to deliver more heat due to the fact that the Tesla turbine outlet gases have a higher temperature. The increase of the condenser heat is 5,56%. This rises the condenser efficiency from 0,776 to 0,787, which can be considered as an average efficiency for condensers.

8.1.2. Overheating the working fluid 20 K

With these values, the power delivered by Tesla turbine is 1,663 kW. Comparing with the first calculations the power increases 9,47%.

The heat exchanger, as happened in the section above, transfers more heat energy. The amount of energy transferred is Q_{12}'' = 37,02 kW, increasing a 12,03%. The efficiency of the evaporator is reduced from 0,85 to 0,81. The explanation is the same than in 8.1.1. point.

Finally, the heat delivered by the coolant inside the condenser increases 12,08%. In consequence, the efficiency of this exchanger rises from 0,776 to 0,798.

8.1.3. Comparison between three calculations

Tab. 20: Comparison between non-overheated and overheated

	Overheating		
	0 K	10 K	20 K
Q_{34} (kW)	-31,71	-33,67	-35,54
Q_{12} (kW)	33,05	35,08	37,02
$W_{turbine}$ (kW)	1,52	1,60	1,66
Efficiency	0,04	0,04	0,04

The relation between the temperature and the turbine power is represented in the fig. 25 presented below:

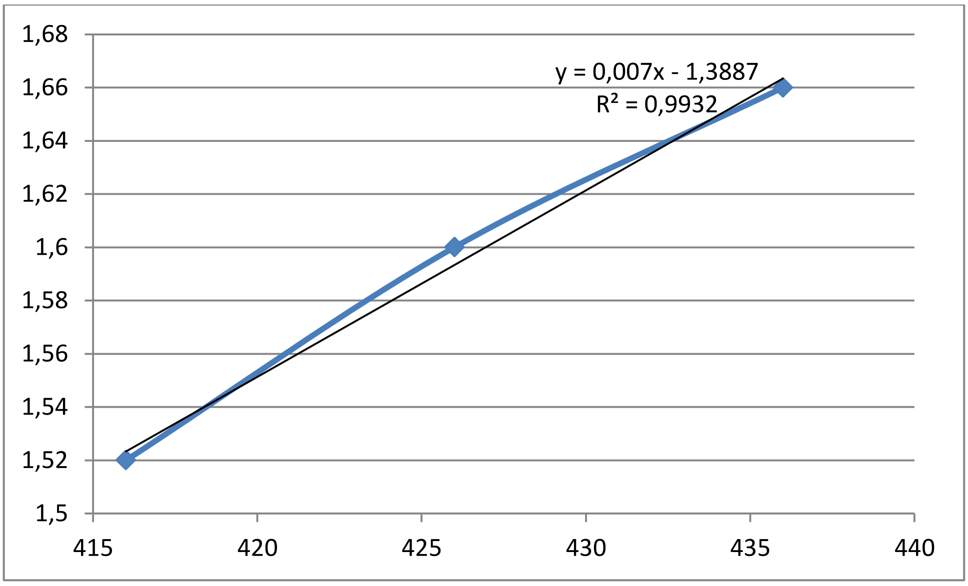


Fig. 30: Linear regression of Temperature vs turbine power

The relation between the temperature and the turbine power can follows a linear regression with quite good accuracy.

8.2. Other refrigerants used in ORC

The refrigerants used for this sensitivity study are: R365mfc (closest to the SOLKATHERM coolant), R236fa and R245fa. For this study, the inlet turbine temperature has been considerate T= 425 K. In this way, phase change from vapor to liquid inside the turbine is avoided because the higher saturation temperature for the pressure of 1,48 MPa corresponds to R365mfc (416,1 K). Calculating the ORC cycle with two new refrigerants, Tab. 18 shows comparison between the three coolants:

Tab. 21: Values of the three refrigerants

	R365mfc	R236fa	R245fa
Tubine power	1,59	1,64	1,83
Q_{12}	34,88	35,36	38,62
Q_{34}	-33,48	-33,90	-36,97
Global efficiency (%)	4,01	4,15	4,27
Heat exchanger efficiency	0,83	0,77	0,79

One important factor in these coolants is the saturation temperature at the pressure of 1,48 MPa. For the R236fa this value is 360,36 K and for the R245fa is 380 K. When these refrigerants enter inside the turbine are highly overheated, that means that the turbine delivers more power when both new refrigerants are used than the R365mfc. The global efficiency is higher and the same happens with the heats added and removed from the cycle. To choose between any of the three refrigerants, one requires a more thorough study, such as a simulation and other specifications of each product.

8.3. Mass flow

The last sensitivity study is based on changing the mass flow of the R365mfc. The results are shown in Tab. 19 below:

Tab. 22: Results changing mass flows

Mass flow	Turbine power	Q_{12}	Global efficiency
0,132	1,52	33,05	4,03
0,2	2,30	50,07	4,03
0,5	5,76	125,17	4,03

The table above presents the values of power, heat and global efficiency with different mass flow values. The first thing to note is that the global efficiency does not change for any of the three mass flows. This means that the calculations are proportional to the mass flow. In reality, this would mean a new design, not scalable with the mass flow rate. But, generally, it can be observed, that when the mass flow is increased, the installation has to be bigger, consequently more expensive and heavier, but delivers significantly more power for auxiliary devices. Other aspect to consider is that the pressure drops in the installation will rise with the amount of mass flow.

8.4. Consumption calculations

This section is going to present values of specific fuel consumption (SFC) by adding the ORC system inside the helicopter. Is necessary to now if the aircraft, with the electric power given by the turbine plus the engine power, can save fuel.

The first step is to introduce the variables involved in these calculations:

- Kerosene mass: m_{kero} = 560 kg (conventional mid-size helicopter takes)
- ORC mass: m_{ORC} = 25 kg
- Fuel consumption: $\dot{m}_{kero}$ =123 kg/h
- Engine power (GTD-350): P_{GTD} = 300 kW
- ORC power: $\dot{W}_{turbi}$ = 1,5 kW

Having these values the specific fuel consumption and flight time can be calculated as:

$m_{fuel} = \frac{\dot{m}_{kero}}{P_{GTD}}$ (eq. 12) ⟶ m_{fuel} = 0,41 kg/kWh

$t = \frac{m_{kero}}{\dot{m}_{kero}}$ (eq. 13) $\longrightarrow$ t = 4,55 h ~ 4 h and 30 min.

This result corresponds to the SFC without the system included. The equations below will show how the weight of the system and the power delivered will affect to the helicopter specific fuel consumption and the flight time:

$m'_{fuel} = \frac{\dot{m}_{kero}}{P_{GTD} + \dot{W}_{turbi}}$ (eq. 14) $\longrightarrow$ **m'_{fuel} = 0,408 kg/kWh**

$t' = \frac{m_{kero} - m_{ORC}}{\dot{m}_{kero}}$ (eq.15) $\longrightarrow$ **t' = 4,35 h ~ 4 h and 20 min.**

The specific fuel consumption has decreased, but the problem is that the flight time has been reduced either. The APU's mass could be reduced and the value of specific fuel consumption would be smaller. Even so, this technology needs to be re-worked, improved for future aircraft applications.

9. POSSIBLE DIRECTIONS OF RESEARCH

Nowadays, more than 250 power plants worldwide are working with. Some fields of application are:

- Waste heat recovery: is the most extended development field. The applications of the waste heat recovery are very large. Every industry which normally disposed of heat can use ORC to recover some of this energy.

- Biomass power plants: the main advantage to use the ORC in biomass power plants is that this cycle can produce electricity with small or medium power plants.

- Geothermal plants: the ORC is also perfectly adapted for this kind of application. However, it is important to keep in mind that for low-temperature geothermal sources (typically less than 100°C), the efficiency is very low and depends strongly on heat sink temperature.

- Solar thermal plants: the ORC allows a lower collector temperature, a better collecting efficiency (reduced ambient losses) and hence the possibility of reducing the size of the solar field than the usual steam Rankine Cycle.

  This field of study has a very promising direction. There is, for example, one ORC solar thermal of reference situated in Honolulu (Hawaii) which has this features to emphasize among other (www.turboden.eu/en/public/downloads/11-COM.P-6-rev.10%20-%20SOLAR%20ENGLISH.pdf):

  - Net solar collector surface: about 75.000 m2
  - Heat transfer fluid: mineral oil at 270ºC nominal
  - Total gross electric power: 6 MW
  - Gross electric efficiency: 20.5%

As is said, the range of research possibilities of the ORC is very wide. There is, among others, a web page called www.orcnext.be which has a very large number of publications about this field. Some examples of the research performed by investigators are:

- S. Quoilin. Sustainable energy conversion through the use of Organic Rankine Cycles for waste heat recovery and solar applications. 2011.
- N. Espinosa, I. Gil-Roman, D. Didiot, V. Lemort, B. Lombard, S. Quoilin. Transient Organic Rankine Cycle Modelling for Waste Heat Recovery on a Truck.
- S. Quoilin, M. Orosz, V. Lemort. Performance and Design optimization of a low-cost solar organic Rankine cycle for remote power generation. Solar Energy, 2011.
- M. Chys, M. van den Broek, B. Vanslambrouck, M. De Paepe. Potential of zeotropic mixtures as working fluids in organics Rankine cycles. Energy, 2012.

The researches presented above are just one example of the amount of people working on the ORC.

10. CONCLUSIONS

Following the completion of the document, can be concluded that:

The ORC is a growing technology with a great potential and the research of it is very important to reach objectives of environment, recovering energy by raising the device efficiency.

As has been checked in this thesis, the possibilities of coolants working with ORC are very broad. In this case, the objective was to try to validate the IMP Gdansk Turbine studies, confirm own model, and then design a circuit to recover some of the heat on helicopter's turboshaft engine. However, as this theoretical work have shown, it is not possible as of now, bearing in mind low efficieny and high added weight. Another objective of this thesis has been to try to replace the APU from the helicopters. Due to the results obtained has been proved that this is not possible. Nowadays, the power delivered by APUs in helicopters is around 70 kW. The power delivered by this ORC with Tesla turbine is 1,5 kW at the given mass flow rate. There is a great difference between these two values. Despite this, it could be possible to install this cycle and reduce the size of the APU. With the fuel consumption study has been proved that the system of this project reduces very slightly specific fuel consumption by reducing time of flight.

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