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Design and preliminary tests of ORC (organic Rankine cycle) with two-stage radial turbine

Seok Hun Kang [a], [b], [*]

[a] Korea Atomic Energy Research Institute, Daedeok-daero 989-111, Yuseong-gu, Daejeon, 305-353, South Korea
[b] Korea Institute of Energy Research, 152 Gajeong-ro, Yuseong-gu, Daejeon, 305-343, South Korea

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ABSTRACT

This paper concerns the design and preliminary tests of the ORC (organic Rankine cycle), which generates electric power using R245fa as a working fluid. A two-stage radial turbine expander is designed with an aim of improving the cycle performance by increasing its pressure ratio. The turbine is coupled with a high-speed generator without gear box incurring speed reduction. The turbine is designed in consideration of the thermodynamic properties of the working fluid and the cycle conditions. The design processes of the turbine and cycle are presented in the paper. The performance of the developed cycle and the turbine is examined experimentally, and the factors which influence the performance of the developed ORC are analyzed.

1. Introduction

Rapidly increasing fossil fuel consumption has led to many serious energy and environmental problems such as global warming, air pollution, and depletion of the ozone layer, as well as energy shortages and security issues. As a result, many researches are focusing on the utilization of low-grade heat sources. The ORC (organic Rankine cycle) is regarded as one of the most suitable methods of converting low-grade heat into power among several well-known technologies including the supercritical Rankine cycle, the Kalina cycle, and the trilateral flash cycle [1–3]. The ORC is also known to have superior characteristics in terms of its simplicity and availability, and is already widely applied in many practical areas [4].

The ORC has the same system configuration as the steam Rankine cycle, but it uses organic fluids with low boiling points as a working fluid. The main merit of the ORC is that it is able to generate power using low temperature heat sources like industrial exhausting heat, geothermal heat, and solar thermal energy because of the low boiling point and high evaporation pressure properties of its working fluid. In addition, the ORC is characterized by its simple structure, high reliability, and ease of maintenance [1]. The expander of the ORC is more compact than that of the steam Rankine cycle, since the density of the ORC's working fluid is higher than that of steam. Furthermore, the compactness and efficiency of the ORC can be enhanced by utilizing a dry working fluid as it does not need a super-heater [5]. A considerable amount of research is being conducted on its application for the energy recovery from industrial exhausting heat, biomass energy, the internal combustion engines of ships and cars, solar and geothermal energies, etc.

The ORC technology was demonstrated back in the late seventies and early eighties [6–8]. Today, ORC systems for large-scale industrial heat recovery, biomass and geothermal plants are commercially produced by just a few companies (TRUBODEN, ORMAT, Barber-Nichols, etc.) possessing strong turbine design and manufacturing technologies [9–11]. However, many researches are still being performed with the aim of developing a small-scale (kW scale) system and the technology required for its application to internal combustion engines of cars or ships, solar and geothermal energies, and micro CHP (combined heat and power) systems [8].

A large body of numerical and experimental research has been conducted concerning the ORC, and a number of experimental works have risen remarkably from a decade ago. However, most of the results of thermal efficiency tests conducted in previous studies were found to be low, which was mainly due to the small capacities

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[*] Korea Atomic Energy Research Institute, Daedeok-daero 989-111, Yuseong-gu, Daejeon, 305-353, South Korea. Tel.: +82 42 868 8080; fax: +82 42 868 2075.
E-mail addresses: shkang73@gmail.com, kang@kaeri.re.kr.

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(lower than 10 kW) of the proposed systems. In addition, only a few researches have been conducted on the development of a high-efficiency expander machine whose design took into consideration the system's characteristics such as the cycle operation conditions and the thermodynamic properties of the working fluid. In most of the previous researches, the ORC expanders were designed by utilizing the existing screw, scroll and turbine compressors in the reverse mode, which were themselves modified from commercial refrigeration systems [3,8,12].

Bao et al. presented a comprehensive review of the working fluid selection and the choice of expansion machines for use in the ORC system [1]. They analyzed the influence of the working fluids' types and thermophysical properties on the ORC's performance, as well as the design and operating characteristics of various expansion machines such as turbine, screw, scroll and piston expanders. Recently published experimental researches are as follows. Bracco et al. designed a prototype ORC, and showed the test results obtained in stationary and transient operating conditions. A small-sized (about 1 kWe) scroll expander and a generator from the compressor component of an existing commercial HVAC (heating, ventilation and air conditioning) were installed in the system [13]. Declaye et al. investigated the experimental characteristics of an open-drive scroll expander integrated into an ORC using R245fa as the working fluid. The expander was a commercial air compressor modified to operate in the expander mode. A maximum cycle efficiency of 8.5% was investigated [8]. Aleksandra presented experimental investigations of the hermetic turbogenerator installed in the ORC plant operating with R227ea as the working fluid, and the ORC's electric efficiency was observed to be 4.88% [12]. Li et al. experimentally analyzed the effect of varying the working fluid mass flow rate and the regenerator on the efficiency of an ORC operating on R123. A single-stage axial flow turbine was installed in the system, and a generator was connected to the turbine with a coupler. The experimental results of the power output and the ORC efficiency were shown to be 6.07 kW and 7.98% [3]. Qiu et al. presented an experimental investigation involving a biomass-fired ORC, for which a vane-type air compressor was modified and used as an expander. The electricity generation efficiency and power output were observed to be 1.41% and 861 kW [14]. Lee et al. examined the transient responses of a 50 kW ORC subject to change of the water coolant in the condenser with R245fa as the working fluid, and presented the effect of varying the water coolant flow rate in the condenser on the system's performance [4]. Pei et al. constructed a 3.75 kW ORC system using an R123, and applied a radial turbine to the ORC; the result of their experiment showed isentropic turbine efficiency of 62.5%, while the ORC efficiencies based on turbine shaft power and electricity output were 6.6% and 3.0%, respectively [10]. Quoiline et al. presented both a numerical model of an ORC and an experimental study of a prototype working with an R123. A scroll expander was used, and its isentropic effectiveness ranged from 42% to 68%. The maximum cycle efficiency was 7.4%. The pressure ratio over the expander varied from 2.7 to 5.4, and its influence on the system performance was observed [15]. Wang et al. developed a prototype ORC with a cooling capacity of 5 kW and tested it under laboratory conditions. They applied micro-channel-based heat transfer components and a scroll-based expander to the ORC. The measured isentropic efficiency of the scroll expander reached 84% [16]. Nguyen et al. developed a prototype ORC using n-pentane as the working fluid. A radial turbine coupled to a high-speed alternator directly was used. The power output, thermal efficiency and isentropic turbine efficiency were found to be 1.47 kW, 4.3% and 49.8%, respectively, when the evaporator-condenser pressure ratio was 4.07 [17]. Manolakos et al. presented the on-site experimental evaluation of the performance of a low-temperature solar ORC. Solar heat and HFC-134a were used as the heat source and working fluid, respectively [18]. Kane et al. designed and tested a small hybrid solar power system composed of an ORC comprising a hermetic scroll expander-generator and solar collectors [19]. Yun et al. proposed and evaluated ORC with multi expanders in parallel and experimentally evaluated the feasibility and the fundamental characteristics of the proposed ORC by testing it in different operating modes [20]. Peris et al. characterized the system performance of the ORC designed and built for CHP application and the expander performance through test for micro-CHP applications [21,22]. They also verified the performance of ORC operating in actual industrial conditions and assessed its profitability [23]. Cho et al. conducted experimental study to develop the ORC utilizing fluctuating thermal energy source [24]. Fu et al. designed a 250 kW ORC using turbine expander, and presented the preliminary results under off-design conditions [25]. Jung et al. demonstrated the feasibility of using a zeotropic mixture as working fluid through an experimental study with a 1 kW ORC unit [26]. Lecompte ea al. presented an overview of ORC architectures and the available experimental data [27]. Hu et al. conducted a detailed design and off-design performance analysis based on the preliminary design of turbines and heat exchangers, and presented performance data [28]. Minea investigated the technical feasibility of 50 kW prototype ORC using industrial waste or renewable energy sources at temperatures varying between 85 °C and 116 °C [29]. Xing et al. investigated condensation heat transfer of R245fa in a tube and the effect of inclination angle [30]. Higashi et al. presented R245fa properties measured with two types of isochoric methods [31]. Song et al. reviewed the application and research status of the scroll expander applied to ORC, including its technical features, performances and the main technical limitations existing in application [32].

An expander is a key component that affects the efficiency, size and cost of the ORC system. Generally, expanders are categorized as two types: the velocity type, such as turbine expanders, and the volume type, such as screw, scroll and piston expanders [1,13]. The turbine expander is recognized for its high efficiency and compactness, compared to volume type ones. But it has disadvantages such as high cost and low efficiency in off-design conditions [1]. The turbo expander is categorized as axial and radial types. The axial turbine has a superior advantage in the high expansion ratio which can be increased by adding the expansion stage [9,10]. On the other hand, the radial turbine is known to be suitable for system conditions where the flow rate is low, and is more compact than the axial one [33,34].

Cycle performance is significantly influenced not only by turbine efficiency but also by its expansion ratio. The increases in the turbine expansion ratio and the evaporator-condenser pressure ratio result in improvements in the Carnot and cycle efficiencies. However, the radial turbine, which typically has a single-stage, is limited in terms of increasing the expansion ratio. Generally, the expansion ratio of a single-stage radial turbine is known to be about 4 [34], but such a small value restricts the increase of the pressure ratio [35].

From this perspective, a two-stage radial turbine composed of a HPT (high-pressure turbine) and a LPT (low-pressure turbine) is designed to increase the expansion ratio and to compensate for the weak points of the single-stage one. An ORC capable of producing 40 kW of electric power is also designed. R245fa is adopted as the working fluid, as it is suitable for cycle operation conditions, and is environmentally friendly and safe [16,36]. The R245fa has been used in many studies because of its thermodynamic suitability for low-temperature heat recovery and environmentally friendly and safe characteristics, and its molecular weight, critical pressure and