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Performance study of a twin-screw expander used in a geothermal organic Rankine cycle power generator

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ABSTRACT

The ORC (organic Rankine cycle) system is an effective technology to generate electricity from low temperature heat sources. The twin-screw expander is a key component that is commonly used in the small-to-medium capacity ORC system to convert thermal energy into work. In this paper, the performance of a twin-screw expander is theoretically and experimentally studied. A mathematical model is developed and subsequently validated using experimental data. The effect of several important factors including expander speed, suction pressure and inlet superheat on the expander performance is investigated. Results indicate that the expander speed and suction pressure have large influences on the expander performance, while the inlet superheat has relatively small effect. The isentropic efficiency of the expander decreases from 0.88 to 0.6 and the expander volumetric efficiency decreases from 0.88 to 0.7 as the expander rotational speed increases from 1250 to 6000 rpm. The results further show that the expander volumetric efficiency decreases from 0.91 to 0.85 as the expander suction pressure increases from 0.33 to 0.47 MPa. Furthermore, the energy conversion efficiency of the studied ORC system using the twin-screw expander is as high as 7.5% under the site conditions.

1. Introduction

Consideration of the limited fossil fuel reserves and fears of the effects of environmental pollution have led to a growing interest in the generation of power from non-fossil-fuel based thermal sources. As a result, there is increased interest in energy recovery from low grade thermal sources, which include solar thermal, geothermal, flue gas, waste thermal energy and hot water produced in thermal processes. Exploitation of energy from these low grade thermal sources has attracted considerable attention from the viewpoint of improving the energy utilization efficiency and reducing greenhouse gas emissions. One of the most promising means of energy conversion is the ORC(organic Rankine cycle) system due to its simplicity and superior thermal efficiency [1].

Many studies have been conducted on ORC systems in the past few decades. These studies include proof-of-concept demonstrations [2,3], selection of working fluids [4–6], and economic optimization of the ORC system [7–9]. These studies indicated that the key components affecting the performance of the ORC systems are the expander and heat exchangers. Li et al. [10] performed energetic and exergetic investigations on an ORC system at different heat source temperatures and found that the isentropic efficiency of the expander is the most critical factor for optimizing the performance of ORC systems. Lee et al. [11] further demonstrated the effect of inlet superheat of the expander on the performance of a 50 kW ORC system during dynamic operation.

The selection of the expander strongly depends on the operating condition and capacity of the ORC system. The expander can be classified into two categories: dynamic expanders (such as axial flow turbines and radial flow turbines) [12–15] and volumetric expanders (including reciprocating piston-cylinder expanders, scroll expanders, rotary displacement expanders, and screw expanders) [16–23]. Lemort et al. [16] experimentally studied the performance of an open-drive oil free scroll expander integrated into an ORC working with refrigerant HCFC-123 and developed a semi-empirical model. Quoilin et al. [17] investigated the performance of a scroll expander using this semi-empirical model. Declay et al. [18] further experimentally evaluated the performance of an open-drive scroll expander using R245fa as working fluid and Giuffrida [19] utilized the semi-empiric model to investigate the performance of the open-drive scroll expander using other working fluids such as HCFC-141b and HCFO-1233zd(E). Ibarra et al. [20]

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Nomenclature

A	area, m^2
C	flow coefficient in leakage
h	specific enthalpy, J/kg
m	mass, kg
$\dot{m}$	mass flow rate, kg/s
N	rotational speed, s^{-1}
p	pressure, Pa
Q	heat rate, W
T	temperature, K
u	specific internal energy, J/kg
v	specific volume, m^3/kg
V	volume, m^3
W	power, W

Greek symbols

α	surface heat transfer coefficient
φ	angular angle of the expander, degree
η	efficiency
ρ	density

Subscripts

c	expander
dis	discharge
e	electric motor
ele	electric energy generation
g	working fluid
hs	heat source
i	inlet
ind	indicated
iso	isentropic
o	outlet
suc	suction
t	theoretical
v	constant specific volume
w	working chamber

developed a thermodynamic model and investigated the performance of ORC system with a scroll expander at part-load operating condition. The performance of a single-screw expander used in an ORC system was also experimentally studied by researchers [21,22]. Bao and Zhao [23] recently reviewed the working fluid and expander selections for an ORC system. Among these different types of expanders, the twin-screw expander is considered to be the best candidate for small to middle power capacity ORC systems (10–300 kWe) [24]. Leibowitz et al. [25] developed and investigated twin-screw expanders for cost-effective power production for approximately 20 years. However, very little reported experimental data are available in the literature due to commercial confidentiality.

Recently, Andreas [26] theoretically investigated the energy efficiency of waste heat recovery using screw expanders. Papes et al. [27] analyzed the twin-screw expander for ORC systems using computational fluid dynamics with a real gas model. They found that the pressure drop occurred during the filling process and that over- or under-expansion could occur due to discrepancy between the expander design and actual operating conditions. The results revealed that the isentropic efficiency of the expander was largely affected by the pressure ratio over the screw expander. However, this model was too complicated for engineering design and was not validated by experimental data. Another research effort reported that the relation between the inlet pressure of the expander and isentropic efficiency was more complicated [28]. Hsu et al. [29] experimentally investigated the performance of a 50 kW ORC system and screw expander at different supply pressures and expander pressure ratios. The results demonstrated that a screw-expander ORC could be operated with a wide range of heat sources and heat sinks with satisfactory cycle efficiency.

Although the results of a few theoretical and experimental investigations on the twin-screw expander are available, the literature provides little reliable experimental data or thermodynamic models for analyzing the performance of the twin-screw expander used in the medium-scale ORC system. In this paper, a thermodynamic model incorporating the expander geometry parameters is developed to investigate the performance of a twin-screw expander used in an ORC system. This model is experimentally validated. An ORC prototype is fabricated and installed for this purpose in the Huabei Oilfield. The performance of the twin-screw expander is first evaluated under different operating conditions, and then, the effect of several important factors, including the expander inlet suction pressure, rotational speed and inlet superheat, on the expander performance is further investigated. This evaluation provides useful information for the design of twin-screw expanders, as applied in the ORC system.

2. Geothermal organic Rankine cycle and experimental setup

Fig. 1 shows a picture of the 200 kW ORC system that was installed at the Huabei Oilfield to extract geothermal heat from abandoned oil wells to generate electricity. The Huabei Oilfield in North China has been exploited since 1976 and achieved massive production of petroleum products in the past few decades. Some oil wells produced oil via water injection. After years of oil exploration, these oil wells no longer produce oil. However, these abandoned oil wells store large amounts of geothermal energy in the form of hot water. The hot water temperature is approximately 100 °C; this water traditionally was used to maintain the temperature of oil production processes or to provide heating for office and residential buildings. Massive amounts of thermal energy are still directly discharged into the environment, which is wasteful and also pollutes the local environment. Therefore, an ORC system using the twin-screw expander was designed and installed to recover the thermal energy from hot water at a temperature above 90 °C and at a flow rate of 500 m^3/h. R123 was selected as the working fluid due to its unique thermal property which could lead to high thermal efficiency [30,31] and make the system compact by requiring less heat transfer area [7]. The twin-screw expander is oil-free and a separate oil system is designed to supply the lubricating oil to bearings and gearings. The detailed geometry of the twin-screw expander is listed in Table 1.

Fig. 2 shows a schematic of the ORC system. Hot water from the abandoned oil wells flows into the evaporator where the working fluid R123 absorbs the energy and becomes vapor under high temperature and pressure. This R123 vapor flows through the twin-screw expander and is expanded to generate mechanical work to drive the electrical generator. The expanded vapor from the expander then flows to the condenser, where it is cooled and condensed by cool water from the cooling tower. The condensate is finally pumped back to the evaporator and the cycle is repeated.

The system is well instrumented, and the measurement points of the system are indicated in Fig. 2. The marker "T" represents a