ENFOQUE PRÁCTICO ENLA ENSEÑANZA DE EL CICLO ORGÁNICO DE RANKINE (ORC) EN UN CURSO DE TERMODINÁMICA APLICADA

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A PRACTICAL APPROACH FOR TEACHING THE ORGANIC RANKINE CYCLES (ORCS) IN AN ADVANCED THERMODYNAMICS COURSE

ABSTRACT:

Higher Education Institutions must consider the most recently developed technologies to increase energy efficiency. A significant share of the heat used in industry is wasted while still being at usable temperature levels and hence a significant energy saving potential is present in this sector. The Organic Rankine Cycle (ORC) is a system that uses low-grade waste or renewable heat to produce electricity and lower grade heat and can be integrated into a variety of applications. In this paper, an introduction to ORCs is presented, and then, a practical example of a laboratory session using an experimental test bench based in this technology in a last year bachelor's degree course is detailed. A commercial ORC machine was run in the laboratory session, where the students were able to explore its operation through the graphical interface. They applied the main thermodynamic concepts in the interpretation of the behavior and seen the utility of this science in recently developed environmentally friendly technologies. Then, the students simulated a real case based on the valorisation of exhaust gases from an engine installed in a wastewater treatment plant. Students agreed that the combination of both parts in this session is beneficial for their understanding and that ORC machines are a viable solution to control climate change.

Keywords:Combined Heat and Power (CHP); Higher Education (HE); applied thermodynamics; laboratory session; experimental setup; real problem solving

RESUMEN:

Las instituciones de educación superior deben considerar las tecnologías desarrolladas más recientemente para aumentar la eficiencia energética. Una parte importante del calor utilizado en la industria se desperdicia mientras se mantiene en niveles de temperatura utilizables y, por lo tanto, existe un potencial significativo de ahorro de energía en este sector. El Ciclo de Rankine Orgánico (ORC) es un sistema que utiliza residuos de bajo grado o calor renovable para producir electricidad y calor de menor grado y se puede integrar en una variedad de aplicaciones. En este documento, se presenta una introducción a los ORC y, a continuación, se detalla un ejemplo práctico de una sesión de laboratorio con un banco de pruebas experimental basado en esta tecnología en un curso de licenciatura del año pasado. Se ejecutó una máquina de ORC comercial en la sesión de laboratorio, donde los estudiantes pudieron explorar su funcionamiento a través de la interfaz gráfica. Aplicaron los conceptos termodinámicos principales en la interpretación del comportamiento y vieron la utilidad de esta ciencia en tecnologías recientemente desarrolladas amigables con el medio ambiente. Luego, los estudiantes simularon un caso real basado en la valorización de los gases de escape de un motor instalado en una planta de tratamiento de aguas residuales. Los estudiantes acordaron que la combinación de ambas partes en esta sesión es beneficiosa para su comprensión y que las máquinas ORC son una solución viable para controlar el cambio climático.

Palabras clave: Producción combinada de calor y energía (CHP); Educación superior; termodinámica aplicada; sesión de laboratorio; banco de ensayos experimental; resolución de problemas reales

1.- INTRODUCTION

Thermodynamics courses are necessary for engineers to understand how energy is transferred [1]. The common concepts taught and practised in every thermodynamics course include basic thermodynamic cycles. Then, (mostly but not restricted to) engineering students can go deep in the different branches of applied thermodynamics, to be prepared to work in industrial processes, renewable energy installations, varied hot and cold production systems, and combined heat and power (CHP) plants, among many others. According to European Universities Association (EUA), universities have a critical role to play as key energy stakeholders so different energy technologies, systems, economies, and markets, among others, are all combined to solve the existing challenges holistically [2].

A technology that is becoming relevant in the recent years in the field of sustainable energy generation is the organic Rankine cycle (ORC), which can increase the global efficiency of different industrial and renewable energy sectors. Its operation is like that of a typical Rankine cycle, but instead of using water it uses an organic fluid with lower critical temperature to be used at lower temperatures, where most industrial waste heat can be reutilised in CHP processes [3]. Up to date, several examples of successful methods of teaching classical Rankine (steam power) cycle in higher education institutions can be found in the literature. Most of them include robust simulators because they can be developed for applied thermodynamics teaching to analyse different cycle configurations and operating conditions simply, and responding to the need for quick data and system performance analysis [4].

The real practising of these concepts shown in theory and practised with computer software must be considered to reach a deeper understanding of the concepts. Kandpaland Broman [5] include among their recommendations to strengthen renewable energy education programs the introduction of practising training to the students, for instance, by conducting laboratory sessions or visits to actual working systems. Bornasal et al.[6] concluded that the process of initiating, problematizing, and resolving is important to absorb new concepts so that the learning process follows a framework of conceptual growth that can be replicated in the courses.

However, ORC systems can be applied to small-scale applications and therefore offer a solution to study a novel sustainable energy application in universities. Meyer et al. [7] showed the design process required for the construction of a small-scale ORC test rig and that there were any problems with product selection, acquisition, and machine assembly. In this way, Bonk et al. [8] proposed and designed a micro-scale 1 kW ORC test rig for both educational and research purposes but at this time there are no results about the successful implementation for both applications.

Because of the notoriety of the ORC systems in the last years as a way of producing sustainable electricity [9] and that their scale is suitable for laboratories, their introduction into practising sessions of engineering studies can be successful to work thermodynamic concepts and to extend the ORC knowledge. The waste heat recovery is going to become very relevant to reach a decarbonisation of the industrial sector and the green electricity production. Despite the technology has been intensively investigated during the recent years, and many successful cases and technology providers can be found, it is still difficult to find it in comparison with other well-established technologies like photovoltaic panels. This work presents how a laboratory session using a commercial ORC module and real problem solving can be introduced and the main concepts to consider in the development of a laboratory session with different parts and approaches. The main tasks performed by the students, and the results and outcomes of this educational activity has been defined and justified. This session has a great replicability potential in many applied thermodynamics and industrial processes university courses and become a common learning activity because a significant number of higher education institutions have developed or purchased ORC test rigs for research that can be adapted for teaching.

2.- THE ORGANIC RANKINE CYCLE (ORC)

2.1.- THE ORC CYCLE

The ORC system uses a higher temperature source to produce mechanical energy and rejecting heat to lower temperature sources. Its basic operation follows the Rankine cycle principles and therefore presents the same components, and the working fluid (also known as the refrigerant) follows the same processes (Fig. 1). ORC cycles (both bottoming in a combined cycle and stand-alone) appear to be profitable in case of low-temperature heat demand. Otherwise, a flexible ORC is required to match the heat demand. For industrial users, a simpler configuration without ORC can be more competitive than a flexible ORC, based on upfront costs, discount rate, and feed-in tariffs.

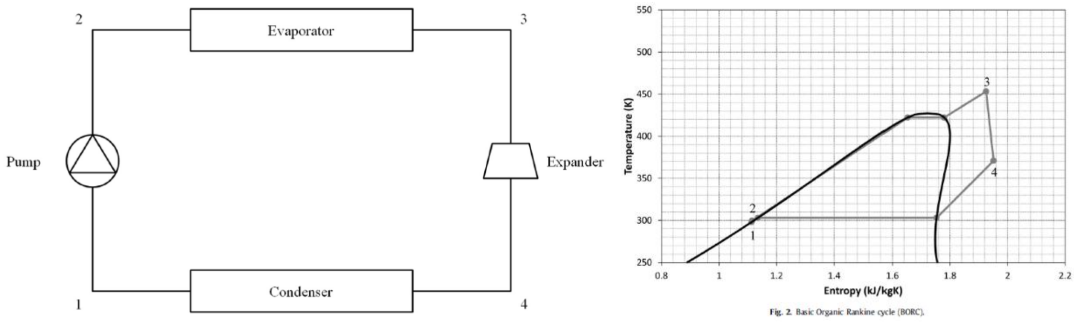


Fig. 1. Basic ORC schematic and its operation in a Ts diagram (using HFC-245fa)

From point 1, the saturated/subcooled liquid is pressurised using a pump, typically diaphragm type. Then, the thermal level of the working fluid increases by using an evaporator, in which the heat is typically exchanged using waste heat or renewable sources. There, the working fluid is first heated in liquid phase until reaching the saturation temperature at the corresponding pressure, then is evaporated, and in the final part of the evaporator this working fluid, in the gas phase, is superheated to have a dry expansion. Next, the working fluid is expanded, and there the energy of the fluid is converted into mechanical energy. A great part of it is converted into electrical energy which can be used for self-consumption, or it can be injected into the electricity grid. Finally, this thermodynamic cycle is closed by condensing the working fluid, after desuperheating it. Although the heat rejected by the condenser can be dissipated to the ambient, it is preferable to use it in another process that can reutilise this lower temperature waste heat. The thermal efficiency of the ORC cycles is calculated, dividing the output power generated per the input heat (Equation (1)), in the same way than conventional Rankine cycles.

$$\eta_{th} = \frac{\dot{W}_{turbine} - \dot{W}_{pump}}{\dot{Q}_{evap}} = \frac{(h_3 - h_4) - (h_2 - h_1)}{(h_3 - h_2)} \qquad (1)$$

Different ORC architectures have been proposed to enhance the system efficiency (higher ORC power output for the same heat input) by different methods. However, to be technically feasible and require minimum maintenance and reduce operational problems, their complexity must be limited. In this way, the regenerative configuration (Fig.A.1) highlights because it has energetic and operational benefits with the only addition of an extra heat exchanger, the regenerator (also called recuperator).

2.2.- ORC WORKING FLUIDS

The most extended ORC working fluid is the HFC-245fa (HFC: HydroFluoroCarbon) by its critical point adequate to offer high performance for this type of applications, zero ozone depletion potential (ODP), dry slope, high vapour density, high latent heat, and moderate pressures, among others. The main problem is its relatively high Global Warming Potential (GWP) value (858). Besides the many benefits offered by natural refrigerants, HFOs (HFO: HydroFluoroOlefin) and HCFOs (HCFO: HydroChloroFluoroOlefin) seem to be promising candidates to replace HFC-245fa in existing installations. Table A.1 (included in Appendix) shows the main properties of the HFC-245fa, and two candidates, HCFO-1223zd(Z) and HFO-1336mzz-Z, which the main benefit compared to HFC-245fa is the very low GWP value, approximately 1.

3.- ORC LABORATORY SESSION

3.1.- THE COURSE SELECTED TO IMPLEMENT THE SESSION

The course selected to introduce the ORC laboratory session is “Energy Management in Industrial Plants”, included in the 2nd semester of the Bachelor's Degree in Electrical Engineering. It is given in 45 classroom hours and 67.5 hours of personal work (4.5 ECTS, European Credit Transfer and Accumulation System), and the structure followed by it is shown in Fig.A.2.

The objective of the course is to meet the increasing demand for energy efficiency solutions in the industrial sector, focusing on the need for efficient management of energy resources. Thus, this course is meant to offer technical knowledge and tools to audit and improve the energy efficiency of different types of industrial plants, as well as to implement energy-saving measures. The laboratory sessions have the purpose of putting in contact the students with the practical aspects of the main concepts seen in the theory sessions through different methods, like laboratory practising or visiting real installations.

3.2.- STRUCTURE OF THE LABORATORY SESSION

The length of the laboratory session is 2 hours and 30 minutes, is composed of three main parts, the recommended maximum number of students is 10, and the lecturer should have experience in ORC systems. The session starts with an introduction to the technology, its range of temperatures and power, main applications, and main differences if compared to other waste heat recovery technologies, among others. Then, the main components (and typically required specifications), architectures and working fluids are commented, specifying their effect on the environment and climate change.

After that, the students are brought to the ORC module and examine the position of the components, and the professor explains the function of other additional components required for safety or correct operation. The ORC module is turned on by the professor, and some arbitrary conditions are set. The students observe the evolution of the measured parameters in a screen until it reaches steady-state conditions. Then, another arbitrary condition is selected, and when it reaches a steady-state, they compare the parameters measured with the previous situation to discuss the effect of the input conditions on the ORC and the electricity generation.

Finally, the students solve a problem related to a typical situation, taking data from a real case situation an discuss with the professor about the results. They must deliver to the professor the calculations made and the conclusions of the results to be evaluated.

4.- EXPERIMENTAL SETUP

The experimental setup used in the laboratory session is a 1.5 kW rated power output commercial ORC module based on a regenerative configuration and initially designed to be used with the HFC-245fa working fluid (Fig.2). The main application of the ORC module used is the small-scale CHP, and heat sink and source temperatures correspond to that of low-grade heat sources.

a)

b)

c)

Fig.2. a) Commercial ORC module, b) boiler and oil ring, and c) air-cooled chiller used for the laboratory session

The main components of the ORC module are expander based on volumetric (scroll) technology, brazed plates heat exchangers, and regenerative configuration. The operating conditions are set by two secondary circuits, one composed by a boiler where a continuously pumped thermal oil is heated by a set of resistances and simulates the waste or useful renewable heat, and another that exchanges heat with water in the condenser at lower temperatures and carries the heat to an air-cooled chiller. The maximum thermal oil inlet temperature is 160 °C and the maximum cooling water inlet temperature is 45 °C.

The ORC module is fully monitored for research purposes (Table 1), and this set of sensors will also be used to show to the students the working fluid operating parameters (temperature and pressure) that determinates the thermodynamic state of it in each point of the circuit. The working fluid mass flow rate, and secondary fluids volumetric flow rate are also collected as well as the electrical power generated by the expander and that consumed by the refrigerant pump. All the measurements, gathered each second, are continuously displayed on a screen, and the measurements can be registered for their further analysis.

Measured parameter	Sensor	Uncertainty
Temperatures	K-type thermocouples	±0.5 ºC
Pressures	Piezoelectric pressure transducers	±0.5 kPa
Working fluid mass flow rate	Coriolis mass flow meter	±0.3%
Electrical power	Digital wattmeter	±1.55%
Thermal oil volumetric flow rate	Vortex flowmeter	±0.028 m^3/h
Cooling water volumetric flow rate	Electromagnetic flowmeter	±0.5%

Table 1. Measured parameters, measuring instruments and measurement uncertainty

The students are asked to calculate the parameters shown in Table 2, where also the formulas required can be shown.

Parameter	Formula	Units
Net electrical power output ($\dot{W}$)	Directly measured	kW_e
Heat source heat transfer rate ($\dot{Q}_{evap}$)	$\dot{Q} = \dot{m}c_p\Delta T$	kW_{th}
Heat sink heat transfer rate ($\dot{Q}_{cond}$)	$\dot{Q} = \dot{m}c_p\Delta T$	kW_{th}
Electrical efficiency (η_{el})	$\eta_{el} = \dot{W}/\dot{Q}_{evap}$	%
Thermal efficiency (η_{therm})	$\eta_{therm} = \dot{Q}_{cond}/\dot{Q}_{evap}$	%
Global efficiency (η_{global})	$\eta_{global} = \eta_{el} + \eta_{therm}$	%

Table 2. Parameters calculated in the ORC characterisation

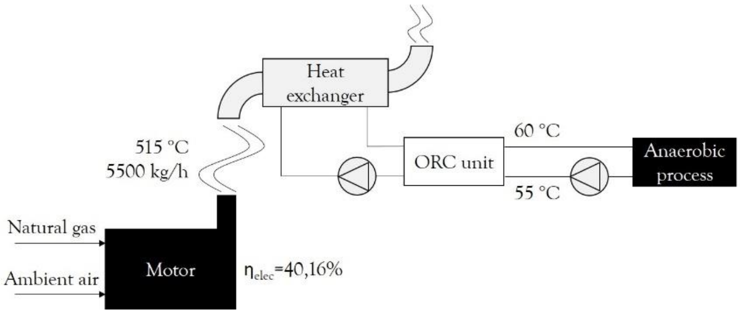
5.- CASE STUDY

The proposed case is the revalorization of waste heat profiting exhaust gases from a natural gas motor installed in a cogeneration system of a wastewater treatment plant. The characteristics of the motor are given in Table 3.

Parameter	Value
Electric efficiency	40.16%
Exhaust gases temperature	515 °C
Exhaust gases mass flow rate	5500 kg·h^{-1}

Table 3. Values of the proposed case motor

The proposal specifies that the waste heat recovery project includes a gas/thermal oil heat exchanger, a thermal oil circuit, and an ORC machine (Fig.3). Besides the electricity produced by the ORC machine, also the heat exchanged in the condenser is going to be used for the anaerobic digestion process in the wastewater treatment plant, at temperatures between 55 and 60 °C, so that the ORC is going to be used for CHP. The electricity output of the ORC is also given by the professor, as shown in Fig. 3.



ORC electricity output in kW		Condensation temperature (°C)		
		65	**55**	**45**
Evaporation temperature (°C)	**210**	315	330	-
	200	330	300	285
	190	305	285	265
	180	-	265	245

Fig.3. Schematic and conditions of the proposed project to the students

The students are asked to determine:

- the available thermal power of the exhaust gas of the natural gas motor (522 kW);
- the operating conditions of the commercial ORC module (profitable heat source heat transfer of 330 kW, exhaust gas output temperature of 303 °C);
- and the payback period of the investment considering that the ORC module is operating 8000 hours per year, the investment cost is 100000 €, and the electricity price is 15 c€ per kWh (yearly benefit of 42000 € and a payback period of 2.38 years).

6. OUTCOMES

The students have an adequate reaction to this complete laboratory session, and they obtained the results before finishing the laboratory session. This fact was favoured because of the reduced group and the experience of the professor that knew which aspects of the ORC module must be highlighted during the laboratory session. In the final opinion questionnaire completed by the students, from 1 (lowest satisfaction) to 5 (highest satisfaction), the average values for the answers were obtained between 3.6 and 4, resulting in the highest satisfaction with the skills possessed by the professor and the potential of application of ORC to halt climate change.

The students were interested and asked about the real utilisation of this new technology and in which field can be most commonly found. Also, they asked about typical design and operation problems seen in operating machines, and which technologies are the main competitors for the small-scale generation of electricity from waste or renewable heat.

This laboratory session was useful to make the students mostly remember the concepts seen in the basic thermodynamics and heat transfer courses. Additionally, very different concepts like heat exchanger design strategies, motor efficiencies, dry expansion, uncertainty propagation, or economic feasibility were put together to solve the proposed problems.

7.- CONCLUSIONS

New environmental challenges require well-prepared engineers, aware of the new solutions available in the market. Applied thermodynamic courses offer an excellent opportunity to introduce this kind of technologies, such as ORC. This paper presents the methodology and the results of an ORC laboratory session designed for bachelor's degree students.

The ORC operating principles, main applications, configurations, and working fluids have been exposed and can be used for the basic knowledge required. Same concepts must be transmitted to the students before starting the practical part of the session. The ORC used in this session is a commercial module in which new, environmentally friendly working fluids have been tested. The presence of this module offers a quick and economical solution for the laboratory session. The students have performed a real test and have observed which are the main parameters used to control its operation. From that, they have calculated some energy parameters relevant to characterise the ORC module. Finally, from a proposed case that use data from a real application (waste heat available in the exhaust fumes of a cogeneration motor), the students have selected an ORC solution, and they have calculated the economic feasibility of it.

The satisfaction of the students has been significant, and the application of this kind of practices is recommended for advanced courses of different kinds of bachelor's or master's engineering degrees. If no ORC module is available at the university, experimental data from literature can be retrieved, or a micro ORC system can be built.

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APPENDIX

Parameters	HFC-245fa	HCFO-1223zd(Z)	HFO-1336mzz-Z
Chemical name	1,1,1,3,3-pentafluoropropane	(Z)-1-Chloro-2,3,3,3-Tetrafluoropropane	cis-1,1,1,4,4,4-Hexafluoro-2-butene
Molecular weight (kg kmol^{-1})	134	130.5	164
Critical Temperature (ºC)/Pressure (MPa)	154.01/3.65	438.75K/3.57	171.3/2.90
Slope	Dry	Dry	Dry

OEL (ppm)	300	800	500
ASHRAE Standard 34 Safety Class	B1	A1	A1
ALT (year)	7.6	0.1096	0.060274
ODP/GWP	0/858	0.00034/1	0/2
Normal boiling point (NBP) (ºC)	14.81	17.97	33.40
NBP latent heat (kJ kg^{-1})	196.23	195.52	165.67
Evaporating pressure at 125ºC (MPa)	2.21	1.80	1.28
Condensing pressure [a] (MPa)	0.16	0.14	0.08
Vapour/liquid density [a] (kg m^{-3})	9.13/1333.5	7.65/1258.3	5.38/1359.5
Vapour/liquid c_p [a] (kJ kg^{-1} K^{-1})	0.96/1.33	0.84/1.25	0.87/1.21

Table A.1. Thermophysical properties of candidate working fluids. Thermophysical calculations based on [10].

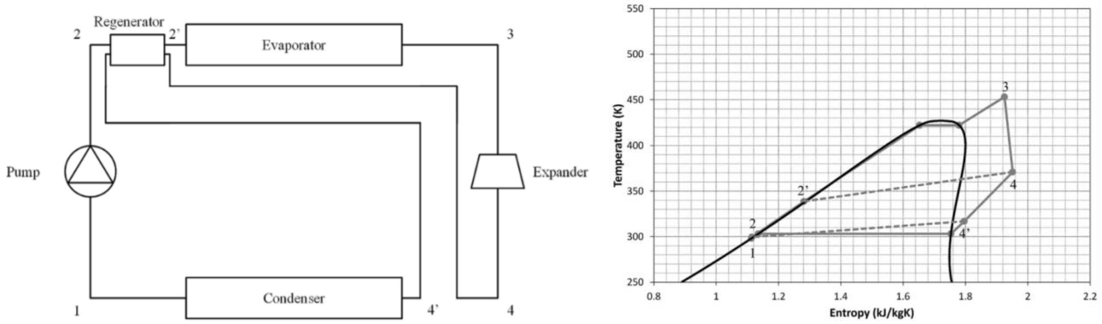

Fig. A.1. Regenerative ORC schematic and its operation in a Ts diagram (using HFC-245fa)

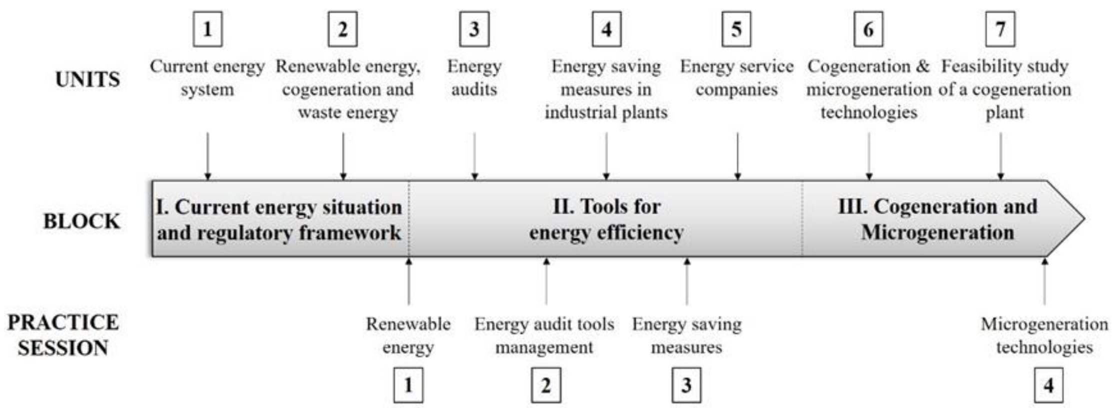

Fig. A.2. Structure followed by the Energy Auditing and Management course