Energy 41 (2012) 514–524

Contents lists available at SciVerse ScienceDirect

Energy

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

Design and experimental study of ORC (organic Rankine cycle) and radial turbine using R245fa working fluid

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ARTICLE INFO

Article history:
Received 10 November 2011
Received in revised form
16 January 2012
Accepted 16 February 2012
Available online 22 March 2012

Keywords:
ORC (Organic Rankine cycle)
R245fa
Turbine
Power generation

ABSTRACT

In this study, an ORC (Organic Rankine Cycle) capable of generating electric power using a low-temperature heat source was developed and an experimental study was conducted. A radial turbine directly connected to the high-speed synchronous generator was also designed and developed. R245fa was adopted as a working fluid, in consideration of the operation conditions of the cycle and its environmentally-friendly characteristics. Experiments were conducted to analyze the operational characteristics and performance of the developed ORC. The efficiencies of the cycle and the turbine, electric power of the developed ORC with respect to the operation conditions were investigated in a series of experiments. The factors which influence the performance of the developed ORC were analyzed and discussed.

1. Introduction

Recently, oil prices have been fluctuating dramatically due to the expansion of various economies around the world, particularly those of China and India, to conflicts in the Middle East, and to the enforcement of stricter environmental regulations concerning greenhouse gas emissions. Under these circumstances, research on the ORC (organic Rankine cycle), which could convert low-grade heat to electric power, has been attracting more attention as a high efficiency energy technology in recent decades [1]. The ORC is understood as the most realized one among several proposed technologies for generating electricity via the utilization of low-grade heat sources. Therefore, it is capable of enhancing energy utilization and reducing greenhouse gas emissions [2]. In addition to this, the ORC offers a number of advantages such as its simple structure, the availability of its components, and the easiness of its application to local small-scale power generation systems.

The ORC is structurally similar to a typical Rankine cycle but uses organic fluids as a working fluid instead of water. Organic fluids are suitable for the ORC because their specific vaporization heat is much lower than that of water. This enables the ORC to produce electricity by using low-temperature heat sources. The ORC is mainly used as a power generation system utilizing low-grade heat sources, and has a temperature range of 60–200 °C [3–6]. Generally, heat is considered to be moderate-to-low grade when it is less than 370 °C [2]. In the energy-to-power conversion industry, thermal efficiency becomes uneconomically low when the exhaust-stream temperature drops below 370 °C. However, recovering low-grade waste heat in power generation becomes economically viable when using ORCs. It has been estimated statistically that low-grade waste heat accounts for more than 50% of the total amount of heat generated in industry [7].

The ORC is not merely the subject of laboratory studies as more than one hundred ORC plants are now operating to generate electricity commercially, and the ORC has also applied to diverse fields including industrial waste heat, solar thermal power, geothermal heat, biomass combustion heat, engine exhaust gases and so forth [1]. ORC manufacturers such as ORMAT, Turboden, BNI, Adoratec, UTC, and Electratherm have been present on the market since the beginning of the 1980s. All of them use the turbine as an expander, except Electratherm, which uses a screw expander [8]. Large-scale ORC plants have been successfully demonstrated, such as in the geothermal plant in Altheim, and in the biomass-fired CHP plants in Admont, Lienz and Heidelberg [9]. In Europe more than 120 ORC plants are in commercial operation, with sizes ranging from 0.2 to 2.5 MW, using biomass combustion heat [10].

The expander is a key part of the ORC system, and two types of expander, the turbo and the scroll, are generally used [8]. The scroll expander is a good candidate for the expansion device of small-scale ORC systems because of its simple operation, low rotational

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doi:10.1016/j.energy.2012.02.035

speed, reliability, and capability to handle high-pressure ratio [1]. The turbo expander, on the other hand, offers many advantages, such as its compact structure, small size, light weight, stability, superior and efficiency, and the majority of commercial ORC plants use it [8,9].

Nguyen et al. developed and tested a small-scale ORC which used *n*-pentane as a working fluid and was driven by heat sourced from a gas-fired boiler. The developed system was capable of generating 1.5 kW of electricity with a thermal efficiency of 4.3% [11]. Manolakos et al. presented their on-site experimental evaluation of the performance of a low-temperature ORC for reverse osmosis desalination. The system used R134a as the working fluid and obtained technically feasible results [12]. Quoiin et al. performed a numerical and experimental study on an ORC which used R123 as the working fluid and a scroll expander. The scroll expander was originally an oil-free open-drive scroll compressor, adapted to operate in reverse. It was used to drive an asynchronous machine through two belt-pulley couplings and a torque meter used to measure the expander shaft power [1]. Wang et al. developed a concept that combines an ORC with a conventional vapor compression cycle. They developed a 5 kW cooling capacity prototype system which used R245fa (1,1,1,3,3-pentafluoropropane) as the working fluid and tested it under laboratory conditions. The system used micro-channel-based heat transfer components and a scroll-based expander and compressor. The scroll expander is a positive displacement scroll compressor modified to operate in reverse [2]. Larjola designed an ORC using a high-speed oil-free turbo generator-feed pump [13]. Yamamoto et al. designed an ORC by using an electric evaporator instead of an external heat source. R123 and water were used as the working fluids and experiments were conducted to compare each fluid. Its maximum cycle efficiency and electric power were shown to be 1.25% and 150 W, respectively [3]. Pei et al. constructed an ORC system with a turbine using R123 and conducted a preliminary test on the constructed system. The cycle efficiency, based on electric power and turbine shaft power, was shown to be 3.0% and 1 kW, respectively. In addition, several problem-solving techniques were presented, such as the avoidance of cavitation in the pump [9].

Previous studies also showed the influence of the working fluid thermodynamic properties on ORC performance [14–19,32]. Hung et al. parametrically analyzed the effects of various working fluids such as benzene, ammonia, R11, R12, and R134a on the efficiency of ORCs. They showed that the slopes and shapes of the saturated vapor curves of the fluids primarily affected system efficiency [20,21]. Hettiarachchi et al. presented a cost-effective optimum design criterion for ORCs utilizing low-temperature geothermal heat sources. The optimum cycle performance was compared for various working fluids including ammonia, HCFC123, *n*-Pentane, and PF5050 [22]. Wei et al. conducted a system performance analysis and optimization of an ORC system using R245fa as the working fluid and driven by exhaust heat. They also analyzed the thermodynamic performances of an ORC system when subjected to disturbances [6]. Aljundi analyzed the effects of using alternative dry fluids on the efficiency of the ORC and compared them with other refrigerants [23]. Rayegan et al. developed a procedure for comparing the capabilities of working fluids when they are employed in a solar ORC under similar working conditions. They considered the REFPROP 8.0 [24] database with 117 organic fluids as the reference [25]. Suna et al. developed mathematical models and an optimization approach to simulate an ORC power plant, and searched for optimal operating strategies in order to achieve either the best thermal efficiency or the most net power generation [26] of the system.

Table 1
Properties of R245fa (HFC-245fa).

Molecular name	Molecular weight	Critical pressure	Critical temperature
$CF_3CH_2CHF_2$	134 g/mol	3640 kPa	427.2 K

Although many studies on ORCs have been conducted, only a few papers have presented an experimental study of an ORC equipped with an expander which could generate electricity. And most of the expanders thus employed were not designed considering cycle condition but obtained by modifying existing compressors, they showed low efficiencies lower than about 20% [1,2,9]. Therefore, the previous results showed low system performances that their cycle efficiency and electric power were lower than about 3% and 1.5 kW, respectively [3,9,11].

For the purposes of the present study, an ORC generating a nominal 30 kW of electric power was designed and an experimental study conducted. A radial turbine was also designed by considering the cycle operation condition and the thermodynamic properties of the working fluid (R245fa) to increase its performance. A high-speed synchronous generator was directly coupled

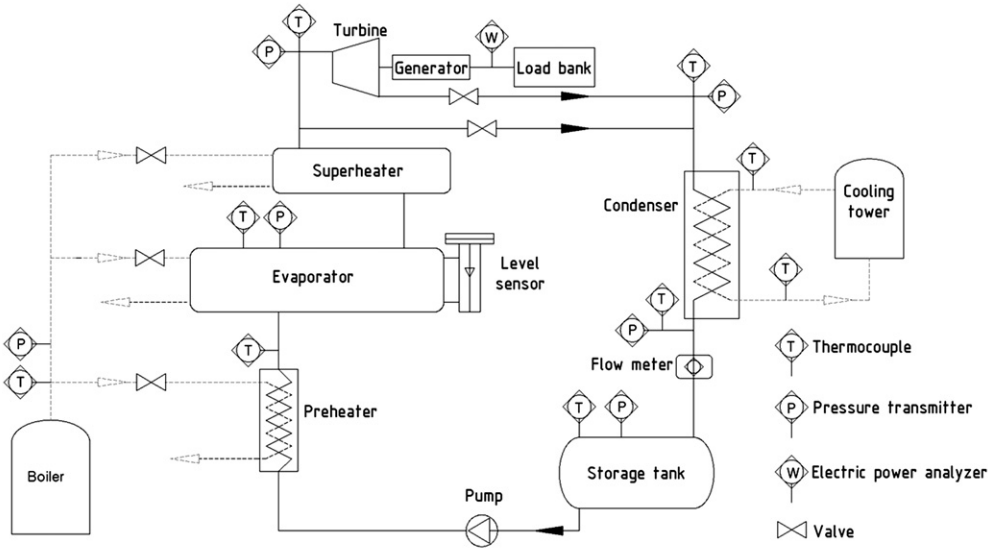

Fig. 1. Schematic diagram of the designed ORC system.