ISSN 1392-1207. MECHANIKA. Vol. 29, No. 3, 2023: 200–206

Parametric Study on the Exergy Analysis of a Dual Evaporator Cooling Cycle Powered by the Organic Rankine Cycle

Rabah TOUAIBI*, Hasan KÖTEN**
**Laboratory of Industrial Fluids, Measurements and Applications (FIMA), Faculty of Science and Technology, Khemis Miliana University, Algeria, E-mail: r.touaibi@univ-dbkm.dz*
***Department of Mechanical Engineering, Istanbul Medeniyet University, Istanbul, Turkey,*
E-mail: hasan.koten@medeniyet.edu.tr

https://doi.org/10.5755/j02.mech.32652

1. Introduction

Exploitation Refrigeration is the most common refrigeration approach applied in vapor compression and has been used in widespread applications including water chillers, cold spaces, and air conditioning. It has shown high efficiency and can exploit a wide variety of refrigerants as the working fluid. What is more, it is compact. However, the Vapor-compression refrigeration system consumes higher-quality electrical energy to run its compressor; Electricity consumption due to refrigeration installations constitutes 15% of the global electricity production [1]. The fast development of the economy in current years has led to the issues of energy scarcity and environmental contamination that are attracting worldwide attention. Renewable energy and industrial waste heat recovery have become efficient strategies for rational use of fossil fuel and mitigating environmental problems. In another study, air conditioning systems found to constitute around 30-50% of electricity demand in cities. The development of renewable energies and the recovery of waste heat have long been imperatives of economic growth. Many forms of low-grade energy, such as industrial waste heat, geothermal and solar, are widely considered renewable energy sources, helping to reduce energy scarcity and environmental pollution. The ORC cycle is an effective low-power conversion solution due to its simplicity, stability, and safety advantages [2]. Moreover, many low-power ORC cycle energy recovery systems have been widely studied and applied in recent years [3-8]. In an attempt to improve the ORC's efficiency cycle, new systems joining the refrigeration cycle and the ORC have been developed. The proposed system possessed a higher thermal efficiency and power and cooling capacity than a single ORC system. This combined system has gained significant research attention because the energy exploited by refrigeration and air-conditioning equipment is considered as the largest industrial energy consumption [9]. Combined systems are commonly classified into different categories based on different refrigeration cycles [10-14]. The Rankine cycle was combined with an absorption cooling cycle, and water-ammonia was utilized as the working fluid [15, 16]. Zahedi et al.; proposed a combined cycle consisting of the ejector refrigeration cycle and Rankine cycle, in this paper, the authors propose a combined system comprising a hybrid Rankine cycle and an ejector refrigeration cycle to generate thermal energy and refrigeration [17]. Elakhdar et al., studied a thermal system combining ejection refrigeration and the organic Rankine cycle to produce electricity using a parabolic solar panel. The suggested solar thermal system composed of two cycles: combined cycles and a solar collector, where the combined cycles are an ejector refrigeration cycle and an ORC cycle. In this context, a solar thermal system is generated to determine and monitor the working fluid's outlet temperature and the absorber and glass temperatures of the parabolic receiver [18]. Salim et al. were also interested in optimizing an ORC cycle and a steam compression cooling cycle for heat sources with temperatures between 120°C and 150°C; with the main purpose to find an optimal system using the efficiency and cost forms, a sensitivity analysis was performed to optimize the system [19]. Kaşka et al, made a study on the performance of the refrigeration cycle combined with the ORC cycle, which allows cooling hydrogen at the inlet of the compressor providing compression at constant temperature in the Claude cycle intended for liquefaction of hydrogen from a geothermal source [20]. Rabah et al. carried out a novel study on a combined system that was proposed to recuperate thermal energy at moderate temperature through the use of a cascaded ORC cycle to feed a cascaded cooling cycle; An energy and exergy analysis is performed on the studied system in order to determine its performance using diverse working fluids under the same experimental conditions, considering the effect of some operating parameters on the cycle performance [21].

This study examines the performance of a combined power and cooling system comprising an organic Rankine cycle and a dual evaporator cooling cycle to improve its performance based on an energy and exergy analysis considering that the field of cold production consumes a lot of energy either for refrigeration or air conditioning. The organic Rankine cycle has become an important technology in the field of renewable energy and waste heat recovery. In this work, this technology is proposed to power a dual evaporator refrigeration system that has a high performance compared to other conventional systems. A description of the system configuration, thermodynamic modeling and energy and exergy analysis for different operating conditions are presented in this work. Different models of the system have been simulated for different working fluids. The performance of the system is presented in terms of energy and exergy efficiency under different operating conditions.

2. Methodology

This section presents an energy and exergy analysis of a combined system composed of an ORC cycle and a Dual Evaporator Cooling cycle. This analysis is followed by a comparative study based on three working fluids R134a, R290, and R600 in order to select the fluid that is most appropriate for this type of system and will improve its performance.

2.1. Description of the combined system (ORC- DECC)

The basic diagram of the ORC-Dual-Evaporator combined cycle is depicted in Fig. 1 which consists of two main cycles, an ORC cycle (Fig. 1, a) intended to produce mechanical energy which consists of a pump, an ORC evaporator, a turbine, condenser, and a Dual Evaporator Cooling cycle (Fig. 1, b) which compose of a compressor, a condenser, three expansion valves, and two evaporators. The system aims to transmit the net mechanical power $\dot{W}_{net}$ of the ORC cycle turbine to the Dual Evaporator Cooling cycle. The system uses the same working fluid in both cycles combined. The fluid divides into two branches after the condenser to perform refrigeration in two different evaporators. The fluid passes through the second evaporator (evaporator 2) under constant pressure while expanding in the second expander with constant enthalpy. The fluid then undergoes constant enthalpy expansion in the third expansion valve to reach the same pressure as the fluid entering the evaporator 2. On the other hand, the fluid goes through the first evaporator and expands in the first expansion valve while being constantly heated (evaporator 1). Both branches' fluids are directed toward the compressor.

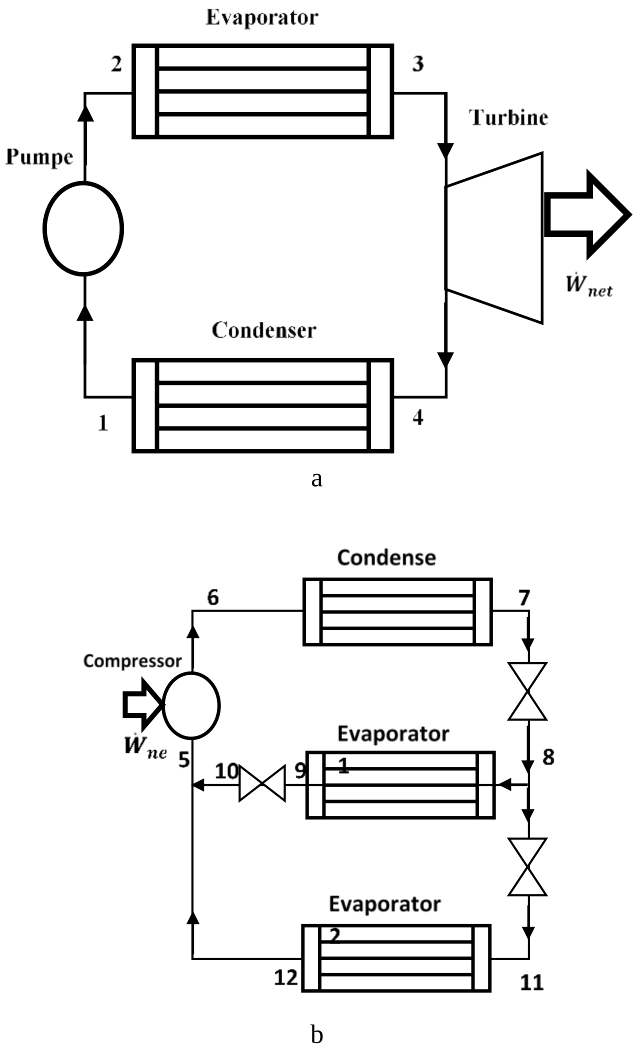

Fig. 1 Combined system (ORC- DECC) Basic diagram

2.2. Energy balance of the combined system (ORC-Dual Evaporator)

The principle of thermodynamics must be applied in order to analyze the energy consumption of ORC- Dual-Evaporator combination cycles. The energy conservation equation is expressed using the first principle of thermodynamics for an open system as shown below [22–24].

Table 1 summarized the general equations corresponding to the above-mentioned principle.

$$\sum \dot{m}_{in} h_{in} + \sum \dot{Q}_{in} + \sum \dot{W}_{in} = = \sum \dot{m}_{out} h_{out} + \sum \dot{Q}_{out} + \sum \dot{W}_{out}. \quad (1)$$

Table 1

Energy balance of combined cycle ORC- DECC

Energy balance of the Organic Rankine Cycle (ORC)	
Components	Energy balance equations
Pump	$\dot{W}_p = \dot{m}_{ORC}(h_2 - h_1)$
Evaporator	$\dot{Q}_{evap} = \dot{m}_{ORC}(h_3 - h_2)$
Turbine	$\dot{W}_{tur} = \dot{m}_{ORC}(h_3 - h_4)$
Condenser	$\dot{Q}_{cond} = \dot{m}_{ORC}(h_4 - h_1)$
Compressor	$\dot{W}_c = \dot{m}_{DECC}(h_6 - h_5)$
Condenser	$\dot{Q}_{cond} = \dot{m}_{DECC}(h_6 - h_7)$
Expansion valve 1	$\dot{m}_{DECC} h_7 = \dot{m}_{DECC} h_8$
Evaporator 1	$\dot{Q}_{evap1} = \dot{m}_{DECC1}(h_9 - h_8)$
Expansion valve 2	$\dot{m}_{DECC1} h_{10} = \dot{m}_{DECC1} h_9$
Expansion valve 3	$\dot{m}_{DECC2} h_8 = \dot{m}_{DECC2} h_{11}$
Evaporator 2	$\dot{Q}_{evap2} = \dot{m}_{DECC2}(h_{12} - h_{11})$
Mass balance $\dot{m}_1 = \dot{m}_2 = \dot{m}_3 = \dot{m}_4 = \dot{m}$	

2.3. Combined system exergy balance (ORC- Dual Evaporator)

The combined system equation's general exergy balance is expressed as follow:

$$\sum \dot{m}_{in} ex_{in} + \sum \dot{E}x_{in}^{Q} + \sum \dot{E}x_{in}^{W} = = \sum \dot{m}_{out} ex_{out} + \sum \dot{E}x_{out}^{Q} + \sum \dot{E}x_{out}^{W} + \dot{E}x_D. \quad (2)$$

The exergy destruction denoted by $\dot{E}x_D$ and the other terms in Eq. (3) can be given as:

$$\dot{E}x_D = T_0 \dot{S}_{gen}, \quad (3)$$

$$\dot{E}x_Q = \left(1 - \frac{T_0}{T}\right)\dot{Q}, \quad (4)$$

$$\dot{E}x_W = \dot{W}. \quad (5)$$

The flow exergy is noted as:

$$ex_{ph} = h - h_0 - T_0(s - s_0). \quad (6)$$

The first and second laws of thermodynamics will be used in the analysis of the combined ORC-CRS cycle. Table 2 provides the general equations that correspond to this principle.

Table 2

Exergy balance of combined cycle ORC- DECC

Exergy balance of the Organic Rankine Cycle (ORC)	
Components	Exergy balance equations
Pump	$\dot{m}_1 ex_1 + \dot{W}_p = \dot{m}_2 ex_1 + \dot{E}x_{D\,p}$
Evaporator	$\dot{m}_2 ex_2 + \dot{E}x^Q_{evap\_ORC} = \dot{m}_2 ex_2 + \dot{E}x_{Devap\,-ORC}$
Turbine	$\dot{m}_3 ex_3 = \dot{m}_4 ex_4 + \dot{W}_T + \dot{E}x_{D\_T}$
Condenser	$\dot{m}_4 ex_4 = \dot{m}_1 ex_1 + \dot{E}x^Q_{cond\_ORC} + \dot{E}x_{cond\,-ORC}$
Exergy balance of the Dual evaporator cooling cycle (DECC)	
Components	Exergy balance equations
Compressor	$\dot{m}_5 ex_5 + \dot{W}_C = \dot{m}_6 ex_6 + \dot{E}x_{D\,-C}$
Condenser	$\dot{m}_6 ex_6 = \dot{m}_7 ex_7 + \dot{E}x^Q_{cond\_DECC} + \dot{E}x_{Dcond\,-DECC}$
Expansion valve 1	$\dot{m}_7 ex_7 = \dot{m}_8 ex_8 + \dot{E}x_{D\,-ev1}$
Evaporator 1	$\dot{m}_8 ex_8 + \dot{E}x^Q_{evap\_DECC\,-1} = \dot{m}_9 ex_9 + \dot{E}x_{Devap\,-DECC\_1}$
Expansion valve 2	$\dot{m}_9 ex_9 = \dot{m}_{10} ex_{10} + \dot{E}x_{D\,-evap2}$
Expansion valve 3	$\dot{m}_8 ex_8 = \dot{m}_{11} ex_{11} + \dot{E}x_{D\,-evap3}$
Evaporator 2	$\dot{m}_{11} ex_{11} + \dot{E}x^Q_{evap\_DECC\,-2} = \dot{m}_{12} ex_{12} + \dot{E}x_{Devap\,-DECC\_2}$

2.4. The performance of the combined cycle (ORC- DECC):

The Eqs. (7) and (8) were used to determine the performance of the ORC system.

Thermal efficiency

$$\eta_{ORC} = \frac{\dot{W}_{net}}{\dot{Q}_{evap}}, \tag{7}$$

$$\dot{W}_{net} = \dot{W}_{tur} - \dot{W}_P. \tag{8}$$

Coefficient of performance

The coefficient of performance (COP) of a refrigeration machine reflects its thermal efficiency. It is important to note that a refrigeration machine is efficient if its COP is as high as possible. It is expressed by the following relationship:

$$COP = \frac{\dot{Q}_{evap1} + \dot{Q}_{evap2}}{\dot{W}_c}. \tag{9}$$

Energy efficiency of the combined system (ORC-Dual Evaporator). The energy efficiency of the combined system:

$$\eta_{sys} = \frac{\dot{Q}_{evap1} + \dot{Q}_{evap2}}{\dot{Q}_{evap\_ORC} + \dot{W}_P}. \tag{10}$$

The performance of the ORC-DECC combined system is expressed by the following equations. Exergy efficiency of the ORC cycle:

$$\eta_{ORC\_SYSY} = \frac{\eta_{ORC}}{\eta_{Carnot}}, \tag{11}$$

$$\eta_{Carnot} = 1 - \frac{T_L}{T_H}. \tag{12}$$

Exergy efficiency of the DECC cycle:

$$\eta_{DECC\_SYS} = \frac{\dot{E}x^Q_{evap1} + \dot{E}x^Q_{evap2}}{\dot{W}_c}, \tag{13}$$

$$\dot{E}x^Q_{evap1} = \left(\frac{T_0}{T_{evap1}} - 1\right)\dot{Q}_{evap1}, \tag{14}$$

$$\dot{E}x^Q_{evap2} = \left(\frac{T_0}{T_{evap2}} - 1\right)\dot{Q}_{evap2}. \tag{15}$$

Exergy efficiency of the combined system: (ORC-DECC):

$$\eta_{ex\_SYS} = \eta_{ORC\_SYS}\eta_{DECC\_SYS}. \tag{16}$$

3. Results and discussion

A new design of the combined ORC-DECC system based on thermodynamic analysis is presented in this work. The effect of operational parameters on the performance of the combined system using Refprop software is discussed in this section. Table 3 shows the values of the input parameters of the combined ORC-DECC system.

The results in this section will focus on the effect of operating temperature on the performance of the ORC cycle and the ORC-DECC combined cycle using three organic fluids, R134a, R290 and R600. In this section, we investigate the impact of the ORC cycle evaporator temperature on the performance of the ORC cycle and the combined ORC-DECC cycle using the three selected organic fluids. For this purpose, specific operating parameters are specified, including the evaporator temperature of the DECC side and the condenser temperature, which carry these values $T_{evap1\_DECC} = 0°C$, $T_{evap2\_DECC} = -20°C$ and $T_{cond} = 40°C$. The evaporator temperature on the ORC side is controlled over a temperature range of 70°C to 90°C. Fig. 2 shows the variation of the energy efficiency of the ORC cycle as a function of the evaporator temperature of the ORC cycle.

Table 3

Input parameters values of combined cycle

Parameters	Values
Mass flow rate of ORC cycle $\dot{m}_{ORC}$, kg/s	1
Evaporator ORC temperature T_{evap_ORC}, °C	80
Condenser ORC temperature T_{cond_ORC}, °C	40
Temperature of evaporator 1 T_{evap1_DECC}, °C	0
Temperature of evaporator 2 T_{evap2_DECC}, °C)	-20

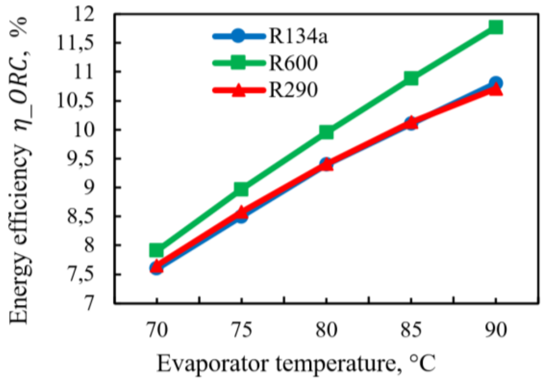

Fig. 2 Effect of evaporator temperature on the energy efficiency of ORC cycle

The results demonstrate that increasing the temperature of the ORC evaporator has a beneficial influence on the energy efficiency of the ORC cycle and the performance of the ORC-DECC combined cycle; the energy efficiency increases significantly for the three organic fluids tested. However, when the findings for the three fluids are compared, we discover that the energy efficiency of an R600 fluid is higher than the others. The energy efficiency of the ORC cycle increases from 7.91% to 11.77%. Figure 3 illustrates the variation of the combined system's energy efficiency as a function of evaporator temperature on the ORC cycle.

Fig. 3 showed that the energy efficiency of the combined cycle increased significantly over the temperature range studied, reaching a maximum value of 40. 22%. The use of the organic fluid R600 gives the best performance for the combined system; the system efficiency increased from 27.10% to 40.22% over the temperature range of the ORC cycle evaporator from 70°C to 90°C. Accordingly, the results in Figs. 2 and 3 illustrate that the ORC cycle evaporator temperature has a favourable effect on the performance of the combined VCRS-ORC system for all identified working fluids, especially the organic fluid R600. In this section, we investigate the influence of DECC evaporator temperature on the performance of the refrigeration cycle and the ORC-DECC combined cycle using the three organic fluids chosen, to accomplish this, certain parameters are fixed, specifically the evaporator temperature on the ORC side and the condensation temperature, which have the values $T_{evap\_ORC} = 80°C$ and $T_{cond} = 40°C$ respectively, while the evaporator temperature varies over a temperature range of -10°C to 10°C for evaporator 1 and - 40°C to -10°C for evaporator 2. The variation of the refrigeration cycle coefficient of performance as a function of the DECC evaporator 1 temperature is represented in Fig. 4.

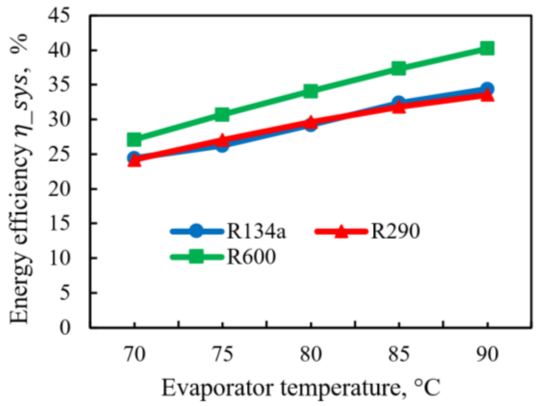

Fig. 3 Effect of ORC evaporator temperature on the energy efficiency of the combined cycle

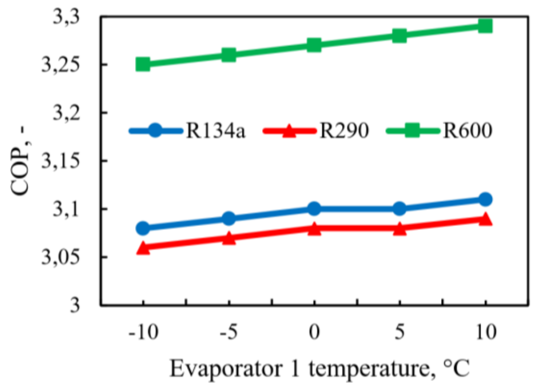

Fig. 4 Effect of the DECC evaporator 1 temperature of on the COP of DECC cycle

Fig. 4 indicated that the temperature of evaporator 1 of the DECC cycle has a significant effect on the coefficient of performance of the refrigeration cycle and the combined ORC-DECC cycle, with the coefficient of performance increasing significantly for the three organic fluids studied. When comparing the results for the three organic fluids, it is clear that the coefficient of performance of R600 is higher than the others. It is also clear that the coefficient of performance of the DECC cycle increases between 3.25 and 3.29. The variation of the coefficient of performance of the refrigeration cycle as a function of the temperature of the DEEC evaporator 2 is illustrated in Fig. 5.

Fig. 5 showed that the temperature of evaporator 2 of the DECC cycle has a significant effect on the coefficient of performance of the refrigeration cycle and the performance of the combined ORC-DECC cycle, the coefficient of performance of the cycle increases significantly for the three organic fluids studied. Comparing the results obtained for the three organic fluids, it can be seen that the coefficient of performance in the case of R600 fluid is higher compared to the others, it is also noted that the coefficient of performance of the VCRS cycle increases. from 2.07 to 4.28. Fig. 6 shows the variation of the exergy efficiency of the combined ORC-DECC cycle as a function of the evaporator temperature of the ORC cycle.

Fig. 6 showed that the combined system's exergy

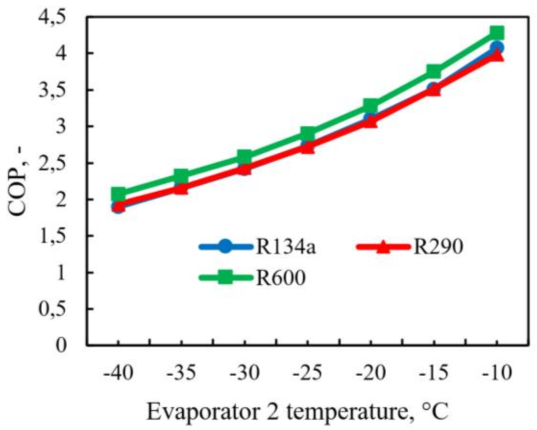

Fig. 5 Effect of the evaporator 2 temperature on the COP of the DECC cycle

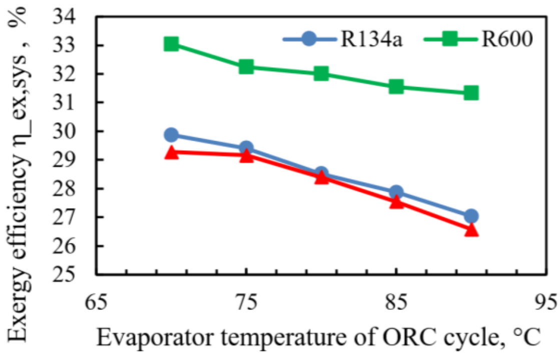

Fig. 6 Effect of evaporator temperature of ORC cycle on the exergy efficiency of combined cycle

efficiency dropped significantly with increasing evaporator temperature on the ORC side for the three organic fluids, while the exergy efficiency for the R600 fluid is very high compared to the other fluids. For the temperature of 70°C, the maximum reached a maximum value of 33.04%. In this section, we investigate the influence of the evaporator temperature of the DECC cycle on the exergy efficiency of the combined ORC-DECC cycle using three different organic fluids. For this purpose, some parameters are defined, including the evaporator temperature on the ORC side and the condenser temperature, which have the values $T_{evap\_ORC} = 80°C$ and $T_{cond} = 40°C$ respectively, while the evaporator temperature varies between -10°C and 10°C for evaporator 1 and - 40°C to - 10°C for evaporator 2.

Figs. 7 and 8 showed the variation of the exergy efficiency of the DECC refrigeration cycle as a function of the temperature of evaporator 1 and the temperature of evaporator 2.

Fig. 8 showed that the evaporator temperature of the DECC cycle has a considerable effect on the exergy efficiency of the refrigeration cycle; for the three organic fluids studied, the exergy efficiency of the cycle augmented remarkably due to the effect of the evaporator 2 temperature and decreases due to the effect of the evaporator 1 temperature; when the findings for the three organic fluids are compared, the coefficient of performance for an R600 fluid is higher than the others. It is also noticed that the exergy efficiency of the DECC cycle increases from 32.47% to 38.82% for evaporator 2. It is also worth noting that the exergy efficiency of the DECC cycle reduced from 40.03% to 30.18% for evaporator 1.

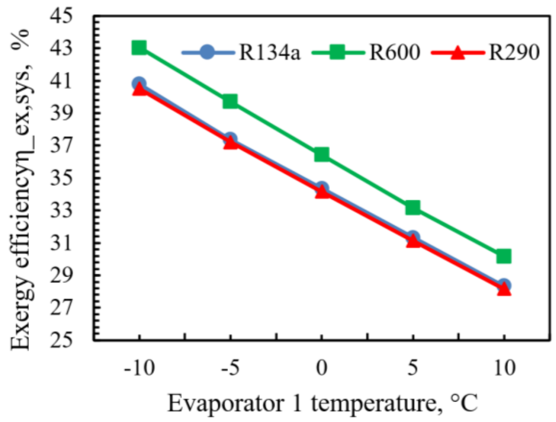

Fig. 7 Effect of evaporator 1 temperature on the exergy efficiency of combined cycle

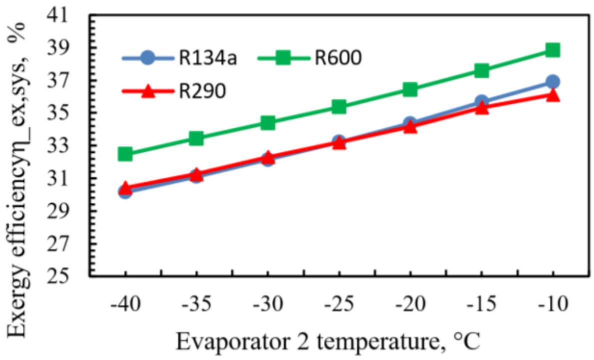

Fig. 8 Effect of evaporator 2 temperature on the exergy efficiency of combined cycle

4. Conclusion

Energy and exergy analysis of a combined cycle consisting of an organic Rankine cycle and a dual evaporator cooling cycle were performed in this study in a specific temperature range; three different working fluids, R134a, R290, and R600, were used as working fluids. The results show that R600 is the best organic fluid for the given parameters among the three. The results were based on the effect of specific operating parameters, such as operating temperature, on the performance of the ORC and combined cycle; the effects of the ORC evaporator temperature and the temperatures of both evaporators were taken into account. The ORC cycle's evaporator temperature has a positive effect on its exergy efficiency; in the case of R600 fluid, the exergy efficiency increases from 7.91% to 11.77%, while the system efficiency increases from 27.10% to 40.22%. The temperature of the first evaporator of the dual evaporator cooling cycle has a significant effect on the cycle coefficient of performance for the three organic fluids studied; it is also noted that the coefficient of performance of the dual evaporator cooling cycle increases from 3.25 to 3.29. It is also noted that the coefficient of performance of the double evaporator refrigeration cycle increases from 3.25 to 3.29 and that the exergy efficiency of the dual evaporator cooling cycle decreases from 40.03% to 30.18%.

Acknowledgement

This work was financially supported by the University of Djilali Bounaama Khemis Miliana.

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R. Touaibi, H. Koten

PARAMETRIC STUDY ON THE EXERGY ANALYSIS OF A DUAL EVAPORATOR COOLING CYCLE POWERED BY THE ORGANIC RANKINE CYCLE

S u m m a r y

This study focuses on a combined power generation and cooling system comprising an organic Rankine cycle and a dual evaporator cooling cycle. A parametric study based on exergy analysis was performed using different organic fluids: R134a, R290 and R600 in order to determine its optimal operation. The results show that the thermodynamic parameters that were studied, such as the operating temperature of the evaporator of the ORC cycle and the dual evaporator cycle on the performance of the system are of great importance and improve the performance of the combined system including energy efficiency and exergy efficiency using R600 as the working fluid. Furthermore, the results indicate that using R600 as the working fluid for both cycles improve the system performance.

Keywords: combined cycle, refrigeration, organic rankine cycle, dual evaporators, exergy analysis

Received January 7, 2023
Accepted June 14, 2023