Research article

Experimental and Theoretical Study to Increase the Solar-Organic Rankine Cycle Efficiency

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Under conditions of high climate temperature and environmental pollution, scientists are turning to the use of new and renewable energy. The solar Organic Rankin Cycle (ORC) is greatest technology for converting low or medium-temperature energy sources into electricity. For the purpose of generating steam from solar energy to power the organic Rankin cycle a system consists of solar pond, flat plate collector and parabolic dish was designed, implemented, and tested to use in organic Rankin cycle (ORC). The novelty in the present work is the use of the solar pond as storage of heat that does not lose because the salinity gradient middle layer in the pond does not allow heat to pass through it, as well as the use of reheating to enhance the thermodynamic efficiency. Also, an analytical model has been made to enhance the output power and efficiency of the solar thermal ORC according to some organic control criteria. A Cycle of solar thermal power plants (ORC) is simulated with four refrigerants, R144a, R123, R124 and R245fa of working fluid's performance. The cycle net-specific work can be verified at the highest efficiency as a function of turbine extraction numbers, over-temperature, and evaporation temperature. Superheated steam was obtained at a temperature of 327 °C to be used in the Rankin cycle of the solar energy system which is generated in this work. The maximum output power improvement is 9% when using the working fluid R123 for R124,5. 5% for R245fa, and approximately 2.8 for R144a. And the thermal efficiency of ORC is higher with R123 compared to 144a by about 2.2%. Furthermore, it also concluded that both inlet and outlet temperatures of a turbine are very important factors that affect the operational performance of organic Rankin cycle power generation systems.

1. INTRODUCTION

The unsustainable nature of fossil fuels, as well as their horrific impact on the environment, raises worries about the need to develop an environmentally beneficial alternative energy source, especially as our reliance on fossil fuels grows rapidly. The search for an environmentally sustainable energy source show us alternatives to all forms of fuels and energy carriers that are safe, clean, and distinct from fossil fuels, such as the sun, wind, tides, hydropower, and biomass. Solar energy is selected among these components because it has the potential to offer the cleanest, most sustainable energy for the longest period of time. Nowadays, the use of renewable energies is an important goal to confront the rise in electricity prices, global warming, and environmental pollution.[1,2] this point of view, countries have tended to build power plants that operate on solar energy to produce large amounts of electricity on a small to large scale.[1] These stations have the advantage of using thermal storage to store thermal energy and use it on demand for electricity.[3] This avoids the use of batteries in photovoltaic cell configurations and achieves thermochemical latent storage.[4] The organic Rankine cycle (ORC) is therefore one of the most popular energy cycles to combine with solar thermal collectors, and is an ideal choice for low and medium temperature levels, typically up to 300°C.[5] The solar Organic Rankine Cycle system , in general, seems to be one of the most reliable renewable energy-based technologies to satisfy major energy demands. Also, the Solar organic Rankine cycle based poly-generation systems are energy-efficient systems that can generate various useful energy outputs, including electricity, heating, cooling, drying, desalination, and hydrogen. As a result, combining solar organic Rankine systems with poly-generation units is the most efficient way of generating multiple useful outputs while still using a renewable energy source[6] The Or-

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ganic Rankine Cycle (ORC), unlike the conventional Rankine cycle that uses water as its working fluid, uses an organic fluid. The Conventional Rankine Cycle or Real Rankine Cycle equations are valid for the Organic Rankine Cycle (ORC).[7] Tian et al. and Wu et al. [910] found that the use of a recovery device increases the efficiency of ORC by approximately 25%. But, Liu et al.[8] used a two-stage ORC and obtained an ORC efficiency improvement of 8% to 12%. Soulis et al.[9] studied a two-stage solar-driven ORC and performed a geospatial analysis to properly evaluate this technology and found that the overall system performance ranged from 2.2% to 2.8% year-on-year. ORC is a cycle like the traditional water/steam Rankine cycle but works with organic fluids and is generally a less complex unit than the water/steam Rankine cycle.[10,11] ORCs are widely used for power generation from medium to low-temperature solar energy sources.[12,13] There is a continuous increase in research activity related to ORC energy systems in the past years, which has proven the value of this technology and its ability to improve energy sustainability.[14,15] It was concluded that the maximum efficiency increases with increasing the evaporation temperature and the extraction number, however, it decreases by increasing the superheat temperature, since the work of the turbine grows by increasing evaporation rate and superheat temperatures but decreases with increasing the extraction rates. Organic Rankine cycle (ORC) as a power generation method from medium and low thermal grade heat sources is currently a strong player in the market. Recently, the energy demand has increased dramatically, despite environmental concerns and global warming, so there has been much interest in using low thermal cycles such as ORC.

Rowshanzadeh's work[16] study evaluates the different areas in which ORC can be applied effectively while minimizing the relevant cost. They concluded that ORC could be used in a bottom cycle recovery or high-pressure gas turbine with lower costing in comparison with the other technologies. Operating ORC by solar energy is more cost-effective compared to generating energy by other methods in addition to the ability to store energy in PCM storage. ORC[17] has also been used in gas-cooled nuclear reactors to improve thermal efficiency. ORC is similar to the steam cycle in respect to the working fluid, whereby water is replaced by a high molecular mass liquid with a lower boiling temperature compared to water which makes the characteristics of the ORC liquid favorable for low heat recovery applications below 400°C. ORC has advantages over the steam cycle because ORC working fluids have a higher molecular weight than water. This increases the fluid mass flow rate for the same turbine volumes and improves turbine efficiency. The turbine efficiency is around 85% in partial load applications and the system can start up faster. Most importantly, the boiling point of ORC fluids is less than water; hence, they can be applied at lower temperatures. Bellos et al.[18] have simulated ORC with reheat cyclopentane to enhance thermodynamic cycle efficiency. They concluded that according to the optimization procedure of cycle design, the proposed design increases power and financial performance compared to the usual design. An analysis of the solar-powered organic Rankine cycle using flat plate collectors was performed by Wang et al.,[19] giving an improvement in the system efficiency by 7.8%. An ORC driven by flat plate solar collectors tested by Pinerez et al.[20] gives a maximum efficiency of 14.6%. Tzivanidis et al.[21] used ORC with equivalent solar collectors and they concluded that an investment payback period is close to nine years and the annual system efficiency is 15.1%, these results agree with the experimental data of Georgousis et al.[22] Guangli et al.[23] have tested a two-stage ORC that is being proposed for the recovery and utilization of low-grade heat from single flash geothermal power plant exhaust flue fluids using working fluids R227ea and R116. The results show that[24–29] the thermal efficiency and amount of electricity produced by a solar ORC system can be increased by lowering the condensing temperature.that work with different solar collectors.

Many researchers have shown that (ORC) systems are the most efficient and reliable method of converting waste heat from low and medium temperatures into usable power.[30–34] Therefore, the present article focuses on applying a new idea using the initial heating through the solar pool and the surface collector, then converting the warm water coming into superheated steam using the concentrated solar collector in the ORC. Thus, using pre-heated water with the solar collector gives temperatures in most seasons sufficient to ignite the ORC system in the present study to cover this scientific gap.

2. EXPERIMENTAL WORK

The present test facility for steam generation shown in figure 1 consists of a solar pond, flat plate collector, and parabolic dish. The solar pond has three different salt concentration zones called the lower convective zone, non-convective zone, and upper convective zone with a cross-section area of 7.3m2 is designed and manufactured for water heating. The depth of the pond is 1.04 m. The second element is a flat plate collector that has an area of 2m2. The solar pond is connected in parallel with the flat plate collector. The outlet heated water from the solar pond and from the flat plate collector is connected to the parabolic dish solar collector that has an area of 2m2. The parabolic dish adjustable mechanism is made of metal to support the weight of the parabolic dish and absorber. The main function is to allow the parabolic dish to align at various angles to capture the sunlight rays depending on the movement and position of the sun. The outlet heated water from the solar pond or the flat plate collector is connected to the parabolic dish solar collector and the steam outlet from the parabolic dish is connected to the organic Rankine cycle.

3. RESULTS AND DISCUSSION

Figure 2 shows the temperature gain from the solar system. The steam outlet from the parabolic dish is connected to the steam turbine of the organic Rankine cycle. Figure 2 displays the temperature rises over three days from 9 AM to 5 PM. The figure shows that the collector gives an average

Table 1. Solar system main dimensions

No	Part	Units
1	Cross-section area of the upper convective zone	7.3m^2
2	Depth of the pond	1.04 m
3	Flat plate collector area	2m^2
4	Parabolic dish solar collector area	2m^2

Fig. 1. Steam generation system

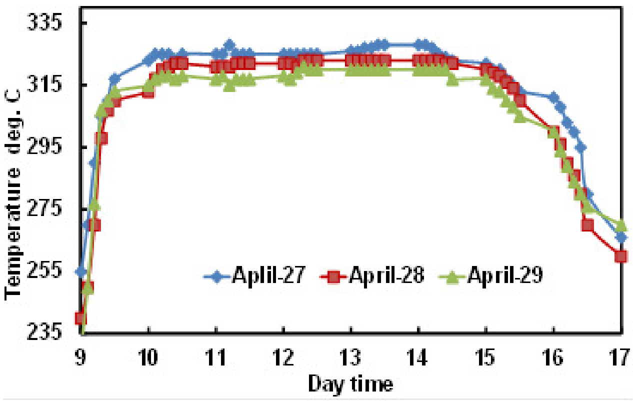

Fig. 2. Temperature rise through a three days

temperature of about 320oC from 10 AM until 3 PM with small differences between the three-day measurements. Data were recorded for many days every month throughout the year but only three days were represented because they have the same values of temperatures.

The measurements were also carried out through different year months, and the results are shown in figure 3. The figure shows the temperature curve increases from 260oC in January and increases to 327oC in June, July, and August, and then decreases gradually in December to 260oC. The estimated power output from the steam generator system of the solar collector, and a 50 Kw to 60 Kw was obtained from the present system through a year is represented in Figure 4. Figure 5 indicates the monthly collector efficiency, with maximum efficiency of 69.79% occurring in July and minimum efficiency of 34% in January.

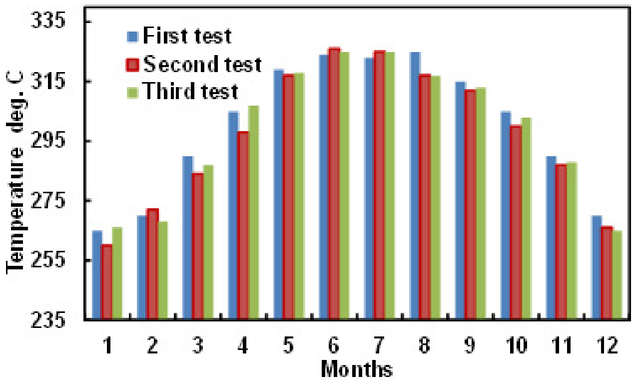

Fig. 3. Temperature rise through a year

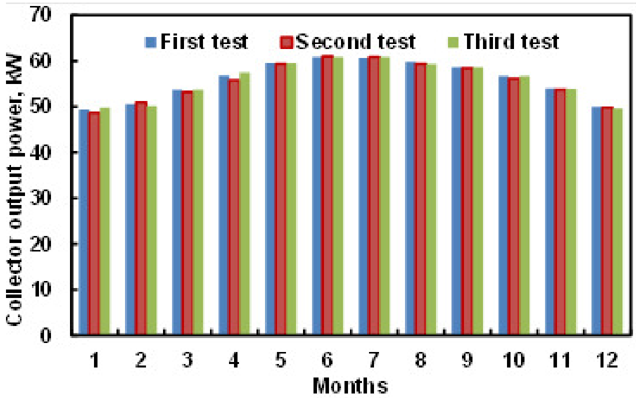

Fig. 4. Collector output power, kW

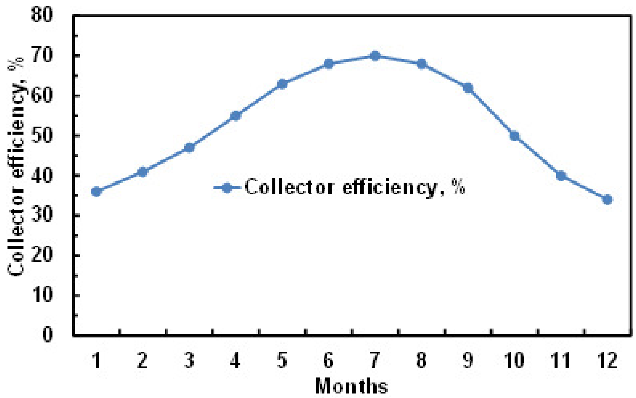

Fig. 5. Collector efficiency during a year months

3.1. ANALYTICAL MODELING OF THE STEAM GENERATION SOLAR SYSTEM

When performing the exergy analysis on the ORC system, the effects of these cycle parameters on the performance of the ORC system were analyzed by changing evaporation temperature, condensation temperature, and superheating temperature. Organic liquids R-134a and R-245fa are used in solar-powered low-temperature thermal power plants.[4]

The simple derivation for the analytical clarification of the thermal efficiency of the parabolic dish collector receiver (boiler) shown in Fig. 5 is presented similarly to [29] as the following.

$$\eta_o = 0.6869 - 1.4709\,(T_c - T_o)/G_d \quad (1)$$

where G_d is the solar incident irradiation which equals 1100 W/m^2, T_c, and T_o are the temperatures at the collector and the surrounding. And if the parabolic dish solar collector surface area is A_d which gives incident solar energy (Q_{id}) equal to:

$$Q_{id} = A_d G_d \left[1 + (T_o/T_{sun})^4/3 - (4\,T_0/3T_{sun}) \quad (2)\right.$$

The amount of useful heat extracted from the solar system (Q_u) is as follows:

$$Q_u = \eta_o Q_{id} = \eta_o A_d G_d \left[1 + (T_o/T_{sun})^4/3 - (4\,T_0/3\,T_{sun})\right] \quad (3)$$

where Tsun is the sun's surface temperature which is assumed as 5800K. The energy balance in the receiver of the solar collector parabolic dish (boiler, Qb) can be written as:

$$Q_b = Q_u - Q_{loss} - Q_{hrs,1} - Q_{hrs,2} \quad (4)$$

where Qhrs1 and Qhrs1 are the heat input to the organic Rankine cycle, Qloss is the boiler thermal heat losses (convective, radiation, and conductance parts) which can be written as:

$$Q_{loss} = (UA)b\,(T_c - T_o) \quad (5)$$

On the other hand, the efficiency of the parabolic dish solar collector depends on the thermal efficiency, Equ.11 (η_o),), and the thermal losses coefficients (a1, a2), which are given by manufacturer data is expressed as follows:

$$\eta_{sol} = \eta_o - [(T_m - T_o)/G_d]\,[0.95 - 0.005\,(T_c - T_o)] \quad (6)$$

3.2. SOLAR ENERGY AND ORGANIC RANKIN CYCLE MODELS

Like the Rankine cycle, the ORC cycle shown in Fig. 6 has the same thermodynamic conditions and works in the same method but uses mainly organic working fluid instead of water. This cycle consists of a pump, boiler (evaporator), turbine (expander), and condenser. But, the ORC cycle works at low-temperature heat sources of less than 400°C. The working fluid characteristics make the ORC suitable for these low-temperature heat sources. The ability of these high molecular weight working fluids makes phase transition from saturated liquid to saturated vapor possible at lower temperatures. In the present work, different organic working fluids were used to analyze the thermodynamics of the ORC system, and the optimization of its cycle parameters is studied. Based on the principle of exergy analysis, the effects of evaporation temperature, of the system are investigated. The collector's thermal loss coefficient is Ub = 0.5W/m2K, whereas the outside area is considered according to the boiler geometry. In respect of the solar energy cycle, the solar pond (thermal storage) thermal energy (Qste) can be obtained by applying the energy balance equation in the storage fluid (solar pond) as:

$$Q_{ste} = \rho V C p d T_{ste}/dt \quad (7)$$

where ρ is the density of the gas, Cp specific heat capacity, V, and Tst are tank volume and mean temperature respectively. The working fluids R123, R124, R144a, and R245fa were chose

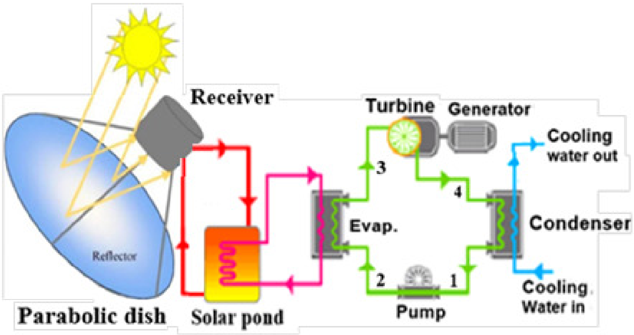

Fig. 6. Collector efficiency during a year months

$$\sum E\dot{x}_i = \sum E\dot{x}_e + \sum E\dot{x}_D \quad (8)$$

$$i \sum \dot{m}_i ex_i + \dot{E}x_Q = e \sum \dot{m}\, ex_e + \dot{E}x_W + \dot{E}x_D \quad (9)$$

where the subscript i, e, is the inlet and exit exergy flow from the control volume around the solar pond (storage of energy), Ėxi and Ėxe are the exergy transfer by work and heat, respectively and ĖxD is exergy

destruction. In this area of steady, different indicators have been used to evaluate system performance. First is the solar collector field useful heat gain, Q_{CL}, can be calculated as follows:

$$Q_{CL} = A_{pCL}\,[DNI \cdot f_c \cdot \eta_{o,CL} - (T_{mCL} - T_a)\,(U_{l,1} + U_{l,2})] \quad (10)$$

where $A_{p,CL}$ is the aperture area of the solar collector field, DNI is the direct normal irradiance, f_c is the cleanliness factor (ratio of the optical efficiency in average dirty conditions to the optical efficiency with the same optical element in clean conditions), η_{oCL} the optical efficiency of the solar collector field, T_{mCL} is the mean temperature of the solar collector field, $U_{l,1}$ and $U_{l,2}$ are the heat loss coefficients based on the aperture area of the solar collector field, and *To* is the ambient temperature. The power consumption of the organic Rankine cycle feed pump, W_P, is computed as follows:

$$W_P = \dot{m}_{ORC}\,(h_2 - h_1)/\eta_{sp} = V_{ORC}\dot{m}_{ORC}\,(P_2 - P_1) \quad (11)$$

where $\dot{m}_{ORC}$ is the mass flow rate of the organic working fluid, η_{sp} is the isentropic efficiency of the feed pump, h_1 and h_2 the specific enthalpy at the pump inlet and exit, the index *s* refers to a state achieved after an isentropic compression or expansion, and the pressure.

The solar fraction is defined as the ratio of the amount of solar energy received to the total energy required by the system:

$$SF = Q_{solar}/\,(Q_{solar} + Q_{sux} + Q_{boiler}) \quad (12)$$

where Q_{solar} is the solar useful energy, Q_{sux} is the auxiliary energy in the solar cycle and Q_{boiler} is the boiler energy required for the organic Rankine cycle. The organic working fluid in the liquid state at the maximum operating pressure (state 2) enters the heat exchanger. In the evaporator, heat is transferred from the high-temperature heat transfer fluid, heated through the solar collector field, to the organic working fluid. The amount of heat recovered in the heat exchanger (boiler) or the heat transfer rate in the heat exchanger, Q_{rec}, is given as follows:

$$Q_{rec} = \dot{m}_{ORC}\,(h_3 - h_2) \quad (13)$$

where the exit enthalpy from the heat exchanger, $h_3 = h_g(T_s)$. The power output of the turbine, $\dot{W}_T$, is calculated as follows:

$$\dot{W}_T = \dot{m}_{ORC}(h_3 - h_{4s})\eta_{sT} \quad (14)$$

where η_{sT} is the isentropic efficiency of the turbine. The isentropic exit enthalpy from the turbine (state 4) can be calculated using following equations; $x_{4s} = (s_{4s} - s_f)/s_{fg}$, [where, $s_{4s} = s_3 = s_g(T_s)$] as:

$$h_{4s} = h_f + x_{4s}h_{fg} \quad (15)$$

while turbine exit enthalpy (actual) can be written using the turbine isentropic efficiency as:

$$h_4 = h_3 - \eta_T(h3 - h_{4s}) \quad (16)$$

where η_T is the isentropic efficiency of the steam turbine and *s* denotes the isentropic.

In the case of dry organic working fluids, the state point after the expansion in the turbine is superheated. The heat transfer rate in the condenser, Q_c, is calculated as follows:

$$Q_c = \dot{m}_{ORC}(h_4 - h_1) \quad (17)$$

The power output from the ORC is calculated from [26]:

$$\dot{W}_{net} = \dot{W}_T - \dot{W}_p \quad (18)$$

where $\acute{W}_T$ is turbine power and $\acute{W}_T$ is pump power. The overall energy efficiency of ORC is the ratio of net power output to energy input, and the overall exergy efficiency of ORC can be defined as:

$$\eta_{ORC} = \dot{W}_{net}/Q_{re}, \text{ and } \varepsilon_{ORC} = \dot{W}_{net}/\dot{E}x_i \quad (19)$$

Energy efficiency for the overall system can be calculated by ratio of net power output from ORC and the cooling capacity of the evaporator to the total heat energy entering the overall system[27]:

$$\eta_{ORC} = \left(\dot{W}_{net} + Q_{eva}\right)/(Q_{geo} + Q_{solar}) \quad (20)$$

The expression of the exergy efficiency for the combined system[28] is:

$$\varepsilon_{overall} = \left[\dot{W}_{net} + Q_{eva}((T_0/T_E) - 1)\right]/\left(\dot{E}x_{geo} + \dot{E}x_{solar}\right) \quad (21)$$

Figure 7 shows the effect of turbine inlet temperature on the organic Rankine cycle net output power for different working fluids of R123, R124, R144a, and R245fa. The figure shows an increase in cycle net power by increasing the inlet temperature of the turbine, and R123 gives the highest net ORC power. The figure indicates that the ORC with working fluid R123 gives the highest performance in terms of net power output. Four refrigerants, R123, R124, R245fa, and R134a, were examined and the results were compared in terms of working fluid performance to increase the net output power. Also, the effect of reducing the adaptation temperature on net power was also studied. When the condensing temperature was decreased from 25°C to 15°C, the improvements in net output power were 13.8%, 10.58%, and 6.33% for R123, R144am and R245fa respectively in basic organic Rankine cycle status which using R124 as shown in figure 8. Increasing the condensation temperature decreases the exergy efficiency of the system and the output power of the turbine and increases the exergy loss of the system. The present result agrees with that of Daniarta et al.[29] and other researchers who have shown that (ORC) systems are the most efficient and reliable method of converting waste heat from low and medium temperatures into usable power.[30–34]

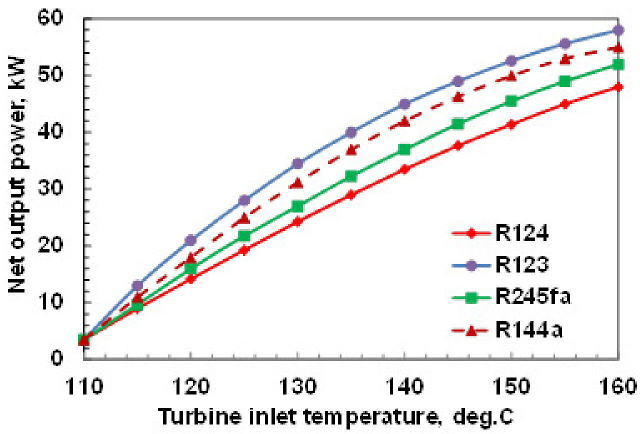

Fig. 7. Effect of working fluid on output net power

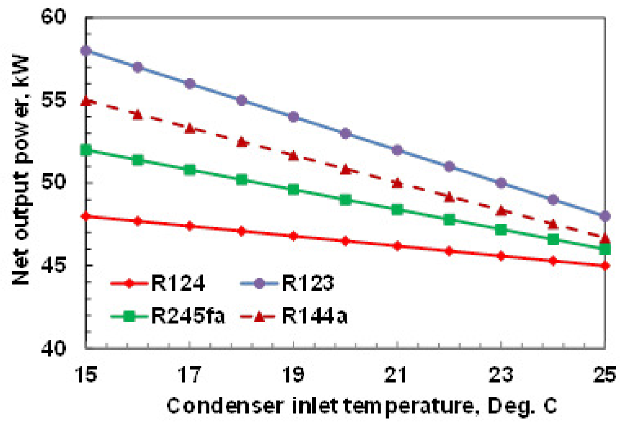

Fig. 8. Effect of condenser inlet temperature on the ORC net power output

Figure 9 shows the effects of increasing the inlet temperature of the turbine on overall cycle efficiency. Increasing overall cycle efficiency is evident with an increased in turbine inlet temperature. It is observed that when the inlet temperature of the turbine increased from 140 to 330°C, the overall efficiency increased by about 16.4% with the use of working fluid R123 concerning R124, and the boost is reduced with the other working fluid. As the turbine inlet temperature increases, the inlet enthalpy of the turbine slightly increases, which, in turn, increases the steam cycle efficiency; thus, the overall cycle efficiency increases. For the whole system, exergy efficiency takes into account the fuel of the system which corresponds to the fuel of the heat exchanger. The product is the effective mechanical power (mechanical power supplied by the turbine minus mechanical power consumed to power the pump):

$$\eta_{ExORC} = \dot{W}_{net\text{-}orc}/\dot{\mathbf{E}}\mathbf{x} - \text{ORC} \quad (22)$$

Figure 10 depicts the results of the ORC thermodynamic efficiency and the exergy efficiency. It is clear that the exergy efficiency decreases by increasing the turbine inlet temperature, while the overall thermal efficiency increases with the inlet turbine temperature. That is higher temperature at the inlet enhances the ORC performance for the reheat-

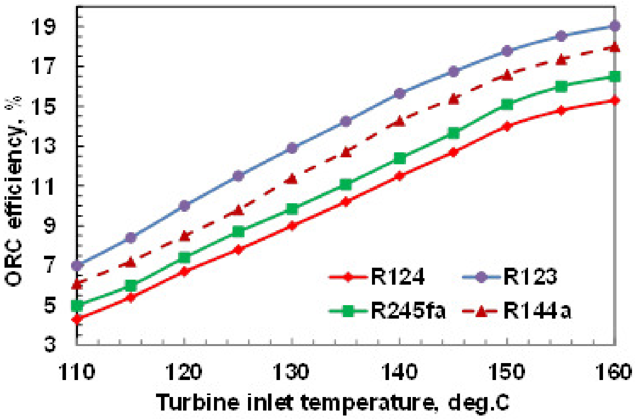

Fig. 9. Effect of turbine inlet temperature on the overall system efficiency

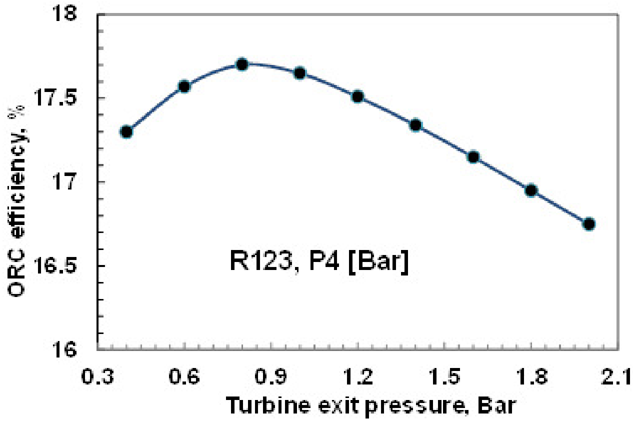

Fig. 11. Effect of turbine exit pressure on the ORC ef ficiency

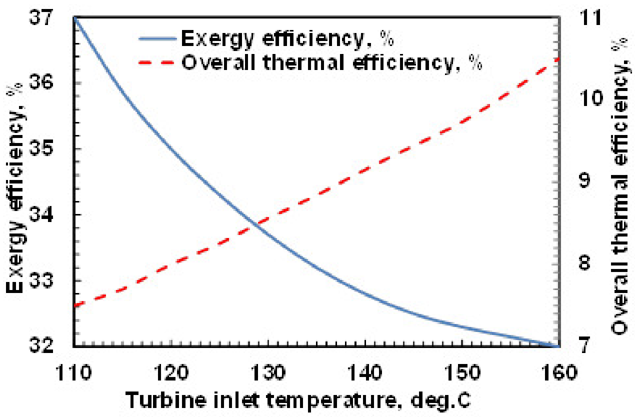

Fig. 10. Effect of evaporator exit temperature on ef ficiency

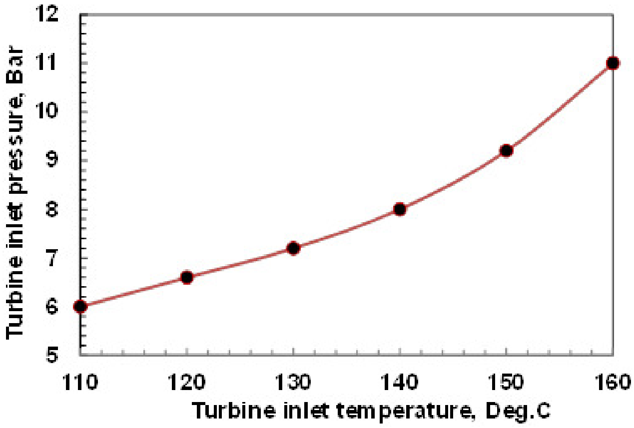

Fig. 12. Effect of turbine exit pressure on the ORC ef ficiency

ing system, a reasonable result according to the aforementioned analysis (Figure 9).

The overall system efficiency has higher values when the turbine inlet temperature increase. However, increasing inlet fluid temperatures may create manufacturing difficulties or increase costs. In any case, the process in the 110-160°C range is an easy manufacturing option that can lead to sustainable designs. That is increasing the evaporator exit temperature enhances the output power of the turbine and the exergy loss in the condenser, decreasing the exergy efficiency simultaneously. As the temperature at the evaporator outlet (point 3) gradually increases, the system energy efficiency and turbine output increase. The reason for these effects is that the temperature of the organic working medium is directly proportional to the evaporation temperature, that is, the higher the evaporation temperature, the greater the working capacity of the organic working medium. And evaporator of the heat transfer temperature difference decreases with the rise of evaporation temperature, reduces the friction loss of organic working medium, the irreversible loss, and exergy efficiency increases.

Also, Fig. 10 indicates that the exergy efficiency of the organic Rankine circulatory system decreased with the rise of turbine inlet temperature. That is due to the rise in turbine inlet temperature increasing the heat absorption of the organic working fluid. Besides, increasing the turbine inlet temperature also increases the heat absorbed by the constant pressure in the condenser and the irreversible loss of the system but decreases the cycle exergy efficiency. The turbine output power increases with the rise of superheating temperature due to increases enthalpy of working substance at the inlet of the turbine and increases in the enthalpy drop of working fluid in the turbine. On the other hand, a superheating temperature increase increases the condenser exergy loss, evaporator exergy loss, and total exergy loss. Figure 11 shows the effect of turbine exit pressure or condenser inlet pressure on the ORC efficiency. The efficiency increases and reaches an optimal pressure and then decreases as pressure increases. Figure 11, concluded that a pressure of 0.76 bar is, in this case, the most optimal middle pressure to use in the condenser. Figure 12 shows the effect of turbine inlet temperature on the turbine exit pressure. Figure 8 compares the turbine inlet pressure of the R123 organic working fluids as a function of evaporation temperature varying from 110C to 160C. When the turbine inlet pressure temperature is increased, the corresponding turbine inlet pressure increases.

3. CONCLUSION

The outcomes of this work is very optimistic. By implementing a solar energy system with organic Rankin cycles, gives high energy with good overall efficiency. The effect of design parameters such as types of the organic fluids, turbine inlet temperature, and condenser temperature on system performance was studied using thermodynamic mathematical models with concentration on energy efficiency. It is so important when implementing ORC system to choose the proper type and size of the solar collector and thermal energy storage tank, in order to reduce global warming and environmental pollution. Different types of working fluids were used to analyze the organic solar Rankin cycle and study the effect of the on the system's overall efficiency.

The results show that increasing the temperature of the steam entering the turbine and lowering the condensing temperature increases the overall system efficiency and improvement the economic performance of the system. Using R123 as a working fluid for ORC gives better efficiency than the other three tested fluids. This research confirmed the ability of ORC to produce electricity from low-temperature heat sources such as solar energy. Thus, it is easy to use in areas not covered by electricity supply lines for home buildings and others. Another gain is no emissions or global warming by using a solar-powered ORC.

Nomenclature

A_d	Surface area of the parabolic dish solar collector
Cp	Specific heat capacity
DNI	Direct normal irradiance
$\acute{E}x$	Exergy transfer
$\varepsilon_{overall}$	Exergy overall efficiency
f_c	Cleanliness factor
h	Specific enthalpy
G_d	Solar incident irradiation
$\dot{m}_{ORC}$	Mass flow rate of the organic working fluid
ORC	Organic Rankin Cycle
Q_{id}	incident solar energy
SF	Solar fraction
T	Temperature
U_b	Collector's thermal loss coefficient
V	Tank volume
W	Power consumption
$\acute{W}_T$	Turbine power
η_o	Thermal efficiency
ρ	Density of the gas

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