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A small-scale solar Organic Rankine Cycle power plant in Thailand: Three types of non-concentrating solar collectors

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ABSTRACT

Power generation from solar energy is one of many alternative ways to solve the current energy crisis and environmental problems affecting our world. In this study, a system that utilizes low-temperature heat (under 100 °C) from solar energy to generate electricity by a small-scale Organic Rankine Cycle system is proposed. The system is analyzed using three different capacities of the ORC system with R-245fa (20, 40 and 60 kW_e) in combination with solar water heating system (SWHS), using four different models (SORC-I, SORC-II, SORC-III, and SORC-IV). Compound parabolic concentrator (CPC), evacuated-tube and flat-plate collectors were used to generate heat with optical efficiency ($F_R(\tau\alpha)_e$) of 0.72, 0.57, 0.74, overall heat transfer coefficient (F_RU_L) of 0.97, 0.75, 3.62 W/m^2-K, and collector area of 2.16, 2.37, 2.08 m^2 per unit, respectively. The maximum power output, the CO_2 emission, and the economic analysis in terms of levelized cost of electricity (LCOE) were evaluated by a mathematical model. The weather data from Bangkok, a representative city in the central part of Thailand, was used for simulations. The simulation results shown that, if the number of collectors is the same on all systems, the system can produce the highest power output when combined with the CPC collectors. In terms of the economic analysis, the 60 kW_e ORC system has the lowest LCOE value of 0.20 USD/kWh if coupled with 950 units of evacuated-tube collectors without initial investment of the collectors into consideration. In this case, the system can produce the power output of 113.5 MWh/Year, and reduce CO_2 emission of 62.2 Ton CO_2 eq./Year. If investment cost is taken into account, a LCOE of 0.67 USD/kWh can be achieved by the same system but coupled with 900 units of the same collectors. In this case, the system power output is 110.0 MWh/Year, and CO_2 emission are reduced by 60.3 Ton CO_2 eq./Year.

1. Introduction

The utilization of fossil fuels for power generation has led to many environmental problems, e.g. Gagnon et al. (2002) reported that greenhouse gas (GHG) emissions from natural gas and coal (with and without SO_2 scrubbing) power plants contributed 443, 1050, and 960 kt CO_2 eq./TWh, respectively. Environment problems could be decreased moving to renewable energy resources for power generation (Wang et al., 2014). In recent years, solar energy is one of the renewables that has been gaining increasing attention and traction. It is a resource that never depletes, therefore its worth to develop and explore so it can help to move from fossil fuel technologies to renewable ones (Giostri et al., 2012).

Thailand is a country with direct normal solar radiation in the range of 1350–1400 kWh/m^2-year (Janjai et al., 2011), making it unsuitable for the use of Concentrating Solar Power (CSP) technologies that require radiation above 1500 kWh/m^2-year (Domínguez Bravo et al., 2007; IEA, 2003; Purohit and Purohit, 2010). In recent years, power systems with small-scale Organic Rankine Cycle (ORC) compared to steam Rankine cycles ones have gained focus due to their low-temperature heat source requirement, high energy conversion efficiency, small impact on the environment (Wang et al., 2014), and active way of transforming solar thermal energy into electricity (Mavrou et al., 2015). ORC technology has greatly improved, due to its power generation ability from low-temperature heat sources (Bao et al., 2011; Calise et al., 2015; Delgado-Torres and García-Rodríguez, 2010; Jung et al., 2015; Pei et al., 2010), its suitability to be applied on regionalized small-scale power plants (Garg et al., 2016; Quoilin et al., 2013; Quoilin and Lemort, 2009). Furthermore, their application is more attractive when the system can be integrated with a solar water heating system

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Nomenclature

A	area (m^2)
P	power (kW_e)
t	time
I_T	total solar radiation on the tilted surface (W/m^2)
$\dot{Q}$	useful heat rate (kW_{th})
T	temperature (°C)

Greek symbols

Δ	difference

Subscript

Amb	ambient
i	inlet
max	maximum
o	outlet
U	stop using time
Coll	solar collectors
k	hot water flow rate order (minimum to maximum)
ORC	Organic Rankine Cycle
S	start

(SWHS) (Giostri et al., 2012).

For SWHS combined with the ORC power generation, Thawonngamyingsakul and Kiatsiriroat (Thawonngamyingsakul and Kiatsiriroat, 2012) presented a solar ORC (SORC) power generation system in Thailand, consisting of evacuated-tube solar collectors and a 280 kW_e ORC system with R-245fa. Chaiyat (Chaiyat, 2015a, b) studied a 20 kW_e ORC power generation by solar energy based on economic and environmental indicators. The ORC system was tested and the system efficiency was evaluated. Higgo and Zhang (Higgo and Zhang, 2015) experimented with a small-scale ORC power generation test bed for low-temperature heat source. Marion et al. (2012) developed a model based on heat transfer equations to find out the potential of the system that combined a single glazed flat-plate solar collectors with a small-scale ORC system. Wang et al. (2014) proposed a SORC system, with compound parabolic concentrator (CPC) collectors. The system was tested by changing the value of the environment temperature, and thermal oil mass flow rate that passes through the vapor generator. Tchanche et al. (2009) studied a 2 kW SORC power generation from hot water with temperature around 90 °C as heat source. Delgado-Torres and García-Rodríguez (2010) proposed a low-temperature SORC power generation. CPC, evacuated-tube, and flat-plate collectors were used to produce hot water for the ORC system.

Likewise, there is some research done on solar combined heat and power (SCHP), Bocci et al. (2015) analyzed a SCHP system that can generate electrical power, heating and cooling, and fresh water. Calise et al. (2015) analyzed a small-scale SCHP system by using evacuated flat-plate solar collectors for heat generation. Baral and Kim, 2014) presented a SCHP system under the climate of Busan, Korea. Vacuum tube and flat-plate solar collectors were used to produce hot water temperature of 125 and 90 °C, respectively as heat source for an ORC system. Zhang et al. (2006) presented a trans-critical CO_2 Rankine cycle. The system consists of the ORC system, the evacuated-tube solar collectors, the feed water pump, and the heat recovery systems. In the work of Sonsaree et al. (2017a, 2016, 2017b) a combination of vapor compression heat pump (VCHP), solar collectors, and an ORC system were presented. The VCHP was used to upgrade heat either from the SWHS and waste heat from an industrial process. The results show the system can be applied in the industrial sector with large number of collectors and large amount of waste heat.

From the literature review above (Domínguez Bravo et al., 2007; IEA, 2003; Janjai et al., 2011; Purohit and Purohit, 2010), it can be noted that the CSP technologies are inappropriate in Thailand. Despite the fact that ORC systems have been extensively applied for power generation from heat sources with low-temperature, there are only a few designed with solar collectors in mind to utilize thermal energy with temperature lower than 100 °C. Moreover, only one type of solar collectors such as flat-plate, evacuated-tube, or CPC are considered for heat generation in a small-to-medium scale ORC power generation system with capacities lower than 20 kW_e, and higher than 250 kW_e. These capacities are not suitable to be applied on regionalized small-scale thermal power plants. Furthermore, in terms of the economic analysis, there are also a few analyzed in terms of the levelized cost of electricity (LCOE), which is a good indicator that helps compare other power technologies using electricity cost (USD/kWh).

On the other hand, in recent years the Ministry of Energy in Thailand has been promoting and sponsoring SWHS combined with

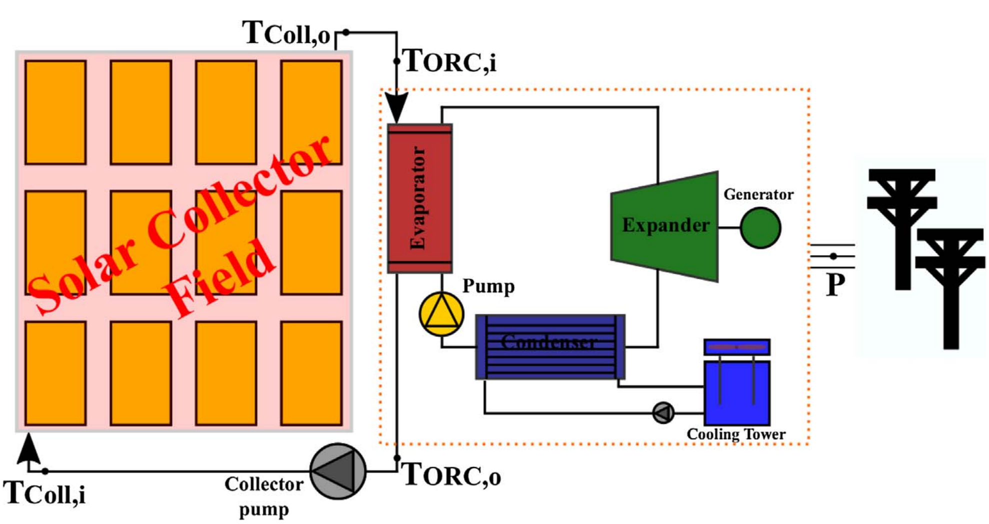

Fig. 1. A small-scale SORC power system.

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