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Effect of resistive load on the performance of an organic Rankine cycle with a scroll expander

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An experimental investigation is performed for an organic Rankine cycle system with different electrical resistive loads. The test rig is set up with a small scroll expander-generator unit, a boiler and a magnetically coupled pump. R134a is used as the working fluid in the system. The experimental results reveal that the resistive load coupled to the scroll expander-generator unit affects the expander performance and power output characteristics. It is found that an optimum pressure ratio exists for the maximum power output. The optimal pressure ratio of the expander decreases markedly as the resistive load gets higher. The optimum pressure ratio of the scroll expander is 3.6 at a rotation speed of 3450 r/min for a resistive load of 18.6 Ω. The maximum electrical power output is 564.5 W and corresponding isentropic and volumetric efficiencies are 78% and 83% respectively.

1. Introduction

The interests in low-grade heat sources, which are abundantly available in renewable energy sources, grew dramatically with the awareness of greenhouse effect. A number of novel solutions have been proposed to generate electricity from the low-grade heat. ORC (Organic Rankine Cycle) has been paid much more attention in recent years as a very promising technology for energy conversion with the low boiling temperature working fluid (e.g. refrigerants) [1]. Generally, the available low-grade heat sources utilized by the ORC systems include geothermal energy, solar energy, biomass combustion, exhaust gases of gas turbine, and waste heat from power plant [2]. Unlike traditional power cycles, ORC can be applied to small-scale power generation with high flexibility and low maintenance requirements [3]. ORC can be used as a prime mover or integrated with another mover for the combined heat and power generation system. Power generation plants integrating with ORC systems are beneficial to energy consumption and greenhouse gases emissions.

The selection of organic working fluids is of vital importance to the ORC system. An organic fluid is usually characterized by a saturated vapour line with positive slope in the *T*–*s* (Temperature–Entropy) diagram which guarantees the working fluid is still at the superheated vapour state in the expansion process [4]. Many research works have been carried out to select the most suitable working fluid for the ORC system. Badr et al. [5] investigated thermodynamic and thermophysical properties of organic working fluids for the ORC system. Saleh et al. [6] concluded that the fluids with relatively low critical temperature are preferred for the system. Li [7] systematically investigated 14 ORC working fluids under various heat source levels, i.e. the various application domains. This paper performed a comprehensive study for both energy and exergy performance under different operating conditions and various ORC system configurations, such as reheat, regenerative ORC and ORC with internal heat exchanger. Instead of adopting only one working fluid for an ORC system, a mixture of several different working fluids has been accepted in recent years. Aghahosseini et al. [8] conducted a theoretical study of six types of pure and zeotropic mixture refrigerants: R123, R245fa, R600, R134a, R407c and R404a in an ORC system with low-temperature heat source, and found the mixed working fluids are more suitable for the system due to the nonisothermal phase change. Based on the simulation results, Declaye et al. [9] concluded R134a is a good

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choice for an ORC system with a smaller size expander. Additionally, Tchanche et al. [10] considered that R134a is the most suitable working fluid for small-scale solar applications in terms of thermodynamic and environmental properties.

The selection of expansion devices for an ORC system depends on the operating condition and the size of the system. Qiu et al. [11] evaluated several expansion devices for micro-CHP ORC systems including turbine, scroll, screw and vane expanders, and suggested that both scroll and vane expanders are suitable for micro-scale ORC systems with capacity ranging from 1 kW to 10 kW. Ali Tarique et al. [12] stated that a scroll expander is the best choice for small capacities due to the more flexible operation characteristic. As a scroll expander is a positive displacement machine with a fixed expansion ratio, a high efficiency could be achieved at a specific pressure ratio [13]. Scroll expander is considered to be more reliable with less number of moving parts, no inlet and outlet valves [14]. Though various studies on the scroll-based ORC system have been carried out through modelling and experimental investigations, there are few researches on the system operating characteristics. Wang et al. [15] carried out ORC system experimental test and found the isentropic efficiency of scroll expander is in the range of 70%–84%. Harada [16] found an isentropic efficiency is over 70% for a $1kW_e$ scroll expander using R134a and R245a as working fluids. Zhang et al. [17] presented a theoretical model for low-grade heat-driven Rankine cycle with a scroll expander and showed a thermal efficiency of 11%. Hogerwaard et al. [18] concluded that the minimum superheating leads to high ORC efficiency and expander isentropic efficiency. Declaye et al. [19] presented the experimental study of scroll-based ORC with R245fa, and found that the isentropic efficiency of the expander degrades faster at lower pressure ratio and high rotation speed. Antonio Giuffrida [20] simulated the performance of an ORC system with a small scroll expander on the basis of a semi-empirical model, and concluded that the expander efficiency is the most sensitive parameter in a low-temperature ORC system. Clemente et al. [21] developed a one-dimensional model of a scroll expander in an ORC cogeneration system and found that there is an optimum expansion ratio maximizing the ORC efficiency, but the influences of electrical load and rotation speed of the expander are not considered. To improve the performance of ORC system, various configurations are proposed, such as the regenerative cycle. Mago et al. [22] compared a regenerative ORC with the basic ORC, and found that regenerative ORC achieves higher efficiency with a lower irreversibility. As for the ORC electrical power output characteristics, there is limited research on the effects of electrical load connected to the ORC system. Pan et al. [23] carried out experimental research on the performance of a scroll expander in ORC system with working fluid R123, and remarked that the electrical loads affect rotation speed, isentropic and mechanical efficiencies of scroll expander, and the power output from the generator. Wu et al. [24] investigated the performance of a scroll expander in a small-scale ORC system through experimental testing. The scroll expander modified from a scroll compressor operated stably in the built ORC testing bench, and was tested under different conditions with various electric loads. The electric loads were adjusted by changing the number of the bulbs connected to the power generator. Five electric loads were adopted, that is, turning on 2 bulbs, 4 bulbs, 6 bulbs, 8 bulbs and 12 bulbs, and a maximum output power of 1200 W was achieved with 12 bulbs. It is also found the isentropic efficiency of the scroll expander increases with the electric load. In addition, Tang et al. [25] conducted an experimental testing of a low-grade heat ORC power generation system using a scroll expander with working fluid R600a, and found that the generator power output increases with the decrease of the load resistance at the same rotation speed. They also pointed out that electrical loads should match with the expander-generator power output characteristics to get the optimal performance.

Although the number of published experimental studies on scroll-based ORC is on rise, most of scroll expanders were modified from refrigerating compressors. Wang et al. [26] found a maximum expander isentropic efficiency of 77% and power output of 1 kW from a scroll expander modified from a compliant scroll compressor using R134 as working fluid. More precisely, it is important to determine some operating parameters for achieving the system maximum energy efficiency; these parameters include pressure ratio, inlet condition and electrical load applied to ORC system. Therefore the effects of electrical resistive load on the performance of the ORC system with a small-scale scroll expander-generator unit are investigated experimentally in this paper; six different resistive loads are tested. The influences of electrical resistive load on electrical power output and scroll expander efficiencies are clarified under the same inlet condition.

2. Experimental system

A schematic diagram of the ORC system with instrumentation is shown in Fig. 1(a). A small-scale scroll expander-generator unit is employed in the system, which consists of an oil-free type of scroll expander and a separated electrical generator. An electric steam boiler is used as a low-temperature heat source in the system, and its temperature and mass flow rate could be adjusted. R134a is selected as the working fluid and heated to be high-pressure vapour in an evaporator by the steam from the boiler. The high-pressure vapour of R134a flows into the scroll expander, where its enthalpy is converted into shaft work to drive the generator for electricity generation. Then the low pressure vapour from the expander outlet flows through a regenerator to preheat the liquid working fluid from a storage tank, afterwards the low pressure vapour flows into a condenser for condensation, then the liquefied working fluid flows into the storage tank. Finally the liquid working fluid in the storage tank is pumped into the evaporator at high pressure to start the next cycle. Cold water is employed to condensate the low pressure vapour in the condenser and the steam in a cooler. The P–h (Pressure–Enthalpy) diagram of the ORC system is shown in Fig. 1(b). A vapour by-pass line is installed to completely isolate the expander for the starting period and some emergency cases. Various operation conditions can be achieved by the valves V1–V7 for the system. The liquid working fluid pump is controlled by a frequency adaptor.

Based on the schematic diagram shown in Fig. 1(a), an experimental test rig of the ORC system is built as shown in Fig. 2. The electrical generator is coupled directly to the scroll expander in the unit [27]. The specifications of main equipment are presented in Table 1, and the measuring devices accuracies are listed in Table 2. OMEGA PXM Series pressure transducers and K-type temperature sensors are installed. A liquid flow meter is used to record the flow rate of R134a and a data acquisition system is employed to record the system parameters during operation by a computer. The power output of electrical generator is determined by voltage and current using a Power Quality Analyser.

Once the steady-state regime of operation is reached, a complete measurement data set is produced. These experimental data include pressure, temperature, working fluid flow rate, and electrical load voltage and current. Subsequently, those data are processed to determine the isentropic and volumetric efficiencies of the scroll expander and electrical efficiencies of the ORC system.