Applied Thermal Engineering 129 (2018) 155–164

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Dynamic performance analysis of solar organic Rankine cycle with thermal energy storage

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HIGHLIGHTS

- A dynamic model of SORC was developed considering time-varying solar radiation.
- The factor *FSR* was defined to reflect the effect of TES on dynamic impact.
- Resonance occurs by the combined effect of TES capacity and solar disturbance.

ARTICLE INFO

Article history:
Received 22 February 2017
Revised 17 September 2017
Accepted 4 October 2017
Available online 5 October 2017

Keywords:
ORC
Thermal energy storage
Dynamic performance
Disturbance
Solar energy

ABSTRACT

This paper discusses the dynamic performance in a small-scale solar organic Rankine cycle (SORC) with thermal energy storage (TES) considering solar disturbance. A dynamic model of SORC is developed. The factor *FSR* (Fluctuation Suppression Ratio) is defined to reflect the effect of TES on suppressing the dynamic impact. The dynamics of the SORC are found to contain resonance characteristics. With the interaction between solar disturbances and system thermal inertia (mainly determined by TES capacity), the energy superposition could cause dynamic resonance. In order to study the dynamic performance of the SORC, the influence factor including TES capacity, solar fluctuation (period, amplitude, average solar) and evaporation temperature were analysed, while FSR and the total system efficiency were the indicators which represent the system stability and performance respectively. The simulation result shows that within a certain solar period, there is a specific TES capacity range leading to resonance. The proper TES capacity should be selected according to local solar fluctuations to effectively suppress dynamic impact in the initial design phase.

1. Introduction

Fossil fuel shortage and global warming are becoming severe. Moreover, with the increasing energy demand, electricity price has increased by about 12% in the past decade [1,2]. Solar energy has great potential to produce electricity as a clean energy. A number of researchers have worked on improving solar thermodynamic cycles. The applications of ORC using renewable energy to the electricity generation have attracted much attention. ORC has been proposed because of its high efficiency in recovering the low-grade heat, such as geothermal energy, ocean thermal energy, waste heat, and solar energy [3,4]. ORC exhibits great flexibility, high safety, good reliability, and simplicity [5]. Solar organic Rankine cycle (SORC) has been proposed as an effective measure to use solar energy [6].

Most research about SORC is simulated to analyze performance using the steady-state model [7,8]. The studies include the analysis about working fluid, solar collector [9], type of system structure, optimization of system parameters etc. Ksayer [10] investigated the influence of the evaporator temperature in SORC utilizing the hot water (393.15 K) as heat source instead of real solar radiation. He et al. [11] developed the SORC by TRNSYS, and investigated the system efficiency and heat loss from the types of working fluid, flow rate, evaporation temperature, and TES capacity.

However, real solar radiation is unstable heat source that is easily affected by weather and season. The instability of solar energy is an important factor restricting the efficient utilization. As shown in Fig. 1, there is a huge fluctuation in the solar radiation in the year (up to 779.5 W/m^2 per minute), taking the Fort Peck region of the United States as an example [12]. Solar is fluctuated by seasonal alternation, day and night alternation, and the weather changes (dusky, sunny, and cloudy). The actual operation of the SORC is often under off-design conditions. Especially in some

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https://doi.org/10.1016/j.applthermaleng.2017.10.021
1359-4311/

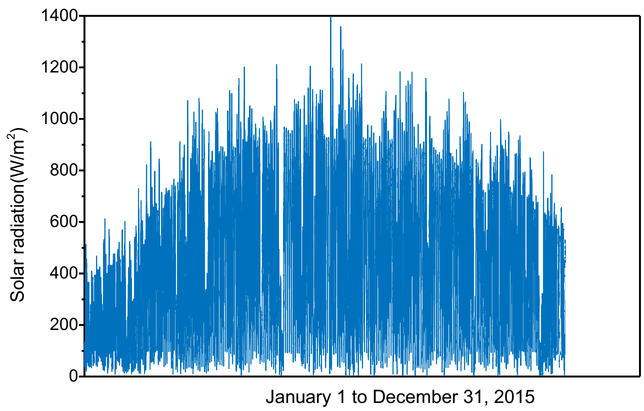

Fig. 1. Real-time solar radiation in 2015 at Fort Peck, in the United States.

disturbances (such as cloud interference), the dynamic impact will greatly influence the system performance, and even cause damage [9]. Some studies have been focused on the dynamic model of the SORC. Hajabdollahi et al. [13] optimized the RSORC by hourly analysis considering evaporator pressure, condenser pressure, refrigerant mass flow rate, number of solar panel (solar collector), and storage capacity. Bamgbopa et al. [14] found that the evaporator and the condenser are critical components of the simplified transient modeling using R245fa.

However, there are few research on the dynamic performance of SORC under solar disturbance. Zhao et al. [15] investigated the dynamic performance of SORC without TES on the off-design condition caused by cloud disturbance. They found that the output power shows a high sensitivity to the variation of heat source. As TES is a critical component of SORC to reduce the dynamic impact, the dynamic performance of SORC with TES is studied in this paper.

In order to ensure the normal operation of SORC, TES is necessary in the system. TES was integrated into SORC to reduce the dynamic impact caused by time-varying solar radiation [16]. TES has two significant advantages. First, TES can achieve peak load shifting of the output power to meet the requirements. Solar energy could be stored during the day and release it to generate electricity at night [17]. Therefore, in the large-scale SORC, the thermal storage system usually has a complex design [18,19] and uses phase-change storage [20] materials to ensure high-density energy. Second, TES provides solar energy during periods of cloudy weather to ensure the stable operation of the system [21]. The sudden change in input power negatively affects the expander and consequently the stability of the system [22].

In this paper, a dynamic model of a small-scale SORC system is developed. Dynamic performance of SORC is analyzed on the off-design condition caused by solar disturbances. The factor FSR (Fluctuation Suppression Ratio) is defined to reflect the effect of TES on suppressing dynamic impact. In order to study the dynamic performance of the SORC, the influence factor including TES capacity, solar fluctuation (period, amplitude, average solar) and evaporation temperature are analyzed, while FSR and the total system efficiency were the indicators which represent the system stability and performance respectively.

2. Performance simulation methods

The dynamic model of small-scale SORC system consists of two parts: solar collector system and basic ORC. The system includes solar collector, TES, pump, evaporator, expander, condenser, and pump. The evaporator is the thermal link between the two parts.

In the SORC (Fig. 2), water is the medium in the solar collector system, while R245fa (critical pressure: 3.651 MPa, critical

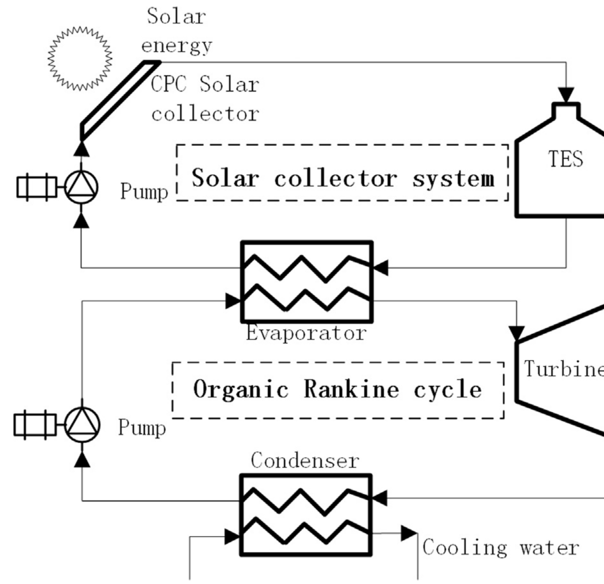

Fig. 2. Schematic diagram of the SORC power system.

temperature: 427.16 K, ODP: 0, GWP: 1030) is the working fluid in the basic ORC. Water absorbs heat from the solar collector and transfers heat to the organic working fluid through the evaporator. R245fa absorbs heat in the evaporator, and then goes into the expander to generate power. Then the low-pressure organic steam from the outlet of the expander goes into the condenser to release heat. Finally, the organic working fluid is pressed by the pump to the evaporator to absorb heat again to complete the cycle.

2.1. Component models

2.1.1. The model of solar collector

Solar energy, which is absorbed by solar collector, mainly includes the direct radiation and scattered radiation. The direct radiation is the solar radiation spread by straight line, which is mainly related to the solar altitude angle, altitude azimuth, and latitude in the place. The scattered radiation refers to the solar through the atmosphere, horizon, water vapor and so on. The radiation on the solar collector can be shown as the following formula [13]

$$\dot{I}_t = \left(\dot{I}_b + \dot{I}_d\frac{\dot{I}_b}{\dot{I}_h}\right)R_b + \dot{I}_d\left(1-\frac{\dot{I}_b}{\dot{I}_h}\right)\left(\frac{1+\cos\beta}{2}\right)\left(1+\sqrt{\dot{I}_b/\dot{I}_h}\sin^3\left(\frac{\beta}{2}\right)\right) + \dot{I}_h\rho_g\left(\frac{1-\cos\beta}{2}\right) \quad (1)$$

$\dot{I}_b$ means the direct radiation; $\dot{I}_d$ means the scattering radiation; $\dot{I}_h$ means the sum of direct radiation and the scattering radiation; R_b means the ratio of actual surface radiation and the horizontal radiation; β is the slant angle of collector; ρ_g means the environment reflection coefficient.

The heat absorption capacity of solar collector can be represented as the function of hot water mass flow rate ($\dot{m}_{htf}$) and collector heat transfer rate ($\dot{H}_{colletor}$) in heat collection cycle:

$$\dot{Q}_{colletor} = \dot{m}_{htf} \times \dot{H}_{colletor} \quad (2)$$

The heat transfer rate of solar collector ($\dot{H}_{colletor}$) can be calculated by the total solar radiation of inclined plane in unit area ($\dot{I}_t$), the effective heat exchange area ($A_{collector}$) and the collector efficiency ($\eta_{collector}$):

$$\dot{H}_{colletor} = \eta_{collector} \times \dot{I}_t \times A_{collector} \quad (3)$$