University POLITEHNICA of Bucharest
Faculty of Mechanical Engineering and Mechatronics
Department of Therodynamics, Thermal Engines and Refrigeration Equipment

DOCTORAL THESIS ABSTRACT

Contributions to the study of waste or renewable thermal energy recovery using organic Rankine cycles

Author: Eng. Taban Daniel

PhD supervisor: Prof. Dr. Eng. Alexandru DOBROVICESCU

DOCTORAL COMMISSION

Chairman	Prof. Dr. Eng. Mariana-Florentina ŞTEFĂNESCU	from	University Politehnica of Bucharest
PhD supervisor	Prof. Dr. Eng. Alexandru DOBROVICESCU	from	University Politehnica of Bucharest
Reviewer	Prof. Dr. Eng. Viorel POPA	from	"Dunărea de Jos" University of Galati
Reviewer	Prof. Dr. Eng. Mugur BĂLAN	from	The Technical University of Cluj-Napoca
Reviewer	Prof. Dr. Eng. Valentin APOSTOL	from	University Politehnica of Bucharest

Bucharest
2021

Content

Introduction

PhD Thesis entitled CONTRIBUTIONS TO THE STUDY OF WASTE OR RENEWABLE THERMAL ENERGY RECOVERY USING ORGANIC RANKINE CYCLES is part of the concerns of the research team of the Department of Therodynamics, Thermal Engines and Refrigeration Equipment (TMETF), Faculty of Mechanical and Mechatronics Engineering (FIMM) of the POLITEHNICA University of Bucharest (UPB). The thesis was developed at the Faculty of Mechanical and Mechatronics Engineering of UPB and contains original contributions in the field of classification and modeling of waste heat recovery (WHR) systems or renewable sources, from the desire and need to investigate new possibilities of WHR or from renewable sources via an organic fluid Rankine cycle (ORC). Due to the growing interest in the use of ORC systems for the recovery of waste or renewable energy, in this thesis new design schemes have been designed, studied through the modeling of energy and exergetic calculation iterations.

In this thesis were approached and studied two of the most common directions of recovery of waste heat or renewable energy through an ORC system, the first direction studies the potential for thermal energy recovery from internal combustion engines (MAI) through flue gases results from the combustion process, and the second direction studies the potential for recovery of renewable thermal energy generated by the sun through solar radiation. The study of thermal energy recovery from the two sources mentioned above is of great importance because it is nowadays an alternative to energy production without consuming additional natural resources. The recovery of thermal energy from the gases emitted by the MAI through an ORC system called MAI-ORC systems delivers a surplus of energy resulting from a primary process whose efficiency is below 50%. On the other hand, the recovery of thermal energy from solar radiation through an ORC solar system called S-ORC is required as an energy production solution whose main purpose is to reduce the consumption of depletable natural resources and protect the environment.

The thesis brings original contributions related to the modeling of MAI-ORC systems using as input data the flue gas parameters from a compression ignition engine (MAC) that equips the MAI-ORC experimental stand within the TMETF department, as well as the creation of a calculation program and a working interface with the help of specialized software for studying the behavior of energy and exergetic output parameters of a complex MAI-ORC system coupled with a refrigeration system with mechanical vapor compression called MAI-ORC-IFV. Exergetic analysis and exergoeconomic optimization of the MAI-ORC-IFV system explicitly developed in this thesis are also original contributions for the study of waste energy recovery systems.

Regarding the S-ORC solar system, original contributions were made by studying the optimal positioning of solar collectors and developing a calculation model to establish the optimal conditions for location and operation of the ORC module.

During the five years of doctoral school, the author actively participated in the implementation of the replacement of non-performing equipment and additional instrumentation of the experimental stand MAI-ORC within the TMETF-UPB department.

The thesis is structured in 8 chapters, a number of 214 pages written in 1 row, comprises 55 tables and 157 figures. At the end of the paper, 110 bibliographical references are presented in the order of their citation in the text.

In Chapter 1, a bibliographic research was elaborated regarding the current state of knowledge and the main sources of thermal and renewable energy were identified as well as the temperature regime at which they are found. The ways of thermal energy recovery and the principle of operation of the predominantly encountered schemes were detailed.

Chapter 2 presents the main working fluid selection characteristics for ORC cycles, analyzing compatible fluids in four main directions: physical, environmental, thermodynamic and economic properties. The working fluids were characterized according to the hot source temperature, saturation slope, environmental protection, operational safety as well as from an economic point of view.

Chapter 3 develops from a constructive and functional point of view the ORC schemes with thermal energy recovery from the flue gases resulting from the MAI. Mainly described are simple, double, mixed, regenerated, preheated, reheated, ejector schemes and complex systems.

The basic ORC scheme is analyzed from a thermodynamic point of view in Chapter 4 of the doctoral thesis, where the operation of the ORC system that recovers the flue gases from a MAI that equips an experimental stand within the FIMM-TMETF was simulated. The chapter presents the input data obtained experimentally by MAI Roman Brașov, the choice of the scheme for simulating the operation, the modeling of the ORC system, as well as the results obtained.

The experimental installation for the study of the thermal energy recovery of the flue gases of the internal combustion engine using an ORC system is presented in Chapter 5. All the steps preceding the equipment of the microgeneration group are presented, determining the energy balance, how to acquire functional parameters, establishing the functional model of ORC system, choosing working fluids, developing documentation and sizing of the functional model, experimenting with the installation and control block, making the functional prototype, the current equipment stage of the microgeneration group.

Chapter 6 deals theoretically with the potential of using solar thermal energy to produce electricity using ORC cycles. The influence of solar radiation intensity and thermal energy flux on a unit surface received by flat plate thermal collectors (FPSC) was studied and the positioning system of solar collectors was modeled. The basic scheme and modeling of the S-ORC system were presented, and finally the validation of the model and the results compared to other reference works was presented.

The analysis of the optimized MAI-ORC-IFV coupling is presented in chapter 7 of the doctoral thesis. Starting from the basic construction scheme and the working parameters determined experimentally in Chapter 5, an energy analysis was performed in the first phase based on a thermal calculation model, implemented with the help of EES (Engineering Equation Solver) software. Energy analysis quantifies only the amounts of energy entering and leaving the system, taking into account only external losses. In order to identify the destruction of usable energy inside the system, the concept of exergy was used, which identifies the true measure of the quantity and quality of a certain energy in correlation with the intensive parameters of the environment. At the end of the chapter are presented the results of the study and the possibility of optimizing the construction scheme in order to reduce the loss of exergy.

In order to find the optimal functional and constructive solutions of the MAI-ORC-IFV coupling in chapter 8 of the thesis, exergoeconomic analysis was used. This analysis involves the realization of a laborious mathematical model that takes into account absolutely all parameters, resulting in the real highlighting of the areas or component equipment in which the usable energy (exergy) is destroyed. The procedure of finding the optimal solutions based on the exergoeconomic analysis makes the junction between the Thermodynamics of irreversible processes and the Economic Analysis.

At the end of the doctoral thesis are presented the general conclusions of the paper, the original contributions of the author as well as the directions of future research. The thesis ends with the list of works published in extenso and the bibliographical references in the order of their citation in the text.

Acknowledgment

Thank God for the health and manpower received for the elaboration of this work, in which I had the privilege and enjoyed the collaboration of specialists with exceptional professional and human qualities from the Department of Therodynamics, Thermal Engines and Refrigeration Equipment, Faculty of Mechanical and Mechatronics Engineering from the POLITEHNICA University of Bucharest, to whom I would like to thank.

I thank my family for accepting all the sacrifices required by my involvement in the activities related to the preparation and elaboration of this paper. I thank my father for his parental guidance, patience, and counsel, my brother for his unconditional support, my wife and son for their warmth and support in all that I have done for my spiritual and professional accomplishment.

I would like to express my gratitude, respect and thanks to the doctoral supervisor, Prof. Dr. Eng. Alexandru DOBROVICESCU for the patience with which he supported me, for the professional competence and special human qualities, for the professional support with which he guided me during the elaboration of the doctoral thesis. and last but not least for the motivation and determination he instilled in me both during my bachelor's and master's years and during my doctoral studies.

I would like to thank Prof. Dr. Eng. Valentin APOSTOL especially for the unconditional support both professionally and especially spiritually with which he guided me from the first day *we met. I also thank him for the trust he gave me and for the warmth with which I was received when I decided, under his guidance, to give the first hours of laboratory and seminar as an assistant doctoral student in the TMETF department.*

Special thanks and I would like to express my gratitude to Prof. Dr. Eng. Horaţiu POP, whom I consider primarily a friend and colleague, for the help and support offered for the preparation of the doctoral thesis, for the advice and patience o during the last 10 years, in which I interacted both as a student - teacher and especially as department colleagues. I thank them for the consultations and guidance I received in drafting the published and supported articles and last but not least for the dedication ang gift he manifests both professionally and humanly towards students and department colleagues.

Thanks to all my professors and colleagues in the thermodynamics department of FIMM, especially Şl. dr. eng. Claudia IONIŢĂ, prof. dr. eng. Eugenia VASILESCU, Şl. dr. eng. Beatrice IBREAN, Şl. dr. eng. Cătălina DOBRE, Şl. dr. eng. Adina GHEORGHIAN, Şl. dr. eng. Mihaela CONSTANTIN, eng. Mariana STAN, eng. Laurenţiu GHEOLDEA, eng. Mircea HERA, eng. Ştefan MITREA, eng. Mugurel OPREA for their professional help, friendship, as well as for their scientific collaboration.

Author

Chapter 1 - Current state of research in the field of waste heat recovery or the use of thermal energy from renewable sources

This paper focuses on the study of mechanical energy production using a renewable energy source or residual thermal energy recovery (RCR) using a Rankine cycle with organic fluids (ORC).

One of the most widespread systems that releases more than half of the energy obtained in the combustion process into the environment is the internal combustion engine (MAI). On the other hand, solar energy is an inexhaustible form of energy waiting for the right solution to be collected. The Rankine Organic Cycle (ORC) follows the same principles as the traditional Rankine steam cycle used in most power plants to produce electricity, but uses an organic fluid instead of water. The working fluids for these cycles can be selected from a long list of candidates, including freons, hydrocarbons, hydrofluorocarbons, siloxanes and mixtures of these components. These distinctive features make ORC the most reliable option for energy recovery from unconventional heat sources, such as hot geothermal water, biomass combustion, RCR from industrial processes and solar thermal applications. We can say that systems based on ORC cycles have reached the technological maturity of development at medium and large scale for geothermal heat sources and applications of residual thermal energy recovery from biomass combustion, but are still rare at small to micro scale. The organic Rankine cycle can be used with any source from which thermal energy is obtained at a low and medium temperature level to produce mechanical and electrical energy respectively. The main heat sources for ORC cycles have been listed in the introductory chapter and are generally represented by steam, liquid or flue gas flows resulting from the operation of other heating systems [25].

1.1 Thermal energy recovery from internal combustion engines (MAI)

About 30% -40% of the fuel energy in internal combustion engines is converted into useful mechanical work, the rest is residual thermal energy expelled into the environment by the flue gases and engine cooling systems [14]. The recovery and use of this waste heat saves fossil fuels, reduces the amount of greenhouse gases released into the environment and can be used to generate electricity [6,15].

The two primary sources of residual thermal energy from an MAI are the resulting flue gases (with an average temperature level) and the engine coolant (with a lower temperature level). Previous studies in this area involve the recovery of each source, as well as the potential for simultaneous thermal energy recovery from both engine coolant and exhaust gases [6].

A review of the literature on CPR shows that thermal energy can be obtained from the MAI with sufficient exergy to justify the implementation of a secondary cycle. Many researchers acknowledge that the recovery of thermal energy from engine exhaust has the potential to reduce fuel consumption without increasing emissions, and recent technological advances have made these systems viable and cost-effective. Cycle and workflow recognition is the main topic of research, as they are considered to have the greatest impact on system performance.

A system built on the principle of an organic Rankine cycle has four main components: the evaporator, the expander or turbine, the condenser and the pump, shown in figure 1.1.

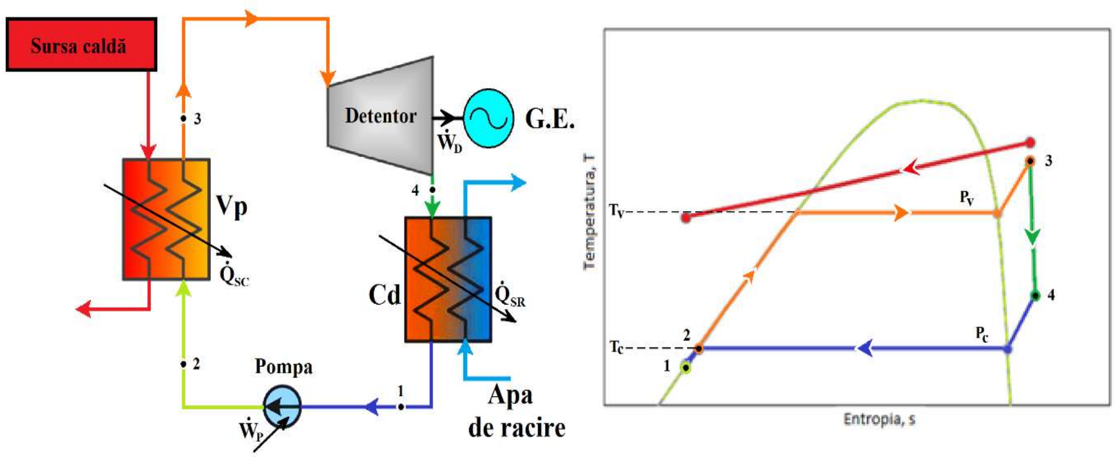

Figure 1.1 ORC diagram and cycle representation in the T-s diagram

The working fluid takes over the thermal energy flow from the hot source (SC) is heated and then vaporized in the heat exchanger called Evaporator (Vp), the resulting vapors then relax from the vaporization pressure pv, in the turbine or expander (D), until at a pressure pc thus generating mechanical work, the low pressure vapors from the outlet of the expander enter the condenser of the installation (Cd) where it condenses giving heat to the cooling medium - cold source (SR), the resulting liquid is pumped by the pump P from the pressure condensation denoted pc to the vaporization pressure denoted pv then resuming the cycle.

In literature can be found different configurations of schemes for ORC systems both classical schemes from the minimum of components and various adaptations, improvements and optimizations of it depending on the parameters of the heat source and the thermo-physical and thermodynamic properties of the working fluid. . These schemes will be detailed in chapter 3 of the doctoral thesis.

1.2 Energy production through a Solar ORC system (S-ORC)

Solar irradiance is a huge form of free energy that could be exploited and transformed into a form of energy that can be used by different types of radiation sensors. Solar energy through its applications is now used in a wide variety of fields such as building heating, building cooling, heat generation for industries, electricity generation, food refrigeration, water heating, distillation, drying, cooking and other various processes. Among other things, solar energy could be the "fuel" for various cooling technologies such as: Stirling machine or refrigeration plants with absorption and ejection. Using thermal energy to ensure absorption, the system offers the possibility to consider the sun as fuel for this system by providing cooling in summer when this source is abundantly available [26].

Global Horizontal Irradiation (GHI) is the most important parameter for calculating energy efficiency and evaluating the performance of flat panel photovoltaic technologies and flat panel solar collectors. On the other hand, Direct Normal Irradiation (DNI) is one of the parameters of great importance for calculating energy efficiency and evaluating the performance of solar energy concentration (CSP) and photovoltaic solar concentrators (CPV) technologies. The DNI is also important for calculating the global irradiation received by inclined or solar-tracked photovoltaic modules.

Given the abundance of solar radiation, the development of the collector market and the variety of working fluids, ORCs operated by solar collectors are particularly attractive for various applications such as grid electricity generation, water desalination, air conditioning and refrigeration, heat and power generation. household electricity, trigeneration, etc. [28]. In the doctoral thesis were studied different types of collectors for S-ORC systems, the equation underlying the calculation of the efficiency of flat plate thermal collectors and were presented the most common operating schemes. It was noted that for each application improved from the basic S-ORC scheme, the additional costs and complexity of the installation (collector area and number, geo-tracking devices, storage devices, preheaters, heat recuperators, will be balanced). additional pumps, second expander, etc.) compared to the increase in efficiency resulting from these implementations. The selection of the working fluid plays a decisive role in the efficiency of the S-ORC system. Most of the studied applications achieve the best efficiency using „isentropic” and „dry” working fluids with the lowest possible critical temperature. Water and organic fluids with higher critical temperature lead to a yield similar to that of heat recovery systems of the MAI-ORC type, at high temperature levels, which are also found in S-ORC systems with solar collectors of concentrator type or parabolic. It is also clear that organic fluids are more interesting than water when used as a working fluid in the ORC cycle, because water requires much higher operating pressures, has instability due to very large variation of the specific volume during the phase change in the liquid. in steam. Organic fluids, in the saturated state, can function in the supercritical field, thus avoiding the high degree of overheating required in water/steam cycles, thus avoiding the problems associated with the high moisture content in the final phase of steam expansion in the turbine or expander [43].

Chapter 2 - Organic fluids compatible for use in ORC cycles

The working fluid has a decisive role on the performance of MAI-ORC or S-ORC systems, being necessary a thorough analysis from a thermodynamic point of view as well as an exergetic analysis of the system in order to select a fluid with optimal characteristics in operation. The main working fluid selection criteria for ORC systems were presented. However, the performance of the ORC system remains the most important parameter to consider in terms of characterizing and then selecting the ideal working fluids in operation.

Because the use of ORC cycles is always associated with low temperature thermal energy recovery, organic fluids must have relatively low boiling temperatures. The freezing point must be lower than the lowest temperature that the fluid in the system can reach. High molar mass fluids have a positive impact on expander efficiency. However, fluids with high critical pressure and high molar mass require larger heat exchange surfaces. Low viscosity in both the liquid and vapor phases is required to reduce pressure drops in heat exchangers and pipes.

Also very important for the selection of the working fluid are the safety characteristics of the fluid. Non-toxic and non-flammable fluids are preferred for use as high risk agents. In order for an agent to be used as a working fluid it must be characterized by ODP (ozone depletion potential) equal to 0, GWP (global warming potential) less than or equal to 150 (starting in 2022) [46] and low atmospheric life [47]. The operation in a subcritical or transcritical cycle of an ORC system is determined by the temperature of the heat source and the properties of the working fluid. The fit between the type of thermodynamic cycle, the working fluid and the heat source is important for the optimization of the ORC system.

As in the case of MAI-ORC systems, the working fluids for S-ORC cycles can be classified in terms of heat source temperature or vapor saturation curve in the T-s diagram, which requires the state of the fluid at the outlet of the expander after adiabatic expansion.

The peculiarity of compatible organic fluids for ORC systems is that they can be used at a vaporization temperature lower than the usual working temperature for a conventional water turbine, thus providing high efficiency. The organic fluids frequently used in ORC systems are: hydro-fluoro-carbonates (HFCs), ammonia, butane, isopentane, toluene, etc., which generally have a high level of molecular weight.

More than 40 working fluids that are currently used in ORC applications have been characterized in this paper. The classification of these fluids was done according to the critical temperature, a very important parameter when the hot source has a low temperature and it is desired to recover as much thermal energy as possible. The main fluids encountered in the MAI-ORC and S-ORC cycles were characterized by a series of current criteria such as: slope of the dry saturated vapor curve, environmental protection, operational safety and economic criterion.

Chapter 3 - Rankine cycle schemes with organic fluids

In this chapter are classified and detailed the main configurations and operating schemes of ORC systems found in the literature, which have as primary heat source the flue gases released after burning fuel in the Ministry of Interior. From a constructive point of view, the systems that use the minimum of equipment for financial reasons are highlighted in operation, but also improved and optimized models of the basic scheme.

The most common ORC schemes were presented in this chapter, starting with the simple schemes, there were also presented schemes with preheating, regeneration, two expanders, with a expander and an ejector, mixed cycles and double cycles.

Through each additional equipment added to the basic scheme, which aims to maximize the efficiency of the system, there is the problem of recovering and amortizing the additional investment during the operation of the equipment. It has often been shown that there is an optimum of equipment for low and medium temperature heat recovery through an ORC cycle, the heat flow taken over being a decisive parameter in this case.

For each application improved from the basic ORC scheme, the additional costs and complexity (preheaters, recuperators, second expander, etc.) will be weighed against the increase in efficiency resulting from these implementations. No configuration is optimal for each residual heat source, therefore a thermodynamic analysis directed to the specific heat source to be recovered must first be performed.

Research suggests that a properly designed ORC system for the RCR of the exhaust gas engine can reduce emissions and pay for itself through fuel savings in a relatively short period of time (approximately 2-5 years), depending on the primarily by annual journeys, these researches being carried out on long-haul freight trains. Therefore, the system can help meet future emission standards while reducing operating costs.

Chapter 4 - Recovery of waste thermal energy from the flue gases of an internal combustion engine

In this chapter, the operation of a simple ORC cycle was simulated and theoretically analyzed, having as input data the flue gas parameters from a MAC mounted on an experimental stand. The type of engine used on the stand is D2156MTN8 Roman Brașov equipped with a turbocharger and is mounted on an experimental configuration from the University POLITEHNICA of Bucharest, Faculty of Mechanical and Mechatronics Engineering, Department of Thermodynamics, Engines, Thermal and Refrigeration Equipment.

Depending on the experimental input data of MAI Roman, a theoretical thermal calculation for the ORC cycle was performed using in simulation a series of working fluids compatible with the temperature regime of the hot source, at different loading loads.

The data obtained experimentally from the measurement with specific equipment corresponding to 40%, 55% and 70% engine load and speed of 1750 rpm were presented. It has been observed that for some of the working fluids the thermal efficiency decreases as the overheating increases, and for other working fluids, the thermal efficiency increases and then decreases, thus presenting an optimal value.

At the end of the study it was observed that the values obtained for the thermal efficiency cannot be directly associated with a certain group of working fluids. The working fluid must be carefully selected, depending on the application. For the analysis performed in this chapter using as input data the parameters of the internal combustion engine D2156MTN8 Roman Brașov it is observed that the most suitable working fluid is R1233zd (E) not only for the highest thermal efficiency of the ORC system, but also because has a very low GWP and is classified as part of safety group A1.

The study showed that the ORC system, as a technical solution, can be successfully applied to recover the thermal energy released by the MAI flue gases. This technology can be easily applied in the case of stationary engines and more difficult in the case of car engines due to the rapid change in operating conditions. However, the electricity production obtained, in the case of stationary motors, could be used to supply the auxiliary systems of the equipment, or it could be used for the consumption or lighting of a private building or delivered to the main electrification network.

Chapter 5 - Experimental installation for the study of thermal energy recovery of the MAI flue gases using an ORC system

This chapter continues the study and puts into practice at an experimental level, the optimization of the residual thermal energy recovery cycle obtained from an internal combustion engine (MAI) through an organic Rankine cycle (ORC), aiming at generating electricity through an electrical generator (GE) or drive a refrigeration system with mechanical vapor compression (IFV).

In order to establish a basic scheme as simple as possible, it was necessary to develop a calculation model for identifying and optimizing the constructive solutions of the coupling of the mixed cycle MAI-ORC through an exergetic and energetic analysis. The analysis aimed to find the optimal operating and design structure for this system in order to obtain maximum power. The input data for the analysis of the optimized coupling were taken from the internal combustion engine that equips the MAI-ORC experimental stand located within the Department of Thermodynamics, Engines, Thermal and Refrigeration Equipment. The stand was designed and built to experimentally investigate the possibilities of improving the coefficient of performance of an internal combustion engine by coupling it with an ORC system to recover the thermal energy dissipated by the engine. The execution of this stand was funded under the research contract code PN-II-PT-PCCA-2011-3.2-0059 "High efficiency micro-cogeneration hybrid group equipped with electronically assisted ORC" acronym - GRUCOHYB.

The chapter presented a synthesis of the research carried out within the project. In the first stage the recovered thermal energy is expected to be used (i) to obtain electricity with a system based on the Rankine cycle, using an organic substance as working agent, and / or (ii) to heat a thermal agent or activate a cycle. refrigerator. From the point of view of the analyzed diagrams and cycles, the operation was limited to two variants: a) The ORC cycle with the slope of the non-negative vapor saturation curve without overheating the vapors at the entrance to the expander, in which it was observed that the cycle, in the chosen functional variant cooling of the condensed liquid; b) ORC cycle with slope of the vapor saturation curve non-negative with vapor overheating at the entrance to the expander and with internal heat exchanger recuperator.

The sizing of the functional model was performed following an extensive study in which 60 variants were analyzed through 6 functional schemes applied for 10 working fluids. The working fluids were selected through a bibliographic research based on application-specific criteria. Due to the constructive, economic and safety features of the application that was the subject of the research, SES36 - Solkatherm and R245fa were chosen at the time as working fluids.

For the acquisition and storage of data was used the existing PLC system for the generator set which was extended both in terms of hardware and software to meet the needs of the ORC installation, this PLC is connected to a PC to allow easy use of the PLC operating system of.

Due to the problems raised by the purchase of the working fluid SES36 and R245fa, the constraints related to the legislation that provides for these fluids to be replaced by 2030 as well as mechanical failures in the Thonson expander, the Department decided to rehabilitate the experimental stand from a constructive point of view by purchasing new component equipment. Pursuing this goal, it was considered to find feasible solutions both technically and financially.

It was decided that the working fluid that will serve the rehabilitated stand should be R134a, in order to eliminate in this way any constraint regarding the acquisition, operation and degree of environmental pollution. The working fluid R134a is the most used working fluid in the world in the field of refrigeration and air conditioning but also in ORC type installations for low temperature regimes.

Following the theoretical thermal calculation applied on the scheme of the experimental stand and with the new working fluid modeled in EES (Engineering Equation Solver) [94], it was proved that it has good thermodynamic characteristics in terms of COP [47].

From the initial scheme it was considered to keep all the components that can operate at normal parameters with the working fluid R134a. For optimal operation, it was decided to replace the condenser and the expander of the ORC equipment. Also, due to the high pressure (approximately the pressure of 28 bar at a temperature of 85 ^{o}C) that will be reached at the level of the evaporator heat exchanger for R134a, it was considered to purchase a new evaporator sized appropriately for the new operating mode. After performing the thermal calculation and simulation functions it was decided to replace the plate condenser with a Bitzer K203H multitubular condenser.

With the installation of the Expander and the Condenser on the experimental stand, improvements were also made to the PLC data automation and reading table. The energy parameters of the output electric current produced by the generator that equips the Bitzer expander will be read by the Phoenix Contact modules in the PLC.

All these steps aimed to determine the energy balance of the experimental stand equipped with ORC, respectively for its automatic operation. The experimentally obtained data will be interpreted and validated in order to find the optimal solution for coupling the MAI-ORC system with an IFV or absorption type refrigeration installation (IFA). For this purpose, the possibilities of coupling between the two systems are already analyzed from a technical and financial point of view, taking into account the multitude of refrigeration equipment that are part of the inventory of laboratories of the Department of Thermodynamics, Engines, Thermal and Refrigeration Equipment.

Chapter 6 - Use of solar thermal energy to generate electricity using S-ORC cycles

For the modeling of the S-ORC system, first of all an analysis was performed of the influence of the solar radiation intensity and implicitly of the heat flux received by the solar collectors placed vertically [97] and horizontally [98] on a platform with a surface unitary with the help of tabular data from the Romanian standard SR 6648-1: 2014 and SR 6648-2: 2014 [99,100]. The purpose of the analysis is to establish from a technical point of view, the optimal solution for placing the solar collectors in a vertical or horizontal plane. The input data for determining the optimal positioning is a particular case detailed in the paper [97].

Within the platform from the work mentioned above, the collector surfaces are very restrictive, being reduced to two areas: one in vertical plane at 90^0 consisting of 3 arrangements with equal rectangular surfaces totaling $15m^2$ and the second arrangement in horizontal plane with the same surface available.

To establish the optimal mounting position of the collectors, the first modeling was done taking into account the available surface in the vertical plane arranged on three rectangular sections, external, located in a U-shape, and for the second modeling a surface was used which is located in horizontal plane of rectangular shape. FPSC were chosen for the study because they meet all the conditions specific to the area in which they are to be installed.

From the comparison of the obtained data, the advantages of positioning the solar panels in horizontal plane were observed. The average values of solar radiation intensity for the two positions in the sunny months were analyzed, more precisely from March to October. In the winter months there are negligible values of the average intensity of solar radiation, which does not justify the commissioning of the complex system.

The solar ORC system proposed for the study is presented in figure 6.1 and will contain in the first phase the minimum of equipment necessary for operation. It consists of a FPSC, a closed-circuit storage tank (ST) in which water is circulated by the pump (Pw) and the ORC module. The main components of the ORC module are: Evaporator (Ev), Expander (Ex), Condenser (Cd) and Pump (P). As the Sun rises, the FPSC receives solar energy in the form of direct and indirect irradiation, leading to an increase in the temperature of the water inside the ST.

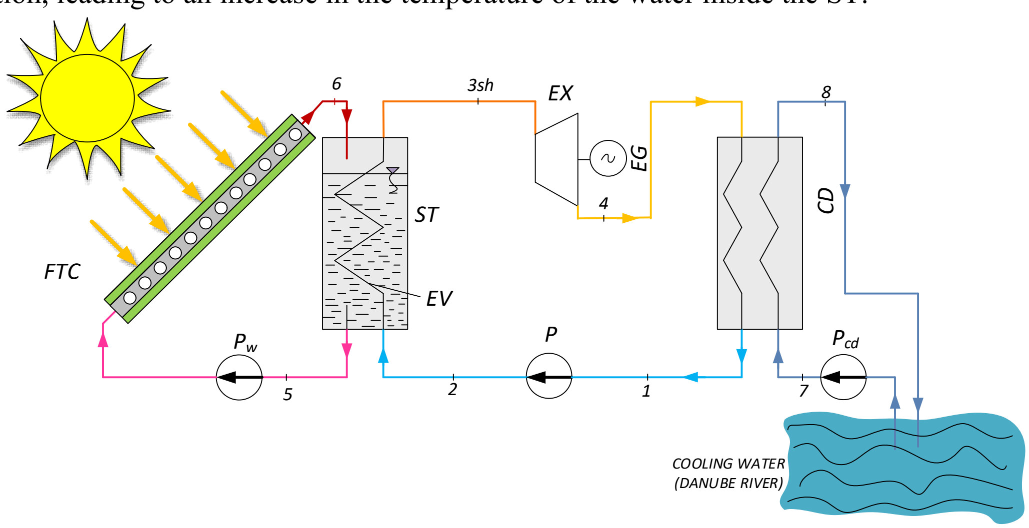

Figure 6.1 Operating diagram of the S-ORC system

The ORC solar system was modeled by dividing it into two main sections, a first section FPSC - storage tank - water pump and the second, the ORC module. Both sections were modeled based on energy balance equations and were interconnected. A simple thermodynamic model has been developed for the ORC module. The input data used to generate the results based on the scheme correspond to the situation in which the complex system of renewable energy production is located on the Danube River, near the city of Galati.

Only „dry” working fluids were selected due to the low vaporization temperature and the small degrees of overheating that can be achieved in the ORC module. The use of „dry” working fluids will ensure that at the exit of the Expander the thermodynamic state is of superheated vapors, thus avoiding the problems of drip formation.

As the analysis period approaches summer, the starting point of the ORC module is approaching sunrise, which means a longer operating time and therefore higher energy production.

The ORC solar system was modeled and a program was implemented in Microsoft Excel and connected with the Engineering Equation Solver software. The validation of the results was performed based on other similar works performed and reported in the literature. The results were obtained for four working fluids, namely: R1234yf, R1233zd (E), HFE7100 and R290. The heat flux absorbed by the ORC module at the evaporator was set to 7 kW. The ORC module starts operating when the water temperature in the storage tank reaches 70 0C and stops when the temperature drops to 45 0C. The results highlight that:

- for the specific conditions of the Danube river near Galati city, the ORC module will operate from March to September. The operating time depends on the availability of solar energy, being longer in mid-summer;
- the volume of water inside the tank has an important influence on the operating time of the ORC module and also on the energy production. Of the four cases chosen, 200, 350, 400 and 600 liters of water, the analysis shows that the volume of 350 liters is a compromise between the operating time and the net output power of the ORC module;
- the highest output power of the ORC module for R1233zd (E) is obtained from the four fluids, followed by R290, R1234yf and HFE7100;
- R1233zd (E) produces the highest thermal efficiency of the ORC system, followed by R290, R1234yf and HFE7100;
- in July, for the specific conditions of the Danube river near Galati city, the highest energy production of 2.22 kWh is achieved when the ORC solar module runs on fluid R1233zd (E), followed by 2.17 kWh for R290, 2 , 13 kWh R1234yf and 2.10 kWh for HFE7100, respectively;
- the energy production from March to September for specific conditions of the Danube river in Galati city is: 254.19 kWh when the ORC solar module works with fluid R1233zd (E), followed by 249.38 kWh for R290, 244.93 kWh R1234yf and 241.62 kWh for the HFE7100.

Chapter 7 - MAI-ORC-IFV optimized coupling analysis

The objective of this chapter is to identify and optimize the constructive solutions of the ORC-IFV mixed cycle coupling through an exergetic and energetic analysis.

The proposed concept for analysis combines an ORC cycle with a mechanical vapor compression refrigeration system (IFV) to form a thermally activated cooling system (ORC-IFV). The crankshaft of the ORC expander and the IFV compressor shaft are directly coupled to reduce energy conversion losses. Another peculiarity of the ORC-IFV scheme is the use of a single working fluid to drive both thermodynamic cycles. In this sense, a hydraulic route has been implemented that will convey the working fluid necessary for both cycles, with a single condenser heat exchanger.

The combined ORC-IFV system has potential advantages over other thermally activated refrigeration systems in terms of performance and simplicity. Also compared to IFA the combined

ORC-IFV system has flexibility because when there is no cold requirement it can produce electricity. This is true for applications where thermal energy from the heat source is available in all seasons. During hot summer periods, all available thermal energy can be converted into mechanical energy and then into refrigeration, and in winter when there is no need for cold, the system can produce electricity.

The configuration of the ORC-IFV installation as well as the working fluid were established following an extensive study in which the functional schemes encountered in the literature were analyzed. The working fluids were selected through a bibliographic research based on criteria specific to the application of ORC but also good results in IFV systems. The working fluid chosen for modeling the combined ORC-IFV system is R245fa. The input data for the analysis of the optimized coupling were taken from the MAI Yanmar detailed in Chapter 5. The mathematical model is based on mass, energy and exergy balances for different constructive structures of the ORC-IFV scheme.

The basic construction diagram and the representation of the cycle in the P-h diagram of the ORC-IFV installation is presented in figure 7.1.

Detailed energy and exergetic analyzes were performed in detail in the doctoral thesis. Exergy expresses the true measure of the quantity and quality of a certain energy in correlation with the intensive parameters of the environment. Exergy is destroyed in a specific process of energy conversion. Minimizing energy damage to key components of an energy system provides the strategy to be followed to optimize the structure and operation of the system.

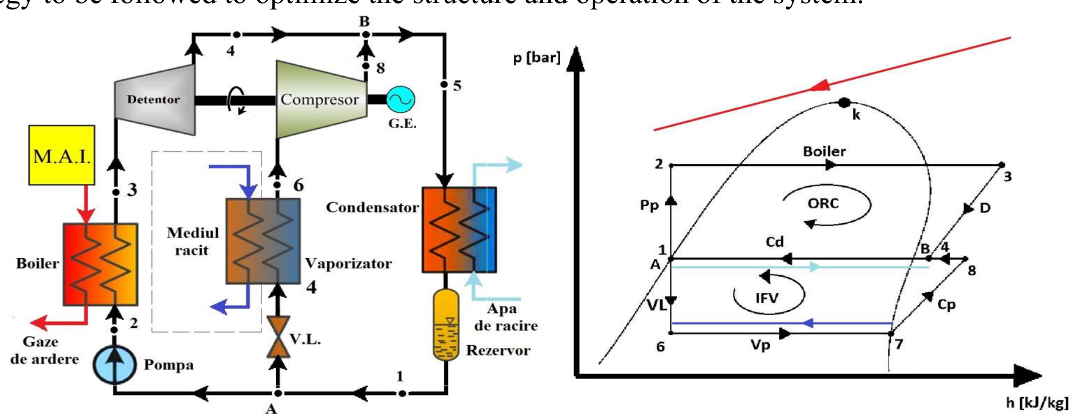

Figure 7.1 Basic scheme and thermodynamic cycle of the proposed ORC-IFV system for analysis

From the exergetic analysis it was concluded that in order to reduce the area corresponding to the destruction of the exergy in the heater, the inlet temperature of the ORC fluid should be increased. The loss of exergy in the heating of the working fluid can be reduced so that from the Boiler we take less heat from the flue gases to heat the working fluid. This preheating can be done by mounting a heat exchanger in front of the boiler through which the working temperature of quite high temperature will pass from the outlet of the expander, also this scheme can be improved by mounting a regenerative heat exchanger between the outlet of the working fluid of Condenser.

Figure 7.2 shows the diagram with Regenerator. Due to the large temperature difference between the outlet of the working fluid from the Expander before the Condenser and its entry into the Boiler evaporator, it is justified to introduce a heat exchanger called Regenerator, on the ORC installation circuit, which can preheat the working fluid before Boiler, the purpose being to reduce the exergy losses registered in the heating, vaporization and overheating process in the Boiler, these materializing implicitly in increasing the energy and exergetic efficiency of the composite system.

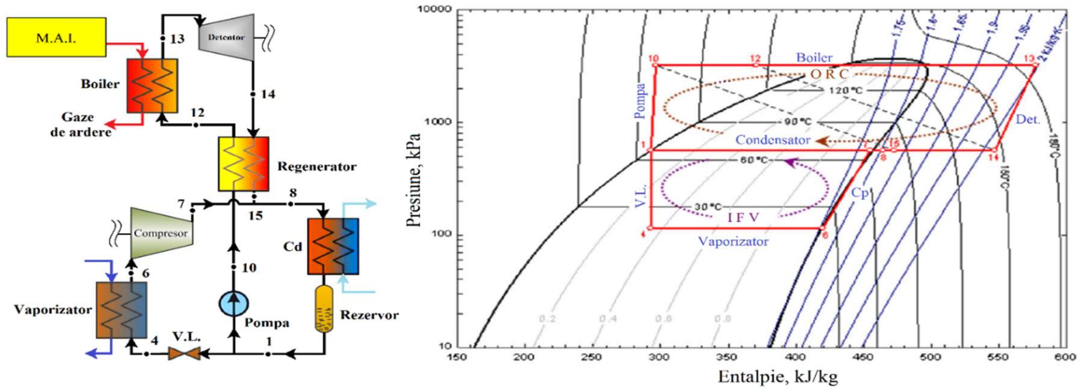

Figure 7.2 Diagram and thermodynamic cycle of the ORC-IFV system with Regenerator

The results of the mathematical modeling based on the exergetic analysis of the ORC cycle operation with R245fa, without overheating, with Regenerator heat exchanger, for a 100% engine load, were obtained based on energy and exergetic calculation and are presented in the doctoral thesis.

Chapter 8 – Exergoeconomic optimization of the ORC-IFV coupled system

Exergoeconomic analysis is the only method of investigation and optimization procedure that takes into account the fact that any thermodynamic system is in interaction with two environments:

a) a physical environment determined by a system of intensive parameters such as pressure, temperature and chemical potential, and
b) an economic environment characterized by prices of raw materials and equipment and sets of regulations to ensure sustainable development.

Given that energy is a conservative measure (Principle I of thermodynamics) and that it, in principle, is not consumed and therefore can not appear, conceptually, in economic balance sheets must be found another concept, non-conservative to define usable energy consumption , this is exergy. The exergoeconomic analysis realizes the economic balance accounting both the cash flows related to the operating process and the investment ones. The exergoeconomic optimization method aims at identifying the exergy destruction of each functional area and assigning its monetary cost.

High-cost areas of exergy destruction will be the first targets of optimization procedures, the effect of each local cost reduction will be verified globally.

In order to quantify the value of a zonal destruction, the fuel, the product, the loss and the coefficient of exergetic performance were evaluated for each operational area.

The scheme of the IFV installation operated with ORC system was divided into seven operating areas: 1) ORC Evaporator (Boiler); 2) Expander; 3) Compressor; 4) Condenser; 5) Throttling valve; 6) IFV Evaporator; 7) ORC liquid pump.

In order to assess how the investment expenditure saves the monetary cost of zonal exergy destruction, the exergoeconomic factor f_k [106] was calculated for each equipment, where the index k represents the equipment.

To calculate the chemical exergy of diesel with the chemical formula $C_{12}H_{23}$, an ideal device known as the Van't Hoff equilibrium box [107] was imagined in which the reactants as well as the products enter and exit the parameters of the environment T_0 and p_0. The processes that take place in the equilibrium box (reaction chamber) take place stationary and in thermodynamic equilibrium conditions.

Unlike thermoeconomic cost correlations in which the purchase cost of an equipment is estimated by a function of the quantity of material resources used, in the case of exergo-economic correlations the cost is specified according to the exergetic performance coefficient (or defined based on the Principle Second of Thermodynamics) or decision variables that define exergetic performance (such as exergy destruction) and depending on a factor that determines the exergetic product of the equipment.

In view of current environmental considerations and regulations (mainly increased GWP), which no longer allow the use of SES36 - Solkatherm and R245fa working fluids in all types of installations, it has been necessary to find replacements with the same thermodynamic characteristics, but and compliance with environmental and operational safety criteria. In order to choose the most suitable working fluid for the MAI-ORC-IFV system, following an analysis from the point of view of the selection criteria: environment, operational safety, technical and economic, which were also described in Chapter 2, performed an updated study on working fluids with a critical temperature between 150 and 200 ^{0}C. It has been observed that R1224yd (Z) and R1233zd(E) meet all the above criteria and are currently the working fluids with the thermodynamic characteristics closest to their predecessors SES36 and R234fa.

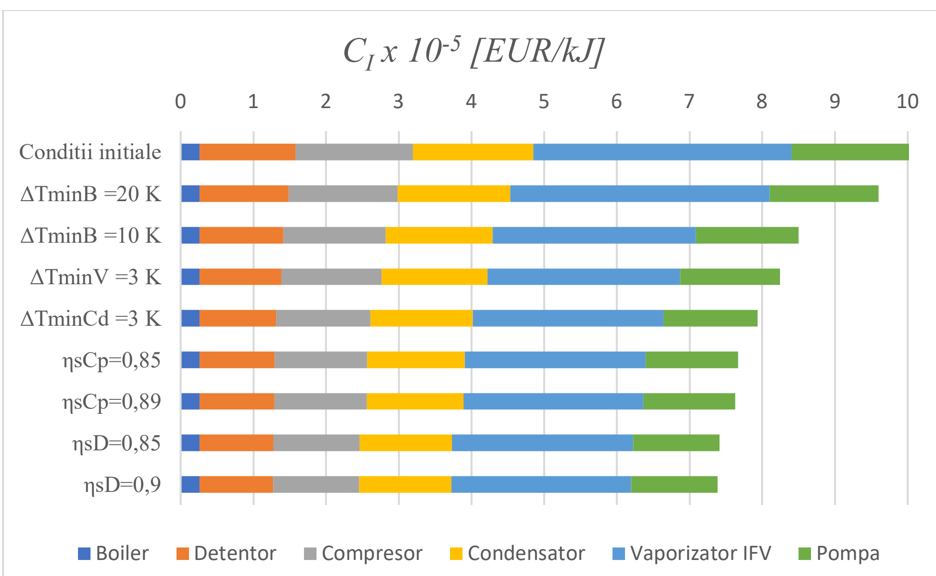

Figure 8.1 Variation of unit cost of exergy destruction C_I x 10^{-5} [EUR/kJ] for each piece of equipment, depending on the required optimization parameters

The results obtained for the working fluid R1224yd (Z) were presented according to the variation of several decisional parameters, among which the minimum temperature difference in ΔT_{minCd} Condenser, the minimum temperature difference in ΔT_{minV} Evaporator, the minimum temperature difference in ΔT_{minB} Boiler, as well as variation of the efficiency of the η_{sCp} Compressor or of the η_{sP} Pump.

Table 8.1 Energy and exergetic results obtained for the ORC-IFV scheme using the working fluid R1224yd (Z)

COP_{IFV} [-]	COP_{ORC} [-]	COP_{ORCIFV} [-]	η_{ex} [%]	$\dot{m}_{fluiIFV}$ [kg/s]	$\dot{m}_{fluidORC}$ [kg/s]	$\dot{m}_{fluidORCIFV}$ [kg/s]	ψ_{Cp} [%]	Ψ_D [%]	$\psi\Delta_{TB}$ [%]
8.89	0.1797	1.529	7.003	0.1681	0.073	0.2411	2.667	2.613	34.68
Ψ_P [%]	Ψ_{PiCd} [%]	Ψ_{VL} [%]	Ψ_{am} [%]	Q_B [kW]	Q_{Cd} [kW]	Q_{Vp} [kW]	$\dot{W}_D$ [kW]	$\dot{W}_{Cp}$ [kW]	$\dot{W}_P$ [kW]
0.2237	13.66	1.991	0.3358	17.05	43.1	26.06	3.063	2.931	0.1315

In the results presented in figures 8.1 and 8.2 was also specified the value of the modified parameter, compared to the initial calculation conditions. The initial calculation conditions took into account the following input data: $\Delta T_{minCd} = 8$ K; $\Delta T_{minV} = 8$ K; $\Delta T_{minB} = 30$ K; $\eta_{sCp} = 0.8$; $\eta_{sP} = 0.8$. In the results presented in figures 8.10 and 8.11, the value of the modified parameter was also specified, compared to the initial calculation conditions.

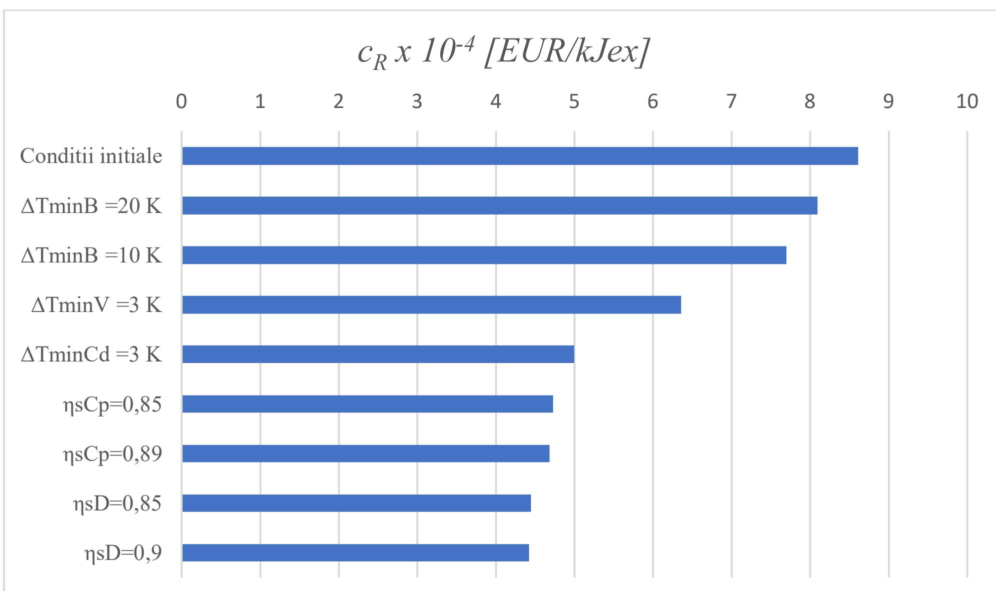

Figure 8.2 Variation of unit cost of exergy product c_R x 10^{-4} [EUR/kJ] for each piece of equipment, depending on the required optimization parameters

The cost of the exergy product unit c_R [EUR/kJex] drops to almost half as a result of the optimizations mentioned above as seen in the graph in Figure 8.2. Table 8.1 presents the main energy and exergetic results of exergoeconomic optimization using the working fluid R1224yd (Z).

Conclusions

C.1. General conclusions

The main aim of this paper was to identify, study and optimize both theoretically and experimentally the potential for thermal energy recovery from waste or renewable sources through a Rankine cycle with organic fluids (ORC).

Chapter 1 presented the current constructive solutions for residual or renewable thermal energy recovery, among which we list: steam injection, thermoelectric effect, heat recovery through refrigeration systems with absorption or through a Rankine cycle with organic fluids. The heat released by the flue gases and their high temperature justify the use of an ORC type heat recovery system that aims to produce mechanical or electrical energy.

Organic fluids compatible for use in ORC cycles were presented in **Chapter 2** of the doctoral thesis. Given the multitude of working fluids that can be used, a characterization of them has been developed according to the main selection criteria, which take into account the thermodynamic properties (hot source temperature and the slope of the dry saturated vapor curve), the safety characteristics in exploitation, environmental protection characteristics and last but not least by economic criteria. Among the main characteristics that the ideal working fluid must meet we can enumerate the reduced impact on the environment, good safety characteristics, thermal and chemical stability, to be an isentropic or dry fluid, to have a latent heat of vaporization as high as possible, high density, specific heat as high as possible, critical temperature above the maximum operating temperature of the cycle, reasonable temperature and pressure, low cost and good availability. However, there is no fluid that meets all of the conditions listed above. In the present study, two working fluids were noted, R1233zd (E) and R1224 yd (Z), which are close to the conditions imposed for the study, such as: critical temperature, environmental and operational safety criteria, as well as good technical specifications. These fluids were used in the modeling in the following chapters.

The classification and detailing of the main configurations and operating schemes of the ORC systems found in the literature, which have as primary heat source the flue gases resulting from the fuel combustion process in the MAI, were detailed in **Chapter 3**. They were listed and described the main construction schemes ORC, among which the simple ones, with regenerator, with preheater, schemes with reheating, ejector, complex systems, etc. From a constructive point of view, the systems that use the minimum of equipment for financial reasons are highlighted in operation, but also improved and optimized models of the basic scheme. Through each additional equipment added to the basic scheme, which aims to maximize the efficiency of the system, there is the problem of recovering and amortizing the additional investment during the operation of the equipment. It has often been shown that there is an optimum of equipment for low and medium temperature thermal energy recovery through an ORC cycle, the heat flow taken over being a decisive parameter in this case. Following the bibliographic study, it was decided the mathematical modeling by thermal and exergetic calculation of the simple ORC schemes, composed of the minimum of equipment.

For the theoretical study of waste thermal energy recovery, in **Chapter 4** we used a case study using as input data the parameters of the flue gases from a MAC D2156MTN8 Roman Brașov with a nominal power of 57.3 kW. Following the establishment of the operating conditions, the choice of the working fluids for the thermal calculation implemented with the help of the Engineering Equation Solver (EES) software, the net obtained power and the efficiency of the system resulted. It has been observed that if the MAC load increases, so does the net power of the ORC system. The highest net power is obtained using the working fluid R1233zd (E). An output power of 3.6 kW of the ORC system was obtained when the engine is running at a load of 40%, 5.7 kW at a load of 55% and 6.7 kW at a load of 70%. When these values are compared with the rated power of the engine for the respective loads, it is observed that the percentage of waste thermal energy recovery has an average value of 6.5% of the rated power of the engine. These values are not to be neglected. If the net output power is converted to electricity by using an electric generator and a conversion factor of 0.98 is chosen, then the electricity production could be: in case of a 40% charge of MAC of 3.5 kWe , in case of load 55% would be 5.5 kWe and in case of load 70% of 6.5 kWe. The ORC system as a technical solution for waste thermal energy recovery of MAI can be applied successfully and easily in the case of stationary engines, but more difficult in the case of car engines due to the rapid change in operating conditions.

Chapter 5 presents in the first part a synthesis of the researches carried out for the design and construction of the experimental installation for the study of the thermal energy recovery of the MAI flue gases with the help of an ORC system. The microgeneration system for electricity and heat is equipped with a stationary four-stroke Yanmar Diesel MAC with a maximum power of 40 kW provided with an electric generator. The steps of simulation, elaboration, sizing as well as the establishment of the scheme of the functional model and of the control block were presented. The project was completed in 2015 with the commissioning of the experimental ORC system. Due to the poor efficiency and the losses caused by the leaks in the Tonson expander, but also to the new regulations regarding the environmental protection, it was necessary to upgrade the experimental stand and change the working fluid that serves the ORC system. In order to preserve a large part of the existing equipment, the operation of the ORC system was simulated with working fluids that respect all the environmental and operational safety criteria. It was decided to replace the SES36 working fluid with R134a, change the Tonson expander with a Bitzer expander with built-in electric generator, change the Condenser as well as upgrade the PLC data control and reading system. For the data acquisition part, the new control panel and data reading has been improved with several equipments, including a Danfoss frequency converter, and for the collection of electricity consumption data, an energy analyzer has been purchased for measuring electrical parameters. The aim was to update and upgrade the ILC 190 ETH2 PLC program, upgrade the Human Machine Interface (HMI) program, upgrade the data storage program and perform functional tests. All these approaches have as final goal the determination of the energy balance of the micro-cogeneration hybrid group equipped with ORC, respectively for its automatic operation.

Chapter 6 conducted a theoretical study on the use of solar thermal energy for electricity production using S-ORC cycles. For the modeling of the S-ORC system, an analysis of the influence of the intensity of solar irradiance was performed, through the heat flux that can be received by a system consisting of solar collectors that can be placed on a unit surface formed by a vertical plane or a horizontal plane having as input data a series of statistical data from the Romanian standard SR 6648-1: 2014 and SR 6648-2: 2014 during a year on the Danube river Galaţi city. Following the study it was observed that a number of factors lead to obtaining the values of the average intensity of direct solar radiation are. Among them can be listed: climatic conditions, positioning according to altitude, orientation of the collectors in the two planes and of course the angle of incidence of the sun's rays that takes into account the calendar month and the positioning of the Sun to the earth. Data were analyzed and processed for the months in which sufficient values of the global solar irradiance flux were recorded to engage an ORC solar cycle. From the comparison made with the help of mathematical modeling, the advantages of positioning the solar panels in the horizontal plane are observed. During the months presented in the study, it was observed that the average intensity of solar radiation for the vertical plane has close values, for each month, located on average at about 150 Wh/m^2. In the case of placing the solar panels horizontally, the values obtained for the same calendar months are much higher, registering even 400Wh/m^2 in the summer months. This clearly shows the advantages of positioning solar panels in the horizontal plane. Next, the S-ORC solar system was modeled by dividing it into two main sections, a first FPSC section - the storage tank - the water pump and the second, the ORC module. Both sections were modeled based on energy balance equations and were interconnected. A simple thermodynamic model has been developed for the ORC module. The operation of the ORC module is related to the water temperature at the outlet of the storage tank which will have a value set for activating the ORC module. From the simulations performed, an optimal volume of 350 liters of water was fixed for the storage tank. The modeling validation was performed considering as working fluid R1233zd (E) and the case of FPSC collectors. The working fluid was selected following an analysis in the directions described in Chapter 2, namely thermodynamic, environmental and operational safety characteristics. The study showed that the ORC module reaches its starting state in the months between March and September. The highest power output of 254.19 kWh is achieved when the ORC solar module runs on R1233zd (E) fluid. Energy production is not very high, but it could partially cover part of the energy consumption required for the operation of the platform or transformed into electricity and supplied to the main grid. The results show that the ORC solar module can be used and integrated in a complex system for producing renewable energy from natural sources located on the Danube River, near the city of Galați or in the town of Năvodari in Romania.

An in-depth analysis of the optimized internal combustion engine coupling-Rankine cycle with organic fluids-refrigeration with mechanical vapor compression (MAI-ORC-IFV) was performed in **Chapter 7** of the doctoral thesis. The objective of this chapter was to identify and optimize the constructive solutions of the ORC-IFV mixed cycle coupling through an exergetic and energetic analysis. Input data for optimized coupling analysis were taken from the stationary internal combustion engine MAC Yanmar model 4TNV98TGGEHR using fluid SES36. In order to analyze and optimize the basic scheme of the ORC-IFV installation, diagrams with exergy losses were drawn according to the variation of the additional parameters $\Delta t_{\_minB}$, $\Delta t_{\_minCd}$, Δt_{siB}, which directly determine the exergetic and energetic efficiency. Thus Δt_minB imposes the vaporization temperature and $\Delta t_{\_minCd}$ imposes the condensation temperature and it is observed that a large part of the amount of exergy introduced through the flue gases is consumed in the Evaporator boiler as follows: 22.14% in the heater, in the Evaporator 32.41% and only 2.89% in the superheater. The exergetic analysis of the basic cycle highlights the shortcomings of the construction scheme revealing possible operational and constructive changes to improve its performance. After establishing the scheme provided with the Regenerator heat exchanger of the ORC-IFV system, the previously developed mathematical model was reconfigured and based on the resulting data it is observed the decrease of exergy losses especially in the heating and vaporization stage of the working fluid. This decrease of losses in the two heat exchange zones leads to the increase of the exergetic efficiency by 0.7% and implicitly of the COP of the ORC-IFV installation.

Chapter 8 focuses on the exergoeconomic optimization of the ORC-IFV coupled system. The exergoeconomic optimization procedure requires performing an exergoeconomic analysis on the functional areas, determining the values of the chemical exergy of fuel and flue gases, and finally the exergoeconomic cost correlations are modeled. The working fluid R1224yd(Z) was implemented in the exergoeconomic calculation program according to the variation of several decisional parameters, among which the minimum temperature difference in Condenser ΔT_{minCd}, the minimum temperature difference in Evaporator ΔT_{minV}, the minimum temperature difference in Boiler ΔT_{minB}, as well as the variation of the efficiency of the η_{sCp} Compressor or of the η_{sP} Pump. It was found that the lowest exergetic yield ηex and the highest relative destruction is in the Boiler. Optimizing the heat exchange surface resulted in a unit cost of exergy product c_R = 7,694·10^{-4} [EUR/kJex]. The condenser has the second smallest exergoeconomic factor. Exergy destruction must be reduced. The optimization of the heat exchange surface of the Condenser led to the obtaining of a unit cost of exergy product c_R = 6,355·10^{-4} [EUR/kJex]. The cost of destroying the exergy in the Pump, as well as the cost of amortizing the cost of purchasing the pump are the lowest in the system. The compressor has a low acquisition cost but induces a high cost of exergy destruction which suggests choosing a more expensive compressor with a higher isentropic compression efficiency. The result of the unit cost of exergy product following the increase of the isentropic efficiency of the Compressor is c_R = 4,683·10^{-4} [EUR / kJex]. In the Expander 's area, both the cost of amortizing the acquisition cost and the cost of energy destruction are high which indicates the possibility of reducing the cost, with energy destruction by choosing a better expander, a trend tempered by the cost of the Expander higher than for example, the cost of the Compressor . Optimizing the isentropic efficiency of the Expander leads to obtaining a unit cost of exergy product c_R = 4,422·10^{-4} [EUR/kJex].

The cost of the exergy product unit c_R [EUR/kJex] drops to almost half as a result of the above - mentioned optimizations. For the complex MAI-ORC-IFV system, the optimizations resulted in a COP_{ORCIFV} = 1.529 and a refrigerating power Q_{Vp} = 26 kW.

C.2. Original contribution

Based on the conclusions presented above, the original contributions can be summarized as follows:

- modeling a MAI-ORC system using as input data the flue gas parameters from a MAC model D2156MTN8 Roman-Brașov;
- modeling an optimized MAI-ORC system using as input data the flue gas parameters from a MAC model Yanmar model 4TNV98TGGEHR of 40 kW;
- creation of a calculation program with the help of EES software and a working interface of HMI type for the study of the behavior of the energetic and exergetic parameters of output from a MAI-ORC-IFV system with the possibility to modify the input data and obtain the results in the shorter time;
- elaboration of a calculation model for establishing the optimal conditions for location and operation of the ORC module within an S-ORC solar system;

- modeling an S-ORC solar system located on the Danube river near Galati city;
- active participation for the implementation of the works for the replacement of the non-performing equipment and for the additional instrumentation of the experimental stand MAI-ORC within the TMETF-UPB department;
- modeling and exergetic analysis of a complex MAI-ORC-IFV system;
- exergoeconomic optimization of the MAI-ORC-IFV system.

C.3. Future research directions

Future research directions may involve:

- commissioning of the MAI-ORC experimental stand;
- improving the constructive schemes MAI-ORC that aim at obtaining a better efficiency with the minimum of equipment;
- resumption of experimental research for working fluid R134a;
- data acquisition through the PLC module in order to compile a database with experimental determinations for the working fluid R134a;
- elaboration of the database processing methodology;
- processing the database and the results obtained;
- functional optimization of the experimental stand.

Published articles

1. **D Taban**, A Dobrovicescu, V Apostol, H Pop, Optimized coupling analysis of Internal Combustion Engine (ICE)-ORC-MCRS, The 8th International Conference on Advanced Concepts in Mechanical Engineering ACME 2018 Section 7 21.

2. H Pop, V Apostol, V Bădescu, M H K Aboaltabooq, T Prisecaru, E Pop, M Prisecaru and **D Taban**, Working fluid selection procedure for ORC-based systems coupled with internal combustion engines driving electrical generators, ACME 2018 Section 7.

3. **Taban Daniel**, Pop Alina, Dobre Cătălina, Apostol Valentin, Prisecaru Tudor, Determining the optimal positioning of a system of three vertical solar collectors according to geographical orientation, Revista Termotehnica nr.1 3025 - 2018.

4. Apostol V, Pop H., **Taban D.**, Tanase B., Gheorghian A., Dobre C., Pop E., Prisecar T., Stanciu C., Thermodynamic assessment of a solar organic Rankine cycle (ORC) integrated in a complex system for renewable energy production from natural sources located on Romania's Danube river near Galati City 978-1-7281-1532-0 2019 IEEE pp 328-332.

5. Alexandru Racovitză, Horațiu Pop, Valentin Apostol, Tudor Prisecaru, **Daniel Taban**, Comparison between Organic Working Fluids in order to Improve Waste Heat Recovery from Internal Combustion Engines by means of Rankine Cycle Systems, Revista de chimie vol 71, Nr. 1, Bucureşti 2020 p 113-121.

6. Cătălina DOBRE, Mihaela CONSTANTIN, **Daniel TABAN**, Maria DRAGOMIR, Energy, Entropy, Exergy (3E) Analysis of a Micro-Cogeneration Unit Using an Alpha Type Stirling Engine,

36th IBIMA International Conference on Advanced Concepts in Mechanical Engineering, Materials Science and Engineering 444 (2021) 082003, Granada, Spain (ISBN: 978-0-9998551-5-7).

Selective Bibliography

[6] Charles Sprouse III, Christopher Depcik, Review of organic Rankine cycles for internal combustion engine exhaust waste heat recovery, Applied Thermal Engineering 51 (2013) 711-722

[14] Robert Morgan, Guangyu Dong , Angad Panesar, Morgan Heikal, A comparative study between a Rankine cycle and a novel intra-cycle based waste heat recovery concepts applied to an internal combustion engine, Applied Energy 174 (2016) 108–117

[15] Viorel Bădescu, Mahdi Hatf Kadhum Aboaltabooq, Horaţiu Pop, Valentin Apostol, Malina Prisecaru Tudor Prisecaru, Design and operational procedures for ORC-based systems coupled with internal combustion engines driving electrical generators at full and partial load, Energy Conversion and Management 139 (2017) 206–221

[24] João S. Pereira, José B. Ribeiro, Ricardo Mendes, Gilberto C. Vaz, Jorge C. André, ORC based micro-cogeneration systems for residential application – A state of the art review and current challenges, Renewable and Sustainable Energy Reviews 92 (2018) 728–743

[25] Anandu Surendran, Satyanarayanan Seshadri, Performance investigation of two stage Organic Rankine Cycle (ORC) architectures using induction turbine layouts in dual source waste heat recovery, Energy Conversion and Management: X 6 (2020) 100029 – carte ORC

[26] Lavinia Grosu, Andreea Marin, Alexandru Dobrovicescu, Diogo Queiros-Conde, Exergy analysis of a solar combined cycle: organic Rankine cycle and absorption cooling system, International Journal Energy Environment Energu (2016) 7:449–459

[28] Tryfon C. Roumpedakis, George Loumpardis, Evropi Monokrousou, Konstantinos Braimakis, Antonios Charalampidis, Sotirios Karellas, Exergetic and economic analysis of a solar driven small scale ORC, Renewable Energy 157 (2020) 1008-1024

[43] Evangelos Bellos, Christos Tzivanidis, Investigation of a hybrid ORC driven by waste heat and solar energy, Energy Conversion and Management 156 (2018) 427–439

[42] Andreea Marin, Adrian Untea, Lavinia Grosu, Alexandru Dobrovicescu, Diogo Queiros-Conde, Performance evaluation of a combined organic rankine cycle and an absorption refrigeration system, Termotehnica 1/2013

[46] Gequn Shu, Lina Liu, Hua Tian, Haiqiao Wei, Guopeng Yu, Parametric and working fluid analysis of a dual-loop organic Rankine cycle (DORC) used in engine waste heat recovery (2013)

[47] Ana Alexandru, Daniel Taban, Iulian Uța, Sinteză asupra schemelor constructive ale sistemelor energetice de tip ORC, Sesiunea de Comunicări Stiințifice Studențești – Secțiunea 05-1 Termotehnică, Motoare, Echipamente Termice și Frigorifice, FIMM, UPB, (2014)

[94] S.A. Klein, Engineering Equation Solver (EES), Academic Comercial V9.471, F-Chart Software,1992-2013

[97] Taban Daniel, Pop Alina, Dobre Cătălina, Apostol Valentin, Prisecaru Tudor, Determining the optimal positioning of a system of three vertical solar collectors according to geographical orientation, Revista Termotehnica nr.1 3025 - 2018

[98] Tănase Beatrice, Gheorghian Adina, Zamfir Mădălina, Bădescu Viorel, Pop Horaţiu, Comparative study on the positioning of solar collectors vertically or horizontally taking into account the restrictive conditions imposed by the dimensions of the renewable energy production system, Revista Termotehnica nr.2 3040 – 2018

[99] SR 6648-1:2014 Ventilation and air conditioning systems – Calculation of heat input from exterior - fundamental prescriptions

[100] SR 6648-2:2014 Ventilation and air conditioning systems - External climatic parameters
[106] Bejan A., Tsasaronis G., Moran M.., Thermal design and optimisation, John Wiley and sons, 1996
[107] Kotas T.J. The exergy method of thermal plant analysis, Department of Mechanical Engineering Queen Mary College University of London, Butterworths 1985