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Research Article

ENERGY COST ANALYSIS OF AN ORGANIC RANKINE CYCLE WITH EXHAUST GAS IN OFF DESIGN CONDITIONS

T. Phueksaphanrat[1]
E. Schulz[2]
A. Koonsrisuk[1,*]
[1] *School of Mechanical Engineering, Institute of Engineering, Suranaree University of Technology, Muang District, Nakhon Ratchasima 30000, Thailand*
[2] *School of Mathematics, Institute of Science, Suranaree University of Technology, Muang District, Nakhon Ratchasima 30000, Thailand*

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ABSTRACT:
Organic Rankine cycles (ORC) can be used for the conversion of heat to generate power. This study proposes a thermodynamics optimization of a subcritical Organic Rankine Cycle (ORC) and the golden section method was used to search for an optimum operating condition that provides a maximum net work output for the prescribed heat source temperature ($T_{hf,in}$), cooling fluid temperature ($T_{cf,in}$), mass flow rate of heat source, ($\dot{m}_{hs}$).Generally, the heat source and heat sink temperatures are assumed to be constant in the theoretical analyses of ORC power plants. However, they fluctuate in real practice. Then this study also disscuss the off-design simulations. The exhaust gas from a boiler of Suranaree University of Technology Hospital (SUTH) is used as a heat source with the temperatures in the range of 140 - 160°C. Also, the heat sink temperatures simulated are based on the weather of Nakhon Ratchasima Province, Thailand. The maximum net power output, thermal efficiency, exergy efficiency was 5.23 kW, 9.21% and 29.37%, respectively. Levelized cost of energy (LCOE) of this study was 8.2 Baht/kWh.

Keywords: *Organic rankine cycle, R245fa, Off design, Waste heat recovery, LCOE*

1. INTRODUCTION

Suranaree University of Technology Hospital (SUTH) is located in Nakhon Ratchasima Province of Thailand. In each department of SUTH have to keep clean by hot such as Disinfection of patient kits, Disinfection of various surgical equipment and Sterilization of food containers for patients. The heat that is used comes from the boiler that burns the fuel of the engine. Which the combustion will produce more exhaust and leave to the atmosphere which is waste heat.

Each exhaust or heat can recover, such as using hot air to bake the product to warm or expel moisture before entering the oven. Exhaust from the engine or exhaust from the boiler to produce hot air or produce low pressure steam. At present, there are technologies that can be used to low temperature heat to generate electricity. One technology that has received widely attention is the Organic Rankine Cycle (ORC) technology.

Organic Rankine cycle (ORC) can convert proficiently low temperature thermal energy into electricity and has been respected as a technology to recover the waste heat, resulting in obvious improvement of the energy utilization

* Corresponding author: A. Koonsrisuk
E-mail address: atit@sut.ac.th

efficiency. Moreover, ORC has a compact structure and needs less of maintenance work, while the difference thing between ORC and the traditional Rankine cycle is that the working fluid of water is replaced with organic fluids. These features make the ORC technology very outstanding in current and many researchers are already performed to consider the feasibility, performance and optimization of the ORC plant [1].

The ORC power plant operates in the same way as a steam power plant, which generates electricity from the expander. The expander will drive the generator. The steam that leaves the expander enters the condenser. The steam is rejected and condensed to liquid. And then the liquid is sent back to the evaporator by pump to receive heat until it becomes a vapor to continue expander. The difference between the ORC power plant and the steam power plant. The ORC power plant uses organic substances instead of water, which has a lower boiling point than water, allowing the use of heat sources with low temperatures.

Extensive varieties of studies have been conducted, including in solar energy utilization Delgado-torres and García-rodríguez [2] analysis of the low-temperature solar ORC is carried out. The higest temperatures of the solar cycle raise to 150 ˚C are considered using four different solar collector designs. Kosmadakis et al. [3] use solar with ORC, it is called two-stage RO solar Rankine system. It was found the Rankine cycle with the RO system is connected to a steady heat source, the specific cost is severely reduced to 1.06 V/m^3 from 6.85 V/m^3. Wang et al.[4] propose a low-temperature solar Rankine system utilizing R245fa refrigerant is proposed and an experimental model is designed, built and tested. An average power output of shaft is 1.64 kW. The efficiency of the overall power generation estimated is 4.2%.

Application in geothermal system Kanoglu [5] used an exergy analysis to analyze performance on a 12.4 MW the Stillwater binary geothermal power plant constitutive in Northern Nevada, USA. The plant exergetic efficiency is determined to be 29.1% depend on the exergy of the geothermal fluid at the vaporizer inlet. Liu et al. [6] optimize the heat sink temperature rise as well as the evaporation and condensation pressures of different mole fractions of R600a/R601a mixtures to generate the maximum net power output for geothermal temperatures of 110 ˚C, 130 ˚C and 150 ˚C and heat sink temperatures not lower than 70 ˚C. The results show that the geothermal ORC maximizes the net power using R600a/R601a with R600a mole fractions from 0.7 to 0.9. The systems using R600a/R601 mixtures generate 11%, 7% and 4% more power than that using pure R600a for each inlet temperatures.

And application in waste heat recovery, Zhao et al. [7] investigated the steady and transient performance of a diesel engine with and without an ORC system. R245fa is the working fluid. The mass flow rate of exhaust gas is 0.1999 kg/s and temperature at the evaporator inlet is 626 K at the system design point. The mass flow rate of ORC working fluid and the evaporation pressure are defined to be 0.265 kg/s and 0.9 MPa. The temperature and mass flow rate of the heat sink at the condenser inlet are 333.15 K and 3.2 kg/s. The simulation results show that the maximum net output power of the diesel engine integrated with the ORC system increase to 4.13 kW. Dual with ORC has raised the thermal efficiency of engine by 0.66% and decreased the engine brake specific fuel consumption (BSFC) by 3.61 g/(kWh). Parimal et al. [8] studied an ORC system operating on the exhaust gases of a truck diesel engine. The results confirm that a system with optimal components should be able to obtain a 15% fuel economy improvement over the duty cycle. Zhang et al. [9] investigated the influence of torque of single-screw expander on the ORC performance used in waste heat recovery is gained for various conditions of diesel engine and the effects on performance indexes of single-screw expander and thermal conversion efficiency. The highest power output are 10.38 kW and efficiency of shaft is 57.88% are gotten at 1538 rpm. The highest volume efficiency, efficiency of adiabatic and expansion ratio of expander are 90.73%, 73.25% and 4.6, respectively. The greatest ORC efficiency is 6.48%, which is obtained at 250 kW diesel power output and the torque of single-screw expander is 64.43 Nm. Larjola [10] use basic properties of high-speed ORC (HS-ORC) for three various heat source: hot water, exhaust gas of a gas turbine and combustion gases of solid fuel. Total efficiency means, percent of the heat source can be converted to electric power. The temperature each heat source is 425˚C for HS-ORC 500 kW and 1500 kW have total efficiency 17%.

Moreover, Sung et al. [11] have designed and constructed a 200-kW ORC system. Manente et al. [12] have designed and compared the pressure layout couple with the single pressure in the utilization of a geothermal heat source in the temperature range 100-200 ˚C. Chagnon-Lessard et al. [13] simulated numerically and then optimized ORC with consider to brine inlet temperature and condenser temperature. Vivian et al. [14] designed optimizations of four ORC configurations, operating with 27 working fluids and recovering heat sources in range 120–180 ˚C. Pan and Wang [15], Wei et al. [16], Astolfi et al. [17] and Wang et al. [18] analyzed and optimized on ORC net power output. All of the authors that designed and optimized the net work output. They input parameter, but do not show the method that optimized.

From the previous research, the waste heat was recovered from several sources of but never used waste heat from the boiler. And the above mentioned references about designing and optimization provide few guidelines to design an ORC plant providing maximal net work output, they have already fixed or assumed some parameter, but do not search to match with a heat source and heat sink, was shown in [11-18].

Then, this study propose a thermodynamics optimization of a subcritical Organic Rankine Cycle (ORC) and the golden section method was used to search for an optimum operating condition that provides a maximum net work output for the prescribed heat source temperature ($T_{hf,in}$), cooling fluid temperature ($T_{cf,in}$), mass flow rate of heat source, ($\dot{m}_{hs}$) and pinch point temperature differences will be shown in Section 4.2. And studying the operation of the system when the system is not operating at parameters designed (off-design). Such as the heat source temperature and the heat sink temperature is fluctuated, as shown in Section 4.4. A MATLAB code was developed and used in this simulation. The exhaust gas from the boiler in Suranaree University of Technology Hospital (SUTH*)* as a heat source to study the simulation of electricity production by the ORC power plant. R245fa is used as the working fluid. And Levelized Cost of Energy (LCOE) is analyzed.

2. THEORY

The ORC cycle consists of 4 main components, namely a refrigerant pump, evaporator, expander and condenser, as shown in Fig. 1. The T-s diagram of the organic Rankine cycle is shown in Fig. 2.

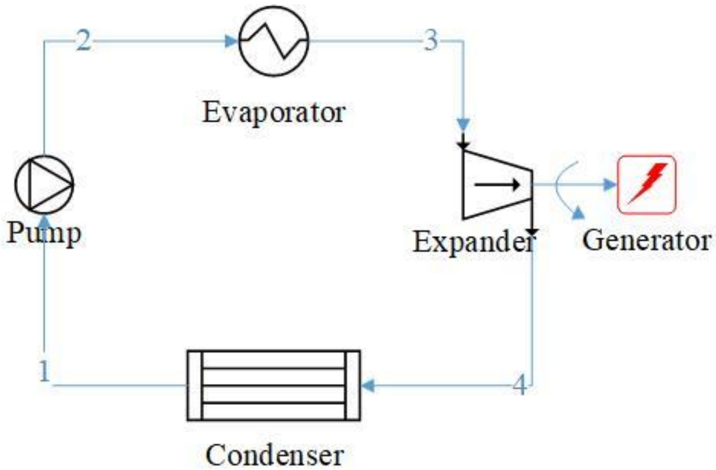

Fig. 1. Schematic diagram of the ORC system.

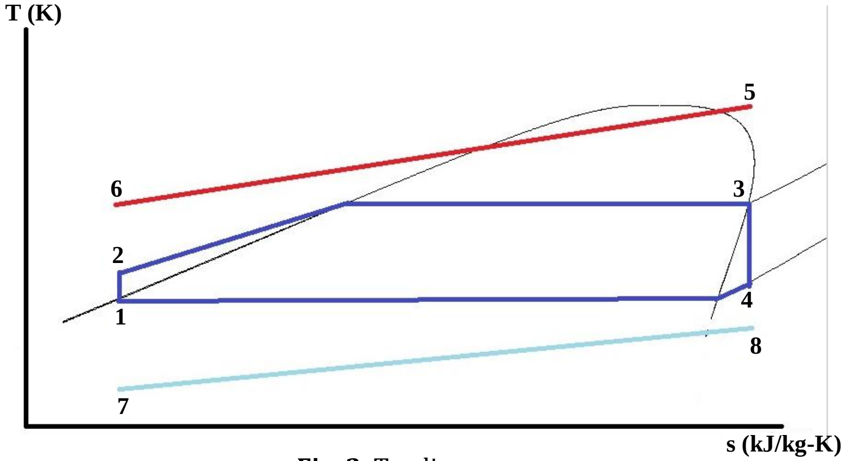

Fig. 2. T-s diagram.

In Fig.2, the saturated-liquid working fluid (point 1) is pumped to evaporator (point 2). It is heated in the evaporator at constant pressure until it becomes a saturated vapor (point 3) and then it is expanded in the expander. After the expansion (point 4), the working fluid is cooled in the condenser at constant pressure until becomes a saturated liquid [19].

The performance of the ORC system can be computed as follows:

The power of the ORC pump is given as follow:

$$\dot{W}_p = \dot{m}(h_2 - h_1) = \frac{\dot{m}(h_{2s} - h_1)}{\eta_p} \quad (1)$$

The energy governing equation of the evaporator is given as follow:

$$\dot{Q}_{evap} = \dot{m}(h_3 - h_2) \quad (2)$$

The power output of the expander is given as follow:

$$\dot{W}_t = \dot{m}(h_3 - h_4) = \dot{m}(h_3 - h_4)\eta_s \quad (3)$$

The energy governing equation of the condenser is given as follow:

$$\dot{Q}_{cond} = \dot{m}(h_4 - h_1) \quad (4)$$

The net work output of the ORC system is given as follow:

$$\dot{W}\dot{m}_{weft} = \dot{W}_t - \dot{W}_p \quad (5)$$

The thermal efficiency of ORC is given follow:

$$\eta_{th} = \frac{\dot{W}_t - \dot{W}_p}{\dot{Q}_{evap}} \quad (6)$$

Levelized Cost of Energy (LCOE) [20] is given as follow:

$$LCOE = \frac{Inv + \sum_{t=1}^{n} \frac{PEC}{(1+r)^t}}{\sum_{t=1}^{n} \frac{W_{net} t_{OP}}{(1+r)^t}} \quad (7)$$

3. METHODOLOGY

This study thermodynamically designed the operating parameters of an ORC power plant. A MATLAB code was developed to model the processes that described in Section 2. The golden search method was used to optimally match the evaporation and condensation pressure to the heat source and heat sink inlet temperature. The working fluid mass flow rate, evaporation pressure, and condensation pressure were varied to search for the maximum net power output. The exhaust gas of the boilers of SUTH was used as the heat source of the cycle. R245fa was selected as the working fluid. The working fluid properties were determined using NIST REFPROP.

Several studies designed the ORC power plant with the objective of maximizing the cycle efficiency. Maximum efficiency can be interpreted as that maximum output is obtain while minimum input is provided. On the other hand, this study aimed to maximize the net power output, instead of the cycle efficiency. As the heat source of this study is waste heat, the extraction of heat from the heat source to produce power output as much as possible is the objective of this study.

3.1 Parameters of system

The actual operation of a boiler, it was found that the exhaust gas temperature fluctuating in the real operation of the boiler of SUTH in the range of 140-160 ˚C, and in addition, the ambience temperature changes throughout the year. The ambience temperature is a mean temperature of Nakhon Ratchasima Province winter (January), summer (April), and rainy (September) season. Other variables are defined as follows.

- Temperature of heat source, $T_{hs,in}$ = 140, 150, 160˚C
- Mass flow rate of heat source, $\dot{m}_{wf}$ = 0.9198 kg/s
- Temperature of heat sink, $T_{cf,in}$ = 21.91, 30, 33.1 ˚C
- Mass flow rate of heat sink, $\dot{m}_{cf}$ = 1 kg/s
- Isentropic efficiency of pump, η_{sp} = 0.75 and turbine, η_{st} = 0.8 [21]

3.2 Levelized Cost of Energy, LCOE

Energy cost analysis of electricity production is calculated as follows.

- Maintenance cost, Z_{OM} = 5% of ORC price
- Life time, n = 20 years
- Operation time, t_{OP} = 19h/day and work 365 day/year
- The discount rate, r = 7.12%
- Operating cost, Z_{OP} = 15,000 Baht/month for 1 person
- Investment cost, Inv = equipment (pump, condenser, evaporator, generator, storage tank)

Flow chart of mathematical simulation of ORC is illustrated in Fig. 3.

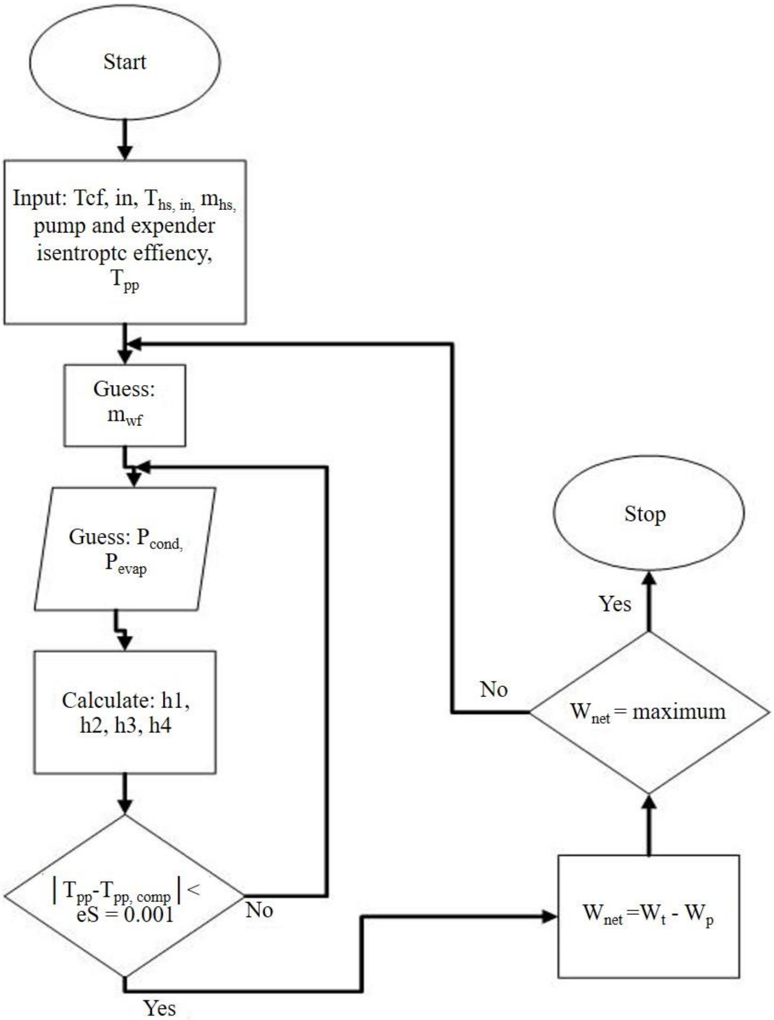

Fig. 3. Schematic of organic Rankine cycle process.

4. RESULTS AND DISCUSSION

This section is devided to 3 sections. In section 4.1 is validation, section 4.2 indicate that the code ability to search the net work output that more than reference. And section 4.3 simulation of SUTH in design condition and off-design operation.

4.1 Validation of program

The developed program for the parametric simulation of ORC was validated with article [22] are presented in Table 1.

Table 1: Results of validation.

Input			
Working fluid	Cyclopentane		
η_{sP}	0.65		
η_{sT}	0.85		
W_{net} (MW)	1		
P_1 (kPa)	288.8		
P_3 (kPa)	3342		
T_5 (K)	553.15		
T_7 (K)	335.15		
Chc (kW/K)	40.08		
Cca (kW/K)	349.66		
Output	**[22]**	**Present work**	**%error**
T_1 (K)	358.15	358.35	0.056
T_{2a} (K)	380.27	379.99	0.074
T_3 (K)	489	489.19	0.039
T_4 (K)	396.41	396.03	0.096
T_{4a} (K)	370.63	370.75	0.032
T_6 (K)	408.7	407.12	0.387
T_8 (K)	348.85	349.03	0.052
Q_{56} (kW)	5790	5853	1.088
Q_{78} (kW)	4790	4853	1.315
η_{th}	0.1727	0.1709	1.042

According Table 1 shows the results of the comparison of the accuracy of the program with the research article, where available data is inputted to the program at the beginning and output is the result of the program compared to the article. It was found that the results from the program were close to the article, with less than 2% error. Therefore, this developed program is reliable and will be used in various simulations.

4.2 Ability of algorithm for performance enhancement

It was found that several studies examined the ORC performance by specifying some certain values of operating parameters, especially the evaporation and condensation pressure. Some studies optimized the ORC performance by searching for the working fluid mass flow rate that provides the maximum net power or maximum efficiency. On the other hand, as specified in Section 3, the present algorithm searches for the mass flow rate, evaporation, and condensation pressure that provides the maximum net power output with a certain pinch point temperature (highest temperature difference) at the evaporator and condenser. It was believed that this can thermally match the operating parameters with the heat source and heat sink.

To prove that the algorithm can increase the plant performance, a comparison was made. The heat source temperature ($T_{hf,in}$) and heat sink temperature ($T_{cf,in}$) from a study of Sung et al. [11] were used as the input of the present algorithm to allow it to design the operating parameters of an ORC plant (e.g. mass flow rate, evaporation and condensation pressure, UA of heat exchangers). The net work output and efficiency from the algorithm were compared with those of Sung et al. as indicated in Table 2.

Table 2: Searching results between the present work and reference.

Input	Sung et al. [11]	
$T_{hs,in}$ (˚C)	122.6	
$T_{cf,in}$ (˚C)	25.3	
m_{hs} (kg/s)	17.2	
Output	[11]	**Present**
W_{net} (kW)	105.8	317.42
efficiency	8.6	8.42

According to Table 2, the net power output of the present study is about 3 times of Sung et al. while the efficiencies are at the same order of magnitude. This could be ensure that the present algorithm can design the operating conditions that increase the plant power output.

4.3 Thermodynamic design at normal operation condition

In the simulation to find the maximum net work. The design values is required that temperature of heat source, $T_{hs,in}$ = 150˚C and temperature of heat sink, $T_{cf,in}$ = 30 ˚C. The results show in Fig. 4. Figure 4 shows the net work output increased with increasing mass flow rate and there is the maximum net work output is about 5,225 W with mass flow rate is 0.29 kg/s.

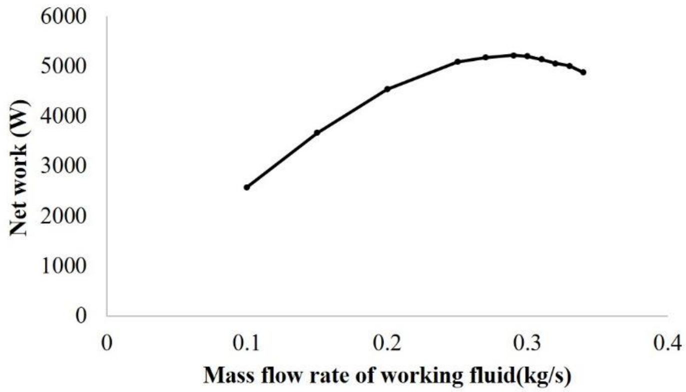

Fig. 4. Mass flow rate of working fluid versus net work.

4.4 The influence of the heat source and heat sink

The exhaust gas from a boiler of SUTH is used as a heat source with the temperatures in the range of 140 - 160°C. Also, the heat sink temperatures simulated are in the range of 21.95 – 33.1˚C. The size of condenser and evaporator are fixed as the same value in Table 3. The simulation system will change the value of condensation pressure and evaporation pressure to generate the net work output constant as shown in Figs. 5, 6 respectively.

Table 3: Mass flow rate that net work is maximum.

Description	Value
$\dot{m}_{wf}$(kg/s)	0.29
W_{net}(W)	5,225
η (%)	8.69
ξ (%)	58.87
$ξ_p$ (%)	29.37
UA_{cond} (W/˚C)	3911.36
UA_{evap}(W/˚C)	2606.47
V3/V4	3.97
P_{cond}(kPa)	334.52
P_{evap}(kPa)	1215.18

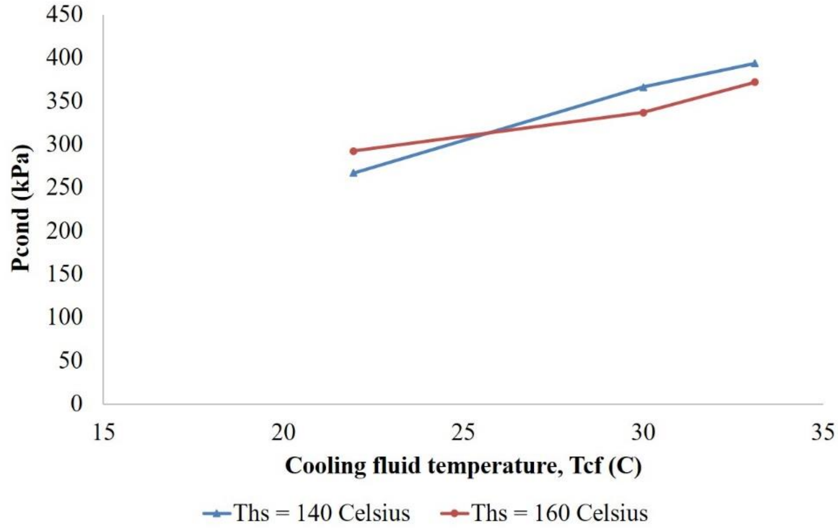

Fig. 5. Condenser pressure of heat source and heat sink is fluctuated.

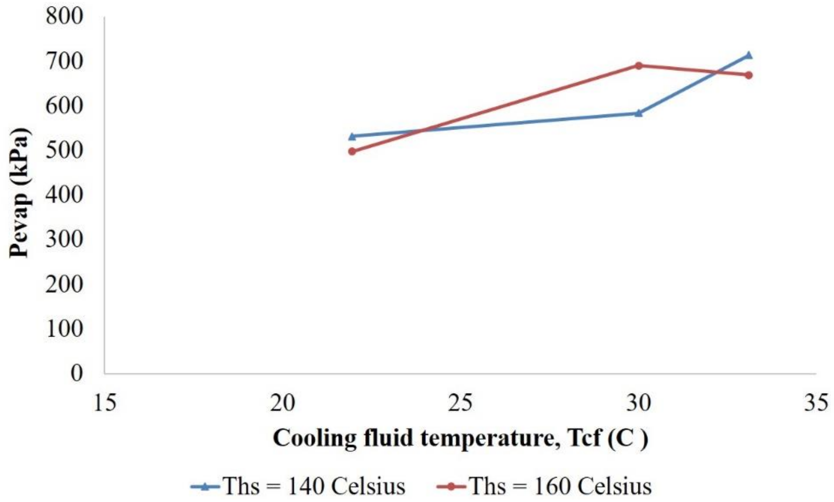

Fig. 6. Evaporator pressure of heat source and heat sink is fluctuated.

Figure 5. shows the condensation pressure increased with increasing heat sink temperature because UA of heat source is fixed. Then, to generate the net work output constant, condensation pressure has to increase.

Figure 6. shows the evaporation pressure increased with increasing heat sink temperature same the condensation pressure. Because UA of heat source is fixed and condensation pressure increase. The enthalpy at evaporator has to increase before enter to expander to generate the net work output constant.

4.5 Levelized Cost of Energy, LCOE

The result of evaluating energy potential by developing mathematical models of the ORC is show in Table 4.

The results of the unit cost analysis of electricity generation using the organic Rankine cycle show in Table 4. The analysis shows that the project cost is 268,000 Baht, which is calculated as the cost of per unit of electricity is equal to 8.2 Baht / kWh. Since the current electricity in Thailand is about 4 baht per unit, it shows that it is not worth the cost. Therefore should be looking for other methods of optimization.

Table 4: Results of unit cost analysis of electricity generation.

Description	Value	Unit
Capacity of ORC	5.22	kW
Maintenance cost 5% of ORC price (ZOM)	13217.22	Baht/year
Operation time (tOP)	6,935	h/year
Cost of operation (ZOP)	180,000	Baht/year
Discount rate (r)	7.12	%
Life time of ORC (n)	20	year
Investment cost (Inv)	268,000	Baht
Electricity production cost (PEC = ZOP + ZOM)	193,217	Baht
Levelized of electricity cost (LCOE)	8.2	Baht/kWh

5. CONCLUSION

In this study, interested in recovery exhaust gas from the boiler in Suranaree University of Technology Hospital (SUTH) as a heat source to study the simulation of electricity production by the ORC power plant of R245fa working fluid to obtain maximum power. And this study propose a thermodynamics optimization of a subcritical Organic Rankine Cycle (ORC) and the golden section method was used to search for an optimum operating condition that provides a maximum net work output for the prescribed heat source temperature ($T_{hf,in}$), cooling fluid temperature ($T_{cf,in}$), mass flow rate of heat source, ($\dot{m}_{hs}$) and pinch point temperature differences. The net work output, thermal efficiency, exergy and LCOE have been investigated. Based on the present analysis, the results are concluded:

- The cooling fluid temperature (T_{cf}) is equal to 30˚C and heat source temperature ($T_{hf,in}$) is equal to 150 ˚C, which are the design condition. The maximum net work output is equal to 5.23 kW.
- The thermal efficiency and exergy are 9.21% and 29.37%, respectively.
- The condensation pressure and the evaporation pressure increase with increasing heat sink temperature.
- The project cost is 268,000 Baht.
- Levelized cost of energy (LCOE) is 8.2 Baht/kWh.

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ABBREVIATIONS AND SYMBOLS

Symbols	*Meaning*
Inv	Investment cost (Baht)
LCOE	Levelized cost of electricity (Baht/kWh)
n	Life time of ORC
ORC	Organic Rankine cycle (kW)
t_{OP}	Operating time (day/year)
r	Discount rate (%)
PEC	Production electricity cost (Baht/year)
Z_{OP}	Operating cost (Baht)
Z_{OM}	Maintenance cost (Baht)
$Z_{pipping}$	Pipping cost (Baht)
T	Temperature (˚C)
P	Pressure (kPa)
W	Work (kW)
h	Enthalpy (kJ/kg)
s	Entropy (kJ/kg)
m	Mass flow rate (kg/s)
U	Overall heat transfer coefficient (W/m^{2}K)
A	Area (m^2)
Q	Heat rate (kJ/kg)

η	Efficiency (%)
ξ	total exergy efficiency
ξ_p	exergy efficiency for power production

Subscript	*Meaning*
s	Isentropic
P	Pump
C	Condenser
t	Turbine
E	Expander
Th	Thermal
PP	Pinch point
In	Inlet
n	Net
max	Maximum
wf	Working fluid
evap	Evaporator

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