Evaluation of an Organic Rankine Cycle Using a Non-Imaging Solar Concentrator for Different Working Fluids

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Abstract

The Organic Rankine Cycle (ORC) is a feasible technology that can be applied for small-scale power generation in residential and commercial buildings. However, a solar thermal power plant may not compete with that of a thermal power plant using conventional heat source such as coal or natural gas but environmental impact. On the other hand, the cost of a power plant may be reduced by improving the system performance. Using non-imaging concentrators can eliminate the necessity of sun tracking system. Covering the concentrators by evacuated glass tube can reduce the heat loss from the absorber, and improves the effective life-cycle of optical components. Therefore, a non-imaging concentrator was considered as a steam generator of solar power plant. In order to evaluate the system performance, simulations were conducted by using aspenHYSYS software for different working fluids. The maximum performance is obtained for the case of R-141b for the pressure difference of 39 bars to be 15.3%. The best performance improvement is attained for water and R-141b to be about 8.2% and 7.8%, respectively. The working fluid, R-141b shows a better performance due to its lower boiling point and may be preferable for small scale applications.

Key words: Organic Rankine Cycle, solar power, non-imaging, compound parabolic concentrator, involute reflector.

1. Introduction

The rising demand for energy, the limited source for fossil fuels and their harmful effects in environment (e.g. global warming) have encouraged to the worldwide search for cleaner energy sources. Renewable energy such as geothermal, wind, solar etc. have no bad effect on environment. Among renewable energy sources, solar energy has a special place because it is the most plentiful energy source and the other forms of renewable energies are indirectly powered by sun [1]. Many technologies have been developed to utilize the solar energy for heat and electric generation. The electric generation using solar energy can be done directly by photovoltaic systems and indirectly by solar-thermal power cycle. Although the photovoltaics can be used for small-scale applications, high-temperature thermal power plants that work based on conventional Rankine cycle may not be economic in small-scale application. Moreover, solar thermal power plants may not compete with that of a thermal power plant using conventional heat source such as coal or natural gas but environmental impact [2]. On the other hand, cost of a power plant may be reduced by improving the system performance. For small scale applications and improved performance, Organic Rankine Cycle can be considered. Therefore many studies have been done to develop ORC cycle. Wolpert and Riffat [3] made the study of a low-temperature (<100 °C)

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solar ORC design using heat pipe solar collectors for electricity generation with hydrogen generation as energy storage system. Tchanche et al. [4] evaluated working fluids in a low-temperature solar ORC by taking into account different parameters: pressures, mass and volume flow rates, efficiencies, cycle heat input, safety and environmental data and found that working fluids with high boiling point like methanol and water are very efficient but the presence of droplets during the expansion process is a drawback. Rayegan and Tao [2] developed a procedure to select the working fluids used in solar Rankine cycles and found that eleven working fluids can be recommended in solar ORCs that used low or medium temperature solar collectors. Calise et al. [5] proposed a novel small-scale solar system based on an evacuated flat-plate solar collector and Organic Rankine Cycle. The solar system was evaluated for different climatic conditions and it was obtained that the efficiency of ORC remains around 10% during the year. The working fluid has important effect on the performance as well as consideration of environmental pollution and required power for steam generation. Furthermore, using non-imaging concentrators can eliminate the necessity of sun tracking system which causes additional cost. Covering the concentrators by evacuated glass tube can reduce the heat loss from the absorber, and improves the effective life-cycle of optical components including reflector and absorber.

The main objective of this study is to use a non-imaging concentrator in an Organic Rankine Cycle (ORC) to eliminate the requirement of sun-tracking system and to decide the optimum working fluid for the ORC in different conditions. Moreover, in order to improve the effective life cycle and performance with low heat loss configuration, the concentrator was covered by evacuated glass tube. The system was evaluated for different working pressure.

2. Analysis model

2.1. Geometry of the non-imaging concentrator

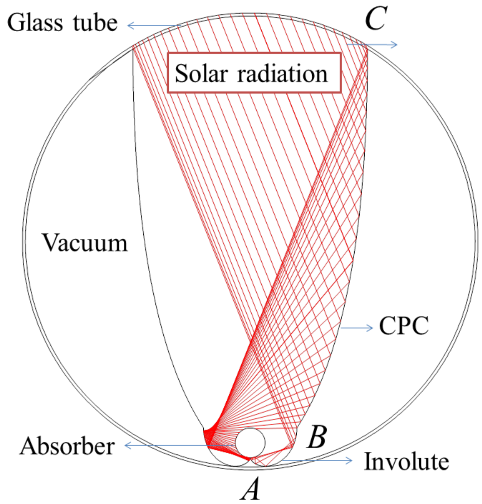


Figure 1. Cross section geometry of the non- imaging concentrator

The non-imaging concentrator is a two-stage, line-axis concentrator and consists of compound parabolic and involute reflectors with a tubular absorber [6]. The design is mainly based on the exploitation of uniform distribution of temperature on absorber and approaching to the highest possible concentration within the acceptance angle. Furthermore, the concentrator is covered by an evacuated glass tube to eliminate the convective and conductive heat losses, to provide easy maintenance, and to protect the reflector from external condition. The cross section geometry of the non-imaging concentrator is shown in Fig. 1. The parabola BC represents the one half of the compound parabolic reflector and the curve AB represents the one half of the involute reflector.

2.2. Solar power plant using ORC

The boiling point of the working fluids in ORC is much lower than steam, thus it is not required to reach high temperatures to generate vapor for a running micro-turbine or expander. Therefore, ORC can be used for small scale applications (etc. domestic electric generation) and is required lower temperature compare to the Rankine Cycle that use water.

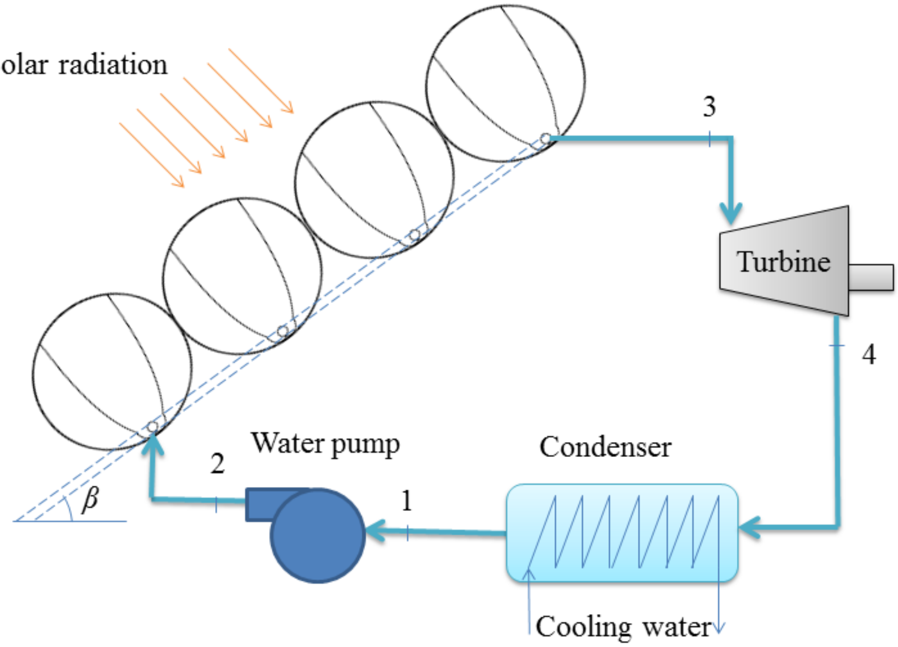


Figure 2. Organic Rankine Cycle using a non-imaging concentrator

The considered ORC using non-imaging concentrator mainly consists of the several components as seen in Fig.2. The main component is solar concentrator that can be used as an evaporator to obtain intense heat flux for steam generation. The concentrator has low heat loss configuration and eliminates requirement of sun tracking system which is mandatory for an imaging concentrator. The tilt angle β of the concentrator was decided to harvest the solar energy all the year round to be 23.44° for Sendai, Japan (38°15′7′′N and 140°53′5′′E). A steam turbine is used to generate mechanical work by using high pressure steam. A condenser is used to transform the vapor into liquid for re-vaporizing in cycle. The pump is used to provide circulation and to compress the working fluid to working pressure.

3. Analysis method

3.1. Solar collector performance

After being transmitted through the glass cover and reflected from the specular surface, the insolation q_s is absorbed by the receiver pipe based on the absorbing ability. The useful energy gain depends strongly on the energy losses from the absorber, due to both the convective heat loss to the ambient air and radiative heat loss to its surroundings. The thermal efficiency of the solar concentrator can be obtained by the ratio of the useful energy gain to the incident radiation on the aperture of concentrator. In this case, the thermal efficiency can be expressed as [7-9]:

$$\begin{aligned}\eta_{th,con} &= \frac{\dot{Q}_u(t)_c}{q_s(t)A_c} \\ &= \eta_{opt} - \frac{UA_a(T_a - T_{amb})}{q_s(t)A_c} - \frac{\varepsilon\sigma A_a\left(T_a^4 - T_{amb}^4\right)}{q_s(t)A_c}\end{aligned} \tag{1}$$

where the first term indicates the optical performance which is the ratio of the absorbed energy to the available energy and is a function of the reflectivity of reflector ρ_r, transmissivty of glass cover τ_c and absorptivity of absorber α_{ab}. The second and final terms show heat losses from the absorber through convective and radiative heat transfer, respectively.

3.2. Organic Rankine Cycle performance

The working fluid gets in the pump to be compressed to the working pressure with an isentropic compression. The compressed working fluid is heated by solar concentrator unit to achieve vapor in superheated region. The superheated working fluid pass throughout turbine with isentropic expansion to obtain mechanical work that can be converted into electricity by electric generator. After the expansion, the saturated vapor and liquid mixture get into condenser to reduce the temperature to obtain saturated liquid for a new circulation. The efficiency of the Rankine cycle can be calculated by:

$$\eta_{th,cy} = \frac{w_{net}}{q_i} = 1 - \frac{q_o}{q_i} \tag{2}$$

where w_{net} is net work of cycle and can be determined by:

$$w_{net} = q_i - q_o = w_t - w_p \tag{3}$$

where q_i and q_o are the incident radiation and output heat from the condenser, respectively. w_t and w_p are output work by turbine and energy consumption by pump, respectively. In order to decide the cycle efficiency, the net work is obtained by taking into account the useful energy. However, some heat loss occurs from the total available energy on the aperture of concentrator to obtain the useful energy. The overall system efficiency should be considered by taking into account of cycle and concentrator efficiency. Thus, the overall system efficiency can be determined by:

$$\eta_{th,all} = \frac{w_{net}}{q_i / \eta_{th,con}} \qquad (4)$$

More than 50 working fluids have been considered and evaluated in the literature about their effect and some of them have been rejected by protocols due to their environmental effect and their phase out as required [10]. In this work, benzene, cyclohexane, methanol, Refrig-113 and R-1 41b were selected as the working fluids. The selected organic working-fluids have lower boiling temperature and lower specific heat from water as seen in Tab. 1. The simulation was conducted by using aspenHYSYS program.

Table 1. Thermal properties of the working fluids

Component	Boiling Point (°C)	Critical Temperature (°C)	Critical pressure (°C)	Specific heat (kJ/kg.C)
H2O	100	374.15	22120	4.311
Benzene	80	288.95	4924.39	1.519
Cyclohexane	80.73	280.05	4053	1.691
Refig-113	47.55	214.33	3410.83	0.841
R-141	32	205.7	4340	1.083
Methanol	64.65	239	7376.45	3.494

In order to facilitate the evaluation some assumptions were made as follows. The thermal efficiency of the concentrator was calculated as a function of absorber temperature. The incident angle was considered as normal incident. The absorber was considered having selective surface. The value of the optical component, reflectivity of reflectors, transmissivity of glass tube, and absorptivity and thermal emissivity of absorber are 0.9, 0.95. 0.9 and 0.07, respectively. The concentrator efficiency for different working fluids is decided by assuming the absorber temperature as the average temperature of inlet and outlet fluid of the collector. The initial parameters to build the simulation are shown in Tab. 2.

Table 2. Initial parameters to build the simulation

Parameter	Value/constrain
Property package	Peng-Robinson
Pump adiabatic efficiency	90%
Turbine adiabatic efficiency	90%
Mass flow rate	10kg/s
Initial pressure	1 bar (100 kPa)
ΔP by Pump	19bar (1900 kPa)
ΔP by Turbine	19bar (1900 kPa)
Initial temperature	25 °C (298.15K)

The vapor fraction for concentrator output was set to be 1. Namely, after the heating process on the concentrator, it was assumed that 100% steam generation occurs.

4. Results and discussions

4.1. Thermal efficiency

Figure 3 shows the efficiency of the concentrator for different absorber temperatures. When the absorber temperature is equal to the ambient temperature, heat loss does not occur. Thermal efficiency reaches to the maximum value and represents the optical performance. As the absorber temperature increases, the heat loss from the absorber increases. The theoretical value of the maximum absorber temperature reaches to about 550°C and the efficiency decreases to minimum value. For higher thermal performance of concentrator unit, the heat loss from the absorber must be reduced by decreasing average absorber temperature.

The output temperature can be decided by achieving the 100% vapor fraction. Thus, the average absorber temperature was obtained and the thermal efficiency of the concentrator for each working fluid could be obtained in accordance with the absorber temperature. Fig. 4 shows the thermal efficiency of the collector, Rankine cycle and overall system for different working fluids. The collector efficiency varies due to different absorber temperature for different working fluids. The higher absorber temperature causes higher heat loss from the system and reduces the thermal efficiency. Therefore, a system with higher absorber temperature shows lower thermal performance. The best collector efficiencies are obtained in order of R141b, methanol, Refig-113, water, benzene and cyclohexane. In the same manner, the cycle efficiency is related with boiling temperature of the working fluid. The R-141b has lowest boiling temperature and shows the best efficiency since low temperature will be enough to vaporize all working fluid. The best cycle efficiencies are obtained for R-141b, Refig-113, benzene, water, methanol and cyclohexane, respectively. Although the methanol shows preferable performance in the concentrator unit; its cycle efficiency is comparatively low because of its low boiling point and high specific heat. The best performances of the overall system are obtained for R-141and Refig-13, respectively. The efficiency of water and benzene shows quite close performance to each other. The cyclohexane shows lower performance compared to those of the other working fluids. Consequently the working fluids with low boiling point and low specific heat capacity can improve the overall system efficiency substantially.

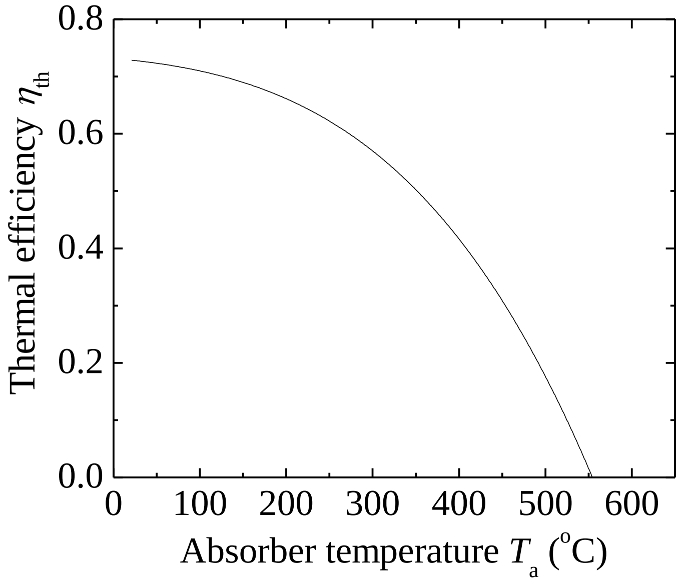
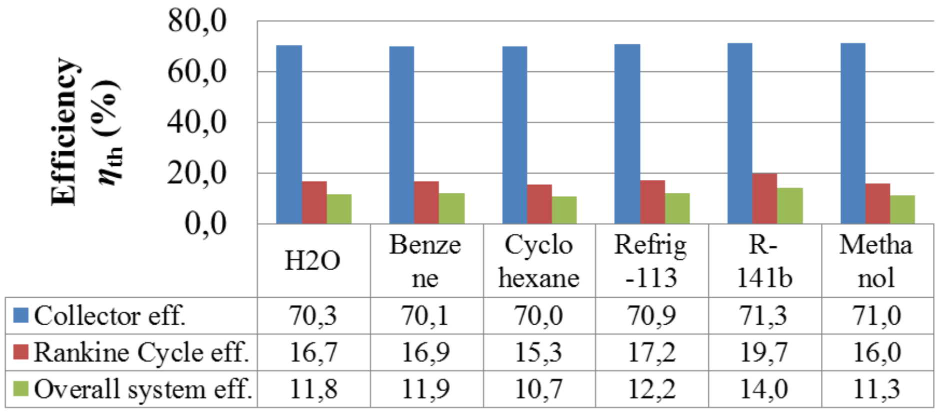


Fig. 3: Thermal efficiency of concentrator as a function of the absorber temperature



	H2O	Benzene	Cyclohexane	Refrig-113	R-141b	Methanol
🟦 Collector eff.	70,3	70,1	70,0	70,9	71,3	71,0
🟥 Rankine Cycle eff.	16,7	16,9	15,3	17,2	19,7	16,0
🟩 Overall system eff.	11,8	11,9	10,7	12,2	14,0	11,3

Fig. 4: Thermal efficiency of collector, Rankine cycle and overall system.

4.2. Pressure effect

The pump pressure difference was changed as a calculation parameter. The other parameters are considered as indicated in Tab. 2. Figure 5 shows the thermal efficiency of the concentrator, cycle and overall system with change of the pump pressure difference for the selected working fluids. In Fig. 5a, the collector efficiency is shown. When the differential pressure increases, the thermal efficiency decreases because the absorber temperature increases due to increasing solar radiation requirement for steam generation in higher absolute pressure of the circulation. The highest performance reduction was observed in the case of cyclohexane and benzene to be about 3%. The lowest reduction was in the case of methanol as 1.5%.

Figure 5b shows the cycle efficiencies of the working fluids. The cycle performance increases, as the pressure difference increases. Due to higher compression in the pump, more energy appears in turbine. On the other hand, the required pump power increases while the pressure differential increases; it has slight effect on the efficiency due to its relatively low power requirement.

The highest improvement in the thermal efficiency is seen for the case of water from pressure difference of 3 bars to that of 39 bars and it is about 12%. Refig-113 can be operated no more than the pressure difference of 30 bars due to its low critical pressure. The slope of the thermal efficiency becomes even for the case of R-141b and cyclohexane. On the other hand, the efficiency slope for the working fluids, water and methanol, are inclined for even the pressure difference of 39 bars. Thus, these kinds of fluids can be used for larger scale power-plants to generate more electricity.

Figure 5c shows the overall performance of the complete system. The maximum performance is obtained for the case of R-141b for the pressure difference of 39 bars to be 15.3%. In the sequel, the overall performance of water is 14%. On the other hand, the best performance improvement is attained for water and R-141b to be about 8.2% and 7.8%, respectively. For the pressure difference of 29 bars, which is the working pressure limit for refig-113, the best performance was seen for R-141b as refig-113 has a thermal efficiency of 12.9%.

Finally overall system performance increases about 5-8% for high pressure difference in the pump for different working fluids. This increase in pressure difference may be preferable to achieve better efficiency in a larger scale application. Although the working fluid, refig-113, has lowest specific heat, R-141b shows a better performance due to its lower boiling point and may be preferable for small scale applications.

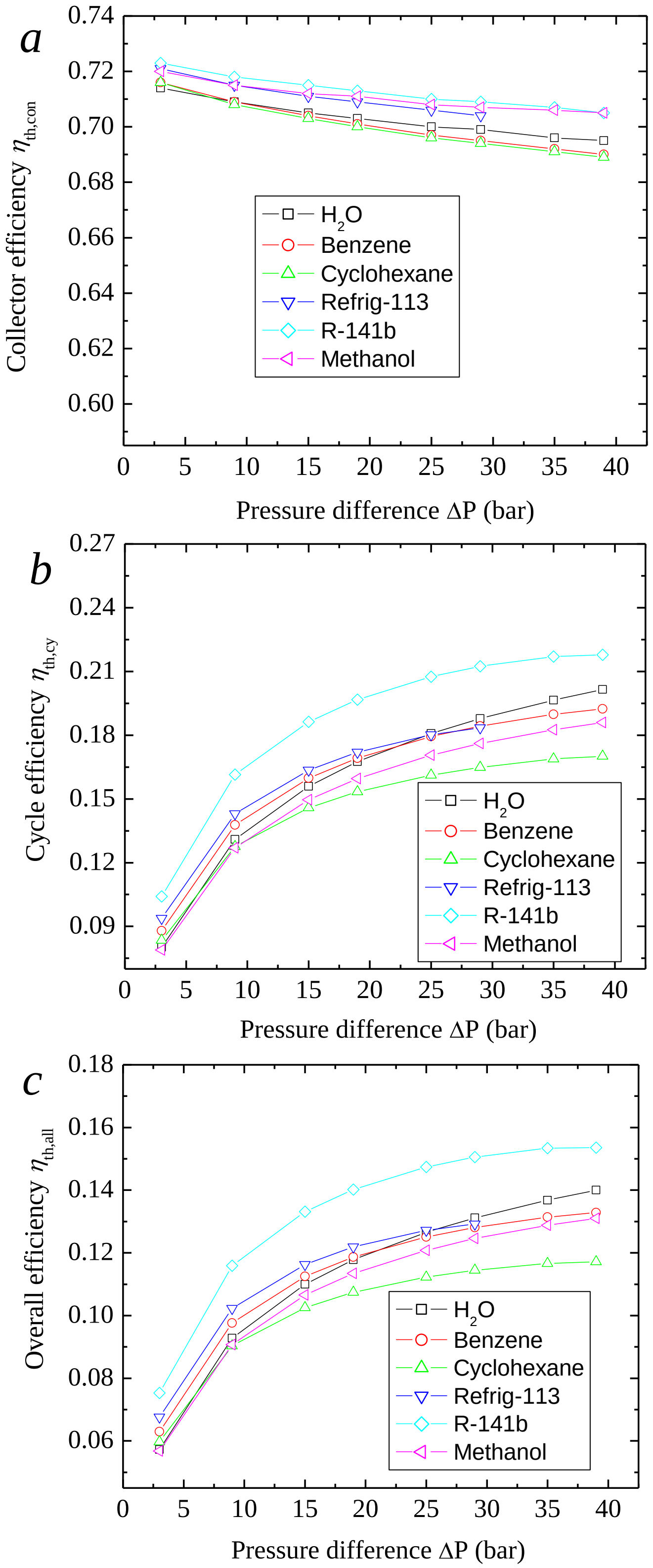


Fig. 5: Thermal efficiency of concentrator (*a*), cycle (*b*) and overall system (*c*) as a function of pressure difference

V. Conclusions

A non-imaging concentrator was considered to be steam generator of a solar power plant. Water, benzene, cyclohexane, R141b, Refig-113 and methanol were considered as working fluids of the Organic Rankine Cycle. In order to evaluate the system performance, simulations was conducted by using aspenHYSYS. The following points summarize the results of this work.

Thermal performances of the concentrator and cycle were evaluated for different working fluids. Finally overall performance of the complete system was evaluated. The higher absorber temperature causes higher heat loss from the system and reduces the thermal efficiency. Achieving the 100% vapor fraction on the output of the concentrator was considered as an initial criteria. Thus, the average surface temperature of the absorber for different working fluid was changed in accordance with the required heat to achieve full vaporization. The best collector efficiencies are obtained in order of R141b, methanol, Refig-113, water, benzene and cyclohexane in accordance with the average temperature of absorber.

Thermal efficiency of the concentrator, cycle and overall system were evaluated also for different working pressure of turbine and pump and for different working fluids. The maximum performance is obtained for the case of R-141b for the pressure difference of 39 bars to be 15.3%. The best performance improvement is attained for water and R-141b to be about 8.2% and 7.8%, respectively. The working fluid, R-141b shows a better performance due to its lower boiling point and may be preferable for small scale applications.

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