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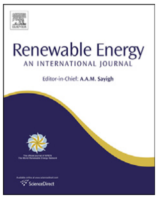

An experimental study on the organic Rankine cycle to determine as to how efficiently utilize fluctuating thermal energy

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ABSTRACT

Thermal properties of the available energy such as maximum temperature and thermal energy capacity are greatly influenced to the design of energy conversion system like the organic Rankine cycle (ORC). Useful thermal energy can be obtained from: waste heat energy, geothermal energy, solar heat energy, biomass energy, and so on. However, these cannot usually be supplied at constant levels. Hence, the temperature and flowrate of the thermal energy can vary while the ORC is working. In order to efficiently utilize such fluctuating thermal energy, an experimental study was conducted while adjusting the mass flowrate and the temperature of the working fluid. Three supersonic nozzles and an impulse type turbine were applied. The supersonic nozzle was adopted to increase the spouting velocity for efficient operation of the impulse turbine. The nozzle was designed to reach a velocity of Mach 1.6 at the nozzle exit, and three nozzles were used to control the mass flowrate in this experiment. The experimental results were compared with the predicted results obtained by the cycle analysis.

1. Introduction

The importance of renewable energy is increasing not only because of the depletion of fossil fuels but also because of its role in environmental protection. Among the many systems capable of producing renewable energy, the organic Rankine cycle (ORC) is usually applied to produce mechanical energy or electricity from the thermal energy of heat sources. If a heat source has high temperature and a large amount of thermal energy, as those found in geothermal sources, the ORC can be a highly efficient facility. However, most heat sources have low-grade thermal energy such as the waste heat discharged by small and medium sized industrial complexes. These kinds of heat sources typically cannot provide constant and continuous thermal energy. Even though some of this energy may be used directly for heating, most of this available thermal energy is discarded. With these considerations in mind, a study was conducted to efficiently obtain renewable energy from these kinds of fluctuating thermal energy sources.

Selection of a suitable working fluid is important to improve the system efficiency of ORC. More than sixty working fluids have been examined for various heat sources, such as waste heat [1–4], solar energy [5–7], and low-grade heat source [8,9]. The published research exploring appropriate working fluids has also been reviewed [10–12]. Ultimately, different working fluids have been recommended depending on the cycle. In this experiment, the adaptable working fluid is very important because the available thermal energy was expected to fluctuate and its temperature could be low. Thus, more than sixty working fluids were screened and eleven working fluids were selected by considering the basic requirements such as not depleting the ozone layer, and low greenhouse warming potential quotient, as well as being non-flammable, non-toxic, safe and stable to handle, economical, and efficient. From eleven working fluids, six working fluids were selected by the operating conditions which were determined to the turbine inlet temperature (TIT) of 60 °C and the temperature of 30 °C on the condenser. Through the cycle analysis with the equal efficiencies on the components, the system efficiency was shown to R-245fa > R-236ea > R-236fa > R-1234ze > R-134a > R-227ea. Hence, R-245fa was chosen for this study.

In order to convert thermal energy to electricity, it needs an expander. There are a number of different types of expanders used

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Nomenclature

A	cross-sectional area [m^2]
D	diameter [m]
h	specific enthalpy [kJ/kg]
M	Mach number
$\dot{m}$	mass flowrate [kg/s]
P	pressure [N/m^2]
Re	Reynolds number
s	specific entropy [kJ/kg K]
T	temperature [K]
U	uncertainty
x	streamwise direction

Greek symbols

η	efficiency [%]
Π	power [kW]
ρ	density [kg/m^3]
υ	specific volume [m^3/kg]

Subscript

1	nozzle inlet
5	pump inlet
6	pump outlet
in	input
is	isentropic process
out	output
s	saturated state
sys	system
t	total
tb	turbine

on the ORC, including scroll, screw, reciprocating piston, vane and turbo type, and so on. When the mass flowrate is widely varied due to the fluctuating thermal energy, the turbo-type expanders can be a good candidate because they can work well at various rotational speeds as well as they can be compact [13–18]. Hence, the turbo expander, hereafter called a “turbine”, should be operated at partial admission. If the turbine is intended to operate in partial admission conditions, it should be an impulse type. In the impulse type turbine, an appropriate way to obtain more output power is to increase the spouting velocity of the working fluid. However, the speed of sound in the saturated vapor of R-245fa is approximately a quarter the speed of sound in steam. Hence, three supersonic nozzles and an impulse type turbine were applied to the ORC in order to obtain output power continuously from the fluctuating thermal energy of the heat source, and also to find a better cycle on the ORC, which could operate with the low-grade thermal energy.

2. Experimental facility

A schematic diagram of the experimental facility is shown in Fig. 1. It consists of a pump, an evaporator, a condenser, a regenerator, and a turbine. In the evaporator (D), the working fluid was heated by the thermal mass whose mass flowrate and temperature were controlled by the heat source (C). Before entering the evaporator, the working fluid is heated in the regenerator (H) to increase the thermal efficiency of the system by utilizing the thermal energy remaining after the expansion process on the turbine (A). The turbine consists of an impulse type rotor and supersonic nozzles which were installed circumferentially around the rotor casing to adjust the mass flowrate of the working fluid according to the fluctuating thermal energy. A generator (B) was directly connected to the turbine.

The working fluid supplied from a tank (E) was pressurized by a pump. Its mass flowrate could be adjusted by controlling the rotational speed of the pump or by installing a bypass valve (I). A flowmeter was installed ahead of the regenerator (H). Thermometers and pressure sensors were installed along the main line before and after on each device. The temperature measured ahead of the turbine inlet was transmitted to the heat source (C) to control the evaporated temperature of the working fluid. In order to control the saturated temperature in the returning line, the cooler (G) monitored the temperature measured at the exit of the condenser (F). Fig. 2 shows a cycle using a pressure–enthalpy (P–h) diagram; the digits in the figure are matched with those shown in Fig. 1. A picture of experimental facility is shown in Fig. 3. Table 1 shows the installed the measuring instruments and their measurement accuracy in full scale.

3. Nozzle and turbine

If an impulse type turbine is applied as the expander, the nozzle can play a very important role in performance, because the working fluid is fully expanded in the nozzle and its power is then transferred to the rotor. Hence, the spouting velocity at the nozzle exit, along with the mass flowrate, determines the output power of the turbine. In order to increase this velocity, the nozzle was designed to have a converging and diverging shape. As a design point, the pressure of 1.265 MPa and the temperature of 100 °C were chosen

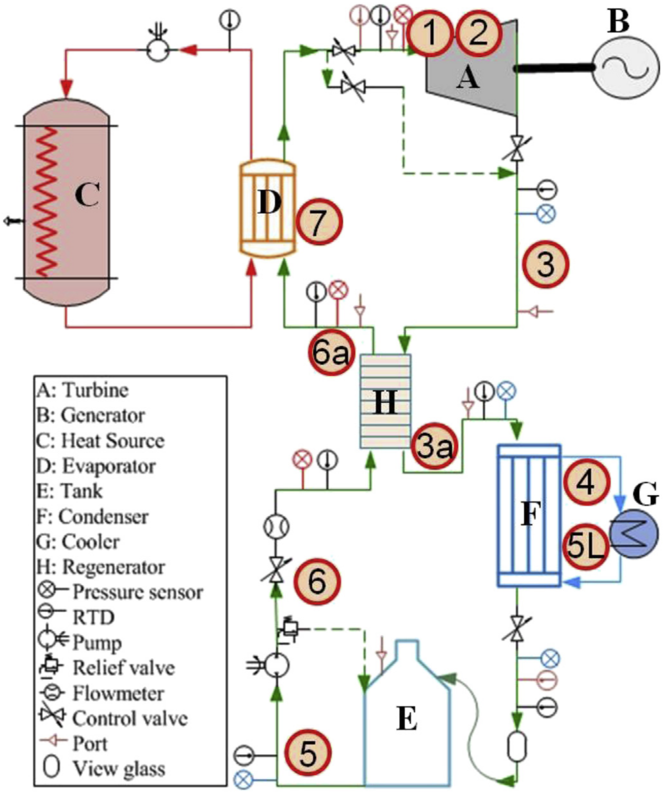

Fig. 1. Schematic diagram of the experimental facility.