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Experimental study of Organic Rankine cycle system by using R141b as working fluid

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Abstract

Organic Rankine cycle (ORC) is one of the renewable energy to generate power at low temperatures; however, the thermal and physical properties data of the working fluid in this system are limited. In this regards, the experimental study by using R-141b as the working fluid and hot water (i.e. 50°C and 90°C) on the ORC system was conducted in order to evaluate the ORC performance via changing temperatures. Further, the air compressor was modified to act as a multi-vane expander in the ORC system. Energy and exergy analysis of ORC system was done by using Engineering Equation Solver (EES) program.
It was found that the performance of the expander is acceptable and suitable for operating conditions. In addition, the heat source temperature has a direct effect on expander performance. The higher temperatures of the heat source led to an increase the expander inlet temperature. This system satisfied maximum thermal and exergy efficiency and they found equal to 1.8 % and 21%, respectively. Moreover, the rotation speed and power of expander are equal to 1200 RPM and 2.331 kW respectively. It was concluded that the working fluid R-141b is suitable for ORC system due to consider the working fluid that do not need high temperatures to evaporate.

Keywords: Organic Rankine cycle (ORC), multi-vane expander, refrigeration (R-141b), engineering equation solver (EES), heat source temperature.

الخلاصة: دورة رانكن العضوية هي واحدة من الطاقات المتجددة لتوليد الطاقة في درجات حرارة منخفضة. في هذا البحث، ركز على الدراسة التجريبية لنظام دورة رانكن العضوية باستخدام R-141b كمائع عمل وماء ساخن كمصدر حراري تتراوح درجة حرارته بين ٥٠درجة مئوية و٩٠ درجة مئوية. كان الهدف من الدراسة هو تقييم أداء منظومة رانكن العضوية عن طريق تغيير درجات الحرارة. تم تعديل ضاغط الهواء ليكون بمثابة موسع متعدد ريش في النظام. وجد من خلال الاختبار أن أداء الموسع مقبول ومناسب لظروف التشغيل. تم إجراء تحليل الطاقة والاكسيرجي لنظام دورة رانكن العضوية باستخدام برنامج حل المعادلات الهندسية. أظهرت النتائج أن درجة حرارة المصدر الحراري لها تأثير مباشر على أداء الموسع. أدت الزيادة في درجة حرارة المصدر الحراري إلى زيادة درجة حرارة مدخل الموسع. وجد أن النظام لديه أقصى كفاءة حرارية وكسيرجي تبلغ ١,٨٪ و٢١٪ على التوالي، وكانت سرعة الدوران ١٢٠٠ دورة في الدقيقة، وكانت قدرة الموسع ٢,٣٣١ كيلو واط. تم استنتاج أن مائع العمل R-141b مناسب لنظام دورة رانكن العضوية بسبب اعتبار مائع العمل لا يحتاج إلى درجات حرارة عالية للتبخر.

1. INTRODUCTION

In recent years, consumption of fossil fuels has increased and caused problems for the environment, such as global warming and the depletion of the ozone layer. The Steam Rankin cycle is the technology that uses high temperatures between (250-400) °C to generate electrical energy. High temperatures are sometimes not available, in addition to the loss of heat from it. The Organic Rankin cycle is considered one of the most important methods that uses low temperature sources such as biomass, geothermal, wind, and solar energy to generate electric energy. The expander is one of the key components of the ORC system, which leads to improve cycle efficiency. The choice of the expander is important; it depends on the operating conditions and the amount of power production. Two types of expanders can be classified. The former is velocity type, such as axial turbine and radial turbine. The latter is second displacement volume type such as scroll expander, screw expander, and multi vane expander [1]. The large-scale (ORC) system developed and spreaded around the world, but there is an economical and widely used technology that small ORC system for applications less than 100 kW [2]. The ORC components depend on the thermal and physical properties of the working fluid. Therefore, the working fluid must be selected carefully to obtain high efficiency and improve the ORC system. In general, the working fluids have low boiling point than water. These fluids are used for air conditioning and cooling operations. The heat source of temperature and the ambient temperature mainly affected on the working fluid. The higher values of molecular weight of the working fluids reduced the number of stages of the turbines and it needs a high heat for the exchanges due to the high heat transfer coefficient. It was found experimentally that hydrocarbons (HCs) are a good choice as an organic fluid due to their low cost, high efficiency, and environmentally friendly. There are different types of hydrocarbons, such as R600, R601, and R245fa [3]. R-141b is considered an organic fluid with the Chemical formula (CH_3CCl_2F) [8]. Dueng, et. al. [4] carried out an experimental studied to evaluate the performance of a scroll expander in the ORC system for generating electrical energy by using a working fluid R-141b. They studied the effect of superheated on efficiency and power, with a constant mass flow rate. They found that when superheated increases, the efficiency increases, it reaches 0.52%, and the isentropic efficiency ranges between (17.83% - 18.5%) Marion, et.al. [5] presented a thermodynamic analysis and experimental of the (ORC) system with a refrigeration system by using a multi vane expander and a multi vane compressor. They used 12 working fluids in the modelling and choice R1270 as the ideal working fluid. It was found that the using of a multi- vane expander with a multi- vane compressor preferred. Piotr. K [6] presented a review study on the multi-vane expander applications. It was concluded that it is suitable for limited applications with low cost for manufacturing and it can work in low pressure. In addition, it was found that the thermal efficiency of the ORC with multi-vane expander ranges between 0.75-7.65% and power of expander between 65W to 8kW.

In this paper, an experimental study on the ORC system by using working fluid R-141b and energy, exergy analysis of all compounds of ORC was conducted in order to evaluate the ORC performance. Furthermore, the influence of heat source temperature change (hot water) on expander inlet temperature, rotational speed, power output of expander, and efficiency of ORC are studied

2. DESCRIPTION OF THE ORC SYSTEM

The ORC system consists of four key components; the multi-vane expander, the evaporator, the condenser, the pump, and heater. Figure 1 shows schematic of the ORC system. The working fluid is pumped from the condenser to evaporator by the pump. The heat exchanger is heated by hot water to ensure that fluid is completely vaporized and the liquid does not enter the expander. The thermal energy is transferred from the water to the R-141b. The vapor then passes through the multi-vane expander and thermal energy converted into mechanical energy to rotate the shaft. The vapor (R-141b) enters the condenser which it is cooled by the air flowing through the plate of condenser to convert R-141b to liquid and the cycle returns again. The components of ORC model in study is presented in Figure 2. Moreover, the T-S diagram of the ORC system illustrated in Figure 3. The measurement data of device is presented in Table 1.

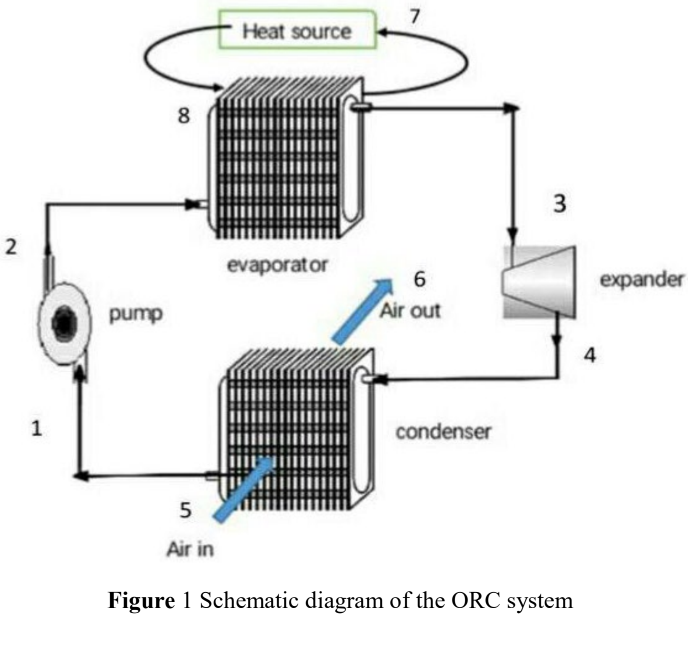

Figure 1 Schematic diagram of the ORC system

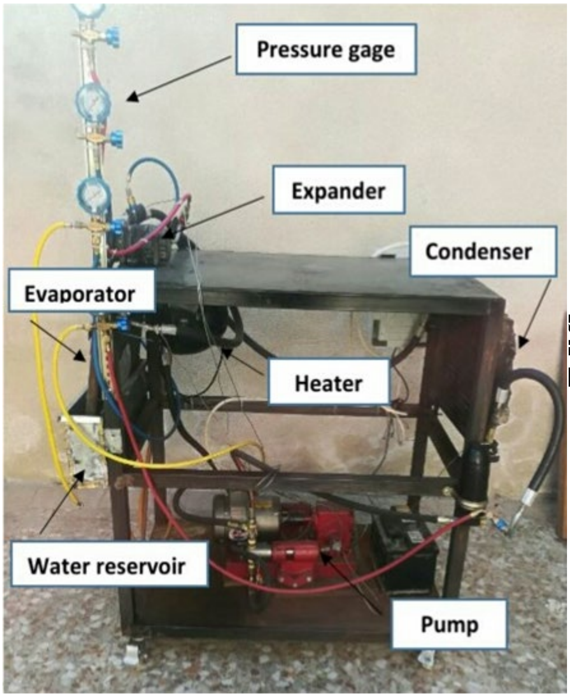

Figure 2 The ORC model in this study

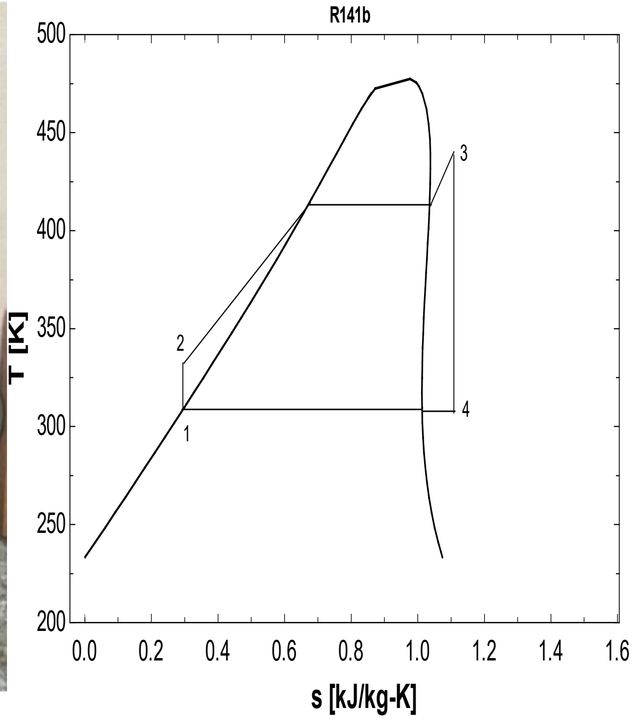

Figure 3 T-S diagram of the ORC system

Table 1 Measurement of the main parts for ORC

Parameter	Type	Range	Uncertainty
Pressure	Gage pressure (HS-466 NAL)	0-35 bar	± 0.5%
Temperature	K-type thermocouple	-270-1260°C	± 0.5k
Rotation speed	Laser digital tachometer(DT-2234C)	2-99,999 rpm	± 0.5% rpm
Air velocity	K(AT-350) an anemometer	0.00-20.00 m/s	± 3rdg+0.2m/s

3. WORKING FLUID

The selection of the working fluid is important for the efficiency of low temperature for ORC and focused on the thermodynamic properties of the fluid. The working fluid must be non-toxic and non-flammable, availability, cheap cost, and the corrosive must be low. The organic fluid should have high latent heat, high density, and high density means to an improved the mass flow rate [7]. In this study, it was selected R-141b as a working fluid. This was due specific properties such as a non-flammable, non- corrosive, available and cheap. It was also required low pressure and temperate during service life. It was considered amongst dry fluids that do not need high temperatures for heated. The thermal and physical properties of the working fluid that used in the present study are showed in Table 2 [8].

Table 2 Thermal and physical properties of R-141b [8]

Working	Molecular mass	Critical	Critical	Critical Density	Boiling point
R-141b	116.95	204.2	4.25	1.25	32.05

4. MATHEMATICAL MODEL

In this section, two types of analysis have been used. The first type is energy analysis by applying the first law of thermodynamic. The main aims of energy analysis is to calculate the thermal efficiency of ORC and power of expander.

The second type is exergy analysis and applying the second law of thermodynamic. The main performance of exergy analysis is to measured exergetic efficiency and exergy destruction in each component (ORC). Then this analyzes are executed in Engineering Equation Solver (EES) software.

The first and second thermodynamic analysis law are applied in a steady state of all components. These calculations are depended on the parameters such as of temperature, pressure and flow rate, which are measured by experimental tests. The working fluid flow rate ($\dot{m}_f$) considered itself the pump flow rate from the manufacturer, the water flow rate ($\dot{m}_w$) according to the volumetric flow rate during the time unit. The condenser contains a fan to condensate R-141b and air flow rate ($\dot{m}_e$) according to by measuring the fan air velocity, condenser area, and air density. The environmental conditions are T_0=15°C, P_0=1.01325bar. The governing equations energy and exergy analysis of all component of ORC was done. Table"3. Shown the thermodynamic equations was used in analysis. The exergy destruction (Ex_D) rate is a parameter to determine the reversibility and convert the low heat or medium into work. In eqs. (1) to (17) represent the energy and exergy analysis of all compound ORC [9].

4.1 Energy Analysis

Expander $$W_{exp} = \dot{m}_f\,(hf_3 - hf_4) \quad (1)$$

Evaporator $$Q_{in} = \dot{m}_f\,(hf_3 - hf_2) \quad (2)$$

Condenser $$Q_{rej} = \dot{m}_f\,(hf_4 - hf_1) \quad (3)$$

Pump $$W_P = \dot{m}_f\,(hf_2 - hf_1) \quad (4)$$

Cycle $$\eta_t = (W_t - W_P)/\,Q_{in} \quad (5)$$

4.2 Exergy Analysis

The total exergy rate can represent as shown in the eq. (6).

$$Ex = \dot{m} \times e \quad (6)$$

$$e = (h-h_0) - T_0(s-s_0) \quad (7)$$

Expander $$\eta_{exp} = Wexp/Ex_3-Ex_4 \quad (8)$$

$$Ex_{D,exp} = (Ex_3 - Ex_4) - W_{exp} \quad (9)$$

Evaporator $$\eta_{ev} = Ex_3 - Ex_2/\,Ex_7 - Ex_8 \quad (10)$$

$$Ex_{D,ev} = (Ex_7 - Ex_8) - (Ex_3 - Ex_4) \quad (11)$$

Condenser $$\eta_{con} = Ex_6-Ex_5/Ex_4-Ex_1 \quad (12)$$

$$Ex_{D,c} = (Ex_4 - Ex_1) - (Ex_6 - Ex_5) \quad (13)$$

Pump $$\eta_p = Ex_2-Ex_1/W_p \quad (14)$$

$$Ex_{D,P} = W_p - (Ex_2 - Ex_1) \quad (15)$$

Cycle $$\eta_{ex} = W_{net}/E_{in} \quad (16)$$

$$E_{in} = \dot{m}_w\,[(h_1-h_2-T_0\,(s_1-s_2))] \quad (17)$$

5. ORC EQUIPMENT DETAILS

The components of ORC models used in this study are shown in Figure 4. The compressor selected as a multi-vane expander contain of cylinder, rotor, two covers, and vanes made of iron. It is similar to a multi-vane expander but the vane made of iron instated of graphite. The vapor is entered into the expander through inlet port (6.5mm) and exits through outlet port (10mm). There is inside the shaft moves as a result of mechanical energy transformed due to heat. The expander speed range from 0-3000 RPM. The rotational speed is measured by the taco meter. The compressor is easy to repair, low cost, and locally available. The expander inlet pressure in this work range from 1.5-7 bar. Figure 4a shows the multi-vane expander in the present study. In this work used an evaporator for the purpose to heating the working fluid before inlet the expander. Connected with the evaporator water reservoir to increase the temperature of working fluid with the help of heater connecting with it. For the purpose of increase the inlet temperature of the expander. The heater is adopted to heat the water inside the reservoir before inlet the evaporator until it reaches the required temperature to convert the refrigerator liquid into steam. Figure 4b shows the heater used in the test.

The working fluid inlet the evaporator and there is a heat exchange between the fluid and the hot water passing through the fins. Figure 4c shows the evaporator used in this work. The method was used hot water as a heat source is acceptable because it is available, cheap, uncomplicated and does not require design equipment. The process of heating water better and faster than heating with air. The experimental work contains a condenser connects with it a cooling fan. The steam inlet the condenser and turns into a liquid by a cooling fan when the steam condenses completely and reaches its liquid state. The cycle is repeated again. Due to the performance of the condenser is affected by ambient temperature assume the system is running in the morning when the ambient temperature drops. Air is used as a cooling source and this method is simple, uncomplicated and inexpensive. The value of condenser pressure range from (1.5-3) bar and condenser temperature range from (23-45) ° C. Figure 4d shows the condenser used in the testing. Selection of the pump from the ORC system is a difficult due to different input operating conditions. In our test using an electrically driven pump because it is a small size, contains two-inlet port for long operating life, and low mass flow rate. The purpose of the pump is to raise the working fluid pressure before inter the expander. Figure 4e shows the electrical pump used in this work. In addition, the experimental data at different point for R-141b presented in Table 3.

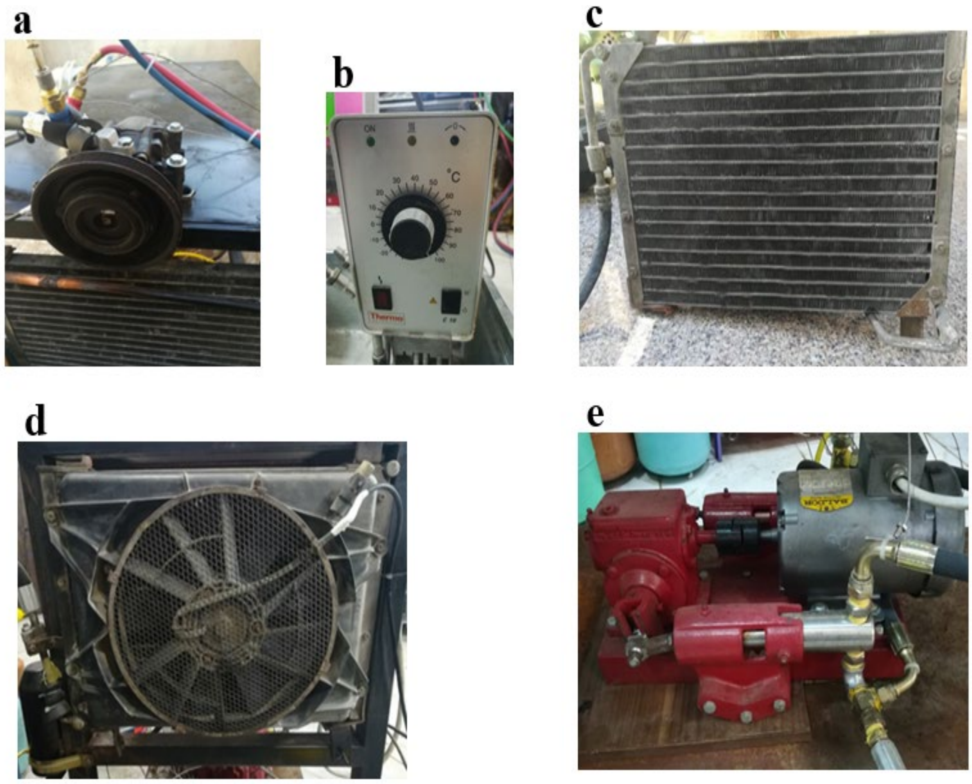

Figure 4: The components of ORC model: (a) the expander, (b) the heater, (c) the evaporator, (d) the condenser and (e) the electrical pump

Table 3 The experimental data at different point for R-141b

State	Fluids	m (kg/s)	P (bar)	T (°C)	Ex (kW)
1	R-141b	0.312	2.5	26.2	-35.26
2	R-141b	0.312	7	27.5	-34.15
3	R-141b	0.312	7	85.7	-24.84
4	R-141b	0.312	2.5	51.3	-32.18
5	Air	0.2268	1.0132	22.1	1.126
6	Air	0.2268	1.0132	25.6	2.881
7	Water	0.103	x=0	90	15.76
8	Water	0.103	x=0	32.5	2.508

6. RESULTS AND DISCUSSION

The experimental test was done in the month of October and November 2019 in a cooling workshop in Wasit city/ Iraq. The time of the test was taken between 9:30 am to 12 pm. The mass flow rate of working fluid R-141b was constant at 0.312 and the heat source temperature ranges from (50-90) °C during the test. Figure 5 shows the experimental test were conducted on 23th of October 2019 for R-141b at heat source temperature 50°C and constant expander inlet pressure 7 bar. It was found that expander inlet temperature 46.2° C, air inlet temperature 26.3°C, and rotation speed 653 RPM. Figure 6 shows the experimental tests was conducted on 27th of October 2019 at heat source temperature 90°C and pressure 7 bar. The expander inlet temperature 83°C, air inlet temperature 21°C, and rotation speed 1200rpm. It shows that the increases of heat source temperature lead to increasing the expander inlet temperature, rotation speed, and decreases the condensation temperature.

Figures 7&8 show the effect of heat source temperature variation on the expander power outlet, thermal efficiency. The maximum power 2.331 kW at maximum heat source 90 °C. The heat source temperature was increased, the different between expander inlet and outlet temperature was increased and the power outlet increased. The increment of power outlet means that increase thermal efficiency of ORC system, it reach maximum value 1.8% at maximum heat source temperature 90°C, and the value decreased at minimum heat source 50°C. The mass flow rate of working fluid R-141b was constant during the test.

The heat source of temperature changed with the exergy efficiency of all compounds such as the expander, the condenser, the evaporator, and the pump as shows in Figure 9. The exergy efficiency of the expander of 61% and the condenser, evaporator, and the pump of 24.1%, 44%, and 15.5% respectively at a minimum temperature of 50°C. The maximum exergy efficiency at the expander is 75.2% at 90°C and the minimum exergy efficiency of the pump of 19 %. The exergy efficiency in the evaporator and condenser at the maximum temperature 90% to 55.2% and 46.6% respectively.

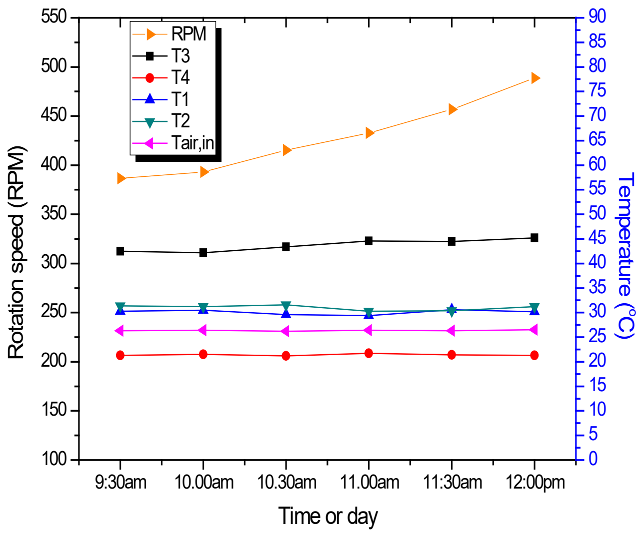

Figure 5 Experimental data of ORC with R-141b using 50°C heat source temperature on 23th of October, 2019

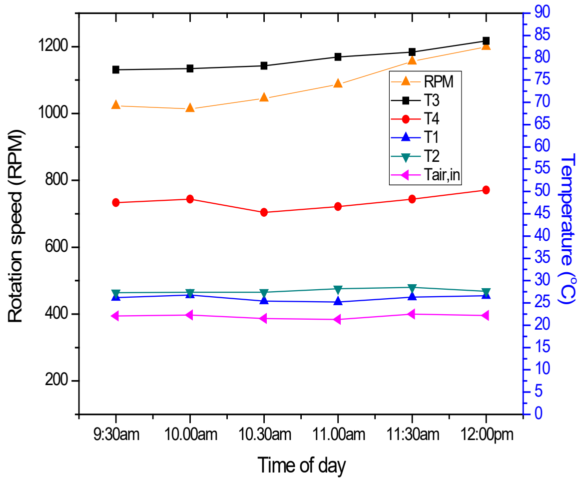

Figure 6 Experimental data of ORC with R-141b using 90°C heat source temperature on 27th of October, 2019

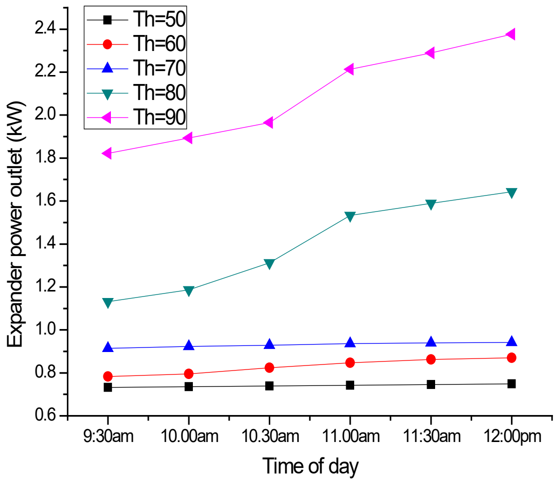

Figure 7 The effect of heat source temperature change on the expander power outlet

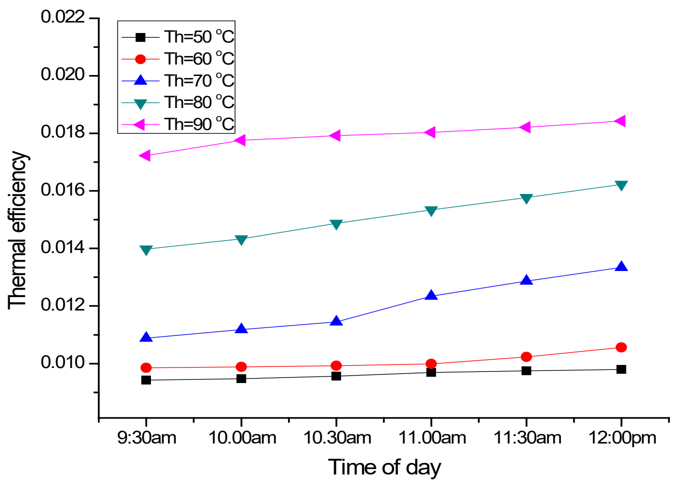

Figure 8 The effect of heat source temperature change on thermal efficiency

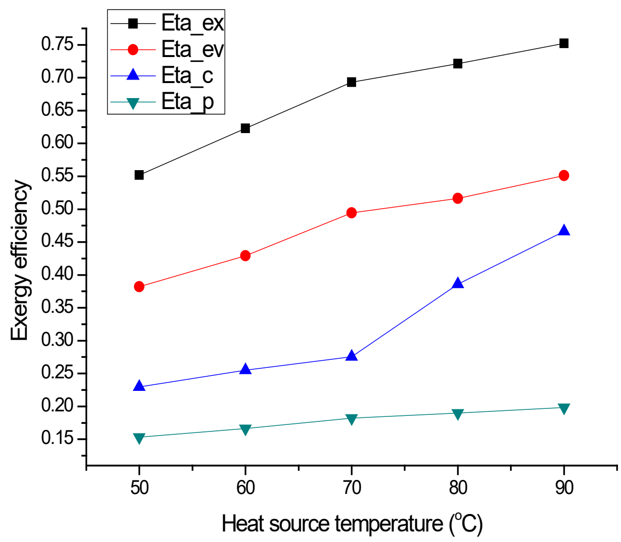

Figure 9 Variation of heat source temperature with exergy efficiency of all compound ORC

It can see the heat source temperature increased effect of exergy destruction of all compounds ORC as shows in Figure 10.The first exergy destruction of 4.938kW in the expander because of the increased temperature of the expanded inlet and the second exergy destruction of 2.996KW in the condenser and the evaporator, pump of 1.267kW, 1.743kW.

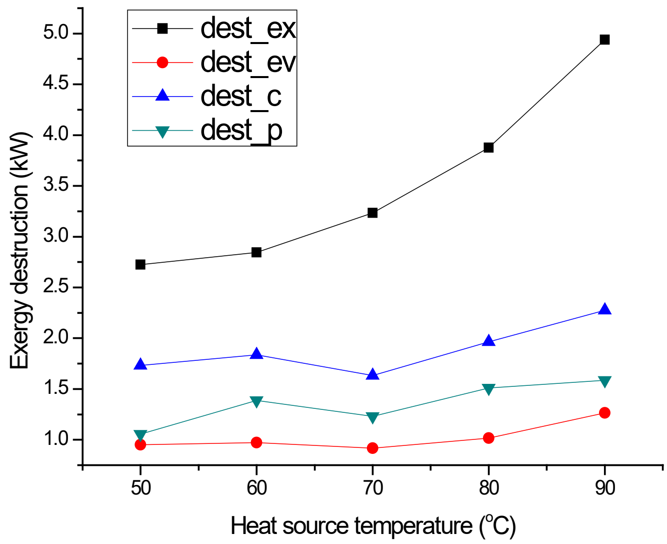

Figure 10 Variation of heat source temperature with exergy destruction

Figure 11 shows that the comparison between the thermal efficiency and the exergy efficiency of the ORC. When the maximum heat source temperature is 90 °C, the exergy efficiency was 20.6% and thermal efficiency was 1.8%. It shows the increase of heat source temperature lead to increasing thermal efficiency and exergy efficiency. Figure 12 shows T-S diagram of the test.

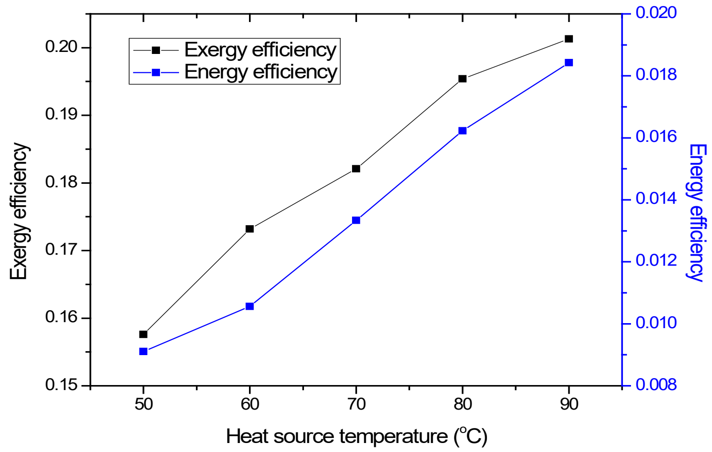

Figure 11 Comparison between thermal efficiency and exergy efficiency

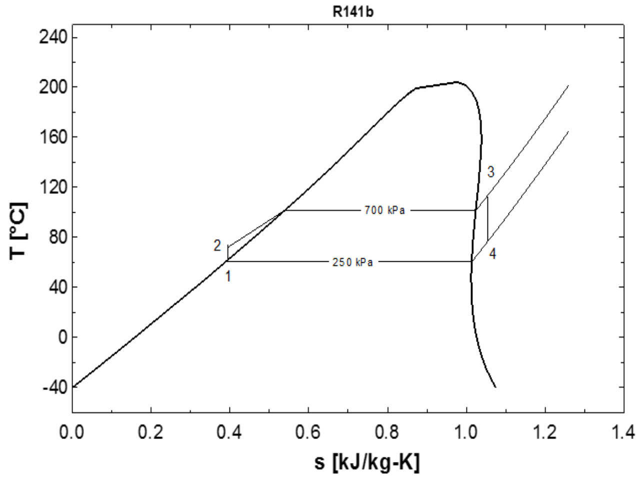

Figure 12 T-S diagram of the experimental test

7. COMPARISON WITH OTHER STUDY

By comparing with other study such as [10]. Figure 13 shows that the thermal efficiency of present study more than the thermal efficiency of previous study because the working fluid mass flow rate of the current study is greater than the mass flow rate of previous study and this leads to increased expander power as well as thermal efficiency.

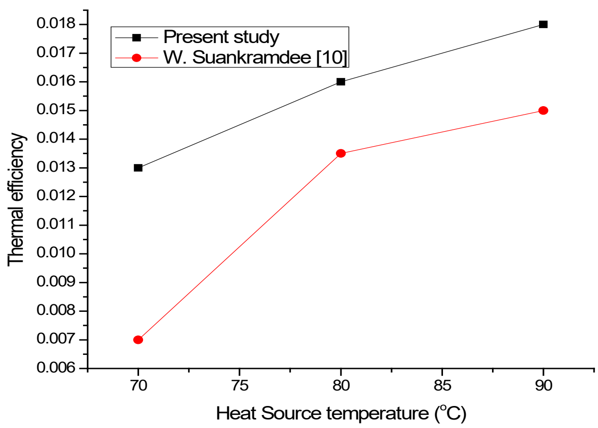

Figure 13 Comparison between the present study and previous study

8. CONCLUSION

In this paper, the aim of an experimental study to evaluate the performance ORC by using working fluid R-141 and a study of the effect of increasing the heat source temperature on the expander inlet temperature. The experimental results show that the expander inlet temperature was increased with the increased of heat source temperature. This effect on ORC performance parameter such as, thermal and exergy efficiency, expander power, and rotation speed. The maximum expander inlet pressure was found in experimental results with multi vane expander, which was 7 bar. The maximum thermal and exergy efficiency of ORC at R-141b was 1.8 %, 20.6%, respectively. The output power of the expander increased with expander inlet temperature increase and maximum was 2.331 kW. The maximum rotation speed was found in experimental results, which was 1200rpm. Concluded that the performance of the R-141b with a multi-vane expander for ORC are appropriate.

NOMENCLATURES

Q	Heat transfer rate (kW)	ExD	Exergy destruction (kW)
W	Power (kW)	η	Energy efficiency (%)
hf	Specific enthalpy (kJ/kg)	η_{is}	Isentropic efficiency (%)
Ex	Exergy rate (kW)	η_{ex}	Exergy efficiency (%)
$\dot{m}$	Mass flow rate (kg/s)	EES	Engineering Equation Solver

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