



24th COBEM - 2017



24th ABCM International Congress of Mechanical Engineering
December 3-8, 2017, Curitiba, PR, Brazil

COBEM-2017-1179

EXERGY ANALYSIS OF A COUPLED UNIT TO PRODUCE ELECTRICAL ENERGY AND COLD WATER

Souza, R. J.

Medeiros Neto, J. L.

Federal University of Paraíba, University City, 58059900, João Pessoa, Paraíba, Brazil
ronelly84@hotmail.com; eng.joaomedeiros@gmail.com

Santos, C. A. C.

Federal University of Paraíba, University City, 58059900, João Pessoa, Paraíba, Brazil
carloscabralsantos@yahoo.com.br

Abstract. *This work presents an exergetic analysis of an Organic Rankine Cycle (ORC), used for recovery energy from low temperatures heat sources, connected to a Single-Effect Absorption Refrigeration System (ARS). Both are based on heat sources with reduced energetic availability cost such as biomass, geothermal, waste heat and solar energy. The ARS data were consulted in a catalog of commercial Absorption Chillers. The connection between the systems is essentially made through thermal exchanges involving the ORC condenser and a cold water storage tank located between the ARS and the ORC. Using the same heat source, the combination of both systems aims to produce the cooling effect and mechanical power, besides increasing the overall efficiency of the system. Classic thermodynamics models have been developed based on the determination of some input parameters such as the heat available at the thermal source, the pressure ratio in the ORC system and the cooling capacity of the ARS. The ORC system studied works with R134a as working fluid, whereas the ARS works with the lithium bromide-water pair. The simulation results showed that the connection between both systems, using the same heat source, increases the mechanical power of the ORC from 0.65 kW to 7.05 kW for an ARS cooling capacity varying from 5 TR to 50 TR. The energy efficiency remained the same (about 27%) for the same cooling capacity range, whereas the exergy efficiency increased from 49.6% to 51.2%.*

Keywords: *Organic Rankine Cycle, Absorption Refrigeration System, Coupled Unit, Exergetic analysis.*

1. INTRODUCTION

Over the last few decades, issues related to economic, social and environmental development have been heavily influenced by energy issues. The growing increase in world energy demand, especially in the economic developing countries, has triggered a great interest of the scientific community, to develop new technologies adapted to the economic and environmental concerns. Examples of these types of technology are systems powered by renewable energy sources or from waste heat from industrial processes (Mendoza, 2013).

Chen, C.-L. *et al.*, (2016) claim that after 1928, the world's population increased from 2 billion to 7 billion people over a period of 84 years. In addition, the forecast for 2024 is that this number will increase to 8 billion people, which causes concerns to government authorities and scientific communities. This increase of the population, together with the recent climate changes, generate the need for a greater consumption of energy.

A growing number of researchers have studied the performance of integrated systems, which are characterized by high efficiency in the thermal utilization of the energy source. Depending on the energy availability and the purpose of the system, different configurations and working fluids can be evaluated so that the best possible results can be achieved. A great advantage from some types of integrated systems is the possibility to use low and medium temperature thermal sources. This makes it possible to increase the amount of exergy transformed into useful product and decrease the amount of heat rejected into the atmosphere.

Different types of technology have been adopted in order to transform thermal energy from low temperature heat sources into mechanical energy and the cooling effect. Among the main technologies, the Organic Rankine Cycle (ORC) is one of the most outstanding to produce mechanical energy, due to the simplicity and availability of its components, as well as the relatively easy and inexpensive maintenance (Quoilin, 2009) and the Absorption Refrigeration Systems (ARS) to produce the cooling effect, due to the low need of electric power.

The ORC system is characterized by using an organic fluid as working fluid instead of water. One of the main characteristics of the organic fluid is the low boiling temperature compared to that of the water. For this reason, some heat sources such as geothermal, solar, biomass and waste heat from industrial processes can be used to convert thermal energy into mechanical energy (Chaiyat, 2015).

The analysis made by Aman *et al.*, (2013) showed the potential of an ARS, operating with the ammonia - water pair, for use in residential air conditioning. The power of the analyzed system was 10 kW, powered by solar thermal energy. Through energy and exergy analysis, it was discovered that the absorber was the equipment where the greatest exergy loss occurred (63%), followed by the generator (13%) and the condenser (11%). In addition, it has also been shown that the exergy losses in the condenser, the absorber, the generator and the evaporator increase with temperature.

The study conducted by Chaiyat and Kiatsiriroat (2015) showed the feasibility of a method of combining an ORC system with an ARS to increase efficiency and reduce the condensation temperature of the ORC system. In this case an ORC system, operating with R245fa as working fluid, and an ARS, operating with the pair lithium bromide – water, were used. It was observed that the efficiency of the ORC system increased by 7%, while the ARS provided 15°C cooled water.

Grosu, L. *et al.*, (2015) developed an exergetic analysis to evaluate a solar driven combined cycle consisting of an ORC system (using R245fa as working fluid) and an ARS (operating with the water-lithium bromide pair). The objective of the combined system is the power supply and cooling for a building of a particular university. The results showed that if solar collectors supplied water at 140°C and mass flow rate of 0.5 kg/s, the system could provide a mechanical power of approximately 5.24 kW and a cooling capacity of 45.6 kW. The overall thermal efficiency and exergy efficiency were approximately 38% and 26%, respectively.

Energy and exergy analyzes, led by Mohammadi *et al.*, (2017), evaluated the performance of the integration of compressed air energy storage systems with Combined Cooling, Heating and Power Systems (CCHP systems). The latter consists of a gas turbine, an ORC system (using the Toluene as working fluid) and an Absorption System (operating with the water-ammonia pair). It was observed that, for specific operating conditions, the combined system analyzed can provide a net power of 33.67 kW, a cooling load of 2.56 kW and 1.82 ton of hot water per day, with an overall efficiency of 53.94%.

Rubio-Maya *et al.*, (2016) conducted an economic-technological analysis of a geothermal driven polygeneration system. The system, in the form of a cascade, is composed of an ORC machine (1st level), an Absorption System (2nd level) and a heat exchanger (3rd level). These three thermal levels produce power, cooling and useful heat at the same time. The study concluded that, despite the relative low efficiency of the ORC systems (around 10%), the cascade configuration not only increases the overall energy efficiency of the system but also its profitability. In addition, the low thermal efficiency of the ORC is compensated by the fact that more thermal energy is being transferred to the next thermal level.

Thus, the studies cited so far address four different types of thermal sources. These are: combustion gases, solar energy, natural gas and geothermal. Among these types, the most abundant and easiest to capture is solar energy. Herold *et al.*, (2016) state that solar energy being used as an energy source for refrigeration is a simple concept and can be developed through photovoltaic systems (for vapor compression refrigeration systems) or solar thermal energy (for absorption or adsorption systems). For the same authors, despite the benefits and recent falls in prices of solar energy capture systems, there are many challenges in implementing these systems. An example would be the thermal delay associated with the thermal capacitance of the system. Another example is the need of refrigeration at night, which would lead to hybrid systems. Herold *et al.*, (2016) also provide an idea of the efficiency of solar driven Absorption Refrigeration Systems. Although this efficiency depends on factors such as the design of the cycle and the temperature of the thermal source, single and double effect Absorption Systems can reach COP of approximately 0.46 and 0.65, respectively. The Vapor Compression Systems, powered by photovoltaic energy, can reach a COP of 0.45.

In a detailed study about Organic Rankine Cycle (ORC), Macchi and Astolfi (2017) devoted an exclusive chapter to ORC systems powered by solar energy. According to them, this type of system can be applied to electrical power supply (for the conventional electrical network) and isolated systems for cogeneration purposes. Energy storage, due to the intermittent characteristic of the solar energy supply, is a necessity of any isolated system. However, if this storage is properly sized, the use of ORC systems powered by solar energy becomes economically attractive (especially in isolated areas), when compared with conventional systems such as diesel engines or photovoltaic systems. ORC systems powered by solar energy can also be used in a hybrid way, i.e. if there is no thermal storage system, they can be configured in parallel with other types of systems such as photovoltaic, fuel cells, wind turbines, waste heat recovering boilers, etc. The main consequences of this type of configuration are the reduction in the consumption of fuels and the increase of the overall efficiency of the system.

In this study, an exergy analysis of an ORC system coupled to a single-effect ARS will be presented. The cooling capacity of the Absorption Chiller is varied according to commercially available systems. Both systems are fed from the same thermal source. The combination of the systems has the aim of producing the cooling effect and increasing the mechanical power obtained from the ORC system, with the consequent increase of the overall efficiency of the system.

2. SYSTEM DESCRIPTION

The system consists of an Organic Rankine Cycle (ORC), an Absorption Refrigeration System (ARS) and two thermal storage tanks for the hot water and cold water circuits. The ORC system comprises a steam generator, an expansion device, a condenser, a liquid accumulator and a pump.

For this work, commercial Absorption Chillers data were used, available in a specific catalog (Johnson Controls, 2016). Such devices are single-effect systems, which operate with the water-lithium bromide pair and are fed by hot water. According to the manufacturer, they can significantly reduce the operating costs of the system compared to electrically powered systems. Besides the low energy consumption, the manufacturer states that these systems are a very appropriate way for the energy utilization of thermal sources such as biomass, waste heat from industrial processes and solar energy. The feed temperature of such systems may range from 70 to 95°C. The operating principle of the system is shown in Fig. 1.

At point 5, superheated steam of R134a leaves the steam generator and is expanded until it reaches the state of point 1, thereby generating the desired mechanical power. Then, the working fluid follows its course through the condenser that will remove the heat from the system. At point 2, the R134a will be in the saturated liquid state, so to ensure that only liquid enters the pump, the fluid will pass through a liquid accumulator so that when it arrives at point 3 it is in the compressed liquid state. From point 3 to point 4, the working fluid passes through a pump that provides the pressure required for the fluid to enter the steam generator, receives heat from the heat source and restarts the cycle at point 5.

Points 6 and 7 are, respectively, the inlet and outlet of the cold water subsystem responsible for removing heat from the ORC system, whereas points 8 and 9 are the input and output of the hot water subsystem responsible for the supply of thermal energy.

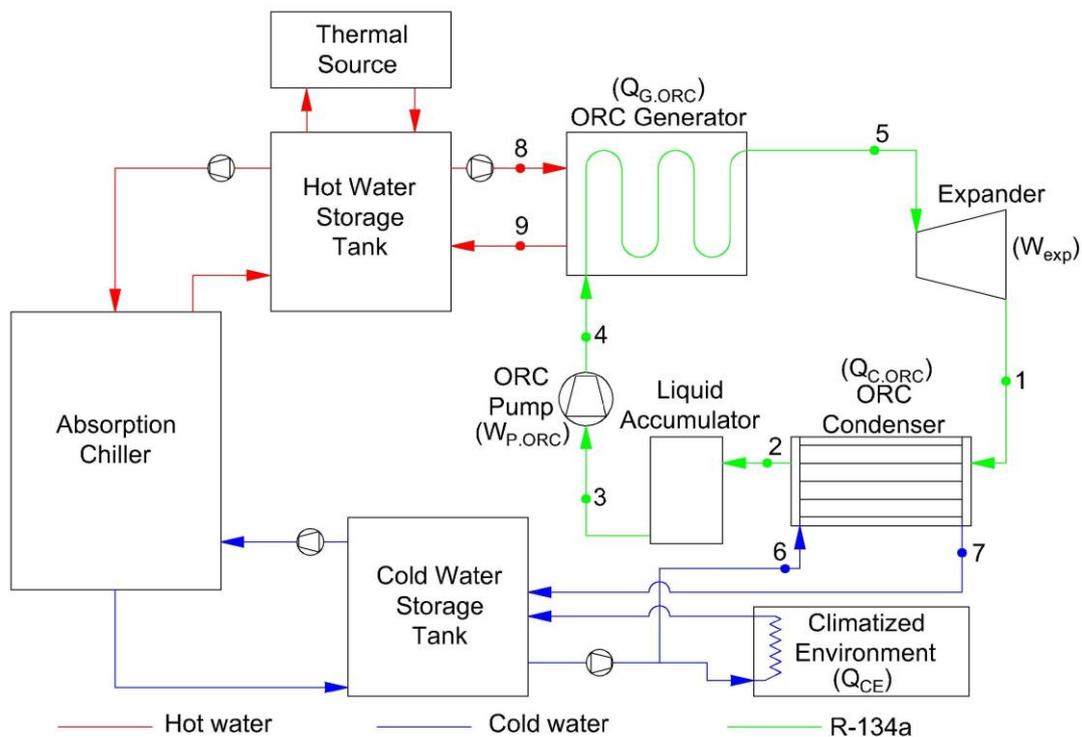


Figure 1. Schematic diagram of the ORC system coupled to a ARS.

The main objective of the coupling of the ORC system with an Absorption Chiller is to reduce the condensation temperature of the ORC system, which, consequently, will allow it to obtain higher values of mechanical power. The heat removal of the ORC system is done by a cold water subsystem, through heat exchanges with the ARS evaporator. In addition, the same subsystem is used for air conditioning of a given environment. The ARS feed is made from the same thermal source used for the ORC system. Therefore, the efficiency in the use of the energy tends to increase, since the coupled system also allows to obtain the refrigerating effect as a product, as well as increase the production of mechanical power.

3. THERMODYNAMIC MODEL

The mathematical model of the system considers that the hot and cold water storage tanks are appropriately sized so that it provides the temperature levels required by the ORC and ARS systems. Absorption Chillers data are taken from catalogs of leading manufacturers in the market. With such data it is possible to estimate the mechanical power that will be delivered by the ORC system.

Data relating to energetic and exergetic efficiency, net power and irreversibilities are obtained from input parameters such as cooling capacity of the Absorption Chiller and energy availability of the heat source.

This study, which is restricted to steady-state flow of the working fluid, is based on the principle of mass conservation, the first law (energy analysis) and second law (exergy analysis) of thermodynamics.

3.1 Energetic analysis

The energy analysis of the equipment was done by applying mass conservation (Eq. (1)) and the first law of thermodynamics (Eq. (2)), assuming that each component of the cycle is enclosed by a control volume.

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} = \dot{m} \quad (1)$$

where \dot{m}_{in} is the mass flow at the inlet, \dot{m}_{out} is the mass flow at the outlet and \dot{m} (kg/s) is the mass flow due to the steady-state.

$$\dot{Q}_{C.V.} + \sum \dot{m}h_{in} = \sum \dot{m}h_{out} + \dot{W}_{C.V.} \quad (2)$$

where $\dot{Q}_{C.V.}$ and $\dot{W}_{C.V.}$ (both in kW) are, respectively, the heat and the work flowing through the control volume, h_{in} and h_{out} (both in kJ/kg) are, respectively, the specific enthalpy at the inlet section and the outlet section of the equipment in question.

For this work, the heat rejected by the ORC system is directly linked to the cooling capacity of the Absorption Chiller. For calculations purposes, it was considered that the mentioned cooling capacity is divided equally between the ORC system and the air-conditioned environment (\dot{Q}_{CE}), according to Eq. (3). Thus, assuming a control volume enclosing the condenser and the liquid accumulator of the ORC system, we obtain the Eq. (4).

$$\dot{Q}_{C.ORC} = \dot{Q}_{CE} \quad (3)$$

$$\dot{Q}_{C.ORC} = \dot{m}(h_3 - h_1) \quad (4)$$

where h_3 and h_1 are, respectively, the specific enthalpies at the liquid accumulator outlet and at the condenser inlet.

Considering that the pump of the ORC system is adiabatic and isentropic, and that the supplied power to it is 0.03 kW (NRP catalog), the enthalpy at point 4 can be obtained by Eq. (5).

$$\dot{W}_{P.ORC} = \dot{m}(h_3 - h_4) \quad (5)$$

where h_4 is the specific enthalpy at the input of the ORC steam generator. Equation (6) provides the supplied heat to the cycle through the steam generator of the ORC system. As there is no work involved in the process and the parameters of point 5 are specified as input data, the supplied heat is expressed as follows:

$$\dot{Q}_{G.ORC} = \dot{m}(h_5 - h_4) \quad (6)$$

where h_5 is the specific enthalpy at the steam generator outlet. The work obtained from the expansion device, considering that the expansion process occurs adiabatically and isentropically, is given by Eq. (7).

$$\dot{W}_{exp} = \dot{Q}_{G.ORC} - |\dot{Q}_{C.ORC}| \quad (7)$$

Thereby, the net work obtained from the cycle can be expressed by Eq. (8), and the thermal efficiency of the coupled system (Fig. (1)) is calculated through Eq. (9).

$$\dot{W}_{net} = \dot{W}_{exp} - |\dot{W}_{P.ORG}| \quad (8)$$

$$\eta_{thermal} = \frac{\dot{W}_{exp} + |\dot{Q}_{CE}|}{\dot{Q}_{G.ORG} + \dot{Q}_{G.ARS}} \quad (9)$$

where \dot{Q}_{CE} is the product obtained from the air-conditioning environment and $\dot{Q}_{G.ARS}$ is the heat that should be supplied to the ARS.

3.2 Exergetic analysis

According to (Moran, 2016), exergy can be defined as an opportunity to produce work when two systems, in different thermodynamic states, come into contact, that is, it is the maximum theoretical work that can be obtained as the two systems come into equilibrium.

Energy analysis does not return any information concerning the irreversibilities of thermodynamic processes. However, exergetic analysis provides this information as well as providing means of knowing in which equipment the exergy loss can be minimized.

The exergy balance for a control volume, considering the steady-state process, is obtained by Eq. (10).

$$\dot{E}_D = \sum_j \left(1 - \frac{T_0}{T_j} \right) \dot{Q}_j - \dot{W}_{CV} + \sum_i \dot{m}_i e_i - \sum_o \dot{m}_o e_o \quad (10)$$

where \dot{E}_D (kW) represents the destroyed exergy rate or the irreversibility of a given component. Analyzing the right side of Eq. (10), \dot{Q}_j represents the heat transfer rate at the boundary where the instantaneous temperature is T_j , \dot{W}_{CV} is the mechanical power transferred into or out of the control volume and the last two terms represent the amount of exergy entering and exiting the control volume with respect to mass transfer (Aman, 2014).

Bearing in mind that kinetic and potential exergies can be neglected, exergy per unit mass of a fluid flow can be obtained through Eq. (11).

$$e = h - h_0 - T_0(s - s_0) \quad (11)$$

where e is the specific exergy flow, in kJ/kg, at the point in question. The specific enthalpy h (kJ/kg) and the specific entropy s (kJ/kg.K) are both with respect to the temperature T of the analyzed point. The terms with index "0" represent the reference state data. The temperature and pressure values for referred state were, respectively, 25°C and 1.013 bar.

Based on the information presented so far, the irreversibilities of each equipment can be found through equations 12 to 18.

Expansion device:

$$\dot{E}_{D,exp} = \dot{m}(e_5 - e_1) - \dot{W}_{exp} \quad (12)$$

Condenser:

$$\dot{E}_{D,cond} = \dot{m}(e_1 - e_2) + \dot{m}_{cw}(e_6 - e_7) \quad (13)$$

where \dot{m}_{cw} is the mass flow rate of the cold water subsystem and can be expressed by Eq. (14).

$$\dot{m}_{cw} = \frac{|\dot{Q}_{C.ORG}|}{c_{p,water}(T_7 - T_6)} \quad (14)$$

Liquid Accumulator:

$$\dot{E}_{D,LA} = \dot{m}(e_2 - e_3) \quad (15)$$

ORC Pump:

$$\dot{E}_{D,P} = \dot{m}(e_3 - e_4) - \dot{W}_{P,ORC} \quad (16)$$

ORC Steam Generator:

$$\dot{E}_{D,gen} = \dot{m}_{hw}(e_8 - e_9) + \dot{m}(e_5 - e_4) \quad (17)$$

where the mass flow of the hot water subsystem (\dot{m}_{hw}) is given by Eq. (18).

$$\dot{m}_{hw} = \frac{|\dot{Q}_{G,ORC}|}{c_{p,water}(T_8 - T_9)} \quad (18)$$

Therefore, the total exergy destroyed is given by Eq. (19).

$$\dot{E}_{D,total} = \dot{E}_{D,exp} + \dot{E}_{D,cond} + \dot{E}_{D,LA} + \dot{E}_{D,P} + \dot{E}_{D,gen} \quad (19)$$

The exergy efficiency for the ORC system (Eq. (20)) can be calculated by the ratio between the exergy of the product and the exergy of the input. For the case under study, the exergy of the input will be the exergy difference between points 5 and 4.

$$\varepsilon = \frac{\left(\frac{\dot{W}_{exp}}{\dot{m}} \right) + (e_1 - e_2)}{2(e_5 - e_4)} \quad (20)$$

where it is considered that the exergy variation of the air-conditioned environment is equal to the exergy variation between the input and output of the ORC condenser. It is also considered that the exergy variation in the ARS generator is equal to the exergy variation in the ORC steam generator.

3.3 Important assumptions

The present work was developed assuming some considerations for the systems involved, as follow:

- Steady state conditions;
- Equipment and piping are considered completely insulated. Eventual energy losses due to heat transfer are neglected;
- The pump and the expander are isentropic devices;
- The power considered for the pump was 0.03 kW;
- The thermal fluid storage tanks are appropriately sized to meet the demands of the systems;
- One of the proposals of this work is the use of thermal energy sources that require low cost of operation, such as solar, geothermal, waste heat and biomass;
- The thermal load removed from the air-conditioned environment is of the same order as the thermal load drawn from the ORC condenser;
- The power of the auxiliary circulation pumps is not taken into account in this study;
- The ARS performance is not scope of this work.

4. RESULTS AND DISCUSSIONS

According to the thermodynamic model described in section 3, it was possible to determine the performance of the system under different working conditions. The power obtained from the ORC system (according to the cooling capacity of the Absorption Chiller), the energy efficiency, the exergy efficiency and the destroyed exergy (irreversibilities) were determined.

Figures 2 and 3 refer to simulations made for 5, 10, 20, 30 and 50 TR cooling powers, for input pressure and temperature of 14 bar and 90°C, respectively, and for pressure ratio of 2.

Figure 2 shows the influence of the increase of the Absorption Chiller's cooling capacity on the net power obtained from the ORC system and the total exergy destroyed. This net power ranges from 0.65 kW to 7.05 kW for cooling capacities from 5 to 50 TR. The total destroyed exergy (irreversibilities) increases from 0.55 kW to 5.4 kW for the same range of cooling capacities. The increase in power is attributed to the greater amount of heat that can be withdrawn from the ORC system. Therefore, it is possible to design an ORC system with a greater capacity, thus allowing the selection of a bigger expansion device. The fact that more heat can be withdrawn from the ORC system implies that a greater amount of heat is being supplied to the cycle. This lead, as shown in Fig. 2, to the increase in the system irreversibilities caused mainly by the temperature difference between the hot and cold fluids and the losses in the expansion process (Wang, 2013).

Another fact, which must be considered, is that the pump power of the ORC system was considered to be the same for each calculated condition of the system. This implies that the actual net power levels, obtained by the cycle, are discretely smaller since the power obtained from the expansion device is much greater than the power supplied to the pump.

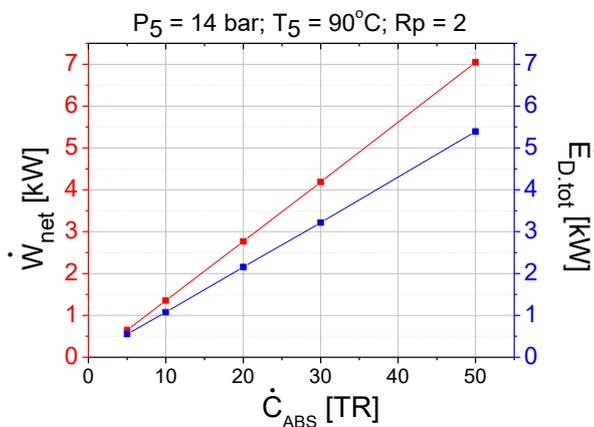


Figure 2. Effect of the refrigeration capacity of the Absorption Chiller on the net power and the destroyed exergy of the ORC system.

The energetic and exergetic efficiencies of the coupled system (Fig. 3) are obtained through equations 9 and 20, respectively. The first law analysis resulted in constant efficiency values around 27.3%, for Chiller Absorption refrigeration capacities ranging from 5 to 50 TR. The values for second law efficiency ranged from 49.6% to 51.2% for the same refrigeration capacities range. This increase in exergetic efficiency stems from the fact that the power obtained from the ORC system increases as the Chiller's cooling capacity increases.

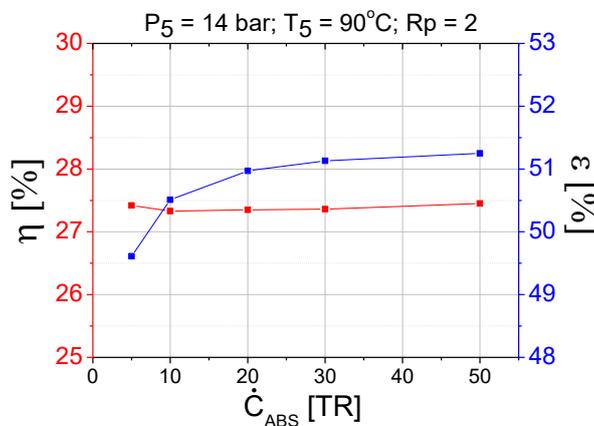


Figure 3. Influence of the Absorption Chiller's cooling capacity on the energy and exergy efficiencies of the ORC system.

Figure 4 provides information about net power and total destroyed exergy, as a function of the inlet temperature of the expansion device. The fixed operating conditions were: 14 bar pressure at the inlet expansion device, pressure ratio

of 2 and Absorption Chiller's cooling capacity of 10 TR. As the temperature rises from 70°C to 90°C, the net power increases slightly from 1.21 to 1.35 kW, a fact that can be explained by the increase of the entropy at the expander inlet. For the same temperature range, the destroyed exergy increases from 0.55 to 1.1 kW, a circumstance that results from the increase of the irreversibilities of the system.

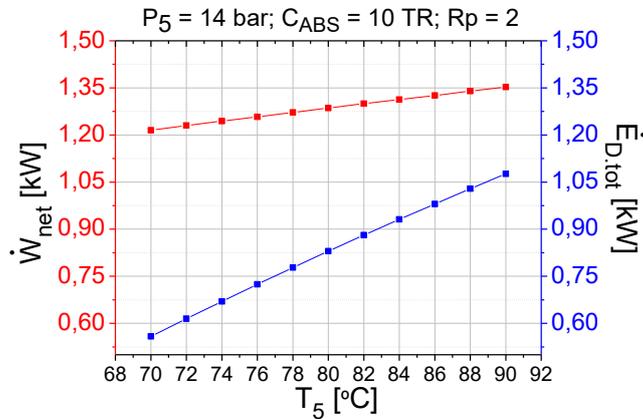


Figure 4. Effect of the expansion device inlet temperature on net power and exergy destroyed of the ORC system, for the same Absorption Chiller's cooling capacity (10 TR).

The analysis of equations 9 and 20 come to the results in Figure 5 by keeping the inlet pressure of the expander, The Absorption Chiller's cooling capacity and the pressure ratio constant. This figure shows the behavior of the first and second law efficiencies as functions of the inlet temperature at the expansion device. Energy efficiency remains practically constant around 27.2%. This occurs only due to the discrete increase in the net power obtained from the ORC system, as observed in Fig. 4, since this efficiency does not consider the irreversibilities of the system. In the case of the exergetic efficiency, a decrease from 52.1% to 50.5% is observed, with the variation from 70°C to 90°C at the point 5 temperature. This decrease in the exergetic efficiency stems from the increase of irreversibilities caused by the increase in temperature. Since, the exergetic variation in the ORC generator and in the ARS generator are considered the same for the present case, then this factor has an even greater influence. In contrast, for the same temperature variation, the net power is also increasing. As a result, the drop of the exergy efficiency is attenuated.

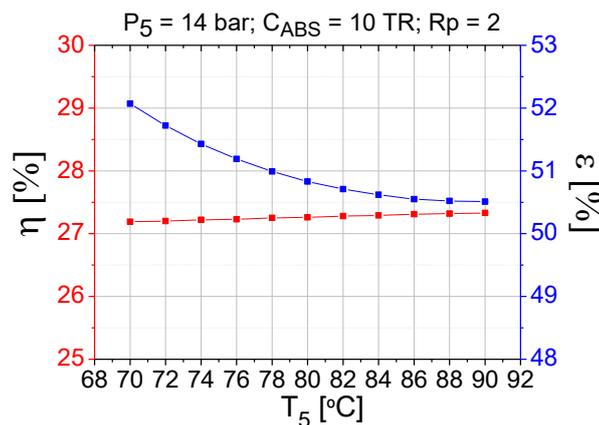


Figure 5. Influence of the expansion device inlet temperature on the energetic and exergetic efficiencies of the ORC system, for the same Absorption Chiller's cooling capacity (10 TR).

5. CONCLUSIONS

This work proposes the optimization of an Organic Rankine Cycle (ORC) by coupling to an Absorption Refrigeration System (ARS) which refrigeration capacity was varied according to commercially available Chillers. Both systems are powered by the same thermal source. The main objectives were the reduction of the condensation temperature of the ORC system, the possibility of designing a higher capacity ORC system and consequently the net power obtained, and the exergetic analysis of the system.

Mathematical models of the ORC system were used to analyze the performance of the system in different working conditions. Absorption Chillers with cooling capacities of 5, 10, 20, 30 and 50 TR were selected from a specific catalog. Such equipment are single-effect systems, which operate with the lithium bromide-water pair, are fed by hot water and can considerably reduce operating costs compared to electrically powered Chillers.

The results show that by increasing the cooling capacity of the Absorption Chiller it is possible to design higher capacity ORC systems. Cooling capacities ranging from 5 to 50 TR result in an increase of 0.65 kW to 7.05 kW, in the net power of the ORC system, a fact that can be explained by the greater amount of heat being withdrawn from the ORC system. However, it was observed that irreversibilities increase from 0.55 kW to 5.4 kW for the same range of cooling capacities. For these working conditions, energy efficiency remained approximately constant at around 27.3%, since it does not consider the irreversibilities of the system, while the exergy efficiency increased from 49.6% to 51.2%.

Results were also obtained to evaluate the effect of the input temperature, of the expansion device, on the performance of the system. The temperature was varied from 70°C to 90°C, while the expander inlet pressure, the pressure ratio and the cooling capacity of the Absorption Chiller were kept constant at 14 bar, 2 and 10 TR, respectively. The net power obtained from the ORC system discreetly increased from 1.21 kW to 1.35 kW while the destroyed exergy increased from 0.55 kW to 1.1 kW. For the same operating conditions, the first law efficiency remained constant at 27.2% while the second law efficiency decreased from 52.1% to 50.5%, a fact that can be explained by the increase in temperature.

In the sense of the enrichment of the analysis done in this work, in future works, it would be interesting to consider dimensioning the storage tanks of thermal fluid as well as the environment to be conditioned. With respect to the ORC system, the analysis of the system operating with different working fluids and the selection of the expansion device according to the capacity of the Absorption Chiller would be of great importance for a more detailed study of the system. Finally, the Exergoeconomic analysis would identify the costs inherent in the acquisition of equipment, acquisition of inputs and operating costs.

6. ACKNOWLEDGEMENTS

The first author acknowledges the financial support of the Conselho Nacional de Desenvolvimento Tecnológico – CNPq, and the second author the financial support of the Fundação de Apoio à Pesquisa do Estado da Paraíba – Fapesq.

7. REFERENCES

- Aman, J., Ting, D.S.-K., Henshaw, P. "Residential solar air conditioning: Energy and Exergy analyses of an ammonia-water absorption cooling system", *Applied Thermal Engineering*, 62 (2013) 424-432.
- Chaiyat, N., Kiatsiriroat, T. "Analysis of combined cooling heating and power generation from organic Rankine cycle and absorption system", *Energy*, 91 (2015) 363-370.
- Chen, C.-L., Li, P.-Y., and Le, S. N. T. "Organic Rankine Cycle for waste heat recovery in a refinery", *Industrial & Engineering Chemistry Research*, 55 (2016) 3262-3275.
- Johnson Controls, 2016. "York Commercial & Industrial HVAC" <http://www.johnsoncontrols.com/nl_nl/-/media/jci/be/netherlands/products/files/be_york_chillers_and_heatpumps_en_2016.pdf>
- Grosu, L., Marin, A., Dobrovicescu, A., and Conde, D. Q. "Exergy analysis of a solar combined cycle: organic Rankine cycle and absorption cooling system", *International Journal Energy Environment Engineering*, 07 (2016) 449-459.
- Herold, K. E. et al. "Absorption Chillers and Heat Pumps", Second Edition, CRC Press, 2016.
- Aman, J., Ting, D.S.-K., Henshaw P. "Residential solar air conditioning: Energy and exergy analyses of an ammonia-water absorption cooling system ", *Applied Thermal Engineering*, 62 (2014) 424-432.
- M.J. Moran, H.N. Shapiro, *Fundamentals of Engineering Thermodynamics*, Wiley, 2006.
- Macchi, E. e Astolfi, M. "Organic Rankine Cycle (ORC) Power Systems. Technologies and Applications", Woodhead Publishing Series in Energy, Number 107, 2017.
- Mendoza L. C.; Caracterización de un expansor scroll para ciclos combinados de potencia y refrigeración por absorción. Tesis Doctoral. Universitat Rovira i Virgili, Tarragona, 2013.

Souza, R. J., Medeiros Neto, J. L. and Santos, C. A. C.
Exergy Analysis of a Coupled Unit to Produce Electrical Energy and Cold Water

Mohammadi, A., Ahmadi, M. H., Bidi, M., Joda, F., Valero, A., Uson, S. "Exergy analysis of a Combined Cooling, Heating and Power system integrated with wind turbine and compressed air energy storage system", *Energy Conversion and Management*, 131 (2016) 69-78.

NRP catalog. "National Refrigeration Products". <<http://www.nrproducts.com/products/PDF/NRP-Catalog.pdf>>

Quoilin, S., Lemort, V., and Lebrun, J. "Experimental study and modeling of an Organic Rankine Cycle using scroll expander", *Applied Energy*, 87 (2009) 1260-1268.

Rubio-Maya, C., Martínez, E. P., Romero, C. E., Díaz, V. M. A., Pacheco-Ibarra, J. J. "Techno-economic assessment for the integration into a multi-product plant based on cascade utilization of geothermal energy", *Applied Thermal Engineering*, 108 (2016) 84-92.

Wang, D., Ling, X., Peng, H., Liu, L., Tao, L. "Efficiency and optimal performance evaluation of organic Rankine cycle for low grade waste heat power generation", *Energy*, 50 (2013) 343-352.

8. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.