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Design and thermodynamic and thermoeconomic analysis of an organic Rankine cycle for naval surface ship applications

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ABSTRACT

This paper presents the thermodynamic modeling of an organic Rankine cycle (ORC) that uses waste exhaust energy of a 1000 kW diesel generator on a naval ship. Seven different working fluids have been selected as the ORC fluids. The commercial software (EES) has been used to predict the thermodynamic properties of the selected fluids. The efficiency of the ORC goes up to 32% with toluene. For the needed generator power of 500 kW on cruising, the ideal ORC can produce 118 kW power with the working fluid toluene. Assuming an isentropic efficiency for the turbine and the pump of the case ORC to be 0.75 and 0.20, respectively, and neglecting the losses at the ORC electric generator, the electric power output of the ORC cycle becomes 92 kW. The power of the diesel-ORC system becomes 592 kW while the combined efficiency is calculated as 0.349. The ORC saves 25,500 L of diesel fuel (US$24,870) and reduces 67.2 tons of CO_2 emissions at the end of 1000 operating hours. ORC working fluids may result different efficiencies at different temperatures. Therefore, a combined ORC system is proposed to get higher efficiencies at different thermal loads. The exergy efficiencies and irreversibilities were calculated.

1. Introduction

Energy is ability of a system to do work. High cost of energy and the environmental effects of energy consumption cause enormous stresses on the world. Fossil fuel has commonly been used to produce energy. But, the consumption of fossil fuels has caused many environmental problems including air pollution, acid rain, and global warming. Rankine Cycle using fossil fuel is still a dominant power supply method.

Low-grade waste heat accounts for 50% or more of the total heat generated in industry, and it has generally been discarded due to lack of efficient recovery methods. Therefore, recovery of low-temperature waste heat and renewable energy is attracting much research attentions [1]. Rankine cycle using water as working fluid does not allow efficient recovery of waste heat below 370 °C. Many problems are encountered in steam Rankine cycle when water is used as the working fluid: Superheating is needed to prevent condensation during expansion, risk of erosion of turbine blades, high pressure in the evaporator, and complex and expensive turbines [2,3]. Various thermodynamic cycles can be used for conversion of low-grade heat to work, such as supercritical Rankine cycle, organic Rankine cycle, and Kalina cycle. But organic Rankine cycle has the characteristic of simple structure, easy maintenance and high reliability [4]. Therefore, it has many uses including industrial waste heat [5], biomass energy [6], geothermal energy [7], and solar energy [8]. Guo et al. studied thermal efficiency, influence of recuperator and exergy destruction for a 240 MW pulverized coal-fired power plant. The analytical results show that the mixture that matches with heat sink has the greatest efficiency and the mixture that matches with heat source has the lowest superheat degree. There exists no optimal working fluid for all indicators (thermal efficiency, heat exchanger area, mass flow and volumetric flow etc.) [5]. Liu et al. presented the results of thermodynamic modeling studies of a 2 kW biomass-fired system with organic Rankine cycle. They used three different environmentally friendly refrigerants to predict the efficiency of the system [6]. Desai and Bandyopadhyay reported thermo-economic comparisons of organic Rankine and steam Rankine cycles powered by line-focusing concentrating solar collectors. They also proposed a simple selection methodology, based on thermo-economic analysis, and a comparison diagram for working fluids of power generating cycles [8]. Hung et al. investigated the effects of turbine inlet temperature and condenser outlet temperature at different pressures on the efficiency of the Rankine Cycle for different working fluids [9]. Bao and Zhao have reviewed the influence of working fluid

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Nomenclature

A	heat transfer area (m^2)
h	enthalpy ($kJ\ kg^{-1}$)
I	*irreversibility*
$\dot{m}$	mass flow rate ($kg\ s^{-1}$)
υ	specific volume ($m^3\ kg^{-1}$)
P	pressure (Pa)
R	resistance ($m^2\ KW^{-1}$)
s	specific entropy ($J\ kg^{-1}\ K^{-1}$)
S	entropy ($J\ K^{-1}$)
T	temperature (K)
U	overall heat transfer coefficient ($Wm^{-2}\ K^{-1}$)
$\dot{V}$	volumetric flow rate ($m^3\ s^{-1}$)
w	specific work ($J\ kg^{-1}$)

Greek letters

ρ	density ($kg\ m^{-3}$)
$\in$	effectiveness of heat exchanger
η	efficiency (%)

Subscripts

ex	exergy
f	fouling
i	internal
lm	log mean
o	external
ORC	organic Rankine cycle
P	pump
PP	pinch point
rev	reversible
s	isentropic
t	turbine

properties on organic Rankine cycle, the screening of working fluid, and the comparison of different types of expansion turbines [4].

Different types of waste heat recovery technologies can be used onboard ships, which can be turbo charging of air into the engine, absorption refrigeration, thermoelectric generation, or combined power cycles [10]. The International Maritime Organization has developed a global CO_2 reduction index known as the Energy Efficiency Design Index for new ships and the Ship Energy Efficiency Management Plan for all ships. The new chapter added to MARPOL ANNEX VI Regulations for the prevention of air pollution from ships, which was implemented on January 1, 2013, aims to reduce the emission of greenhouse gases, specifically CO_2 emissions [11]. Implementing CO_2 reduction measures will result a significant reduction in fuel consumption. Therefore, searching for new energy conservation methods that can be applied onboard ships is necessary [12]. The potential of waste heat recovery is among the most important technologies to lower fuel consumption. Larsen et al. compared ORC, the Kalina cycle, and the steam Rankine Cycle in a combined cycle application with a large marine two-stroke diesel engine. It is concluded that the ORC has the greatest potential for increasing the combined thermal efficiency [13]. Carcasci et al. illustrated the results of the simulations of an ORC combined with a gas turbine in order to convert waste heat into electric power. Four different ORC working fluids were compared to identify best choice. Rankine cycle was optimized by varying the main pressure of the fluid at different temperatures. The possible use of a superheater was also investigated in order to increase electrical power [14]. Khaljani et al. optimized a cogeneration system consisting a gas turbine and an ORC with selected decision parameters. It is reported that the gas turbine inlet temperature has important role on the trade-off between exergy efficiency and cost criteria [15].

In this study, seven different ORC fluids have been compared on an ORC design which uses the thermal energy of a diesel engine of a naval ship. A combined ORC cycle using two different ORC fluids has been proposed to reach higher efficiencies.

2. Organic Rankine cycle (ORC)

Organic Rankine cycle (ORC) applies the principles of Rankine cycle using an organic fluid that has a low boiling point to recover heat from low temperature heat sources. A simple ORC converting waste heat from exhaust gases into useful work, and a typical T-s diagram is seen in Fig. 1.

There are four main components and ideal processes of this system: An evaporator for recovering waste heat from exhaust gases, a turbine for expansion of the working fluid and producing work, a condenser for transferring heat to the environment, and a pump for increasing the pressure of the working fluid. Evaporator is the component to recover waste heat which may be in various types, such as solar heat, waste heat of flue gas, and geothermal heat. The fluid is heated in the evaporator and a phase change occurs from compressed liquid to saturated vapor. After the evaporator, the working fluid at high pressure expands in the turbine and produces electrical work at the generator connected to the turbine. According to the 2nd law of Thermodynamics, a heat engine should run between at least two heat sources to produce net work. Therefore, some amount of heat should be transferred to outside environment in condenser to change phase of the working fluid to saturated liquid at an ideal Rankine cycle. Then, the liquid is pumped into the evaporator to absorb waste heat. Even though the points 1 and 2 seem to be the same points in T-s diagrams as seen in Fig. 1, actually they are two different points. The point 2 is after the pump where the point 1 is before the pump.

A higher evaporator pressure gives better efficiencies in ORC power systems. But one restriction for evaporator pressure is pinch point (PP) temperature which shall be kept above zero. Pinch point is defined as the point at which the temperature difference between the hot and the cold fluid is minimum. This point is a fundamental parameter when designing a practical ORC. Pinch value must always be positive, in order to make the heat exchange possible. A small value of pinch corresponds to a very difficult heat transfer and therefore requires more heat exchange area. The minimum temperature difference occurs in evaporator at the point of saturated liquid as seen in Fig. 2.

3. Working fluids

The saturation curve is the most crucial characteristic of an ORC working fluid. This characteristic affects the cycle efficiency, fluid applicability, and the arrangement of the associated equipment in an ORC power-generation system [9]. The slope of the saturation vapor curve of a fluid in T-s diagram can be negative (e.g. water), vertical (e.g. R11), or positive (e.g. *n*-hexane), and the fluids are called "wet", "isentropic", and "dry", respectively. Typical T-s diagrams of wet, isentropic, and dry fluids are seen in Fig. 3.

Wet fluids like water need to be superheated, because as they enter the turbine in saturated vapor phase, the percentage of satu-