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Preliminary Design of Organic Rankine Cycle using Solar Thermal in Hungary

Diki I. Permana, Dani Rusirawan, and Istvan Farkas

ABSTRACT

Renewable energy sources have grown in popularity in a variety of applications over the last century, particularly in solar power generation. Exploiting solar energy in low-medium temperature systems via the organic Rankine cycle (ORC) is a prospective idea for producing clean energy in remote areas at a low cost. The amount of solar energy available in Hungary is sufficient to power the ORC system. In this study, a parabolic through collector (PTC) solar collector is used to convert solar thermal energy into a heat stream that is used to boil the working fluid of R134a, which was chosen as a good ORC working fluid because it has a low boiling point as well as a low ODP and GWP value. Many recent studies have studied solar-ORC both from a theoretical and experimental point of view in various areas, especially in design system. In this study, the preliminary design that overcomes the need for solar-ORC, including an analysis of energy, the efficiency of the system, and turboexpander characteristics using different pinch temperatures (10 °C and 5 °C) will be elaborated. The weather data in June is used for initial data input, for calculations in the PTC solar collector. The result shows that the ORC system with 5 °C has a better result in view of the energy from the turbine and the thermal efficiency, compared to the ORC system with 10 °C.

Keywords: Parabolic through collector, planning, pinch temperature, solar thermal, working fluid.

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I. Introduction

Renewable energy sources have become increasingly important in a wide range of applications in the last century, particularly in the power generation. Solar energy has surpassed wind and biomass as the most popular renewable energy source due to its reasonable availability [1]. Solar energy is an energy source for addressing critical energy issues such as global warming, ozone depletion, and high electricity prices [2].

Exploiting solar energy in low-medium temperature systems using the organic Rankine cycle (ORC), is an intriguing idea for producing clean energy and affordable in remote areas. ORC is well known as the most affordable system that convert any heat resource into electricity such as geothermal brine or excess steam [3], industrial waste heat [4], biomass, municipal waste heat and solar energy.

ORC utilizes heat from the working fluid or refrigerant which has a low boiling point, as it similar case with utilizing a water stream with a conventional Rankine cycle. In this study, solar thermal is used as a heat source by using a solar collector component to boil water from the tank. According to Solargis, the amount of annual global horizontal irradiation for Hungary is between 1100 and 1350 kWh/m^2 which makes it a relatively good site for installing solar thermal collectors combined with an ORC system [5].

Many recent studies have studied solar-ORC both from a theoretical and experimental point of view in various areas. Reference [6] study about the bibliometric review that explained the relation of solar-ORC with other disciplines and the future research that related with solar-ORC. For example, the cycle optimization is common research in solar-ORC, namely multi-generation or regenerative or trigenerative. Reference [7] did a simulation analysis of small-scale solar ORC trigenerative systems. On the other side, [8] investigated regenerative solar-ORC using different climate conditions. According to such research, the conclusion of using cycle optimization is improve both of energy production and increase of thermal efficiencies.

Another discipline that related to future research in solar-ORC is the application of thermal energy storage (TES). The TES is well-known for latent heat energy storage (LHES) which to storage energy in solid phase and it will be release in liquid phase. Reference [9] examined the integrated of TES solutions for a domestic-scale solar combined heat and power through ORC systems. Meanwhile, the phase change material (PCM) usage in solar-ORC has been carried out since the beginning of 2020. The PCM is suitable for excellent heat-converting material in evacuate tube collectors (ETC) between of 2018 – 2019 [6]. Reference [10] are the researchers who conduct a numerical analysis of LTES using encapsulated PCM for solar thermal energy generation plant.

However, the solar-ORC concepts for engineer supplies have been extensively discussed but rarely implemented, especially in Hungary. However, with the solar thermal potential mentioned above, it is important to study ORC generators with heat sources from solar thermal.

This study will report the optimum design that overcomes the need for solar-ORC including analysis energy and efficiency of the system, turbo-expander characteristics using different of pinch temperature (10 °C and 5 °C).

II. Material and Methods

A. Solar-ORC Concept

The Fig. 1 shows the scheme of the ORC cycle consisting of an evaporator, turboexpander, condenser, and pump. In the boiler, there is heat transfer occurred between hot steam and working fluid or organic fluid which has a low boiling temperature so that the working fluid changes phase into steam vapor which has sufficient temperature and pressure to turn the turbo-expander and the rotation can be converted into electricity by the generator.

The first and second laws of thermodynamics should be implemented in determine the performance of the ORC. The amount of work generated, and the heat required by the ORC can be determined by the energy equilibrium equation. The equations in each component are given in details as follows [11]:

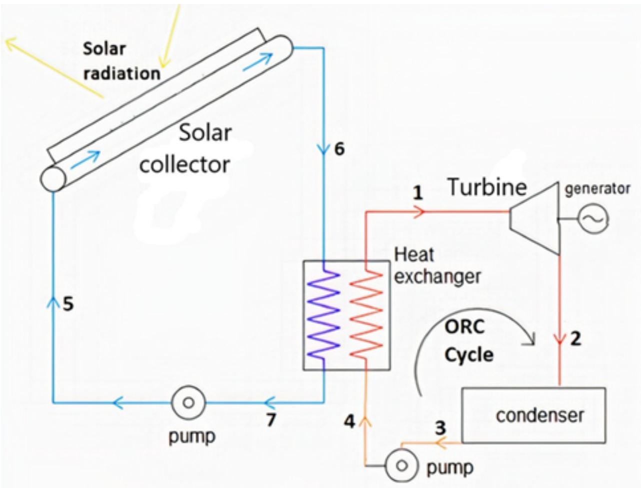

Fig. 1. Simple schematic of solar-ORC.

Process 1-2, turbine:

$$\dot{W}_{turbine} = \dot{m}(h_1 - h_2)\,\eta_{turbine}, \tag{1}$$

Process 2-3, condenser:

$$\dot{Q}_{out} = \dot{m}(h_2 - h_3), \tag{2}$$

Process 3-4, pump:

$$\dot{W}_{pump} = \frac{\dot{m}(h_4 - h_3)}{\eta_{pump}}, \tag{3}$$

Process 4-1, evaporator:

$$\dot{Q}_{in} = \dot{m}(h_1 - h_4), \tag{4}$$

The net power output of solar-ORC can be evaluated through the following equation:

$$\dot{W}_{net} = \dot{W}_{turbine} - \dot{W}_{pump} = (h_1 - h_2) - (h_4 - h_3), \tag{5}$$

meanwhile, the thermal efficiency is as follows:

$$\eta_{thermal} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{\dot{W}_{turbine} - \dot{W}_{pump}}{\dot{Q}_{in}}. \tag{6}$$

In the equations the $\dot{W}_{turbine}, \dot{W}_{pump}$ are work on turbine and pump respectively, while $\dot{m}$ is mass flow rate (kg/s), h is specific enthalpy (kJ/kg), and $\dot{Q}_{in}$, $\dot{Q}_{out}$ are the heat enters and exit from the system. The (1-6) are valid in the ideal condition when all the processes are supposed to be isentropics, where all losses arisen are ignore.

Under the actual operational conditions many losses occur including an increasing entropy in the compression and expansion processes. In this study, the isentropic efficiency for turbine ($\eta_{turbine}$) is set at 75% and for pump (η_{pump}) is 90%.

Meanwhile, the solar collectors that will be used in the recent study is using parabolic tube collector (PTC) with the surface area surface (A_{SC}) around 1.7 m^2. The performance of the PTC will modelled using a steady-state efficiency (7) [12]:

$$\frac{\dot{Q}_u}{A_{sc}} = 0.761\,K_\theta\,G_b - 0.22\left(T_{c,out} - T_{c,in}\right) - 0{,}000503\left(T_{c,out} - T_{c,in}\right)^2, \tag{7}$$

where G_b and K_θ are the global solar irradiation (Wh/m^2) and incident angle of the solar collector, respectivelly. While the solar collector useful heating product (Qu) is found by using the following (8):

$$\dot{Q}_u = \dot{m}C_p\left(T_{c,out} - T_{c,in}\right). \tag{8}$$

B. Working Fluid and T-s Diagram

In this study, the author set the pinch of temperature inside evaporator is about 10 °C and 5 °C. At the same time in the condenser the temperature is about 5 °C. The R134a was chosen as a working fluid due to having a low value of ozone depletion potential (ODP) and global warming potential (GWP) with 0.0 and 1300, respectively [13]. Moreover, R134a is suitable for working fluid that can generate energy from stream under 100 °C [14].

The details of R134a working fluid properties are given in Table I.

Fig. 2 depicts the type of T-s cycle of R134a working fluid that is dependent on the pressure of the working fluid in the evaporator when heat is applied. If the working fluid pressure is less than the critical pressure (P_1<P_{crit}), during heat transfer in evaporator, the working fluid will evaporate from the liquid phase to gas phase by passing through the 2-phase region, this process is called a sub-critical cycle (process cycle: 1-2-3-4-1). Meanwhile, the detail of each parameter and some assumptions will be given in Table II.

TABLE I: THE PROPERTIES OF R134A [15]

Parameters	Unit	Value
$T_{critical}$	°C	101.06
$T_{boiling}$	°C	26.5
$T_{freezing}$	°C	-101
$P_{critical}$	MPa	4.059
Molar mass	g/mol	102.03
Type	-	Isentropic
ODP	-	0
GWP	-	1300
ASHRAE class	-	A3
LEL	%Vol	N/A
UEL	%Vol	N/A

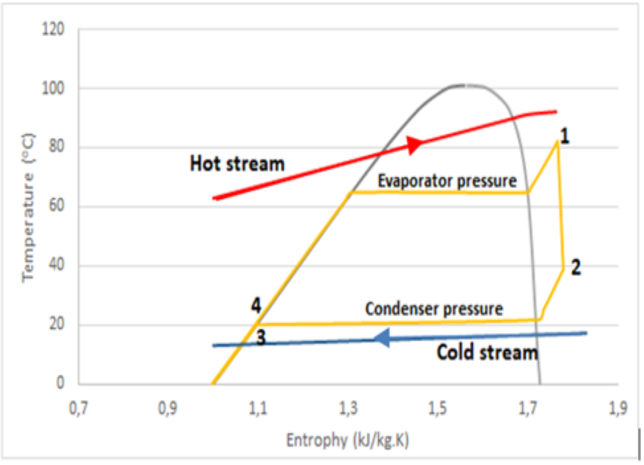

Fig. 2. Process statement of R134a.

TABLE II: SOLAR-ORC PARAMETERS OF DIFFERENT PINCH TEMPERATURE

Parameters	Value (10 °C)	Value (5 °C)
$T_{evap,in}$ (°C)	92	92
$T_{evap,out}$ (°C)	62	62
T_1 (°C)	82.13	87.13
T_2 (°C)	38.8	38.85
T_3 (°C)	20	20
T_4 (°C)	20.4	20.4
$T_{cold,\ in}$ (°C)	15	15
$P_{evaporator}$ (Mpa)	1.88	2.11
$P_{condenser}$ (Mpa)	0.57	0.57
mdot (kg/s)	1.5	1.5

III. RESULT AND DISCUSSIONS

In this section, a report on the theoretical result of the preliminary design of solar-ORC parameters including the performance of the cycle and performance of the turboexpander will be presented.

A. Hungary's Solar Irradiation

In this study, the incident angle modifier for the solar collector is 45° and hourly average of global solar irradiation in summer conditions (June) in Gödöllő, Hungary is 142.3 Wh/m^2 (presented in the average values of direct normal irradiation), and the peak of ambient temperature is around 30 °C.

Fig. 3 is the collector's heating product produced by parabolic through collector at an average hour in one month. By using (7) it is found that the highest *Qu* is reached at the peak sun position. Furthermore, by (8), the output temperature of the solar collector, which will be used to heat the ORC working fluid in the evaporator by converting it into a steam turbine, can be determined. Based on Fig. 3 it can be seen that the PTC could reach the maximum output temperature 92 °C.

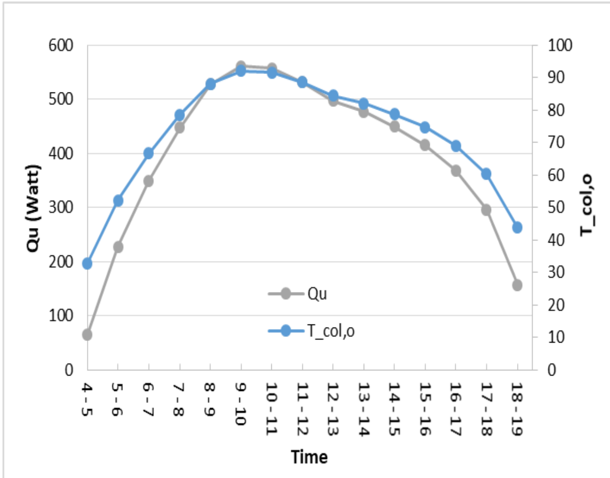

Fig. 3. The heating product and outlet temperature of solar collector.

B. Performance Cycle

This section discusses the energy performance characteristics of the ORC using R134a working fluids. The calculation results are presented in Fig. 4.

Fig. 4 shows how much energy is produced by each components of R134a using two different pinch temperatures at the evaporator. It can be seen that for R134a with 5 °C pinch temperature produce the highest of $W_{turbine}$ compare to 10 °C, with the values are 27.81 kW and 25.49 kW, respectively.

Moreover, for *Wnett* produce by pinch temperature of 5 °C is larger than by pinch temperature of 10 °C with the values are 26.38 kW and 24.05 kW, respectively. Meanwhile, for the eficiency thermal of ORC system is about 7.21% is produce by the system that using pinch temperure of 10 °C and its sligtly less compare to the ORC system that using pinch temperature of 5 °C with 7.83%. This condition was occurred due to the pinch temperature with 5 °C is greater in utilizing energy from the solar collector compared to the pinch temperature of 10 °C.

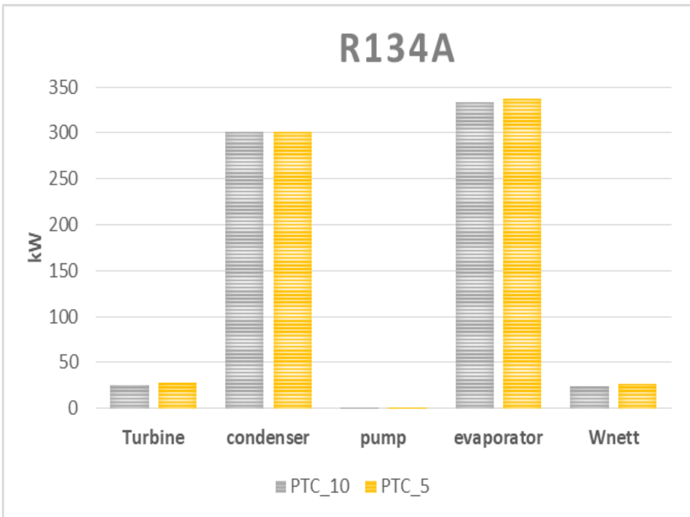

Fig. 4. The energy generation by each component.

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C. *Performance of Turboexpander*

Fig. 5 shows the characteristics of W_{shaft} produced by turbo-expander, in 2 (two) different pinch temperatures i.e. 5 °C and 10 °C.

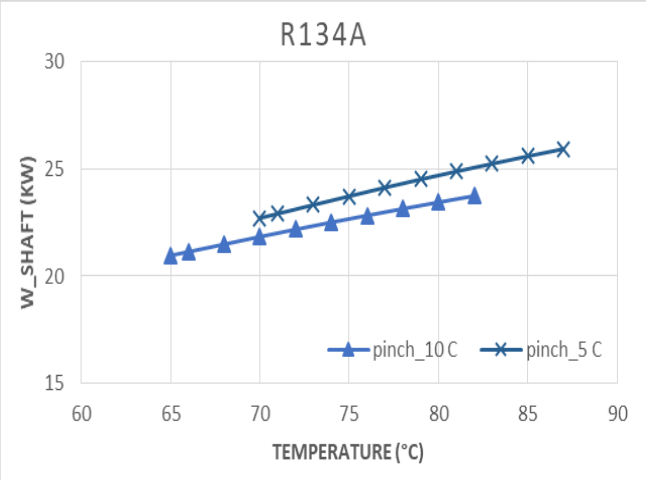

Fig. 5. W_{shaft} vs temperature.

Based on Fig. 5, it can be seen that for both pinch temperature, W_{shaft} are highly influenced by inlet temperature entering turbo-expander. For the pinch temperature 5 °C, *Wshaft* around 25.94 kW, is produced at inlet temperature of 87 °C, while for the pinch 10 °C, the highest of *Wshaft* i.e. 23.7 kW, is produced at inlet temperature 82 °C. This condition was occurred due to the difference of an evaporator pressure at each pinch temperature. At the pinch temperature 10 °C, the evaporator pressure is 1.88 MPa, while at the pinch temperature 5 °C, the evaporator pressure is 2.11 MPa. The evaporator pressure difference will affect the enthalpy inlet values.

IV. Conclusion

The initial design and calculation basis for obtaining energy from solar thermal utilization through ORC has been carried out. A basic thermodynamic calculation differences in the pinch temperature (10 °C and 5 °C), and PTC solar collector are implemented in the design. Gödöllő's weather data in June with outlet temperature of PTC around 92 °C and R134a working fluid, are used as case study. The result shows that the pinch temperature of evaporator at 5 °C produces larger energy compared to 10 °C, with the values were 27.81 kW and 25.49 kW, respectively. Moreover, the thermal efficiency of the system that uses pinch temperature of 5 °C and 10 °C were 7.83% and 7.21, respectively.

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Conflict of Interest

Authors declare that we do not have any conflict of interest.

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