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Dynamic performance investigation of organic Rankine cycle driven by solar energy under cloudy condition

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A B S T R A C T

Organic Rankine Cycle (ORC) is promising in utilizing low-medium thermal energy, and solar energy is widely considered as the most attractive renewable energy for the future. Consequently, electricity production by coupling ORC and solar energy can reduce the fossil fuel consumption and lower the CO_2 emissions over the world. However, the intensity of solar radiation keeps changing throughout the daytime, so it is important to study the daytime performance of solar-ORC system to guarantee a proper operation.

Based on the discretized parameter model built in Dymola, dynamic performances of a small-scale power plant driven by parabolic trough collector (PTC) under clear sky and cloudy sky conditions are analyzed in this paper, respectively. The results show that degree of super heat, evaporation pressure and output power are relevant to direct normal irradiance (DNI) and follow the variation of DNI from morning to afternoon. Particularly, this paper pays attention to analyze the system's responses to the cloud blockage using the dynamic model. It shows that short period (5 min) of cloud blockage of the sun poses no severe influence, while the cloud occurring at morning can cause the system to break down easily. In addition, a conventional PID control strategy is considered for the PTC-ORC system under the weather condition of cloudy sky. The optimized system can generate 105.54 kWh and the system without control can generate 84.95 kWh. The generation can improve 24% compared to the system without control.

1. Introduction

In recent years, interest in the utilization of renewable resource has grown dramatically. Among all the renewable sources of energy available, solar energy is the most abundant one and is available in both direct as well as indirect forms [1]. It's free and clean which does not make any noise or any kind of pollution to the environment [2].

Some technologies aim to directly convert the solar energy to electricity, which mainly depend on the photovoltaic material. On the other hand, some technologies use the collectors to get the solar thermal energy and then drive an organic Rankine cycle (ORC) system to generate the electric power [3]. In addition, ORC is similar to a steam Rankine cycle which is based on the vaporization of a high pressure liquid [4]. Many studies have been conducted on the ORC system, such as the working fluid selection [5–8], optimization of operating condition [9–12], thermodynamic analysis of system performance [13,14], and experimental research for ORC system [15–17]. Currently, there are several main types of solar collector in the market, such as parabolic trough collector (PTC), tower collector, dish collector and Fresnel collector. The parabolic trough solar collector has the advantages of high maturity, flexible scale and relative low investment cost, thus it is very suitable for solar-ORC system. Here comes a realistic problem during the operation of these solar-driven ORC systems that the system can get affected by the clouds. With lower working condition temperature compared to others [3], the PTC-ORC system will suffer the worst situation when cloud occurs, and due to the dynamic behavior of cloud drift along the time, the entire system should be considered as a dynamic model system.

The dynamic model of ORC system has been analyzed by many researchers in the past decades [14,18–20]. Wei [19] compared the two types of dynamic ORC system used for waste heat recovery (WHR) to the experimental data, and concluded that the discretized parameter method has higher accuracy while the moving boundary

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Nomenclature

A	Area, m^2
c_p	Specific heat capacity, J/(kg·K)
E	Empirical coefficient
F	Frequency, Hz
f	Darcy resistance coefficient
x	Vapor quality
h	Specific enthalpy, J/kg
H_{lv}	Latent heat of vaporization, J/kg
DNI	Direct normal irradiance, W/m^2
l	Height, m
Ja	Jacob number
$\dot{m}$	Mass flow rate, kg/s
M	Mass, kg
X_{tt}	Martinelli factor
N	Rotation frequency, Hz
Nu	Nusselt number
Pr	Prandtl number
P	Pressure, Pa
Q	Heat transfer rate, W
Re	Reynolds number
S	Modified factor
T	Temperature, K
U	Heat transfer coefficient, $W/(m^2{\cdot}K)$
V	Volume, m^3
$\dot{V}$	Volume flowrate, m^3/s

Greek letters

ρ	Density, kg/m^3
τ	Time, s
η	efficiency
μ	dynamic viscosity, Pa·s
σ	surface tension,N/m
α	convective heat transfer coefficient, $W/(m^2{\cdot}K)$
θ	Incident angle, degree
α_s	solar elevation, degree
δ	declination angle, degree
ω	solar hour angle, degree

Subscripts

in	inlet
out	outlet
out_s	outlet for isentropic process
rot	rotation
s	swept
w	wall
f	Working fluid
p	pump
sat	saturation
eva	evaporation
con	condition
I	Integer
D	differential
l	saturated liquid
v	saturated vapor
tf	transfer fluid/secondary fluid

method has a quicker calculation speed. Also Wei [20] studied the thermodynamic performances of an ORC system driven by exhaust gas under disturbances, and found that the system output power and efficiency will deteriorate with the departure from nominal state exceeding 30%. Quoilin [21] analyzed a small-scale ORC system for energy recovery from a waste heat source with variable flowrate and temperature and gave three different control strategies to optimize the system performance. Using the control strategy, the system can operate under the optimization state. Zhang [22,23] used the moving boundary method to develop an ORC dynamic model based on waste heat energy conversion systems, and gave the constrained predictive controller which can achieve satisfactory performance for set-point tracking and disturbance rejection.

However, there are some differences between the ORCs driven by solar energy with those driven by waste heat. Firstly, the heat source of the solar energy has a regular pattern of having high temperature at noon and low temperature at both morning and afternoon. Secondly, the outlet temperature of thermal oil cannot decrease too low as it has to return to the collector, unlike the waste gas which is discharged into the environment.

Twomey [24] analyzed the dynamic performance of a small-scale ORC system driven by evacuated tube collectors. The system was simulated for a full day (24 h). The paper showed this ORC system with 50 m^2 collector area has the maximum instantaneous power of 0.676 kW. Antonelli [25] analyzed a low-concentration solar power plant with the condition of five consecutive days and made the control strategy on volumetric expanders with variable rotating speed to make the system operate effectively. The results showed the potential of volumetric expanders to be a valid alternative to the use of thermal storage or auxiliary heat source. Rodat [26] developed a dynamic model for Fresnel power plants and the model had been validated with experimental data. The paper also simulated the response of the system on sunny days and tested a DNI perturbation. Calise [27] studied the hybrid multi-purpose plant including an ORC driven by geothermal energy and solar energy which can supply electricity, cooling, heat and desalinated water. The system was investigated under different time bases and the results show the system is highly flexible and efficient.

Some work focused on solar ORC system with thermal storage. Manfrida [28] analyzed the solar ORC system associated with latent heat storage which was simulated under dynamic solar radiation conditions over one week period. The results showed the system with latent heat storage can provide power in 78.5% during the operating time and the averaged efficiency of ORC is 13.4%. Li [29] studied the dynamic performance of solar ORC with thermal energy storage (TES) under disturbed condition. The results showed that the system thermal inertia can not only cause different amplitude and delay time in fluctuations of output power but lead to dynamic resonance with a specific TES capacity range.

However, there are still some issues that these papers have not concentrated on, one of them is the effect of clouds in actual condition. The solar radiation disturbance caused by clouds will directly influences the ORC system bottoming with the solar collectors. The duration time cloud remains, when cloud appears during the day, and the scale of corresponding impact are all worth a deeper investigation. Another valuable issue is that how the working condition changes when the solar radiation increases at noon if there is no control strategy adopted in the system.

This paper analyzes the system performance of a small-scale PTC power plant from morning till afternoon under different kinds of mass flowrates of working fluid and studies the variation