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A study of the optimal operating conditions in the organic Rankine cycle using a turbo-expander for fluctuations of the available thermal energy

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ABSTRACT

The organic Rankine cycle is widely used to obtain electric power from renewable energy sources, such as solar energy, geothermal energy, and waste thermal energy. In a typical ORC, a turbo-expander or volumetric expander is applied to convert the thermal energy to mechanical energy. The turbo-expander is widely used for large-scale output power because it has merits when used with large mass flowrates; the scroll expander is used for small-scale output power. In ORCs that produce small-scale output power, the available thermal energy as a renewable heat source usually cannot be supplied continuously. For fluctuating levels of available thermal energy, positive displacement machine has difficulty in adjusting the mass flowrate. In order to regulate the mass flowrate for varying thermal energies, a small-scale radial-type turbine and supersonic nozzles were designed specifically for this study. R245fa was used as the working fluid, and the thermodynamic properties of the working fluid in the cycle were predicted on the basis of the designed turbine blade and nozzle shape even though the mass flowrates were varied. The output powers at the off-design operations were predicted for the full range of 30 kW according to the number of nozzles used.

1. Introduction

Much research on renewable energy has been conducted as fossil fuel supplies have begun to be depleted. Most of research has focused on obtaining useful energy efficiently from wind power, solar energy, wave power, waste thermal energy, geothermal energy, and so on. Solar energy is usually converted directly to electric power through the solar cell or to thermal energy through a solar collector. Wind power, geothermal energy, waste thermal energy and wave power are typically transformed into mechanical energy by a turbine or volumetric expander. In addition, most transformed mechanical energy is converted to electric power by a generator. The organic Rankine cycle (ORC) has been widely used for these types of energy conversion because it can convert low-grade thermal energy to useful energy. This occurs because the working fluid (refrigerant) used in the ORC has general characteristics of a low evaporating temperature and a high condensing temperature compared with steam.

An appropriate working fluid for the ORC can be selected through reviewing several aspects, such as the application, level of available heat source, efficient-operation, and so on. In addition, the working fluid should satisfy mandatory criteria [1], such as being environmentally friendly, non-toxic, non-flammable, economical etc. Furthermore, it should not destroy the ozone layer, and also it has a feature of low greenhouse warming potential quotient as well as safe and stable to handle. As a result of these criteria, natural refrigerants such as carbon-dioxide can be used in the ORC, but they require higher operational costs. Thus, working fluids that have been improved from the CFC/HFC refrigerants are widely used in the ORC. Thirty-five screened working fluids have been examined in order to determine their adaptability to the ORC by the cycle performance [2]. The results demonstrated that the working fluids with a high density and high latent heat provide a high unit turbine work output. Working fluids are generally classified as dry ($ds/dT > 0$), isentropic ($ds/dT \cong 0$), or wet fluid ($ds/dT < 0$) depending on the slope of ds/dT in the saturated vapor curve. In the ORC, dry or

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Nomenclature

A	cross-sectional area [m^2]
a	speed of sound [m/s]
C	absolute velocity [m/s]
c_p	constant pressure specific heat [kJ/kg K]
D	diameter [m]
f	frictional coefficient
h	specific enthalpy [kJ/kg]
M	Mach number
$\dot{m}$	mass flowrate [kg/s]
P	pressure [N/m^2]
r	radial direction
R	degree of reaction
Re	Reynolds number
s	specific entropy [kJ/kg K]
T	temperature [K]
U	circumferential velocity [m/s]
V	velocity [m/s]
W	relative velocity [m/s]
x	streamwise direction

Greek symbols

β	blade angle [degree]
ε	partial admission rate [%]
η	efficiency [%]
θ	circumferential direction
κ	specific heat ratio [c_p/c_v]
λ	roughness [m]
Π	power
ρ	density [kg/m^3]
υ	specific volume [m^3/kg]
Ω	rotational speed [RPM]

Subscript

1	nozzle inlet
2	rotor inlet and nozzle exit
3	rotor exit
4	saturated vapor state
5	pump inlet
6	pump outlet
7	saturated liquid state
HX	regenerator
in	input
j	jet
N	nozzle
s	isentropic process
pump	pump
t	total
t–t	total to total
th	thermal
throat	nozzle throat

isentropic fluids are more favorable because they do not require superheating in the evaporator in order to avoid forming moisture in the working fluid during the expansion process.

With regard to solar thermal energy, the ORC was applied to convert the low-grade heat of the solar energy to electrical power. Researches [3–6] to select the appropriate working fluids and to improve the system efficiency were conducted for a low-temperature solar ORC. From the overall analysis including the requirements for the working fluid, R134a, R152a, and R600 were recommended as suitable working fluids in the ORC driven by heat sources with temperatures below 90 °C. The system efficiency was improved from 4.9% to 8.6% using a regenerator for the irradiation of 750 W/m^2. As an application of the high rotational speed expander in the solar ORC, a small-scale turbo-expander was applied to produce an output power of 1.34–1.44 kW when its rotational speed reached 65,000–80,000 RPM [7,8]. Instead of generating electrical power, the solar ORC was used in desalination. Isopentane, isobutane, and R245fa were recommended as adaptable working fluids [9–11].

Waste thermal energy or low-grade heat can be recovered as useful energy by the ORC. Therefore, many ORC systems are being used in these areas. The total heat recovery efficiency was increased when the temperature of the waste heat source was high, and the hydrogen bond molecules such as water, ammonia and ethanol were inappropriate as working fluids because they required a large vaporizing enthalpy [12]. In an ORC for energy recovery of low-grade waste heat, R134a was recommended as the suitable working fluid [13]. In an ORC using the low-grade energy source such as a solar pond or ocean thermal energy, wet fluids with very steep saturated vapor curves in the T–s diagram were recommended [14]. The optimal operating condition in an ORC for waste heat recovery was studied with R245fa. The results demonstrated that the system efficiency and the net power peaked when the degree of sub-cooling was between 0.5 and 0.6 K [15]. For industrial applications, an output power of 20 kW was obtained using the ORC in the ceramics industry, and its efficiency reached 12.5% [16].

In order to generate electrical power from thermal energy through the ORC, a generator coupled with an expander is used. In systems with small-scale output power of less than 10 kW, volumetric expanders are used widely because their efficiency could be better than that of turbo-expanders and their rotational speed is lower based on the design point operation. Thus, scroll, screw, or vane-type expanders have been widely used in small-scale ORCs [17–19]. For 2 kW shaft power, a system efficiency reached 4.6% with R245fa [20]. In a solar cogeneration ORC, a system efficiency of 3.47% was achieved at an output power of 676 W [21]. In order to remove the power consumed by the pump, two scroll expanders with directional valves instead of a pump were used in the ORC, and a continuous power of 20 W was achieved [22].

For large-scale ORC systems, turbo-expanders have been used widely because they exhibit high efficiency for large mass flowrates. In addition, they operate at high rotational speeds so that the ORC can be designed to have a compact size. However, turbo-expanders are not widely used for small-scale ORC systems because they have lower efficiencies at small mass flowrates and require a high-speed generator. Nevertheless, turbo-expanders have merits because they can operate at off-design points for varied mass flowrates. Usually, the thermal energy for regenerating through the ORC is not supplied constantly; therefore, the operating mass flowrate should be adjusted to maintain the cycle according to the available thermal energy. Turbo-expanders maintained their good working characteristics even though the mass flowrate was varied. A millimeter-scale turbine, of which the rotor diameter was 30 mm, was used in the ORC: a system efficiency of 1.25% was obtained at 20,000 RPM for an output power of 150 W [23]. Turbo-expanders of 1.34–1.44 kW were used in the ORC using solar thermal energy [7,8]. A radial-type turbo-expander