Renewable Energy 68 (2014) 651–661

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

# Wind effect on the performance of a solar organic Rankine cycle

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ARTICLE INFO

*Article history:*
Received 24 September 2013
Accepted 3 March 2014
Available online 25 March 2014

*Keywords:*
Solar energy
Organic Rankine cycle
Solar thermal
Co-generation

ABSTRACT

The effects of wind, ambient temperature and solar radiation on the simultaneous productions of mechanical work and heat by a solar Rankine cycle are studied. The on site experimental study uses the pentafluorobutane R365mfc as working fluid in a system consisting of a small-scale single glazed flat plate collector, a micro turbine, a condenser and a pump. The theoretical study focuses on the prediction of the optimum operating temperature of the collector according to the solar radiation, the temperature of air and the wind speed. Then, the total production of mechanical and thermal energy is calculated during a sunny day for which various wind speeds are simulated. The results highlight the effect of wind on the corresponding production and they also establish the value of the recommended evaporating temperature according to weather conditions.



## 1. Introduction

Renewable energies (solar, wind, biomass, geothermal) reduce the use of fossil fuels and limit the environmental impact of modern human activities. Thus, solar energy is increasingly used as a sustainable alternative energy source for buildings [1], although its application is still mostly limited to domestic hot water production (DHW) or photocurrent generation. However, organic Rankine cycles (ORC) offer an interesting alternative as they enhance low-grade thermal energy [2–4]. Most applications use heat rejected by industrial systems. However, recent studies show that solar energy can also be a promising heat source for ORC [5–16]. Existing applications concern mainly large-scale facilities used for electric energy production or for drinking water production by the desalination of seawater [17,18]. Except for the latter case, the low graded heat rejected during the cycle is not valued. The first and second thermodynamic laws can easily demonstrate that when the evaporator temperature increases, the Rankine cycle efficiency increases. Inversely, the thermal efficiency of a solar collector decreases when its operating temperature increases. In a solar organic Rankine cycle, a solar collector heats the evaporator. Then, an optimum production of mechanical energy requires operating the system at an optimum evaporation temperature corresponding to the best compromise between these two trends [5,6,19]. The first solar ORC configuration uses an evaporator heated by a heat transfer fluid (HTF) heated by a solar collector. The second solar ORC configuration is the direct vapor generation (DVG) in which the solar collector operates as an evaporator. This configuration provides a higher evaporation temperature and thus a higher efficiency than the HTF configuration. Furthermore, the thermal inertia of a DVG system is lower than HTF system making it faster to start. However, it makes DVG system more sensitive to environmental changes. Thus, an alternation of sunny and cloudy periods may fluctuate the evaporating temperature and organic steam production and fluctuate the turbine speed. Therefore, many studies are interested in finding energetic optimum working conditions for these two configurations. Bou Lawz Ksayer [13] studied the theoretical performance of a 100 $m^2$ solar ORC system running in HTF configuration. The system produces electricity and hot water for a typical housing. Heat accumulated in a storage unit during the day helps to maintain the electric power generation during the night. The efficiency of the cycle is based on the selected operating temperatures of the evaporator and the condenser. The study takes into account a turbine isentropic efficiency of 85% and a pump efficiency of 90%. Cycle efficiency varies from 9.6% to 14.3%. However, the study does not include the instantaneous collector thermal efficiency whose output power is fixed at 400 $Wm^{-2}$. Wang and Zhao [7] calculated the expected performance of a DVG solar ORC unit using different working fluids based on R245fa and R152a mixtures. In their study, the terminal evaporation temperature and solar collector fluid outlet are respectively maintained at 80 °C and 85 °C. The isentropic efficiency of the turbine is 80%. Depending on the composition of the mixture, the predicted efficiency varies from 8.5% to 10.4%. The addition of an internal heat exchanger (IHE) to

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http://dx.doi.org/10.1016/j.renene.2014.03.010

**Nomenclature**

*Symbols*

| | |
|---|---|
| $a$ | thermal diffusivity, $m^2\ s^{-1}$ |
| $g$ | gravity, $m\ s^{-2}$ |
| $G$ | solar radiation, $W\ m^{-2}$ |
| $H$ | specific enthalpy, $J\ kg^{-1}$ |
| hc | convection exchange coefficient, $W\ m^{-2}\ K^{-1}$ |
| hr | radiation exchange coefficient, $W\ m^{-2}\ K^{-1}$ |
| $K$ | thermal conductivity, $W\ m^{-1}\ K^{-1}$ |
| $L$ | collector height, m |
| $mCp$ | heat capacity, $J\ K^{-1}\ m^{-2}$ |
| $\dot{m}$ | mass flow rate, $kg\ s^{-1}$ |
| $Nu$ | Nusselt number |
| $P$ | pressure, Pa |
| $\dot{Q}$ | area related thermal power, $W\ m^{-2}$ |
| $Ra$ | Rayleigh number |
| $S$ | surface, $m^2$ |
| $t$ | time, s |
| $T$ | temperature, K |
| $U$ | heat transfer coefficient, $Wm^{-2}\ K^{-1}$ |
| $v$ | specific volume, $m^3\ kg^{-1}$ |
| $w$ | wind speed, $m\ s^{-1}$ |
| $\dot{W}$ | area related mechanical power, $W\ m^{-2}$ |

*Greek letters*

| | |
|---|---|
| $\alpha$ | absorption coefficient (solar radiation) |
| $\beta$ | thermal expansion coefficient, $K^{-1}$ |
| $\delta$ | spacing, m |
| $\varepsilon$ | emissivity/absorption coefficient (IR) |
| $\eta$ | efficiency |
| $\nu$ | kinematics viscosity, $m^2\ s^{-1}$ |
| $\theta$ | collector tilt relative to the horizontal, deg |
| $\sigma$ | Stefan–Boltzmann constant, $W\ m^{-2}\ K^{-4}$ |
| $\tau$ | transmission coefficient (solar radiation) |

*Subscript*

| | |
|---|---|
| a | air |
| b | absorber |
| c | condenser |
| env | environment |
| m | mounting of the collector |
| g | collector glass |
| opt | optimum |
| p | pomp |
| s | isentropic |
| t | turbine |
| tot | total |
| 1 | turbine inlet |
| 2 | turbine outlet |
| 3 | condenser inlet |
| 4 | condenser outlet |
| 5 | pump outlet |
| 6 | collector inlet |
| 7 | collector outlet |

preheat the mixture at the pump outlet thanks to the residual heat from the turbine outlet increases the system efficiency up to 9.8% and 11.5%. In a second study [8], the authors proposed an improvement by adding a vapor - liquid separator at the collector outlet, a second collector in series with the first one that overheat the vapor, a second turbine and a steam generator heated by the residual energy from the second turbine. Assuming isentropic turbines and constant operating conditions, their study predicted an optimum energetic performance up to 18.77%. Sun et al. [9] studied the performance of a solar Kalina cycle operating with water and ammonia in HTF configuration. Assuming an ideal turbine, their theoretical study focuses on the dynamic behavior of the system. The expected daily energetic efficiency is 10.6%. Gang et al. [10] studied experimentally the performance of a 1 kW ORC facility using R123 as working fluid. The measured energetic efficiency is 6.8% when the temperature difference between the heat source (hot oil) and cold source (water) is 70 °C. This corresponds to typical temperature difference encountered in solar ORC systems. Tchanche et al. [11] studied theoretically the energetic and exergetic performances of a 2 kW HTF micro-solar ORC system used for the desalination of seawater by reverse osmosis. They consider a turbine isentropic efficiency of 70% and found that for the three fluids studied (R134a, R245fa, R600), the conversion of solar energy into mechanical energy is less than 5%. They also conclude that the addition of an IHE is beneficial in the case of a dry medium. Wang et al. [12] studied experimentally the performance of a micro solar DVG ORC system in which the turbine is replaced by a valve. Studies are conducted using 0.6 $m^2$ flat plate collectors and different mixtures of R152a and R245fa. The measured solar collector efficiencies are typically 21%–23%. The Rankine cycle efficiency depends among other things on the mixture composition and varies from 4.16% to 5.59% and the expected overall system efficiency goes from 0.88 to 1.28%. Papadopoulos et al. [14] compared ORC cycles performances operating with about 34 fluids. Their study includes among other things a multicriteria objective function taking into account the cost and environmental impact. Temperatures of hot and cold sources are 90° and 20–25 °C, which are closed to the temperatures encountered in solar ORC units. Energetic efficiencies are between 7 and 8% for most fluids studied. Gang et al. [16] studied the theoretical performance of a solar ORC system working with flat plate collectors used in DVG configuration and concentrating collectors used in HTF one. Heat storage units are also used and filled with phase change materials. The simulations are processed in steady state case and consider realistic efficiencies for the solar collectors, the turbine, the pumps, the generator and heat exchangers. The predicted efficiencies range between 6% and 8.5%.

Considering the relatively small mechanical efficiency given in previously published experimental studies, one promising alternative application to electricity production could be to use solar ORC cycles as heat power combined system (HPC). However, the proper sizing of the components is a complex problem that includes both predictable data (collector and other components performance characteristics) and unpredictable values (environmental conditions). According to the authors' knowledge, no studies have been published regarding the simultaneous effect of wind, air temperature and solar radiation on a solar ORC DVG system performance. This is a lack of knowledge that may miscalculate the expected energy production from such system. Previous works has only concerned solar collectors. Taherian et al. [15] studied the dynamic behavior of a thermosyphon solar water heater collector. Their experimental study validated a model based on the energy exchanges between the glass, the absorber and the environment. The study was also conducted on days with sunny and cloudy periods for which the effect of the collector thermal inertia is important [12]. Despite that the model does not predict